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F. Caviglioli

*International Conference
on Military Conversion and Science
“Utilization/Disposal
of the Excess Fissile Weapons Materials:
Scientific, Technological and Socio-Economic Aspects”*

Center of Scientific Culture “A. Volta”
Como, Villa Olmo – 18-20 March 1996



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Villa Olmo - Center of Scientific Culture "A. Volta"
Hosts of the International Conference
on Military Conversion and Science
"Utilization/Disposal of the Excess Fissile Weapon Materials:
Scientific, Technological and Socio-Economic Aspects"
18-20 March 1996

*The authors are responsible for the choice and the presentation
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**INTERNATIONAL CONFERENCE ON
MILITARY CONVERSION AND SCIENCE
“UTILIZATION/DISPOSAL OF THE
EXCESS FISSILE WEAPON MATERIALS:
SCIENTIFIC, TECHNOLOGICAL
AND SOCIO-ECONOMIC ASPECTS”**

Center of Scientific Culture “A. Volta”
Villa Olmo, Como, Italy
18-20 March 1996

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Outcomes of the International Conference Military Conversion and Science “Utilization/Disposal of the Excess Fissile Weapon Materials: Scientific, Tecnological and Socio-Economic Aspects”

18-20 March 1996 - Como, Italy

The end of the Cold War confrontation greatly improves the prospects for peace and disarmament. The nuclear arms reduction agreements between the U.S. and the states of former USSR will mean that large quantities of highly-enriched uranium (HEU) and weapon plutonium (W-Pu) will no longer be used for military purposes. The ongoing dismantlement of tens of thousands of nuclear weapons retired under the START I and START II treaties and U.S. and Russian unilateral reductions should result in over 100 tonnes of excess W-PU and 700 tonnes or more of excess HEU. In addition, there are currently over 100 tonnes of separated civilian plutonium, which could also be used in nuclear explosives.

The international scientific and technical community is faced with the problem of finding reliable methods for the disposition (utilization or disposal) of these quantities of fissile materials that meet the criteria of ensuring nonproliferation and the irreversibility of nuclear arms reductions in a timely and cost-effective manner, while protecting the environment and public health and maintaining nuclear safety.

The international conference on Military Conversion and Science, “Utilization / Disposal of the Excess Fissile Weapon Materials: Scientific, Technological, and Socio-Economic Aspects,”

held on 18-20 March 1996 in Como, Italy, evaluated the issues related to this pressing question facing the international scientific and technical community.

The problem of disposition of HEU is technically straightforward and profitable: it could be completely converted to civil use by blending down to low-enriched uranium for reactor fuel, which has substantial commercial value. To this purpose, the U.S. and Russia have signed an agreement under which the United States will purchase 500 tonnes of HEU from dismantled Russian weapons over the next 20 years. This agreement reduces the stockpile of weapons-usable materials and provides a direct financial incentive for continued weapons dismantlement. The U.S. is planning also to blend down its own excess HEU. There are limitations on the rate at which this material can be introduced onto the markets for both uranium and enrichment services, some of which could be addressed by political decisions. To reduce proliferation risk and contribute to irreversibility, blending of HEU could be done in the near term, independently of the release of the material onto the commercial market.

The disposition of W-Pu is more complex since it is impossible to eliminate its potential proliferation hazard by simple dilution operations or other chemical processes. Although civil plutonium is currently recycled in commercial reactors in Europe, neither the US nor Russia have the technological experience and appropriate facilities to start plutonium disposition on a large scale in the near future.

Because no plutonium disposition option is ready for immediate implementation, storage will be required for a substantial period for all options. It is therefore urgent and essential to provide safe and secure storage facilities for fissile materials, and to ensure that all weapons-usable fissile materials, both military and civilian, are secure and accounted for. International cooperation toward this end, including the construction of a safe and

secure storage facility at Mayak, Russia, should be continued and expanded.

During the period of storage, placing the material under international safeguards could provide the international community with confidence that this material will not be re-used in weapons.

Transportation of weapons-usable fissile materials also requires special attention, to ensure safety and nonproliferation. In some cases, this may argue for disposition solutions that would minimize the amount of transportation required.

The preliminary conversion of metal plutonium weapons components to stable, unclassified forms is an essential first step for all disposition options. There is no fundamental technical obstacle to accomplishing this conversion, but industrial-scale facilities for this purpose do not yet exist in either the United States or Russia. Several chemical and mechanical processes are being considered.

Scientific, technological, environmental and economic aspects of different options for final W-Pu disposition were discussed at the meeting. Some options achieve the security goals of plutonium disposition by use of the plutonium as reactor fuel, while others involve disposal of the material as waste. It is desirable to ensure that disposition of excess weapons plutonium results in a reduction in overall stockpiles of separated weapons-usable plutonium. This would be consistent with the proposed global fissile cutoff convention prohibiting further production of plutonium and HEU for nuclear explosives.

The nuclear industry's existing experience with plutonium fuel, particularly in Western Europe but also in Russia and Japan, provides the foundation for peaceful use of the energy potential of excess weapons plutonium in either fast-neutron or light-water reactors. It was noted that CANDU reactors in Canada could also use plutonium fuels. Disposal of plutonium is also a viable option to be considered, based on existing experience with the manage-

ment of high-level wastes (with appropriate modifications to the known processes for the inclusion of substantial quantities of plutonium).

The Russian Ministry of Atomic Energy (MINATOM) prefers to use plutonium as reactor fuel rather than disposing of it as waste. The MINATOM concept emphasizes the use of excess weapons plutonium in fast-neutron reactors. A single new-design Russian fast neutron reactor, of the BN-800 type, would be sufficient to process 50 tons of excess weapons plutonium to spent fuel during 30 years of operation. Different designs for fast-neutron breeder, conserver and burner reactors developed in other countries were also presented. In addition, possibilities exist to use operating light-water reactors of the VVER-1000 type or new-design light-water reactors. However, Russia has no experience with plutonium-uranium mixed oxide (MOX) fuel in light-water reactors, and development of this option is now underway. Other available thermal reactors in Russia are not well suited to the use of MOX fuel.

France and Russia, in their bilateral cooperation, are considering the possibility, as an initial step, of construction of pilot conversion and MOX fabrication facilities with a capacity of 1-1.3 ton plutonium per year, which would be sufficient for partial cores of the existing BN-600 fast reactor and the four existing VVER-1000 reactors at the Balakovo site.

The United States is intensively studying a wide range of disposition options, including options for both disposal and use as fuel in thermal reactors, and expects to have the information legally required for a decision by the end of 1996. Methodologies for analyzing and selecting among the alternatives were presented at the conference.

The nuclear industry in the European Union has accumulated over the last ten years a thorough practical experience in the use of civil plutonium with various isotopic compositions in existing thermal power plants. Japan also has substantial experi-

ence in the use of plutonium as reactor fuel, which was described at the conference. It was emphasized that this experience puts the nuclear industry in Europe in a position to provide its expertise to the U.S. and Russia for the use of W-Pu as MOX in light water reactors.

It was agreed that the U.S. and Russian optimum final plutonium disposition options could be different because of their different experience base and their economic and political situations.

Japanese participants pointed out that Japan is using nuclear energy only for peaceful purposes and that the countries which produced weapon plutonium are responsible for its disposition.

Disposition of plutonium should be accomplished as quickly as practical, to ensure the irreversibility of nuclear arms reductions. At the same time, it is also important that disposition of U.S. and Russian excess weapons plutonium should proceed in parallel, so as to maintain similar stockpiles of fissile materials as the reductions process continues. To facilitate such a parallel program, a Strategic Materials Reduction Treaty (SMART) was proposed, establishing an agreed timetable for rapid, mutual reduction of inventories of weapons-grade fissile materials. There was broad support for this idea.

Ongoing bilateral and multilateral cooperation on plutonium disposition was described, and it was generally agreed that this cooperation was essential and should be continued and expanded substantially. The conference underlined that all types of international cooperation should be pursued, including work through international governmental and non-governmental organizations, with a particular focus on carrying out the technical development and demonstrations required to implement the disposition options. Initiatives to solve this problem from international organizations should be welcomed, as part of the broader culture of peace.

There was an extensive discussion, with a variety of differ-

ing views, concerning the economics and other advantages and disadvantages of the closed nuclear fuel cycle versus the open nuclear fuel cycle in the present and for the long term, including the availability of uranium resources. These points will continue to be the focus of technical and economic debate for some time to come.

There was an extensive discussion of the economics of plutonium disposition. A key problem is financing the large capital investments of hundred millions of U.S. dollars required for realization of excess weapon plutonium disposition, both in Russia and in the U.S.

Taking into account the present economic situation in Russia, it is desirable to organize an approach to financing of Russian disposition on an international level that can be sustained over the long term, proceeding step-by-step. Different proposals were discussed. It was agreed that there is an urgent need to find a financing approach acceptable to all parties involved as soon as possible.

It was agreed that an international joint-venture that would build and operate plutonium disposition facilities under stringent nonproliferation controls, financed through additional sales of Russian HEU, could be a potentially promising approach to addressing the most difficult issues facing the disposition problem in Russia.

The importance of ensuring nuclear safety throughout the process of disposition, and of obtaining public acceptance of weapons disposition activities, was underlined. The important role of the mass media in shaping the public attitude toward this problem was emphasized.

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OPENING OF CONFERENCE

The International Conference on Military Conversion and Science “*Utilization / Disposal of the Excess Fissile Weapon Materials: Scientific, Technological and Socio-Economic Aspects*” was opened in the presence of local authorities, honourable guests and members of the international and local organizing committees.

Mr. A. Botta, Lord-Mayor of Como, Mr. G. Livio, President of the Province of Como, Mr. V. Keniakin, Ambassador of the Russian Federation in Italy, Mr. E. Campo, Head of the Division of the Italian Ministry of Foreign Affairs, Dr. V. Kouzminov, Chief of the UNESCO Venice Office, Prof. M. Martellini, Secretary General of the Landau Network Coordination Center, Prof. G. Casati, Dean of the II Faculty of Science of the University of Milan welcomed the participants in the conference and contributed to the justification of the programme of this international encounter.

The opening session was followed by Prof. U. Farinelli's presentation of the introduction to the conference and outline of the conference programme.

The full texts of presentations by Mr. E. Campo, Prof. M. Martellini, Prof. G. Casati, Dr. V. Kouzminov and by Prof. Farinelli are provided in these proceedings.

Eugenio Campo

Riunendo a Como, alla vigilia del Vertice dei G7 a Mosca sulla sicurezza nucleare, eminenti scienziati perché forniscano una risposta agli interrogativi che pongono sulle conseguenze dello smantellamento degli ordini nucleari, il Landau Network ha reso un grande servizio al mondo politico, al mondo scientifico e all'umanità intera.

Cadute oramai le barriere ideologiche e cessati i condizionamenti della guerra fredda, è tempo per gli scienziati di parlare con franchezza sulle grandi questioni di oggi connesse agli sviluppi scientifici ed ai pericoli che sovrastano il futuro ed è tempo per i Governi ed i politici di prestare ad essi la massima attenzione.

Il Ministero degli Esteri è lieto di avere concorso pur con le sue limitate risorse al successo delle iniziative di dialogo che hanno fatto del Landau Network un centro di qualificata competenza per la discussione di problemi scientifici che hanno riflessi in campo sociale ed economico.

Siamo lieti del pari che il Landau Network abbia instaurato un collegamento organico con l'UNESCO attraverso l'Ufficio Regionale di Venezia. Sarebbe utile e fecondo di risultati un collegamento analogo con tutte le organizzazioni internazionali che si pongono lo stesso obiettivo di sviluppare il dialogo e la collaborazione con gli scienziati dell'est europeo, in primo luogo con il Comitato Scientifico della NATO. Il Ministero degli Esteri offre la sua piena disponibilità a favorire questi sviluppi.

English Translation

This encounter at Como organized by the Landau Network with eminent experts discussing the theme of nuclear disarmament is timely on the eve of the G7 Summit which will take place in Moscow.

It is necessary that the experts here openly discuss all questions related to scientific development and their risks to humanity and bring this information to the attention of all Governments.

The Ministry of Foreign Affairs is pleased to have been able to assist the highly qualified center of the Landau Network in this initiative.

We are also pleased that the Landau Network has established an effective collaboration with UNESCO through its Venice Office. The Ministry is favourable to these joint collaborations with international organizations and the development of dialogues and exchanges with scientists from eastern Europe as well as the Scientific Committee of NATO.

Giulio Casati

Maurizio Martellini



The disposition of fissile materials from dismantled nuclear weapons is the main topic discussed and evaluated in the International Conference of Military Conversion and Sci-

ence “Utilization/Disposal of Excess Fissile Weapon Materials: Scientific, Technological and Socio-Economical Aspects” organized by the Landau Network Coordination Centre (LNCC) at the Scientific Cultural Centre “A. Volta” in collaboration with UNESCO Venice Office, the Italian Ministry of Foreign Affairs, ENEA and Moscow International Energy Club.

The LNCC is a higher education cooperation structure activated in December 1993 in the frame of the activities of the Scientific Cultural Centre “A. Volta”, a non-profit, non-governmental cultural association.

The LNCC is devoted to enhance any form of cultural and scientific cooperation between scientific institutions and communities on a world-wide basis and particularly among scientists belonging to countries of the former Soviet Union and Europe. The LNCC has been founded by Prof. Isaak Khalatnikov, Honorary Director of the Landau Institute in Moscow, Prof. Giulio Casati, Dean of the Second Faculty of Sciences of

Milano University and Prof. Maurizio Martellini, Professor of Physics at Milano University.

We believe that no real safety, no real control is possible without complete confidence among the Nations. With the end of the Cold War, the world is more linked and the prospects for world-based joint projects of peace and global disarmament are less utopistic! The LNCC wishes to contribute to this general process by helping the development of mutual understanding among East and West Country scientists, as well as among opinion makers and political leaders.

On the other side, the LNCC with the contribution of the Cariplo Foundation for Scientific Research, has recently signed a protocol of cooperation between the Russian Academy of Sciences and the Italian Universities in Lombardy devoted to the assignment of a certain number of fellowships. In this connection, we would like to thank Prof. Roberto Artoni, President of the Cariplo Foundation for Scientific Research, for having allowed the concrete realization of this project which goes in the direction of that “culture of peace” advocated in the opening talk by Dr. Vladimir Kouzminov, Chief of the UNESCO Venice Office.

We should mention in the end that our International Conference, the third in order on similar topics, has been made possible thanks to the continuous and strong support of the local Municipality of Como, the Italian Ministry of Foreign Affairs, the Italian Ministry of University and Scientific Research and the UNESCO Venice Office. In this connection we are particularly pleased to mention Dr. Eugenio Campo, Chief of Cultural Policies Office of the Italian Ministry of Foreign Affairs, Dr. Vladimir Kouzminov, Chief of the UNESCO Venice Office and Prof. Giorgio Salvini, Minister of University and Scientific Research.

We think that it would be nice to conclude our introduction with the words of Minister Salvini “we are all conscious that there are danger and tragedies in our future, but we must face them together”.

Vladimir Kouzminov



Mr. Chairperson
of the Organising Committee
Mr. Lord-Mayor of the City of Como
Respective representatives
of Italian authorities
Ladies and Gentleman,
Dear colleagues,

I am honoured, on behalf of Prof. Federico Mayor, Director General of UNESCO to welcome you to the International Conference on Military Conversion and Science “*Utilization/Disposal of the Excess Weapon Plutonium: Scientific, Technological and Socio-Economical Aspects*”, which is convened by the Landau Network for Scientific Exchange with the involvement of the UNESCO Venice Office, the Italian Ministry of Foreign Affairs and in co-operation with a number of national and international institutions among which I am particularly pleased to mention ENEA and the Moscow International Energy Club.

More than one year has passed since the first international meeting was convened by the UNESCO Venice Office in Venice, Italy with the general title “*Military Conversion and Science*” and at which the importance of a very balanced and scientifically justified approach to the problems of nuclear disarmament was underlined. Since then our Office has found very effective and reliable partners particularly the Landau Network and the Centre of Scientific Culture “*Alessandro Volta*” which expressed their readiness to co-operate with the UNESCO Venice office in general reflections of military conversion problems with special attention paid to nuclear disarmament problems.

We realise that the problems of military conversion and of nuclear disarmament are covered by many political and specialised international organisations and from the very beginning I should like to underline that we do not intend to penetrate and overlap their areas of competence. Our objectives are to arrange purely scientific reflections of the problems, and we expect that their outcomes could further help the political institutions to take more balanced decisions related to the above delicate issues.

Ladies and gentlemen,

The United National Educational, Scientific and Cultural Organisation, (UNESCO) was created 50 years ago on 16 November 1945 in London when representatives of the governments of 37 countries signed the UNESCO Constitution.

UNESCO was established shortly after the Second World War, one of the most violent and destructive political and military conflicts in the history of mankind. UNESCO's major objectives are the same as that of other specialised agencies of the United Nations Systems: to promote ***"international peace and the common welfare"*** through ***"collaboration"*** among nations.

In this endeavour however, UNESCO plays a specific role, because peace must be founded ***"upon intellectual and moral solidarity"***, because ***"wars begin in the minds of men it is in the minds of men that the defence of peace must be constructed"***. Its mission is above all ethical, concerned with the human spirit.

These basic objectives of UNESCO are still valid inspite of the fact that more than 50 years have passed after the Constitution's elaboration and adoption.

The UNESCO's constitutional mandate to construct the defences of peace in the minds of men and women has become even more important now when the world community has started its transfer from the dominant culture of war to the culture of

peace. This process which has been started with the end of the Cold War, is still slow and fragile and needs active actions in all areas of human activities and first of all in intellectual life.

That is why a few years ago, UNESCO launched the Culture of Peace Programme which should unite all components of intellectual efforts aimed at the promotion and introduction in our life of the ideas and principles of peace.

The culture of peace is the process of building trust and co-operation between peoples. It means learning to use words instead of weapons to resolve conflicts. It means fighting hunger and social injustice rather than each other. It means governments spending their resources on social programmes, not armies.

The Culture of Peace Programme of UNESCO is focused on the above philosophy and is composed of concrete actions aimed at the creation of favourable socio-economic, political and cultural environment at international, regional, sub-regional and national levels. It is also believed that the ideas of a culture of peace should reach not only political circles of member-states but also each family and each individual who are in fact the basis of our society.

The concept of a culture of peace was first elaborated for UNESCO at the International Congress on Peace in the Minds of Men in Yamoussoukro, Cote d'Ivoire, July, 1989. UNESCO was urged by the Congress to ***“construct a new vision of peace culture based on the universal values of respect for life, liberty, justice, solidarity, tolerance, human rights and equality between women and men”***. The Yamoussoukro Declaration called on UNESCO to promote education and research on peace and to develop measures for the ***“enhanced application of existing and potential international instruments relating to human rights, peace, the environment and development”***.

Virtually every meeting of the UNESCO Executive Board as well as the 27th and 28th General Conferences of the Organisation have discussed the concept of a culture of peace since it

was first proposed in 1992. From the beginning the Governing Bodies of UNESCO recognised its basis in the respect for human rights and universal values enumerated in the Declaration of Yamoussoukro. They considered it as the expression of the fundamental mandate of UNESCO to ***“contribute to peace and security by promoting collaboration among the nations through education, science and culture”*** and that UNESCO’s role is an integral part of the overall responsibility of the United Nations family contributing to the construction of peace.

Of course, this is not an easy task for people and organisations involved in the culture of peace process, especially at this initial phase.

Within this process, science, an unique phenomenon of mankind and integral part of its culture, occupies a special, very delicate position since it has been one of the major contributors to the creation of giant wars arsenals world-wide. During the Cold War period, some countries made intensive use of both fundamental and applied science for military research and development for creating sophisticated arms for mass-killing and mass-destruction.

Enormous capital investments have been made to date in building research centres and production capacities for this purpose. Into these military-oriented R&D efforts the best brains of almost all industrially developed countries were poured consequently military-industrial complexes can be considered as the most qualified institutions for resolving the problems of military conversion and moreover they should take a lead in this process, international organisations of different levels play an important role in this particular field.

A number of international governmental and non-governmental organisations have already made and continue to make their substantial contribution in identifying the role of Science in the culture of peace.

Among them we should mention the Pugwash Conference,

the North Atlantic Treaty Organisation (NATO), the Organisation for Security and Co-operation in Europe, the Council of Europe and of course the United Nations with its specialised Agencies, among which we should mention the International Agency for Atomic Energy and UNESCO.

What has UNESCO done in this particular field?

The Genoa Declaration on Science and Society which was elaborated and adopted by the Genoa Forum on UNESCO on Science and Society in October 1995 has emphasised the role of science as one of the most valid instruments for the dialogue between cultures and identified the basic principles applied to science and to scientific communities. The respect of these principles and the latter's introduction into practice will help to avoid the intensive involvement of science into military R & D.

During last year UNESCO sponsored the establishment in Israel of the *UNESCO-Hebrew University of Jerusalem International School for Molecular Biology and Microbiology* under the general title "Science for Peace".

In December 1994, in Venice the UNESCO Regional Office for Science and Technology for Europe convened the International Round Table on Military Conversion and Science mentioned above as a follow-up of the recommendations of the International Seminar on Brain Drain Issues in Europe held in 1993.

This Round Table was productive and its findings have contributed to the better understanding of the problems of R & D conversion. Moreover this international meeting outlined some urgent issues of the military conversion process which should be brought to the attention of scientific communities and to national and international scientific institutions.

Issues to examine include science and technology status in military R & D, human resources dislocations, incentive strategies, socio-economic phenomena such as brain-drain, the transformation of educational and scientific institutions and of culture in general.

It was stated that the machinery of conversion is to be driven in parallel with the new culture of peace being promoted by UNESCO.

The meeting also emphasised that strategically driven military conversion aims to minimise waste of intellectual resources and maximise the exploitation of existing technologies and materials for civilian use.

The problems of the utilisation of the military nuclear complex for peaceful purposes were presented at this meeting by Prof. P. Zaleski from France in his paper with the same title which analysed different points of view on this issues.

The participants in the meeting had a common feeling that among scientists working in different countries or even in the same countries but in different institutions there is not a common approach in this critically important area and moreover each option is not enough elaborated.

It should be mentioned that the involvement of scientific communities in the process of the justification of the necessity of nuclear disarmament was very productive and visible.

Let us only recall the concept of “*nuclear winter*” which was a result of common efforts of specialists from practically all areas of modern science, constant efforts of the Pugwash Conference as well as other internationally sound projects which in fact provided political leaders with a solid scientific background for the elaboration and adoption of famous nuclear disarmament treaties which were concluded in late 1980s.

Several years have already passed since then and unfortunately we can say that a mutually acceptable and scientifically justified way of a nuclear disarmament is not found yet.

Some different technologies and methods of the utilisation and disposal of fissile materials extracted from nuclear weapons are well known but they are not appropriately elaborated and sometimes can not be accepted due to socio-economic or environmental considerations.

This was a major reason to convene another international meeting to reflect the state of the art of these vitally important scientific problems and to better understand the possible ways of the most peaceful, socio-economically and environmentally acceptable nuclear disarmament.

We should remember that for almost 50 years enormous capital and intellectual investments were made to elaborate and to produce these tremendous nuclear arsenals and the problem is how to return to people even a small part of material resources accumulated so far. Even a part of these resources could substantially contribute to meeting basic socio-economic needs of our society.

Needless to say that the full elimination of the danger of nuclear conflicts from human life will depend to a great degree on the success of nuclear disarmament process. Therefore the role of science in this particular area should become more important and consistent. The unification of efforts of specialists of different nations and scientific institutions is urgently needed since we consider international co-operation is one of the most effective mechanisms for resolving vitally important problems facing humanities.

I strongly believe that our international conference which is a united effort of different international and national organisations, institutions and individual scientists will contribute to the clarification of the above mentioned issues as well as to the culture of peace.

Since our meeting is a purely scientific event its outcomes will be open to all those who wish to be acquainted with the scientific problems of nuclear disarmament and therefore we shall do our best to disseminate the materials of the Conference as widely as possible.

On behalf of UNESCO and its Venice Office, I should like to express our gratitude to Prof. M. Martellini and his colleagues from the Local Organising Committee, the Direction of the Cen-

tre of Scientific Culture “Alessandro Volta” and Academician I. Khalatnikov, Chairperson of the Landau Network for providing our Conference with excellent facilities and services which I think is a pledge for the success of our initiative.

Our gratitude is also addressed to the Scientific Organizing Committee which managed to contact practically all scientific institutions in the world for the elaboration of the Conference Programme and for the selection of best experts.

Let me finally wish you full success in your scientific deliberations.

Introduction to the Conference and Outline of the Programme

Ugo Farinelli



Just as chemical energy, in addition to being used in explosives, is also used to heat our homes or move our cars, so nuclear energy also has a peaceful utilisation, in nuclear reactors that generate electricity.

The dual nature of nuclear energy has originated many problems but has also created several opportunities.

In 1955, the American President Dwight I. Eisenhower launched the programme “Atoms for Peace”, which had the objective of diffusing civil nuclear technologies among the countries that had peaceful intentions, provided they would accept stringent controls to verify that information and materials supplied for civil nuclear applications would not be diverted to military utilisation.

In a great international conference held at the end of August 1955 in Geneva, under the auspices of the United Nations, the Americans unveiled many of the scientific discoveries and of the methods developed for the peaceful use of nuclear energy, which until that moment had been classified as secret because of their possible implication for military applications. They were surprised to find the Russians equally available and open. It was soon clear that in many cases the same routes had been followed and the same results had been reached, while in many

other cases the approach had been completely different, and the results obtained in the East were complementary to those from the West. For instance, to study neutron transport and diffusion in a reactor the Russians, with a strong mathematical tradition but still without the electronic computers available in the US, would develop ingenious methods based on analytical calculus, while the Americans would employ numerical methods more congenial to computers.

The surprise and the excitement of the scientists participating in the conference for this reciprocal discovery was such that they may have gone some way beyond the instructions they had originally received, and the exchange of information, soon published and made available to everybody, was quite larger than it had been planned at the start.

In the following fifteen years or so, nuclear energy for peaceful applications had a rapid development, maybe even more rapid than it was justified by the maturity and the economic value of this technology. A commercial practice was developed, according to which the USA and the USSR did not sell the nuclear fuel, which could be exploited also for military uses, but rented it, so that when it had finished its cycle in the reactor, it was to be returned to the country of origin.

On the wake of the “Atoms for Peace” programme, and in the frame of the United Nations, the International Atomic Energy Agency (IAEA) was founded, with headquarters in Vienna. Also this Agency had, since the beginning, a double mandate. On one side, it was charged with a function of surveillance and safeguard in all the countries that wanted to access to a peaceful nuclear programme, carrying out inspections to all nuclear plants and an accurate book-keeping of all nuclear material, in order to verify that their activities were only directed to peaceful nuclear programme, carrying out inspections to all nuclear plants and an accurate book-keeping of all nuclear material, in order to verify that their activities were only directed to peace-

ful applications. On the other side, it had the mandate of promoting the peaceful uses of nuclear energy.

In those times (I am referring in particular to the 1960's) there was such an enthusiasm and optimism concerning nuclear energy that today appear unjustified and difficult to understand. One of the fathers of nuclear energy, both military and peaceful, Alvin Weinberg, then director of Oak Ridge National Laboratories in Tennessee, USA, went as far as predicting that nuclear energy would diffuse so much and would be so inexpensive, that it would become unnecessary to measure the individual consumption of electricity ("too cheap to meter"). This prediction did not materialise: when in 1973 the first oil crisis put in doubt the possibility of continuing to rely on oil, only few countries (notably France and Japan) felt like reacting to this crisis by turning to large-scale utilisation of nuclear energy; and when at the end of the 1980's the preoccupation on the stability of the global climate put under suspicion all fossil fuels, nuclear energy was seen as a cure worse than the illness.

Why did this change of attitude occur? For two, interrelated reasons: the increase in investment costs necessary for the construction of nuclear plants, and the mounting fears about their safety. The connection between the two derives from the fact that the more and more stringent requests on the safety features of the plant increase its cost. and make their licensing procedure, at all stages of design, construction, commissioning and operation, longer and more uncertain, introducing long dead times in which interests on invested capital run anyway.

If the "Atoms for Peace" programme reflected in some way a guilt complex on the part of some Americans for having developed and used such a deadly weapon, many others, who had no reasons to feel guilty, never forgave the "original sin" of nuclear energy, its military and destructive origin. An antinuclear movement was thus born, and grew steadily with time, worried about the safety of civil nuclear plants and of possible

releases of radioactivity. This preoccupation was directed more against civil nuclear plants (that until the very serious accident at Chernobyl had made no human casualty nor released dangerous quantities of radioactivity) than against nuclear military applications, that with all the test explosions conducted in the atmosphere until 1967 has released enormous quantities of radioactivity, many times more than the Chernobyl accident itself, and caused other very serious damage to environment and health, both in the USSR and in the USA.

But let us go back to the specific theme of the connection between military and civil nuclear applications. The bomb by itself has practically nothing in common with a nuclear reactor: no more than a bomb based on chemical explosives has in common with the engine of a car, based on a series of chemical microexplosions in the cylinders.

Where military and civil technology are interconnected in the production of nuclear materials necessary for the weapons. This concerns both the enrichment methods used to produce highly enriched uranium for the nuclear weapons, and how enriched uranium for reactor fuel; and for the production of plutonium, which is obtained by irradiating uranium in a nuclear reactor.

In 1968, after long discussions, the Non-Proliferation Treaty (NPT) was signed; two years later it was ratified and entered in force. This Treaty requires the signatories which do not possess nuclear weapons to engage not to acquire them in the future; while the five countries that at the time of the signature already has such weapons (namely USA, USSR, France, the United Kingdom and China) were engaged to gradually decrease their arsenal and to rely less and less on nuclear weapons for their defence. In jargon, “horizontal proliferation” (i.e. the birth of new nuclear weapon states) is discouraged as well as “vertical proliferation” (the increase in number and destructive power of the arsenals of the five official nuclear weapon states). In addi-

tion, nuclear countries pledge not to supply to other countries nuclear weapons, or materials, instruments and knowledge that would facilitate the acquisition or development of peaceful nuclear technology in non-nuclear weapon countries which have signed the NPT. These last will submit their nuclear plants to the safeguards and inspections by the IAEA.

The TNP had a certain success in limiting horizontal proliferation: the situation today is not much worse than it was in 1970; however the non-nuclear weapon states accuse the nuclear states that they have done very little to respect their obligation to reduce vertical proliferation. Only the dramatic changes in the East at the beginning of the 1990's have allowed to see at the horizon a substantial reduction of nuclear arsenals, which however proceeds rather slowly.

Nuclear states have difficulties in convincing the others that nuclear weapons are neither necessary nor useful, while at the same time they show to be very reluctant to renounce to them. For this reason, the majority of non-nuclear weapon countries, and especially developing countries, went in a very controversial mood to the conference that in the Spring of 1995 was convened, after 25 years of NPT, to decide whether for an indefinite time, but the criticisms expressed in the conference are likely to have an echo for a long time.

When Jimmy Carter was President of the United States, he made (in 1977) another step in the direction of making horizontal proliferation even more difficult than the NPT already made it. Carter had been a nuclear engineer, and knew what he was talking about. His preoccupation was that civil nuclear programmes could open the way to proliferation, and his idea was that to make this impossible, or at least much more difficult, it was necessary (and sufficient) to control two critical points: uranium enrichment and separation of plutonium from irradiated fuel. For the first point, not much more could be done than what was already being done, except avoiding that enrichment

plants were built in other countries and putting a stricter control on the leak of information on the relative technology. As for the second point, it was sufficient to prohibit any chemical operation on irradiated fuel, renouncing to recuperate plutonium also for civil utilisation and to reuse the unburned fraction of uranium 235, or to separate the fission products for an easier disposal after vitrification (i.e. the inglobation of radioactive materials into a glass-like structure that cannot be attacked by water or by chemicals present in the ground).

This last part raised very negative reactions from the European allies of the United States, from Japan and also from the Soviet Union. These countries considered that renouncing to recycle irradiated fuel and to recuperate the non utilised part of the fissile materials was an unacceptable limitation to the energy one could obtain from the available uranium resources, which were being studied especially in France (at the time with the prototype Phénix reactor), in Britain and in the Soviet Union, but also in the United States, Japan, Germany and Italy. Its main advantage is that it allows to exploit uranium so deeply as to make the cost of the procedure energy practically independent from the cost of uranium, and therefore virtually unlimited: known uranium deposits, including those at low concentration of uranium ore, would be sufficient for millions of years, without considering the uranium dissolved in sea water. With fast neutron reactors, nuclear energy becomes equivalent to a renewable source of energy. In addition, at that time German legislation required fission products to be separated from the fuel in order to facilitate their storage them for unlimited periods of time, and therefore made chemical treatment of irradiated fuel practically mandatory.

Who was right. Carter or the others? In retrospective, I think that Carter was right, but for the wrong reasons. He was right in assuming that there was no hurry to exploit completely the nuclear fuel and to turn to fast breeder reactors, and one could

wait thirty of forty years before having to worry: but this turned out to be the case because nuclear energy did not develop as much and as fast as it was generally predicted (in large part as a consequence of the unpredictable Chernobyl catastrophe), and the uranium market unexpectedly reversed its trend completely, with a fall of prices (in real terms) of a factor of live or more.

On the other hand, it is still doubtful whether civil nuclear power is the main route to proliferation, or if it would be simpler for a country that intended to build nuclear weapons to use a completely distinct and secret programme, with specialised reactors for plutonium production or, better still, to set up a uranium enrichment capability (as the subsequent experience would show, in particular in the case of Iraq).

As a consequence of his policy, Jimmy Carter requested and obtained the organisation, through the International Atomic Energy Agency in Vienna, of a huge exercise of examining and assessing all nuclear technologies, and in particular those connected with the fuel cycle, called the International Nuclear Fuel Cycle Evaluation (INFCE). In 61 meetings of eight working groups made up of experts from all over the world (519 scientists from 46 countries and five international organisations) held in Vienna between the end of 1977 and the beginning of 1980, plus two plenary meetings, all the aspects of nuclear technologies which could be significant from the point of view of proliferation were examined, and this was also an occasion for rethinking all the choices that had been made so far.

The results were not extraordinary, and probably not worth the effort that went into the exercise. Some proposals for new, non-proliferating technologies were presented, like an enrichment scheme from France based on small differences in chemical properties of the different isotopes of uranium, which would not lend itself to military applications (because it would take too long a time to bring the system to equilibrium for high

enrichments). Several hypotheses which had been examined and, for one reason or another, had been abandoned, were revived and discussed: among these, the possibility of using thorium, instead of uranium, as the basis of the nuclear fuel cycle, and the idea to use systems based on accelerators rather than self-sustaining reactors (these two concepts were later combined in a proposal brought to the attention of specialists and of public opinion by the Nobel prize winner Carlo Rubbia).

The most concrete output of the work of INFCE was a set of practical recommendations on how to store plutonium recovered from spent fuel under international surveillance, and how to control that it would be used for civil applications only, so as to make fuel reprocessing possible without undue proliferation risks.

On the whole the conclusions of INFCE, although written in cold and scientific terms, were closer to the European starting point than to Carter's, and were basically pessimistic on the possibility of finding a technical fix to the problem of proliferation. The message that transpired from it (although not bluntly formulated) was addressed to the politicians: "If you want to find a solution to the problem of nuclear proliferation, it is a political solution you must be looking for. You must remove the motivations for which the countries want to proliferate, you must make the possession of nuclear weapons uninteresting and counterproductive. Otherwise, you may delay of some years the acquisition of nuclear weapons by one country or another, but you won't stop it forever."

In a way it would be interesting to revisit the discussions and the conclusions of INFCE in view of the great changes that have taken place in the meantime. We do not have the presumption to suggest that this feat would be feasible within the horizon of a Conference like the present one, even if the range of competencies represented here is impressive, and if a number of us did actually participate in the original INFCE exercise.

However, it will be interesting to cover some of the ground in this direction. Let us see how we propose to do this.

First of all, we will start by having a view of the orders of magnitude of the problem and opportunity represented by the amount of fissile material made available by the dismantling of the nuclear weapons consequent to the Start agreements and to unilateral decisions by the USA and Russia. This will be briefly done in the **first session**. We already have the general feeling that this availability will not represent a fundamental asset for nuclear power, although it is far from negligible.

This **session** will also set the stage for assessing the future demand of nuclear materials and, if possible, the possibilities of supplying them. One large unknown factor is the amount of nuclear power that will be installed in the future. In many areas of the world, it is likely that the present level of nuclear power supply will remain roughly unchanged. The notable exceptions are the Far East, where a substantial growth is envisaged, and Eastern Europe, where a general tendency to install more nuclear power is contrasted on one side by lack of capitals and on the other side by the possibility that some of the present reactors will be shut down for safety problems. It is therefore most appropriate to have in this session two talks from eminent representatives from these areas, notably from Japan and from Russia.

Plutonium utilisation is possible in thermal reactors as well as in fast neutron reactors. A large cumulated experience on plutonium recycle in light water reactors as well as on the associated production of mixed uranium-plutonium oxide fuels (MOX) exists especially in Europe, and we will have a number of presentations covering this point. Some presentations will also concern the use of plutonium in fast neutron reactors (where experience exists in Europe, Japan and Russia), including some new ideas connected with the burning of weapons plutonium. Some problems exist and some operational caution has to be

applied, and it is quite possible that some reactor types (like the old VVER 440 reactors) are not quite suitable for plutonium burning. All these points will be covered in the **second session**.

The main purpose of the disposition of weapons-derived plutonium is to make the nuclear disarmament process as irreversible as possible, and to leave as little separated plutonium around as feasible, in order to reduce the dangers of diversion, theft or fast reconversion to military uses. This can be accomplished in at least two ways, by mixing it with radioactive fission products and disposing of it in a substantially irreversible way, or by using it in reactors, so as to burn a part of it and have the rest in the form of spent fuel, which is as inaccessible as weapons material as any spent fuel from a civil reactor. The reactors in which to use it can be the more common thermal reactors (especially, but not exclusively, of the light water type) or the less easily available fast neutron reactors, which may present some advantages as plutonium burners. The **third session** will be devoted to general considerations on the comparison of these issues and on the preferred pathways foreseen by Russia and the United States. In this context, it is clear that the most significant contributions must come from these two countries, as the main stake-holders in this matter. However, some contributions from other countries may help clarify the issue. Another consideration to be kept in mind in this respect is the need for a safe storage (hopefully under international to be kept in mind in this respect is the need for a safe storage (hopefully under international safeguards) of the plutonium before its disposition, which will in any case take a considerable amount of time. Finally, the connection with the civil plutonium deriving from reprocessing of spent fuel cannot entirely be avoided: it would make little sense to reduce the amount of weapons plutonium if the stockpile of separated, unirradiated civil plutonium should soar inordinately, or to ban the transnational shipment of weapons plutonium if such transport is routinely done for civil

plutonium (bearing in mind that both can be used to make bombs, even if the civil plutonium is less effective and requires a more sophisticated technology). All these questions will hopefully be addressed in the session.

Economics is one of the elements in choosing between different disposition options. Economics aspects will be dealt with in the **fourth session**, together with social consequences of these options. In particular, there is no agreement at the moment on whether weapons plutonium has a positive value (as an energy source) or a negative value (as a waste one has to get rid of). This may depend on different conditions which should be analysed. The immission of plutonium from dismantled weapons (and even more that of uranium) may affect adversely a market (of natural uranium and of enrichment services) which already faces difficulties due to a uranium and of enrichment services) which already faces difficulties due to a demand that is lower than the potential supply (although in the last year the price of uranium has shown a significant growth). Finally, the economic evaluation involves predictions over a considerable time (including changes in risk) which require skillful approaches.

The **fifth session** concerns safety and environmental aspects of the operation, which may influence the economics and the regulatory aspects of the choice between alternatives. It is quite clear that this choice has a bearing on the waste disposal problem. Here again there seems to be a variety of opinions.

In the **final session** we shall try to wrap up the conclusions of the discussions, to identify the problems on which we have one opinion, and to identify the roots of the difference of opinions on other problems. If we manage to do this, I am sure these three days of effort will not be without some utility.

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SESSION 1

Perspectives of Nuclear R&D

Nuclear Disarmament and Risks of Proliferation

Paolo Cotta-Ramusino



1. Fifty Years of Nuclear Weapons

More than fifty years have passed since the nuclear bombing of Hiroshima and Nagasaki. During this time we have witnessed the intense yet futile competition between the United States and the Soviet Union regarding the design, construction and deployment of nuclear weapons and their delivery systems. The whole period of the Cold War has been dominated by the nuclear arms race.

The end of the Cold War coincides with the beginning of nuclear disarmament, that is with a dramatic reversal of tendency. But 50 years of nuclear armaments can certainly not be erased instantly and without problems. Nuclear disarmament therefore presents itself as being a long and complicated process, in which there are, and will be, no shortage of problems and contradictory aspects, with periods of good progress which will probably alternate with periods of delay and reversal.

Before talking about nuclear disarmament and its problems, it may be useful to remember some data which in a synthetic way, even if necessarily schematic, can be chosen to represent these 50 years of nuclear arms race.

- Since 1945 about 130000 nuclear warheads have been built - of these the United States have built about 70000 and the USSR more than 55000.

- From the 1960s to the present day two enormous nuclear arsenals have been facing each other, each of which was at all times made up of more than 10000 weapons. The largest number was reached in 1967 by the U.S.A. (32500 weapons) and in 1986 by the USSR (45000 weapons, if not more).
- About 2050 nuclear tests have been carried out, of which 514 in the atmosphere (or in any case not underground).
- The countries in possession of nuclear arms have passed from one (1948) to 8 (today). Of these 8 nuclear countries, 5 declare themselves officially as being so (USA, Russia, Great Britain, France, China) and 3 are *de facto* (Israel, India, Pakistan).
- More than 250 tons of plutonium and 2 200 tons of highly enriched uranium (HEU) have been produced for military use.
- Apart from the production of nuclear arms, we must remember the production of the nuclear delivery systems. For example, the United States alone have produced about 67 500 nuclear missiles¹.
- The construction and management of nuclear arms and of the hundreds of thousands of delivery systems has meant a colossal expenditure for humanity. According to an estimate published in the Nov-Dec '95 issue of the *Bulletin of the Atomic Scientists*, the United States alone have spent since 1940 the equivalent of about 3900 billion U.S. dollars (current 1995 value) for their nuclear programs. This is more than 150 times the cost, in 1995 US dollars, of the Manhattan Project. The USSR has probably spent a similar amount which, together with the expenditures of the "minor" nuclear powers, brings the total cost of nuclear weapons to something in the region of nine thousand billion dollars, equivalent to nine times the present annual Italian GNP.

Two points very worthy of separate attention are the loss of human life and the consequences on the environment which

have been caused by military nuclear activities from the post-war era to today. In this respect, we should take into account the consequences of nuclear tests (in particular in the Pacific islands, in Nevada, in Kazakhstan), of accidents and contamination occurred in places where plutonium was produced, of the management of radioactive waste. As an example, consider the Mayak/Chelyabinsk-65 plant in Ozersk where more than 26000 sqkm, and more than 400000 people have been contaminated².

Lastly we must mention the specific social consequences which the nuclear arms race has brought about in the ex-USSR, where the military effort has consumed a far higher quota of national resources than that of corresponding Western Countries. A significant example of the economic and social distortion caused by the arms race was the creation of entire cities closed to the outside world and dedicated to the production of fissile material and other products for nuclear weapons. The total population of these cities has been estimated to be over 700000³.

The production and maintenance cost of nuclear arms has therefore been very high with regards the use of resources, the loss of human life, the ecological damage caused, the social problems created, and overall the risk of a nuclear catastrophe that has been with us for the last 50 years. On the other hand the military utility of those weapons has been close to zero. After Hiroshima and Nagasaki nuclear weapons have never been used in any of the numerous conflicts which have developed during the last 50 years.

Despite the great variety of nuclear warheads in terms of explosive yield and of range and type of delivery systems, despite the sophisticated strategic concepts that have been developed, no flexibility for the use of nuclear weapons has emerged in the real world.

The belief that even a limited use of those weapons would have caused a global catastrophe has fortunately prevailed. Nu-

clear weapons therefore represent a unique phenomenon in the history of mankind: never has so much energy been dedicated to the development, the production, and the deployment of weapon-systems which, for about 50 years, have been accumulated in large quantities, without being used.

2. Plutonium and Uranium for Military Purposes

The first inheritance of the arms race is the enormous quantity of fissile material produced - that is highly enriched uranium (HEU) and plutonium. The fissile material is classified as being weapon-grade if the isotopic composition is above a certain level (93% of U-235 for highly enriched Uranium and 93% of Pu-239 for plutonium).

In order to build even a rudimental pure fission bomb it is not necessary to have only weapon-grade type material on hand. Also plutonium with a higher percentage of Pu-240 or uranium with a lower percentage of U-235 can be used for the preparation of a bomb.

In this respect, the International Atomic Energy Agency in Vienna (IAEA) defines the *significant quantity*, from the point of view of the possible illegal manufacture of nuclear weapons, as being 8kg of plutonium and 25kg of U-235 contained in HEU (enriched with more than 20% of U-235).

In reality, according to a recent estimate of the Natural Resources Defence Council (NRDC) in Washington D. C., a fission bomb could be constructed with an amount between 1 to 6kg of plutonium and between 3 to 16kg of U-235 contained in HEU depending on the technical capabilities of the nuclear proliferators and the explosive power of the bomb they intend to produce.

If on one hand the quantity of fissile material needed to construct a fission bomb is quite modest, on the other the quantity

of Pu and HEU produced by countries which possess nuclear weapons is extremely vast.

A recent report by the U. S. Department of Energy declares⁴ that the same DOE acquired, between 1944 and 1994, 111.4 tons of plutonium for military use, of which 99.5 tons are still in its inventory.

An estimate made by A.S. Diakov⁵ claims that the quantity of plutonium produced by the USSR/Russia up to 1995 is about 126 tons.

With regards to enriched Uranium, the same U.S. DOE declared that it had produced a total of 994 tons of HEU, of which the amount destined for nuclear weapons has been estimated as being 730 tons⁶, while the corresponding quantity⁷ for the USSR/Russia could be anything from 15% to 30% larger than that of the USA.

Following the dismantlement of the nuclear weapons, a considerable part of this fissile material has been, or will be, declared *in excess*: this regards at least 100 tons of plutonium and 700 tons of HEU.

Apart from fissile material connected with military activity, large quantities of plutonium exist in the spent fuel of nuclear reactors; in fact this is the most consistent part of the existing plutonium.

There is also some plutonium of civil origin which has already undergone the process of separation. An estimate made by the C.I.S.A.C. of the American National Academy of Science in 1994 gives the total amount of Plutonium existing in the world in 1992 as being 1100 tons, and foresees that this amount will increase in the year 2000 to 1600-1700 tons.

The problems which concern the enormous quantity of fissile material produced are above all those regarding security. The main obstacle which bars the way to the construction of rudimentary nuclear weapons is not the lack of the necessary technological information, but rather the difficulty of obtaining fissile

material. The problem therefore is how to avoid that countries or illegal organisations, which may be interested in acquiring nuclear weapons, manage to obtain HEU and plutonium.

The plutonium contained in the spent fuel of nuclear reactors is very difficult to reach since, by definition, it is not separated from the rest of the radioactive waste.

On the basis of the experience accumulated in 50 years of nuclear weapons, it is also reasonable to expect that intact nuclear warheads (in active duty), being protected by military structures, may not easily fall into the hands of potential nuclear proliferators⁸.

In other words, the dismantled warheads, as well as the separated civilian plutonium may form the weakest link in the chain of the control of fissile material.

This problem has been brought to the general public's attention after to the demise of the USSR and the relative political, economical, and organizational difficulties which appeared in the former Soviet republics.

The warheads which must be dismantled have a long road ahead of them before they arrive at their final destination. First of all the warheads must be de-activated (that is, the trigger which is located in the external part of the warhead must be removed). Then they must be transported to the deposits to which they are directed. At this point the warheads must be opened, separating the fissile material contained in a metal container or *pit* from the rest of the warhead (chemical explosive, secondary system in thermonuclear devices, etc).

Now the *pit*, which contains the plutonium (or the enriched uranium), can be further dismantled only when the final disposal of the fissile material has been decided.

From the security point of view the process of dismantling a warhead therefore presents the following problems:

- The security of the transport of the de-activated warheads to the deposits.

- The accurate checking and registration of all the warheads and pieces of warheads which are dismantled.
- The safe custody of the *pits* while awaiting the disposal of the fissile material.
- The decisions concerning the disposal of the fissile material and its safe implementation.

It must be emphasized that the large number of warheads to be dismantled will impose a prolonging of the custody phase of the fissile material in the form of *pits*, and that consequently the relative security problems will remain for some considerable amount of time, whatever may be the choices concerning the disposal of the fissile material.

With regards to the enriched uranium, its logical destination will be the dilution with natural or depleted uranium, so to create low enriched uranium which may be used in nuclear reactors.

A similar choice is not feasible for plutonium since the mixing of the different isotopes of plutonium does not eliminate the risk connected to nuclear proliferation. On the other hand, mixing plutonium with other elements (uranium) is a procedure which can be easily reverted by chemical reprocessing.

With regards to the disposal of the plutonium, among the numerous choices proposed and considered in the before-mentioned report of the American National Academy of Science, there are two which emerged as the most worth of consideration:

1. To consider the plutonium the same as waste and to keep it in custody indefinitely after having treated it in such a way as to make access difficult. (For example, vetrifying it together with a highly radioactive material)
2. To use the plutonium for the preparation of MOX fuel (mixed oxides of U and Pu) to be burnt in civil nuclear reactors.

The choice between the two above options will be determined by different factors, and not only by a question of securi-

ty. The practicability of the second solution, for example, will be determined by the existence of an adequate number of plants which can prepare of MOX, by the characteristics of the nuclear reactors which can use this fuel, by the economic advantages of the whole operation (cost of MOX opposed to the cost of low level enriched uranium fuel), by the political attitudes of the countries which are potentially interested in the use of plutonium as nuclear fuel.

For example, the hostility of public opinion in some Western countries towards the nuclear choice could play a part - just as the belief of the Russian government that "plutonium is a national treasure" could have weight in the opposite direction.

With regards to the time needed for dismantling nuclear warheads, we can easily realize that the speed of this operation most likely will not be very high. It is instructive to compare the following data which refers to the USA⁹:

- Average number of American nuclear warheads produced annually in the years 1959 and 1960: more than 7000.
- American nuclear warheads dismantled in 1969: more than 3000.
- Years in which more than 2000 American nuclear warheads were dismantled per year: 1959, 1964, 1966, 1968, 1969, 1975, 1976.
- Average number of American nuclear warheads dismantled annually in the post cold war era (from 1991 to 1995): 1550.

As far as Russia is concerned, notice that since 1986 it has dismantled nuclear weapons at an initial rate of between 2000 and 3000 per year.

The rate seems to have slowed down now to less than 2000 warheads per year¹⁰.

3. Illegal Traffic of Nuclear Material

Since the demise of the Soviet Union, western public opinion has been worrying about the possibility of a dramatic increase in nuclear proliferation. Particular anxiety has been caused by:

- The possible creation of new independent nuclear States among the republics of the ex-USSR.
- The prospect of an intense illegal traffic of fissile material or even of whole nuclear warheads.
- The possible migration of large numbers of technicians and scientists from the ex-USSR to countries interested in buying nuclear weapons (in Russia there are reportedly about 2000 people who have a detailed knowledge of the design of nuclear weapons and around 3000/5000 experts in the production of fissile material¹¹).

Fortunately the present situation is quite a long way from these pessimistic predictions.

More than 6000 tactical nuclear weapons have been reportedly transferred from 14 ex-Soviet Republics to Russia without incidents.

Kazakhstan, Belarus and Ukraine, on whose territory strategic nuclear weapons are still deployed, have signed the Non-Proliferation Treaty as non-nuclear countries, declaring in this way their explicit will to renounce the possession of nuclear weapons.

Up to this moment there is no evidence that significant episodes of recruitment of Russian nuclear scientists have taken place on behalf of countries interested in nuclear proliferation.

Finally, with regard to the episodes of illegal traffic of nuclear material, tens if not hundreds of cases have been reported. Most of these cases have proven, however, to be of dubious authenticity or in any case irrelevant¹².

Only a few significant episodes of nuclear smuggling have been identified, as are mentioned later. However even in these

significant cases the whole picture is not very clear. In particular, even when the fissile material confiscated has been significant and the identity of the thieves established, there is no significant information regarding the possible buyers, whether they be States or criminal organizations.

The following table shows the main episodes of theft of fissile material so far identified¹³. Please note that all the confiscated quantities do not reach the minimum quantities needed to build a single bomb.

1. Podolsk, Russia 9.10.1992 Kg 1.538 HEU (90% enriched)
2. S. Petersburg March 1994 Kg 3.5 HEU
3. Tengen (Baden-Wuerttemberg) 10.5.1994 g. 5.6 Pu-239
4. Polyarny (Murmansk) June 1994 Kg 4.5 HEU (20% enriched) (stolen 27.11.93)
5. Vilnius 1994 Kg 2 HEU hidden in 4 tons of Berillium
6. Munich 10.8.1994 g. 560 MOX with g. 363 of Pu-239
7. Prague 14.12.1994 Kg 2.72 HEU (87.7% enriched)

The relatively optimistic evaluation made so far regarding the problem of illegal traffic of nuclear material and the overall effects of the disintegration the USSR on nuclear proliferation, must not, however, make us think that the dangers on this front can be considered marginal in the future.

If the situation has been kept (relatively) under control up to now this does not necessarily mean that it will remain so indefinitely, especially in the absence of an adequate international initiative which face up to the numerous problems left to be solved.

With regard to these problems, we must remember some hard facts.

- The quantity of fissile material present in Russia is extremely high and the systems of protection, control and accountability of nuclear material need significant improvement.
- The (illegal) transport of fissile material in quantities which are significant from the point of view of nuclear proliferation

can take place with a relatively simple level of precautions, and on the whole fairly easily.

- In the world there exist countries (or criminal groups) which are, in principle, interested in buying nuclear fissile material.

Furthermore in the Russia of today (as in other parts of the world) the illegal or semi-legal traffic of various commodities is a widespread phenomenon which does not seem destined to decrease in the near future. The situation regarding Russia's nuclear activities is further complicated by the difficult economic conditions in which technicians and scientists are forced to live. This contrasts sharply with the relatively privileged conditions that they enjoyed not too long ago.

Up to now the Russian authorities have shown that they are able to cope with such a difficult and complex situation. The logical reply from the more industrialized countries should have been the development of a comprehensive initiative to support the programs for the control of the nuclear material in Russia.

Among the steps to be taken, one should enlist specific agreements allowing the drawing of a detailed "nuclear map" of today's nuclear superpowers with a list of all the locations, the quantities, the type of pits, the warheads, the parts of warheads, the separated fissile material, and allowing a wide-ranging system of international inspections.

Another reasonable initiative is the development of scientific, technological, and economic cooperation between scientific institutions of the more industrialized countries and Russian nuclear research and production facilities.

All these initiatives have been, at least partially, carried ahead, but the rhythm and the dimension has been insufficient, as has also been the financial commitment of the more industrialized countries, with respect to the gravity of the situation. The whole affair has been accompanied by political-bureaucratic obstacles of a various nature, in particular with regards to the def-

initiation of the agreement concerning the *exchange of data* in order to put together the “nuclear maps”, which we mentioned above.

The United States, being by far the Western country which has committed herself more, has in five years (from 1992 to 1996) destined an overall sum of about 530 million dollars to programs regarding the problems of the nuclear facilities in Russia¹⁴, which is about 1/300th of her current expenditure for her own military nuclear programs (33 billion dollars in 1995).

The obvious question is this: for global security, is it more important to have an extra submarine with nuclear missiles patrolling the oceans, or rather to develop initiatives which prevent the transfer of fissile material to terrorist groups or countries interested in acquiring atomic weapons?

4. Nuclear Proliferation

While discussing about the illegal traffic of nuclear material, we are naturally led to consider the countries which are potentially interested in buying this material. In other words who are the potential proliferators and how high is the probability of a successful nuclear proliferation?

The scientists who participated in the first phase of the construction of the atomic bomb and several American politicians of the immediate post-war era, thought that, in the absence of an international control over atomic energy, nuclear weapons would have spread to many countries, even though no one foresaw the building of a global number of nuclear arms, remotely comparable to the present one.

The number of nuclear countries has instead remained minimal with respect to the initial pessimistic predictions. A true regime of nuclear non-proliferation has been established and has shown notable stability during all these years.

There are five nuclear countries officially recognised as such (USA, Russia, France, Great Britain, China) and there are three *unofficial* nuclear countries (Israel, India, Pakistan).

All or almost all the countries in the world, with the notable exception of the three undeclared countries, have adhered to the Non-Proliferation Treaty (NPT). This treaty was extended indefinitely in May 1995.

Therefore the first element which has contributed strongly to the containment of nuclear proliferation is the NPT Treaty, that together with the treaties which establish nuclear weapons free zones in Latin America (Treaty of Tlatelolco), in Oceania (Rarotonga), and (in the near future) in Africa (Pelindaba), provide a clear framework of international legislation.

Other elements that have contributed to the strengthening of the non-proliferation regime are the significant costs tied to the construction and maintenance of nuclear arms, and the difficulties and costs of the acquisition of fissile material.

These last elements become even more important if compared to the evident uselessness of nuclear weapons. Nuclear weapons have never been used in a conflict since the Second World War. Even the simple presence of nuclear weapons has shown itself to be a marginal element in the principal conflicts, local or not, which have developed since 1945. Think of Korea, of Vietnam, of the Falklands, of the Middle-East wars etc.

In recent times a strong push towards the strengthening of the non-proliferation regime has been given by the disarmament steps taken by the nuclear powers.

The dramatic reduction of the emphasis given to nuclear weapons by the USA and Russia in the years 87-94, the unilateral and bilateral initiatives for nuclear disarmament and the relative treaties, the treaty (in preparation) on the total prohibition of nuclear experiments (CTBT) are all elements which have contributed and contribute to diminishing the role of nuclear weapons in international politics.

Lastly the non-proliferation regime was enhanced by the failure or voluntary abandonment of various attempts of nuclear proliferation.

South Africa built 6 fission bombs of the *gun-assembly* type that they successively dismantled. Brazil and Argentina have abandoned their nuclear projects, North Korea has been persuaded to abandon its attempts to acquire fissile material for nuclear weapons, and Iraq has been forced to abandon similar attempts.

We must now consider the opposite type of motivations, that is the ones that can encourage a country to try to acquire nuclear arms, even in violation of the NPT Treaty.

The possession of nuclear weapons has for a long time been associated with a misplaced international prestige.

Possessing nuclear weapons means belonging to an exclusive club of countries, which includes, for example, all the permanent members of the United Nations Security Council.

Another aspect we must consider is that acquiring nuclear weapons can have contrasting effects on nearby countries: it can frighten them or push them to nuclear emulation. We can understand, however, that a country, surrounded by a hostile environment or one perceived as being such, might think of playing the nuclear card. The cases of the clandestine nuclear powers (Israel, India and Pakistan) fit clearly this scheme.

Countries that are today considered to be potential proliferators are some countries of the Middle East. Among these the name which appears most frequently is that of Iran.

In fact the position of Iran on the nuclear problem is not clearly supportive of the non-proliferation regime. Observers, even of different opinions, all agree that Iran could try to acquire a sufficient quantity of fissile material for a few nuclear warheads¹⁵.

The open or hidden desire to violate the non-proliferation regime may be influenced by the overall attitude of all the nu-

clear powers, and of the United States and Russia in particular, regarding nuclear disarmament.

If nuclear disarmament proceeds quickly, if the emphasis on nuclear weapons is rapidly reduced until it disappears, then the general attitude of the international public opinion will be less and less prepared to condone nuclear proliferation and the prestige connected to the possession of nuclear arms will fade away.

If instead the disarmament process should slow down, and if the emphasis on the nuclear component of defense will be kept at the present level, if not increased, then the net effect on the non-proliferation regime can be the most unwelcome one.

There are various elements which suggest that the second hypothesis, the most unfavorable one, is not the most unlikely.

5. Nuclear Strategies after the Cold War

The problem we would like to discuss briefly may be formulated in a very simple way: how many nuclear weapons will be left after the implementation of the present disarmament agreements and what will be the role assigned to the nuclear weapons which remain?

The connection with the problem of nuclear proliferation is clear: if the nuclear powers plan to maintain in the foreseeable future a high number of nuclear weapons and an aggressive nuclear strategy, then they are also planning to send the wrong message to potential proliferators.

A recent estimate has established that 7500 American nuclear warheads (including the *hedge*) could be allowed after the implementation of Start II (the ratification of which by the Russian Parliament, we must remember, presents many difficulties). An equal number of Russian warheads plus the warheads of minor nuclear countries would bring the total number of war-

heads to well over 16000. This is the amount of nuclear weapons that are likely to survive the present disarmament agreements.

So there is the serious risk that the emphasis on the role of nuclear weapons will be maintained high by the large number of weapons that will be kept intact in the arsenals of the major powers, by the reluctance of the 'minor' nuclear powers to join the disarmament process and by reluctance of all the nuclear powers to change their ideas and procedures concerning the possible use of nuclear weapons in conflict.

With regards to the nuclear strategy of the major nuclear powers we observe:

- The American *nuclear posture review* of 1995 does not significantly modify the conditions of use for nuclear arms. It explicitly plans for an increase of operational warheads if the political conditions in Russia should deteriorate.
- The American Congress sustains the necessity for a revision of the ABM Treaty and proposes a larger expenditure in the anti-missile defense systems
- Russia has restricted the policy of nuclear *no-first-use* so as to make it practically irrelevant. Russia declares that she will not initiate the use of nuclear weapons, only if the opponent will be a non-nuclear country that does not belong to any military alliance which includes nuclear countries.
- Russia is making the old NATO doctrine its own on the role of nuclear arms to countervail a possible inferiority in the field of conventional weapons. In particular some Russian political and military leaders speaks insistently about a "new" role for tactical nuclear weapons, the removal of which had been announced with separate unilateral initiatives by Presidents Bush and Gorbachev, but which had never been established by treaty.

Lastly, a question of the greatest importance is the problem of the alert-levels of the nuclear delivery systems. Maintaining a

good part of the nuclear delivery systems at maximum alert levels was a characteristic of the entire period of the Cold War. This meant that ground-based missiles could be launched not after an enemy attack, but simply after the warning that enemy missiles had been launched and were on their way to their targets. A number of the submarines equipped with nuclear missiles have been kept in continuous navigation, ready to launch their missiles at the shortest notice. Similar levels of alert were kept by nuclear bombers.

After the end of the Cold War, the levels of alert were changed, but only slightly¹⁷. This is a most relevant fact, since the disarmament process can proceed by two different tracks: by decreasing the number of weapons and by rendering the use of the existing weapons less and less accessible.

Keeping nuclear weapons in the *ready-to-use* condition not only continuously presents the risk of a *war by mistake*, but also directly establishes a significant barrier to the further development of nuclear disarmament.

6. Conclusions

The post Cold-War world is not yet a world free of nuclear weapons, and there are significant elements which oppose the elimination of these weapons of mass destruction.

The role assigned to nuclear weapons by the super powers is still one of great importance. This not only does not eliminate the risk of a global nuclear conflict, but also has a significant effect on the incentives and risks of nuclear proliferation.

The presence of large quantities of fissile material available for nuclear weapons and the problems of the control of this material, could in the future facilitate nuclear proliferation, or the construction of rudimental nuclear weapons by criminal organizations.

Even if the recent progress in the field of nuclear disarmament has certainly been historic, the tasks of the international community with regards to nuclear weapons are far from being finished.

The decisions concerning the procedures and methods for the disposal of the excess-weapon fissile material and in particular of the weapon-grade plutonium, is one of the problems to be faced, but it is far from being the only one.

Among the many other problems we have mentioned or schematically discussed, there are the ones concerning the control, the accountability of the existing fissile material, the reduction of nuclear warheads (reaching and going beyond the limits fixed by the current disarmament-agreements), the reduction of the overall emphasis given to nuclear weapons, the reduction of the levels of alert. We also mentioned the involvement of the minor nuclear powers in the disarmament process. All these aspects will play an important role in the future evolution of the non-proliferation regime.

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Principal Viewpoint on Nuclear Energy Development in Japan

Sadao Kijima



1. Introduction

Electric power generation by Light Water Reactor has already covered a good deal of the electricity demand in most of developed countries including Japan. Japan considers that the utilization of Plutonium is also very important in terms of securing the energy resources in the future.

The early part of this paper briefly describes the potential role that Uranium can play as an energy resource. This paper also presents Japan's principal viewpoint for Plutonium is also very important in terms of securing the energy resource. This paper also presents Japan's principal viewpoint for Plutonium utilization taking account of nonproliferation aspects.

2. The Role of Uranium as an Energy Resource in the 21st Century and Afterwards

The framework of nuclear energy development program in Japan has been provided by "The long-term program for research, development and utilization of nuclear energy", which Japan Atomic Energy Commission (JAEC) revises about every 5 years. The newest revision was issued in June, 1994 through al-

most 2 years of debate by a number of people who have various opinions including anti-nuclear. The author itself contributed to the debate, and following quotations from the longterm program are consistent with its own opinion.

This newest long-term program describes the importance of nuclear energy as follows:

“World energy consumption has been increasing ever since occurrence of the industrial revolution. In terms of oil consumption, it was only about 100 million tons a year in the middle of the 19th Century, but by 1990 it reached 8,000 million tons. The world population doubled in the last 40 years, but over the same period the world energy consumption increased more than 4 times, which means that per capita energy consumption has also doubled. Energy consumption is closely geared to factors such as level of economic development and life quality. With the advent after Second World War of a society depending on mass production and mass consumption, there has been a sharp increase in energy consumption. For a time after the two oil crises energy consumption did not increase as much as it had before, but after that it resumed its upward trend on account of lower oil prices and other factors, and that trend still continuing”.

Figure 1. illustrates the several predictions of the global primary energy consumption which have been carried out so far. Summarizing these predictions, the global primary energy demand is 13~24 billion tons oil equivalent (TOE) in 2050, and 18~41 TOE in 2100.

Figure 2. shows the comparison of the cumulative oil consumption and the deposits. This indicates that one trillion barrels of the present proven oil resources are to be exhausted between 2020 and 2040, and even the 2.2 trillion barrels of the ultimate oil resources are to be exhausted by 2100 at latest.

It is said that natural gas will also have been exhausted by around 2070, as long as the great deal of new resources are not

discovered. These mean that the ultimate available fossil resources except for coal will have been used up by the middle of the 21st century.

Then, we carried out analyses on a long-term scenario that nuclear energy compensates the lack of fossil resources. Figure-3 gives the cumulative demand of natural Uranium corresponding to a model case assuming that WEC's energy outlook until 2020 will keep the same pace after 2020. It is also assumed that all of nuclear energy is covered by conventional LWR. This results also indicate the known natural uranium also will have been used up by around 2050, and the ultimate Uranium resources cannot cover the very long-term demand. Figure-4 illustrates the results of an example analysis which performed to clarify the effects of FBR introduction to the demand reduction of natural Uranium. It is known that the breeding ratio and the out-of-core time of spent fuels are the key factors, these results indicated that the very long-term. Uranium demand can be covered by the ultimate resources in case the breeding ratio is 1.2 and out-of-core time of spent fuel is two years.

3. Japan's Principal Viewpoint for Plutonium Utilization

(Peaceful use)

It is Japan's grand rule that the utilization of nuclear energy have to strictly limited only for peaceful use. Relating to this principle, the long-term program of Japan Atomic Energy Commission describes as followings:

"Japan today enjoys the fruits of its past efforts in development and utilization of nuclear energy with consistent limitation to peaceful purposes, and it will be important in the future to hold on to such posture of peaceful use of nuclear energy and to develop nuclear energy policy appropriate to a nation

committed to peaceful use of nuclear energy. That being the case, Japan intends to redouble its efforts with respect to winning international confidence concerning non-proliferation of nuclear weapons, development of technology for peaceful use, acting internationally in a way that befits and advanced nation in peaceful use of nuclear energy and transparency and availability of information.

With respect to obtaining international confidence regarding non-proliferation of nuclear weapons, Japan has worked for maintenance and reinforcement of the system comprised by the Non-Proliferation Treaty and the IAEA safeguards based on it as the important international framework which guarantees compatibility of peaceful use and non-proliferation of nuclear weapons as well as making efforts of its own. At the same time it is important for Japan to clearly express once more its firm determination to limit itself to peaceful use and to show that there is absolutely no possibility of developing nuclear weapons in terms of either systems or actual conditions by refraining from possession of any technology related to nuclear weapons”.

(Information disclosure)

This program also emphasizes the importance of information disclosure in order to accomplish the above-mentioned objectives as followings:

“The Atomic Energy Basic Law stipulates the requirement to make public the results of research on development and utilization of nuclear energy in order to ensure that it will be for peaceful purposes, and efforts have always been made for such transparency in the past. Those efforts to make information on nuclear energy public will be continued in the future on the basis of full realization of the great importance of transparency to ensuring only peaceful use. Furthermore, it is important to always bear in mind the need to formulate nuclear energy policy on the basis of what the Japanese public wants in view of how closely peaceful

use of nuclear energy relates to the daily lives of the Japanese people. Accordingly, improved measures will be sought for obtaining understanding and cooperation on the part of the general public through transparency and availability of information so as to reassure people about the safety of nuclear energy”.

(R&D program for establishment of fuel cycle)

Based on these principles, Japan is carrying out a series of R&D programs in order to establish the fuel cycle so that the future energy security can be assured. Our master plan is expressed as follows:

“As a country practically without its own energy resources, it is indispensable for Japan to plan for its energy security on the basis of the future outlook in order to be able to continue to maintain and develop its economic and social activity. Uranium resources are limited just as fossil fuel resources are, and it cannot be denied that if the present situation with use mainly of light water reactors continues, uranium supply-demand relation will be tight by around the middle of the next century. Japan intends to guarantee its future energy security by steadily carrying forward research and development efforts aimed at future commercial commissioning of nuclear fuel recycling. Involving reprocessing of spent fuel and recovery of plutonium, uranium, etc. for reuse as nuclear fuel. Another reason for doing so is that recycling of nuclear fuel is also meaningful in terms of sparing resources and the environment and improving management of radioactive waste. Specifically, with the basic idea of first having a long period during which fast breeder reactors, which will make it possible to raise the efficiency of utilization of uranium resources by leaps and bounds since they produce more nuclear fuel than they consume, are used alongside light water reactors take over as the mainstream of nuclear power generation, research and development will be steadily carried forward in stages on the basis of cooperation between

government and the private sector for the purpose of establishing a technological system of nuclear fuel recycling based on fast breeder reactors so as to be able to commission fast breeders commercially by about the year 2030 after first passing through the prototype reactor and the demonstration reactor stages. Furthermore, from the standpoint of establishing the comprehensive technological system concerning use of plutonium that will be needed in the future age of fast breeder reactors and long-term overall improvement of the economic efficiency of nuclear fuel recycling, it is important first to carry out nuclear fuel recycling on a certain scale. Therefore, it is intended to build reprocessing plants on a commercial scale to gain experience in operation and bring about nuclear fuel recycling based on existing light water reactors. Regarding the economic efficiency the nuclear fuel cycle, although at the present time it is estimated that use of MOX fuel by light water reactors will be somewhat more costly than direct disposal of the spent fuel, there is substantially no difference if one considers total power generation cost. Therefore it is intended to work for improvement of economic efficiency from a long-term perspective, including standardization of fuel specifications”.

(No surplus Plutonium)

Japan realizes that it is inevitable to obtain the worldwide understanding that we never have intention to take any action threatening the nuclear nonproliferation. It is one of countermeasures that Japan possesses no surplus Plutonium. This fact explained the next chapter.

(Plutonium from Weapon)

Japan's principle on the treatment of Plutonium from nuclear weapon is as follows: “If, now that the Cold War is over, a shift takes place in international society from emphasis on military concerns to emphasis on the quality of life, nuclear energy,

too, can be expected to play an important role in improving the quality of life (peaceful use). At the present time the matter of what to do with the nuclear materials resulting from dismantling of the nuclear weapons left behind by the Cold War is a very important international problem. The basic consideration should be that of preventing those nuclear materials from being used for military purposes again, and the idea has occurred to some that a good way of ensuring that would be to use them as fuel in nuclear power generation. That means we will come across a happening symbolizing the current world trends that the technology for peaceful use of nuclear energy. Looking back on the history of nuclear energy, one sees that under the Cold War structure one aspect of nuclear energy was unfortunately maintenance of order in international society by its use as a military deterrent, but it is to be earnestly hoped that in the 21st Century nuclear energy will cast off its military yoke to be used solely for the peaceful purpose of supporting the stability and development of international society so as to contribute to the good of mankind, as it should have been from the outset”.

“While, on the one hand, progress is being made between the United States and Russia in nuclear disarmament as a result of the end of the Cold War, on the other hand, management and control of nuclear weapons in the ex-Soviet Union has become less unstable, and there is now anxiety about possible new proliferation of nuclear weapons in unstable regions.

Regarding fears of proliferation of nuclear weapons in the ex-Soviet Union, it is important to proceed with nuclear disarmament in a safe and steady manner. As for, particular, the plutonium and other nuclear materials resulting from dismantling of accountancy so as to ensure that they will not be reused for nuclear weapons. Although such nuclear materials should be appropriately disposed of by the countries concerned as their own problem, it is also important that other countries collaborate in devising long-term solutions to that problem. On the ba-

sis of awareness of the significance of doing so from the viewpoint of promoting nuclear disarmament and prevention of proliferation of nuclear weapons, Japan intends to contribute to storage and other measures adopted with respect to such nuclear materials by the countries concerned out of consideration of its basic standpoint of promoting utilization of nuclear energy that is limited to peaceful purposes”.

4. Approximate Estimation of Supply and Demand of Plutonium in Japan

(Revised reflecting the cancellation of Demonstration ATR)

The production of the supply and demand of Plutonium depends on the progress of related nuclear development programs. Followings are results of approximate estimations of supply and demand of Plutonium in Japan which were carried out based on the development plan as of August 25, 1996. These figures are to be revised in case such as the schedules of related program change.

All the Plutonium is under IAEA's safeguard, and it is always being confirmed that it is never utilized for any other objective except for the peaceful use. The fraction of fissile is reprocessed Plutonium is 60~70%, and Following estimations summarized in Tabel 1 to 5, were carried out for the fissile Plutonium.

(1) Estimation of Supply / Demand of Domestically Reprocessed Pu

1) 1994~1999

Table 1
Annual balance

1 Demand	2 Supply
“JOYO” (Experimental FBR)	Tokai Reprocessing Plant
“MONJU” (Prototype FBR)	
“FUGEN” (Prototype ATR) etc	
0.6 ton / yr	0.4 ton / yr

Table 2
Cumulative Balance

1 Cumulative Domestic Demand (1994~1999)	2 Cumulative Domestic Supply (1994~1999)
“JOYO” (Experimental FBR)	Tokai Reprocessing Plant and
“MONJU” (Prototype FBR)	Returned Plutonium from Overseas
“FUGEN” (Prototype ATR) etc	Reprocessing Plant
0.6 ton	0.4 ton

2) 2000~2010

Table 3
Annual Balance

1 Demand	2 Supply
“MONJU” etc. 0.6 ton / yr	Rokkasyo Reprocessing Plant
Demonstration FBR 0.7 ton / yr	4.8 ton / yr
Full MOX ABWR 1.1 ton / yr	Tokai Reprocessing Plant
<i>Thermal MOX</i> 2.6 ton/yr	0.2 ton/yr
Total 5 ton / yr	Total 5.0 ton / yr

Table 4
Cumulative Balance

1 Cumulative Domestic Demand (2000~2010) “JOYO”, “MONJU”, “FUGEN”, “DFBR” 10~15 ton (*) Full MOX ABWR Thermal MOX 25~30 ton Total 35~45 ton	2 Cumulative Domestic Supply (2000~2010) Rokkasyo Reprocessing Plant <i>Tokai Reprocessing Plant</i> Total 35~45 ton
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(*) The amount of Plutonium required to operate reactors for R&D such as “JOYO”, “MONJU”, and so forth is approximately 15 ton. In case that the Plutonium supply from Rokkasyo reprocessing plant decreases, the period when the domestic supply cannot cover the domestic demand may occur. In such a situation, at least 10 ton of plutonium is supplied from the Rokkasyo plant, and remain is covered by the Plutonium returned from the overseas reprocessing plant.

(2) Plutonium reprocessed in Overseas Plants

Table 5

1 Cumulative Amount by around 2010 30 ton.	2 Supply Basically, the Plutonium reprocessed in the overseas plants are utilized in the full MOX ABWR or LWR, after they are fabricated to MOX fuel in overseas plants and transported. (However, in case the shortage of Plutonium for R&D reactors occurs before the normal operation of Rokkasyo plant, some of them are utilized to compensate it).
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5. Conclusion

The development of Fast Breeder Reactors, which is very useful to utilize the energy of Plutonium and can play a significant role to cover the energy demand in the future, is facing several difficulties. Although France is carrying out its best effort to accomplish the full power operation of Super Phenix I, they had to meet some troubles to overcome in the course of developing it. We also heard that Russian program is being involved in financial problems. And, FBR, development program in Japan is also undergoing the difficulties due to secondary sodium leak of prototype FBR “MONJU”. However, FBR is a very important option that we should not abandon, and we hope that every developed countries in the field of FBRs will collaborate to establish their utilization technologies.

Figure 1
**Primary Energy Consumptions
 in the Global Energy Projections**

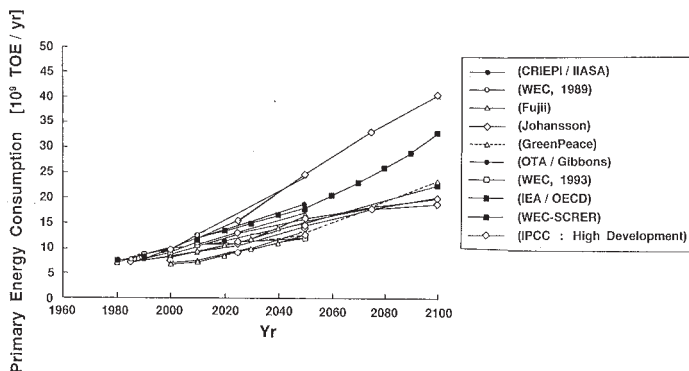


Figure 2
**"Cumulative" Oil Consumptions
 in the Global Energy Projections**

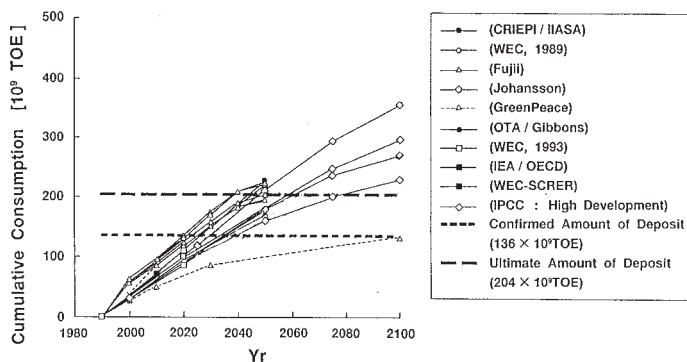


Figure 3
Cumulative demand for natural uranium

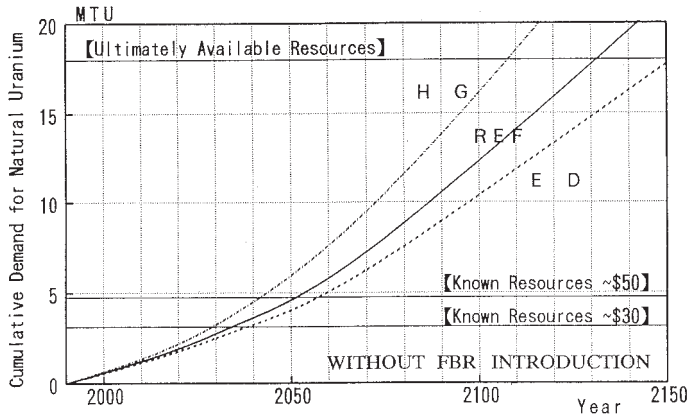
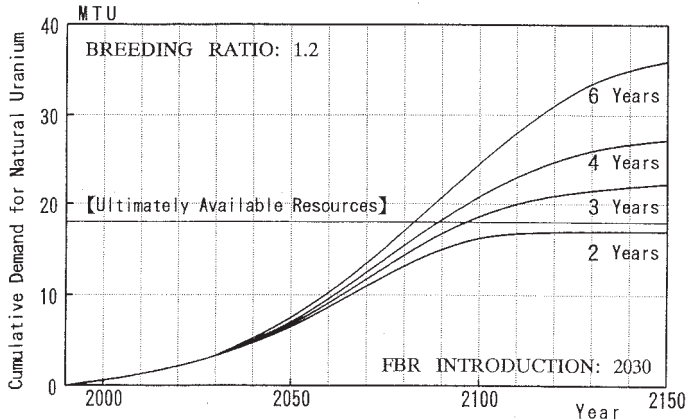


Figure 4
Cumulative demand for natural uranium



Nuclear Power of Russia

O. Favorsky, V. Kagramanian, L. Ryabev



O. Favorsky



V. Kagramanian

The development of the Russian fuel production and power generation complex is supposed to meet the requirement of the sustainability of power generation in Russia, and to some extent that in Europe, being in compliance with traditions and relations formed thus far. The “Energy Strategy of Russia”^{*} adopted by the RF Government in December 1994, defines the ways for the most efficient use of resources and potentials of the complex through its dynamic development and adequate solutions for economic, ecological, safety problems faced. It considers the aforementioned requirement as well. And the development of nuclear power in Russia is an important element to ensure the realization of this requirement.

At the moment, 9 of the 15 nuclear plants operating in the

^{*} The Energy Strategy of Russia, Moscow, 1994.

CIS are located in Russia, with total capacity of 21.242 MWe. By the end of 1995, 29 reactors were operated, including 13 VVER type (6 VVER-440 and 7 - VVER-1000); 11 RBMK, 1 fast reactor BN-600 and 4 small graphite moderated, water cooled district heating reactors BN-600 at Bilibino NPP.

All reactors of NPPs are operating reliably at base load, except for variable loading of reactors at Bilibino NPP, which is used to meet both power and heat demand of that outlying area. The thirteen VVER recorded an average annual load factor of 52.7% with a lifetime average to the end 1995 of 65.8%. The eleven RBMKs recorded an average load factor for 1995 of 54.8 and an average lifetime load factor of 71.7% to end 1995. The fast reactor recorded a load factor of 70.4% in 1995 and lifetime figure of 69.4%.

Table 1
**Characteristics of Nuclear Power Plants
Operating in Russia**

General Data	YEAR			
	1991	1992	1993	1994
Installed Capacity (Mwe)	20242.0	20242.0	21242.0	21242.0
Electricity Output (Billion kWh)	120.0	119.6	119.2	97.8
Share in Total Output (%)	11.4	11.8	12.7	11.3
Load Factor of Installed Capacity (%)	67.7	67.28	57.22	52.6
Number of Safety System shutdowns Per Unit	1.04	1.32	0.79	0.38
Operational Breakdowns:				
- to be reported according to INES	38.0	31.0	29.0	13.0
- caused by personnel errors	48.0	33.0	48.0	52.0
- Total (incl. other Breakdowns)	172.0	205.0	154.0	127.0

In 1993, the Russian NPPs produced 12.48% of the total amount generated in the country, while in 1994 they produced 11.3% of the total production. To the end of 1995 the Russian units have generated a total of 1713.51 TWh over some 358 reactor-years of operation. The average performance data for all nuclear power plants are presented in Table 1.

Ensuring safe operation of facilities is the primary goal of nuclear power industry. To achieve this goal, long-term measures are being pursued and periodically reviewed in the light of actual results and the relevant plans for reconstruction and modernization. At the same time being, the first stage of work has been completed. Information on non-standard operation events at NPPs and their assessment using the IAEA International Nuclear Events Scale (INES) reflects the improvement in performance of operating plants and their comparability with that in countries with developed nuclear power industry. To fully implement these projects, the capital investment of \$5.4 Billion is required by the year 2000.

It is interesting to mention also that an idea of the earlier decommissioning of first generation units to improve the Russian nuclear power safety was not justified by the Russian-American joint research carried out in 1994-95 on the alternative options for the development of power industry. The study was done in the frame of the agreement between Russian Prime Minister and US Vice-President.

Normal operation of NPPs does not result in radioactive contamination of environment above the background, irrespective of the distance from the plant. Better ecological impacts of reliably operating NPPs belongs to key arguments, when compared to fossil fuels.

All operational NPPs in Russia received ecological certificates approved by regional environment monitoring authorities. These documents indicating major factors of the plants' environmental impacts are the main tool to ensure ecological safe-

ty of units. As a result of measures taken, hazardous environmental impacts of nuclear fuel fabrication facilities are currently estimated as insignificant.

Within the framework of the “Energy Strategy for Russia” during the restructuring of the Russian fuel and energy complex in the next 10 to 15 years steps have been determined to develop nuclear power sector. The necessary level of development by 2010 is 125 billion KWh (22 GWe of installed capacity), i.e. 11% of total domestic electricity generation. Maximum level of power generation at NPPs in 2010 could be 160 billion KWh (28 GWe of installed capacity), i.e. 13% of the total output.

The development of the nuclear power sector is economically justified due to the following considerations:

a) Nuclear power industry is the only sector of the energy complex which does not require mining of natural resources in the near future. In contrast to conventional power production based on fossil fuels, where one of the most important problems is securing of fuel supplies (which means vast capital investment), the nuclear power program up to 2010 can be carried out using readily available and cheap stocks of uranium, 1.5-2.0 times in excess of demand.

Problems in fuel supply for nuclear power industry may arise only by the year 2030, assuming a sharp increase in the installed capacity. For example, a growth in capacity by 2030, which would provide 30% of total power generated in Russia by NPPs, could result in exhaustion of all uranium stock available within 30-35 years. The outcome could be found if new uranium deposits were discovered in Russia or ex-weapons uranium (WU) was used; another option would be the introduction of closed fuel cycle using civil and ex-weapons plutonium (WPu); or development of nuclear power industry based on thorium. An approximate estimate shows that the total energy potential of ex-weapons uranium to be used in thermal reactors and ex-weapons plutonium to be used in fast reactors could

correspond in the long run to an electricity generation of 12-14 trillion KWh, i.e., 12-14 as much as annual output in 1993, and thus save around 3.5 trillion cubic meters of natural gas. That would create a realistic possibility of guaranteeing the export of natural gas to Europe. According to Western estimates by 2000 the export volume of natural gas from Russia should amount to 131 billion cubic metres, by 2010 - to 184 billion cubic metres, and by 2020 - to 204 billion cubic metres.

b) Analysis of nuclear fuel production capacity requirements for various development options in the nuclear power sector up to 2010 indicates that production capacity is also enough to assure any of the options and there will still maintain significant production reserves. Furthermore, average load in work capacity of nuclear fuel fabrication facilities ranges from 10 to 76 per cent.

c) Analysis of the power industry construction companies and regional construction entities assumes that the powerful production infrastructure formed to date, including construction enterprises and companies dealing with installation and assembling, is capable of achieving an annual work level of \$120-150 million per unit, which makes the planned program of nuclear power industry development up to 2010 totally feasible.

The major companies involved in the machine manufacturing for nuclear power industry are: The coordination centre for nuclear power machine construction at Minatom of Russia "Energy Machine Manufacturing Corporation, Ltd.", "TENMA" ltd., MGO "Energomash", "Atomenergomash Ltd", "Izhorsky Zavod Ltd", "Podolsk Machine Building Works Ltd", and others.

Assuming the supply of equipment by main unit manufacturing plants and the maximum development alternative for the nuclear power industry from 1997 to 2010, the average load of "Izhorsky Zavod Ltd" would be 1.38 units per year with an average capacity of 782 MWe per year (29% of production capaci-

ty), and that of “Atommash Ltd” would be 1.62 units per year with an average capacity of 1.187 MWe per year (40% of production capacity). The load of “Leningrad Metalworks” Ltd would be 75-100% of production capacity. Units of small capacity require an insignificant part of the main program in terms of steel and labour, and the program of their planned commissioning will be secured by the production capacities “Izhorsky Zavod” Ltd and joint venture “Podolsk Machine Building Works” Ltd.

d) Highly developed R&D facilities in the sector ensure the implementation of the program of nuclear power industry development up to 2010 and thereafter. The program is based on new generation reactor projects, supported by a highly developed network of test facilities and centers. Among nuclear reactors for installation at nuclear power plants, priority is given to:

- VVER-640 (Project NP-500), thermal capacity of 1800 MW, the pilot unit to be installed at Sosnovy Bor in Leningrad district;
- VVER-1000 (Projects NP-1000 and NP-1100), thermal capacity of 3000-3300 MW, the pilot unit to be installed at the Novovoronezh nuclear power plant.

A whole range of economic and technical factors will determine the priority within this group for realization on schedule of intermediate capacity reactor projects based on rich experience gained with VVER-440 and VVER-1000 reactors. This indicates an evolution path for the improvement of nuclear power plants as shown by the world experience. The decrease of reactor capacity and the energy density of the core makes it possible to considerably improve safety without losing competitiveness.

The list of perspective projects includes fast reactors (BN-800) to use civil and ex-weapons plutonium and to burn long-live radiotoxic minor actinides.

To supply energy to outlying regions and industrial districts and cities, a range of projects for small size nuclear power in-

stallations (2.5-150 MWh are planned - the so called small scale power production.

e) Analysis of the competitiveness of the planed nuclear power plants power generating facilities at the Russian energy market with fossil fuel ones shows the following:

- if capital investment in NPP exceeds that in combined cycle power plants by maximum 1.5 times, and if it is 15-20% higher than in coal-fired plants, then the nuclear option will be the most efficient in all regions of Russia;
- to maintain the competitiveness of NPPs against thermal steam-gas combined cycle power plants (CCPPs), capital investment in nuclear plants should not exceed the corresponding amounts for thermal CCPPs by more than 1.8 times for the North West and Central Russia, by more than 1.9 times for the Northern Caucasus, by more than 1.7 times for the Middle Volga region and by more than 1.6 times for the Urals;
- to maintain the competitiveness of nuclear power plants against coal-fired plants, capital investment in nuclear plants should not exceed the corresponding amounts for coal-fired plants by more than 1.08 times for the Urals, by more than 1.1 times for the Middle Volga, by more than 2.1 times for the North West and Far East and by more than 1.25 times for Central Russia.

As of the end of 1994, the average cost of power generation at operating nuclear power plants was 26% less than the average cost at the seven largest thermal power plants in Russia. The mentioned Russian-American joint research also confirms the results presented above.

Under the present situation of declining production of energy resources (especially of oil and gas) and their inevitable exhaustion in the near future, nuclear power industry can be considered as a guarantee of energy security in Russia and Europe.

Considering the development of the nuclear power industry in this aspect, it is possible to distinguish two main stages:

- maintenance of nuclear power generation capacity in the next 10-15 years at the current level of electricity production by reconstruction and technical upgrading of the units, by completion of the construction of new nuclear power plants and the development and realization of projects of new generation, high safety nuclear power plants;
- early establishment of the necessary pre-conditions for a significant future increase in the nuclear contribution to the total energy balance of the country and especially for a large-scale development of nuclear power industry after 2010, with a nuclear share in the which produce around 30% to 35% of total power generated in the country, 40%-50% for European part.

The accomplishment of above-referenced works will help resolve the following strategic tasks aimed at power independence for Russia and Europe in the near future:

1) the diversification of national energy sources and saving of fuel resources to ensure the necessary exports (the share of gas used in Russian electricity production is more than 60%, whereas in most Western countries it is between 25% and 30%). Even today it is possible to release for exports the additional energy resources by a higher utilization of operational capacities of the nuclear power plants available. For example, only by maintaining 1994 electricity production by Russian NPPs at the level of 1993, it would have been quite possible to generate additionally 22 billion KWh of electricity, and consequently save about 5.5 billion cubic metres of natural gas.

The annual saving of natural gas of nuclear power could in 1995 be 25 billion cubic metres or which, at present export prices, amounts to \$2 billion. (The whole effect for the entire period utilizing nuclear power plants could be 440 billion metres of gas or \$35 billion at current world market gas prices.);

2) the establishment of realistic conditions for the increasing of electricity export to European countries. Even in the near fu-

ture, there is a prospective increase in the export of electricity and in the realization of investment projects paid back by exports of electricity, for the support of construction of new generation facilities for electricity export, in particular, nuclear power plants. In this connection, great importance is given to the availability of surplus resources primarily in the energy systems directly adjacent to the borders of Russia. The North West energy system is an example where around 50% of electricity is produced by nuclear power plants. The planned decommissioning of units at Leningrad and Kola nuclear power plants, to begin in 2003, should be accompanied by replacement units with enhanced safety standards. Implementation of the projected interconnection Russia-Poland-Germany is extremely significant, especially since it could improve the possibilities for export of electricity from the energy system of Central Russia. The share of nuclear power generation there is at present more than 20%;

3) the solution of the problem of disposition of ex-weapons plutonium and disposal of radioactive waste within the framework of the large-scale development of the nuclear power industry based on fast reactors, and the introduction of a closed fuel cycle.

4) Of late, a keen and crowing interest has shown by banks and investment funds to Russian power sector of economy.

Estimates of the investment requirement of the nuclear power industry jointly evaluated by Russian-American researchers indicate that in the period up to 2005 on the most optimistic scenario, development costs for the nuclear power industry will amount to \$8.83 billion. The greatest part of capital will be required in the period 2000-2005, when it is planned to put into operation 5.5 GWe of new installed capacity nuclear power plants. Safety enhancement constitutes roughly half of the total investment.

Investment projects, selected by Russian and foreign organizations for financing by international credit institutions and by

investors, where construction of the units should be completed for their commissioning by 1998.

The completion of the construction of unit 3 at the Kalinin nuclear power plant, for example, is considered as economically justified. Unit 3 of the Kalinin nuclear power plant, with a second-generation VVER-1000 reactor, is 75% complete. According to the most optimistic assessments, to bring this unit into operation will take four years, and roughly \$347 million investment is required. This unit can be considered as a candidate for private financing using the BOT principle whereby the unit in question returns to State ownership at the end of its design service life. With a 60:40 ratio of loan to equity, it will be necessary for private investors to invest around \$140 million*.

Investments in the nuclear power industry in Russia are relatively attractive and will have great practical significance for ensuring power independence secure both in Russia and in Europe.

* Ryabev G.D., "Nuclear Power in Russia: Status and Prospects", Nuclear Europe Worldscan, 1 112, Jan./Feb. 1996.

SESSION 2

**Technical Problems and Possibilities
of Civilian Utilization of HEU and Pu:
Alternative Strategies (MOX);
Operational/Safety Problems**

Potential Contribution to the Recycling of Weapons Grade Plutonium In NPPs

D. Haas, C. Vandenberg, Y. Vanderbork



D. Haas

Abstract

Since 1986, more than 270 tons of MOX fuel rods have been fabricated in the BELGONUCLEAIRE Plant located at Dessel (Belgium) and, for the main part, loaded in commercial reactors in France, Switzerland, Germany and Belgium. Their excellent in-reactor performance up to 50 GWd/tHM has been demonstrated through surveillance programmes as well as specific experimental tests. That is the reason why BELGONUCLEAIRE

advocates the recycling of weapons grade Pu as MOX.

This paper presents the main achievements of MOX fabrication in Europe and particularly in Belgium, and its commercial utilisation in Light Water Reactors. It describes also the important contribution that BELGONUCLEAIRE can provide to promote and implement the MOX option.

1. Introduction

A direct result of the Strategic Arms Reduction Talks (START) treaties is that the United States and Russia have a binding agreement to dismantle warheads into components. This will generate large amounts of high enriched uranium (HEU)

and weapons grade plutonium (W-Pu). Regarding the latter material, although it is difficult to predict precisely when and in which quantities it will be available, it is anticipated that 100 to 200 MT (50-50 to 100-100 for the USA and Russia respectively) will be stockpiled before its final disposal in the coming decades.

There is a consensus that these quantities of W-Pu must be transformed as soon as possible in order to fix plutonium in an environmentally inoffensive form such that it is inherently as difficult to recover the fissile material from the immobilised form as it is from standard spent fuel. Among various technical options studied at the moment, there are two main possibilities allowing to meet this goal:^{1,2,3}

- either to use it as nuclear fuel for electricity production in civil power plants and to keep the remaining plutonium in association with the fission products in spent fuel in a once-through strategy;
- or to blend the W-Pu with fission products to fabricate a highly radioactive but stable compound by vitrification, and to dispose of it in a deep geological repository.

The choice of using plutonium as nuclear fuel (MOX) is natural considering technical, economical and safeguards aspects. This paper describes the potential contribution of the Belgian industry to this solution which is also based on the broad experience of other European countries (mainly France and Germany) in the field of MOX fuel technology.

2. Belgonucleair's Experience with Plutonium

Since its creation in 1957, BELGONUCLEAIRE has worked in the field of plutonium and has gained appreciable experience in the study, fabrication, fuel management and licensing of plutonium-bearing cores for FBRs, PWRs and BWRs. Already in 1963, it irradiated mixed oxide fuel (MOX) in a small pressur-

ized water reactor (PWR) in Belgium and since then, BELGONUCLEAIRE has fabricated fuel for fast breeder reactors (FBRs) and for light water reactors (LWRs). In putting into practice the use of this strategic material in nuclear reactors, we had to solve problems associated with fabrication, plant operation, safety, safeguards, security, transport and storage. This section briefly describes these topics^{4, 5, 6, 7}.

Today, MOX technology is in industrial use in France, Germany, Switzerland and Belgium. About 400 tons of MOX for LWRs have been fabricated and irradiated successfully. Among those 400 tons, 270 were produced by BELGONUCLEAIRE between 1986 and 1995. This quantity contains 13 tons of W-Pu in LWRs.

2.1. An Early Beginning in MOX Fabrication

After a period of R&D programmes performed jointly with the National Research Centre (SCK.CEN) in its laboratories, BELGONUCLEAIRE now owns an industrial fabrication plant, called P-Zero (P0) which is operating since 1973. The plant is located in the Mol-Dessel nuclear site in Belgium.

The R&D programme covering all aspects of MOX fuel research was started in the 1960's initially within the framework of a co-operation between EURATOM and the US Atomic Energy Commission and later in various programmes carried out with the backing of the Belgian Government and the European Union.

The industrial plant P0 was first used to fabricate fuel for demo-programmes in LWRs and FBRs. From 1977 to 1985, BELGONUCLEAIRE fabricated more than 18,000 fuel rods for various FBRs and more than 225 MOX assemblies were irradiated in the LWRs of four European countries (cf. Table 1). As a result of these programmes, it was shown that MOX fuel can reach the same performance as standard uranium fuel or even behave better than the latter.

2.2. The Industrial Phase

Since 1986, MOX fuel is produced on a commercial basis for LWRs of the countries shown on Table 1. Since then, the MIMAS (Micronized MASter blend) process has been used to obtain a fuel which is best adapted to LWR fuel specifications and large scale production, and which is soluble for the purpose of civil reprocessing. This process is described schematically in Fig. 1. The MIMAS MOX pellets are composed of a solid solution of UO_2 and PuO_2 homogeneously dispersed in a UO_2 matrix. This result is obtained through two blending steps: the primary (or master) blend obtained by ball-milling and the secondary (or final) blend.

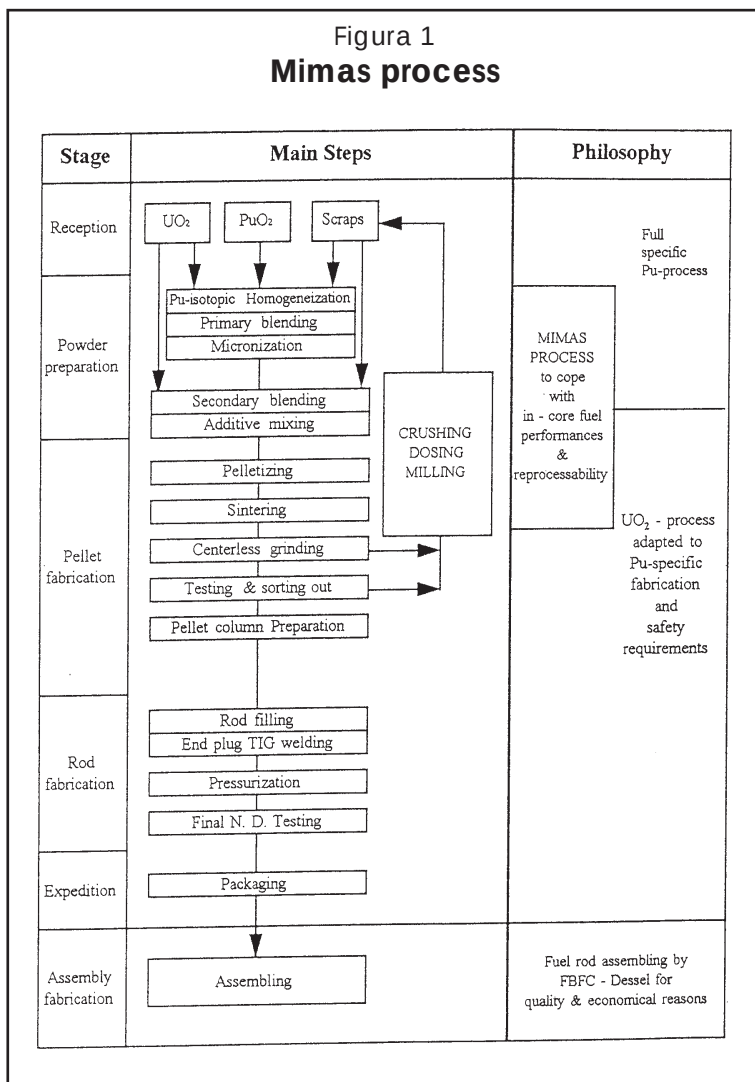
The MIMAS process presents several advantages:

- the primary blend (30-40 % Pu) can be stored immediately

Table 1
**LWRs Loaded with MOX fuel from the
PO plant - Dessel (Jan. 1996)**

Country	Demonstration programmes		Commercial deliveries	
Belgium	PWR	BR3	PWRs	DOEL 1
France	PWRs	CNA	PWRs	SLB 1 & 3
		CAP		GRAVELINES 4 & 5
Switzerland	PWR	BEZNAU 1	PWR	BEZNAU 1
Germany			PWRs	GRAFENRHEINFELD
				BROKDORF
				PHILIPPSBURG
				UNTERWESER
			BWRs	GUNDREMMINGEN 1 & 2
Sweden	BWR	OSKARSHAMN		
The Netherlands	BWR	DODEWAARD		
Italy	BWR	GARIGLIANO		

Figura 1
Mimas process

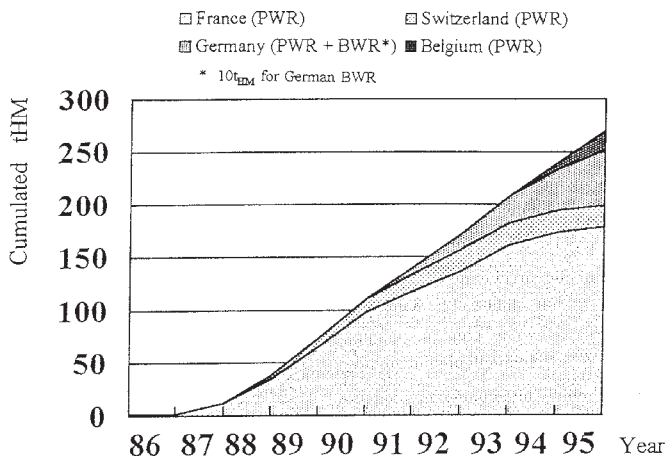


- under usual safeguard control and used later, upon request, for fabrication of pellets after the final blend step;
- high flexibility for Pu isotopic composition homogenisation through cross-blending;
 - demonstrated economical viability shown by full capacity production;
 - mature technology.

By end of 1995, more than 150,000 fuel rods had been manufactured by BELGONUCLEAIRE which represents about 270 tons of MOX out of the 400 tons fabricated world-wide.

More than 90% of the production is currently being irradiated in commercial LWRs of has already been unloaded from these reactors. Fabrication experience is presented in Fig. 2. Fig. 3 summarises the irradiation experience gained so far. The be-

Figura 2
Cumulated mimas production at Belgonucleaire



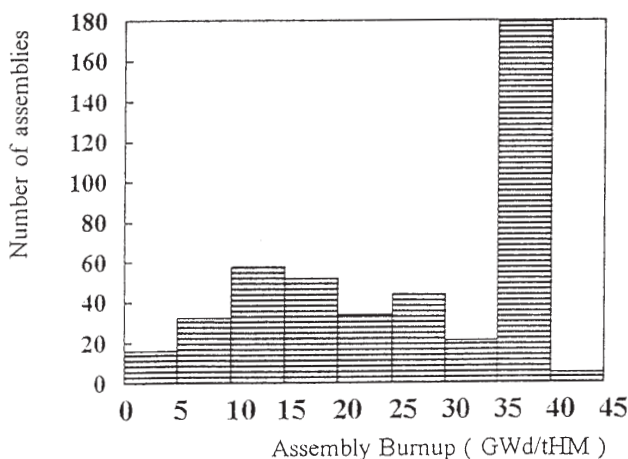
haviour of the fuel has been demonstrated to be very similar of that of the corresponding UO_2 fuel.

On the basis of in-reactor behaviour and post-irradiation results (with fuel having reached up to 80,000 MWd/tM) it can be said that MOX is a proven mature industrial fuel for NPPs.

The future (1996-2005) decade) for BELGONUCLEAIRE's MOX activities shall be characterised by the following evolution:

- an increased share of BWR (8x8 or 9x9) fuels and thus a need for even more flexibility requested from our production;
- a trend to increase the Pu content in the product for two reasons:
 - a request for high burn-ups;
 - a tendency to decrease the fissile Pu content in the powder received from the reprocessors;

Figura 3
Mimas fuel commercial irradiation experience



- a trend to receive Pu with higher activity, with an effect on the radiation doses and on the thermal heat dissipated by the powder, both having a direct effect on production efficiency;
- the ICRP-60 recommendations.

To meet the main new constraints imposed by this evolution, adaptation of the MOX plant is necessary in the following directions:

- the decrease of the percentage of fissile Pu content and the higher Pu enrichment go along with a more important heat generation in the powders, requiring modification of the powder blending and transfer system;
- a significant increase is foreseen of the neutron emission by the even isotopes of plutonium (Pu 238, Pu 240 and 242): this is leading to the massive introduction of neutron shielding in the workshops;
- personal exposure is to be reduced also by remote process control and by mechanisation of different process steps.

For the long term perspectives, additional improvements shall probably be requested depending too on the customer's particular requirements.

Finally, the MOX production experience shall also be improved by permanent analysis and feed-back of the fabrication data and by implementing the necessary qualification programmes e.g. to demonstrate the fabrication of new products (new powder types).

The same MIMAS process has been adopted by COGEMA for the Cadarache (since 1996) and MELOX plants. It will lead to a cumulated production of more than 1,200 tHM of MIMAS fuel by the end of the century.

It should be noted that the production of the COGEMA and BELGONUCLEAIRE plants is commercialised world-wide through the COMMOX G.I.E. (Groupement d'Intérêt Economique).

2.3. Plant Licensing and Construction Expertise

At the same time as developing the MOX product and MOX fuel fabrication, BELGONUCLEAIRE has progressively built up MOX fuel plant engineering expertise.

BELGONUCLEAIRE's capabilities in this field rely mainly upon three achievements, namely the existing Dessel Plant (P0), the project for the Dessel plant extension (P1) using the MIMAS process and a participation in the MELOX project in France.

This expertise is being largely expanded and updated by the continuously growing operating data base of the P0 plant as it has been working at full capacity since 1989.

From the point of view of the environment, the sensitive areas of safety and proliferation have been thoroughly studied in Belgium which is a densely populated country located in the heart of Europe and which does not contain large uninhabited areas that can be isolated easily. These factors - which are of great importance in the context of the present discussion - have been treated at length in numerous publications and will be discussed briefly again below.

2.3.1. Environmental Effects

The MIMAS process is based on the dry processing of UO_2 and PuO_2 powders which are mixed, compacted and sintered. It includes direct recycling of most of the quantities of scraps produced which avoids storage of the latter and the need for expensive auxiliary facilities.

The waste is practically always in the solid state which reduces the amounts for disposal in the storage facilities.

2.3.2. Safety Aspects

The use of plutonium with relatively high contents of Pu 241, Am 241 and Pu 238 produced in LWRs has necessitated specific studies of radiation shielding problems since the plant is only partially automated to assure greater flexibility, and

since the new ICRP recommendations shall decrease the admissible doses to the workers.

Over a total industrial operating period of more than 20 years, the mean radiation dose has always been kept below the permitted value.

The P0 plant, together with the P1 plant, were subjected to other safety studies pertaining e.g. to criticality, fires, accidents due to external causes, in accordance with regulations imposed by the Belgian law and the EURATOM Treaty under the supervision of the Licensing Body.

2.3.3 Safeguards and Traceability

Belgium has been a party to the EURATOM Treaty since its initiation in 1958 and adheres to the Non-Proliferation Treaty (NPT) with all its implications. It has been a strong supporter of an unconditional extension of the Treaty with no limitation on duration.

The BELGONUCLEAIRE plant in Dessel is subjected to the strictest safeguards system. In addition to the national authorities, IAEA and EURATOM teams permanently inspect the plant. The inspection procedures are constantly rationalised by highly competent personnel in order to minimise the loss of capacity and to optimise, where necessary, the human and material resources.

The proper handling of fissile materials is continuously controlled and accounted by the twofold international and independent monitoring systems. No relevant discrepancies have been identified to date.

2.3.4. Security

The physical protection of sensitive materials such as plutonium is defined by the Convention on the Protection of Nuclear Materials which is already over ten years old. This means that they are under constant surveillance by guards or electronic de-

vices and are surrounded by a physical barrier with a limited number of points of entry under appropriate control. Access is restricted to persons whose reliability has been ascertained.

In Belgium, the physical measures, rules and systems are determined by the Ministry of Justice. Most of these are not revealed to the public so as to increase their efficiency, while others are made visible as a dissuasive measure.

2.3.5. Transport of Fissile Materials

BELGONUCLEAIRE, through its daughter company TRANSNUBEL (set up in 1976), has acquired considerable experience with the transport of radioactive materials, especially spent fuel, plutonium dioxide and MOX assemblies. The companies work in close collaboration to solve various specific problems pertaining to safety, safeguards and the conservation and protection of the environment. So far, TRANSNUBEL has successfully carried out some 1,000 transports of radioactive substances every year without any major difficulties.

2.4. MOX Fuel Engineering Expertise

Since it started developing MOX fuel fabrication technologies in the 1960s, BELGONUCLEAIRE has been directly involved with research and development programmes, including fuel fabrication, irradiation testing either in research and reactors or in LWR power plants and post-irradiation work in collaboration with competent laboratories in Belgium (CEN.SCK - Mol) and / or in other European countries.

The reactors used for such tests were:

- the BR3 PWR (15 MWe) located at Mol, shutdown in 1987
- the CNA PWR (located in Chooz), shutdown in 1991
- the DODEWAARD BWR in the Netherlands
- the BESNAU 1 PWR in Switzerland
- the BR2 test reactor in Mol, using mainly the pressurised water loop designated CALLISTO (27 rods).

Since 1980, BELGONUCLEAIRE has organised international MOX fuel test and demonstration programmes, aiming at evaluating the mechanical and thermal behaviour of its fuel in LWR conditions. Mechanical testing includes ramp and transient tests. Thermal testing makes use of instrumented fuel rods. These programmes are financed by laboratories, utility companies of fuel manufacturers from several countries in Europe and Asia and from the US.

Particular examples of these programmes are:

- the PRIMO programme: irradiation and ramp testing of PWR MOX fuel rods in the BR3 PWR up to 50 GWd/tM (1987 to 1993).
- the DOMO programme: irradiation and ramp testing of BWR MOX fuel segments in the DODEWAARD reactor up to 60 GWd/tM (1987 to 1996).
- the FIGARO programme: irradiation in the BEZNAU 1 PWR MOX fuel rods (up to 50 GWd/tM) followed by ramp testing including central temperature measurement and pressure detection (1995-1997).
- the NOK M109 & M308 programmes: irradiation in the BEZANU 1 PWR of MOX fuel rods and segments (up to 55 GWd/tM) followed by ramp testing for PCI (Pellet-Clad Interaction) behaviour determination.
- the ARIANE programme: this programme is aimed at determining the source terms from high burnup MOX and UO_2 fuels irradiated in DODEWAARD (NL), NEZANU 1 and GÖSGEN (Switzerland).

A status of recent experimental programmes as well as new proposals is presented in Table 2.

3. What Could be BELGONUCLEAIRE's Contribution to the Disposition of W-Pu?

BELGONUCLEAIRE can make available its experience of the MOX fuel fabrication process that uses PuO_2 powder of different origins as well as its know-how regarding the construction or the operation of MOX fuel fabrication plants if it is decided to construct such a plant in the USA or in Russia^{8, 9, 10, 11}. Moreover, its experience in MOX fuel engineering and irradiation programmes will be a valuable asset to support any licensing study¹².

3.1. Contribution to MOX Processing

As indicated above, after 1984 BELGONUCLEAIRE developed the MIMAS fuel fabrication process. This process which is essentially a dry process is a simple well-tried method. It has

Table 2
Mimas fuel - Experimental programmes

Fuel type	Reactor	Burnup (GWd/tHM)	Status	Programme
17x17 rods	BR 3	41	Examination completed	PRIMO
17x17 rods	BR 3 & BR 2	60	Under examination	Bilateral
14x14 rods	BEZNAU-1	49	Under examination	FIGARO, NOK M 109
14x14 segments	BEZNAU-1	55	Extension of irradiation underway	NOK M 308 (not started yet)
8x8 segments	DODEWAARD	58	Examination completed	DOMO
8x8 segments	DODEWAARD	50	Under examination	ARIANE
14x14 uel rods	BEZNAU-1			
17x17 segments	MTR	30	New programme proposed	Helium release determination
8x8 segments	DODEWAARD and MTR	60	New programme proposed	High burnup behaviour and He release

been used in the fabrication of more than 60% of the rods produced so far for irradiation in LWRs over the world. This share will further increase in the future with the start-up of MELOX.

The MIMAS process produces excellent isotopic homogeneity of the Pu in the product, even with Pu of various origins (LWRs, GCRs, ex-W-Pu), of various forms (PuO_2 powder or a UO_2 - PuO_2 powder mixture) and for various batch sizes. Therefore, it is now considered as world reference and could be easily adopted for MOX fabrication with W-Pu, for large scale demonstration programmes or later fuel reloads deliveries. Such deliveries would be treated commercially through COMMOX.

Of course, the solution, called EUROFAB by the USDOE, which consists in using existing facilities in Europe for the fabrication and US utilities for the burning, necessitates transcontinental transports of the materials and thus further licensing steps.

3.2. Contribution to Licensing, Designing or Constructing a Fabrication Plant

BELGONUCLEAIRE has made the preliminary conceptual design of P1 as a possible extension to its existing P0 plant and has also included in its studies the decommissioning aspects. The main features of P1 are given in Table 3. It has a nominal capacity of up to 60 tHM/yr. (for LWR fuel) and is of modular design. It is based on the MIMAS process and has been designed in such a way to permit its adaptation as a result of the experience acquired with P0.

Fig. 4 shows schematically the lay-out of the plant. Fig. 5 is the general planning schedule for its construction and indicates a lead time before production limited to four years for construction once the authorisation has been obtained. This plant, relying upon an existing design integrating the experience gained in operating the existing plant as well as the know-how of the plant engineering, could be built in the countries (USA, Russia)

where the W-Pu is available, after transformation into oxide powder. The plant could be accommodated in existing nuclear facilities, after a proper feasibility study. The advantage of this scenario versus EUROFAB is to avoid expensive and time consuming overseas shipments.

3.3. Contribution to Fuel Engineering

BELGONUCLEAIRE has managed for more than 15 years R&D programmes on the behaviour of fuel (UO_2 and MOX) under irradiation. This gave the company the experience required to perform code calibration, licensing support, qualification of a new product and improved knowledge of fuel through the International Programmes. A fuel data base on about 60 PWR and 50 BWR MOX fuel rods and results of already performed pro-

Table 3

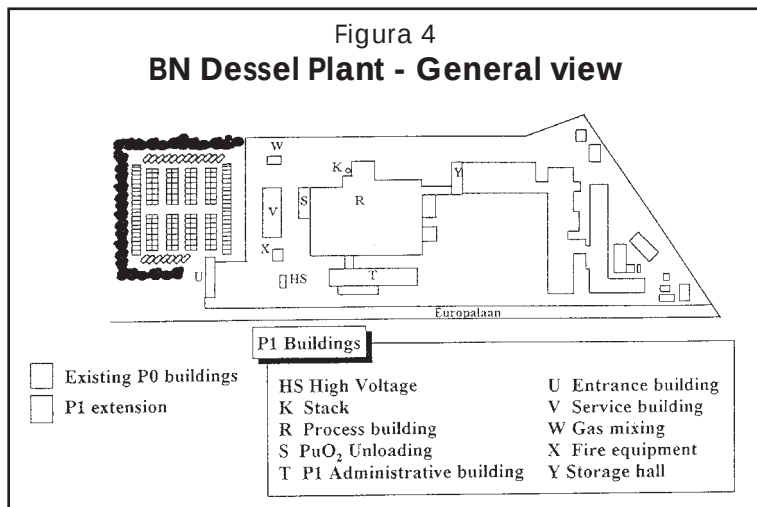
P1 - A new medium size flexible mox fuel plant

Capacity	Design capacity: 60 tHM/year
Flexibility	Line organization adapted for high operation flexibility: • P0 experience for small campaigns / multi-clients / multi-designs • two fabrication lines (NB: 4 lines with P0) • redundant / flexible handling Plant lay-out adapted for flexibility along plant life: • possibly progressive (de)-commissioning • prudent & progressive remote operation • in-life process & capacity upgrades
Other characteristics	Design for high Pu-contents (10-12%) and high burnup/age Pu (45 GWd/tM - 2 yrs) - Design complying with latest safety regulations: • radio-protection: ICRP-60 • advanced fire protection • aircraft crash resistance • earthquake resistance

grammes are immediately available. In the frame of the use of W-Pu in commercial reactors, BELGONUCLEAIRE could propose typical qualification programmes of fuel fabrication and irradiation.

Starting with W-Pu, MOX fuel can be manufactured in the Dessel plant as a demonstration of the MIMAS process. Base irradiation and/or ramp testing can be performed in a MTR like BR-2 (Mol, Belgium), HFR (Petten, The Netherlands) or HALDEN (Halden, Norway), or in a commercial NPP. Postirradiation examinations can be organised in various laboratories with our expertise for the analysis and interpretation of the results.

We propose to the international community to launch a new programme which could be named "P.I.T." (Plutonium Investigation Testing) including the fabrication of MOX elements and their testing in either MTRs or as lead assemblies in commercial NPPd.

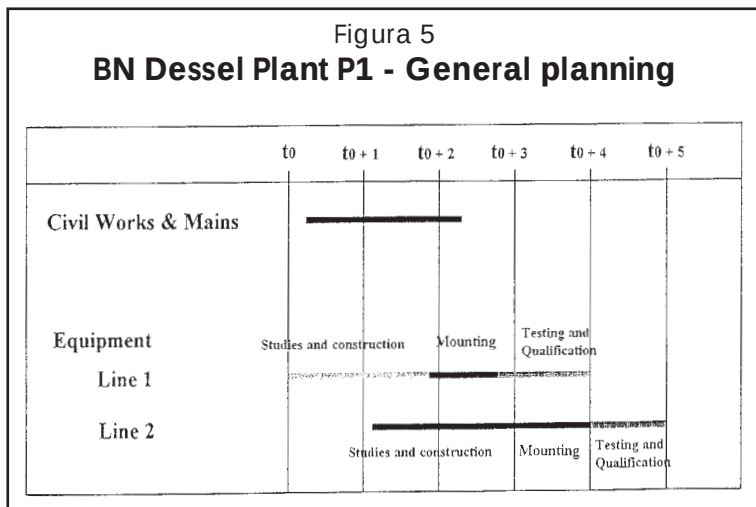


Short fuel rods with isotopic compositions close to that of W-Pu (95% Pu 239) have already been fabricated. They have been used for core physics validation experiments (results are available) and could serve for new experiments.

4. Conclusions

The utilisation of W-Pu as MOX for irradiation in LWRs is an attractive, mature and economical solution which answers the criteria issued in Dec. 1994 by the DOE for the “spent fuel standart”.

The choice of this solution will allow a quick start of the programme if standard MOX fuel is used and if the selected fabrication technology is the one for which both fabrication and irradiation experience are maximum. MOX fuel can be manufactured either in Europe, in existing facilities (EUROFAB), or - as



a further step - in new MOX plants to be built in the USA and Russia, taking advantage of existing facilities.

Both possibilities would benefit from the experience acquired in Europe with this type of fuel and in particular at BEL-GONUCLEAIRE:

- Mature fabrication technology (270 tHM fabricated with the same MIMAS process).
- Large irradiation experience in both PWRs and BWRs (240 fuel assemblies in the range 35-40 GWd/tHM burnup and 60 GWd/tHM as peak pellet in commercial reactors).
- Plant operation for more than 20 years and availability of an existing design for a plant of 60 tHM/yr. capacity.
- Post-irradiation results to support MOX licensing.

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Experience and Activities in the Field of Plutonium Recycling in Civilian Nuclear Power Plants in the European Union

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Abstract

The European Union industry has established a world-wide leadership position in manufacturing and exploiting plutonium bearing fuel (Mox). About 15 to 20 tons of plutonium have been manufactured in the Mox fuel fabrication plants of E.U. companies.

The current capacity of about 60 tons of Mox fuel per year is being upgraded to reach 400 tons/year by the year 2000. As a result, the excess amounts of separated plutonium, presently stored in the European Union, should no longer raise but should steadily decrease to converge to zero.

Studies by the European Commission have indicated that the best use at present of weapons-grade and reactor-grade plutonium is to burn it in operating and future planned nuclear reactors. Disposing of plutonium by blending it with fission products or immobilising it into synthetic matrices appears to be far from being an industrially viable option. Following this path would mean to continue storing the excess plutonium of both military and civilian origin for an unknown, but very long period of time.

For these and other reasons, the European Commission is striving

to foster international cooperation between the European Union companies, having a long industrial experience accumulated in the field of recycling plutonium, and, so far, the Russian Federation and the Newly Independent States. This cooperation is aiming at supporting projects that could be mutually beneficial to all parties involved.

To meet this objective, several programmes have been established either bilaterally or multilaterally, in particular within the framework of the International Science and Technology Centre (I.S.T.C.) in Moscow. Some examples of such collaborations will be described.

1. Introduction

Under the terms of the START Treaty, warheads should be dismantled at an assumed rate of 2 000 per year. This activity should free a large quantity of highly enriched uranium and weapons-grade plutonium that add to the burden of the countries concerned.

From a technical viewpoint and focusing on plutonium management, disposal of weapons-grade material at a meaningful industrial scale already represents a major problem in the short term. The problem of storage become even worse in the long term and could be at odd with the very spirit of the disarmament initiative.

The option of plutonium disposal through blending with fission products or immobilisation into synthetic matrices is far from being a viable industrial option. Following this path would mean to continue storing the excess plutonium for an unknown, albeit very long period of time.

Studies of the European Commission have concluded that the use of weapons-grade and reactor-grade plutonium in operated and planned nuclear reactors is a viable option, in economical and industrial terms but also with regards to physical control and safeguarding.

The pioneering and long standing experience acquired by European Union's organisations in the field of civilian use of plutonium allows these organisations to play a pro-active role in the implementation of several international cooperation and assistance programmes of the Union, either on a bilateral or multilateral basis.

This article will therefore concentrate on describing the present capabilities and programmes of European Member States, mainly in Belgium, France, Germany and the United Kingdom; the experience and activities of the general directorates of the European Commission will then be reviewed in particular in the area of research & development, nuclear safety, radiation protection, safeguarding, transport, combating illicit trafficking, and in the area of international cooperation and assistance; finally, ISTC projects in the field of plutonium recycling that are supported by the European Union will be presented as a pioneering example of future collaboration with the Russian Federation and the Newly Independent States.

2. Experience and Activities in the European Union

The **European Union** industry has acquired a thorough knowledge and experience of plutonium and Mox fuel handling, transport, physical protection and safeguarding, based on actual industrial achievement.

Mixed oxide (Mox) fuel, made by blending reactor-grade plutonium with natural or depleted uranium, is currently in industrial use in light water reactors of nuclear power plants in Belgium, France and Germany. More than 400 tons of Mox fuel have been fabricated and have permitted the recycling of more than 20 tons of reactor-grade plutonium. Thirty-four LWRs are fully licensed in Europe for using Mox fuel and fifteen reactors are actually loaded with plutonium fuel.

On average 21 tons per year of plutonium will be separated from LWRs and AGRs fuel in the reprocessing plants of La Hague (F) and Sellafield (UK) for the next 10 years; of this total, 15 tons per year will be European plutonium. The reprocessing of fuels from the Magnox GCRs is currently supplying a further 2.5 tons/year of separated plutonium.

With 15 to 20 tons of plutonium so far manufactured in E.U. Mox fuel fabrication plants and a production capacity of 60 tons of Mox fuel per year, soon to be upgraded to 400 tons/year, the European Union industry has placed itself in a world leadership position in the field of plutonium bearing fuel (Mox) manufacture and utilisation. As a consequence, the excess amounts of separate plutonium presently in store in the European Union will not raise any more but will converge to zero in the near future.

The European experience accumulated in the field of reactor-grade plutonium (RG Pu) with various isotopic compositions is a valuable basis for the application of these recycling technologies to the use of weapons-grade plutonium (WG Pu) in power reactors.

In **Belgium**, a high level of expertise has been reached. Of the 400 tons of Mox fuel or so fabricated thus far in the world, about 270 tons (equivalent to the recycling of 13 tons of Pu) were produced in Belgium. Mox fuel has been used in the first European PWR (the 11.5 MW BR-3) at the Belgian Nuclear Research Center at Mol already in 1963.

The PO Mox fuel fabrication plant of Belgonucléaire, at Dessel, has been operated since 1973 with a capacity of 35 t HM per year; a P1 extension of 60 t HM/year being foreseen. For the fast reactor programmes, Belgonucléaire has fabricated more than 18 000 fuel rods using more than 6 t HM for different customers during the period 1977-1985, in particular for 40% of the core of the German SNR-300 at Kalkar. For the light water reactor programmes, Belgonucléaire has fabricated 150 000 rods (i.e. about 800 fuel assemblies and 270 t HM) between 1986 and 1995 for many various clients.

In 1995, 16 Mox fuel assemblies were loaded in Belgian PWRs, 8 in the 900 MW Tihange-2 unit and 8 in the 970 MW Doel-3 station; this is the first time that Mox fuel elements are being used at a commercial scale in power reactors in Belgium.

In **France**, plutonium was first separated in December 1949 from an irradiated rod of CEA's Zoé reactor at Fontenay-aux-Roses and its production started in 1958 at Marcoule and 1966 at La Hague. Then the fabrication of plutonium bearing fuel was developed to feed the fast neutron reactors Rapsodie at Cadarache, Phénix at Marcoule and Superphénix at Creys-Malville.

For economical reasons, the mid-term interest focused on the Pu recycling in water reactors. From 1974, Mox fuel use experience has been developed in the Chooz 310 MW PWR in the Ardennes; the plutonium recycling in civil power plants continued at an industrial scale in 1987 with the fifth reload of Saint-Laurent-des-Eaux-B-1 PWR. Now, nearly 500 Mox fuel assemblies have been loaded in the seven EDF's PWRs operating with this fuel at Saint-Laurent, Gravelines, Dampierre and Blayais. EDF has 16 PWRs licensed to use Mox fuel and intends to burn Mox fuel in 28 PWRs of 900 MW as from year 2000. For the future, a plutonium version of the European Pressurized Reactor EPR is currently studied by the consortium EDF-EVU-NPI(Framatome+Siemens).

Today the plutonium content in the 1100 tons of spent fuel unloaded yearly from EDF's PWRs is well over 10 tons, but only 850 tons/year of spent fuel are reprocessed leading to 8.5 tonnes of separated Pu.

By the end of 1994, 460 Mox fuel assemblies had been supplied by Framatome to seven French 900 MW PWRs and abroad. Since 1989 the fabrication of Mox fuel is done in the Cogema's CFCa plant at Cadarache which was previously dedicated to fast reactor fuels and has a capacity of 30 tHM/year; in the future this plant will be dedicated to fabrication of Mox fuel for

the German LWRs. In 1995 the new 120 tHM/year Melox plant at Marcoule started industrial fabrication of Mox for supplying EDF's PWRs requirements; this plant could easily be upgraded to a 160 tHM/year capacity. Construction of a new Mox plant is foreseen at La Hague; this facility will be able to accommodate various type of Mox fuel and its capacity will be in the range of 80 tHM/year.

As far as cooperation with Russia is concerned, the French government signed in November 1992 a bilateral agreement on collaboration in the field of nuclear weapon destruction in Russia and peaceful use of the released fissile materials. The Aida programme is aimed at facilitating the reduction of the considerable amount of Russian weapons-grade plutonium and at defining an efficient method for its utilization. French and Russian scientists are studying the feasibility of building the so-called Tomox facility in Russia to transform some 1.3 t WG Pu/year into approximately 1.5 tons of Mox for the 600 MW Beloyarsk FBR and 20 tons of Mox for the 4 Balakovo 1000 MW VVERs.

In **Germany**, plutonium fuel recycling in thermal reactors dates back to 1966 with the insertion of Mox assemblies into the VAK reactor at Kahl, followed in 1970 by the loading of Mox in the 350 MW PWR at Obrigheim. Several commercial power PWRs and BWRs were then loaded with Mox. The Alkem 25 tHM/year Mox fabrication plant started operation at Hanau in 1965; it was handed over later to Siemens, but was shut down in 1991. A new 120 tHM/year Mox fabrication plant was built at Hanau's site next to the Alkem plant, but was in turn abandoned in 1995.

Presently the 21 LWRs in operation with an installed capacity of 23.6 GW produce 450 tons/year of spent fuel containing approximately 4.5 tons of plutonium. So far about 18 tons of plutonium were separated, of which 7 tons have been fabricated to Mox fuel elements and recycled in thermal reactors mainly PWRs, the balance being stored in different forms; about 1.5 t

Pu have been used for the manufacturing of the core loading for two fast reactors, the Kalkar SNR and the small KNK-II prototype. Up to year 2003 it is expected that 42 tons of separated plutonium are available for re-use in German reactors. At present 11 PWRs and 2 BWRs are licensed to use Mox elements and 6 other NPPs have applied for the use of Mox.

A total of 250 Mox assemblies have been manufactured and loaded in Germany LWRs; the overall German experience with these Mox fuel elements is excellent.

Regarding cooperation between Germany and the Russian Federation, an initiative was started in 1993 to transfer equipment and technology from Siemens AG to Russia for processing weapons-grade plutonium into Mox fuel. The German Foreign Ministry has funded a feasibility study on Mox use with WG-Pu, the result of which being a proposal to build a pilot fabrication plant at Chelyabinsk on the basis of Siemens know-how.

In the **United Kingdom**, the processing and storage of plutonium at BNFL's Sellafield site started in the early 1950's and included civil plutonium from 1964 onwards. Thermal Mox fuel has been made for a number of reactor types including GCRs, BWRs and PWRs. Five Mox assemblies were loaded in the first AGR at Windscale with excellent results. Also about 20 tons of fast reactor Mox fuel has been made in the period since 1970; this was used in the prototype PFR operated by UK AEA at Dounreay, Scotland. Altogether the UK stockpile of civil plutonium is substantial with some 80 tons RG Pu, half as irradiated fuel in storage ponds, and half as separated PuO₂ stored under rigorous safety, security and safeguards measures. UK has an enormous potential for recycling Pu from reprocessing of natural uranium Magnox fuels, the obvious reactors to burn Mox fuel being the AGRs; but this has not yet been developed on an industrial scale. To demonstrate Mox fabrication, in 1993 BNFL brought into operation its 8 tHM/year MDF facility at Sellafield with an annual capacity of 20 PWR assemblies and its first cus-

tomers, the Swiss NOK, received delivery of Mox fuel in 1994. The 120 tHM/year SMP Mox fabrication plant is currently under construction adjacent to the Thorp reprocessing plant which came into operation at Sellafield in 1994; SMP, designed to fabricate Mox for various types of reactors, is due for active commissioning in late 1997.

Concerning cooperation with Russia, BNFL's 1991 collaboration agreement with the former soviet ministry was extended until 1997 with the Ministry of Atomic Energy of the Russian Federation (Minatom) and covers the whole of the nuclear fuel cycle from R & D, through design, construction, operation and decommissioning. Specific Mox technologies are part of the programme and a BNFL-Minatom working group is investigating a potential process to transform Pu into PuO₂.

3. Experience and Activities of the European Commission

Disposing of excess plutonium of any origin is a major concern for the public, but even more so when considering surplus military plutonium. Given the currently implemented policy of disarmament and non-proliferation, the European Union has a vital interest that nuclear weapons states, and Russia in first instance, realise quickly the disposing of its plutonium stock. This approach would help contributing towards reduction of excess stockpiles of military fissile material; it would strengthen the enforcement of the international non-proliferation treaties and also foster the implementation of the Russian-American disarmament agreement. The fastest and more economical solution for disposing of the surplus WG Pu would be to recycle it in existing nuclear power stations, in line with the Russian Federation statement on plutonium being a precious source of energy for its population.

Russian plans to date have focused on recycling plutonium in fast neutron reactors, such as the BN-600 operating at Beloyarsk (Siberia) and BN-350 at Schvevchenko (Kazakhstan), or the few BN-800s presently at the planning stage. Russian research centres have begun studying the use of Mox in VVER pressurized light water reactors using technologies similar to those used in the PWRs in operation in eight European Union Member States. Russia currently has seven 1000 MW VVER in service at Balakovo, Kalinin, and Novovoronezh, and seven others under construction; more 1000 MW VVERs are operating or under construction in neighbouring countries.

The huge quantities of fissile materials transferred from the military sector to the civilian sector pose a new challenge. Development of new techniques and adapting existing ones, requires an important **R & D** effort as well as investing into industrial plants. While European Union industry and Member States are already contributing a major effort to that end in Russia, the European Commission's Directorate General for Science, Research and Development -**D.G. XII**- and **Joint Research Centre -JRC-** have also taken significant steps in this direction. The Euratom Framework Programme includes a research and technological development and demonstration scheme for nuclear fission safety covering the period 1994-1998. Much of the JRC's effort in the field of nuclear materials is developed in relation with the European Safeguard Research and Development Association ESARDA, grouping all the European Member States, the JRC being in charge of the association's permanent secretariat. A strong collaboration is also pursued between this association and the American Institute of Nuclear Materials Management INMM. As soon as September 1994, the Commission issued its COM(94) 383 communication to the European Council and European Parliament for an assistance programme to Russia to monitor the fissile materials from disarmament; this programme is based on the JRC's works.

Several projects were approved during the Summit of the heads of the E.U. Member States at Essen and are in progress and financed by the Commission's Directorate General for External Relations: Europe and the Newly Independant States, Common Foreign and Security Policy, External Service -**D.G. IA**-Technical Assistance to C.I.S. -TACIS- budget. Priority in the nuclear fission safety was given to training with the main project of creating the Russian Methodological and Training Center RMTc at Obninsk, near Moscow, where more than 1000 experts are expected to be trained.

In addition, the JRC is currently developing research aimed to design new plutonium fuels; European scientists devoted to this task work in the JRC's Institute for Transuranium Elements -ITU- in Karlsruhe, in close cooperation with experts of the most concerned Member States (D,F,UK). The ITU currently investigates a novel scheme for burning weapons-grade plutonium (WG Pu) in conventional light water reactors with a view to optimising the destruction rate of plutonium and increasing the proliferation resistance of the resulting spent fuel. The main feature of this scheme is the use of a fuel based on WG Pu and weapons-grade high enriched uranium (WG HEU) in an inert matrix. Ex-military nuclear non-fissile materials such as tritium and beryllium need also to be disposed of in the civilian sector and research is underway to using them in fusion programmes.

In the field of **nuclear safety**, the European Commission's Directorate General for Environment, Nuclear Safety and Civil Protection -**D.G. XI**- has developed considerable experience in the definition and application of regulations and conventions for plutonium handling and transfers. Required safety standards are based upon a philosophy of defense in depth which minimises the probability of incidents or accidents during fabrication, transport and reactor use of nuclear fuels. Any design of Mox fuel assemblies and Mox loaded reactor core has to obey the same safety requirement as UO₂ elements and core; PuO₂

fuel rods and assemblies have to meet the same thermal and mechanical limits as specified for UO₂ fuel. Transient and accident simulations (loca, lofa) for PWRs and BWRs cores containing Mox fuels show only small differences compared with those for pure UO₂ cores. Altogether, no significant changes occur by the introduction of plutonium bearing fuel as long as adjustments are fulfilled to fit the Mox neutronic properties : higher neutron absorption requiring greater neutron flux, higher temperature coefficient, lower proportion of delayed neutrons, behaviour under load-follow conditions and at high burn-up levels.

Responsibility of D.G. XI includes the **radiation protection**. Fresh fuel assemblies containing plutonium have a higher dose rate than the standard UO₂ elements: this entails special handling radiological protection measures, including use of a dedicated examination ring for in-plant handling. For radioprotection reasons as well, it is better not to store Mox fuel for a long period of time, as plutonium progressively turns into radioactive americium.

Materials **transport** comes under the authority of the Commission's Directorate General for Transports -**D.G. VII**-. Shipment of plutonium must meet the same standards used for other radioactive materials; they are based on the integrity of the package under any accident conditions, thus ensuring the same level of protection for the workers, population and environment independent of the selected transport mode. Supplementary tests, far beyond the present IAEA criteria, can be imposed by national authorities on the containers selected for special shipments, such as was done for the sea transport of plutonium between France and Japan. Other conditions above and beyond the safe container are also imposed (e.g. shock absorbers for road and rail shipment) so as to minimise and to avoid complete loss of the cargo or involvement of the cargo in case of extreme fire. This is the case for the transport of plutonium be-

tween La Hague and Rokhasho Mura where the following measures are in force: ship with double hulls, compartmental holds, redundant fire prevention and suppression systems, monitoring of cargo's temperature, routing and time-scheduling navigation.

Transport of radioactive materials is managed for preventing accidents with the normal traffic and other precautions are inspired by security reasons like physical protection (escorts, radar systems). It is necessary to consider possible causes of package failure: for such cases emergency response planning and preparation is foreseen. The strengthening of regulations and practices are currently under review and discussion for a wide range of activities and responsibilities related to transport of sensitive nuclear materials; the opportunity is considered to issue specific regulation notably for the development of a new Type C safer package for the air transport of plutonium. The European Commission's Standing Working Group on Safe Transport of Radioactive Material, which includes representatives of the Members States' safety authorities, is actively involved in these activities for the implementation of which the European Parliament has earmarked a significant 1996 budget. This programme stresses as well the need for assistance and training of the staff of the competent authorities of the Russian Federation and the Newly Independent States.

The production, movement and processing of nuclear materials, including plutonium bearing spent fuel and separated plutonium, are subject to strict **safeguards** procedures aimed to verify that their use continues to be as declared, that is to ensure that they are not illicitly made into nuclear weapons or explosive devices. The Commission's regional safeguards system operated by the Directorate General for Energy **D.G. XVII-E's** Euratom Safeguards Directorate deals with the individual nuclear operators within the territory of the European Community Members States and the Euratom system constitutes a regional

safeguards system which complements the different national systems of accountancy & control, and the UN's international safeguards authority IAEA. The Euratom safeguards system is since 1957 founded in European law (Euratom Treaty's Chapter VII) and it applies to all civil nuclear materials; its mission is to detect diversion from peaceful use, to check that specific uses are correct and that obligations imposed by suppliers are respected.

Since 1970, Euratom has carried out continuous inspections at plutonium bulk facilities. Given that the existing industrial reprocessing plants and Mox fuel fabrication facilities, as well as number of Mox burning power stations, are all located within the territory of the European Community, Euratom has obviously gained substantial experience in safeguarding these parts of the fuel cycle, a fact which is reflected by the amount of inspection effort dedicated to that area. This trend will lead in the future to increasing activities related to sensitive nuclear materials of which plutonium takes a prominent role. The European Commission is open to share the experience gained in this field with those countries embarked on the disposition of weapons-grade fissile materials.

Illicit trafficking in nuclear material continues to pose a global risk and a potential danger to public health and safety. The European Commission recommended in 1994, the COM(94)383 communication to the European Council and the European Parliament on the illicit trafficking of nuclear materials and radioactive substances, with recommendation of a series of measures for combatting this practice. Several Commission's General Directorates are involved, including DG 1, DG 1A, DG XI, DG XII, JRC, DG XVII and DG XXI. The nature of the materials involved in this trafficking is quite various and in some occurrences only minor quantities of plutonium were at stake, as was the case of the well publicized seizure at Munich international airport. A close cooperation has been implemented between the Commis-

sion and the concerned organizations of the Russian Federation: Gosatomnadzor, Minatom and Kurchatov Institute. Four projects were initiated to improve the nuclear material accounting & control system in Russia and seminars were organized for the training of the personnel. A long term action in this field is developed at the RMTC centre of Obninsk with Tacis financing. The achievement in Russia of an efficient system of accounting and control of fissile material in the industrial nuclear facilities requires important resources and an international cooperation is indeed needed; the European Commission is joining efforts with the USA and Japan to reach this objective.

4. Participation of the European Union in the International Science and Technology Centre (I.S.T.C.)

The **International Science and Technology Centre (ISTC)** is an intergovernmental organization established in March 1994 by an international agreement with four initial parties, the European Union, Japan, the Russian Federation, and the United States, now joined by Armenia, Belarus, Georgia, Kazakstan and Kyrgystan. ISTC recently broadened participation with admission of a first funding partner, the European Organization for Nuclear Research CERN in Geneva. The task of ISTC is to develop, approve, finance and monitor science and technology projects addressing the following objectives :

- to provide weapons scientists and engineers in Russia and other interested states of the CIS opportunities to redirect their talents to peaceful activities;
- to contribute to the transition to market-based economies responsive to civil needs;
- to support basic and applied research and technology development for peaceful purposes;

- to promote the integration of scientists and engineers from Russia and other CIS states into the international scientific and engineering communities.

The ISTC operates with two administrative bodies: the Governing Board and the Secretariat, located in Moscow, with an executive Director and three Deputies all from the initial Parties to the Agreement. To manage its affairs, the Governing Board is advised by a Scientific Advisory Committee and is helped by a standing Coordination Committee.

The ISTC currently supports 202 projects for 81.6 M\$, providing opportunities for more than 11 000 scientists and engineers, previously involved in the development of weapons of mass destruction, to engage in peaceful activities. The European Union is funding or co-funding 133 of these projects for a total amount of 29.6 M\$, provided through the Tacis programme. The European Commission is the E.U. management body for the ISTC, with DG IA in charge of administrative and political aspects, and DG XII in charge of the evaluation and monitoring of projects.

ISTC projects span a wide spectrum of technology and research domains, including a little more than 10 % of projects pertaining to nuclear fuels and storage. The European Commission supports the involvement of European organisations at all levels from the definition of projects to the development and exploitation of results, although the latter must be dealt outside the ISTC framework.

As an example, when the ISTC was set up in 1994, Commission's Directorate General for Energy - **D.G. XVII** - took the initiative of proposing a project, now known as ISTC Project **N.369**, on the **“study of the technical and economic feasibility of the use of ex-weapons plutonium and civil plutonium as fuel for both fast and thermal reactors”**. It received an encouraging response from a number of European Members States already active in that field, Belgium, France, Germany and the

United Kingdom, and submitted a draft study for examination by the Ministry of Atomic Energy of the Russian Federation (Minatom). This initiative resulted in Minatom officially submitting in 1995 the Project N.369 to Governing Board of the ISTC, which approved its funding by the E.U. for 0.58 M\$.

In this example of practical collaboration, E.U. industrialists involved in plutonium recycling technology expressed their interest in collaborating with Russian research teams through the project development. The companies involved are **Belgonucléaire** (Belgium), **BNFL** (United Kingdom), **Cogéma** (France), and **Siemens** (Germany).

On the Russian side, Minatom appointed seven Russian research and engineering institutions to conduct the feasibility study, making one of them responsible for directing and coordinating the project: the **Institute of Physics and Power Engineering IPPE** in Obninsk. The other participants are the All-Russia Scientific Research and Design Institute of Power Technology A-RSRDIPT in St Petersburg, the “Bochvar” All-Russia Scientific Research Institute of Inorganic Materials A-RSRIIM in Moscow, the “GidroPress” Special Design Bureau SDB GP in Podolsk, the “Chlopin” Radium Institute RI in St Petersburg, the Experimental Design Bureau of Machine Building EDBMB in Nizhnij Novgorod, and the Governmental Specialized Project Institute GSPI in Moscow.

The N.369 **feasibility study**’s aim is to put emphasis on the first stage of Pu recycling in Russia with large amount of separated civil plutonium being accumulated at PO Mayak and quantities of released weapons plutonium, and with few reactors actually using plutonium. The study is based on a comparative system analysis of the technico-economic parameters of various scenarios for using WG Pu and RG Pu.

A major concern within the public opinion is in first instance to make sure that the excess separated plutonium from military origin can be disposed of as soon as reasonably possible. The

material derived from the dismantlement of the warhead pit consists of metal plutonium and the first step towards denaturation is to convert this metal into plutonium oxide PuO_2 ; this is to be achieved inside the military facilities workshop and the study of this step is not part of the Project N.369. But before it can reach an industrial stage, this first phase will require process development, time and investments.

The second step of denaturation of the ex-military plutonium is to use it in fabricating Mox fuels and this is to be done inside civilian, internationally safeguarded facilities where PuO_2 can be handled. The third and final step towards denaturation is the irradiation of the Mox fuel assemblies inside the core of the power reactor where plutonium is burnt and mixed with highly radioactive fission products and trans-uranium elements, making it resistant to diversion or use in explosive devices.

Given the above mentioned time incurred in developing industrial scale facilities necessary to deal with ex-military plutonium and considering also the fact that civil separated plutonium in stockpile is as well a public opinion concern, it seems reasonable to take opportunity of this delay to accelerate, as soon as possible, familiarization of the operators with the valuable experience of recycling excess inventories of RG Pu as Mox fuel in operating power reactors.

The Project N.369 feasibility study considers three different options:

- fast neutron reactors to be built on a single integrated site with the appropriate fuel cycle facilities;
- pressurized light water reactors VVER already in service, under construction and planned, partly loaded (one third of core) with Mox fuel assemblies, as well as in fast reactors;
- pressurized light water reactors of VVER type in operation modified to handle full Mox cores.

The comparison of all options is to be performed on the ba-

sis of an uniform methodology using data obtained in a coherent manner. The work is done taking into account the conditions existing in the nuclear power development and the economic context of Russia, as well as available experience in Mox utilization abroad, inter alia in Belgium, France, Germany and the United Kingdom.

The economic assessment of these options will be made within the framework of a system analysis integrating the following parameters:

- efficiency and timescale of inventory drawdowns;
- non- proliferation concerns;
- people's health and environmental protection;
- resistance of materials to diversion;
- nuclear safety.

The programme comprises two phases, each lasting a year:

- Phase 1: Characterization of the principal fuel parameters for fast and thermal reactors (BN-600, BN-800, VVER-1000, VVER-500) having full or part Mox cores, taking into account the most stringent safety requirements. Calculation of investment and operating costs for successive stages of plutonium use in the reactors and in fuel cycle and storage facilities.
- Phase 2: The above mentioned results will serve as input data to a system analysis of the various scenarios, using a standard methodology, so as to determine their economic efficiency, with a view to the impact assessment from the point of view of radiological protection, waste management and evaluation of measures to prevent misuse of nuclear materials.

The human resources mobilized, over two years, for the Project N.369 at the seven Russian institutions amount to 1300 men x months, corresponding to an average 50 scientists and engineers. The basic data will be calculated using neutronic codes widely used in the similar studies carried out by IAEA and

OECD, taking into account the balance of energy produced and changes in isotopic composition; mathematical models will be used to determine the technico-economic feasibility of the options and scenarios. The Russian research institutes will make their data banks, software and data-processing capability available to the project. Progress reports will be produced and the findings of the study will be published in the specialized national and international press and at international scientific meetings.

The Project N.369 is guided by a **Joint Steering Committee (JSC)** composed of experts from the Russian Federation and the European Union. Members of this JSC are representatives of the seven Minatom's specialized institutes, the European Commission and the four nuclear fuel industrial companies of Belgium, France, Germany and the U.K.

The JSC or its Secretariat, which is assured by representatives of the IPPE and Commission's DG XVII, meets twice a year either in Russia or in the European Union. The last JSC meeting was held in Saint Petersburg on October 30-31, 1995, and 1996 meetings will take place in Brussels and Sellafield. The trilateral organization of the JSC is a very typical aspect of the Project, its fundamental object being to create a dialogue and to assure an efficient collaboration between operators from the East and the West of Europe.

With the definite intention of avoiding repetition works and encourage complementarities and cross-fertilization between different programmes and different institutes, it has been decided that links be established between Project N.369 and **other projects related to plutonium use** and also funded by the **ISTC**. Several projects, either already approved or still under review, have been identified as bearing a potential complementarity with N.369 ; their results or conclusions could represent a significant and beneficial input to take into consideration.

The approved ISTC projects deserving to be mentioned are:

- **N.116**, funded by the E.U., pertains to the development of computational and methodological techniques for verification of nuclear data bases used in calculations of neutron-physical characteristics and used in analysis of nuclear reactor safety. This reactor physics project will last 3 years, and is focused on VVER reactors. It involves also simulation and experimental works at the ROMB stand in Chelyabinsk-70. The leading institute is the NIKIET-RDIPE in Moscow and E.U. collaborating industry includes GRS (Germany), Framatome (France) and Belgonucléaire (Belgium).
- **N.273**, funded by the E.U. for 2 years, focus on radiation aspects in nuclear fuel cycle based on reprocessed uranium Repu and Mox fuel, including: calculation of hazardous nuclides; study of radiation characteristics; analysis radiation conditions during pellets and assemblies fabrication; determination of spent fuel characteristics and wastes during production and reprocessing. The Russian institutes involved are the Bochvar and the Kurchatov, and the E.U. collaborators involve the Institute of Transuranium Elements of the JRC in Karlsruhe (Germany), Cogéma (France) and BNFL (U.K.).
- **N.290** concentrates on civil and military plutonium utilisation in fast and thermal reactors, and management of wastes generated in the process. This 3 year project is being funded equally by the E.U. and Japan for a total of 0.45 M\$. The project specificity is to transform plutonium alloys from dismantled warheads to dioxide and to develop technologies of low dust-producing granules of Mox fuel. The leading institute is the Bochvar in Moscow, but the project involves other Minatom's divisions in Dimitrovgrad, Obninsk, Nizhniy Novgorod, Sverdlosk and Chelyabinsk. International collaborators to this project are Siemens and the JRC (Germany), BNFL (United Kingdom) and PNC (Japan).
- **N.332** is concerned with developing safe methods for storing

large quantities of plutonium and uranium from dismantled warheads. ISTC funding was granted for a preliminary feasibility study; if continued, the 2 year project will consist of computation methods and test experiments (conversion into oxide, powder mixture, sintering). The leading institution is the VNIIEF in Arzamas and the supporting organization is the European Commission's Institute for Transuranium Elements ITU in Karlsruhe.

Further related projects are currently under review by the ISTC.

5. Conclusion

The European Union nuclear industry is a world leader in the industrial development and commercial exploitation of mixed plutonium-uranium oxide fuels technology in pressurized light water reactors and is well placed to guide the use of such Mox fuel in the VVER-1000. The experience and activities in this field involves the European Community as a whole, several of its Member States with their national nuclear research organizations, their regulatory authorities and their specialized industrialists, several divisions of the European Commission including its Joint Research Center and its Euratom Safeguards Directorate. The European Union is one of the funding parties of the International Science and Technology Centre ISTC in Moscow which provides mass destruction weapons scientists and engineers in Russia opportunities to redirect their skill to peaceful works; several projects funded by the ISTC are dealing with the use of plutonium of military or civil origin as a fuel in nuclear power plants.

At international level, the experts were given the task to study options for the long-term disposition of fissile materials, particularly of plutonium, taking into account the issues of non-

proliferation, environmental protection, safety, and technical and economic factors. The most rewarding issue is the use of plutonium for electricity generation and a significant contribution can be brought into the picture by the cooperation between scientists and engineers of the European Union and the Russian Federation. The various actions taken in the European Union will contribute to provide an indispensable reference for decision making concerning the disarmament issue. They will pave the way for the orientation of new R & D projects and identify areas of industrial cooperation between countries having experience in this field.

Uranium-Plutonium Fuel for Fast Reactors

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S. Antipov

Introduction

First efforts to utilize plutonium as nuclear fuel date back to 50s.

Those investigations allowed to create in the mid 60s pilot section at PU “Majak”, where the cores for the reactors BR-5, IBR-2, IBR-30 and experimental fuel assemblies for reactor BOR-60 were produced.

The subsequent R&Ds were focused on the mixtures of uranium and plutonium oxides — the main fuel for fast

reactors of the first generation.

The initial investigations of uranium-plutonium fuel were based on mechanical mixing of individual dioxides of uranium and plutonium. In 1980 a “Paket” facility was development at PU “Majak” with the sections of pelleting and fuel element outfitting. The capacity of the facility is 350 kg/year by the sum of uranium and plutonium oxides. Already in 1980-1981 the first 10 full-length fuel assemblies were manufactured (assembling of fuel elements into fuel assemblies was conducted at the Elektrostal plant) and charged into the BN-350 reactor.

In 1969 the decision was taken to establish a pilot-industrial U-Pu fuel production — a complex 300 at PU “Majak”.

Mechanical mixing of metal dioxides was laid as a basis for the technology of fuel manufacture.

The ammoniac technologie of fuel fabrication having been developed at Russian Scientific and Research Institute of Inorganic Material since 1986 alongside with the objective to develop ecologically acceptable (producing little dust) processes, proceeded from the condition to obtain mixed oxides via chemical co-precipitation of the corresponding compounds of uranium and plutonium.

At the beginning of 1987 a pilot — industrial facility “Granat” was designed and constructed at PU “Majak”, which starting from April 1988 has begun to produce U-Pu oxides.

Currently 2 technological processes are at the stage of R and D:

- mechanical mixing of individual oxides (MMO — process);
- method of ammoniac granulation (“Granat”).

The above technologies allow to fabricate powders that can be conventionally presented by 2 classes: dispersed, granulated powder class.

“Granat” method provide for the fabrication of granular with the size of 50 - 1000 mkm (mainly 200 - 800 mkm). Individual oxides being used in the technology mechanical mixing have the particles of the size of up to 20 mkm.

When choosing one or another pattern of obtaining the initial powders, not only dusting but a number of other factors as well should be taken into account. These factors are the following: the possibilities of producing powders with stable properties; simplicity of the technology of core fabrication; absence of additional operations to improve the powder technological properties (for example, granulation, additional calcination, grinding, etc.).

The development of the technology to produce MeO_2 core was commenced in 1963-65.

The initial products were uranium dioxide obtained via ammonia precipitation, and plutonium dioxide obtained via preliminary precipitation of plutonium - ammonium pentaoxalate, providing for fuel ceramic properties of plutonium dioxide.

To provide for the yield the MMO powder require the granulation that includes preliminary compaction, grinding, sieving and pelletizing. The operations enumerated are dust-producing and complicated in view of equipment.

Individual oxides of uranium and plutonium, being used for mechanical mixing, are the most dust-producing at the given level of the technology development.

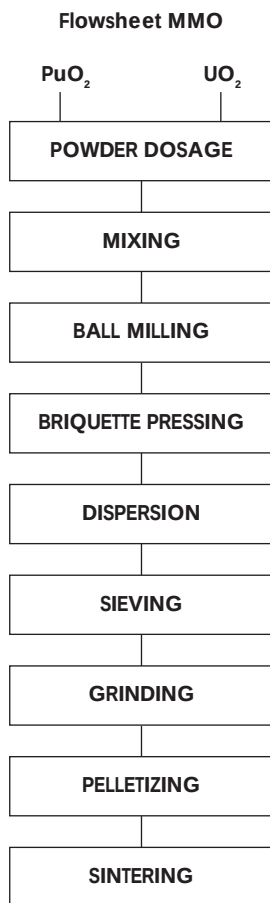
Currently the characteristics and types of initial powders,

Table 1
**Pellet fabrication schemes prepared
from different oxide powers**

Operation	Zol-Gel	Granat	AU(PU)T	PCC	MMO
Reduction of the founding solution	+	+	+		
Dosage up to require composition of Pu / (U+Pu)			+		+
Blending with binder for average composition	+	+	+	+	+
Dispersing of the mixture					+
Preliminary pressurizing				+	+
Ball milling and sieving				+	+
Grinding and mixing with the binders				+	+
Pressing	+	+	+	+	+
Sintering	+	+	+	+	+

Table 1 presents the technological patterns of core fabrication of various types of initial materials. Only pressing and sintering - the two technological operations - are common for all the powder types.

Figura 1
The methods of UO_2 and PuO_2 powders mechanical mixing



heat treatment modes, mixing and dispersion modes are determined. In a member of work this technology is shown to have an extensive possibility to affect in the required direction the powders and cores characteristics.

The strength of the powder granular produced by MMO technologie, is caused by the pressure of preliminary compaction and is easily controlled during the process of granulation and, therefore, there is no need to control this parameter for the given initial powder.

Besides that, the technology of fuel fabrication from MMO powders anticipates the dispersion operation that is carried out with the goal of thin PuO_2 particle's distribution in the UO_2 matrix to form solid solution at the sintering stage.

The degree of grinding and dispersion (uniform mixing of fine dispersed components) influences considerably the physicochemical and technological characteristics of powders, the content of sintered solid solution after sintering, fuel structure and solubility after chemical reprocessing and solution of products rejected. Grinding leads to decrease in size of particles (agglomerates) and shift in their morphology, which causes changes in specific surface, fluidity, bulk density, mouldability and sinterability. The influence of dispersion and grinding on technological characteristics is ambiguous. Dispersion and grinding modes are critical to the process. Inactive grinding and mixing with the use of grinding bodies can somewhat increase fluidity and bulk density, and decrease specific surface. On the contrary, active grinding and dispersion with fine and extra fine grinding processes increases specific surface and decreases fluidity and bulk density. In mixed fuel production, the degree of dispersion determines the size of solid solution zones with different content and allocation of Pu inside fuel pellets.

Presence of Pu-enriched zones in sintered pellets influence the characteristics of Doppler coefficient and solubility in reprocessing of rejected products and irradiated fuel.

Because of this, specifications for reactor cores contain tolerances for zone size and Pu content.

Thus, the mixing, dispersion and grinding processes are the base of mixed fuel production, as they provide for uniform allocation of components and the physicochemical and thermal characteristics in the fuel column. Powders of different origin and character are used in core production; because of this, one of the key aspects is to optimise the mixing, dispersion and grinding processes.

Introduction of a AVS-150 type eddy layer apparatus into the technological process has allowed to improve to a large extent the homogeneity.

Method of Ammoniac Co-Precipitation in the Presence of Surface Substances “Granat”

As a basis for this process the method of uranium and plutonium hydroxide's precipitation in the presence of surface-active substances (SAS) was used.

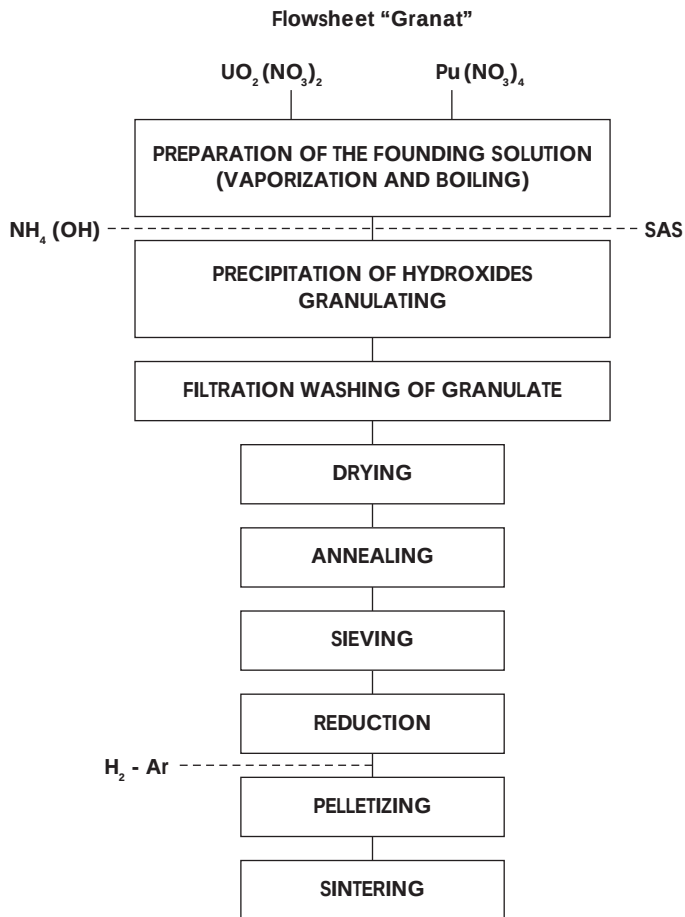
“Granat” powders provides for a low level of dusting at all the stages of technological process of fuel core fabrication.

As a result of the investigation conducted by the Russian Scientific and Research Institute of Inorganic Material and then jointly with PU ‘Majak’ during 1985-1988, positive information was obtained both in view of the product quality and possibilities of the process waste utilization, and the perspectives of the equipment development.

For a short period (about one year) the design of the ‘Granat’ facility was developed, the basic technology equipment was manufactured, the mounting and start-up-and-adjustment work were performed. The mixed oxide's facility production rate is 0.6-0.8 kg/day.

With the ‘Granat’ technology of product fabrication from

Figura 2
**Method of ammoniac co-precipitation
in the presence of surface substances "Granat"**



powders, the properties of initial granular are not changed. They are predetermined at the chemical technological stage of oxide fabrication. At the stage of product fabrication it is impossible to control the granular strength, therefore, this parameter of the initial powder must be controlled to its correspondence with the required value (0.3 – 0.5 kg/ m).

The carried out investigation have shown that the granulation of the 'Granat' facility allows to obtain sleeves with the required structure and composition.

During the period of December 1988 - February 1989 about 50 kg Of mixed oxides with plutonium content of $23.5 \pm 0.5\%$ mass was produced at 'Granat' facility, and about 700 kg of mixed oxides were produced by the beginning of the second quarter of 1993.

Recommendations given on the base of laboratory investigations, were fully confirmed at all the process stage when experimental fuel assemblies were produced in semi-industrial scale.

Sintering

Sintering is the basic stage of production of pelletized fuel. In the process of sintering all physicochemical and technological peculiarities of the initial fuel are revealed, and the most important fuel characteristics are formed, namely density geometry, structure, degree of homogenisation, oxygen co-efficient.

The nature of the initial oxide influences considerably the characteristics of sintered pellets, as it determines the morphology of particles, the specific surface of the powder, bulk density, presence of impurities, etc.

Below are shown the peculiarities of sintering processes for U and Pu dioxides.

There exist fairly strict tolerances on MOX pellets for fast reactors. Many of those are analogical to tolerances on U pellets

in the list of criteria. Utilisation of Pu as the splitting material brings forward new requirements which influence considerably the fuel's performance under irradiation, the working capacity of fuel elements and neutron-physical characteristics of the reactor in general. The basic difference between MOX fuel and U fuel is that for MOX fuel either a homogeneous structure (solid $(UPu)O_2$ solution) is obtained, or fine dispersed Pu inclusions are uniformly allotted within a U counter die, and, which is more, a determined O/Me ratio and U/Pu ratio are obtained.

As a rule, we use batch-operating furnaces with molybdenum/tungsten heaters to investigate and fabricate experimental cores, which makes it possible to attain a sintering temperature up to 2000°C , charge mass up to 2000g and to use H_2 -Ar mixture as the sintering atmosphere. It is known that to attain a pre-stoichiometric constitution of MOX fuel, a gas atmosphere with a corresponding oxygen potential (DGO_2) is needed. But with the use of batch-operated furnaces a regulated oxygen potential is practically unattainable, because moisture in the pellets and in the atmosphere (sorbing on the water-cooled body, shields, heaters) interferes into the furnace.

In batch-operated furnaces humidity does not practically vary, and moisture forming in the process of reduction of pellets influences considerably the o potential. In this case, the o potential of the sintering atmosphere depends on the O/Me ratio of initial oxides, the speed of gas flow, the speed of boats moving through the sintering area, and temperature gradient in the axial and radial directions. All these parameters are controllable and capable of regulating which permits to obtain stable and determined O/Me ratios after sintering, as it was corroborated by the experience of foreign companies in MOX fuel production.

At the Mayak plant cores are sintered in batch-operated shaft high-temperature furnaces.

To provide for control over the sintering atmosphere, a

molybdenum ampoule was inserted into the furnace to isolate the sintering area from the heaters and the body of the furnace. In this case, the moisture of the outcoming gas also depends on temperature, but to a considerably smaller extent.

Completion of this sintering mode made it possible to obtain a regulated O/Me ratio.

Potential Ways of Effective Utilization of Plutonium, Weapon's Grade One Included

In Russia reactor scientists and designers have a unified opinion that plutonium can be most effectively utilized in fast reactors. As distinct from the concept that was shared by us 10 or 15 years ago which envisaged the maximum plutonium breeding we are now engaged in resolving the directly opposite task, namely, producing fuel that would drastically reduce or fully eliminate plutonium breeding.

Several directions are under study. One of them is to produce fast reactor MOX fuel containing much more plutonium, up to 45% against 20-25%. The second one is to prepare plutonium oxide fuel containing the minimum allowable uranium and an inert diluent additive, i. e., fuel that would significantly reduce plutonium breeding.

The two directions of the most effective plutonium utilization through the use of oxide fuel seem promising since, first, much experience has been gained in oxides and, second, the stored civil plutonium is in the oxide form.

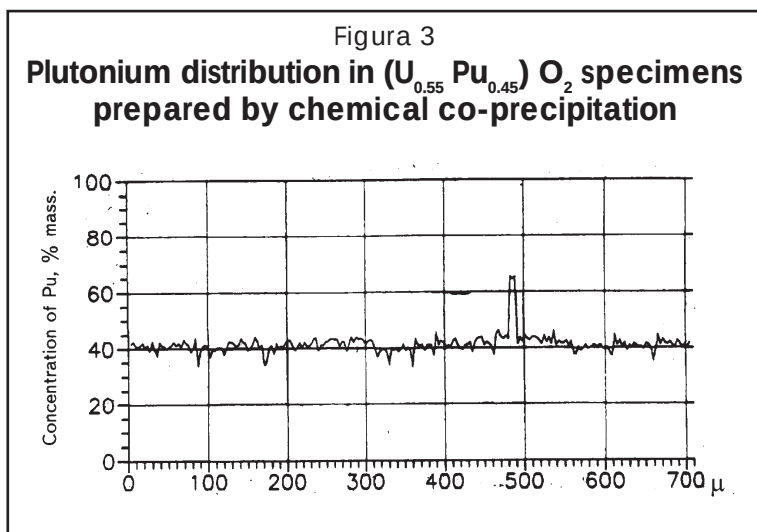
The plutonium content of the fuel now in use in fast reactors is 20-25%; the rest being depleted uranium. However, this fuel inevitably results in significant plutonium breeding. The plutonium breeding ratio can be much reduced if the plutonium content of the fuel is increased while that of uranium is decreased. We decided in favour of the fuel containing 45-50% plutonium.

Use was made of both ammonia co-precipitation and mechanical blending. The specifications for the pellets were the same as those placed on the standard product.

The improved process is capable of producing pellets having the stable density in the narrow range of 10.5-10.7 g/cc. X-ray spectral and x-ray diffraction analyses corroborate the formation of an oxide solid solution (Fig. 3).

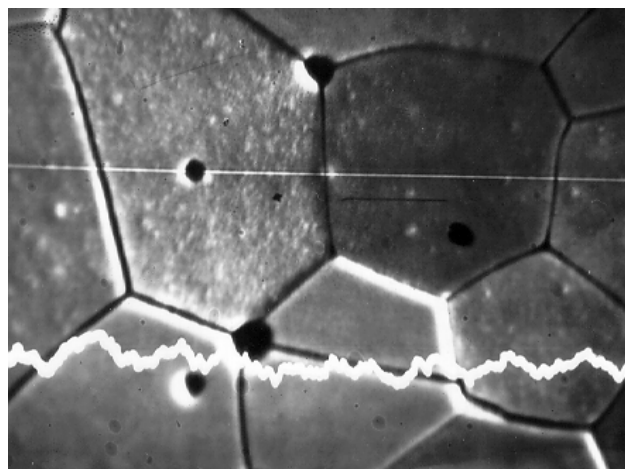
The nitric acid solubility of higher plutonium content pellets depends on the method of the mixed oxide preparation. The pellets of co-precipitated oxides as twofold processed are adequately dissolvable, i. e., 99.4%. The solubility of mechanical blended oxide pellets is but 93.4%.

The second direction of the potential substantial reduction of the plutonium breeding ratio in fast reactors is related to a development of fuel having the minimum permissible content of uranium through partial substituting the latter by an inert diluent.



The work in this field has been initiated. Cerium and aluminium oxides are under study as potential inert diluents; also zirconium oxide is suggested for studies. The choice of those materials has been made based on general implications, since no phase diagrammes of the respective oxide systems or other data are available. To generate some bench mark data the first experiments were conducted using uranium oxide and diluents at the 10% content of the latter. Pellets manufactured from mixed dioxides prepared by the ammonia precipitation method have the density of $10.3 - 10.5 \text{ g/cm}^3$ and fine uniformly distributed pores. The diluent content is as specified; its distribution is adequately uniform (Fig. 4).

Figura 4
Microstructure and distribution Ce



Ce (10 ± 0.5)%

x 2000

Summary

Thus, the technology was worked out for fabrication of MOX fuel pellets from co-precipitated and mechanically blended mixed oxides. Both the processes ensure the homogeneous structure of pellets readily dissolvable in nitric acid upon reprocessing.

To increase the plutonium charge in a reactor – burner the process was tested for producing MOX-fuel having a higher plutonium content and an inert diluent.

It is shown that it is feasible to produce fuel having a homogeneous structure at the content of plutonium up to 45% mass.

Performance and Characteristics of a Small-Sized Oxide-Fuelled Fast Reactor (PRISM) for the Burning of Excess Plutonium

Carlo Artioli, Georgios Glinatsis, Franca Padoani

Abstract

The increasing availability of fissile material and the world-wide perception of the need to reduce or control such material make a new approach towards nuclear reactors necessary. The Nuclear Fission Division at ENEA is presently interested in evaluating various options for the burning of excess plutonium, among which the LWR reactors using rock-like inert matrix fuel in a once-through cycle and fast reactors with recycling. This paper deals with the latter option. A fast system, rich in neutrons, can produce plutonium by breeding, or it can burn it (together with Minor Actinides) with a high degree of effectiveness: this flexibility makes the fast system worth considering.

In the framework of a co-operation project between GE-USA and ENEA, the PRISM MOD D oxide-fuelled reactor (small size, 840 MW) was studied as a burner. A complete set of studies was carried out covering several fields: neutronics, thermohydraulics, dynamics and safety.

A negative void coefficient was achieved thanks to a particular arrangement of the fuel subassemblies (leaky core) and to the enrichment distribution. The central zone, loaded with shielding subassemblies, accounts for a negative void coefficient even in the inner zone. Moreover, this zone could become a suitable place for burning long-lived fission products. As a burner, using a standard fuel, the expected performance is a

consumption of about 60-70 kgPu/TWhe. ULOF and TOP analysis show a begin transient evolution. Only half of the GEMs are sufficient to close the ULOF transient; the reactor power reaches its maximum at 1.35 of the nominal figure during a TOP accident.

A method of detecting a failure in a subassembly and identifying the subassembly concerned was developed. It was demonstrated that it is possible to create a sufficient number of tags for them to be recognised as different by the detector system, by using "cocktails" of only four tag gases. The total gas required to overcome the uncertainties is less than 15 ncm³ of gas/pin. This method assumes that the detector system is unable to measure the absolute quantities, but only the mutual ratios. By processing the results of the detector system with a simple code, the effectiveness of the method can be significantly increased. Moreover, experimental measures can be used to reduce the required quantity of gas.

1. Introduction

Significant quantities of weapon-usable fissile material, namely plutonium and highly enriched uranium, are now considered as surplus to requirements and this excess is doomed to further increase as the arms reduction agreements between United States and Russia are implemented. Moreover the growing and even larger accumulation of plutonium from the civil nuclear program is another formidable element and means that a new approach toward fissile material is required.

The use and disposal of civil plutonium is a difficult matter to handle, as its value is not the same for all countries: greater availability and more recycling may be seen either as a manna from heaven or as a plague. On the other hand, for military plutonium it is perhaps easier to find a common ground and the

use of the keywords “surplus” or “excess” is already evidence of an intention to get rid of it.

But at which cost, and within time frame? As soon as all the variables of the problem are taken into account, including security, safety and environmental impact, it is clear that an approach similar to that for civil plutonium is required. Despite the differences, an analysis of the options for the disposal of the weapon material can cover a large part of that for civil plutonium and vice versa.

Several options have been proposed, varying from vitrification, the launching into space or its use as a fuel, hence exploiting its economic potential. They could be outlined as follows:

- options already technologically available;
- options not yet available, but that would be made available with present technology in the short term;
- long-term options, that in some cases have still to demonstrate their efficacy.

The time schedule should not however hamper further studies of the most promising options, but at the same time the urgency of the plutonium disposal problem compels us to turn towards systems that are or may be available in the short term.

The burning of plutonium in nuclear reactors is one of them. Looking at the various systems proposed, it should be noted that the ‘optimum’ system probability does not exist, but more probably that a combination of potentially ‘optimum’ systems will be the practical and best solution (for instance LWR+LWR-MOX+Fast-Burner). Independently from the chosen system, two issues have to be duly considered: first, the need for intrinsically safe reactors in order to be publically acceptable; second, the problem has to be fully addressed, hence considering the degradation of plutonium in the reactor and the presence of minor actinides (Np, Am, Cm) and long-life fission products (I129, Tc99).

If giving too high a value to plutonium has been one mistake of the past decades, the opposite mistake should if possible

avoided. System dedicated to mere destruction of plutonium, such as accelerators, could be seen as a panacea now, but perhaps as a terrible waste in the future. The flexibility of the system should be a strategic issue. Regardless of economic considerations a fast system, that can act as a breeder or as a burner (to some extent) according to the loaded core, could assure this flexibility.

However the problems of plutonium disposal should not lead us to neglect the problem of waste. A correct ethical approach toward posterity requires systems that neutralise, now, potentially dangerous products.

2. An Oxide-Fuelled Fast Reactor (PRISM)

The Advanced Liquid Metal Reactor (ALMR) is a fast reactor design based on the Power Reactor, Innovative Small-Module (PRISM) concept originated by General Electric, with the objective of obtaining a competitive fast reactor system with improved safety, enhanced plant licensability and simplified plant operations. The ALMR Program was sponsored by US-DOE until fiscal year 1994-95 and is still under development with GE resources.

The solution analysed by GE assumes a metallic alloy of Uranium, Plutonium and Zirconium (U, Pu, Zr) as reference fuel, in both breeder and burner solutions. Innovative elements have been introduced into this system in order to enhance safety:

- the Gas Expansion Modules (GEMs) operate in the event of a loss of primary coolant flow. They are hollow assembly ducts, closed at the top and filled with cover gas trapped in the upper part by the compression of the sodium: at normal operating pressures the sodium level is above the top of the active core. Reduction in pump head makes the gas expand and expel most of the sodium; being located towards the border, this fact increases the neutron leakage and hence inserts a negative reactivity;

- the Ultimate Shut-down Device (USD) is a manually activated device with the means of bringing the reactor to cold sub-critical conditions in the event of a complete failure of the normal scram system;
- the Reactor Vessel Auxiliary Coolant System (RVACS) is a passive system for the removal by natural convection of the shutdown heat for loss-of-cooling events.

Moreover, the PRISM concept presents a high flexibility that makes possible important changes in the core with no effects on the rest of the plant and its performance.

ENEA Oxide-Fuel Core Based on PRISM Mod.B (840 MW_{th})

In the framework of a co-operation project between GE-USA and ENEA (PECOS Program), an alternative core design was developed, to set up an optimised small-size oxide-fuelled core. In particular the tasks performed were:

- optimisation of the breeder solution and minor actinides (MA) transmutation;
- development of a burner core with a high plutonium consumption rate;
- development of a Passive Monitoring Device (PMD) to detect clad failure valid for both options;
- study of a methodology to identify the failed subassemblies, valid for both the options.
- seismic analysis.

As the present topic is the disposal of plutonium, we now refer only to the optimised burner option studied for the PRISM Mod. B (840 MW_{th}).

This optimisation is based on the breakeven core geometric configuration (Fig. 1). In a breakeven core the breeding ratio must be nearly equal to one, and to achieve a net consumption rate of plutonium, and eventually of minor actinides (MA), fertile material must be removed from this configuration. Thank to the flexibility of the PRISM design, only a few other modifica-

tions were necessary to transform the breakeven core into a burner core, assuming the following requirements as guidelines:

- *Reactivity burn-up swing as small as possible*: it assures better loading factors and safety performances in the core. A high reactivity burn-up swing reduces the available CR-Scram reactivity north at the Beginning Of the Equilibrium Cycle (BOEC).
- *Negative, or low positive Na-void effect*: as it is strongly related to safety, it provides for a benign closure in most accident situations.
- *Doppler effect*: notwithstanding the high fissile content it should be sufficiently negative;
- *Breeding ratio significantly less than one*: the Pu quantity-burned per cycle must be consistent with the requirement for Pu and MA economical burning.
- *Classical design solution*: the additional cost of further developments - for instance new material and/or fuels with a high Pu content (>35% for oxide fuel) - must be limited in order to compensate the additional cost of the fuel cycle-length reduction, intrinsic to the burner concept.

Past experience on oxide fuelled core designs as well as the above considerations account for the assumed design limit:

reactivity burn-up swing	$\leq 10\%$
peak fuel burn-up ⁽¹⁾	180 MWd / kg
peak fast fluence ⁽²⁾	3.8 (+23) n / cm ²
peak linear power ⁽³⁾	$\leq 300 \text{ w / cm}$
Transuranic content	$\leq 35\%$

(1) to assure limited cladding strain and fuel pin integrity;

(2) to assure acceptable swelling behaviour in the clad and the core structural material (HT9);

(3) to assure limited fuel pin peak temperature;

A Pu content limited to about 35%, as well as assuring the

use of the present fuel fabrication and reprocessing technologies, provides well known irradiation performances. The chosen reference isotopic composition of the feed fuel was:

Pu-239 / pu (*)	58.003%
U-235 / U	2.0%

(*) 10 year old LWR discharged fuel: Pu / TRU=89.26%

The core divided into two enrichment zones (i.e. different Pu content) and the inner one has the lowest enrichment. A higher enrichment towards the border was found to play a positive role between the place where sodium boiling can occur and favourable Na-void coefficients.

Moreover, to improve the Na-void effect in the inner fuel rings at low enrichment, the seven central fuel assemblies were substituted with an equal number of absorber assemblies. A possible interesting option for this central zone could be issue as a suitable place for burning long-lived fission products. As their transmutation is negligible for a fast neutron spectrum, an appropriate moderation is needed, but this problem has to be investigated.

Another of the most effective changes made possible by the flexibility of the PRISM design is associated with the GEMs. Their number and position has been optimised in order to maximise their reactivity worth, while reducing the mutual interference effects and the 'shield' effects from control rods, that greatly affect their effectiveness. While the metallic solution by GE assumes the GEMs are distributed all along the same ring, for the oxide solution and distribution over more than one ring was adopted. The required calculated GEM reactivity worth was estimated to be about 3\$; this figure provides for a reasonable margin, even taking into account any experimental correction.

Neutronic and Thermohydraulic Analysis Results

The breakeven core was not modified with regard to the total number of assemblies (391) (i.e. the core diameter) and to the number of the control assemblies (9), ultimate shutdown assemblies (3) and radial shield assemblies (66). Different core configurations were considered for the optimisation analysis, varying one or more than one of the following parameters:

- active core height;
- fuel assembly number;
- fuel pin number per assembly;
- fuel assembly distribution in the two enrichment zones;
- batch number;
- cycle length.

In particular, three families were analysed (Fig. 2.1 and Fig. 2.2):

162 fuel assemblies	}	at 271 pins	180 fuel assemblies at 331 pins
180 fuel assemblies			

For each family different sub-families were studied, modifying the other parameters. Each configuration was characterised by its own neutronic performances and safety parameters, related to the design assumptions, and some results are given in Tab. 1, where only the most interesting options are shown.

For instance the 162 fuel A's/42 inch - 271 pin configuration appears as the one with highest peak linear power, peak fuel Burn-up and peak fast fluence. The thermohydraulic analysis on the peak fuel assemblies was performed for this configuration and the results are shown in Tab. 2 and Fig. 3. The design temperature constraint is satisfied in both Beginning and End of Life (BoL and EoL); Fig. 3 shows that the total flat-to-flat dilation for the peak fuel assembly is lower than the design limit.

It attention is paid to the Pu-Consumption rate it will be noted that: on the one hand, in order to increase the plutonium

consumption, the solutions with higher enrichment in Pu content would have been preferable; on the other hand higher Pu content poses more technology and safety problems and it is more difficult to satisfy design and economic constraints. Among the families studied, the 180 fuel assemblies-331 pins, full pellet, made possible high enrichments satisfying design constraints, though reducing the cycle length. This configuration was then defined as the 'reference configuration' and was used for further safety considerations.

Safety parameters for the reference configuration are shown in Tab. 3. Generally speaking, favourable safety parameters were found and an intrinsic reactivity feedback was assured.

- Net axial expansion negative coefficients provide a significant negative feedback during a transient event associated with axial fuel expansion as the temperature rises. In the same way, net radial negative coefficients provide a negative feedback during thermal expansion of the grid plate depending on sodium inlet temperature.
- The Doppler coefficients (TdK/dT) were reasonably good considering the high fissile content and the absence from the burner core of fertile assemblies and axial blanket zones.
- The density coefficients are expressed in term of fractional variation for core reactivity, in the presence of a change of density. Because of the calculation methodology, a positive value implies a negative feedback as material density decreases with increasing temperature; conversely a negative value provides a positive feedback. The high value of the fuel density coefficient and its high temperature gradient assure a large negative feedback.
- In particular negative sodium void effects were achieved, as shown in Fig. 4 and Fig. 5. Fig. 4 shows the Na-void worth per fuel assembly, averaged over the ring, at the beginning and at the end of the fuel cycle. The negative effect in the inner rings is due to the presence of the absorber zone at the

centre of the core. Fig. 5 shows the Na-void worth distribution per assembly for the reference configuration and highlights the achievement of negative values for all assemblies but a few with low-positive values. Negative void effect increases (as absolute value) as the sodium volume fraction increases - for instance reducing the pin diameter - or augmenting the fissile content, while keeping other volume fractions constant. Negative void effect decreases as fission products increase (i.e. at EOEC); moreover it also decreases introducing MA into the core.

- Regarding the β -effective value, it may be noted that it decreases as the fissile content increases. Though a small value implies a reduction of the prompt-criticality margin, safety analysis of accidental situations always shows a benign closure, thanks to all the other parameters.

It is worth noting that locating GEM assemblies in high neutronic importance zones it makes possible to have high GEM reactivity worths with a relatively small number of assemblies (18), of which 6 distributed in the seventh ring and 12 in the ninth.

Safety Analysis

ALMR safety design goal is to accommodate Anticipated Transient Without Scram (ATWS) events, in particular:

- Unprotected Loss Of Flow (ULOF)
- Unprotected Transient Over Power (UTOP); and
- Unprotected Loss Of Heat Sink (ULOHS).

Analysis of ATWS events was performed only for the reference solution at BOEC, the events being initiated with the reactor at its nominal power and the conservative assumption of the non-availability of the passive RVACS.

- The ULOF analysis was performed for two cases: all the four pumps were failed and none of GEMs were failed; the four pumps were failed together with nine GEMs. The

GEMs reactivity worth considered was the effective one, corrected by experimental factor ??? Fig. 6.1-2 show the calculated reactivities and the fuel temperatures for the hot channel: after about 100 seconds the net reactivity and fuel temperature reach stability conditions for both cases.

- The UTOP analysis was performed with the insertion of a positive reactivity up to 5.0\$: this value was determined by the mechanical device that controls the CR's withdrawal. Power rises up to 135% after about 70 seconds, during the UTOP event, and decreases down to an "equilibrium level" of 122% after about 500 seconds, as shown in Fig. 7, that is acceptable in the PRISM design.

The third ATWS event still has to be investigated. In summary, thanks to intrinsic negative feedback and passive safety devices, the analysed ATWS events were proved to be "controlled" and satisfying safety constraints.

Plutonium Consumption and Conclusions

Plutonium consumption performances for the reference core are summarised in Tab. 4. A Pu-consumption rate of about 60 kgPu/TWhe was found, as expected with Pu enrichment of about 35%, equivalent to about 140 kg/core/year.

Higher Pu-consumption rate could be possible introducing other modifications, for example increasing the Pu-content using hollow pellets as shown in Tab. 1. Unfortunately this, or any other solution, introduces additional costs, apart from worsening safety performances (Doppler).

Moreover a burner core introduces economic cost penalties anyway compared to breakeven or breeder cores. While previous neutronic performances remain unchanged, key parameters for a comparison could be:

- amount of TRU that must be processed each year: this is greater for a burner core than for a comparable breakeven core or even more for a breeder, because of the breeding ra-

tio factors and the peak-to-average fuel burn-up ratios:

- cycle length: it is reduced for a burner core;
- reshuffling/reloading strategy and number of fuel assemblies involved; it penalises burner cores because of the reduced plant availability, due to the additional downtime each year.

Nevertheless the acceptability of an over-cost in presence of a high Pu-consumption rate has to be valued weighting political issues rather than economic and/or technical ones.

The most interesting outcome of all the analyses reported in this paper is the conclusion that an optimised small-size oxide-fuelled burner core can provide noteworthy safety performances, including negative Na-void effects and reasonable Doppler, associated with high Pu-consumption rates, about 60kgPu/TWhe. Moreover, while satisfying all technological, safety and economic design constraints, this system could be set up even within a “Classical Design Solution”, thus representing a practical option with immediate applications.

3. Study of a Methodology to Identify a Failed Assembly

The study of a methodology to identify a failed assembly is presented in detail as it is an important safety and economic issue; moreover this methodology has a general value that makes it applicable to a number of fields.

A Passive Monitoring Device (PMD) to detect clad failure was theoretically studied and its prototype was tested at ENEA experimental laboratories. This system can be briefly described as cylinder acting as a delay-line, whose task is to reduce the strong noise produced by Na activation and affecting the detection of fission products.

The PDM is purely addressed to safety and makes possible the mere detection of failure, while an economic approach would

require more detailed information: i.e. the identification of the failed assembly. The basic idea of this identification system was to attach a kind of blueprint to each assembly. This could be possible by inserting a “cocktail” of tag gases into all the pins of each assembly and detecting their loss by means of their daughter activity. The tag gas combination and their mutual ratios will be different and unique for each assembly, so that the spectrometric analysis of the energy and number of gamma emitted by the escaped daughter can identify the assembly concerned.

The choice of tag gases has been restricted to a few materials, the characteristics of which meet the following requirements:

- parents and daughters have to be distinct from cover gas isotopes or fission products;
- parents and daughters have not to be chemically reactive with any reactor components, i.e. they have to be noble gases;
- parent activation cross-section on the one hand has to be low enough to consider the parent stable or almost stable compared to the subassembly life, but on the other hand it has to be high enough to produce a significant quantity of daughters;
- daughter decay constant has to be low enough to allow a significant equilibrium concentration, but high enough to present a detectable activity.

Four gases have been selected - Krypton-78, Xenon-124, 126 and 128:

PARENTS			DAUGHTERS		
	fast σ (barns)	half-life (*) (years)		λ (s ⁻¹)	half-life
Kr-78	.007	3100	Kr-79	5.5E-6	1.455 d
Xe-124	4	5.5	Xe-125	1.13E-5	17 h
Xe-126	.05	440	Xe-127	2.2E-7	36.41 d
Xe-128	.01	2200	Xe-129m	9.0E-7	8.89 d

(*) Assuming the maximum flux reactor

An original methodology was developed was developed at ENEA to address this problem in a general way. The problem can be divided in four stages:

- 1) definition of the number and the type of parents;
- 2) definition of the critical scenarios that rule the minimal usable quantity of gas;
- 3) definition of the “cocktails” of tag gases so that:
 - there is a sufficient number of tags, one per assembly;
 - they are identifiable;
 - the required gas volume has to be consistent with that available in the pins;
- 4) taking the radial flux distribution properly into account.

- 1) The first stage has already been defined, but the method does not depend on these particular gases, and if a choice of non-activated gases could be made, the methods would be even simpler.
- 2) Restart and End Of Life (EOL) are critical times; in the latter, the parent concentration is the smallest; at the restart the daughter's concentration is only beginning to build-up. Taking into account the parameters influencing both scenarios:

$$\text{EOL} \left\{ \begin{array}{l} S \text{ detector sensibility (10Bq)} \\ \phi \text{ max flux (for depletion) (10}^{15} \text{ n / cm}^2\text{s)} \\ T \text{ lifetime (for depletion) (10y)} \\ \tau \text{ breaching - detection delay (10h)} \\ D \text{ gas fraction detected (10}^{-5}\text{)} \end{array} \right\} \text{RESTART}$$

$$\left\{ \begin{array}{l} \phi_R \text{ restart flux (10}^{15}\text{n / cm}^2\text{s)} \\ T_{BO} \text{ black - out time (1d)} \end{array} \right\}$$

An acceptable counting time sets the detector sensibility; the other values, though reasonable, could be modified (for example after testing the delay between the moment the gas slips out

of the failed assembly and the moment it is detected or the fraction that actually reaches the detector) without affecting the methods. Their use is to define the minimum quantities of gas to be inserted in one pin in order to have a measurable signal at the detector of the same intensity. These minimum quantities have been named 'quanta' and for the previous parameters are as follows:

Parent gas	quanta volume (normal cm ³)
Kr-78	3.3
Xe-124	0.03
Xe-126	0.4
Xe-128	1.9

- 3) The identification of the failed assembly is made possible by the analysis of the cocktail of gases reaching the detector, that is unique for each assembly. Nevertheless it is not possible to measure the absolute quantities because of the uncertainties of the migration model and then on the effective fraction of gas reaching the detector. The only valid measurement could be made for the mutual ratio of gas quantities.

Uncertainties

As a background noise is inevitable, the greater the difference among cocktails, the more certain the regression from the detected signal to the correct cocktail and hence to the failed assembly. In order to avoid huge quantities of tag gases inserted into the pins, it is of primary importance to identify the uncertainties affecting the attribution to a given assembly and then the minimum mutual quantities of gas required. Assuming conventional uncertainties on the independent variables within a confidence interval of 2σ , the uncertainty affecting the calculated gas ratios are:

RESTART	22%	R _o quantities of gas charged into the pins	5%	} EOL
		R _e parent gas activation cross-section	15%	
		R _d parent gas depletion	26%	
		R _a daughter decay during flight toward the detector	4%	
	7%	R _t { R _s instant of the gas loss after Restart while daughter concentration is not at equilibrium		

The global uncertainties for the two scenarios were:

RESTART 28%

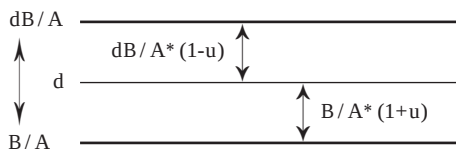
EOL 31%

The latter was the reference value.

The next step is how to create different cocktails that could be identified unambiguously, notwithstanding the uncertainties. Let us define:

$$d = \frac{1+u}{1-u}, \quad u = \text{uncertainty} \quad (\text{for } u = 31\% \rightarrow d = 1.9)$$

Hence two close binary cocktails are recognised as different if their ratio changes by a factor d .



In the example there are two cocktails of gases A and B. In the second one the gas quantity B was increased by d . To identify the cocktail, there must be no overlapping between $B/A*(1+u)$ and $dB/A*(1-u) \rightarrow$

$$d = \frac{1+u}{1-u}$$

The parameter d can be called the ‘uncertainty diameter’ and represents the minimum difference between two gas ratios necessary to differentiate them. As seen before, the minimum quantity of parent gases to give rise to the same signal at the detector was defined as quantum. In order to recognise a cocktail as different, the gas quantity increase has to take place by steps equal to d , so that the n_{th} variation for a given gas, the total gas quantity is the (quantum $\cdot d^n$).

With a little imagination a simplified way to find and represent these quantities was found.

Parent Gas Quantity in a Cocktail

A cocktail can be defined with its own blueprint (BP) as:

$$BP (x_1, x_2, x_3, x_4)$$

where

$$x_i = \log_d \frac{Q_{ai}}{Q_{qi}}$$

Q_{ai} = parent gas quantity loaded into the pin

Q_{qi} = quantum, previously defined as the minimum quantity of a given parent gas

$$d = \frac{1+u}{1-u} \quad \text{“uncertainty diameter”} \quad u = \text{uncertainty}$$

When the loaded quantity is equal to the quantum for that gas it is $x=0$ and because the increase is by step equal to d , the next minimum quantity has to be d times Q_{qi} ($x=1$) and for $Q_{ai}=d^n Q_{qi}$ it is $x=n$. BP (x_1, x_2, x_3, x_4) is then a sequence of full, positive numbers. For economic reasons at least one gas has to be present as a quantum, so that at least one number of the sequence is a zero.

For instance BP (2,0,1,3) means that the concentrations are exactly (or proportional to);

1st gas (Kr-78): quantum $\times d^2 = 3.3 \text{ ncm}^3 \times 3.61 = 11.91 \text{ ncm}^3$

2nd gas (Xe-124): quantum $\times d^0 = 0.03 \text{ ncm}^3 \times 1 = 0.03 \text{ ncm}^3$

3rd gas (Xe-126): quantum $\times d^1 = 0.4 \text{ ncm}^3 \times 1.9 = 0.76 \text{ ncm}^3$

4th gas (Xe-128): quantum $\times d^3 = 1.9 \text{ ncm}^3 \times 6.86 = 13.03 \text{ ncm}^3$

and it is completely equivalent and indistinguishable, for instance, from BP(3,1,2,4) because only mutual ratios are considered.

Graphical Representation

The xi can be viewed as spatial coordinates in a 4-dimension hyperspace, whose axes are the four tag gases and where any cocktail BP (x_1, x_2, x_3, x_4) is a point. Since, as already stated, it is more convenient to have at least one $x_i=0$, the permitted gas combinations will lie in the four positive 3D volumes bounding 1/16 of the hyperspace.

Because the allowed quantities have to increase by step $=d$, the correspondent increase in x will be $\Delta x=1$. Therefore uncertainties can be represented as pseudo-spheres around the BP(x_1, x_2, x_3, x_4) point of diameter equal to one, regardless of the position of the representative point. This fact makes possible the creation of a regular lattice that defines the permitted positions and hence the permitted gas combinations. In an easier 3D representation (only 3 tag gases) the point will lie on the three planes delimiting the positive 1/8 volume, as shown in Fig. 8. The uncertainties will be a pseudo-circle of diameter=1, defining the permitted gas combinations in a square lattice equal to 1.

If the cocktails are very different from each other it could be possible to identify them overcoming even higher uncertainties. For example the spatial distance between BP(1,1,0) and BP(2,1,0) will be 1 ($d=1.9$, uncertainty equal to 31%), while the distance from

the first point and BP(2,3,0) will simply be the conventional geometric distance (in that case 2.24, equivalent to an uncertainty of $1.9^{2.24} = \frac{1+u}{1-u} = 62\%$).

The choice of possible cocktails is flexible and can be made on the basis of volume or cost considerations. Fig. 9 shows an optimisation based on parent gas volumes.

4) Flux and spectrum strongly influence many parameters (parent depletion, daughter production...) and the choice of the assumed uncertainty of 10% cannot take into account by any means the strong radial distribution variations. On the other hand, the choice of a higher uncertainty on the flux will increase the “uncertainty diameter” therefore dramatically increasing the required gas volumes.

A better solution could be the division of the core into different zones, where the flux has a limited spread. For each zone a peculiar “family” of blueprints could be created with the methodology already described. The number of families, and hence the number of zones in which the core could be divided, depends on the number of combinations allowed. Having 4 tag gases we can create:

- 6 different couples AB, AC, AD, BC, BD, CD
- 4 different triplets ABC, ABD, ACD, BCD
- one quartet ABCD

The core was then divided up to 11 zones, where the flux uncertainty was combined with its spread and a total flux uncertainty of 20% was assumed. Considering only the number of cocktails that can be created in a volume of 15 ncm^3 , the number of the permitted blueprints is:

	uncertainty diameter d	blueprint number
AB	1.4	10
AC	1.4	15
AD	1.6	16
BC	1.4	17
BD	1.6	17
CD	1.6	21
ABC	1.4	24
ABD	1.6	36
ACD	1.6	2
BCD	1.6	97
<i>total</i>		325

The total number, only using couples and triples, is 325. There are enough blueprints to allow a selection: the only constraint is the number of families or, in other words, the maximum number of flux zones.

Processing the result of the detector system by a simple dedicated Monte Carlo code, the effectiveness of the method can be significantly increased. The code must analyse the detector signal and indicate all the possible cocktails involved and associate to them the probability of having a correct attribution. For instance the code answer could be:

95%	probability that the failure occurred in the assembly characterised by BP(0,1,3,2);
1%	in the assembly characterised by BP(0,2,3,2);
1%	in the assembly characterised by BP(0,1,2,3);
0.5%	
0.001%	probability of having a simultaneous failure in the assemblies characterised by BP(0,1,3,1) and BP(0,1,3,3); ecc.

Ad hoc experimental measures could make possible an even greater efficiency an smaller gas quantities.

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Table 1
**Neutronic performances for Some Options
 for the ALMR Prism Mod. B Burner Cores**

Configuration	C162-271	C180-331	C180-331
Height (inc)	42	42	42
Pins number	271	331	331
Pellet Type	Full	Full	Hollow
Inner / Outer	72 / 90	72 / 108	72 / 108
Batch Number	5	6	4
Cycle Length (months)	12	8.5	8.5
GEM A's Number	18	18	18
TRU-Enrichment	28.50	35.38	39.33
Pu-Enrichment ⁽¹⁾	26.27	32.86	36.69
TRU Inventory (kg/year)	3314.3	3406.1	3262.8
Consumption Rate ⁽²⁾			
kg / Core / year	102.0 / 97.3	138.8 / 137.4	158.8 / 158.1
kg / TWhe	45.2 / 43.0	61.4 / 59.9	70.3 / 70.0
% Inventory / year	3.078	4.075	.967
Breeding Ratio	0.629	0.504	0.429
BU-Swing (\$)	-10.81	-10.12	-11.80
Peak BU (MWd / kg)	177.90	181.01	165.51
Aver. BU (MWd / kg)	110.63	114.01	104.69
Peak Fast Fluence	3.05E23	2.24E23	1.76E23
Peak Linear Power	322.2	240.2	229.3
Doppler Coeff. (\$)	-1.416	-1.408	/
GEM's worth (\$) ⁽³⁾	-2.848	-3.143	-3.462
CR's worth (\$)	-35.05	-37.29	-40.70
Na-Void Worth (\$)			
Fuel	-0.780	-2.542	-3.050
Total	-6.135	-8.815	-10.138
β -effective	0.00305	0.00290	/

(1) Pu / (Pu+U)

(2) TRU / Fissile Pu

(3) 18 GEMs for all the configurations

Table 2
**T/H-Results for the C162G18/42-72/90
 Peak Fuel Assembly**

	BOL	EOL
<i>Peak Pin Linear Power (W/cm):</i>	323.4	247.7
<i>Nominal Thermal Analysis (°C)</i>		
- Outlet Temperature	523.8	487.1
- Peak Subchannel Temperature	552.8	509.5
- Peak Cladding Midwall Temp.	561.6	516.2
- Peak Fuel Surface Temperature	760.7	668.7
- Peak Fuel Centerline Temperature	2225.6	1789.9
<i>+2 Sigma Thermal Analysis (°C)</i>		
- Peak Subchannel Temperature	596.7	544.1
- Peak Cladding Midwall Temp.	613.7	554.9
- Peak Fuel Surface Temperature	837.9	726.1
- Peak Fuel Centerline Temperature	2453.6	1980.8
- Peak Fuel Surface Temp. (at SCRAM)	899.7	773.3
- Peak Fuel Centerline Temp. (at SCRAM)	2748.0	2191.1
Cladding Target Temperature: 616 °C		
Oxide Fuel Melt. Temperature: 2845 °C (approx.)		

Table 3
Neutronic Results and Performances
for the Reference Solution

Core Configuration	C180G18/42-B-331	
Core Height (inc/cm)	42 / 106.68	
# of Fuel A's / # of Pins per A's	180 / 331	
Inner / Outer	72 / 108	
Batches Number / Cycle Length (months)	6 / 8.5	
TRU-Enrichment (%)	33.17 / 36.86	
Consumption Rate (kg / Core.year) ⁽¹⁾	138.8 / 135.3	
% Inventory / year	4.075	
Breeding Ratio	0.504	
BU-Swing (\$)	-10.12	
Peak / Aver. Burnup (MWd/kg)	181.00 / 114.01	
Peak / Aver. Fast Fluence (10 ²³ n/cm ²)	2.52 / 1.52	
Peak Lin.Power (W/cm; BOEC/EOEC)	240.2 / 227.7	
	BOEC	EOEC
GEM's Worth (\$)	-3.114	-3.171
CR's Worth (\$)	-36.63	-37.95
USD's Worth (\$)	-10.70	-11.10
Uniform Axial Expansion		
Net Effect	-0.22479	-0.22552
Geometry Effect	0.21461	0.21487
Uniform Radial Expansion		
Net effect	-0.66454	-0.66566
Geometry Effect	0.21426	0.21512
Doppler Coefficients		
Inner Fuel	-0.00178	-0.00183
Outer Fuel	-0.00224	-0.00231
Fuel Density Coefficients	0.41010	0.42746
Structural Density Coefficients	-0.00394	-0.00609
Sodium Density Coefficients	0.01116	0.01054
Sodium Void Reactivity (\$)		
Inner Fuel	-0.73394	-0.62633
Outer fuel	-1.89110	-1.83268
Others	-6.18756	-6.35789
Total	-8.81260	-8.81690
Total β - effective	2.9084E-3	2.8887E-3
Prompt Gen. Time ? (sec)	4.8537E-7	5.0901E-7
Delayed Neut. Lifetime ? (sec)	3.4303E-2	3.4006E-2

(1) TRU / Fissile Pu

Table 4
Fuel Inventory and Mass Balance (in kg)
for the Reference Solution

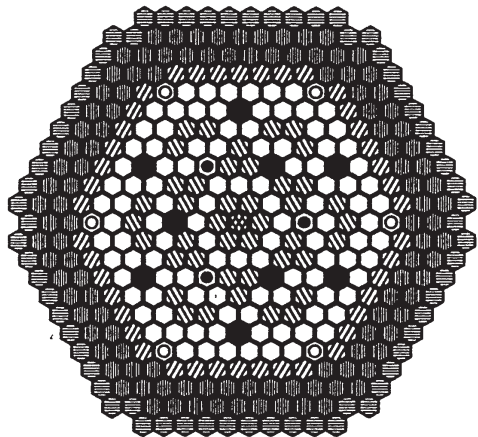
Core Configuration	C180G18/42-B-331	
Batches Number	6	
Cycle Length (onths)	8.5	
TRU-Enrichment (%)	33.17 / 36.86	
Average Enrichment (%)		
TRU	35.38	
Pu / (Pu+U)	32.86	
TRU-Inventory (kg / Core)	3406.1	
Consumption Rate ⁽¹⁾		
kg / Core / year	138.8 / 137.4	
kg / TWhe	61.4 / 59.9	
% TRU-Inventory / year	4.07	
	BOEC	EOEC
Fuel Inventory (kg)		
Pu238	72.7	81.0
Pu239	1682.0	1603.0
Pu241	236.7	219.7
Total Pu	3037.4	2949.9
Np237	141.8	131.9
Am241	171.0	166.3
Am243	34.9	35.9
Total TRU	3406.1	3307.8
U 235	10.5	9.5
U 238	6466.5	6378.6
Total U	6477.6	6388.9
Total F.P.	489.0	675.5

(1) TRU / Fissile Pu

Figure 1
840 MWth PRISM Mod. B Metal Breakeven Core

840 MWt PRISM Metal Core

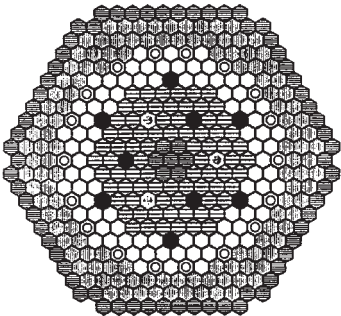
Fissile Breakeven



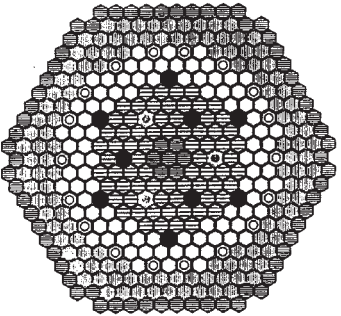
	Driver Fuel	108
	Internal Blanket	42
	Radial Blanket	42
	Control	9
	Ultimate Shutdown	3
	Source	1
	Gas Expansion Module	6
	Reflector	114
	Shield	66
Total		391

Figure 2/1
162 Fuel A's Oxide Fuelled Burner Core Layout

ALMR Mod B Oxide Burner, Core C162



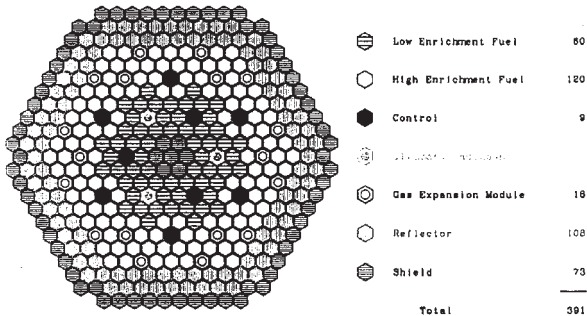
	Low Enrichment Fuel	76
	High Enrichment Fuel	84
	Control	9
	Ultimate Shutdown	1
	Gas Expansion Module	18
	Reflector	126
	Shield	73
Total		391



	Low Enrichment Fuel	72
	High Enrichment Fuel	90
	Control	9
	Ultimate Shutdown	1
	Gas Expansion Module	18
	Reflector	126
	Shield	73
Total		391

Figure 2/2
180 Fuel A's Oxide Fuelled Burner Core Layout

ALMR Mod B Ox Burner. C180G/42 60/120



ALMR Mod B Ox Burner. C180G/42 72/108

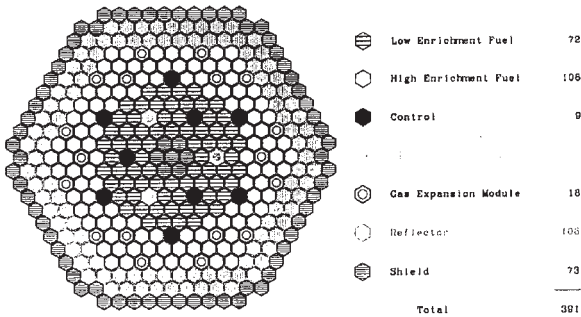


Figure 3
**Flat-to-Flat Dilation (inches) for the Peak Fue A's of the
C162/42 - 72/90 Solution**

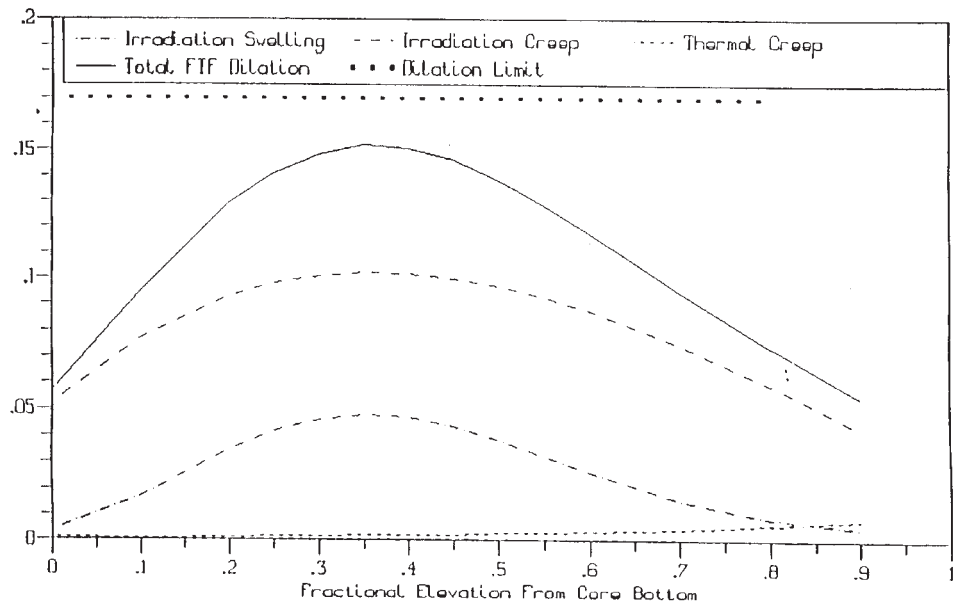


Figure 4
**Na-Void Reactivity Worths (\$/A"sy),
 Averaged Over a Ring, at BOEC and EOEC**

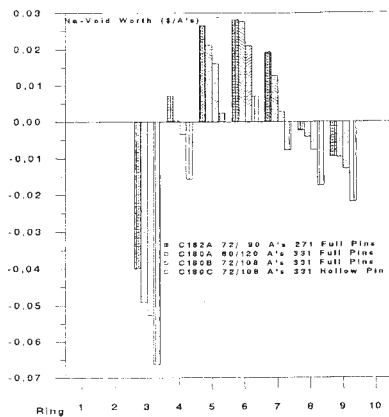
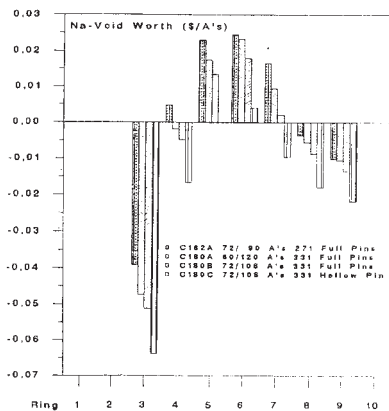


Figure 6/1
Reactivities and Hot Channel Temperature vs. Time, for the ULOF Accident for the Reference Solution (All Pumps Failed)

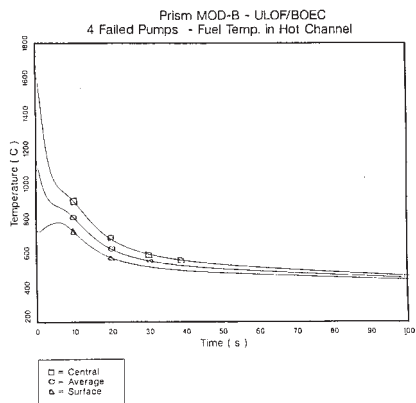
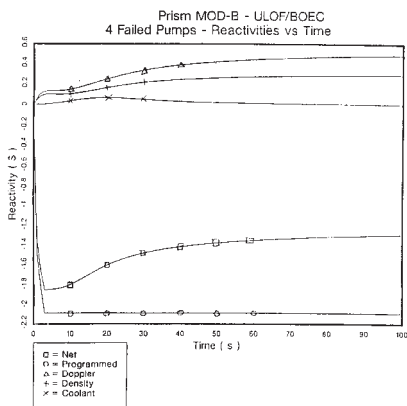


Figure 6/2
**Reactivities and Hot Channel Temperature vs.
Time for the ULOF Accident for the Reference
Solution (All Pumps Failed and Nine GEM Failed)**

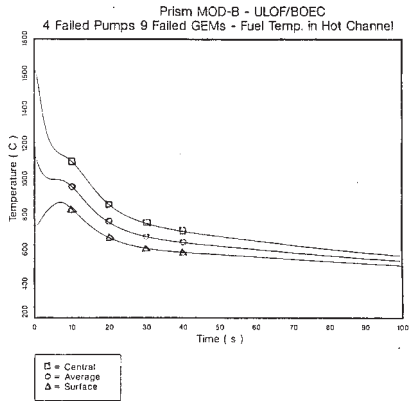
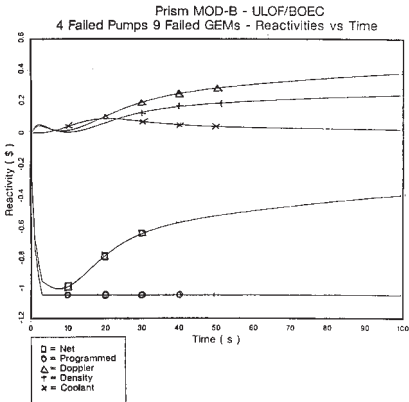


Figure 7
**Reactivities and Total Power vs. Time for the
UTOP Accident for the Reference Solution**

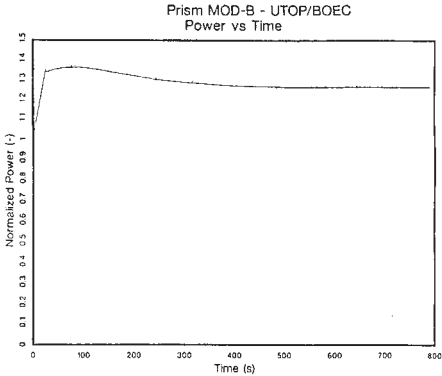
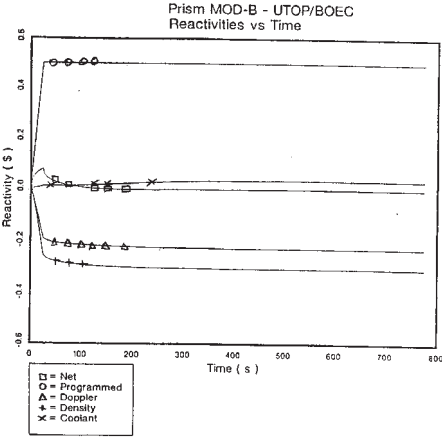


Figure 8
Graphical representation of blueprints in a three-dimensional space (three tag gases used)

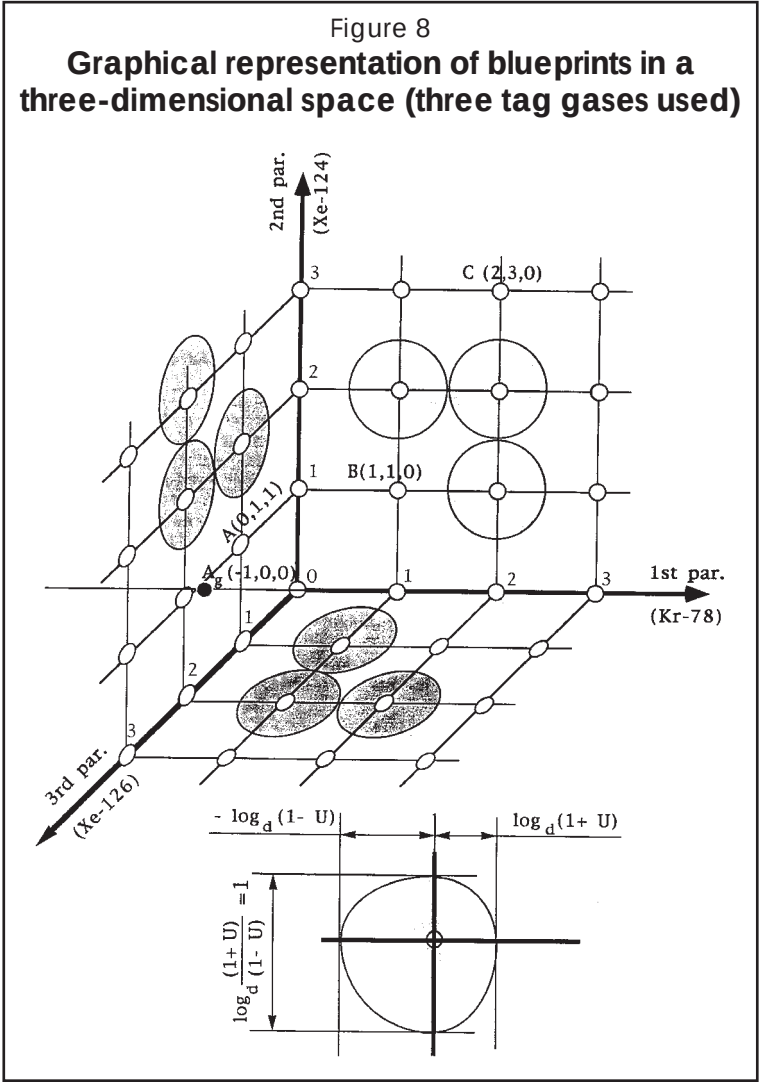
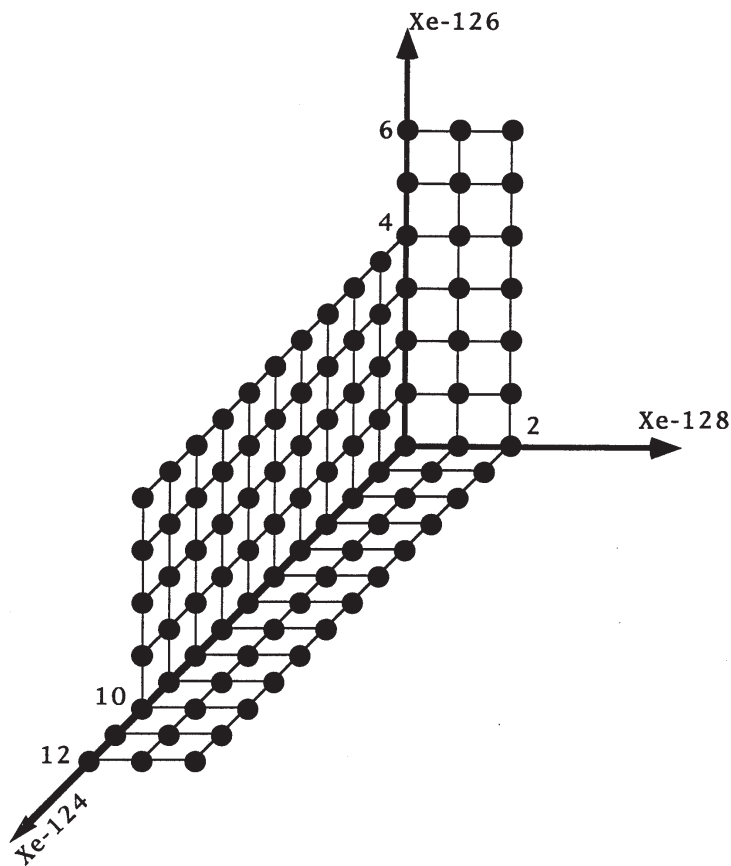


Figure 9
**Optimisation of parent gas volumes in a
three-dimensional space (three tag gases used)**



SESSION 3

**Comparison of Different Options
for Weapon-Grade Pu Utilization:
Connections with Present
Programme for the Recycling
of Civilian Pu**

Getting the Plutonium Disposition Job Done: the Concept of a Joint-Venture Disposition Enterprise Financed by Additional Sales of Highly Enriched Uranium

*Matthew Bunn*¹



There is a growing international consensus that the hundreds of tons of excess weapons material left over from four decades of Cold War arms competition pose, in the words of the U.S. National Academy of Sciences, “a clear and present danger” to international security. Ensuring secure control over weapon-usable nuclear materials, an action plan to stop nuclear smuggling, and international cooperation in disposition of excess weapons plutonium

will all be central items on the security agenda for the P-8 nuclear summit in Moscow next month.

In this paper, I will attempt to outline a concept which has the potential to provide both the substantial financing needed for plutonium disposition and the stable long-term management structure required to implement the effort. But first, it is important to address the earlier steps in the process.

¹ The views expressed in this paper are solely those of the author and should not be attributed to any agency of the U.S. government, or to the U.S. National Academy of Sciences.

Urgent First Steps: Secure, Monitored Storage

Despite the growing international sense of the urgency of fissile material disposition, the fact is that no matter what option we choose, the job won't be finished for decades to come. Therefore, ensuring safe and secure storage in the meantime - along with some form of international monitoring to ensure that the arms reduction now underway are truly irreversible - is by far the most urgent item on the fissile material agenda.

The United States, the states of the former Soviet Union, and other countries are engaged in a far-reaching cooperative program to modernize systems for security and accounting of weapons-usable materials in the former Soviet Union. The United States and Russia are also cooperating to build a modern, safe, and secure storage facility for fissile materials from dismantled warheads at Mayak. Nothing could be a more critical investment in international security than ensuring that the essential ingredients of nuclear weapons do not fall into the hands of terrorists or rogue states. I urge everyone in this room to consider whether their own government is doing enough to solve this critical problem - and if not, to urgently recommend that additional steps be taken.

The problem of placing these materials under some form of international monitoring is also urgent, but there, less progress has been made. The United States has announced that over 200 tons of its weapons-usable material is excess to its defense requirements - roughly 175 tons of highly-enriched uranium (HEU), 38 tons of weapons-grade plutonium, and 13 tons of fuel-grade plutonium - and has begun placing this material under International Atomic Energy Agency (IAEA) safeguards. We have encouraged Russia to do the same; while there have been a few encouraging statements on the Russian side, no concrete action has been taken so far. Moreover, much of the U.S. excess material (and probably the Russian material as well) is in the

form of weapons components, to which traditional safeguards techniques cannot be applied without giving away information that would contribute to proliferation - and much of the rest of the excess material is difficult-to-measure scrap. Thus, before the majority of this material can come under IAEA safeguards, either greatly modified safeguards approaches will have to be developed or the materials will have to be processed to inspectable, unclassified forms, which will take a considerable time.

To fill that gap, the United States and Russia have agreed in principle to undertake a bilateral program of mutual, reciprocal inspections of the plutonium and HEU from dismantled weapons - including inspection measures that would reveal a limited amount of classified weapons information whose exchange between advanced nuclear weapon states does not pose a security risk to either side. Our Presidents have also agreed to an unprecedented exchange of data on our nuclear stockpiles, under which we would tell each other for the first time how many nuclear warheads and how much plutonium and HEU we really have, and to consider other measures to confirm the dismantlement of nuclear warheads. Unfortunately, however, last fall, when an agreement on exchange and protection of classified nuclear information that would have provided the legal basis for these measures was almost complete, the Russian side suspended the negotiations, and the talks have not yet resumed.

Let me emphasize again: these measures to ensure secure, monitored storage - preventing proliferation and ensuring the irreversibility of arms reduction - are more urgent in the near term than is plutonium disposition, the principal subject of this conference.

Fissile Material Disposition: Also Urgent

Nevertheless, it is also critical to move as quickly as practical to actual disposition of excess fissile materials, transforming them into forms that no longer pose urgent security risks. As Russian Minister of Atomic Energy Victor Mikhailov has said, disarmament will only be truly real when we have gotten rid of the materials from which the weapons could be rebuilt. Precisely because it will take a long time, it is urgent to begin: I am reminded of the French marshal, who, when told by his gardener that it would take thirty years for trees to grow along the boulevard leading into his estate, told the gardener he had better start planting tonight, rather than waiting until tomorrow. I am confident that there will be consensus on the urgency of moving forward on fissile material disposition at the nuclear summit next month.

As you all know, HEU disposition is relatively straightforward in a technical sense, and in fact is already being accomplished: the United States and Russia have agreed that the United States will purchase 500 tons of HEU from dismantled Russian weapons over the next 20 years, blended to proliferation-resistant low-enriched reactor fuel. In one stroke, this agreement reduces the stockpile of weapons-usable material at risk of theft, provides a direct financial incentive for continued weapons dismantlement, helps ensure irreversibility of the ongoing arms reductions, pumps needed hard currency into the Russian economy, and provides a valuable commercial product to the U.S. - all without requiring direct Federal subsidies from the U.S. budget. I can report that this agreement is now working - six tons of HEU was blended, delivered, and paid for last year, that figure is increasing to 12 tons this year, and we are now finishing the specific transparency arrangements needed to assure that the U.S. is buying what it thinks it is, and using it only for peaceful purposes. Three weeks ago in Moscow, the

business manager of the Ministry of Atomic Energy described this arrangement to me as “a shining example of U.S.-Russian cooperation”. And the United States is planning to do much the same with its own excess HEU.

The plutonium disposition job is much more difficult - in part because in today's market, fuel made from plutonium cannot compete with cheap uranium fuels, even if the plutonium is “free”.

While plutonium disposition is a harder job, technologies do exist that can get that job done over the next few decades, while meeting the requirements of nonproliferation, arms reduction, environment, safety, and health. Existing light-water of CANDU reactors can burn plutonium as MOX fuel; existing technologies for immobilization of liquid high-level wastes could also incorporate plutonium, making it roughly equally proliferation resistant. Virtually every week there is another proposal for some new technology to apply to this mission - but all these ideas share the severe drawback of requiring a substantial R+D program to prove them out definitively, delaying the day when disposition of this dangerous weapons material can begin.

The Key Questions: Financing and Management

Since the technologies needed to do the job already exist, and new technologies would only delay matters, technology is not the key issue. The key issues revolve around how plutonium disposition can be managed and financed on the immense scale required.

This is a big job - tens of tons of material, hundreds of millions of billions of dollars in required investment, decades to complete. It also involves the unpopular nuclear industry, and a toxic weapons-usable material that the public in many countries has come to fear. In all likelihood, virtually any of the opinions

will face protests by hundreds of thousands of people, not to mention lawsuits and other legal interventions. No one country will be able to get the job done alone: to pull it off will require far-reaching international cooperation, considerable creativity, and an immense investment of political will. Managing a sustainable program lasting decades in such a controversial area will require institutional arrangements of unprecedented durability.

Financing the operation is a particularly difficult problem. For any plausible option, initial investments of hundreds of millions or even billions of dollars will be required. In the United States, it is likely - though by no means certain - that Congress can be convinced to fund these substantial investments, if - and only if - a parallel disposition program is underway in Russia. If Russia simply leaves its excess plutonium in storage in readily weapons-usable form, Congress simply will not fund a U.S. plutonium disposition program. Even if Russia is moving forward, ensuring that the financing from Congress is sufficiently stable over the long term to accomplish the mission will be a difficult challenge. A U.S.-Russian agreement calling for reduction in stockpiles of fissile materials - as will be discussed later by other speakers - could be an important factor in ensuring stable implementation over time.

But with Russia's current economic circumstances, the Russian government is not likely to be able to finance the initial capital investments needed for plutonium disposition anytime in the foreseeable future. Thus, if the plutonium job is to get done, either the international community will have to subsidize it, or some creative financing approach - such as some form of countertrade, where the operation would be financed by exports of some other valuable commodity - will be needed.

What kind of money are we talking about? That depends in part, of course, on the specific disposition technology to be implemented. Russia has made it clear that it will only consider

reactor options, and the reactor options involving the lowest initial capital investment are those involving reactors that already exist - primarily light-water reactors - so that only storage, MOX fabrication, and pit-processing facilities would have to be provided, not additional reactors. (Realistically, Russia cannot expect the international community to help finance expensive new reactors in the name of plutonium disposition when existing reactors could do the job). The fissile material storage facility now being built at Mayak, with U.S. assistance, is estimated to cost roughly \$300 million. The up-front capital cost of a MOX plant big enough to do the job would be of the order of \$600 million - if it were built in the West, and did not face the sort of delays that have often forced up the cost of nuclear projects in recent years. Construction in Russia might cost less, particularly if Germany were to provide the components from the MOX plant at Hanau (the so-called "Hanau East" option). However, anything that might be saved on the \$600 million figure for the MOX plant would probably be added back in the cost of licensing and any necessary modifications to existing reactors. Adding an industrial-scale capability to convert plutonium "pits" to oxide might add another \$100 million, if the facility could be installed in an existing plutonium-handling facility (such as the MOX plant), or more if a new facility had to be built from scratch. So in round numbers, the up-front capital investment required is \$1 billion.

This is not an inconceivable amount to be provided through international assistance. If, for example, the G-7 countries and Russia agreed to split the cost over a five-year period, this would mean an on-budget subsidy from each of these states of only \$25 million per year. I strongly believe this would be an excellent investment in international security, worth far more than its cost.

But after promising to provide \$2 billion to help Ukraine shut the Chernobyl reactor, and \$4 billion to help building

light-water reactors in North Korea, the international community is not particularly eager to immediately undertake another billion-dollar project of this kind. A certain “nuclear compassion fatigue” has set in.

Is there a way such an operation could be financed and managed without requiring such sustained on-budget subsidies from the major powers? I believe the answer is yes, and that the answer lies in the highly-enriched uranium that also comes from dismantled weapons, which is a product with substantial commercial value, whose full market potential is not yet entirely exploited.

A Joint-Venture “Enterprise for Nuclear Security”B

Let me offer the following as an approach to addressing, in part, both the financing and management problems:

Imagine establishing a semi-commercial joint venture between Russia’s Ministry of Atomic Energy (MINATOM) and Western fuel cycle and construction firms - the “Enterprise for Nuclear Security”. This enterprise would be charged with the task of completing and operating the plutonium storage facility now under construction, and building an operating a pit-to-oxide conversion facility and a MOX plant in Russia.

The entire operation would be managed by the international partners in the joint venture, including internationally-managed guard teams and accounting systems at the storage and the processing facilities. Participation by both MINATOM and Western firms would ensure that the MOX produced was appropriate for Russian reactors while meeting the quality standards Western utilities demand - certified by the Western fuel cycle firms the utilities are already accustomed to working with. All the facilities would be under IAEA safeguards, modified as necessary to avoid compromising proliferation-sensitive information re-

lated to plutonium pit design. (Non-nuclear-weapon states such as Germany and Japan would certainly demand such safeguards as a condition for their participation). The United States would accept parallel international monitoring measures at the storage and processing facilities involved in its parallel plutonium disposition program.

The billion-dollar initial capital investment required would be financed, in this concept, by additional sales of HEU above and beyond the 500 tons the United States has agreed to purchase. Russia would transfer to the joint venture's ownership approximately 100 tons of additional HEU, which, at the prices currently prevailing in the U.S.-Russian purchase agreement, would be worth roughly \$2 billion. Rather than releasing that material onto the market all at once - which would crash the uranium price - the joint venture would use this material as collateral against which it could borrow, and meter the uranium into the market slowly, consistent with demand, to pay back the loans. Given discounting for risk and the cost of money, along with the cost of blending the HEU for sale, the total up-front capital available to the joint venture from HEU worth \$2 billion would probably be of order \$1 billion - roughly what is required to finance the initial investments. (Needless to say, perhaps, all the number in this paper are intended do be illustrative, not definitive.)

After that initial capital investment, paid for with HEU sales, operating revenues from sales of MOX fuel (at price equal to or lower than those of LEU fuel of equal energy value, to give utilities an incentive to buy) would be sufficient to pay the continuing operating costs of the facilities, allowing the joint venture to survive as a stable, ongoing commercial enterprise over the long period required - a critical point. That is to say, the fact that MOX costs more than uranium fuel arises largely from the need to pay off the capital cost of the MOX plant: MOX sold at LEU price can more than pay for the operating costs, if the capi-

tal costs have been covered by other means. Any additional profits that might be generated could be split between the joint-venture partners, or used to finance other critically needed nuclear security improvements, such as additional modernization of security and accounting systems for nuclear material.

The joint venture could contract the job of blending the HEU for eventual sale to MINATOM's facilities that are blending HEU for the U.S.-Russian deal, if they had excess capacity, or other firms in the West might get the business. Similarly, the joint venture might determine that until a new MOX plant could be provided, it made sense to contract with European firms for initial MOX production.

Russia does have additional stocks of HEU it no longer needs, and has made some informal inquiries concerning possible additional sales. But no definite arrangements have been reached, in part because of the tight trade restraints Western countries have imposed on Russian Uranium exports. The United States has a stringent anti-dumping agreement in place limiting Russia's access to U.S. markets; the current unwritten Japanese policy is not to buy any Russian uranium at all, primarily because of the islands dispute; and EURATOM has also adopted an informal policy of limiting Russia to a small portion of the European uranium market. Thus, in this approach, the action the G-7 countries would have to take instead of providing on-budget subsidies would be to modify their trade restraints enough to allow uranium blended from the HEU belonging to this MINATOM-Western joint venture to enter their markets. One approach would be to simply count the material belonging to the joint venture as coming not from Russia but from a separate entity - the joint venture - which would not count against Russia's restraints. With uranium prices now recovering to \$12 a pound and still headed upward, and world uranium demand greatly outpacing current production, such a step would be less painful than it might have been a few years ago.

Thus, the "Enterprise for Nuclear Security" concept could potentially make it possible to finance plutonium disposition; create a management structure for implementing plutonium disposition that can sustain itself over the long term; ensure international, rather than merely national, guarding and accounting at the plutonium storage and processing facilities, as well as IAEA safeguards; eliminate an additional 100 tons of HEU; and provide substantial business to both MINATOM's desperate nuclear cities and to Western firms - all at little or no direct on-budget cost to the countries involved.

Russia would have to provide 100 tons of HEU, and would get in return a plutonium storage facility and a MOX plant, along with a long-term commercial relationship with Western fuel cycle firms. The Western countries would have to modify their trade restraints to allow uranium from that additional HEU into their markets, and in return the Western countries and Russia would both get substantial security dividends from disposition of plutonium under stringent nonproliferation controls.

If the international community is going to help Russia finance a MOX plant - whether through direct subsidies or through offering increased access to their uranium markets - some nonproliferation conditions are likely to be required. To insure that the disposition operation itself does not increase risks of proliferation, extremely stringent standards of security and accounting for the material throughout the process will be essential. International safeguards will have to be applied as early in the process as practical. There would have to be commitments not to export the MOX fuel or other plutonium products to countries of proliferation concern; perhaps there would be an agreement that the MOX would be used only by Russia, or only by the nations participating in the joint venture. As the international community's interest is in disarmament and non-proliferation - not in assisting Russia's development of a broad

plutonium fuel cycle, or creating fierce commercial competitors for the West's fuel cycle business - some commitment would be needed that any MOX plant built with Western participation would be used only for weapons plutonium, or only for plutonium that is already separated. That might not be a very onerous commitment, as most of the potential operating lifetime of such a plant would be over in any case by the time the large existing stocks of excess weapons plutonium and separated civilian plutonium were processed. And there would likely have to be some arrangement - however difficult it might be to arrive at - to ensure that new excess stocks of separated plutonium were not built up as fast as the old stocks were built down, or there would be little point in the enterprise.

Of course, if Russia did not want to agree to such conditions, it is always free to do whatever it likes with its plutonium, with whatever financing of its own it can make available - but the prospects for such financing in the near term do not appear very good.

An Ambitious Agenda

To sum up:

First, we must move quickly to modernize security and accounting systems for all weapons-usable nuclear materials, particularly in the former Soviet Union.

Second, we must bring excess plutonium and HEU under international monitoring, to ensure the irreversibility of nuclear arms reductions.

Third, we must move as quickly as practical toward actual disposition of excess plutonium and HEU. Technology already exists to get the disposition job done. The key issues will be how to finance and manage the operation, particularly given its immense scope and controversial nature. An international joint-

venture “Enterprise for Nuclear Security” that would build and operate plutonium disposition facilities under stringent non-proliferation controls, financed through additional sales of HEU, is a potentially promising approach to addressing the most difficult issues facing the disposition problem.

This is an ambitious agenda - but to be any less ambitious, with the immense challenges we face, would be to shirk our responsibilities. Working together, the international community can put together the means to get these jobs done. The future of efforts to reduce nuclear arms and stem their spread depends on our success.

Management of Russian Military Plutonium

C. Pierre Zaleski



Summary

The objective of this paper is to propose and to discuss a solution which makes it possible to store, as quickly as possible, all weapons-grade plutonium no longer used in the Russian military program, in a way that makes diversion extremely difficult, and the re-use in weapons form by the Russian government difficult and visible.¹

Two main conditions apply to this solution. First, it should be achieved in a way acceptable to the Russian government, notably by preserving plutonium for possible future energy production uses; second, the economics of the total system shall be as good as possible and there should be no charge, or a limited one for the storage of plutonium.

I will propose a solution already outlined in Ref.1: to store plutonium in a specially designed fast reactor, or at least a spe-

¹ It seems however clear that whatever durable solution may be developed, an initial temporary centralized storage of weapons and plutonium (and even HEU) from weapons will be necessary as the delays of implamentation of more permanent solutions shall be at least of the order of a decade (except perhaps for HEU). This centralize safe storage is probably the most urgent and the most important task for those who deals with the managment of excess Russian Military Plutonium.

cially designed fast reactor core. I will attempt to demonstrate that this solution compares favorably to other possible solutions, applying the criteria set out in the goal and the two conditions mentioned above.

In addition, this solution should have the following side advantages:

- utilizing available personnel and installations of the Russian nuclear military complex;
- providing possible basis for decommissioning of older and less safe Russian reactors;
- giving a quantitative experience of construction and operation of a series of sodium-cooled fast reactors;

It also, however, presents a major problem: the need for rather large capital investment, with the risk of not getting the appropriate return on investment due to the generally difficult political and economic situation of Russia.

Review of Other Possible Solutions

The solution of mixing plutonium with fission products and disposing of this mixture in irretrievable deep geologic formations would, in our view, not meet the first condition, that is, the approval of the Russian government. In addition, this solution also presents a not negligible net expense, and may be questioned from the nonproliferation point of view, as in the long term one cannot exclude diversion of plutonium even from supposedly irretrievable storage, and the separation from fission products and re-use of plutonium may not pose major difficulties.

Placing the plutonium in the retrievable storage under Russian national or international safeguards may also not be very economic because of the cost of safeguards and the degradation of plutonium quality during the storage period, but more importantly, it presents some diversion risks and it would

not prevent any future Russian government from very easily acceding to the plutonium for military use. Therefore this solution, even if it is probably the only available for the initial temporary storage, shall not be extended beyond the minimum necessary period.

A more promising solution may be to “burn” this plutonium in the form of mixed-oxide fuel in existing light water reactors, modifying its isotopic composition in addition to mixing it with fission products. Here, however, two options are to be considered. One is to export the plutonium to other countries, for example Germany or France, which already have programs for MOX use, the second is to burn it in Russia. It seems to me that the first option has the following drawbacks:

- the difficulty for the Russian government to accept this export, losing its sovereignty over it (Ref.2);
- a possible issue of public acceptance in host country, whose public may be reluctant to deal with a problem it considers outside its responsibility.
- the issue of the value of this plutonium; presently, countries using MOX are not limited by availability of plutonium but rather by a shortfall in fuel manufacturing capacities and the availability of reactors licensed to burn MOX fuel. For example, Electricite de France has recently decided that plutonium will have a zero value on its books. In fact, the Russian plutonium will displace French civilian plutonium, which will have to be placed in storage, with accompanying costs and degradation in quality. Therefore, the Russian plutonium will have to bear this cost, and will have a negative value. This may not be acceptable to the Russian government.
- the substitution of the Russian plutonium for French civilian Pu would in fact also be contrary to present French policy of having a minimum quantity of separated Pu in storage.
- the proliferation benefit of replacing weapons-grade plutonium in storage with civilian Pu would have to be clarified, in-

cluding the question of weapons-worthiness of plutonium depending on isotopic composition and the technical capabilities of potential proliferators, an issue on which there is no agreement (Ref.3).

In summary, it is true that burning Russian plutonium in foreign reactors, for example French reactors, may appear an attractive solution; indeed, EDF's 28 reactors potentially able to burn the plutonium (with 1/3 MOX core), 16 of which are already licensed to do so, could burn the 100 tonnes of available Russian military plutonium in less than eight years. However, the above-mentioned six drawbacks mean that it is not a practical solution.

Therefore, one should rather consider burning or storing Russian plutonium in Russia itself. Burning it in existing Russian LWRs is theoretically possible. However, only some of these reactors of present design may accept plutonium, and no one are licensed for this. In addition, it would take many decades to burn the 100 tonnes in existing Russian LWRs (Ref. 4).

Another possible solution which seems relatively attractive is to burn the plutonium in newly built reactors. Fast breeders, which are clearly better for this purpose than LWRs (Ref. 4 and 4bis), have been proposed as a possible solution. Indeed, by completing two BN-800-type reactors in Russia, construction of which was begun some years ago but frozen for lack of funding, in a once-through cycle one could transform into spent fuel all 100 tonnes of ex-military plutonium in 30 years of operation (Ref. 4 and 4bis).

Concept Proposed: FNPSR or CAPTURE

Finally, the concept that I am proposing, which I have called Fast Neutron Plutonium Storage Reactors (FNPSR) and has also been dubbed CAPTURE (Ref. 5), has as an objective to store a

maximum quantity of plutonium in the reactor core itself for a relatively long fuel cycle duration.

To achieve this, I suggest to seek a reactor core for which the typical design objectives will be:

- large fuel rod diameter - about twice that used in present breeder designs;
- low specific power, in range of 1 MWe per 10-15 kg of Pu;
- high internal breeding ratio, in the range of 0.9-1.0; and
- long fuel residence time, in the range of 10-20 years.

These design goals are consistent with the idea that plutonium has practically no value for the coming decades (there is an excess of Pu) and that in case of ex-military Pu, one may even envisage a fee being charged for its storage, giving it in practical terms a negative value.

If one achieves this 10-15 kg Pu per MWe, between 10 and 7 GWe of CAPTURE type reactors would be needed to store all 100 tonnes of Russian plutonium as soon as the reactors are built. Another solution may also be considered, i.e., to built only half this capacity and irradiate the 100 tonnes of plutonium in two batches. However, this brings us closer to the previous solution with BN-800 reactors, and the differences become less clear-cut.

Assuming construction of CAPTURE reactor series totalling some 8 GWe, after maximum burnup is achieved, in some 30-35 years (15 for development and construction, and 15-20 for in-core residence time), the following options would be available:

- exchange Russian denatured plutonium for U.S. weapons-grade Pu, and use the latter for the second fuel load of the CAPTURE power stations;
- reprocess the spent fuel and re-use the Pu in the same reactors;
- store the denatured Pu in safeguarded, retrievable storage for future use, and use civilian Pu for the second fuel loading.

After two or three fuel cycles in CAPTURE plants, when the reactors have reached the end of their useful life, the following options would be available:

- if nuclear energy is to be discontinued and no development of breeders considered at this time, one could dispose of Pu definitively in underground repositories, or if environmental and proliferation concerns so dictate, burn the Pu in fast burner reactors (cf. French CAPRA program, Ref.5).
- if nuclear energy is developed as a long-term solution, as is expected by some today (notably the French, Russian and Japanese governments), one could use the Pu in fast neutron breeder reactors.
- if the conditions are still not clear 55-60 years from now, one could store the plutonium in a new series of CAPTURE power stations. This would preserve all options, and the eventual decision could wait for a clearer context.

One of the important aspects of this kind of project is timing. The following schedule may be imagined for implementing the CAPTURE idea:

- 10 years for the development and validation of the concept, notably fuel irradiation experiments; however, start of construction on the first reactors could be envisaged before all experimental results are in hand, for example, seven years after the start of the project.
- construction time of 5-6 years, with construction starts every year on three reactor units.

With these rather optimistic assumptions, the total project would take some 15 years, by which time all military plutonium will be stored safely in CAPTURE reactors. Indeed, there is an implicit assumption in this optimistic schedule that the series of CAPTURE reactors, which will be rather simplified version of BN-600/800 (with lower specific power, simpler fuel handling equipment) will not require construction of a prototype.

Given that dismantlement of plutonium warheads will likely

follow dismantlement of ^{235}U warheads, and that plutonium would be needed for fabrication of first fuel loads for CAPTURE about eight years after the beginning of the project, the above schedule is rather consistent with safe disposal of military plutonium.

Technical Aspects

With a plutonium value that is zero or negative - indeed, the owner of plutonium may be obliged to pay a storage fee, covering, for example, storage and safeguards costs - fast neutron breeder cores must be re-optimized.

Therefore, the natural idea is to use as much plutonium as possible in each CAPTURE core, so as to store more Pu per MWe, and also to increase the diameter of fuel rods, thus decreasing the relative share of fuel fabrication in the total cost of a kilowatt-hour. It is also natural to try to increase fuel residence time in order to simplify fuel handling equipment without penalizing availability. It is therefore desirable to seek higher internal breeding ratios in order to allow longer residence time without large reactivity swings.

Meeting these objectives will lead to a higher Doppler coefficient, which plays a positive role in controlling power excursions, but also to a more positive sodium void coefficient, which has an adverse effect on safety.

The core will, therefore, have to be optimized to ensure overall safety. This can, for example, be achieved via a relatively flat core design, with appropriate upper plenum design ensuring that any sodium voiding of a core section will inevitably lead to sodium voiding of the corresponding section of the upper plenum, where the reactivity effect can be designed to be negative.

For reasons associated with core design safety, it seems reasonable to limit the size of the power plant. A logical size

would be between 600 MWe and 800 MWe, as Russian technology for this size of breeder reactor plant is well-developed.

The BN-600 FBR has been operating very successfully for over 10 years, with availability that is not only among the best in the Russian nuclear program, but also among the best in the world, all type of nuclear plants considered. The plant's average availability over 10 years was 97,5%, with a capacity factor of 71%.

In addition, Russia has developed detailed projects for the BN-800 fast breeder reactor, directly inspired from BN-600 technology (Ref. 4). Therefore, with some cooperation from western Europe (Phenix, Superphenix, EFR projects) and Japan (Monju), Russian scientists and technicians should be able to design and build a safe 800-MWe fast neutron power station without too much development.

The above-mentioned core optimization and the development and fabrication of Pu-bearing fuel with large-diameter rods will require close collaboration with western countries, notably with France, which has more experience in Pu-bearing fuel than Russia.

Core and fuel aspect represent the most innovative aspect of the CAPTURE design, and will probably require the most R&D. In fact, the idea that the author expressed in November 1994 was taken up for study by A.A. Kamaev of the Institute of Physics and Power Engineering in Obninsk, Russia and presented in Cadarache, France, in June 1995 (Ref. 6). His conclusions are that if one limits the core dimension by the diameter of the BN-800 vessel, the FNPSR core could not achieve the design objectives proposed in this paper.

The limiting values that Kamaev found were: specific power of 7,4 kg of Pu / MWe, inner diameter of fuel element cladding, about 8,8 mm; fuel residence time of 4,1 effective years; and breeding ratio of about 0,84. However, in his conclusion Kamaev stated: "Achievement of FNSPR type reactor characteristic values is possible in the new reactor plant design developed on the basis of design solution used for the BN-1600 heat re-

moval system. In this case, R&D work should be carried out to substantiate design solutions used for the first time in the practice of home nuclear reactor building industry”.

This clearly shows that the design goals mentioned above are not unrealistic, but will probably need more R&D. In fact, in Kamaev's preliminary review, he did not consider the possibility of increasing the diameter of the reactor vessel beyond that of existing projects (BN-1600) and changing the design of the fuel handling system. His preliminary results show that it would be necessary to study a rather flat core, with even larger diameter, larger fuel volume fraction, larger fuel element diameter and probably larger section of subassembly. This pancake-type core, with low specific power (kilowatt per liter of core), evidently calls for much simplified design of reactor vessel, vessel closure, and fuel handling system, the last perhaps inspired by those used for light water reactors (Ref. 7).

The relatively large vessel diameter required for this core design should not present major construction difficulties or increased costs, as we are talking about a relatively short stainless steel vessel with thin walls (no need to contain high-pressure liquid). The closure, the internals and the fuel handling mechanism should be much simplified compared to the classic breeder design. There may, of course, be some difficulties with the design, as for example the problem of intervention on failed fuel assemblies. One would have to determine by study if it is possible to accept a long waiting time before such intervention, inherent in the type of fuel handling I am suggesting, considering the low probability of this kind of event.

Generally speaking, this simplified vessel - wide and short - and simplified closure with no rotating plug but rather a type of leaktight cell (Ref. 7), associated with BN-800-type components - such as pumps, intermediate heat exchangers, steam generators - may hopefully be considered, with proper design and test efforts, as reasonably proven.

Economic Aspects

A rough economic evaluation of the potential of this project may be done in two ways.

One way of evaluation is to use the 1993 EFR (European Fast Reactor) study carried out by utilities and manufacturers from France, Germany and the U.K., which seems the most recent, serious and pertinent study of the subject, and to transpose it to Russian conditions.

This study (Ref. 8) shows that in a western European context, and assuming zero plutonium value, a serie of 1,500-MWe FBRs can be in the range of economic competitiveness with LWRs, at least with some uncertainty margin.

The EFR design was not optimized for plutonium storage; therefore, some gains can perhaps be anticipated thanks to:

- simplified fuel handling equipment design (fuel handling every 15 to 20 years);
- much lower cost fuel cycle: the large fuel rod diameter makes it possible to produce more energy per rod (for example, four times as much), and the cost of fuel rod fabrication should not be very sensitive to diameter; and
- potential fees to be paid by plutonium owners (for storage function).

These gains should thus lead in the EFR context to a situation very competitive with LWRs. This result should be transposable to the Russian context, assuming well-managed construction of a series of identical plants (10x800-MWe units).

There may, however, be one penalizing point, namely, the 800-MWe size, which is suggested for core design and local pragmatic reasons (the existence of BN-600 and of a detailed project for BN-800). However, this size is only slightly smaller than the largest modern Russian LWR of 1,000 MWe (VVER-1000). Therefore, the economic size-related penalty should probably be significantly smaller than the advantage due to the

re-optimization of the EFR core (see above). In fact, there is a certain tendency in Russia towards smaller reactors (for example, VVERs of 500 MWe and 630-MWe are in current Russian plans); thus, any economic penalty stemming from relative reactor size could disappear or even be reversed.

The second way to evaluate the economic potential of the project is to use the Russian internal comparison. According to V. Kagramanian, head of laboratory of systems analysis of nuclear power at the IPPE (Obninsk), a highly favorable experience has been gained in Russia from fast reactors: the BN-600 has the highest load factor among the country's reactors, and the BN-800 design modified (BN-800M) meets the latest, more stringent safety requirements. The economics of this reactor is equivalent to that of the medium-size thermal reactors (VVERs) or fossil-fired power plant (Ref. 9).

This, combined with gains from core optimization, gives a very positive indication about the economics of the concept.

One can therefore expect the CAPTURE project to have a good potential for competitiveness with LWR projects in Russia, that is, that it could produce electricity at a lower price.

Financial Aspects

The need for new electric power plants in Russia is quite evident. Even if the domestic demand is not growing, because of the developments of energy saving and more efficient energy use, the possibility of exports to neighboring countries and the need to replace older power plants, nuclear or not, justifies some new constructions.

The very difficult economic situation of Russia, however, makes the issue of financing difficult. Therefore, if this project is to go forward, international financing seems necessary, at least for most of the investment required. It seems to me that the in-

ternational community, and especially OECD countries, should be interested in facilitating safe storage of weapons-grade plutonium. Some of the OECD countries also should be interested in maintaining world expertise and increasing operational experience in fast neutron reactor power plants, and the entire international community in helping the Russian economy reconstruct.

A potential additional motivation for the potential lenders may appear if the Russian authorities accept to link the building of these new plants with decommissioning of older and less safe nuclear power plants.

This being said, the important question is how Russia can reimburse the money borrowed for these projects.

What will certainly reassure potential lenders is a contract expressing the reimbursement in a commodity exported normally by Russia which has well-established international value and is in demand in the lending countries, for example, natural gas.

The other advantage to link the reimbursement to gas exports is that Russia can consider that it saves gas when producing electricity with new plant, and reimburses only part of the saved gas.

As the Russians may have a problem to market all their available gas, it would probably be necessary to conclude a separate contract to purchase gas for reimbursement of the CAPTURE project, in addition to normal commercial gas supply contracts.

It is quite clear that financing is the largest obstacle to the entire CAPTURE project. To finance the study and development phase of the CAPTURE project, one can think of all governments interested in the main objective of CAPTURE - managing excess Russian military plutonium - as well as governments interested by the side benefits outlined at the beginning of this paper.

Using as far as possible the expertise and available time of Russian scientists and engineers, as well as their installations, development expenditures for this project should not be excessively high.

Indeed, as some eminent Russian scientists have indicated (Ref. 10), that in the present situation and for a given amount of hard currency, the Russian nuclear industry may perform much more work than western industry. For specific examples related to the upgrading of old Russian reactors, they suggested that Russian industry would be 16 times more efficient than western industry.

To be conservative, it would not be extraordinary to consider a factor of two to characterize the relative efficiencies of the two industries (Russian and western). This may be due to the relatively low cost of labor in Russia expressed in hard currency, as well as the high contribution of labor costs in the total cost of nuclear plant construction.

Assuming further that at least 80% of the construction work on CAPTURE stations could and would be done by Russian industry, the cost, in hard currency and as a percentage of typical western costs for the same work, can be expressed as $80\%/2 + 20\% = 60\%$.

If in addition the development phase is successful, construction of a series totalling some 8 GWe of CAPTURE reactors should not exceed about \$ 10 billion. In these conditions, the project should be self-supporting, with no, or very modest, fee for military plutonium storage. The risks - political, economic and technical - may discourage normal financing. One can, however, imagine that the OECD governments interested in the project may subscribe some sort of guarantee for the risks involved.

Conclusion

The CAPTURE concept seems potentially sufficiently attractive to at least deserve further investigation. The next, relatively inexpensive step, could be the study of cores without the constraint imposed by vessel diameter. If this study leads to satis-

factory results, a slightly more expensive, but still not too costly, step might be contemplated, to study and design a simple, large-diameter, low-height, vessel with a very simplified closure, internals, and fuel handling equipment.

Thereafter, a decision should be taken if more costly steps involving mockups, tests, fuel irradiation, and other design and experimental efforts should be launched. It is so be hoped that at least the first step will be launched in the near future.

Of course the decision to go along with the CAPTURE development should be made by Russian Government, which has to decide if it is in Russia interest to build a series of Fast Neutron Reactors for a total capacity of 8 GWe, and if it wish to commit it Gas resources to finance this investment.

If the decision is positive then Russian Government shall negotiate with interested OECD Governments the term of a loan.

If on the contrary the decision is negative, or if the development of CAPTURE is not successful, the next best solution for Military Plutonium Management seems to be the construction of 1,... 2... or more BN 800 Fast Neutron Reactors. BN 800 is already designed but may be reoptimized for low or negative plutonium value.

For example if two BN 800 are build, they will transform the 100 tons of Military Plutonium in spent fuel during some 30 years of operation.

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Non-Fertile Fuels for Burning Weapons Plutonium in Thermal Fission Reactors

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Abstract

In the last few years, the excess plutonium disposition has become ever more a topical and critical issue. As a matter of fact, more than 200 MT of Plutonium coming from spent fuel reprocessing have been already stockpiled and over the next decade, under the already ratified agreements, another about 200 MT of weapon-grade plutonium are expected to be available from nuclear weapons dismantlement.

On this basis, an ever growing plutonium production is no longer the goal and the already stored quantities should be burnt in power reactors by taking care that no new plutonium is generated under irradiation. This new outlook in considering plutonium has led many designers to reassess the Fast Breeder Reactors (FBR) role and shifting from breeder to burner machines perspective. Several solutions for burning plutonium have been so far proposed and discussed from the safeguards, proliferation resistance, environmental safety, technological background, economy and time schedule standpoint. A proposal for plutonium burning in commercial Pressurized Water Reactors (PWR) by using a non-fertile oxide-type fuel consisting of PuO_2 diluted in an inert matrix is reported hereafter. This solu-

tion appears to receive an ever growing interest in the nuclear community.

In order to not produce new plutonium during irradiation an innovative U-free fuel is being researched, based on an inert matrix which will consist in a mixed compound of inert oxides, such as ZrO_2 , Al_2O_3 , MgO , CeO_2 where the plutonium oxide is dispersed in. The matrix will fulfill the following requirements: good chemical compatibility, acceptable thermal conductivity, good nuclear properties, good stability under irradiation, good dissolution resistance. the plutonium relative content will be comparable to that used in MOX fuel. The fuel is expected to be characterized by a high chemical stability (rock-like fuel), so that after discharge from reactor and adequate cooling time, it can be considered a High Level Waste (HLW) suitable for final disposal in the deep geological formations without requiring any further reprocessing treatment (once-through solution). The fuel pellets, similar to those currently employed in the commercial LWR's will come from the ceramic mixed powders technology or from Gel Supported Precipitation (GSP) microsphere process.

The neutronic calculations show that commercial PWRs partially fed with Pu-inert matrix fuel and operated in a once-through cycle, have good plutonium elimination capabilities. The plutonium still remaining in the spent fuel is quality-poor, difficult to be recovered and then highly proliferation resistant.

Radiotoxicity levels versus time in inert matrix spent fuel, do not show any increase with respect to standard unprocessed spent fuel. A most relevant open issue is, however, the technological development and qualification of this new fuel.

1. Introduction

The end of the cold war and the recent agreements between USA and the states former USSR will make available relevant quantities of weapon grade plutonium (WG Pu) and of highly enriched uranium (HEU); the nuclear weapons reduction established by the START II treaty, signed in 1993 by Bush and Eltsin, and ratified by the American Senate just few weeks ago, should result in about 200 MT of WG Pu and 1000 MT of HEU. These figures are only estimated amounts, since it has not been known precisely how large is the military stock in both parties and there is also a high uncertainty about the size of the residual storage of the fissile materials, i.e. those materials not yet introduced in the nuclear weapons; therefore, most people believe that the quantities which we are dealing with are far higher than the reported values. The international scientific community is faced by the problem of finding a reliable methodology for the disposition and/or management of relevant quantities of strategic materials, in an economic manner, by: eliminating the diversion risk, reducing the environmental impact and the radiotoxicity hazards. It is wishful that the identified solutions will allow a limited recovery of the economic resources employed in the production of nuclear weapons.

2. Highly Enriched Uranium (HEU)

The problem of disposition of HEU is affordable in a rather simple way: it could be completely reconverted to civil utilization by diluting it with natural and/or depleted uranium, down to enrichment values of 3-5%, suitable for being used as fuel in the commercial LWRs. To this purpose, the USA have signed an agreement in summer 1992 with the Russian Atomic Energy Ministry (MINATOM) for purchasing 500 MT of HEU; this

agreement has given rise to heavy disappointment among American industrial and commercial operators of nuclear energy, worried about the perturbation effect that this action might bring to the uranium market. However, strictly speaking from the technical viewpoint, the HEU question is well defined. Some relevant doubts do however exist about the former Soviet HEU stock dimensions; Secretary Mickhailov has revealed in September 1993 that the 500 MT HEU transferred to USA, represent only 30-40% of total HEU existing in Russia (1). Should these news were right, only for Russia would be there a total amount of 1200-1500 MT, much higher than the total 1000 MT estimated for both Super-Powers, confirming in this way the doubts about the real entity of the existing stocks.

3. *Weapon Grade Plutonium*

The management of WG plutonium is more complex since it is possible to reduce its potential hazard by simple dilution operations or other chemical processes. At moment, the WG Pu is stored by Super-Powers waiting for a definitive solution, nevertheless this situation seems to be not sustainable any longer. A quite large number of solutions have been proposed for the WG Pu disposition, some of them are viable, others more or less exotic or unfeasible.

A first solution outlooks the introduction of Pu in glass bodies, possibly mixed to high level radwastes; this option though decisively safer than the simple storage and giving the possibility of permanent storage of the Pu, appears rather costly and still doubtful about its complete irreversibility, i.e. about its definite effectiveness against the proliferation risk.

Another solution consists in the *spiking* process: the Pu is irradiated in reactor for a short time, but sufficient to render it highly radioactive, in order to preclude any easy access to the

material. It is not eliminated however, the problem of the continuous safeguard control being not definitely prevented the possibility of Pu recovering through chemical process; in addition, the associated radwaste management would represent a rather delicate feature for this solution.

Some options consider the WG Pu utilization as nuclear fuel; only by fissioning Pu for producing energy there is in fact the possibility of recuperating a part of the economic investments made for the production of this material. The fission of 200 MT of Pu would produce something like $\sim 200 \text{ GWe-yr}$ of electricity, that is to say about 80% of the world year production of electricity made by nuclear power plants. The entire quantity of estimated HEU and WG Pu would produce through the fission process $\sim 1200 \text{ GWe-yr}$ of electricity, somewhat slightly less than the entire world electrical energy consumption in a year. In terms of equivalent-oil, this huge energetic potential represents 2.3 GTep which would require to have going around over the seas 4600 loads of a 500.000 tonne oil super-tanker; this equivalent-oil quantity corresponds to about 7 GT of carbon dioxide (CO_2) that would not be discharged into the atmosphere.

During the fissioning process Pu is altered and denatured; its isotopical composition is modified moving up towards higher atomic weight isotopes. This worsens the quality at a such an extent that makes the recuperation strongly unattractive either for utilization in thermal reactors or for diversion purposes. Moreover the irradiation generates highly radioactive fission products, which render highly difficult the accessibility to residual Pu. Although there still exist the theoretical possibility of recuperating Pu remaining in spent fuel, the associated complexity and the high technological level that would be necessary, would facilitate the safeguard role of the preposed international organizations (IAEA). Finally, through fission the most of Pu can be transmuted and therefore physically eliminated;

one should consider that this is the really safe way for preventing diversion attempts and for complying with the necessary safety requirements.

4. The Debate on the Civil Pu Role

The discussion about methodologies for WG Pu disposition is connected to the more general issue pertaining to civil or reactor-grade Pu (RG Pu) exploitation. Pu has been ever since considered as a precious material, substitute of natural fissile and therefore relevant efforts have been addressed to increment its production in the perspective of using it especially in fast reactors. Compared to thermal reactors, fast reactors allow, in fact, for a better utilization of U by enlarging of about a factor 100 the energy that can be extracted from a given quantity of mineral material, simply by converting U-238 (99.3% in natural uranium) to Pu-239. During the last few years, however, some facts have modified this kind of approach. One first point is that the U price has undergone a rapidly decreasing trend as an effect of the reduced demand and increased availability of natural U on the world market. Moreover, many experts do think that the reserve exhaustion do not represent a serious problem since new survey activities and technological improvements should render accessible even larger amounts of material. The experience derived from exploitation of other rare materials, such as zinc, tin and copper confirms this consideration, being their price in current money, undergone a continuous decrement during the last decades. Other considerations also play an important role:

- the U stock pile is an increasing function of the accepted extraction cost;
- the natural U price affects only marginally the energy production cost ($\sim 10\%$) and this turns out to be a very limited

- penalty in case of extraction cost increase;
- the ever more urging actions linked to nuclear weapons dismantling will make available large quantities of HEU and WG Pu.

Furthermore, FRs at commercial scale have been delayed in the far future, on the basis of technical, political and economical issues. Moreover, the repeated malfunctions, even though of not relevant entity, happened to Super-Phénix in France and the very recent incident to Monju reactor in Japan, which had been connected to the grid only in August 1995, beyond putting in evidence the management difficulties of those reactors, do bring the public opinion to a negative attitude towards this solution. Pu is presently utilized, even if at a limited extent, in thermal reactors in form of U-Pu mixed-oxide (MOX), whose economic advantage as we will see later on, is more and more questioned. To this respect it appears from the very recent news, that Electricité de France (EdF) holds that Pu recycling in PWRs finds justification only if a burn-up level of at least 60 GWD/T is reached, which stands as a rather hard challenge anyway. On this basis, during last few years a new way of considering Pu has come progressively to taking shape: Pu is not any longer looked as a useful material, but is rather considered as a waste product in UOX cycle, just to get rid of. Given its relevant energetic content, it should be exploited under this respect at the best it can be done, while trying to avoid any further production of it. In this perspective WG and RG Pu can be defined as “excess Pu”.

5. The Pu Elimination by Fission

To the end of Pu disposition, either WG or RG, by fission process, different solutions have been proposed and discussed from the environmental protection standpoint, proliferation resistance, technological background and economic aspects and

planning (2-6). Among these, the following hypothesis appear as the most interesting:

- utilization in FRs;
- utilization in LWRs;
- utilization in HTGRs.

FRs would be the best candidates for Pu burning if the blanket would be replaced by a reflector. This hypothesis has driven the attention of the French designers in order to find a new strategic position for Super-Phénix reactor; in fact the R&D programme approved in 1994 assumed to utilize the reactor as an incinerator for Pu and Minor Actinides (A). The third core, already approved and expected to be loaded during 1998-99, will reach a Pu burning capability of $\sim 20\text{kg/TWhe}$; in the meanwhile a test fuel assembly should be loaded with the purpose of verifying the possibility of reaching burning capabilities of 70-100 kg of Pu/TWhe (CAPRA Programme) and burning at the same time some minor actinides such as Am and Np (7). An analogous function has been outlooked for the hapanese prototype 280 MWe fast reactor Monju, which should be utilised for a minor actinides burning research programme (8). It is evident, however, that due to the very limited number of available FRs, the Pu burning capability through this line would result rather limited. Anyway, the utilization of a FR in a “burner mode” would result in an exactly opposite direction with respect to the original objective. That would go in the sense of a really reduced role of this kind of reactors, perhaps arriving to put under question even their presence in the near-mid future of nuclear energy panorama. Alternatively Pu can be utilized in LWRs as MOX fuel; among the afore mentioned solutions this is the only one which has been thoroughly tested and that starts to have real application at industrial scale. The MOX fraction loaded in the present PWR cores lies in the range 30-40% of the total core. This fraction ensures that power distribution and safety parameters fall within the design margins of UOX cores, in order to not bring any

change to the reactor control system. France, Germany and Japan are getting engaged in research programmes aimed at increasing the MOX percentage in the cores up to 50% or even 100% (10), but that will require careful evaluations since significant modifications to the control system could be necessary. The so far available data demonstrate, however, that the economic benefit in utilizing MOX fuel is not unanimously acknowledged.

Recently, P. Leventhal, Director of the Nuclear Control Institute, has claimed that the Pu recycle as MOX is undoubtedly more expensive than simple storage of spent fuel; nevertheless, many non-technical reasons induce electric utilities to follow this strategy (11). A significant confirmation of that comes from the fact that Electricité de France (EdF), leader in reprocessing and Pu recycling, and resolute supporter of this strategy, for the first time is going to attach a zero value to Pu in its 1995 budget, thus reflecting a comparative cost evaluation of MOX and UOX fuels (12). While other electric utilities, especially in Germany, are operating since several years with a Pu zero value, EdF has maintained a positive value until an economic justification has been possible. Practically, EdF is now admitting that MOX fuel is so highly expensive with respect to UOX fuel that no margins for a positive component of Pu value are available any more. Nevertheless, according to the conclusions of the Seaborg Report, which concluded that Pu should be considered an energy source to be exploited in power reactors as a MOX fuel, EdF has announced at the Global '95 conference that authorization for 12 ore PWR units has been asked to French Nuclear Safety Authority, beyond the already authorized 16 units, to utilize MOX fuel. There is a set of technical reasons which make the MOX management more expensive than UOX. One first issue is that the fabrication of Pu fuel is much more difficult than the only U based fuel, due essentially to safety reasons which require remote installations operation to be used. A second point is that the Am-241 coming from the Pu-241 decay, is a strong neutron

absorber and, together to the Pu-236 decay products, is a emitter. This causes the Pu fuel to be manufactured immediately after reprocessing, in order to avoid ray shieldings and minimize undesirable poisoning elements which would alterate the core neutronic economy. A third important point deals with the allowable number of recyclings in a sequence. During irradiation the Pu composition is modified in such a way to pass from the initial high Pu-239 content to an isotopic mixture where the Pu-240 and Pu-242 contents are increased. The presence of even isotopes degrades the Pu quality at a such low level that Pu coming from a second recycle would be already of so poor quality to render it unusable in a LWR core; to cope with that the Pu could be mixed also with a higher quality Pu, but that not be a decisive solution either. Conversely, the Pu composition is not degraded at such low level as to surely eliminate proliferation risks.

The MHTGR reactor, which has been proposed for Pu disposition is a modular concept of the HTGR and could profit also of the experience anchieved in the military facilities dedicated to tritium production. The fuel for this reactor consists in UOX or MOX microspheres coated by inert ceramic material (SiC) and put in form of small cylinders by an hot pressing process, and finally located in hollow graphite blocks. Some irradiation test have been performed in the past by using Pu fuel coated particles, but either the Pu fuel fabrication or the characteristics of a reactor operated with MOX, would need further and deep verifications. The remarkable difficulties in reprocessing this kind of fuel would constitute a strong barrier in case of an attempt aimed at residual Pu recovery. There exist a main handicap however for this line, that is no reactor of this kind is available at moment and the very few old HTGRs have been shut down. The solutions discussed above, do not completely meet, however, the requirements of a disposition which must be safe, economically viable and above all definitely proliferation resis-

tant. It is, therefore, fully justifiable the research for alternative solutions based on the utilization of nuclear power reactors presently available and operating. In this perspective the PWRs, due to their worldwide diffusion and consolidated technology, appear as the best candidates for Pu disposal by introducing some innovations in their fuel cycle.

6. Inert Matrix Fuel for Pu Burning

In order to not produce new plutonium during irradiation, an innovative *U-free* inert matrix fuel concept is being researched from very recently (13-20). The inert matrix consists in a mixture of inert oxides such as zirconia, alumina, spinel and ceria, where the plutonium oxide is dispersed in. The objective of such a fuel is plutonium burning in commercial PWRs by avoiding the breeding effect, i.e. new Pu-239 generation which takes place when U-238 is present. The plutonium relative content will be about 5%mol, comparable to that one used in the MOX fuel. The matrix will hold characteristics such as: good chemical compatibility, acceptable thermal conductivity, good nuclear properties (low parasitic capture rate), good stability under irradiation.

Moreover, the inert matrix fuel should comply with the following basic requirements:

- proliferation resistance: very low solubility in nitric acid so as to discourage any possible recuperation attempt either from fresh or irradiated fuel by current dissolution techniques;
- economics: the fuel pellets must be manufacturable through the already well established MOX fuel technology (mixed powders technology) or Gel Supported Precipitation (GSP) microsphere process; the inert oxides have to be abundant and easily available;
- burn-up performances: it is expected that this type of fuel shall be able to withstand a batch average burn-up same as

for standard fuel, according to commercial PWR requirements for next decade;

- low environment impact: on the basis of the required high chemical stability, after discharge from reactor and adequate cooling time, the spent fuel should be considered as a HLW suitable for final disposal in the deep geological formations without requiring any further reprocessing treatment (*once-through solution*).

As already found by other authors (6-18), the phase relations of some sintered mixed compounds suggest that the fuel should be characterized by a particularly high chemical stability (*roch-like fuel*) which persists in the irradiated fuel. It is remarkable moreover, that such a type of fuel, after being irradiated will hold only a marginal Pu-239 content and such an high concentration of even isotopes of Pu, which coupled to the its high chemical stability should render this fuel "hinerently safe" from the proliferation standpoint. The wet GSP microsphere process is proposed for fuel manufacturing, in order to avoid the not negligible Pu fines contamination problem during fabrication, being that a most relevant drawback in mixed powders technology. The second positive point for GSP application, is the potential utilization of coated microsphere, same as in HTGR fuel, which would enhance the fission gas retention capability provided that coating integrity is conserved during pellet fabrication.

Candidate inert matrix fuel systems are:

- PuO₂ oxide dispersed in: ZrO₂(stabilized)-Al₂O₃-MgO or ThO₂-Al₂O₃-MgO. These compounds are ternary systems with ThO₂ or stabilized ZrO₂ in solid solution with PuO₂; spinel (Mg₂AlO₄) and Al₂O₃. They are particularly investigated at the JAERI, Japan.
- PuO₂ oxide dispersed in ZrO₂ stabilized with CaO or Y₂O₃, in order to have the highly stable cubic phase zirconia. The use of zirconia, as only matrix material, could require annu-

lar pellets instead of solid pellets, due to its low thermal conductivity.

- PuO₂ oxide dispersed in spinel (Mg₂AlO₄). Spinel is a highly promising ceramic product foreseen for MAs burning in FRs and already studied for fusion technology applications. Annular pellets should be required in this case also, because the rather low melting point of spinel. The inert matrix fuel is also suitable for burning HEU in PWRs: in this case the major advantage with respect to UOX (obtained by denaturing HEU with depleted U), would be that no new Pu from neutronic captures in U-238 is generated.

A R&D activity on the above inert matrix fuel system is presently being carried out as a cooperative effort between ENEA and Polytechnic of Milan.

7. Core Arrangeent and Pu Burning in PWRs

Three core configurations are possible for burning Pu via inert matrix fuel in PWRs:

- a. core 100% loaded with inert matrix fuel;
- b. core partially loaded with inert matrix fuel assemblies (fraction ranging from 1/5 to 1/3), being the remaining part loaded with standard fuel;
- c. core uniformly loaded with all fuel assemblies containing a suitable number of inert matrix fuel rods.

The first configuration would be highly challanging due to the quite large amount of plutonium that could burnt in this case. Because of different neutronic features of Pu with respect to U, such type of reactor would have, however, a dynamic behaviour rather dissimilar from the current PWR one: this fact might affect the reactor contrallability in such a grade that new control systems, addition of large amounts of burnable poisons and other significant countermeasures should be considered.

On the other hand, the urgency in facing the plutonium issue and the need to find simple and more readily viable solutions would suggest that configurations *b.* and *c.* more easily applicable to commercial PWRs, being the characteristics of these layouts much closer to the currently MOX-fuelled cores.

Anyway, possible countermeasures could be the addition of some small fractions of depleted U or even using ThO₂ as a main component for all matrices. In the last case some depleted U could be still necessary in order to reduce the proliferation potential of U-233 produced during irradiation from the Th breeding. In a more general case, Th utilization could constitute an additional option of the solution here proposed which permits the U-233 recoverability; this possibility seems to bring a renewed interest even though it will introduce more complexity in the fuel cycle management (21).

Despite reduction on Pu loaded in each fuel batch, solutions *b.* and *c.* which result equivalent in principle, do not show relevant problems for Doppler and void coefficients, for being rather similar to current PWR MOX-fuelled cores. In fact, the reactivity coefficients of solution *c.* are just slightly lower than those in a conventional PWR (16-22).

A wide preliminary investigation on configuration *c.* has been carried out at Nuclear Engineering Dep. of Politecnico di Milano (16-17). For the analysis an AP-600 type core using 3.2 % U-235 enriched fuel, was selected as Reference Reactor (RR). It is worth to remind that this reactor is characterized by a lower power density with respect to standard PWRs, so that higher power peaks can be allowed without attempting to fuel rod integrity. The Burner Reactor (BR) was similar to the RR with the difference that in the fuel bundle, 56 rods over a total of 264 are substituted by inert matrix fuel rods (IMF).

The IMF rods layout was chosen in such a way to obtain a uniform dispersion of these kind of rods among the standard UO₂ rods, but no optimization was done up to now to this respect.

The fissile Pu mass content has been assumed equal to the U-235 mass content in the 3.2% enriched RR fuel. This amount allows the UO₂ rods within the BR assembly to achieve the same burnup level as that in the RR (24).

The results related to configuration c. show that, no matter the Pu source (RG or WG), more than 98% of Pu-239 is fissioned during irradiation. Also the fissile fraction of Pu is quite high:

~90% for the RG Pu and ~93% for the WG Pu. Furthermore, about 73% of all Pu loaded is burnt in the case of RG Pu and about 81% in the case of WG Pu. An indicator of the proliferation potential of a Pu isotopic mixture is given by fissile to fertile atoms ratio, which goes from 2.45 in fresh fuel to 0.37 in spent fuel if dealing with RG Pu, while goes from 15.1 to 0.5 if dealing with WG Pu. These low fractions of fissile Pu in the spent fuel, make highly unattractive an ever possible recovering attempt. Finally, the all Pu mass is reduced by a factor 3.7 for RG and 5.4 for WG Pu.

It is worthwhile to compare the previous figures of inert matrix fuel to those typical of a MOX fuel (23). Because the presence of U-238 which generates Pu under radiation, the all Pu mass still present in spent MOX after a first cycle, ranges between 60 and 70% of the loaded mass, depending on burn-up level; the burnt Pu fraction goes then from 30 to 40% of the Pu mass which has been loaded in the reactor. During irradiation the Pu isotopic composition moves towards higher mass number isotopes, nevertheless the fissile isotope fraction is still prevailing; in fact, the fissile Pu percentage in MOX goes typically from 71% in fresh fuel to 52-56% in the spent fuel. The above figures show an interest for the IMF solution either in terms of overall Pu reduction or in terms of proliferation resistance. It must be recognized, however, that the inert matrix fuel solution still requires an important research activity for its complete technological qualification.

The significance of the proposal here presented is confirmed

by the many parallel research programmes on Pu burning by inert matrix fuel, which are presently under way at JAERI-Japan, CEA-France, PSI-Switzerland and ENEA/Politecnico di Milano-Italy. Also US research institutions are showing interest of this kind of fuel. An information exchange among these organizations has been already undertaken. The work being carried out at ENEA and Politecnico di Milano on this topic, contributes to a 3-year activity programme on Pu and minor actinides burning in PWRs, performed in cooperation with other European partners and supported by the EU within the EAEC-4th Framework Programme 1994-98.

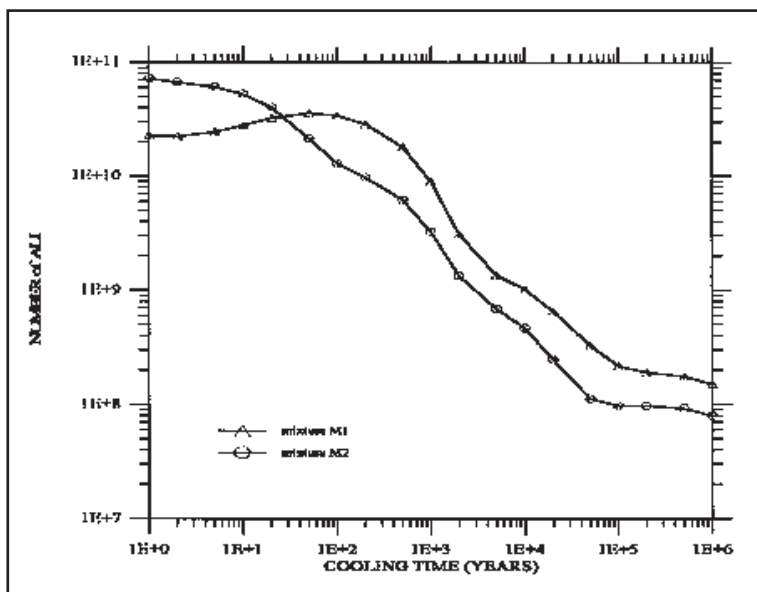
8. Radiotoxicity Issues

Although the Pu mass reduction and the increased proliferation resistance are assumed as key requirements, an analysis has been performed in order to assess whether the option of burning Pu in an inert matrix would produce any increase of actinide radiotoxicity. Radiotoxicity is defined in terms of number of ALI (Annual Limit of Intake):

$$\text{Nb. of ALI} = \sum \{A_i(t) / ALI_i\}$$

where $A_i(t)$ is the radioactivity of each radionuclide at time t after irradiation and ALI_i is the Annual Limit of Intake through ingestion of the public. As reference values, 1 MT of 3.2% enriched uranium spent fuel irradiated up to 34.4 MWD/kg was considered in the RR and the actinides contained in this unit mass have been labelled as mix M1. In the Pu burning option, the Pu in mix M1 was assumed to be recovered with a 2% loss rate, manufactured as inert matrix fuel and irradiated in the BR. The actinides contained in the inert matrix fuel after irradiation, together with those left in the reprocessed spent fuel, after Pu separation, were marked as mix M2. The performed calculations have shown (see curves next page) that the radiotoxicity

of mix M2 was larger than that of mix M1 for a period of about 25 years, because of the larger initial contributions of Am and particularly Cu. The Pu direct contribution was clearly reduced by the fissioning process. After this period the radiotoxicity of mix M2 fell below that of mix M1, under the effect of the lowered direct contribution of Pu and the reduced Am build-up. What is worthy to be stressed is that the significant reduction of Pu overall mass and increase of its proliferation resistance, did not involve any increment in actinide radiotoxicity compared to UOX spent fuel. Finally, if we do refer to radiotoxicity per energy unit, the actinide radiotoxicity in mix M2 becomes about 20% lower than that in mix M1.



9. Conclusions

The Pu coming from nuclear stockpile dismantling represents a true challenge to which the present nuclear technology can find a rational solution.

The weapons Pu holds a not negligible energetic potential, possible to be converted to useful electricity in the already existing commercial PWRs.

In this way the huge economic investments made during the last decades on nuclear weapons, could be recovered at least at limited extent and anyway converted to a peaceful goal.

This objective can be achieved under the optimized conditions of system safety, proliferation resistance, environmental impact and rational use of the technical and scientific competences already existing, by especially implementing innovative solutions in the nuclear fuel cycle, such as for ex. the once-through "U-free" inert matrix fuel devoted to current commercial PWRs.

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A Clever Use of Ex-Weapons Material

Jean Pierre Rougeau



Introduction

According to START I & II Agreements, the United States and Russia are committed to remove thousands of nuclear warheads from their arsenals and, once dismantled, those warheads make available significant quantities of fissile materials: Tritium, Highly Enriched Uranium (HEU) and weapons grade plutonium (wgPu). Part of this material, not needed for future defense programs, will be permanently withdrawn from the military stockpiles and will have to be treated in order to make sure it could never become weapon-usable again, neither for the owner country nor for potential terrorists.

Many studies have been and are still conducted to evaluate options for the disposition of warheads origin fissile materials. But the outcome does vary a lot according to each different material. Tritium is currently being recycled and is still needed in the military industry. The disposition of HEU is well ahead of wgPu treatment since implementation of HEU recycling has already started. As far as wg-Pu is concerned, although civilian grade plutonium is currently recycled in commercial reactors in Europe, there is no consensus yet on the benefits of adopting the same strategy for this material.

A concrete approach of what could be a realistic and clever disposition program is presented to underline the real benefits of the recycling option.

Amounts of Materials Involved

The quantities of fissile materials involved are considerable, especially when compared to civilian industry current needs or even forecasts.

In Russia, stockpiles are estimated to be above 1000 Mt HEU and 150 Mt wgPu. 500 Mt HEU are going to be withdrawn under the so-called "HEU agreement" signed with the U.S., and most of the wgPu is supposed to be withdrawn from the military industry; nevertheless since many different figures have been released either by MINATOM officials or by journalists for both materials the picture is not fully clarified: In the United States, a recent DOE report on military plutonium production and inventories has shown that there were about 85 Mt wgPu in the US military stockpiles. These amounts are actually in various forms and spread over several DOE sites. HEU stocks are unofficially said to be above 500 Mt. But the whole stock is not actual surplus. Those materials will not all be "available". President Clinton officially declared in March 1995 that 200 Mt of military fissile materials were surplus and going to be put under IAEA safeguards. Among the 200 Mt, 165 are HEU and 38 are wgPu according to Hazel O'Leary in a statement last September. A DOE HEU EIS draft released in October 95 assumed a maximum surplus value of 200 Mt HEU, with an estimated 50% enrichment level, which proves that 200 Mt are probably not a definitive figure. It is not the point here to pretend revealing the actual figures in place of official bodies. For practical purpose it is assumed hereafter that the total "available" quantity of wg-Pu amounts to 100 Mt in Russia, which is the most often quoted figure, and to 50 Mt wgPu in the US, quantity which is commonly used in the different DOE scenarios studies.

As far as HEU is concerned, this paper takes into account the currently most reliable figures, that is the 500 Mt Russian HEU from the HEU deal, and 200 Mt US HEU as stated by the DOE.

Recycling of Highly Enriched Uranium

The process used in order to recycle HEU consists in diluting it and thereby transforming it into a low enriched fuel that can be loaded in commercial reactors.

Such blending has two advantages: it is a way of taking HEU away from military purpose and at the same time provides a commercial product.

Energy Resource

Russian and American HEU are not precisely the same materials, and both countries do not plan to blend it exactly the same way.

Whereas Russian material surplus consists essentially in HEU enriched at level above 90%, American HEU is on average 50% U235. Moreover, the isotopic assay of the material used for dilution and of the resulting dilution is different from one country to the other.

Taking into account the isotopy and blending process differences between US and Russian stocks, 200 Mt US HEU would produce 1200 billion kWh and result in saving 32 000 Mt NATU and 19 million SWUs.

In Russia, resulted LEU would generate 4800 billion kWh in place of 150 000 Mt NATU and 90 million SWUs.

Global surplus has a saving potential of 3 years of NATU requirements and 3.5 years of enrichment need in the world.

These comparisons help to figure out why the recycling option of surplus HEU is not a mere option, but rather the solution. On the other hand, it is a way of underlining the negative impact that those materials could have on the enriched uranium industry, which is obviously not in a position to absorb suddenly this new source of supply.

Recycling Implementation

US and Russia signed in January 1994 an agreement whereby Russia would dilute 500 Mt HEU and sell it to US for commercial use. More precisely, diluted HEU was to be transferred during 20 years within annual quantities between 10 and 30 Mt per year. It was afterwards decided that more than 20 Mt was not conceivable: it would be beyond absorption capacity of the market and also above current Russian dilution capacities.

The first delivery of blended LEU occurred in spring 1995, after completion of a purification process which was said to be more difficult and expensive than expected.

The United States has also released in October 95 an EIS draft on HEU disposition that recommends the dilution of American HEU for commercial use in nuclear power plants. But like in Russia, part of the US surplus is at a level of enrichment and impurity that makes commercial recycling unfeasible or unprofitable, especially because of high concentration in isotopes U234 and U236. The recyclable part of US HEU surplus is estimated to be 65% to 85% of the "available" quantity.

The rationales for HEU recycling did not take long to convince. Recycling is actually less a technical issue than a commercial one. The real question is: how to manage the entry of a huge amount of substitution product into the market without long term damage to the enrichment industry? Both parties, US and Russian governments, have agreed that the HEU deliveries should not disturb the Uranium and Enrichment markets and have therefore planned a 20 year completion period.

Recycling of Weapons Grade Plutonium In LWRs

As far as military plutonium is concerned, the challenge is more complex and the industrial solution is not yet selected.

Whereas the military industry is used to handle such a mate-

rial, civilian industry is not familiar with separated wg-plutonium. Civilian nuclear industry is in fact used to deal with reactor-grade plutonium which is a natural by-product of nuclear energy generation; this is the case in those countries that have already chosen the so-called “closed fuel cycle”, and have developed plutonium recycling. On the contrary, in the U.S. many still prefer to keep plutonium included in spent fuel rather than separated and “available”.

But in the military plutonium issue, discussions on whether plutonium is to be separated or not are irrelevant simply because wg-Pu is already separated, and the recycling experience accumulated by the industry will serve to process it safely

NonProliferation

The major goal of wgPu disposition is to prevent anyone of being able to use it as a bomb component. Three actions can reduce the chance that someone could some day easily recover a sufficient amount of such material:

- to reduce total amount of fissile material
- to decrease its concentration in isotope 239
- and to restrict its possible retrieval.

It has been demonstrated, through several years of experience in Europe, that the recycling of civilian Pu in mixed oxide (MOX) fuel for LWRs fulfil these 3 functions.

Illustrative figures quoted hereafter are related to a PWR 900 MW with fuel irradiated at 43 GWd / Mt.

MOX and Pu Balance

The point here is to demonstrate from actual figures the ability of MOX fuel to consume plutonium through energy generation.

One UO₂ fuel assembly does not contain any plutonium when loaded in a commercial reactor but contains about 1 % of this material after irradiation. In concrete words, a 500 kg fuel assembly contains 5 kg plutonium when unloaded. Energy gen-

eration in an UO₂ assembly, which is due to Plutonium for up to 40%, results in a net positive balance of plutonium.

In comparison, civilian MOX fuel is about 7% Pu when fresh for an expected burn-up of 43 GWd/t. Of the 35 Kg plutonium initially loaded, only 25 kg plutonium remains after irradiation. In a MOX assembly, energy generation consumes plutonium.

A LWR power unit, loaded with 1/3 core of MOX fuel, consumes an amount of plutonium in MOX assemblies that equals what is created in UO₂ elements. Higher fractions of MOX assemblies will transform this reactor in a plutonium burner. Reactors of the next generation are currently designed to receive 50% or 100% MOX fuels.

MOX and Isotopic degradation

Recycling plutonium through MOX fuel is the only way of achieving isotopic degradation, because irradiation in LWR actually down grades the material.

Plutonium recovered by reprocessing of spent 43 GWd/Mt UO₂ fuel is about 66% fissile. Its content in fissile isotopes is 55 % Pu239 and 11 % Pu241.

Incorporation in fresh MOX fuel and irradiation result in an increase in Pu241 content but a greater decrease in Pu239 content.

When unloaded, the plutonium is only 54 % fissile, which makes it clearly less suitable for any weapon utilisation.

Plutonium Retrieval

Last of the three actions to be undertaken is to make the material as less accessible as possible.

The irradiation of MOX fuel in LWR produces a matrix of spent MOX fuel from which plutonium cannot be easily recovered.

To retrieve plutonium in a spent MOX fuel matrix is feasible, like to extract plutonium from a spent UO₂ matrix is feasible. But the retrieval is possible only through a costly and technical-

ly demanding industrial process, because of fission products releases. This could not be easily done.

Recycling wgPu through MOX fuel in LWRs fulfils the goals of the disposition program in terms of non proliferation.

Industrial Background

Process

To recycle plutonium through utilisation of MOX fuel requires to implement a very specific fuel fabrication process, that European industry has developed. Even if the raw material is not absolutely similar, civilian industry has enough experience to expect that the process transposition to wg-Pu will not raise any major obstacle.

The first step is to convert plutonium metal into plutonium dioxide which is the usual input of a MOX fabrication line. Such a process does not industrially exist yet and would have to be developed for the disposition program. But detailed studies are currently conducted in cooperation with the surplus owners to design a suited conversion process. Even if all results of these studies can not be released, being still restricted to defense activities area, it is known that several different experiments on wgPu samples were conducted successfully. Obtaining sinterable PuO₂ from wgPu seems reasonably feasible.

Beyond the conversion, the fabrication line itself will be very similar to a traditional civilian MOX fabrication line, with some differences related with the properties of wgPu compared to civilian Pu.

But these process modifications will not induce huge difficulties. Low content in isotopes 238 and 241 would even make the process easier in terms of thermal power, which is 7 to 10 times lower than with civilian plutonium, and in terms of health physics and safety, because, and neutrons emissions are also notably lower.

The only constraint would come from criticality, leading to

the need for some specific adaptation of the civilian MOX technology, for example smaller size equipment in the first part of the facility. Designing an adapted process in terms of criticality is already done for civilian MOX. More criticality will simply result in taking into account new parameters for the plant, but is not harder to achieve than current design.

European MOX industry experience

In Europe, several countries have decided to implement the reprocessing/recycling route for years and have therefore created the related industry. Reprocessing pilot plants have been built in Germany and in Belgium and industrial scale reprocessing plants are operating in France and in the UK. Several European countries like Germany, Belgium, Switzerland, United Kingdom or France do have been involved in the MOX industry, either by operating MOX fabrication facilities or by loading commercial LWR with MOX fuel.

About 400 Mt MOX have already been loaded in commercial reactors since first test in Belgium in 1963, in order to produce more than 100 billion kWh.

18 European reactors, PWR and BWR, have already been loaded with this fuel, without any problem.

Three industrial MOX fabrication plants are operated in France and Belgium totalling more than 200 Mt MOX/y nominal capacity. The UK is also involved in a pilot scale facility and is embarked on a large industrial fabrication plant with completion expected at the end of the century.

After more than thirty years of experience in MOX technology, the European industry is ready to offer a mature fabrication process and to adapt its design for military origin material, which will not induce difficulties.

Economics

Beyond its non-proliferation aspects and its technical feasi-

bility, the wg Pu recycling option is also a way of making the disposition program profitable. A great amount of a very energetic material will in such way produce electricity.

Energy Resource

The amount of material, first, is considerable: 150 Mt of wg-Pu is about three times the world annual production of fissile plutonium in the LWRs. And when compared to the reprocessing industry output, the figure is seven times the quantity currently recovered by reprocessing LWR fuels.

Considering the conditions under which plutonium is loaded in commercial reactors, it is conceivable to assume 4 to 5 % wgPu in MOX fuel. If burned this way in commercial LWR, 150 Mt wgPu would produce more than 1000 billion kWh, which is about 5 times the annual electricity requirement of a country like Italy for example.

Resulted fresh material savings would be around 25 000 Mt of natural uranium and 16 million SWUs, which helps to understand the interest demonstrated by several utilities towards this programme.

Costs

Building wg plutonium stockpiles was part of the defense programs and related costs were included in military budgets. It is hard to anticipate the conditions under which civilian industry will receive this new fuel supply. Anyone knows that this point is essential for reactors owners motivation.

As far as the material form is concerned it is assumed that industry will receive sinterable PuO₂ powder from governmental organisations. In such a case, from a strict MOX industrial point of view, and provided that the conversion costs are supported by governments budgets, the fabrication costs of wg-Pu MOX will be in the range of civilian MOX fabrication costs.

Provided it is transferred to industry in a suitable form, that

is sinterable PuO₂ powder, the wg-Plutonium can be processed in order to produce energy at a competitive price.

WgPu in LWRs Recycling Implementation

The rationales for wgPu recycling option are clear. Provided that needed facilities are available and that entities involved in the program are motivated, the implementation of wgPu disposition will be achieved together with electricity production.

Host reactors

Three kinds of facilities are needed to implement such recycling: the first one includes the conversion plants that will produce PuO₂ powder. The MOX fabrication plants are the second. Those facilities do not exist yet in the US nor in Russia, but would be easily constructed with European cooperation, like it is mentioned above. Thirdly the power plants are needed.

Since wgPu is a very sensitive material in terms of proliferation, it has to be constantly protected while stored, transported or processed. Therefore the best way of anticipating theft risks is probably to keep it inside its original territory. This argument is true not only for power plants selection, but also for all facilities involved in the disposition process.

In addition to proliferation issues, it is quite logical to consider that former USSR and US, having spent huge amounts of money producing wgPu, now get some return on investment by using this valuable material in their own reactors. And those host reactors exist in both countries.

A recent report states that at least 40 US LWRs are technically suited to burn MOX fuel. And according to current studies and calculations, in particular those conducted by Russian Institutes, the VVER 1000 reactor type is also well suited to be loaded with MOX fuel. About 20 of those currently exist or are under construction in Russia and Ukraine.

Those reactors will have to go through licensing procedures

before being able to receive the new fuel. But these procedures should not take any longer than time needed to build MOX plants, that is about 5 years.

Motivation

Last condition in a concrete approach of such a disposition program is the motivation of entities involved in the process.

The actors are on the one hand the DOE and MINATOM, public entities which major goals are to implement safely the governments commitments and to spend the least for the disposition program.

On the other hand, utilities and operators of the reactors must also find their interest in the program, which is to benefit from a new and competitive fuel supply without major core modifications.

The situation is a little different in the US compared to Russia. In Russia where plutonium has always been considered as a “national treasure” that should never be treated as waste and recycling seems to be the prevailing option. In the US, there is a current evaluation of two different options for the disposition program, which are wgPu vitrification and wgPu recycling. In fact, 10 utilities have responded to a DOE request of interest for wgPu recycling in February 96, which means a real change in the U.S. way of considering plutonium..

What Could be a Realistic and Clever Pu Disposition Program

Is the recycling of 50 Mt wgPu in the US and 100 Mt in Russia realistic over a reasonable period?

Considering a 1000 MW LWR 30% MOX loaded every year with 8 Mt MOX containing 320 to 400 kg wgPu, 50 Mt US wgPu could be consumed by 12-15 reactors within 10 years. The quantity of MOX needed would amount to 100-120 Mt/y.

As far as the former USSR stock is concerned, quantity is

more important, but 9 to 11 VVER 1000 loaded with 30% MOX could burn 100 Mt wgPu within 34 years. Such a program would require 70 to 85 Mt MOX/y depending on the Pu content in MOX fuel.

The number of reactors involved in each country gives obviously the rhythm of the recycling program. And an increase in the MOX part of each reactor core could also influence greatly the disposition timing. But considering that those stocks have been produced for 50 years, a 10 to 30 disposition years approach seems not to be out of the picture.

Quantities of wgPu MOX to be fabricated, from 70 to 120 Mt/y, are in the range of existing or under construction industrial MOX fuel plants, which confirms that MOX industry competence is well suited for cooperation in the disposition program.

French Involvement in Russian Disposition Program

An example of the cooperation programs between surplus materials owners and recycling industry is given by the current cooperation between France and Russia in this field.

French and Russian Governments have signed in 1992 an agreement on collaboration towards peaceful utilisation of ex-weapons material, called AIDA MOX.

More precisely, the joint program aims at studying the feasibility of all steps of the Russian wgPu recycling process, from conversion to MOX reprocessing. A comprehensive summary of the program was presented at the Global 95 Conference last September.

Several scenarios are currently evaluated, depending on the type and number of reactors involved. As far as MOX fabrication is concerned, the feasibility of constructing a first facility to incorporate Russian wgPu into MOX fuel for VVER and fast neutrons reactors is currently under study. The TOMOX plant would aim to transform 1300 kg wgPu per year in order to pro-

duce around 20 Mt MOX for 4 VVER 1000 at Balakovo and 1.5 Mt fuel for a BN600 fast breeder.

It would be the first step towards a large facility able to produce MOX for all reactors involved in the disposition program.

It would also be the first step towards the effective start of Russian wgPu disposition.

At the end of 1996, it will result in the definition of an industrial program for wgPu MOX fabrication and in-reactor recycling, preferably in cooperation with other European countries.

Conclusion

WgPu recycling is politically safe, technically feasible, economically profitable, and realistic.

Parties involved do have the means of completing such a program, and they can benefit from the civilian MOX industry experience and know-how. Some cooperation programs have already started.

The only one ingredient missing is a strong political initiative, which is needed to turn, in the decades to come, military plutonium into kWhs. As far as the industry is concerned, the implementation of such a program could start soon.

A CLEVER USE OF EX-WEAPONS MATERIAL

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1- AMOUNTS OF MATERIAL INVOLVED

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	HEU	wg-PLUTONIUM
RUSSIA	1,000 Mt $\Rightarrow$ 500 Mt	150 Mt $\Rightarrow$ 100 Mt
US	(500 Mt) $\Rightarrow$ 200 Mt	85 Mt $\Rightarrow$ 50 Mt

2- RECYCLING OF HYGHLY ENRICHED URANIUM

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	RUSSIA	US	TOTAL
• SURPLUS	500 Mt	200 Mt	700 Mt HEU
• % U235	90 %	50%	
• BLENDING MATERIAL	1.5 %	1.4 %	
• RESULTED LEU	4.4 %	4%	
• BILLION kWh	4 800	1 200	6 000 billion kWh
• SAVINGS Mt NATU Million SWUs	150 000 90	32 000 19	3 years WORLD NATU NEED 3.5 years WORLD SWU NEED

3- PROLIFERATION : MOX IN LWRs

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		Fresh Fuel	Spent Fuel	Balance
• PLUTONIUM BALANCE (43 GWd/t - 4 Years storage)	2 UO2 FA 1000 kg 1 MOX FA 500 kg	0 kg Pu 35 kg Pu	10 kg Pu 25 kg Pu	+ 10 kg - 10 kg
⇒ With 30% MOX Core, Plutonium Balance = 0				
• ISOTOPIC DEGRADATION (43 GWd/t - 4 Years storage)	MOX Fresh Fuel ⇒ Spent Fuel	Pu239 Pu241 Fis Pu 55 % 11 % 66 % 37 % 17 % 54 %		
• ACCESS & RETRIEVAL	Heavy and costly Industrial Process			

TRANSPPOSITION TO WG PLUTONIUM

4- WG PU IN LWRs RECYCLING : INDUSTRIAL BACKGROUND

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PU METAL TO PUO₂	Industrial Process still to Develop
MOX PLANT ADAPTATION • THERMAL POWER • HEALTH PHYSICS AND SAFETY • CRITICALITY	7 to 10 times lower α , γ , neutron Activity Reduction More Constraints
⇒ BENEFIT FROM EUROPEAN MOX EXPERIENCE	
5- WG PU IN LWRs RECYCLING : ECONOMICS	
SURPLUS	150 Mt wgPu
<i>A Clever Use of Ex-Weapons Material - 26/04/1996</i>	

↔	3 years Fissile Pu Production in LWRs 7 years Fissile Pu Recovered by Reprocessing LWR Fuels	
GENERATION	1000 billion kWh	
SAVINGS	25 000 Mt NATU 15 million SWUs	
COST	wg PuO2 Cost wg Pu MOX Cost	Included in Governmental Budgets In the Range of civil Pu MOX Cost
6- WG PU RECYCLING : IMPLEMENTATION		
HOST REACTORS	wgPu Producing Country = wgPu Recycling Country	

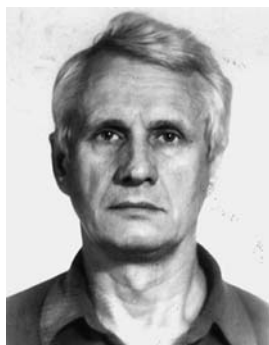
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MOTIVATION	• RUSSIA : Pu = "National Treasure" • US : Vittrification OR Recycling ⇒ 10 US Utilities Interested in Recycling Option
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PROGRAM	Surplus wg-Pu	Reactors Loaded	MOX FABRICATION NEEDS	YEARS
RUSSIA	100 Mt	9-11 VVER 1000 30% MOX	70-85 MtHM/y	34
US	50 Mt	12-15 LWR 30% MOX	100-120 MtHM/y	10

Utilization of Already Separated Plutonium in Russia: Consideration of Short-and Long-term Options

Anatoli S. Diakov



Abstract

Today there are a growing Russia's stocks of separated plutonium, recovered from dismantled nuclear war-heads and from military and civil re-processing plants that present an international security problem. In the long term, the basic Russian approach for disposition of this plutonium is to burn both weapons plutonium and civil plutonium in the fast-neutron reactors, but due to current political and economical situation in Russia this plan can not be realized any time soon. Under such conditions the first priority should be placed on the set up of a plutonium storage regime under bilateral or international control.

Introduction

The overriding objective of U.S. and Russian nuclear disarmament initiatives is to dispose of excess of nuclear fissile materials released from weapons in a such way that they can not be reused in the country of origin or stolen by terrorists group, for military purpose.

The natural disposal method for the weapons-grade uranium is to blend it with natural uranium to produce a nuclear reactor fuel. In February of 1993 the governmental Russian-US agreement have been signed in accordance with 500 tons of Russian weapons uranium which will be recovered from dismantled warheads and mixed with depleted uranium will be sale in the US as raw material to fabricate a reactor fuel. This agreement is being implemented. In 1995 Russia delivered to the United States LEU derived from 6,1 tons of HEU, and in 1996 will deliver the LEU derived from 12 tons of HEU obtained from nuclear weapons.

In the case of weapons-plutonium the situation is much more complicated. The utilization of already separated plutonium, particular of excess plutonium from retired nuclear weapons, is rising a complex set of technical, economical, environmental and political problems. All these problems are closely related and mutually reinforcing. The determination of optimal option for disposition of excess weapon plutonium based on such criteria as technical viability, resistance to theft or diversion, economic, timeliness, environmental protection and others is being studied by Russian and foreign experts.

FSU/Russian Stock of Weapons Plutonium

During the Cold War the FSU / Russian nuclear military production complex produced about of 125 tons of weapons-grade plutonium.

As the results of nuclear arms reduction most of this plutonium will become "surplus". Currently Russia is dismantling nuclear weapons and plutonium components at rate of some 7 tons per year which are being shipped to storage at the disassembly plants near Seversk (Tomsk-7), Ozersk (Chelyabinsk-65)

and Arzamas-16. It is expected that some 100 tonnes of plutonium will be released from weapons in Russia¹.

Furthermore, Russia will continue to produce significant amounts of weapons-grade plutonium. Only 10 of the 13 Russian plutonium-production reactors have been shut down. Although, the three remaining reactors are now operating principally to supply heat to cities Tomsk and Krasnoyarsk, they continue to produce weapons-grade plutonium at a rate about 1.5 metric tonnes each year. The Russian government has obligated that as of October 1, 1994 all newly produced plutonium be not used in weapons and will be stored in the oxide form.

Table 1
**Estimated Weapons Plutonium Production
in FSU/Russia by 1996**

Type of reactor	Power, MWt (designed/upgraded)	Period of operation production MT Wpu	Estimated
A	100/900	06.19.48/06.16.87	6.5
IR-AI	50/500	12.22.51/05.25.87	3.4
AV-1	300/1200	04.01.50/12.08.89	8.9
AV-2	300/1200	04.06.51/06.14.90	9.0
AV-3	300/1200	09.15.52/11.01.90	6.3
1-1	600/1200	11.20.55/09.21.90	8.5
1-2	600/1200	09. .58/12.31.90	8.2
ADE-3	1600/1900	07. .61/08.14.90	11.9
ADE-4	1600/1900	02.26.64/in operat	12.7
ADE-5	1600/1900	06.27.65/in operat	12.1
AD	1600/1800	08.25.58/06.30.92	13.5
ADE-1	1600/1800	61/08.29.92	12.3
ADE-2	1600/1800	63/in operat	13.2
Total	126.2		

Russian Stock of Civil Plutonium

Table 2 presents the amounts of fuels discharged from Russian power reactors² and estimates of the amounts of reactors-grade plutonium.

Russia is reprocessing spent fuel from domestic and Soviet-built reactors VVER-440, BN600 power reactors, naval reactors, and research reactors. At present, about 30 tons of separated reactor-grade plutonium³ in the form of the plutonium dioxide is being stored at Chelyabinsk-65. It is supposed to fabricate this material into reactor fuel before beginning to use weapons plutonium because the growth of the radioactivity in the civilian plutonium due to decay of Pu241 makes it difficult to handle.

Table 2
Russian civil plutonium production data

Reactor's type	Mass of spent fuel MT	Estimated mass of Pu MT
RBMK	6100	38
VVER-1000	1000	11
VVER-440	1250	17
BN-600	65	6
Total	72	

Russian Approach to Plutonium Disposition

The Russian Ministry of Atomic Energy (MinAtom) views plutonium as a valuable energy sources⁷. It's current concept, of how to utilize plutonium, is based on that approach which was developed two decades ago when there was a great energy demand, and entails the following stages:

- near-term stage - secure storage of both surplus weapons and civil plutonium;
- medium-and long-term stages - utilization of civil plutonium and excess of weapons-plutonium in the fast neutron reactors and in the thermal reactors.

Another possibility for the disposition of Russian plutonium is to use it for MOX fuel fabrication and sell this fuel on the world market. The Canadian government as well as Canadian nuclear industry has expressed support to the idea of transforming Russian excess weapon plutonium into MOX fuel and burning it in CANDU reactors. The feasibility study of CANDU option is currently in progress.

Although Russian experts are studying of non-reactor options within the frame of the joint U. S./Russian Plutonium Disposition Study, there is currently little enthusiasm in MinAtom for this approach to plutonium disposition. MinAtom officials repeatedly stated that the priority is given to the use of weapon grade plutonium in nuclear fuel for power production industry and not its immobilization or geologic disposal. Use of the existing vitrification technology has always been perceived as unsafe⁴.

A research and development program was adopted by MinAtom to coordinate efforts on implementation of technology and construction of equipment to use of weapons plutonium in the MOX-fuel fabrication for fast and thermal reactors. This program includes:

- processing of metal plutonium to plutonium oxide in the procedures of its dissolving, filtration, purification, precipitation and heating;
- fabricating of the fuel elements and fuel assembly;
- processing of the radioactive wastes resulted from the conversion procedure;
- production of the containers for secure and safety storage of plutonium dioxide and for its transportation;
- construction of storage facility.

MinAtom requested \$8.5 million as a part of the FY 1995 funds to support this program, but to the end 1995 it has received about 50% of these planned funds⁵.

Storage

Evidently, the time required for nuclear weapons dismantlement is much lesser than even the time to decide on optimal option for disposition of plutonium surplus. Therefore, it is necessary to store this surplus in safe and secure manner. In this context, the construction of storage facility which would provide storage for fissile material from dismantled nuclear weapons, and support the schedule on weapons dismantlement becomes a first priority.

The construction of a fissile material storage facility were begun by MinAtom, with the U.S. assistance, at the Mayak site last Spring, and it's completion is scheduled on 1997. The storage capacity is 50 thousands containers. This facility will corresponds to all modern international standards for safe, secure and accountable storage. The cost of the construction is \$150 million. The U.S. is providing the essential part of financing for material and labor cost, \$75 million was allocated for this project.

Also, (January 13, 1995) the Russian Governmental adopted the program of immediate measures on implementation of the national nuclear material protection, control and accounting system (MPC&A). The strategy for realization this task includes the development of:

- the draft of new legislation to regulate the state activity in this field;
- the concept of national MPC&A system;
- the base documentation to regulate an agency activity;
- the federal program to introduce MPC&A system;

- the technical project of the state information system for MPC&A
- the structure of the inspection service.

Several governmental agencies including MinAtom and GosAtomNadzor are involving in ongoing work. The close collaboration on these issues with Western countries is established. The GosAtomNadzor as a general manager of this program requested \$22.2 million to support program activities but up to now only about of \$1 million have been received for the development of new legislation⁶.

Burning Plutonium in Reactors: State and Prospects

In order to examine what utilization option is the most promising if Russia insists on its approach, a number of criteria were selected in this paper:

- 1) the technical viability;
- 2) timeliness;
- 3) resistance to theft or diversion;
- 4) cost.

Because the lack of information, the cost presented here represents only an estimate of capital investments. Definitely, these set of criteria is not complete and sufficient but it allows to evaluate the merits and disadvantages of the different options.

Fast Reactors

Technical viability

Russia has began experiments with plutonium for fuel fabrication in the middle of 50-th however the systematic studies of plutonium fuel started with BOR-60 reactor in 1970¹. Although,

a number of different kind MOX fuel elements were tested in Russia, the prototype of industrial power production fast reactors BN-350/600 have been fueled mostly with enriched uranium fuel.

The construction of first two fast reactors BN-800 was started at the South Urals site but then has been suspended in the initial stage due to financial problems. The new BN-800 fast reactor is designed and has passed all required examinations. No problems are expected with plutonium of various isotopic compositions. Also, the fast-neutron reactors could process larger amounts of plutonium than LWRs of equal power output, and the radiotoxicity of its spent fuel would be significantly less.

There are three pilot installations in Russia to produce MOX fuel for fast reactors: two at the Mayak association in Ozersk and one at the RIAR in Dimitrovgrad. The capacity of “Paket” installation at the Mayak allows to produce 10-12 fuel assemblies annually (300 kg of MOX fuel with about of 20% of reactors-grade plutonium) for BN-600/350 reactors. The modified installation “Packet” has a MOX production capacity up to 40 fuel assemblies (1 tonne of MOX fuel). The capacity of “Granat” installation at the RIAR is about 1 tonne of MOX fuel. The design and technology of these pilot installations are not corresponding a modern requirements¹¹, and their use for plutonium utilization is doubtful.

The construction of industrial scale MOX fuel fabrication plant Complex-300 to fabricate fuel for BN-800 reactors was started at the Mayak but has been suspended lately in the 50% complete due to financial difficulties. The proposed capacity of this plant is 900 fuel assemblies annually (60 tonnes of MOX fuel).

Timeliness

To implement this stage of plutonium utilization, MinAtom proposes to build four 800-Megawatt fast-neutron reactors: three near Chelyabinsk-65 and one at Beloyarskaya site and to

complete the construction of Complex-300 MOX plant at Ozersk site⁷. The BN800 reactor design allows to irradiate 1,6 tons plutonium per year. If implemented, four reactors would consume 100 tons of plutonium during 15 years. But taking into account that a substantial period of time would be required to built reactor (about ten years) and that each next unit would be installed following a delay 5 years therefore the process of plutonium disposition would start by 2010 and finish by 2030/35,

Resistance to theft or diversion

The chemical processing of metal plutonium to plutonium oxide and mixing operations take place in compact facility within closed area with tight security and monitoring. When MOX fuel is cladde and assembled into subassemblies it becomes rather difficult to steal it because the reactor subassembly is very heavy. The irradiation of MOX fuel results in the creation of the intense radioactivity and increases difficulties for theft. Additionally, an implementation of this plan will diminish risk of diversion and thefts because not only fuel fabrication, but also fuel and plutonium transportation will be under comprehensive control within a closed site.

Cost

Because the lack of information, the cost presented here represents only the estimation of capital investments. The estimated cost for this project is about of \$3.8 billion: \$800 million to complete construction of one BN-800 (\$765 million⁹) and “Shop-300” plant (\$35 million²), and \$3 billion for construction three additional BN-800s.

Light Water Reactors

Technical Viability

In the past in Russia, use of plutonium in thermal reactors was viewed to be ineffective. For this reason no one existing Russian LWR reactors (VVER-440, VVER- 1000) was designed for use of MOX fuel and in Russia there is no experience as well as facility for MOX fuel fabrication for water reactors. Although some Russian experts believe that four modern VVER-1000 units at the Bolakovskaya NPP could be modified and loaded with MOX (1/3 core), but experts from the GosAtomNadzor (Russian Nuclear Regulation Agency) and from Institute of Physics and Power Engineering in Obninsk expressed their doubts⁹ that even modern VVER-1000 reactors can be easily modified at moderate cost and licensed to accept plutonium fuel.

It is well known the Western Europe has the experience of using MOX fuel in thermal reactors, though it does not apply directly to the use weapon plutonium. Currently MinAtom in collaboration with France, Germany and the US is conducting technical and economical evaluation of plutonium utilization in the existing and future Russian commercial LWRs. These studies should be completed this year.

Based on the preliminary results each of four current existing VVER-1000 reactors at Balakovo would recycle 250 kg. plutonium per year, assuming 1/3 loading of the core, and 850 kg per year with 100% core loaded with MOX.

Timeliness

To estimate the period of disposition with use of the water reactors the next scenario is considered. Four VVER-1000 units at the Balakovo are reconstructed and loaded 1\3 of the core by MOX after the year 2000. Two partially completed VVER- 1000 units are redesigned and introduced with 100% core load by

MOX after the year 2005. Also three additional of advanced design VVER-640 will be constructed as replacement power sources for three operating production reactors and put in operation after the year 2010. Their annual plutonium consumption is approximately 370 kg with 100% MOX core¹⁰. When this scenario will implemented completely the annual plutonium consumption would be about 3,8 tonnes.

Obviously, some time is required to carry out research, experimental, design, licensing and construction work on use of MOX fuel in the Russian water reactors, and construction of the MOX-fuel Fabrication plant. In accordance with current estimation the pilot installation could be introduced on line by 2000, with the capacity 1 tonne plutonium per year or 20 tonnes of MOX fuel. Assuming the introduction in operation of the full scale MOX fuel fabrication plant with a capacity 120 tonnes MOX per year by 2005 the disposing of plutonium excess would be finished by 2032-2035,

Resistance to Theft or Diversion

If implemented this option will essentially broaden the geography of plutonium and MOX fuel transportation. Presumably, the chemical processing of metal plutonium to plutonium oxide powder and fabrication MOX fuel elements will be take place at the Mayak site, where is the construction of the storage facility is going on. The Chemical and Mining Combine at Zheleznogorsk (former Krasnoyarsk-26) will produce fuel assemblies while the nuclear power plants dispersed within the great region. Therefore, due to the broadening of the area of plutonium and MOX fuel transportation the risk of theft or diversion is growing.

Cost

To realize this option it is necessary to built three new reactors with a cost up to \$0,9 billion per reactor, to complete the

construction of two reactors with estimated cost at the level of \$1,5 billion. The cost of construction of pilot MOX-fuel fabrication plant is estimated about \$60 million¹² and cost of full scale plant is about \$250 million. In addition some funds require to reconstruct the old four VVER-1000 units. So, the total cost will be at the level of about \$4,5 billion.

Candu

Atomic Energy of Canada and Ontario Hydro propose to dispose of up to 100 tones of weapons plutonium resulting from disarmament programs in Russia and the U.S. by utilizing it as MOX fuel in the Bruce A Reactors, four 825 Mwe CANDU reactors operating in the Canadian Province of Ontario. The outline of the proposal looks as follows: chemical conversion of weapons plutonium components to plutonium oxide at a Russian facility; fabrication of MOX fuel and production of fuel elements for CANDU at a Russian facility; transportation of fuel elements from Russia to Canada; irradiation of elements in two CANDU reactors.

The spent fuel resulting from the process the Canada plans to store on its territory.

Technical Viability

Because of the unique flexibility of the CANDU design to adapt itself to many different fuel cycles, preliminary conclusions indicate that MOX fuel can be incorporated in the design with no changes to the reactor hardware, and within the existing licensed performance envelope. The plutonium concentration in the fuel is about 1,2% and the existing pilot scale fuel fabrication facilities or Complex-300 could be converted for CANDU MOX fuel fabrication purpose.

Timeliness

In accordance with preliminary estimation the full-program of MOX fuel production would begin by 2002. Each 825 Mwe CANDU reactor at the Ontario Hydro's Bruce A Station is capable to utilize about 1 tonne of plutonium. Therefore, it is possible to utilize 50 tons of Russian plutonium and 50 tonnes of the U.S. plutonium at a single station within 25 years.

Resistance to Theft and Diversion

The converting plutonium to plutonium oxide and the mixing operations take place in compact facility located within closed area amenable to tight security and close monitoring. After mixing the plutonium with the depleted uranium oxide, the volume is increases substantially and it makes difficult to steal it.

Certainly, the transportation of plutonium fuel for such long distance creates a significant risk to theft and diversion. However, any diversion should be detected quickly. Also, this risk would be diminished by using a specially designed vessel and supporting transport vehicles, as well as by implementation a special safeguards and security system.

Cost

A key elements of economic evaluation in this case is not the cost of capital investment but is the cost of MOX fuel fabrication, the cost of MOX fuel production facility conversion, and the cost of transportation.

The fabrication of unenriched uranium fuel for CANDU reactors is considerably cheaper with regard to LWR and its about \$65 per kg U²³⁵. On other hand, in current plants MOX fuel fabrication cost is higher than fabrication of uranium fuel. Because there is no data on the MOX fuel fabrication for CANDU, the cost presented here represents only approximations. It is supposed that cost of CANDU MOX fuel including fabrication, cost of depleted uranium and conversion of metal plutonium to

plutonium oxide is a three times higher than an ordinary cost, so it is about \$400 per kg. The plutonium is assumed to be free. The fuel transportation cost is assumed at the level of spent fuel transportation cost \$50 per kg. The cost of conversion of Complex-300 for CANDU fuel fabrication assume on the level funds needs to complete its construction. Under these assumptions the total cost of disposing 50 tons of Russian weapon plutonium would be at the level \$2,25 billion.

Conclusion

Although Russia has some experience with fast-neutron reactors, and the fabrication of plutonium fuel, but due to the lack of funds it is questionable that this option will be realized any time soon. The utilization of plutonium in LWR would be initiated in a shorter period of time and from this point of view this option looks more promising. But taking into account that Russia has an over capacity for production of low-cost LWR uranium fuel, it will be difficult for MinAtom to justify and get a large-scale subsidy to implement LWR MOX-fuel disposition concept. A decisive role on realization of CANDU variant will play a cost of MOX fuel elements production at Russian facility, but also including cost of weapon grade plutonium. Currently, the economic merit of each options is not easy to predict because the lack of information, but evidently a full scale implementation of any option and its realization will take a substantial period of time.

These observations indicate that the real question that needs to be answered is what priority needs to be placed in the strategy of dealing with the problem of weapon plutonium. This question is easily answered when one considers the current turbulent political and economic situation in Russia. The priority that makes the most sense is to concentrate efforts on short-

term options. The main concern, and highest priority for now, must be to create a regime that will prevent the reuse of retired weapons grade material in new weapons and prevent it diversion to the black market. This will create a base for irreversibility of nuclear-weapons reductions and confidence in the international community that no proliferation of nuclear weapons is taking place.

It seems there is only one way to realize this goal. That is to make a determined effort to set up a reciprocal regime of storage of both Russian and the U.S. excess plutonium under bilateral or international control.

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The Minatom Concept of Surplus Weapons Plutonium Utilization in Russia

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V.S. Kagramanian

Introduction

After the end of cold war period when East-West mutual faith is increasing, the process of real disarmament has started and rapidly gained in scope; The number of warheads to be dismantled on both sides is equal to tens thousand. It is expected that hundreds tons of high enrichment uranium and tens tons of weapons grade plutonium will be released from the military field as a result of this process.

Accumulation of weapons grade plutonium released from the nuclear weapons as well as civil plutonium produced by the modern power reactors gives rise to the well-grounded concern of the world public. The problems of plutonium management are not only technological, environmental and economical, these are also political problems since they are closely connected to the nuclear weapon nonproliferation issues and public acceptability of nuclear power.

There are different opinions on what should be the fate of accumulated plutonium stocks in the future. Some are considering plutonium mainly as the wastes of military and civil nuclear industry and studying various ways of deliverance from these wastes, reduced in the end to their disposal in geological strata

in one or other form. These options are still only theoretical and they require large scope of studies to be made on their feasibility, environmental safety and cost-effectiveness.

Others consider plutonium first of all as a raw material for power engineering, which can be utilized in power reactors thus enhancing significant increase of value is inadmissibly low, i.e. less than 1% for modern reactors. This viewpoint is based on the experience gained in many countries on the use of civil plutonium as mixed uranium-plutonium fuel in two reactor types: sodium cooled fast reactors and water cooled water moderated thermal reactors.

It is well known, that plutonium can be utilized in a most effective way in fast reactors. These reactors allow using plutonium of any isotope composition, and they can operate both as plutonium breeders ($BR > 1$) and surplus plutonium burners. When operating in breeder mode on condition that repeated plutonium recycle is provided, unlimited amount of depleted uranium is involved in the its power production process. This can be used for increasing by hundreds times the efficiency of natural uranium utilization and assuring long term development of nuclear power in the future without any limitations on the power resources.

Plutonium utilization in thermal reactors is significantly less effective. It is only possible to burn plutonium in these reactors. Plutonium repeated recycling is hampered by considerable amount of non-fissionable Pu-242 isotope and long-lived radiotoxic isotopes of neptunium, americium and curium (so called minor actinides) accumulated in the spent fuel. At large, efficiency of natural uranium utilization can be increased only by 50% as compared to the existing value.

However even such increase can be of certain interest for instance under conditions of fast reactor development delay.

From the very beginning of nuclear era in our country, the opinion existed that the long term wide-scale nuclear power de-

velopment would not be reasonable without significant increase of utilization efficiency of natural uranium resources and hence of plutonium utilization for energy production. Urgency of this problem for our country has even increased by now owing to the USSR disintegration since most natural uranium resources are located beyond the Russia borders.

Proceeding from this, Minatom Concept has been elaborated on management of released surplus of weapons grade plutonium and accumulated civil plutonium stocks. The essence of this Concept consists in the following postulates:

- in the long-term aspect: cost effective and environmentally safe efficient realization of plutonium power generating capability by means of its use as a fuel for power reactors;
- in the near-term aspect: during the period of reactor technology preparation for plutonium utilization reliable storage of this plutonium should be provided;
- the most important condition for this Concept realization both on the stage of plutonium storage and on the stage of its utilization, is assurance of non-proliferation of fissile materials.

Below brief description of state-of-the-art on this Concept realization is given.

Storage

The storage of civil plutonium released as a result of RT-I chemical plant operation is now provided at the PA MAYAK Works. The total amount of this plutonium is about 30 t. In the recent years, plutonium production as a result of chemical reprocessing of spent fuel received mainly from VVER-440, BN-600 and BN-350 reactors has been about 1 t per year. Some part of accumulated plutonium is of weapons grade, i.e. that obtained as a result of reprocessing of BN-350 and BN-600 fast reactor blanket subassemblies.

At the PA MAYAK site, there are special storage premises adapted for all materials coming as a result of dismantling of nuclear weapons. The amount of materials delivered for storage is determined by the dismantling process rate achieved, i.e. about 2000 warheads a year.

The design of specialized storage has been developed for fissile materials released in the process of nuclear weapons dismantling. This storage construction has been started on PA MAYAK site. Now containers for the fissile materials storage are being received at the site.

Weapons Grade Plutonium Utilization for Power Generation

Demonstration Stage

New Russia is not ready yet for the wide scale utilization of power generating potential of both civil and weapons grade plutonium. Two main users of plutonium are considered: sodium cooled fast reactors of BN type and water cooled water moderated thermal reactors of VVER type.

The validation of plutonium utilization in both fast and thermal reactors has been initiated bearing in mind further use of civil plutonium in these reactors. Of course, there are certain features of weapons grade plutonium utilization however they are not crucial. Besides, when developing MOX fuel manufacturing technology and irradiating this fuel in the reactors just weapons grade material is used.

BN Type Reactors

Considerable experience has been gained in our country on fast reactors and in particular on the reactor technology. BN-350 (start-up in 1973) and BN-600 (start-up in 1980) fast reactors have been built and successfully operated. Also, certain experi-

ence has been gained on manufacturing technology and using of mixed uranium-plutonium fuel in fast reactors. There are pilot lines for manufacturing trial MOX fuel subassemblies at PA MAYAK Works and in Melekess, and over 2000 MOX fuel elements have been irradiated in BN-350 and BN-600 reactors. Post irradiation analysis results have demonstrated fuel characteristics being preserved for required burn-ups.

Now fast reactor technology in our country is almost ready for implementation of demonstration stage on weapons grade plutonium utilization. This demonstration can start in this century. It requires development of so called hybrid core design with partial MOX fuel loading for the BN-600 reactor. This reactor now operates in converter mode using highly enriched uranium. When changing over to the new core design it would be reasonable to eliminate radial blanket, now used for production of weapons grade plutonium. Development of hybrid core design and its realization would require certain additional analytical and experimental studies for safety validation.

Possible rate of weapons grade plutonium utilization in BN-600 reactor hybrid core is 500 kg/year. Taking into account the fact that the reactor life time would expire in 2010, the total amount of utilized plutonium would be about 5 t.

In order to provide BN-600 hybrid core with the fuel, pilot plant should be constructed for weapons grade metallic plutonium conversion into oxide and manufacturing MOX fuel. This plant can be constructed on PA MAYAK site in two or three years using mainly technologies already developed in our country and abroad.

Increasing of plutonium utilization rate in the BN-600 reactor by means of changing over the BN-600 core to MOX fuel is possible in principle, however it would require considerably more studies because of the necessity to observe the strict requirements in force in Russia on sodium void reactivity effect, which should be negative.

VVER Type Reactors

As far as the second direction, i.e. VVER reactors concerned now only analytical and experimental studies are underway to validate the possibility of MOX fuel utilization in operating VVER-1000 reactors, This work has been started in our country because of some slowing down of fast reactor development program and intention to limit accumulation rate of extracted civil plutonium when RT-2 plant will be put in operation in the future for chemical reprocessing of VVER-1000 reactor spent fuel.

First MOX fuel elements for VVER reactors have been manufactured and irradiated by now in test thermal reactor MIR. Critical facility SUPR construction has been started in Obninsk for analytical and experimental validation of neutronic and physical parameters of the VVER type reactor core with MOX fuel. Analytical studies on operational safety, reactor control, accidental parameters and VVER core design improvements issues related to the plutonium utilization are under way. Some 30 or 40 experimental MOX fuel subassemblies for VVER-1000 reactor are going to be manufactured and irradiated.

It seems possible to combine tasks on MOX fuel preparation both for fast reactor technology demonstration stage and for analytical and experimental validation of possibility of plutonium utilization in the VVER-1000 reactors. One pilot plant could be used for both metallic plutonium conversion to the oxide and MOX fuel manufacturing for fast and thermal reactors. Now the design of this plant is being developed on the basis of about 1 t of weapons grade plutonium utilization per, year in the BN-600 and VVER-1000 reactors.

Large-Scale Plutonium Utilization

BN type reactors

On the basis of the positive design and operation experience of the BN-350 and BN-600 fast reactors the BN-800 fast reactor has been designed and construction was initiated of two units

of this reactor. Presently this construction process is actually frozen for the lack of money. According to plans it was assumed earlier to build three such units at the South-Urals site, PA MAYAK and one unit at the Belayarsk site instead of BN-600 to the moment of its decommissioning. Initially fast reactors were aimed at the utilization of civil plutonium being stored at PA MAYAK as a result of spent fuel reprocessing at RT-1 plant. The developed reactor BN-800 design has plutonium breeding ratio value of about 1 i.e. these reactors were supposed to use plutonium produced by thermal reactors as their initial loading, passing then to their own plutonium.

For this purpose it was supposed to arrange reprocessing of BN-800 spent MOX fuel and further repeated plutonium recirculation. To provide these reactors with MOX fuel "Complex-300" shop has been designed and its construction began at the PA MAYAK as well.

At present "Complex-300" construction is suspended because of financial difficulties and the delay in South-Urals NPP with BN-800 reactors construction. Evaluated level of completion is about 50%. The stoppage in "Complex-300" construction results in the technical aging of the design in terms of technology, process equipment, control instruments and automatic devices provided. Today the technical decisions need to be revised.

Studies performed demonstrate that the large-scale weapons plutonium utilization in the quantity of 50 t for 30 years can be realized on the basis of one BN-800 reactor functioning in "once through" cycle, i.e. without spent MOX fuel subassemblies reprocessing. Fuel fabrication for this reactor at a rate of 1.6 t plutonium per year, can be realized at the first line of the "Complex-300". Being financed the first BN-800 reactor and the first line of the "Complex-300" could be started before the year 2005. Utilization of BN-800 reactor at the South-Urals site, where weapons plutonium storage and MOX fuel fabrication plant are being constructed, will allow us, when weapons plutonium is

utilized, to exclude any transport of materials containing weapons plutonium beyond the PA MAYAK site. Such an arrangement of the weapons plutonium utilization allows to meet the most strict requirements in terms of fissile materials non-proliferation insurance.

The second BN-800 reactor, which can be built at Beloyarsk site, can be used for civil plutonium utilization, which is being separated and stored at the RT-1 plant. Fuel for this reactor can be fabricated at the first line of the "Complex-300". as well.

VVER Type Reactors

Before the completion of the program on calculational and experimental substantiation of possibility MOX fuel use in VVER-1000 reactors development of any programs on utilization of weapons plutonium on the VVER reactors basis would be premature. Nevertheless preliminary estimates show, that the existent VVER-1000 reactors and in a larger degree new design reactors of increased safety VVER-640 can, in principle, be considered as a spare version for weapons plutonium utilization in the case if BN-800 construction will not be completed for either cause. In the case with VVER it will be difficult to arrange utilization of weapons plutonium within a single site. Here one have to arrange a safe transportation of the fuel with weapons materials from the MOX fuel fabrication plant near Krasnoyarsk to a number of sites in the European part of Russia with operable VVER-1000 or with new VVER-640.

International Collaboration

The work on substantiation and realization the concept on utilization of excessive weapons plutonium is being conducted in Russia in close collaboration and with certain financial support by Western countries.

With European countries joint calculational neutron physics studies are being conducted on Russian fast and thermal reactors on MOX fuel utilization. Some works are carried out on the substantiation of technology on conversion of metallic plutonium into oxide. Design studies are conducted on pilot installation aimed at the MOX fuel fabrication for the hybrid zone of BN-600 reactor and VVER-1000 reactors.

In collaboration with the USA specialists evaluations are conducted of various options of excessive weapons plutonium management in Russia and in USA. On the basis of these studies perspective directions of collaboration are supposed to be determined as far as optimal options of weapons materials management for each country are concerned.

Russia is very interested in continuation and enlargement of the collaboration. It is connected with the large scale of the task we have encountered in Russia, complex solution of which needs hundreds millions of dollars and today's heavy economical situation in the country, very strong complicating fulfillment of the task.

Conclusion

The fuel cycle industry of Russia has necessary base and experience to begin solution of problems on ensuring safe utilization of weapons plutonium.

Russian concept of plutonium management (both civil and weapons) is based on the fuel cycle closing in the nuclear power industry to increase the efficiency of the fuel use and decrease long lived waste activity.

On the basis of short term program of plutonium management in Russia lies safe and reliable storage of weapons and separated civil plutonium till they will be used in reactors.

An effective option of separated civil plutonium and

weapons plutonium being released with conversion the latter in the spent fuel form can be realized in the frames of a Nuclear Power Center being created at PA MAYAK (RT-1, "Complex-300" and BN-800 reactors).

Further studies are needed on calculational and experimental substantiation of optimal use of MOX fuel in fast reactors BN and in thermal reactors VVER type having in mind non-proliferation aspects, nuclear and radiation safety, economics and ecology.

It is worth while widening and coordination of the international collaboration with the aim of practical realization in Russia the most prepared for conditions of Russia option excessive weapons plutonium, being released, utilization on PA MAYAK basis. This is completion of the "Complex-300" and of one BN-800 reactor, as well as construction of an installation for metal to oxide conversion.

Get SMART: The Case for a Strategic Materials Reduction Treaty, and its Implementation

Neil J. Numark



Summary

Inventories of weapons plutonium removed from nuclear warheads should be reduced as quickly as possible to prevent large-scale rearmament by the United States or Russia and to minimize the risk of theft or sabotage by a sub-national group. The U.S. and Russia should agree to a Strategic Materials Reduction Treaty (SMART) establishing an aggressive timetable for manual reduction of national security needs and schedule the final disposition of this material.

An aggressive disarmament timetable will require an aggressive implementation program. This should take advantage of available resources within the U.S. and Russia as well as in third countries, including potentially both reactor and immobilization options, as long as stringent safeguards and security can be guaranteed at all participating facilities. Many existing light water reactors in the U.S. are well suited to the purpose, and several private operators of these plants have formally expressed interest to the U.S. government in providing such service. Russian fast and light water reactors appear to be less readily available to burn weapons plutonium. Russia, the United States and other G-7 countries should develop international programs to facilitate the most rapid possible reduction in weapons plutonium inventories, consistent with SMART. Such international cooperation

would add credibility and transparency to the nuclear disarmament process in the spirit of the Non-Proliferation Treaty, and could add momentum toward the conclusion of both a Comprehensive Test Ban Treaty and a Fissile Material Production Cutoff Treaty.

This international program should take advantage of existing global infrastructure for the use of plutonium fuel as well as other capability (e.g., in the U.S. and Canada) that could supplement existing civilian Pu use plans, as well as vitrification or other immobilization facilities. In combination, it is reasonable to forecast a global capability to disposition at least 10 tons of weapons plutonium per year. In addition to providing plutonium disposition capacity, third countries should participate in financing disposition programs and offering safe-guards technologies to the global disarmament effort.

Weapons plutonium which the U.S. and Russia declare to be in excess of national security needs and place on the SMART timetable should be held under their ownership and under international safe-guards until sent to various final disposition sites. However, it would be advantageous to establish an international entity with representatives of Russia, the U.S., other G-7 countries and possibly other states to play a role concerning the flow of weapons plutonium to third country disposition sites, based on the resources available in each country. Such entity could also play a role in preventing the further accumulation of stocks of separated civilian plutonium.

1. Introduction

The dismantling of weapons delivery systems by the United States and Russia has already yielded large quantities of material now unneeded for defense purposes, and extensive research is under way concerning the best way or ways to get rid of these materials irreversibly. But while these evaluations progress and the selection of disposition methods remains a subject of great interest, a question that often seems forgotten is: How much of

the dismantled materials will the U.S. and Russia actually *decide* to disposition? Will we declare the vast majority of the dismantled materials to be in excess of national security needs, *and* will we in fact successfully disposition this quantity? Clearly, as successful as disposition programs may be, their benefits to society are limited by whatever amounts of fissile material the U.S. and Russia include in these programs. The United States has declared about 175t of HEU, but only about 40t of Pu, to be in excess of national security needs; to my knowledge no such declaration has yet been made on the Russian side. Furthermore, even the amounts that *have* been declared to be excess are of course not yet irreversibly dispositioned, and there is the risk that they could be returned to weapons use.

I would like to state as the underlying premise of my talk something which is very simple and upon which I think most or all of you would agree: that it is healthier for the planet if both sides downsize our nuclear arsenals as quickly as possible, keep them small, and establish a system of international control to oversee this process. By arsenals, I am including all weapons-grade fissile material that is still in the possession of each country, even it has already been declared to be in excess of national security needs and relinquished by the military, i.e., anything that has not yet been irreversibly converted to a non-weapons-usable form. The point is, it is strange, and inadequate, that we have almost come to accept the dismantling of *delivery* systems as “disarmament”, rather than the dismantling of the bombs themselves. If the bombs still exist, we have not disarmed them.

Let us assume steady progress towards START milestones and, looking just at plutonium, a fairly optimistic scenario in which 50 MT of Pu per side - i.e., roughly half - is declared surplus to national security needs, released for disposition, subjected to IAEA safeguards, and successfully dispositioned over the next two or three decades. Even with such a rosy forecast, a rough calculation shows that there would still be enough remaining

weapons- grade Pu thirty years from today to arm 20,000 war-heads (not just the 3,000 or so allowed under START-II).

Clearly a 50 MT reduction in W-Pu per side is totally inadequate. Even if we were confident that this remaining inventory was extremely well guarded, it would still be in the national arsenal, leaving open the possibility of an all-too-easy resumption of the arms race. Plus, if we accepted indefinite long-term storage of such a large remaining inventory of “loose nukes” (no longer in weapons but not yet dispositioned), we also run the risk of major changes in government and periods of loss of control over the material, potentially leading to diversion.

In any case, it is not even clear that we now on our way to shedding even this inadequately small portion of our arsenals. We forget in good times that there is some risk that the process will lose momentum. There are still those voices in each country who would bring us back into a spiraling arms race.

2. SMART

What can we do to ensure that the U.S. and Russia will indeed eliminate the vast majority of the “loose” inventories? What we need is a *program* and an *agreed reduction timetable* that both sides must honor if they expect the order to do it. The U.S. and Russia need a treaty-level agreement - a Strategic Materials Reduction Treaty (SMART) - establishing a joint framework and timetable for the disposition of fissile materials, and should jointly declare the majority of existing inventories to be in excess of national security needs and schedule its final disposition. SMART should have the following features:

- Goal of achieving a minimal residual inventory within 20 years, from the current inventory of about 100 tons W-Pu per side to perhaps 10 tons each;
- Compliance by whatever method or combination of meth-

ods each country prefers - including domestic and third country options, employing either reactor burning or immobilization or other approved methods - as long as the aggressive treaty goal is met; and

- As a first step, an agreed timetable for deforming plutonium pits, which should be relatively quick and inexpensive. Pits would then need to be refabricated in order to use them in weapons.

According to the U.S. National Academy of Science¹, this last point - pit deformation - would only introduce a delay on the order of months to a rearmament program. However, it would have great symbolic importance, and if we could also reach agreement to decommission all pit fabrication facilities, we would introduce an even greater barrier to a rearmament program.

Implementing SMART would ensure the irreversibility of disarmament. Without such an agreed schedule, it is unlikely we can make rapid reductions because neither side can possibly implement significant cuts without a reciprocal move on the other side. We might instead be engaged, at best, in a game of stop-and-go disposition, with each side constantly concerned that they maintain near-parity with the other, and, at worst, in a stalemate where both sides sit on large inventories indefinitely.

Of course there are voices in both countries arguing that we should hold on to these inventories as they might be needed again for military purposes. This is a narrow and outdated Cold War mentality (and indeed, one of the major reasons that we should get rid of the inventories quickly). As long as the U.S. and Russia reduce inventories *in parallel*, nuclear parity will endure; large reductions are possible before we reach the fissile material inventory level of the other declared nuclear weapons states, China, France and the U.K. Furthermore, once the U.S. and Russia begin to make substantial progress, the other nuclear powers should reduce their inventories as well.

How SMART Fits Into Disarmament Framework

In addition to START II, which the U.S. Congress recently ratified, President Clinton and Yeltsin made a joint statement on the Transparency and Irreversibility of the Process of Reducing Nuclear Weapons at their summit meeting in Moscow in May 1995. Their statement declared that:

“Fissile materials removed from nuclear weapons being eliminated and excess to national security requirements will not be used to manufacture nuclear weapons;

No newly produced fissile materials will be used in nuclear weapons; and

Fissile materials from on within civil nuclear programs will not be used to manufacture nuclear weapons”.

These three elements - no reuse, no new production for weapons, and no transfers from civilian to weapons - are all the right elements, but they are not irreversible. SMART would make the first item irreversible. As an agreement to get rid of existing inventories, SMART would go hand-in-hand with START and with the commitment not to produce more fissile material for use in nuclear weapons (which has yet to be formalized internationally in a Fissile Material Production Cutoff Treaty).

Negotiations have been ongoing to implement other aspects of the May 1995 agreement, concerning increased transparency and irreversibility and the need for an agreement for cooperation allowing data exchanges. Hopefully these items will be resolved in connection with the April 1996 summit. But regardless of progress on this front, SMART can proceed independently.

3. An International Program for Accelerated Disposition of W-PU

How can we achieve the aggressive disarmament timetable spelled out under SMART? I will quickly summarize the cur-

rent prospects for W-Pu disposition within the United States and Russia, and then turn to the potential contribution of third countries towards meeting aggressive disposition milestones.

United States

On the U.S. side, things are moving too slowly and not one kilogram has yet been dispositioned despite various existing technologies that could already have been employed to demonstrate their suitability for the purpose. The reason is that U.S. policy has not yet been decided and unfortunately even pilot-scale efforts will not begin until it has been. The development of disposition options is on hold until at least the end of 1996 when the U.S. Department of Energy expects to announce a decision.

On the other hand, DOE deserves credit for its recent steps to release inventory data, as part of Secretary of Energy Hazel O'Leary's openness drive. The report released by O'Leary on February 6 reveals that the U.S. inventory of Pu totals 99.5 metric tons, including 66.1 MT at the Pantex site in Texas². It is DOE's intention that the release of these details will prompt Russia, China and others to make similar disclosures, and I hope that will occur.

Returning to DOE Pu disposition studies, Figure 1, from their February 1996 draft environmental impact statement, indicates that DOE is evaluating options in three categories: Deep Borehole Disposal; Immobilization Followed by Repository Disposal; and Reactor Options. (Also shown is the "No Action" alternative, which would of course be the worst possible outcome and one which DOE will certainly not select, but is a standard element in the U.S. government's review of the environmental impact of actions it proposes to take).

The use of existing reactors has substantially more support than building new reactors or completing partially-constructed ones, mainly for the obvious reason of economics. (This includes

the option of employing Canadian CANDU reactors, which I will discuss in a few minutes). In December 1995, DOE asked the nation's electric utilities to indicate whether they had an interest in offering one or more reactors for the purpose, and last month received positive responses from several utilities (who are attracted by the prospect of free fuel and a possible subsidy from the U.S. government for conducting Pu disposition activities):

- Arizona Public Service
- Commonwealth Edison
- Duke Power
- Southern Nuclear Operating Co.
- Tennessee Valley Authority
- Washington Public Power Supply System
- Others

Unfortunately DOE tied this request to a related invitation concerning the use of commercial reactors to produce tritium for maintenance of our stockpile of nuclear weapons. Some of the utilities have expressed interest both in producing tritium and burning W-Pu in the same reactors at the same time. The prospect of our the disarmament benefits of burning W-Pu, and is likely to be so controversial that it would seriously delay efforts to employ existing reactors for Pu disposition. My feeling is that if an existing reactor is to be used for tritium production, it should be sold outright to DOE and operated by DOE.

Furthermore, extensive studies are now under way concerning the immobilization option. A December 1995, DOE workshop on the subject seemed to indicate that there are no major obstacles that would prevent immobilization of W-Pu in glass followed by repository disposal. Criticality concerns during processing apparently can be mitigated and a glass with high Pu solubility can be designed. On the other hand, long-term criticality control in a repository may be more difficult to assure. Neutron absorbers are being studied, such as gadolinium, but Pu loading may have to be low to gain licensing approval.

Finally, while the borehole option seems to be receiving positive technical reviews, it is probably the least likely option to be selected for the simple reason that a site would need to be found.

My expectation is that DOE will not narrow down these nine choices to a single strategy when it reaches its decision later this year, but rather make a general determination to develop and demonstrate reactor and immobilization options in parallel. Potentially both options could be pursued in parallel, offering the assurance of some redundancy. This would be consistent with the NAS Reactor Options Panel report, which recommended “brinding both processes on-line by the end of the century of as shortly thereafter as possible”. I would note that we already know that some Pu residues are unsuitable for MOX fuel and a waste management solution will be necessary, so the main question really is whether DOE will also pursue the MOX method of disposition. My hope is that they do and that they develop both options as expeditiously as possible, consistent with SMART objectives.

Russia

Russian experts at this conference have already described possible concepts for utilization of excess weapons Pu in Russia. My understanding is that using MOX in LWRs. At the September 1995 ASME conference in Berlin, Drs. Murogov, Kagramanian and Chebeskov described three possible scenarios: 1) building 3-4 BN-800 fast reactors, which could transform both civil and ex-weapons Pu into spent fuel by 2030 or 2040; 2) using only the existing BN-600 and VVERs, which can burn only 25 tones of ex-weapons Pu in their remaining life; and 3) constructing new VVER-1000s (11 units burning 1/3 MOX could consume 3.3 tons/year)³.

At the conference, Dr. Rybatchenkov of the Ministry of Foreign Affairs of the Russian Federation, noting the financial diffi-

culties in executing these concepts, spoke favorably of the option of disposing Russian W-Pu in existing foreign reactors. Focusing in particular on a proposal from Canada, Rybatchenkov stated that preliminary study “shows that it may be of interest to Russia from political, economic and social points of view.” He noted the benefits of the concept for assuring transparency and irreversibility of W-Pu disposition; offering hard currency to Russia; and creating new work places in Russia’s nuclear industry. Speaking also of other possible partners such as the U.K. (Sizewell), France, Germany, Belgium and even the U.S., Rybatchenkov concluded that “the very idea of using foreign reactors for disposition of Russian weapon grade plutonium seems to be sufficiently productive and deserves a thorough investigation side by side with traditional projects, involving Russian reactors”⁴.

Third Country Scenarios

Taking advantage of available resources not only within the U.S. and Russia but also in third countries, including potentially both reactor and immobilization options, might make possible a more aggressive disarmament timetable under SMART. Under the condition that stringent safeguards and security must be guaranteed at all principating facilities, there could be significant disarmament benefits to broadening our disposition programs in this manner. In addition to assuring accelerated disposition, international cooperation would add credibility and transparency to the nuclear disarmament process.

As I noted earlier, the Canadian nuclear industry has already offered proposals to both the United States and Russia to accept MOX fuel made from W-Pu at Ontario Hydro’s Bruce station. Atomic Energy of Canada Limited projects that four reactors at the 8-unit Bruce station could consume 50 tons of W-Pu in just 12 years (or, for 8 units, 100 tons in 12 years). Ontario Hydro is committed to this proposal, and the Canadian Gov-

ernment is currently addressing it at the highest levels and is expected to announce a position very soon⁵.

Clearly, the Canadian proposal is an important third country scenario, and indeed could be one of the most significant *on any of the options for U.S. or Russian W-Pu disposition*. But additional third-country scenarios should be considered as well for *their* potential benefits to the disarmament process. While it may be desirable to limit the total number of disposition *sites* in order to guarantee security arrangements, third country sites should be among those considered. Figure 2 identifies a range of conceivable domestic and third country MOX scenarios.

Unlike disposition scenarios involving U.S., Russian or Canadian reactors, which would generally be above and beyond existing civilian MOX use plans, these other third-country options, in Europe or Japan, which would take advantage of existing worldwide infrastructure for civilian Pu utilization, could either be *above and beyond* existing MOX use plans, or could potentially *substitute* W-Pu for reactor-grade Pu that is otherwise scheduled to be utilized in these countries. (France, Germany, Switzerland, Belgium and Japan are either already using MOX fuel in LWRs or plan to do so within the next few years).

These options are complicated by the fact that there is already a large surplus of separated civilian Pu awaiting MOX fabrication and disposition, and it will be several years before this backlog can be worked off. (A large portion of that material happens to be nearly weapons-grade itself, resulting from the reprocessing of low-burnup fuel from gas-cooled reactors).

Nonetheless, the feasibility of certain scenarios should be carefully examined as possible further contributions *beyond* what happens in the U.S., Russia and Canada. I think these can be divided into two classes:

1. *Above and beyond existing Pu use plans*: It is conceivable that

third-country reactors could consume some W-Pu beyond existing civilian Pu utilization plans.

The main question is whether existing MOX fabrication capacity would be sufficient to accommodate such additional plutonium, or when it would be available, without building additional capacity just for this purpose.

Reprocessing capacity and MOX fabrication capacity are expected to reach equilibrium over the next decade or so. In the event that reprocessing contracts are cancelled, however, it is conceivable that, after the backlog of separated Pu is worked off, there could be surplus capacity at existing MOX fabrication plants.

Another way would be to use weapons - Pu ahead of already - separated civilian Pu to burn it sooner. But due to the problem of americium buildup in higher-burnup fuel, this could only practically be applied to low-burnup fuels that are nearly weapons-grade. Thus, the benefits would be minimal - mainly just symbolic.

One further scenario for increasing Pu consumption rates in these countries has been proposed by Professor Atsuyuki Suzuki, of the University of Tokyo, under which Japan's government - owned reactors Fugen (Advanced Thermal Reactor) and Monju (Fast Neutron Reactor) would alter their operation to achieve faster Pu depletion, permitting the consumption of up to 2 tons/year of W-Pu⁶.

A problem common to all of these "addition" options in that utilities right now appear to be increasingly disinterested in Pu fuel.

2. *Substitution for existing Pu use plans:* If W-Pu was sent to existing (or already-planned) MOX fabrication facilities *instead of* an equivalent amount of civilian Pu, reprocessing activities necessary to separate that amount of civilian Pu could therefore be deferred until it was no longer necessary to burn W-Pu. This would require complicated arrangements depending on:

- Political decisions by the U.K., France and others that accord enough importance to the disarmament benefits of weapons disposition in existing MOX programs to justify a disturbance to existing commercial fuel cycle service arrangements;
- Future evolution of utility contracts for reprocessing and MOX fabrication services;
- The schedule for reactor loading of already-separated civilian Pu; and
- The willingness of utilities to accept weapons-grade rather than reactor-grade MOX fuel.

Blending Option - There are limits to how long reactor-grade Pu can be stored following reprocessing, due to the building of Americium-241, if it is to be acceptable for MOX fabrication and recycle in reactors. This is especially true for Pu arising from more recent irradiations because of the higher burnup (higher burnup causes a lower grade of Pu including more Pu-241). W-Pu does not have this problem. Thus, a fifth possibility would be to mix W-Pu with separated civilian Pu to dilute the Am-241 problem.

Such blending would not allow as high a throughput rate as possible and is thus less than ideal from a disarmament point of view. But, on the other hand, as a *supplement* to the major disposition pathways, which will probably be in the U.S., Russia and possibly Canada, this could absorb some W-Pu. The question concerning this option is whether reprocessing could be slowed down to match the amount of W-Pu added to the stream. This would allow total inventory reduction; furthermore, the alternative - i.e., no change in the rate of reprocessing - would require more utility burning of Pu, which may be difficult to arrange.

Another blending idea I have heard is to use W-Pu to deal with second generation spent fuel (i.e., spent MOX), which has a still-lower grade (which is for the most part being stored for

the time being). In this case it is not an issue of Am-241, because the fuel is not yet reprocessed, but rather a question of 239 content - second generation MOX fuel would perform better if blended with high-grade W-Pu. However, to me this is not attractive because you might actually cause *more* separation of Pu (spent MOX fuel might not otherwise necessarily be reprocessed, or at least not yet, because there is a backlog of separated first-generation Pu to work off).

The table below summarizes the above - mentioned disposition scenarios in countries with existing MOX infrastructure.

Opposition to third country reactor disposition could be expected from two principal quarters:

1. *Reprocessors*: To the extent that third country disposition in countries already using MOX fuel would substitute for existing plans, it would defer planned reprocessing activities. Possibly these same companies would gain additional MOX fabrication contracts as a result of the disarmament effort, but this would only partially offset the loss of important export sales and the associated employment benefits in France and the U.K. (An analogy can be made to the disposition of highly-enriched uranium (HEU), which will potentially cause economic dislocations to the uranium industry). If substitution is to be at all feasible, it seems that some form of compensation might have to be offered to make up for each ton-year of deferred business, and this must be considered in estimating the costs of this disposition method.

However, we should also keep in mind, in the event these arrangements are too difficult, that W-Pu burning that is above and beyond existing Pu plans would also have disarmament benefits, equivalent to W-Pu disposition in the U.S., Russia or Canada.

Table 1
**Specific third country scenarios
in countries with existing mox infrastructure**

Additions

1. MOX fabrication capacity becomes available due to expiration and/or cancellation of reprocessing contracts
2. Put W-Pu ahead of burning already-separated low-burnup civilian MOX
3. Alter reactor operations to allow higher Pu depletion rates (esp. Fugen and Monju)

Substitution

4. Slow down reprocessing by same rate that W-Pu is introduced into existing MOX programs

Blending

5. Blend with already-separated high-burnup civilian Pu, diluting Am-241

2. *Opponents of Civilian Pu Utilization:* Some organizations that have opposed civilian Pu use also oppose the MOX option for disposition of W-Pu, whether it is in the U.S. and Russia or in third countries, out of concern that this would ultimately lead to greater separation and use of plutonium. However, it should be possible to structure international efforts towards Pu disposition such that we can have the best of both worlds: achieving reductions in the *total* global inventory of separated Pu, *and* sending the signal that this inventory *should remain* low and should be under international control. As discussed below, this requires an international framework that has the goal not only to improve controls over all separated Pu but also to gradually reduce inventories. This would necessarily imply establishing some controls over reprocessing rates - based on demand. W-Pu disposition policies should be announced with a

clear statement concerning the need to reduce *total* separated inventories, and to put remaining civilian and military inventories under greater international control.

Disarmament has increased the Pu glut, and to deal with the glut we must first of all increase the use and disposal of Pu, which is what U.S., Russian and Canadian disposition options would do. In addition, I think this is not just the responsibility of the U.S. and Russia, and other nations with existing MOX infrastructure who can contribute should do so. This also responds to the glut, either by increasing the use of Pu or by slowing the separation of additional Pu.

The National Academy of Sciences concluded in its 1994 report that “substituting excess weapons plutonium for reactor-grade plutonium in existing civilian plutonium fuel programs. Would be the quickest practical means of disposition for excess weapons plutonium *if* the complex international agreements required could be achieved.” The international arrangements that would be needed should be further examined to ascertain which specific scenarios, if any, could offer significant benefits in terms of accelerated disposition, and which therefore should be pursued.

Table 2
Summary of third country disposition

- Contributes to accelerated disposition
- Adds credibility and transparency to the disarmament process
- Could be above and beyond existing MOX use plans, or a substitution for existing MOX use plans
- Opposition from reprocessors and opponents of civilian Pu utilization

4. International Control

Consistent with these thoughts on managing the total supply and demand of Pu, we should establish a *process* ensuring that we do not accumulate excessive stocks of separated civilian Pu, and that the inventories that do exist are kept under international control.

Extensive groundwork has already been laid concerning international Pu storage. I would like to quickly summarize these ideas and then add my further thoughts on international controls over Pu stocks.

An international control system for all fissile material was clearly foreseen at the dawn of nuclear age, but has never been implemented. Based on a U.S. proposal, Article XII of the IAEA's statute, entitled "Agency Safeguards", specifies, among other things, the agency's right:

"to require deposit with the Agency of any excess special fissionable materials recovered or produced as a by-product over what is needed [for peaceful purposes under continuing Agency safeguards] "in order to prevent stock-piling of these materials, provided that thereafter at the request of the member or members concerned special fissionable materials so deposited with the Agency shall be returned promptly to the member or members concerned [for peaceful uses under Agency safeguards]."

The IAEA initiated a study in 1976 of ways to implement International Pu Storage to fulfill this provision, and experts from member states met from 1978 to 1982 to prepare further proposals for IPS schemes, but the concept has lain dormant.

New proposals in recent years concerning weapons material have included: 1) a call for physical protection by the host country and verification by the IAEA, and subsequent extension of this arrangement to civilian material (Scheinman and Fischer); 2) creation of an international Pu depository with an interna-

tional guard force, and a “banking” system in which payments would go to depositors and withdrawals for safeguarded peaceful use would require payment of a fee (Carter and Cote)⁸; and 3) establishing a storage regime first for U.S. and Russian civilian and military inventories, which international regime (NAS)⁹. The NAS also urged agreement on cooperative international approaches to managing the reprocessing and use of Pu to avoid building up excess stocks. This latter idea would more or less internationalize the commercial use of Pu.

A specific way to manage Pu on an international basis so as to avoid the buildup of excess stocks would be for a group of countries, probably the G7 plus Russia, to charter an organization with the specific but vital role of making *agreed determinations* and *arrangements* for Pu separation and disposition. Such organization could be very valuable with respect to arranging third country disposition options for W-Pu as outlined above. Furthermore, it would seek to maintain a demand-driven system for Pu use. Although the reprocessing industry in particular might not welcome such international controls, such controls would at the same time provide a framework for internationally-agreed further industrial use of the closed cycle, which could have benefits to the industry in the future.

5. Conclusion

The conversion of surplus fissile materials over which the governments of the United States and Russia have relinquished military control will have important benefits for all nations of the world. But only if we declare a large portion of our total defense inventories to be surplus to national security needs, and permanently and irreversibly disposition them, will we achieve disarmament benefits that are more than simply symbolic. We need SMART, to take advantage of current warm relations be-

Figure 1 **Suplus Plutonium Disposition Alternatives**

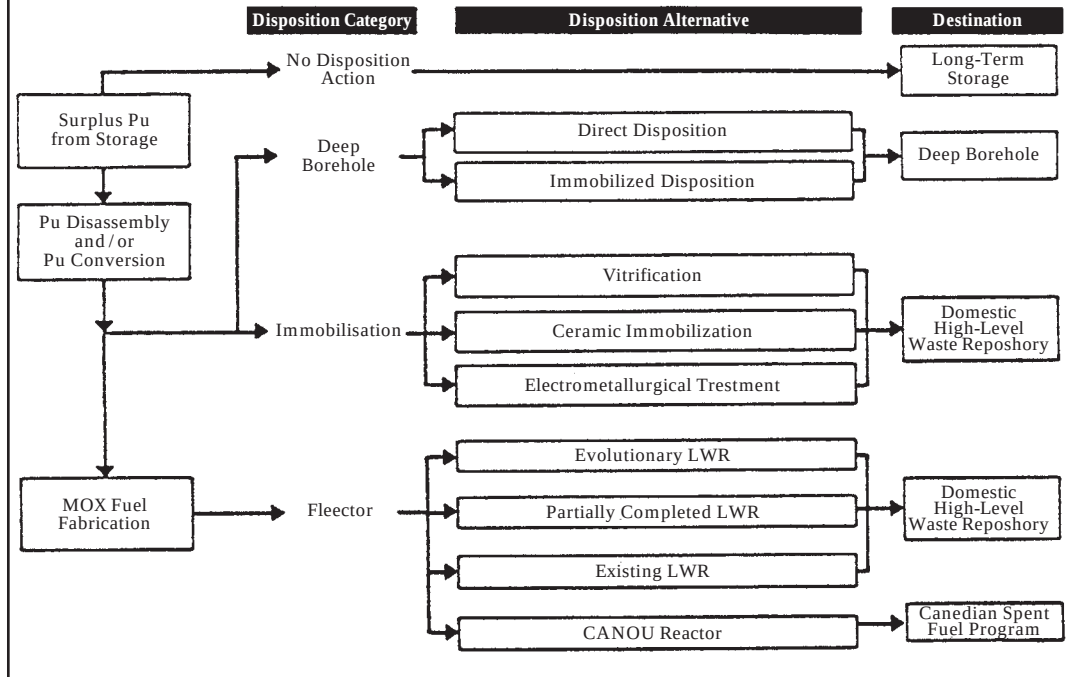


Figure 2
**Conceivable mox scenarios,
 domestic and third country**

Activity	Group I scenarios	Group II scenarios	Group III scenarios	Group IV scenarios
Origin	Russia	Russia	USA	USA
Fabrication	Russia	Belgium, France, Japan, U.K.	USA	Belgium, France, Japan, U.K.
Burning	Russia; All Third Co's ¹	All Third Co's	USA, Canada	USA; All Third Co's
SF Disposal ²	Russia; All Third Co's	Russia; All Third Co's	USA, Canada	USA; All Third Co's

tween the U.S. and Russia and get on the track to disarmament. We also need an aggressive implementation program including third country participation, which should make possible the disposition of at least 10 tons of W-Pu per year, and an international control system over all Pu supply and demand. These efforts will add great credibility and transparency to the nuclear disarmament process in the spirit of the Non-Proliferation Treaty, and possibly momentum toward the conclusion of both a Comprehensive Test Ban Treaty and a Fissile Material Production Cutoff Treaty.

NOTE

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SESSION 4

Socio-Economical Aspects: Cost of Pu Conversion and Fabrication of MOX Fuel

A Proposed Methodology for the Analysis and Selection of Alternatives for the Disposition of Surplus Plutonium

James S. Dyer, Thomas Edmunds, John C. Butler, Jianmin Jia

Abstract

The nuclear states are currently involved in the development of comprehensive approaches to the long-term storage and management of fissile materials. A major objective of this effort is to provide a framework for prevention of the proliferation of nuclear weapons. The evaluation should include non-proliferation, economic, technical, institutional, schedule, environmental, and health and safety issues.

The ANRCP has proposed that an evaluation of alternatives be guided by the principles of decision analysis, a logical and formal approach to the solution of complicated problems that are too complex to solve informally. This approach would consist of four steps:

- 1) identification of alternatives and objectives,
- 2) estimation of the performance of the alternatives with respect to the objectives,
- 3) development of values and weights for the objectives, and
- 4) evaluation of the alternatives and sensitivity analysis.

In order to facilitate the evaluation process, the ANRCP proposes the use of nine objectives grouped into the following categories:

- 1) Non-proliferation objectives (which includes resistance to theft and diversion by unauthorized parties, resistance to retrieval and reuse by the host nation, schedule, and fostering progress and cooperation with other nations and Russia)

- 2) Operational effectiveness (which includes cost, technical viability, and other benefits)
- 3) Environmental, safety, and health considerations

In order to evaluate alternatives on the basis of these objectives, they have been clarified through the definition of secondary objectives in some cases. Once the objectives were defined, the next step is to develop measures of performance associated with these objectives. Some of these measures of performance use natural scales, such as cost (dollars), time (months), and environmental impacts (cubic meters of secondary waste). Other measures require specially constructed verbal scales and the performance of each alternative is assessed based on expert judgment.

1. Background

The end of the Cold War and subsequent arms limitation and reduction agreements have led to a surplus of weapons-usable plutonium in the United States and Russia. In order to prevent the proliferation of nuclear weapons, steps must be taken to manage this plutonium in a manner which takes into account non-proliferation, economic, technical, institutional, schedule, environmental, and health and safety issues.

The purpose of this paper is to define a model and the methodology that could be used to support the selection of alternatives for the disposition of surplus plutonium. There are a number of methods that have been proposed to model preferences and support decisions, and each of them may be used constructively in some contexts. However, we believe that the significance of decisions regarding the disposition of plutonium requires the use of a methodology that can evaluate alternatives involving risk and multiple performance measures, and that is practical, theoretically sound, and transparent to external re-

viewers and interest groups. The one methodology that meets these requirements is multi-attribute utility theory (MAU), which has been supported for use in similar situations by the National Research Council, an agency of the United States National Academy of Sciences.¹

MAU (Keeney and Raiffa, 1976) is one of the major analytical tools associated with the field of decision analysis (Clemen, 1991; Holloway, 1979; McNamee and Celona, 1990; Raiffa, 1968; von Winterfeldt and Edwards, 1986). Simply, decision analysis is a logical and formal approach to the solution of problems that are too complex to solve informally. In the past, decision analysis has been applied to problems such as siting electricity generation facilities (Keeney, 1980), choosing among vendors for the evaluation of alternatives for the commercial generation of electricity by nuclear fusion (Dyer and Lorber, 1982), and selecting a nuclear waste clean up strategy (Keeney and von Winterfeldt, 1994).

The MAU methodology for the evaluation of alternatives for the disposition of plutonium consists of the following steps:

1. Identification of alternatives and objectives
2. Estimation of the performance of the alternatives with respect to the objectives
3. Development of values and weights for the objectives
4. Evaluation of the alternatives and sensitivity analysis

As a first step, reasonable alternatives for the disposition of plutonium must be identified along with the objectives that are used in the analysis. The alternatives and the objectives form a matrix in which each row corresponds to an alternative and each column represents an objective. The cells of the matrix contain estimates of the performance of each alternative on each of the objectives. When these estimates are uncertain, it is often

1 National Research Council, letter to Ben Rusche, DOE/OCRWM, dated October 10, 1985.

appropriate to quantify them with ranges or with probability distributions determined using risk analysis methods (e.g., Clemen, 1991; Keeney and von Winterfeldt, 1991).

Typically, it is possible to gain a number of insights regarding the alternatives simply through a careful inspection of this matrix. For example, one or more alternatives may be “dominated” by another alternative, meaning that the dominating alternative performs as well or better on every objective than the dominated alternative. Alternatives that are dominated can often be eliminated from further consideration in the decision process, which may significantly simplify the remaining steps in the analysis.

Step three creates a value model based on the objectives by defining value functions, if necessary, on the measures of the performance of the alternatives, and by assigning weights to the objectives. This process is carried out with decision makers or their designated representatives, and allows the measures of performance on each objective to be aggregated into a single figure of merit. Finally, this value model can be used to determine a ranking of each of the alternatives, and a sensitivity analysis is typically conducted to determine if this ranking is robust relative to reasonable changes in the weights or the other parameters that determine the value model. This sensitivity analysis may include changes in the value model that are suggested by interactions with representatives of other interest groups or stakeholders.

This process should summarize the critical information needed for an evaluation of alternatives, and provide the insights that both support and explain the basis for this evaluation. However, it is important to emphasize that the decision analysis process does not lead to a computerized model that actually determines the decision for a complex problem. Rather, this process highlights the strengths and weaknesses of alternatives, the implications of tradeoffs among these strengths and

weaknesses, and the sensitivity of the evaluation to the underlying assumptions so that better informed choices can be made.

Any model of a physical process or of subjective preferences will omit some details in the abstraction from the real-world in order to crystallize the essence of the problem. Some of these omitted details may be relevant in the final selection of alternatives by a decision maker or decision makers, particularly when the alternatives are determined to be “very close” in the formal analysis. Further, the appropriate value model for use as a guide to public policy is, in general, not sharply defined. As a result, the decision analysis process will emphasize the support of the decision makers charged with the responsibility for the selection of alternatives, and will attempt to clarify the consequences of each choice. We subscribe to the philosophy that the result of using models should be insights, not numbers.

Sections 2-5 of this report will describe these four steps of the MAU methodology in more detail. Section 6 will summarize the discussion.

2. Identification of Alternatives and Objectives

2.1 Alternatives

The evaluation process begins with the identification of the set of reasonable alternatives that are appropriate for serious consideration. This screening process may be aided by reference to a set of criteria that identify the most important considerations guiding this preliminary selection process. Examples of the use of screening processes to determine reasonable alternatives for the disposition of surplus plutonium are provided by the studies conducted by the National Academy of Sciences (1994) and by Office of Fissile Materials Disposition of the United States Department of Energy (OFMD, 1995).

The reasonable alternatives for plutonium disposition deter-

mined in these studies fall into three categories: reactor alternatives, immobilization alternatives, and borehole alternatives. The reactor alternatives would use surplus plutonium to fabricate mixed oxide (MOX) fuel for nuclear reactors that generate electrical power. The spent fuel from these reactors would ultimately be transferred to a national waste management system for ultimate disposition. The immobilization alternatives combine the surplus plutonium materials in borosilicate glass or ceramics; additional radionuclides may be added to provide a radiation barrier to inhibit recovery and reuse. This material would also be transferred to a national waste management system for ultimate disposition. The borehole alternatives involve the placement of the plutonium in a deep borehole, possibly after the material is immobilized in an inert matrix.

Other alternatives may eventually be considered by the United States and Russia. However, the general methodology for the evaluation of these alternatives should be flexible enough to evaluate and compare any reasonable approach to the disposition of the surplus plutonium.

2.2 Objectives and Measures

The first step in the application of MAU is the development of a “hierarchy” of objectives, criteria, and measures. Objectives are often broad statements of goals. Typically two or more criteria are associated with objectives at the next level of the hierarchy to provide more specific statements of desirable characteristics of alternatives, and to help define the objectives in more detail. In complex decision problems, these criteria may be decomposed further into sub-criteria, and so on, until a sufficient level of detail is reached to allow measures to be identified.

In some cases, these measures may be quantified as estimates on a natural scale, for example, net present value of cost, time, travel miles, etc. In other cases, it may be necessary to construct scales that are more descriptive in nature, and that may

require estimates for the alternatives based on expert judgment. In many cases, these measures are surrogates for higher-level issues.

Useful reference points for the identification of measures for evaluating plutonium disposition alternatives include measures proposed for previous studies involving technology choices (e.g., Keeney, Lathrop, and Sicherman, 1986; Keeney and von Winterfeldt, 1994; Merkhofer and Keeney, 1987), for previous studies concerned with the management and disposition of surplus plutonium (National Academy of Sciences, 1994), and for evaluations of technologies and sites for tritium supply and recycling.

Objectives. The objectives for any decision provide the basis for evaluating the relative desirability of available alternatives. For the purpose of illustrating the methodology, we present the objectives recommended by the National Academy of Sciences (1994) and used by the Office of Fissile Materials Disposition (OFMD, 1995) for the purpose of a preliminary screening. The objectives used by the OFMD for screening the alternatives for the disposition of plutonium were the following:

1. Resistance to theft and diversion by unauthorized parties
2. Resistance to retrieval, extraction, and reuse by the host nation
3. Technical viability
4. Environmental, safety, and health
5. Cost effectiveness
6. Timeliness
7. Fostering progress and cooperation with Russia and other nations
8. Public and institutional acceptance
9. Additional benefits

For this illustration of the methodology, these nine objectives have been reorganized to emphasize the commonality among some of them, and to provide additional detail regard-

ing others. This reorganization is shown in the form of a hierarchy of objectives in Figure 1.

At the highest level of this hierarchy, we have identified three major categories of objectives:

1. Non-proliferation which includes resistance to theft, resistance to reuse, international cooperation, and timeliness (objectives 1, 2, 6 and 7 from the original list of nine)
2. Operational effectiveness which includes and cost effectiveness (objectives 1 and 5 from the original list of nine)
3. Environmental, safety, and health (objective 4 from the original list of nine) which has been decomposed into human health and safety, environmental protection, and socio-economic effects at the next level in the hierarchy

Such a reorganization of the nine objectives would simplify the task of creating a value model, and particularly the assessments of weights on the objectives, as we discuss in Section 4. In addition, this simplified structure would provide a natural means for transferring the insights from the model to the decision maker.

It should also be noted that objectives 3, 8 and 9 from the original list, technical viability, public and institutional acceptance, and additional benefits, have been dropped from the proposed hierarchy. Technical viability refers to the level of technological development associated with the alternative, and is essentially a surrogate for the risk of possible delays and cost overruns. These concerns can be captured in an evaluation through the use of probability distributions on measures of time and cost, if necessary.

Public and institutional acceptance is a major concern in any screening process, and the basis for the elimination of many of the alternatives that may originally be considered. However, the other objectives that have been selected for this illustration are based on meeting public concerns. Therefore, we believe that an alternative selected based on the other eight objectives

will be one that would also be ranked highly on the objective of public acceptability. In addition, the economic impacts of the alternatives on local communities have been included in the proposed measures of the Environmental, Safety, and Health objective, as we shall discuss.

Also, we have deleted the objective of “additional benefits” from this hierarchy. Some of the alternatives may offer the possibility of producing useful by-products, such as the production of electric power by nuclear reactors or the possibility of sharing costs with other programs. However, the most significant examples of these “other benefits” can be captured as offsetting costs, and will be effectively measured by the cost effectiveness objective.

As previously mentioned, Figure 1 represents the highest level of the objectives for selecting a plutonium disposition alternative. Figures 1a, 1b and 1c provide the details for the three main objectives of the analysis: Non-proliferation, Operational Effectiveness and Environment, Health and Safety respectively.

Two comments are in order regarding Figures 1, 1a, 1b and 1c. First, the major purpose of these diagrams, particularly Figure 1, is to assist the decision makers in “making sense” of an evaluation of alternatives based on thirty eight detailed performance measures. The reorganization of the objectives as shown in this hierarchy is neither unique nor fixed. It could be altered based on feedback from those involved in determining policy toward plutonium disposition. Second, the fact that one objective or sub-objective appears at a “lower level” in the hierarchy than another does not imply that it is less important, or that it should receive a smaller “weight” in the analysis than another objective.

The objectives categorized as providing assurance against non-proliferation (Figures 1 and 1a) indicate five distinctly different areas of concern. The first objective is to minimize the opportunities for theft of the materials by unauthorized parties.

Generally, an alternative will be more resistant to theft during the processing steps required to transform the material from weapons-usable plutonium into its final form for permanent disposition if these steps are relatively simple and transparent, if the form of the material is not “attractive” to potential thieves because of size, radioactivity, or other concerns, and if effective safeguards and security can be applied.

The second objective is to maximize the resistance of the disposition alternative to the diversion of the plutonium by the host nation during processing, and to provide an internationally verifiable and acceptable process. Providing adequate accessibility safeguards, and measurement capability will allow an alternative to satisfy international inspection standards and provide assurance that diversion by the host nation is not taking place. Many of the factors considered in the theft subobjective can also apply here.

The third objective is to maximize the difficulty of recovering the disposed material after processing has been completed. The disposed material will be less attractive for reuse by the host nation if it meets the “spent fuel standard”, or would be as costly, detectable, and time consuming to retrieve and fabricate into weapons as the recovery of plutonium from spent commercial reactor fuel. The final form and location of the disposed material will determine its long-term resistance to reuse.

The fourth non-proliferation objective is concerned with fostering international cooperation with the disarmament and nuclear non-proliferation goals. This objective may be related to international relationships, and to issues concerning the civil use of plutonium.

The fifth objective, timeliness, is based on an estimate of the time required for the disposition effort to begin, and on the time required for the completion of the effort once it has begun. These time estimates may be highly uncertain for some of the

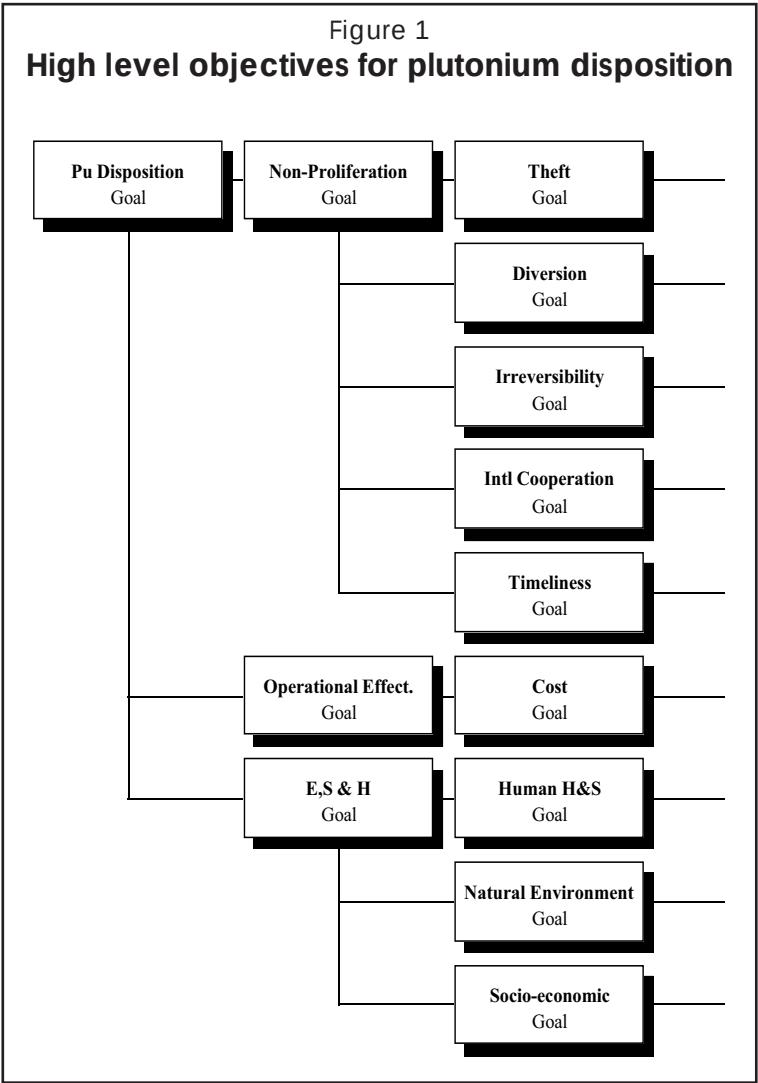
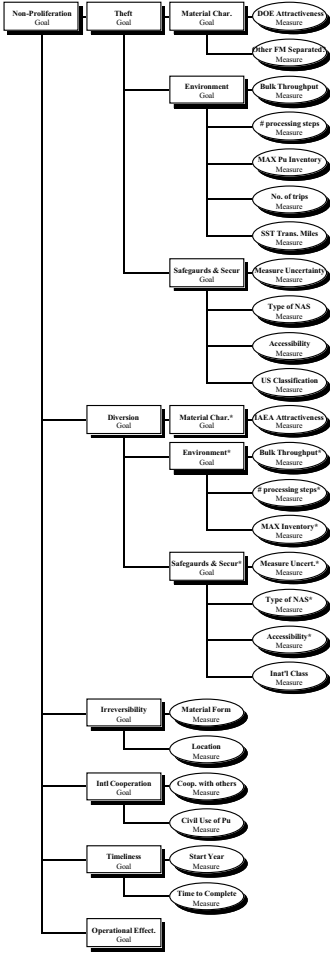


Figure 1a
Detail for non-proliferation objective



alternatives, and can be represented as probability distributions when necessary. The assessment of the uncertainty associated with the time to begin an alternative's disposition process may be influenced by its technical maturity and by its regulatory history. Timeliness influences both international cooperation and the "window of vulnerability" of the material.

An alternative will be considered operationally effective (Figures 1 and 1b) if it has low cost. The cost may consider both life-cycle costs and the initial investment costs, and estimates of both may be uncertain. If so, these estimates should be represented by probability distributions. Revenues resulting from by-products such as electric power may offset some of the costs. The potential for cost sharing with other related projects may also be considered to offset costs.

The objective of protecting the environment, safety, and health has three sub-objectives. The first is minimizing human health and safety risks, which requires minimizing risks to the public from normal operations, minimizing risks to workers from normal operations, and minimizing risks to both from accidents that could result from operations or inter-site transportation activities.

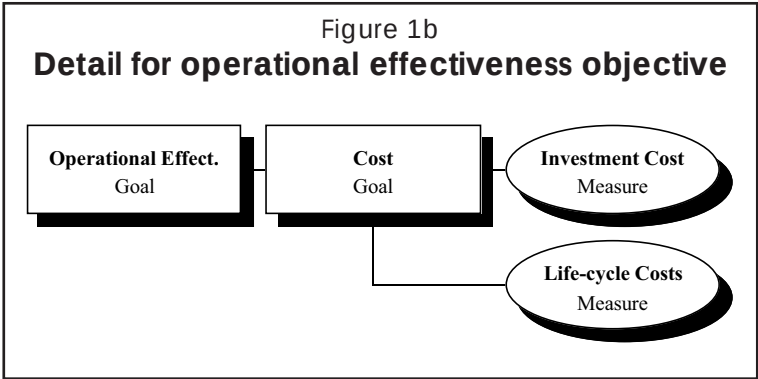
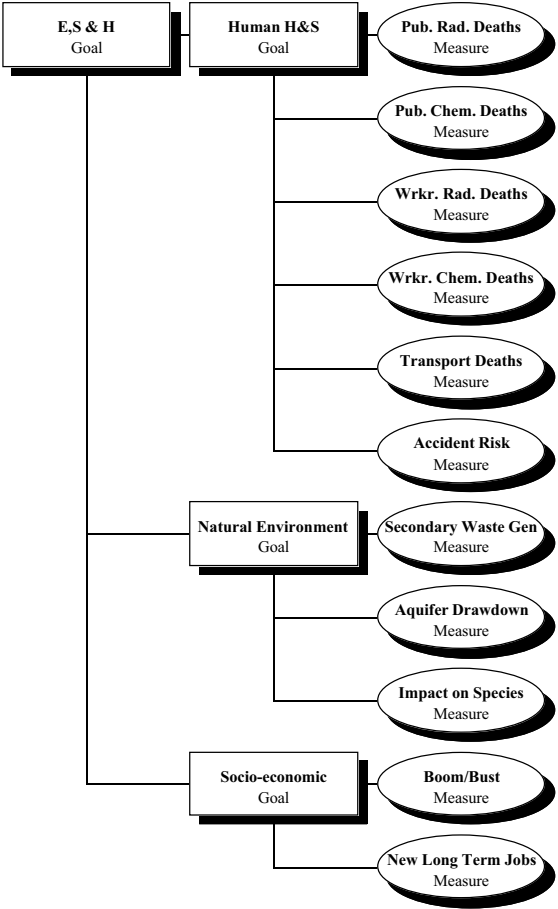


Figure 1c
Detail for environmental safety and health objective



The second sub-objective is maximizing environmental protection. This objective requires the minimization of direct impacts on animal species, the minimization of impacts on local water supply, and the minimization of secondary wastes.

The third sub-objective is related to the socio-economic impacts of the alternatives. The short-term socio-economic disruptions by the alternatives should be minimized, while any long-term economic and social benefits should be maximized. These socio-economic impacts also relate to the screening objective of encouraging public acceptance of the alternative, particularly in the local communities that would be affected by construction and operation.

Measures. In order to evaluate the alternatives, a measure or a set of measures is needed for each of the objectives, as shown in Figures 1a, 1b and 1c. These measures should be selected so that each alternative can be evaluated on each of them, and so that each measure is then logically linked to one or more of the objectives.

The measure or set of measures associated with an objective should cover all aspects of the objective. In some cases the selection of an appropriate measure may be clear. For example, it is customary to measure the life-cycle cost of an alternative in terms of discounted net present value dollars. Similarly, concerns regarding the timeliness of the disposition activities associated with an alternative may be captured by measures of the “time to start the disposition activities” and the “time to complete the disposition activities”. However, when no relevant and/or natural scales are closely linked to an objective, such as maximizing the likelihood of international cooperation, it may be necessary to work with experts to construct a measure to indicate different levels of achievement.

3. Estimation of the Performance of the Alternatives on the Objectives

Given the identification of the alternatives and the definitions of the measures, the next step is to obtain estimates of the performance of each alternative on each measure. This step defines the alternative-by-objective (and measure) matrix that summarizes the overall performance of each alternative on the relevant measures. An example of such a matrix is provided in Figure 3, where performances of three hypothetical alternatives are evaluated on five measures used for illustration purposes only. The entries in the cells in this matrix may be in the form of point estimates, ranges, or in the form of probability distributions. For example, a probability distribution might be represented by a simple three point distribution of the form (0.05 fractile, median, 0.95 fractile), that reflects the uncertainty associated with the estimates of performance. Probability distributions are included for the life cycle and investment costs of an alternative in Figure 2.

A careful inspection of this simple matrix may provide some rich insights regarding the alternatives. For example, one or more alternatives may be identified as clearly inferior because

Figure 2

Example of alternatives by objectives matrix

	MEASURES				
	Life Cycle Costs (\$B)	Investment Cost (\$B) Fatalities	Expected Worker (# species)	Impacts on Species (yr.)	Completion Time
Alternative A	(1, 2, 5)	(2, 2.5, 3)	.001	1	2010
Alternative B	(2, 4, 10)	(2, 3, 5)	.002	0	2025
Alternative C	(-1, 0, 5)	(2, 3, 5)	.001	3	2025

of their poor performance on most if not all of the relevant objectives. Others may obviously “rise to the top” because of superior performance on many of the objectives.

In order to obtain the performance estimates with respect to these measures, a series of assessment meetings may be necessary to focus on the major objectives. For example, experts in the area of safeguards and security (S&S) may be asked to evaluate the performance of the alternatives on the non-proliferation objectives. Other teams may be involved to develop estimates of cost and time, while still other groups may focus on the analysis necessary to develop the measures of environment and health impacts.

4. Development of Value Functions and Weights

Once the performance of each alternative on each measure in the alternatives-by-objectives matrix has been obtained, the next step in the analysis involves assembling the measures into a “super-measure” of the desirability of each alternative. The aggregation procedure is complicated by the diversity of the types and scales of the individual measures. As evident in Figure 2, some measures may be represented by probability distributions while some are expressed as point estimates. Some measures units are dollars and some are cubic meters of secondary waste, while others are defined over constructed scales, further complicating the aggregation procedure.

Utility theory provides the basis for the appropriate approach to aggregate the seemingly disparate measures. It is a logically consistent and tractable means of representing the degree to which each alternative fulfills the objectives shown in Figure 1. The use of utility theory ensures that any recommendation reflects:

- the relative attractiveness of a specific level on a measure

- the relative attractiveness of performance on different measures and objectives
- the interactions, if any, between objectives.

These three issues will be addressed in the following sections. For a more detailed presentation of these topics see Keeney and Raiffa (1976) and von Winterfeldt and Edwards (1986).

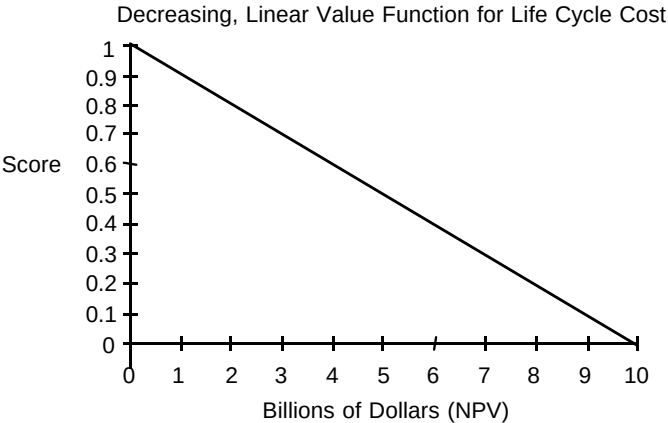
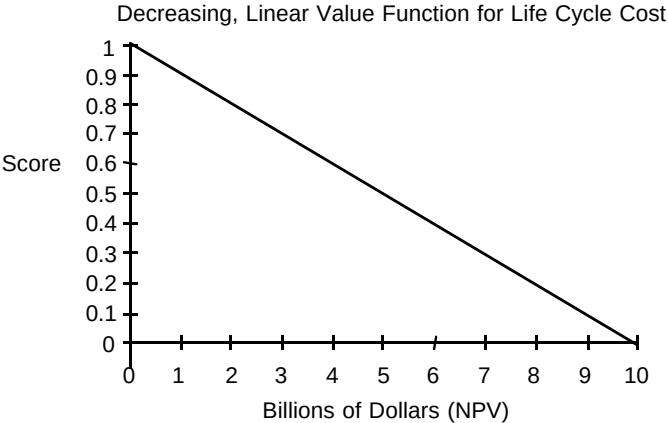
4.1 Single Attribute Value Functions

The relative attractiveness of performance outcomes on a measure is captured by a single attribute value function. A value function is constructed or assessed so that it incorporates a decision maker's preferences for performance on a measure in a utility value or score; a superior objective measure will score higher on the value scale. Value functions can be linear or non-linear as dictated by both normative concerns and the nature of the decision maker's preferences. Once constructed, value functions can be combined with probability distributions to ensure that the risk associated with an alternative is properly evaluated.

Figure 3 illustrates two *hypothetical* value functions. It is particularly important to emphasize that these value functions are used here only for the sake of exposition. The first value function represents the value associated with different levels of the Life Cycle Cost of an alternative. The function is decreasing because lower cost is preferred to higher cost; hence, lower costs receive higher value scores. The function is linear because the range of dollar amounts being considered may be small in comparison to the national budget, so the marginal value of each incremental dollar over this range is assumed to be equal.

The second value function representing "Type of Nuclear Accounting System" (defined per facility as the percentage of time in the facility that "item" accounting is used) is a bit more complicated. Intuitively, the ideal facility would utilize 100%

Figure 3
Two example value functions



item accounting and receive the highest value. Due to the comparative ease of measuring material that is classified as item, even a small decrease from 100% item accounting receives a stiff penalty. Looking at the scores for facilities that use very little item accounting (these facilities rely heavily on “bulk” accounting), it is also clear that moving from 0% item to 10% does not receive a substantial increase in score relative to moving from 90% to 100%. The scale for Type of Nuclear Accounting System is “exponentially biased toward item accounting”.

4.2 Weights

Each objective, sub-objective, and measure in the attribute hierarchy is given a weight. These weights reflect the value tradeoffs among objectives (or sub-objectives and measures within objectives), and are dependent on the ranges of the outcomes considered in the analysis.

As a simple example, consider the problem of choosing among disposition alternatives based on the objectives of cost, ES&H, and non-proliferation. Suppose that three alternatives are under consideration with costs of \$2.2, \$2.4, and \$2.5 billion, respectively, and with representative values on the other two objectives. Now, suppose that a fourth alternative is added to the list with a cost of \$3.0 billion, and with values on the other two measures that lie *within* the ranges of values determined by the original three alternatives. Utility theory prescribes that the weight on cost in choosing among the original three alternatives (where costs range from \$2.2 to \$2.5 billion) should be *smaller* than the weight on cost in choosing among the four alternatives (where costs range from \$2.2 to \$3.0 billion). Intuitively, this is because a wider range of costs is considered in choosing among the four alternatives; i.e., cost is more of a discriminating factor in choosing among the four alternatives than in choosing among the original three.

As a result of this insight, it should be clear that weights on

objectives are not simply measures of the “relative importance” of each objective. Loosely speaking, they are measures of the importance of the *increase* from the worst to the best level of performance on one objective compared to the *increase* from the worst to the best level of performance on another objective. Therefore, weights must be assessed carefully to ensure that the results of the evaluation are consistent with the preferences of the decision maker or decision makers.

This assessment procedure can be based on a dialogue with a decision maker (or a group of stakeholders) that can take the following form. First, we assume that we have specified the ranges over which the performances of the alternatives can vary on each objective; that is, we have identified the “worst” and “best” feasible levels of performance on each objective. Next, we assume that an alternative achieves only the worst levels of performance on each of two objectives, say objective A and objective B. Holding its levels of performance constant on all of the other objectives, we ask the decision maker if it would be appropriate to pay more to increase the performance of this alternative from the worst to the best level on objective A, or to increase its performance from the worst to the best level on objective B?

Suppose that the decision maker responds, “I would pay more to increase objective A from its worst to its best level of performance.” Next, we would ask her to identify a level of performance on objective A so that she believes it would be appropriate to pay the same amount to increase objective A from its worst level to this level of performance as to increase objective B from its worst to its best level of performance. The response to this question determines the ratio of the weights on objectives A and B, and additional questions comparing the other objectives provide sufficient information to specify the numerical values of these weights.

In some cases, it may appear that responses to questions of

this type would be extremely difficult to make. However, the assessment process can be aided by the skills of a trained analyst, and a variety of “consistency checks” can be used to ensure that the responses are meaningful. These assessment protocols are also scripted to minimize biases in the responses, systematic errors that are known to occur as a result of the limitations of human information processing capabilities. For additional details and examples of assessment dialogues, see Keeney and Raiffa (1976) or von Winterfeldt and Edwards (1986).

Weights can be used to combine objectives and measures at different levels of the hierarchy, and the individuals who provide the judgments required to develop these weights may be different, depending on the level. For example, the judgments required to combine the measures for the sub-objectives “minimize number of processing steps” and “minimize attractiveness of material” for the objective Maximize Resistance to Theft may be more appropriately obtained from S&S experts who help evaluate alternatives as described in Section 3.

At the highest level of the hierarchy of objectives, the weights are less related to expert judgment, and much more to questions of policy. These higher level weights should be obtained in interviews with persons representing national policy makers.

4.3 Aggregation Methods

In order to obtain an overall evaluation for each disposition alternative on a higher level objective, we may use an aggregation model that can combine different measures into a single value. The model also must show the results of “sub-aggregation” at lower levels of the objectives hierarchy so that decision makers can better compare the attractiveness of alternatives. Since the decision for plutonium disposition involves both multiple criteria and risk, it is appropriate to use multi-attribute utility models for this study (Keeney and Raiffa, 1976).

If stakeholder preferences are consistent with some special independence conditions, then a multi-attribute utility model $u(x_1, x_2, \dots, x_n)$, where x_i represents the level of performance on measure i , can be decomposed into an additive, multiplicative, or other well-structured form that simplifies assessment. An additive multi-attribute utility model can be represented as follows:

$$(1) \quad u(x_1, x_2, \dots, x_n) = \sum_{i=1}^n w_i u_i(x_i)$$

where $u_i(\cdot)$ is a single-attribute value function over measure i that is scaled from 0 to 1, w_i is the weight for measure i and

$$\sum_{i=1}^n w_i = 1$$

If the decision maker's preference structure is not consistent with the additive model (1), then the following multiplicative model may be used, which is based on a weaker independence condition:

$$(2) \quad 1 + ku(x_1, x_2, \dots, x_n) = \prod_{i=1}^n [1 + k k_i u_i(x_i)]$$

where $u_i(\cdot)$ is also a single-attribute value function scaled from 0 to 1, the k_i 's are positive scaling constants satisfying $0 \leq k_i \leq 1$, and k is an additional scaling constant that characterizes the interaction effect of different measures on preference. The value of k can be determined from one additional question similar to the questions used to determine the objective weights. As a special case when

$$\sum_{i=1}^n k_i = 1$$

the multiplicative model (2) reduces to the additive model (1).

The choice of the appropriate model for aggregation will be based on information collected from interviews with policy makers. For approaches to the assessment of an additive utility model and a multiplicative utility model, see Keeney and Raiffa (1976).

5. Evaluation of the Alternatives and Sensitivity Analysis

5.1 Evaluation and Ranking

Once the single measure value functions have been completely defined, the data from the alternatives-by-objectives matrix (see Figure 2) are converted to component utilities. For measures that are known with a high degree of certainty, this process amounts to supplying the measure as an argument to the value function to obtain a score for each alternative on each measure. If a measure has been defined with a probability distribution, the appropriate value function is applied to the distribution to provide an expected utility value for the measure.

The component value function scores are aggregated, using the correct multi-attribute utility function, within each of the major objectives, and within each of the categories of objectives identified by the decision maker as illustrated in Figure 1. During this aggregation, the weights are used to reflect the trade-offs between measures, and are multiplied by the corresponding scores. This stage of the evaluation process is important and

Figure 4
Example of phase I aggregation

	MAJOR CATEGORIES		
	Non Proliferation	Operational Effectiveness	Environmental Safety and Health
Alternative A	0.7	0.3	0.7
Alternative B	0.5	0.8	0.1
Alternative C	0.4	0.4	0.4

Note: Scores are from 0 (least preferred) to 1 (most preferred). Scores are purely hypothetical.

useful for decision makers as it provides scores for each alternative for the major objectives of the plutonium disposition problem, and on the three categories of objectives identified in Figure 1. At this stage it is possible to examine the relative strengths and weaknesses of the alternatives. A hypothetical example of the results of this phase of the analysis is provided in Figure 4.

It is often possible to obtain important insights from an inspection of this table of scores. In addition to highlighting the relative strengths of the alternatives on the major objectives or the objective categories, alternatives that are dominated may also be identified. For example, these hypothetical scores indicate that Alternative A dominates the No Action alternative since its scores are as good or better on every major category. Note that this table could be created at a "lower level" in the hierarchy as well, highlighting the nine objectives used in the screening process. Comparisons among objectives and sub-objectives at different levels in the hierarchy may also be used to provide additional insights.

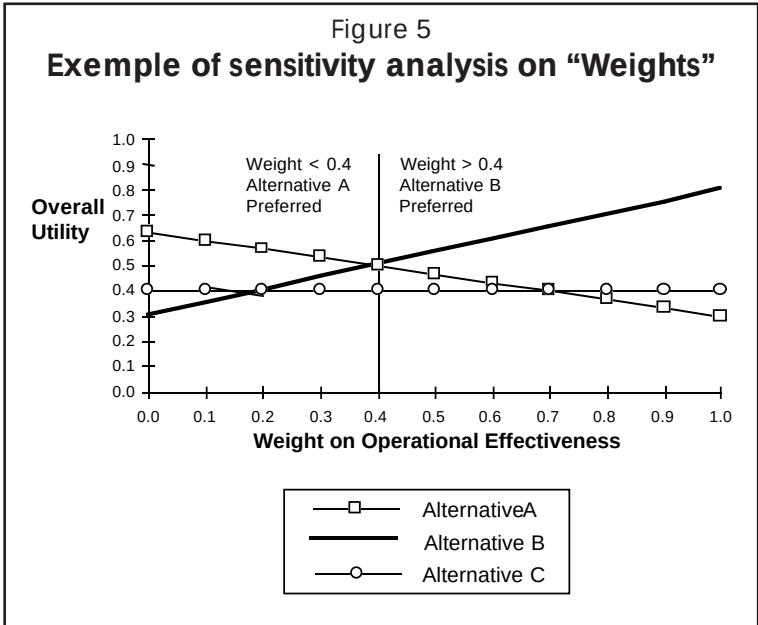
Weights may be assessed to represent tradeoffs between the major objectives. This will allow another level of aggregation to provide a measure of the overall utility of each alternative. This step will allow for quick comparisons regarding the relative desirability of the alternatives, and should provide an excellent means of ranking the field of contending disposition alternatives.

5.2 Sensitivity Analysis

Before final disposition recommendations are made, the analysis must be tested to see if the evaluation of alternatives is robust. This sensitivity analysis basically amounts to making changes in the performance on the measures and/or weights and observing changes in the resulting evaluations and rankings.

It is impossible to predict exactly what sensitivity analyses would be performed as the evaluation process is problem specific and iterative. The following types of analyses have been useful when examining similar problems:

- Change the weight of an important objective while leaving the ratios between weights on other objectives unchanged. This will highlight the effect of changing the emphasis placed on an objective.
- Investigate specific entries in the alternatives-by-objectives matrix (over a reasonable range). In cases where ranges of values or probability distributions are provided as estimates, values other than the mean (average) may be selected for the sensitivity analyses (e.g. the 10th and/or 90th percentile lev-



- els). This process helps test the robustness of the ranking to the assumptions and facts that form the basis of the analysis.
- Manipulate the measures and/or probability distributions to reflect specific viewpoints. For example, it may be appropriate to investigate the implications of an optimistic perspective about the life cycle costs of an alternative. This analysis will demonstrate the effect of different perspectives about the alternatives.

Any sensitivity analyses performed will be summarized in several formats. Numerical results are presented and, where appropriate, graphical representations are also provided. These results should also be explained intuitively to ensure that all participants understand the implications and are able to contribute to discussions.

Figure 5 provides an example of the first type of sensitivity analysis based on the hypothetical scores in Figure 4. The weight placed on Operational Effectiveness is varied from 0 to 1 holding the ratio of all other weights unchanged. This analysis indicates that if the weight on Operational Effectiveness is less than 0.4 (holding the ratios of other weights constant), then Alternative A will be preferred; if it is greater than 0.4, then Alternative B is preferred. Similar analyses could be performed on all other objectives and sub-objectives.

6. Summary and Conclusions

This presentation presents a proposed methodology for the analysis and selection of alternatives for the disposition of surplus plutonium. The approach is intended to be general, and could easily be modified to address specific issues and concerns unique to a country or a stakeholder group.

This approach to the evaluation of alternatives has several advantages over the presentation of a great deal of technical in-

formation in the form of discussion and tables, and then a verbal argument regarding the selection of the preferred alternative. First, the approach brings some order and structure to the evaluation process. It helps to focus the different teams of personnel who are responsible for generating information regarding one or more aspects of the complex alternatives required for plutonium disposition. Second, it provides a "scorecard" that can be used by policy makers and stakeholders to understand, relatively easily, the strengths and weaknesses of the various alternatives. Third, the evaluation and sensitivity analysis can easily reduce the set of "reasonable alternatives" to a smaller subset that may be viable candidates for the final choice, depending on the implied "weights" that are assigned to the objectives.

The selection of alternatives for the disposition of plutonium is a critical issue that requires simultaneous consideration of many conflicting objectives. We believe that this approach can help countries to make these decisions in a logical and informed manner, and to communicate with each other more effectively regarding the rationale behind these choices.

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Economic Assumptions for Evaluating Reactor-Related Options for Managing Plutonium*

Geoffrey Rothwell

Abstract

This paper discusses the economic assumptions in the U.S. National Academy of Sciences' report, *Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options* (1995). It reviews the Net Present Value approach for discounting and comparing the costs and benefits of reactor-related options. It argues that because risks associated with the returns to plutonium management are unlikely to be constant over time, it is preferable to use a real risk-free rate to discount cash flows and explicitly describe the probability distributions for costs and benefits, allowing decision makers to determine the risk premium of each option. As a baseline for comparison, it assumes that one economic benefit of changing the current plutonium management system is a reduction in on-going Surveillance and Maintenance (S&M) costs. This reduction in the present value of S&M costs can be compared with the discounted costs of each option. These costs include direct construction costs, indirect costs, operating costs minus revenues, and decontamination and decommissioning expenses. The paper also discusses how to conduct an uncertainty

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analysis. It finishes by summarizing conclusions and recommendations and discusses how these recommendations might apply to the evaluation of Russian plutonium management options.

1. The Net Present Value of Reactor-Related Options for Plutonium Management

Since the end of the Cold War and the start of decommissioning nuclear weapons by the U.S. and Russia, a problem has presented itself: What should be done with the weapons-grade nuclear materials?

There are two materials to consider: highly enriched uranium (HEU) and weapons-grade plutonium (WPU). Because HEU can be blended down to concentrations appropriate for nuclear power plant fuel, attention has focused on WPU. In the U.S. several organizations have addressed the issue of excess WPU, including the National Academy of Sciences' Committee on International Security and Arms Control.¹ This Committee produced *Management and Disposition of Excess Weapons Plutonium* (see NAS, 1994). Also, the Committee's Panel on Reactor-Related Options for the Disposition of Excess Weapons Plutonium wrote *Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options* (NAS, 1995).

My paper discusses many of the economic assumptions in NAS (1995) for evaluating reactor-related plutonium management options. On the value of economic analysis for this problem, see NAS (1995, p. 280): economic considerations are less important than security in reaching a conclusion about the relative attractiveness of alternative options for WPU disposition. But the study of costs is nonetheless worthwhile, both to assist in ranking options that are not distinguishable on security grounds and to facilitate planning for the investments that will be required for one option or another.

To facilitate an economic analysis, my purpose is to provide a unified method, based on the current economics and finance literature, to guide future evaluations of reactor-related options. Because I will not discuss all economic assumptions in NAS (1995), this paper should be read as an addendum to that report.

To aid nuclear-weapons states in determining how to efficiently manage plutonium, economists would suggest that decision makers use the Net Present Value (NPV) method of economic decision making.² Under this method all costs and benefits (real and monetary) are discounted to the present.³ I discuss the discounting procedure in Section 2.

The uncertainties associated with reactor-related economics complicate the NPV calculations. At least three options are available. First, contingencies (usually in percentage terms) can be assigned to cash flows. Second, the discount rate can be adjusted to reflect project risk. However, determining the appropriate adjustment requires strong assumptions. Third, an uncertainty analysis can be performed to approximate the probability distribution associated with the NPV of each option. The decision maker can then calculate the risk premium associated with each probability distribution. I argue in Section 3 that the third option is most consistent with an economics approach to decision making under uncertainty.

Although the primary *social* benefit to careful plutonium management is a reduction in the risk of proliferation, this is difficult to quantify.⁴ As a starting point, one quantifiable *economic* benefit of a proliferation-resistant plutonium management system is the reduction in on-going Surveillance and Maintenance costs. I discuss this baseline benefit in Section 4. I discuss discounted costs in Sections 5 through 8. Section 9 lists my conclusions and recommendations and discusses their applicability to Russian plutonium management. I conclude by reviewing the limitations of NPV analysis. I begin by discussing the discount rate.

2. The Appropriate Discount Rate is the Real Risk-Free Rate

A difficult parameter to determine in any economic analysis is the appropriate discount rate. Under the NPV method all cash flows for all investment alternatives are discounted to the year when investment choices are made. (Non-monetary flows also should be discounted, but this requires careful consideration; see Section 10.) To simplify this discussion I assume that these choices are made in the present (however, cash flows can be discounted to any base year). An appropriate discounting rate must be selected for each cash flow. Regarding project costs, the discount rate should be such that funds set aside in the present would cover all future costs.

Two types of discount rates must be distinguished: nominal and real. The nominal rate is equal to the real rate plus the inflation rate.⁵ Further, the real rate is equal to the risk-free rate plus a risk premium. Higher rates of return through a risk premium are required by investors for higher risk projects. The risk-free rate is used to discount investments with near certain returns; for example, investments in short-term (U.S.) government securities. In the first quarter of 1996 the nominal risk-free rate in the U.S. was about 5 percent per year. If the anticipated inflation rate in early 1996 over the period of the short-term risk-free investment was 3 percent per year, the anticipated real rate was about 2 percent per year during 1996.⁶ (NAS, 1995, p. 75, uses a 3 percent inflation rate throughout its analysis.) I discuss risk premiums here and appropriate inflation rates in Section 5.2.

If project returns are well defined and if risk is constant over the life of the project, then a risk-adjusted discount rate is appropriate for discounting cash flows. If both assumptions hold, risky costs should be discounted at *less* than the risk-free discount rate and *benefits* should be discounted at *more* than the risk-free discount rate. This is because for risky costs (negative

cash flows), we must set aside funds in the present to cover expected future costs plus a risk premium. A rate lower than the risk-free rate provides for this risk premium. For risky benefits (positive cash flows), funds in the present are equivalent to risk-free benefits minus a risk premium. A rate higher than the risk-free rate provides for this risk premium. (See Copeland and Weston, 1980, Chapter 10). Because risks associated with the returns to plutonium management are unlikely to be constant over time, it is preferable to use a real risk-free rate to discount cash flows and explicitly describe the probability distributions for costs and benefits. The decision maker can then determine the risk premium that equates a risk-free (certainty equivalent) NPV to an uncertain NPV calculated from risky cash flows.

3. Choosing among Plutonium Management Options Requires Uncertainty Analysis

Many cost estimates include a factor (typically a percentage increase) that represents the uncertainty associated with the estimate. Unfortunately, as noted in NAS (1995, p. 82), there is no uniform method of applying contingency factors to cost or benefit estimates. The Electric Power Research Institute (see EPRI, 1986, or later editions) relates the contingency factor to the level of the estimate's detail:

Simplified estimate	30% to 50%
Preliminary estimate	15% to 30%
Detailed estimate	10% to 20%
Finalized estimate	5% to 10%

Therefore, if all reactor-related options are at the same level of detail, the same contingency factor would apply. Also, if the economic benefits have been made at the same level of detail, the determination of those options with positive NPVs is unchanged when all costs and benefits are increased by the same

contingency factor. If this is true, no contingency factor is required in determining whether an investment option has a positive NPV.

If different uncertainties apply to different cash flows, there should be an analysis of the risks associated with estimating costs and benefits, particularly if risk-free discount rates are used. An appropriate approach to decision making under uncertainty is outlined in Nordhaus (1994, Chapters 6-7). The goal is to determine an option's probability of having a positive NPV. The decision maker can then compare the NPV distributions of the different options. How can this probability distribution be approximated?⁷

The first stage of uncertainty analysis is to determine which economic parameters have the greatest impact on the NPV. This is done through sensitivity analysis by varying each parameter, for example, by plus and minus 50 percent, and calculating the sensitivity of the NPV to this change. Those parameters that have the greatest influence on the NPV are retained for further analysis. As Nordhaus states (1994, p. 105), "It should be emphasized that at this initial stage the purpose is to begin with order-of-magnitude estimates of the uncertainties... to determine the important ones and screen out those that contribute little to the uncertainty(y)..." For example, in evaluating plutonium management options, the influential variables are likely to include (see NAS, 1995, p. 376): the discount rate, the reactor construction cost, the market price of electricity, and the cost of plutonium Surveillance and Maintenance, see Section 4.

The second stage is to approximate the distributions of the most influential parameters. Because these distributions can have any shape (normal, lognormal, triangular, uniform, etc.), the probabilities should be described non-parametrically, for example with quintile values, i.e., 20 percent of the distribution is less than the first quintile value and 20 percent of the distribution is more than the fifth quintile value. These probabilities

can be determined either (1) by examining historical data (for example, data on the historical risk-free discount rate), (2) by expert opinion through panel surveys, or (3) by polling the users of the NPV analysis, e.g., decision makers.

The third stage involves either Monte Carlo or Latin Hypercube analysis. Under Monte Carlo analysis, random values of each parameter are generated from the underlying probability distributions and the NPV is calculated. This procedure is done hundreds or thousands of times by computer, generating a probability distribution of the likely outcomes for the NPV. Latin Hypercube analysis involves two steps. First, the probabilities of sets of parameters are calculated from the underlying probabilities. Second, samples based on the probabilities of these sets are selected randomly and the NPV is calculated for each randomly selected set, generating a probability distribution.⁸

These methods for incorporating uncertainty into the NPV analysis give decision makers more information regarding the distribution of an option's NPV, but can reduce transparency in the analysis. If transparency is highly valued and "the value of more complicated approaches is questionable" (NAS, 1995, p. 82), contingency factors should be avoided unless they are directly associated with the detail of the cost estimate or unless options have different levels of detail. On the other hand, if probability distributions for the most important parameters can be transparently modeled, uncertainty analysis allows a more complete comparison of reactor-related options.

4. Economic Benefits: Security and Reducing the Cost of Plutonium Storage

Secure plutonium management gives many benefits. One quantifiable economic benefit of changing the present plutonium management regime is the reduction of on-going Surveil-

lance and Maintenance (S&M) costs. These costs include (1) maintaining plutonium handling facilities, (2) transportation services, (3) inventory and accounting charges, and (4) security and national and international regulatory costs. Implicitly, these activities are a "Monitored Retrievable Storage" program. (See Rothwell, 1993b.) If these costs must be paid in every future year and are not increasing over time, their present value can be calculated as a perpetuity, equal to the product of annual costs and the inverse of the discount rate.⁹

For example, if in the U.S. plutonium could be stored for \$2-\$4 per gram per year (NAS, 1994, p. 122) and there are about 38.2 metric tons (MTPu) of excess weapons plutonium (DOE, 1996), S&M costs would be between \$76.4M (million) to \$152.8M per year in perpetuity.¹⁰ At a 2 percent real discount rate (and assuming no increase in S&M costs) the present value of storage is 50 (equal to the inverse of $2/100$) times \$76.4M to \$152.8M per year, or \$3.8B (billion) to \$7.6B. Therefore, to be economically beneficial (under this benefit only) any reactor-related option should cost no more than \$3.8B to \$7.6B.¹¹

These values should be adjusted for the speed at which plutonium S&M costs would decline as the plutonium was disposed. For example, if the stock of plutonium declines by 3.3MTPu per year for 30 years starting in 10 years, storage costs during the disposal process would be about \$1.5B to \$3.1B, discounted to the present. Because reactor-related options require long disposal periods, their economic benefits are reduced by \$1.5B to \$3.1B.

Of course, the quantification of *social* benefits should be added to this one *economic* benefit. If a reactor-related option provided greater security than could be provided by the S&M option, but at a higher price, decision makers must determine whether the negative NPV would compensate an increase in security. For example, if an advanced reactor was built to consume 38.2 MTPu during 30 years at a (net of electricity sales) PV

cost of \$4.5B (i.e., within the range described in NAS, 1995, p. 325), then at \$2 per gram per year the NPV would be negative \$2.2B (i.e., \$3.8B - \$4.5B - \$1.5B for storage during disposal) or at \$4 per gram per year the NPV would be \$0 (i.e., \$7.6B - \$4.5B - \$3.1B for storage during disposal). At the lower storage cost, decision makers must decide whether the extra security would be worth \$2.2B. Therefore, to understand projected costs for reactor-related options, I discuss economic assumptions affecting these costs in the next three sections. These costs include direct and indirect costs of construction and net operating costs.

5. Capital Costs: Construction and Finance Charges

The direct costs of constructing facilities for plutonium management (including plutonium handling facilities, fuel fabrication facilities, nuclear reactors, waste handling facilities, decommissioning, and disposal facilities) include engineering, licensing, site selection costs, site acquisition costs, site preparation costs, structures construction, and equipment acquisition. Besides land, these direct costs can be categorized as labor (both engineering and construction), materials (including energy), and equipment (both construction equipment and purchased components). To discount these costs into the present involves determining (1) total resource requirements for each stage of construction, (2) unit costs, (3) the time profile of expenditures, and (4) inflation rates over the construction period.

In this section I discuss total resource requirements. I ignore issues in determining unit costs (particularly international extrapolations). I focus on nuclear power plants (NPPs) in the plutonium fuel cycle, however my comments also could apply to plutonium handling and fuel fabrication (or vitrification) facilities. I will not review costs of particular reactor-related options. (See NAS, 1995, pp. 306-329, for an extensive review.) Instead, I

discuss two economic assumptions, then I review two issues associated with financing costs during construction.

5.1. Real Construction Costs

First, consider the assumption that bigger plants have lower unit costs.¹² Although this is often true, this assumption masks the increase in total costs and financing costs that accompany large plants. For example, while there is a decrease in total resource requirements with the doubling of a nuclear power plant from 600 megawatt-electric (MW) (e.g., 1,650/kilowatt, kW, 1992\$, see Braun, 1992) to 1,200 MW (e.g., 1,450/kW 1992\$), total costs increase from \$1B to \$1.75B. As finance capital becomes harder to acquire, smaller units with lower total costs become more attractive. (See my discussion of the influence of increasing competition in electricity generation on the size of new NPPs in the U.S. in Rothwell, 1995, or the review of this discussion in ANS, 1996.) At the limit, modular nuclear units, even with higher costs per kilowatt, become more financially viable than larger nuclear units.

Second, consider the assumption that (because of learning and the ability to spread fixed development costs over more than one unit) total resource requirements decrease with more plants (beyond the obvious savings in building more units at a single site). (See NAS, 1995, p. 318, discussion of first-of-a-kind costs and learning factors.) In the nuclear power industry, this has been empirically demonstrated by the French program. However, most estimates of NPP direct construction costs do not explicitly account for this decrease. These estimates are implicitly either average costs for all projected units or average costs for the later units in a series. Construction cost estimates should explicitly forecast the increase in first (or single) unit costs over expected long-run average costs. (One can interpret the high NPP construction costs in the U.S. as representing the costs on the first or second units for a series of plants that were never built.)

5.2. Discounting Construction Costs

Two other issues associated with total resource requirements involve the time to complete construction. They are (1) financing costs (known as “interest during construction”) and (2) the increase in nominal and real costs over the construction period (known as “escalation during construction”). First, “Interest During Construction” (IDC) in levelized annual cost analysis accounts for the “time value of money.” IDC accounting is equivalent to discounting construction costs to the time of plant completion (which is then levelized over the plant’s life). Under NPV analysis, it is not necessary to include IDC because discounting to the present accounts for the “time value of money.”

Second, there is the problem of adjusting for different inflation rates for different cash flows during construction. If the nominal values of all project costs are expected to increase at the same rate and this rate is equal to the inflation rate anticipated by financial markets, then discounting can be done at the real rate. But all project costs (and benefits) do not increase at a uniform rate. It is easy to assume that if there are competitive labor markets (with the free movement of labor and no shortages of skilled workers), wages will rise at the anticipated inflation rate. Therefore, labor costs can be discounted at the anticipated real rate. On the other hand, the cost of instrumentation and control equipment (now largely based on microprocessor and other advanced technologies) is likely to decline. If the anticipated inflation rate for these costs is negative, the real discount rate would be greater than the nominal rate. For example, if these costs are nominally declining at 5 percent per year, the appropriate real discount rate in the U.S. in early 1996 would be 10 percent per year. In contrast, waste management costs are increasing over time. One could imagine that these costs are nominally increasing at 5 percent per year. Therefore, the real discount rate for these costs would be zero, i.e., income from funds set aside today would just cover future increases in these costs.¹³

If some costs are increasing more rapidly or more slowly than the anticipated rate, these costs must be segregated and discounted separately. If the real discount rate is used, real inflation rates must be used for the segregated cash flows. The real inflation rate is the difference between the anticipated inflation rate and the nominal inflation rate for the segregated cash flow. Following the examples above, the real inflation rate for labor is zero percent (i.e., labor costs are moving with the anticipated inflation rate). For instrumentation it is -8 percent (i.e., these costs are declining 8 percent per year when compared to labor costs). For waste management the real inflation rate is 2 percent (i.e., these costs are increasing 2 percent faster than labor costs). These inflation rates allow one to use the real discount rate and account for differences in inflation for specific unit costs. "Escalation during construction" (EDC) inflates construction cash flows to the time of plant completion. Under NPV analysis, it is not necessary to account explicitly for EDC if cash flows have been properly discounted.

6. Indirect Costs

Indirect cost markups are applied to direct costs for both construction and operation.¹⁴ There are several types of indirect cost, including those identified in NAS (1995, p. 80): "construction facilities, equipment, and support services, safety and environmental engineering, inspection and other quality-assurance activities, project administration, and the like." These cost categories are often added as a percentage of direct costs. These indirect costs (particularly project administration that can include program integration, construction management, and project management fees) can be as large as direct costs.¹⁵

Although the Department of Energy (DOE) has been trying to reform its contracting procedures (see DOE, 1994), there are few guidelines dictating appropriate indirect cost markups.

Therefore, it is not surprising that the DOE found non-uniform treatments of indirect costs among the contractor studies that it had commissioned for the evaluation of reactor options for plutonium management (see NAS, 1995, p. 81).

This non-uniform application of indirect cost percentages affects more than advanced reactor contracting. In response to GAO (1993) and Independent Project Analysis (1993), and other studies, DOE is initiating “Department-wide benchmarking of various indirect-cost categories against the best in class of public and private businesses” and initiating plans “for specific goals for reducing indirect costs.” (DOE, 1994, p. 52)

These initiatives were started before the current Congress and its attempts to balance the U.S. federal budget. Because projects within the DOE compete with one another for funding (for example, funds for advanced reactor projects compete for funding with environmental restoration at DOE laboratories), there will be fewer funds for plutonium management options. Therefore, in the first stage of evaluating reactor-related options care should be taken (1) to identify redundant indirect cost categories and percentages and (2) to equate non-redundant indirect costs across options. Later stages of the evaluation process should consider whether the indirect cost totals and percentages are reasonable under more competitive contracting practices. Where these are not reasonable, guidelines should be determined before specific proposals are requested.

7. Operating Costs and Revenues

This section reviews economic assumptions in evaluating fuel and non-fuel operating costs net of electricity revenues. I argue that the NPV approach should be applied to these costs as it is applied to the benefit of decreasing plutonium S&M charges, direct and indirect construction costs, decommissioning costs, and environmental externalities.

Externalities exist when consumption or production by one party affects another party's well-being or ability to produce. Reactor-related plutonium management causes positive and negative externalities. Some are positive because careful management increases the security of citizens in all nations, not only Americans and Russians. Some are negative such as environmental externalities. If externalities are not properly internalized, inefficiency can result.¹⁶ Because producers of positive externalities do not enjoy all the benefits of production, too little is produced. Because producers of negative externalities do not face all the costs of production, too much is produced. If externalities cannot be internalized, for example, through price mechanisms, activities with positive externalities should be subsidized to bring production to efficient levels. Activities with negative externalities should be charged an implicit price, which is counted as a cost of operation. Of course, implicit prices are unknown and only forecast with uncertainty. As with all operating costs, implicit costs should be included in an uncertainty analysis.

7.1. Fuel Costs

While the NAS (1995, pp. 280-306) review of the cost of mixed plutonium-uranium oxide (MOX) and low-enriched uranium (LEU) fuels is extensive, the same economic assumptions applied to reactor-related facilities also should be applied to fuel facilities. In particular, there is little discussion of the environmental externalities, including decommissioning, of fuel-cycle facilities. For example, use of LEU increases uranium mine and mill tailings. The decommissioning of uranium mines and mills is not fully reflected in uranium oxide prices. Also, using depleted uranium in MOX fabrication, decreases the S&M costs of uranium tailings at the enrichment facilities.¹⁷ Therefore, future evaluations of fuel costs should include the costs of environmental externalities, particularly decommissioning costs.

7.2. Non-Fuel Operating Costs

Following DOE/EIA (1995, p. vii), non-fuel operating costs at U.S. NPPs include routine operating and maintenance (O&M) costs and capital additions during operation: “Approximately 67 percent of the reported O&M costs are labor-related, and the remaining 33 percent are for expenditures for maintenance material and supplies.” There are three types of capital additions: (1) plant retrofits required by the Nuclear Regulatory Commission (NRC), an example being the redesign of the control room; (2) repairs needed to keep a plant operational, such as the replacement of the steam generator; and (3) changes to the plant that will improve performance and productivity. Some recently completed case studies found that for the plants studied, roughly 50 percent of the capital additions were the result of regulatory compliance actions. The other 50 percent were largely due to repair or replacement of plant components. Only a small fraction of the capital additions costs were undertaken to improve plant performance.

In the early 1990s, for all U.S. NPPs above 400 MW in operation by 1993 average annual total O&M costs were about \$95 per kW (1993\$) and capital additions were about \$25 per kW. The average total O&M costs are comparable with O&M costs for new reactors in Table 6-15 of NAS (1995, p. 318), but NAS did not estimate capital additions. Assuming no changes in regulation during operation, capital additions are likely to add 10 percent to annual costs.

Administrative and general expenses (including insurance) and taxes (other than income taxes) have proved troublesome to incorporate into the operating cost analysis. In particular, NAS (1995, pp. 78-79): “There is controversy about the existence, magnitude, and appropriateness of the ‘subsidies’ for government activity associated with government’s freedom from property taxes and insurance costs, and about whether evaluations of the costs of government projects should be adjusted to cover these fac-

tors.” NAS (1995) resolves this problem by performing its cost calculations with and without an adjustment of 2 percent to the fixed charge rate. For new reactors this increases the fixed charge rate about 20 percent. Although this simplification might not influence the conclusions in NAS (1995), private electric utilities do not capitalize property taxes and insurance, so adjustments to the fixed charge rate are inappropriate. These are administrative expenses and should be treated as annual costs.

Beyond the question of how to model these costs is the problem of whether government facilities should pay property taxes and insurance. Traditionally, DOE facilities have contributed “payments in lieu of property taxes” to local governments. These payments, or property taxes, represent a contribution to the provision of local public services. These services include maintenance of roads and other public properties used by the facility and social services, including schools, used by the facility’s employees. In this sense, these payments internalize the costs of externalities generated by the facility. On the other hand, local governments collect taxes on incomes generated at the facility (for example, through sales taxes) and usually collect larger taxes on properties that increase in value because of the facility. Therefore, it is difficult to determine *a priori* whether local governments subsidize DOE facilities. However, to avoid the unfair DOE competition with the private sector in electricity sales, it would be safe to assume that a DOE-financed facility should pay the same property taxes as a private electric utility.

The appropriate insurance charge can be similarly determined. There are several types of insurance to consider. It is convenient to assume that health and safety insurance payments for facility employees are adequately incorporated into O&M costs. (It is possible that health and safety externalities have not been completely internalized because of the lack of information; it is also possible that these costs are higher than their efficient levels.) It is safe to assume that the facility would be covered under the

Price Anderson Act, so off-site damages would be covered after a catastrophic accident.¹⁸ Finally, insurance to cover losses at the facility equal to payments required by the financial community and regulators of private electric utilities should be added to annual administrative expenses for a DOE-financed facility.

7.3. Operating Revenues

One of the benefits of managing plutonium with NPPs is that electricity can be sold to offset costs. These benefits can be represented as negative operating costs. Net operating costs (costs minus revenues) can be discounted in the NPV analysis. To evaluate reactor-related options, three forecasts are required: (1) the future price of electricity, (2) the NPP's capacity factor, and (3) the NPP's operating life. All three forecasts require uncertainty analysis.

Forecasting the price of electricity is particularly difficult now in the U.S. given the possibility of deregulating the electric utility industry during the next decade. (See ANS, 1996.) Assuming a competitive environment, electricity produced at a plutonium-consuming NPP will compete with all other producers of electricity in regional markets for long-term contracts and spot sales. There will be no protection of monopoly rights in captive service territories under rate-of-return regulation. This also implies that the low cost of capital enjoyed currently by the electric utility industry is not likely to continue. Therefore, financing costs assumed in earlier analyses are likely to be too low for future generators and future prices are more likely to be on the high side of estimated ranges.

Because of the stability of production at NPPs, reactor operators will compete for long-term contracts. This reduces the uncertainty associated of forecasting prices.¹⁹ Long-term contract prices will be determined by the low-cost long-term producer. During the life of a future NPP, this is likely to be the gas-fired combined-cycle baseload power generator. Therefore, assump-

tions made in NAS (1995, p. 108) are reasonable: "For our analysis we choose a reference value of \$0.05/kWh with a judgmental 70-percent confidence interval of $\pm \$0.015/\text{kWh}$."²⁰

The second issue in forecasting operating revenues is the annual level of electricity generation. This forecast is typically modeled with the projected capacity factor, i.e., the ratio of average projected generation to the potential maximum generation. But capacity factors vary over the life of the NPP; see Rothwell (1990). Further, this variation with age also varies over time and across reactor manufacturers. Because annual electricity generation is subject to random variation, the capacity factor is uncertain.²¹ Therefore, while it is convenient for comparisons to assume the same base-case capacity factor for all NPPs (for example, 75 percent), the sensitivity of the NPV to the capacity factor should be investigated.

Similarly, the economic operating life of a power plant is uncertain; on modeling this uncertainty, see Rothwell and Rust (1996). While the licensed lifetime could be 40 years, a power plant might not be economically competitive throughout its licensed lifetime. If the primary purpose of a new or modified NPP is to dispose of plutonium, once the excess weapons plutonium has been converted to spent nuclear fuel, decision makers must reevaluate the economics of continued operation at that time treating earlier expenditures as sunk. Because there is the possibility that discounted operating costs of continued operation would exceed discounted revenues, analysis should treat the operating life as uncertain.

8. Decontamination and Decommissioning

Decontamination and Decommissioning (D&D) a nuclear fuel facility or power plant involves several steps: (1) safe shutdown, including the removal of process materials, (2) waste dis-

posal, (3) Surveillance and Maintenance (S&M) until D&D is complete, (4) D&D planning, (5) site contamination characterization, (6) decontamination, (7) demolition or refurbishment of remaining facilities for future use, and (8) environmental restoration. See DOE/EM (1994). But DOE/EM (1994) guidelines post-date cost estimates for plutonium management options. Also, these guidelines have not followed Nuclear Regulatory Commission requirements for decommissioning NPPs. Until there is more D&D experience with NPPs and a detailed correspondence made between this experience and DOE/EM (1994), DOE's Nuclear Energy Cost Data Base formula for NPP D&D is unlikely to reflect future D&D costs for DOE facilities.

For example, there is much confusion surrounding Nuclear Regulatory Commission regulation of NPP decommissioning. From the late 1970s through 1995 the Nuclear Regulatory Commission sponsored studies to estimate decontamination costs for generic Pressurized and Boiling Water Reactors (PWRs and BWRs). See references in Wood (1991) and Konzek, Smith, Bierschbach, and McDuffie (1995). These are approximately \$130M (1992\$) for PWRs and \$170M (1992\$) for BWRs.²² Further, these estimates assume low-level waste management at Hanford with price regulation. If prices are deregulated and allowed to rise to those at Barnwell, decontamination costs could rise by \$94M (1993\$). See Konzek et al (1995, v2). These estimates are for radioactive decontamination because the Nuclear Regulatory Commission is only concerned with releasing the NPP site from its licensing requirements. Electric utilities operating NPPs are now required by the Nuclear Regulatory Commission to maintain Nuclear Decommissioning Trust funds to provide for the eventual *decontamination* of these facilities.

However, costs of other decommissioning operations are not reflected in the decontamination cost estimates. Other D&D costs depend on the requirements of other regulatory agencies. Some of these costs are reflected in estimates done for state

public utility regulatory commissions. See Strauss and Kelsey (1991). For example, the estimated cost of a more complete D&D of Trojan (the unit that served as the model for the Nuclear Regulatory Commission's generic PWR decontamination estimate) in 1986 was \$173M (1986\$), or \$216M (1992\$). Also, the original construction cost of Trojan (see DOE/EIA, 1986, p. 109) was \$860M (1982\$) or \$1,237M (1992\$), so Trojan's estimated D&D cost will be at least 17.5 percent and could be as high as 25 percent (with higher radioactive waste costs) of its construction cost.

While it is instructive to compare projected decommissioning costs with construction costs, most NPP designs were not optimized for decommissioning. With 10-year design and construction periods, 40-year operating lifetimes, and up to 60 years of safe storage before decommissioning, the discounted cost of D&D had little relevance in decision making when NPPs were ordered. Recent experience with D&D has led to nuclear facility design that considers decommissioning. See DOE/EM (1994, p. 2-2): A design trade-off is considered when a design can be changed to facilitate maintenance or decommissioning activities. For example, a storage tank located in a poured reinforced concrete room would be difficult to access for decommissioning. An alternative design that would provide easier access would be preferable from a decommissioning standpoint, for instance one nonload-bearing wall could be built out of easy-to-remove block. Further discussions of this technique, called facilitation, can be found in NUREG/CR-0569 (1979).

Therefore, estimated construction costs could increase to lower future decommissioning costs. Increases in construction plus decommissioning costs likely will be closer to 20 percent of the earlier estimated construction costs than to the rule-of-thumb "that the at-shutdown cost of decommissioning is 10 percent of the construction investment as of startup." (NAS, 1995, p. 84)

9. Conclusions and Recommendations

This section lists the conclusions (•) and recommendations (→) made in this paper and discusses their applicability to Russia.

9.1. The Net Present Value Method and Discounting

- NPV analysis has been accepted by economists as the guide for making investment decisions.
- Plutonium management and disposition options should be ranked by their non-proliferation benefits, and within each security class, options should be ranked by NPV.
- Because uncertainties associated with the costs and benefits of plutonium management will change over time, risk-adjusted discount rates are not appropriate for discounting.
- The most appropriate discount rate to evaluate plutonium management is the risk-free rate with explicit modeling of uncertain costs and benefits.

Although NPV analysis would also be appropriate to evaluate Russian plutonium management options, the selection of the appropriate discount rate for both costs and benefits is more problematic than in the U.S. There has been little historical observation of real interest rates in post-Soviet Russia. One could argue that the real risk-free rate is much higher in Russia than in the U.S. because the social rate of discount is much higher, i.e., in the present situation the Russian people place a higher premium on consumption today than on consumption tomorrow than in the U.S. Further, financial research is required to calculate (1) the appropriate inflation rates for the cash flows in this context, (2) the appropriate risk premiums, including the exchange-rate risk for the nuclear power industry, and (3) the appropriate risk-free discount of future consumption by the Russian people.

9.2. Uncertainty and Risk

- The costs and benefits of plutonium-management alternatives are uncertain.
- All economic variables should be included in an uncertainty analysis. The first step is to determine the most influential variables with sensitivity analysis. Second, specify probability distributions for each of the influential variables. Third, simulate the NPV distribution based on the probability distributions of the influential variables. Decision makers can then evaluate the potential risks of each option.

Uncertainty analysis should be applied to the costs and benefits of Russian plutonium management options. Due to the lack of historical data, probability distributions should be based on expert opinion. Due to the lack of experience of Russian decision makers in evaluating the resulting probability distribution for NPVs, the analysis must be more transparent than in the U.S. The first step is use sensitivity analysis whenever possible.²³

9.3. Economic Benefits

- One economic benefit to changing the current plutonium management regime is a reduction in on-going plutonium Surveillance and Maintenance (S&M) costs.
- The present value of costs for alternative management options should be compared with the present value of S&M costs and any other economic benefits.

Civilian and excess weapons plutonium is stored in dozens of sites in Russia. Before the economic benefit of reducing S&M costs in Russia could be calculated, the storage and transportation system should be rationalized and upgraded. Some of this work is underway with U.S. and European assistance. Because S&M costs are presently so uncertain, they are unlikely to provide an appropriate baseline with which to compare plutonium management costs. Therefore, a more appropriate benefits baseline must be defined for the Russian situation.

9.4. Construction and Operating Costs

- Although larger facilities have lower average unit costs, total costs are higher.
- Budget constraints require consideration of facilities that might be smaller than minimum efficient scale.
- First-of-a-kind costs in the nuclear industry have been larger than expected costs.
- Cost estimates should explicitly model cost increases for first-of-a-kind construction projects.
- The risk-free discount rate is equal to the real risk-free discount rate plus the anticipated inflation rate. In 1996 the real risk-free discount rate was about 2 percent and the anticipated inflation rate was about 3 percent.
- Costs that are expected to increase at the anticipated inflation rate should be discounted to the present at the risk free rate. Cash flows that are expected to increase (or decrease) at rates above (or below) the anticipated inflation rate should be discounted at rates below (or above) the risk-free rate.
- In NPV analysis appropriate real discount rates account for escalation during construction and interest during construction.
- If appropriate discount rates have been used, it is not necessary to include escalation or interest during construction in the NPV analysis.
- Indirect cost estimates have not been uniform across studies of plutonium management.
- Guidelines should be established to describe appropriate tasks to be included in indirect costs, appropriate percentages for the ratio of indirect to direct costs, and appropriate management fees.
- Estimates of front and back-end nuclear fuel cycle costs have not been made at the same level of detail as reactor-related costs.
- The same assumptions for the NPV analysis of reactor-related costs applied to fuel costs.

- One half the capital additions nuclear power plants in the U.S. have been for regulatory compliance; historically capital additions were about 20 percent of total non-fuel operating costs.
- Assuming no changes in regulatory requirements, annual non-fuel operating costs should be at least 10 percent higher to reflect repair and replacement of plant components.
- Accounting for administrative expenses (including insurance) and taxes (other than income taxes) have proved troublesome to incorporate into operating cost estimates.
- Estimates of insurance and tax payments for federal facilities should be equal to these payments for electric utilities operating similar facilities. Insurance premiums implicitly paid by local communities should be included as costs.
- Projecting electricity revenues involves forecasting three uncertain variables: (1) the future price of electricity, (2) capacity factors in each year of operation, and (3) the economic life of the NPP.
- Base line values should be selected for these variables and the sensitivity of the NPV to probable realizations of these variables should be investigated.
- Decontamination and Decommissioning costs based on decontamination estimates are likely to be too low because of the requirements by non-nuclear regulatory agencies.
- Decommissioning and waste management costs, including changes in construction design to facilitate decommissioning, are likely to be close to 20 percent of construction costs.

Recommendations regarding construction and operating costs largely apply to Russia. However, I did not discuss international extrapolations of U.S. cost estimates. There is a near universal assumption in Western economic analysis that Russian labor rates are low and will continue to be low compared to labor rates in the U.S. Although Russia could be deindustrialized and living standards could fall to those in non-industrial-

ized nations, this is unlikely to happen. More likely is a gradual rise of labor rates: first to rates comparable to those in Eastern Europe (e.g., Poland) soon and later (with Eastern European wages) to those in Western European over the time horizon under consideration. Further, because of the complex structure of the nuclear power industry in Russia, indirect costs are also complex. Guidelines for maximum indirect to direct ratios should be established to clarify the cost estimation process.

10. Limitations of Net Present Value Analysis

Although NPV analysis under uncertainty provides the best available technique for economic decision making (because it forces users to make their assumptions explicit), there are two problems with it. First, it is biased toward costs and benefits that can be quantified and monetarized (cash flows). In plutonium management there are many considerations that elude monetarization. The most important is the anticipated loss from a proliferation-related incident, e.g., burning plutonium to cause panic. Other costs that are difficult to quantify are environmental and health and safety effects. Second, NPV analysis is biased toward the present generation. Discounting across generations requires the assumption that future generations will have the same values. This is a strong assumption. Costs and benefits to generations beyond the present must be carefully evaluated. Therefore, NPV analysis under uncertainty should be considered as only the best starting point for further research.

ENDNOTES

1. Other committees at the National Research Council considering related problems include the Committee on Separations Technology and Transmutation Systems (STATS) of the Board on Radioactive Waste Management. See, for example, National Research Council (1995). Also see the American Nuclear Society's 1995 special panel report, ANS (1995).

2. NAS (1995) also considered the levelized annual cost (LAC) approach. While this might be appropriate for comparing kilowatthour costs for electricity generation, the NPV method is more general and is more flexible for comparing non-electricity generating and non-reactor related options. On the NPV method and its superiority over other approaches see, for example, Brealey and Myers (1991, Part 2: Value).
3. The NPV approach must be modified when there are expenditure constraints, e.g., budget or foreign currency constraints. These modifications can be handled by linear programming techniques.
4. NAS (1995, p. 374) considers three classes of management options: current reactor options, vitrification, and advanced reactor options: "The main factors besides timing that affect the comparative security of disposition options are (1) the extent of exposure to theft or diversion in the processing and transportation steps that an option entails and (2) the theft and diversion risks posed by the plutonium in its final form and location." Except for timing, all three classes provide similar non-proliferation benefits. On advanced reactors, see May and Avedon (1994).
5. These are approximations. More correctly, $(1 + \text{nominal rate})$ is equal to $(1 + \text{real rate})$ times $(1 + \text{inflation rate})$.
6. Here, I avoid the question of what the real rate should be by suggesting that the empirical real risk-free rate be used for discounting. Ibbotson and Brinson (1987) and Nordhaus (1994, p. 126) found that real returns between the mid-1920s and the mid-1980s clustered between 0 and 2 percent per year for fixed-interest instruments for premium borrowers. For a summary of the debate over real rates, see Nordhaus (1994, pp. 122-135). For an extended discussion, see Lind (1982).
7. The process described here can be done with the Lotus or Excel spreadsheet add-in, @RISK, available from Palisade Corporation, telephone 607-277-8000 or email palisade@palisade.com.
8. Nordhaus (1994, Chapter 8) describes a final stage of uncertainty analysis: determining the consequences of rejecting a project that has a high probability of being negative, but could have a positive realized NPV. For a more complete analysis of this stage, see Dixit and Pindyck (1994).
9. S&M costs need not be paid forever to be approximated as a perpetuity. For example, at a 2 percent discount rate the present worth factor is 25 (one-half of the asymptotic value) after 35 years. At 7 percent the present worth factor is 10 (approaching an asymptotic value of 14.3) after 18 years.
10. These are costs of storage at new or international facilities built to International Atomic Energy Agency standards. Marginal costs at existing facilities with no other use would be much lower. Because marginal costs are so low and fixed costs are so high, consider the \$2-\$4 per gram to be an average cost, covering both fixed and variable costs.

11. If the discount rate is 7 percent per year, the present value of S&M costs reduces to 14.3 times \$200M to \$400M, or \$2.9B to \$5.7B.
12. This is expressed in NAS (1995, p. 291) as “we apply the widely used rule of thumb that the construction costs and operating costs for such facilities increase as the 0.6 power of output (meaning unit costs will decrease as the 0.4 power of output).” NAS applies this rule to conversion of plutonium metal to oxide.
13. I have argued that a zero discount rate is appropriate for evaluating the cost of decommissioning U.S. nuclear power plants. The costs of decommissioning appear to be rising as fast as returns on Nuclear Decommissioning Trust funds because the scope and standards for decommissioning are increasing. See Rothwell (1993a). Once regulatory requirements and low-level waste costs stabilize, the discount rate would rise, lowering the present value.
14. Other indirect cost categories include government sponsored research and development expenses and government project management costs. These are identified as “other preoperational costs” in NAS (1995, p. 81).
15. As a member of the NAS committee that produced NRC (1996), I am most familiar with cost estimates for the decontamination and decommissioning (D&D) of the U.S. uranium enrichment facilities, see NRC (1996), particularly Appendix J, “Review of Existing Cost Estimates.” Ebasco Environmental prepared a series of cost estimates for this D&D project between May and September 1992. In their final estimate, the direct cost of D&D operations, decontamination facilities, and waste management was \$6.5B (1992\$). Indirect costs, Program Integration, Construction Management, and Management and Operations (M&O) fees were \$6.3B and contingency was \$3.2B. The total cost was \$16B. The indirect cost markup was 43 percent, equal to 26 percent for field indirects, 3.3 percent for home office overhead, and 10 percent for contractor’s profit ($1.43 = 1.26 \times 1.033 \times 1.10$). Program Integration (\$2.6B) included costs associated with project oversight by the M&O Contractor, the Construction Manager, the Remedial Design Engineer, and the costs of preparing environmental impact statements. The Construction Management markup was 5 percent (\$468M) on all direct and indirect costs, not including Program Integration. The M&O Contractor markup was 5 percent (\$491M) on all direct and indirect costs and construction management, not including Program Integration. This included surveillance and maintenance, additional security, contractor design and review, contractor construction engineering, health physics, overhead adders, and markups on construction management. See NRC (1996, p. 268).
16. Another solution to the problem of externalities is to redefine property rights. See Coase (1960). For an application of the Coasian solution to nuclear power plant decommissioning externalities, see Pasqualetti and Rothwell (1993).

17. NRC (1996, Chapter 7) recommends that depleted uranium hexafluoride be converted to uranium oxide for long-term disposition. Use of depleted uranium oxide in MOX fabrication reduces the cost of this disposition.
18. Dubin and Rothwell (1990) calculate that the implicit subsidy to an average NPP of the Price Anderson Act after the 1988 amendments is about \$22M (\$1985). This calculation was based on Nuclear Regulatory Commission estimates that the probability of a loss above \$10B was 1 in 1,250,000. These estimates should be revised given the safety record of the nuclear power industry since 1985. To compare reactor-related options with non-reactor related options, similar implicit subsidies should be calculated. In particular, implicit subsidies to S&M storage options should be determined.
19. The variance of spot prices is considerable. The Wall Street Journal now quotes the weighted average of a megawatthour sold at the California-Oregon and Nevada-Oregon borders for non-firm power on (6am to 10pm) and off (10pm to 6am) peak. The temporal standard deviation of these prices is higher than the reported weighted average, suggesting a high variance with a skewed distribution.
20. The reasoning in NAS (1995, Appendix C) is different from that here because the authors assumed rate-of-return regulation. Their reasoning involves determining (1) the appropriate avoided cost (e.g., as measured by the cost of replacement power as in Che and Rothwell, 1995) and (2) the appropriate cost of capital for government-financed electricity generators. These complications are avoided here by assuming a competitive electricity market for long-term contracts.
21. Rothwell (1996) presents a stochastic model of electricity generation: "Under the appropriate assumptions, one can show that maximizing expected present value for (a nuclear power plant) is equivalent to maximizing the probability of producing output."
22. These values are updated from Nuclear Regulatory Commission estimates of \$105M (1986\$) for PWRs and \$135 (1986\$) for BWRs in Wood (1991, p. 48) with inflation factors in NAS (1995, p. 78). Although Konzek et al (1995) found that the inflation rate for NPP *decontamination* has been lower than the general inflation rate, these estimates are lower than those quoted in NAS (1995, p.84), i.e., a base cost of \$145M (1992\$) for PWRs and \$185M (1992\$) for BWRs plus a factor related to the thermal size of the reactor in megawatts (MWt). For the generic reactor of 3,400 MWt this factor would increase cost by \$44M (1992\$).
23. Although high and low values are given for cost estimates, there is no explicit analysis of the sensitivity of costs and benefits to specific causes in US AID (1995).

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Table 1

**Economic Assumptions
for Evaluating Reactor-Related
Options for Managing Plutonium***

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*Utilization of the Excess Weapons Plutonium:
Scientific, Technological and Socio-Economic Aspects*
Como, Italy
March 20, 1996

Table 2

The Economic of Plutonium Management

- ▶ NAS Committee on International Security and Arms Control (CISAC)
- ▶ NAS. "Management and Disposition of Excess Weapons Plutonium" (1994)
- ▶ NAS. "Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options" (1995).

Table 3

NAS (1995, p. 280): “economic considerations are less important than security in reaching a conclusion about the relative attractiveness of alternative options for WPu disposition. But the study of costs is nonetheless worthwhile, both to assist in ranking options that are not distinguishable on security grounds and to facilitate planning for the investments that will be required for one option or another”.

Table 4

NAS (1995, p.374) considers three classes of disposition options: current reactor options, vitrification, and advanced reactor options: “The main factors besides timing that affect the comparative security of disposition options are (1) the extent of exposure to theft or diversion in the processing and transportation step that an option entails and (2) the theft and diversion risks posed by the plutonium in its final form and location”. Except for timing, all three classes provide similar non-proliferation benefits.

Table 5

Economic Evaluation of Plutonium Management

- ▶ Net Present Value (NPV)
- ▶ Stages of NPV Analysis:
 - ▶ 1st: Preliminary evaluation of the costs and benefits: which options are likely to yield positive NPVs?
 - ▶ 2nd: Rank options by NPV
 - ▶ 3rd: Evaluate specific proposals

Table 6

What is NPV?

- ▶ Net Present Value is discounted benefits (B) minus discounted costs (C):

$$\text{NPV} = \sum_{t=1}^T \frac{B_t}{(1+r)^t} - \frac{C_t}{(1+r)^t}$$

Table 7

Appropriate Discount Rate

- ▶ Nominal Discount Rate = Real Rate + Inflation Rate
- ▶ Real Discount Rate = Risk-free rate = Risk Premium
- ▶ For example, in U.S. in 1996
- ▶ Nominal Rate on short-term government securities = 5%
- ▶ Anticipated Inflation Rate = 3%
- ▶ Real Risk-Free Rate = 2%

Table 8

Risk Adjusted Discount Rates?

- ▶ If risk is constant over the life of the project, then a risk-adjusted discount rate is appropriate
- ▶ But risky costs discounted at less than the Risk-Free Discount Rate
- ▶ And risky benefits discounted at more than the Risk-Free Discount Rate

Table 9
NPV with Risk Adjusted Discount Rates

- ▶ A premium is added to the discount rate

$$\text{NPV} = \sum_{t=1}^T \frac{B_t}{(1+r')^t} - \frac{C_t}{(1+r')^t}$$

Table 10
**Are plutonium management cost
and benefit risks constant over time?**

- ▶ This is unlikely
- ▶ Solution:
 - ▶ (1) Use a real risk-free rate to discount cash flows and
 - ▶ (2) Explicitly describe the probability distributions for costs and benefits

Table 11
The Present Value of Economic Benefits

- ▶ One quantifiable economic benefit
- ▶ Reduction in ongoing Surveillance and Maintenance (S&M) costs: the quicker the reduction in S&M costs, the greater the economic benefit
- ▶ There fore, time to completion matters

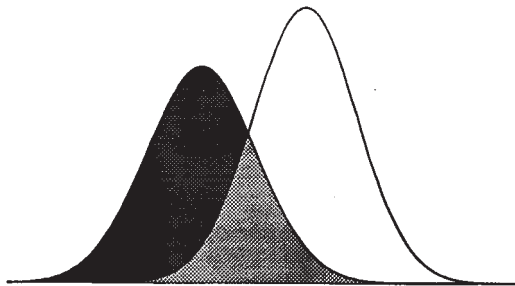
Table 12
Contingency

- ▶ EPRI's Technology Assessment Guide:
- ▶ Contingency factor related to level of estimate's detail
 - ▶ - 30% - 50%: Simplified estimate
 - ▶ - 15% - 30%: Preliminary estimate
 - ▶ - 10% - 20%: Detailed estimate
 - ▶ - 5% - 10%: Finalized estimate

Table 13
Uncertainty Analysis

- ▶ (1) Sensitivity Analysis of economic assumptions
- ▶ (2) Approximate probability distributions of economic variables
- ▶ (3) Monte Carlo approximation of NPV distribution
- ▶ (4) Evaluation of stochastic distribution to determine risk premium

Table 14
Comparing Two NPV Distribution



- ▶ One distribution has lower mean but a higher variance
- ▶ The other has a higher mean but a lower variance

Table 15
Risk Aversion and Risk Premiums

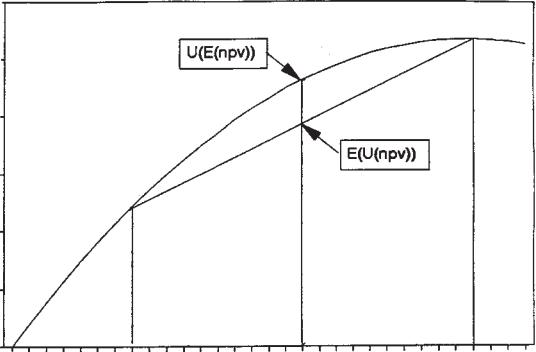
- ▶ (Risk Aversion
- ▶ When the value of the expected NPV is greater than the expected value of NPV
- ▶ Risk Premium:
- ▶ When investors are indifferent between the risk-free outcome and the risky outcome plus a risk premium

Table 16 **NPV and Certainty Equivalence**

- Risk premiums are added to Benefits and Costs before discounting

$$NPV = \sum_{t=1}^T \frac{B_t + RP'_t}{(1+r)^t} - \frac{C_t + RP''_t}{(1+r)^t}$$

Table 17 **A Risk Averse Investor**



The value of the mean NPV is greater than the average value of two risky NPVs.

Table 18

Comparing Different Adjustments to NPV

- NPV without adjustment

$$\text{NPV} = \sum_{t=1}^T \frac{B_t}{(1+r)^t} - \frac{C_t}{(1+r)^t}$$

- NPV with risk-adjusted discount rates

$$\text{NPV} = \sum_{t=1}^T \frac{B_t}{(1+r)^t} - \frac{C_t}{(1+r')^t}$$

- NPV with risk premiums

$$\text{NPV} = \sum_{t=1}^T \frac{B_t + RP'}{(1+r)^t} - \frac{C_t + RP''}{(1+r)^t}$$

Table 19

Economic Assumptions for Evaluating Russian Options

- (Use Net Present Value analysis with Russian-appropriate economic assumptions)
- Determine Russian real risk-free discount rate, risk-premiums, and inflation rates for labor, materials, equipment, and waste management
- Calculate fixed and variable costs for upgrading plutonium management system, compare with costs for disposal
- Conduct sensitivity analysis to determine critical variables outcome plus a risk premium

SESSION 5

Effects of Different Strategies of Waste Disposal: Environmental and Safety Related Issues

Environmental Safety and Health Risks of the Different Plutonium Disposal Alternatives

L.A. Bolshov



1. Owing to the started process of nuclear disarmament, a problem of the future of the excessive weapon plutonium arose. The solution of the problem should satisfy the requirements of non-proliferation of nuclear weapons, providing of people's health and safety, and protection of the environment. Thus, the first task is to convert weapon plutonium into form that would exclude any possibility of military usage of this plutonium. One of

such forms is spent nuclear fuel.

There are two technical methods to reach the standard of the spent fuel. The first way, known as reactor choice, is based on the conversion of weapon plutonium into mixed dioxide fuel (MOX fuel) to be processed in heat reactors. In this case, plutonium is a valuable power resource. An alternative way, known as glazing, assumes mixing of plutonium with high-active waste followed by glazing and burying. In this case, plutonium is merely a kind of waste, which seems to be unjustified extravagance from the economical point of view.

The reactor variant of the weapon plutonium conversion call be implemented faster than glazing. In principle, it provides more effective protection from the possible repeated military usage of plutonium. The reason is that the isotope content of

plutonium is changed and reduced in the process of fuel burn-
ing, while in the process of glazing it remains constant.

According to the data of the Uranium Institute, the total amount of the weapon plutonium in the former USSR reaches 105-130 tons. The estimates of the plutonium power resource made by specialists of the, ENTEK show that 100 tons of plutonium can produce from 1000 to 8000 TWt-h of the electric power, depending on the, applied power technology (heat reactors with opened or closed fuel

Table 1
**Annual Balance of General Plutonium Isotopes.
Open Fuel Cycle, kg/[GW(el)-year]**

	(A) VVER-1000 UO ₂	(B) VVER-1000 PUO ₂ +UO ₂ +Zr	(C) BN-800 PuO ₂ +UO ₂	(D) BN-800 PuO ₂ +Th
<i>Input:</i>				
239 Pu	-	764.2	1910	2421
240 Pu	-	49.4	124	94
241 Pu	-	4.8	12	7.5
242 Pu	-	0.3	0.7	0.3
Pu	-	818	2047	2522
<i>Output:</i>				
239 Pu	124	130	1798	1690
240 Pu	55.2	144.2	262	186
241 Pu	30.9	73.2	22.8	12.5
242 Pu	12	37.2	2	0.8
Pu	222	384	2085	1889+770 kg 223U
<i>Output</i>				
<i>Input:</i>				
239 Pu	124	-634	-112	-731
240 Pu	55.2	95	139	92
241 Pu	30.9	68.4	10.8	5
242 Pu	12	36.8	1.3	0.5
Pu	222	-434	39	-633+770 kg 223U

cycle, fast reactors with $BF = 1.00-1.05$). Tables I and 2 display the estimated data on the possibility to use plutonium in Russian reactors. It is clear that the most effective “furnaces” are fast reactors, the next is VVER-1000 consuming the mixed fuel.

It follows from the above, that the main direction of the weapon plutonium conversion is most likely to be its using as nuclear fuel. In this connection, IBRAE RAS performed assessment of the possible radiological consequences of a severe accident with core melting on the NPP with fuel enriched by Pu-239. These investigations involved:

Table 2
The Possibility of Utilization of Plutonium in Russian Reactors
(Data Presented by Physics and Energetics Institute from
the Report “Engineering Analysis of Production of Uranium-
Plutonium Fuel from Weapon Plutonium, and its Possible
Utilization in Nuclear Energetics”
Minatom of Russia - Siemens - GRS. 1995)

Reactor kg/yr.	Loading Pu, kg/yr	Yield Pu,	Balance, kg/yr
1 VVER-1000	0	223	+223
2 VVER- 1000	254	308	+54
3 VVER-1000	364	395	+31
4 BN-600	1141	1053	-88
5 BN-800	1637	1508	-129

Notes: Reactor VVER-1000 is loaded with: (1) standard poor-enriched UO₂ fuel (4.3% of ²³⁵U, taken as a reference), (2) 1/3 of the reactor is loaded with MOX-FA (concentration of plutonium is 3.5%; poor uranium dioxide with 0.25% of ²³⁵U serves as a carrier, and 2/3 of reactor is loaded with uranium FA (0.25% of ²³⁵U), and (3) 1/3 of the reactor is loaded with MOX-FA but with higher concentration of plutonium in the mixture of oxides (5% Pu) and with lower level of enrichment of uranium (3.7% of ²³⁵U) in uranium FA. Reactors BN-600 and BN-800 are completely loaded with uranium-plutonium fuel.

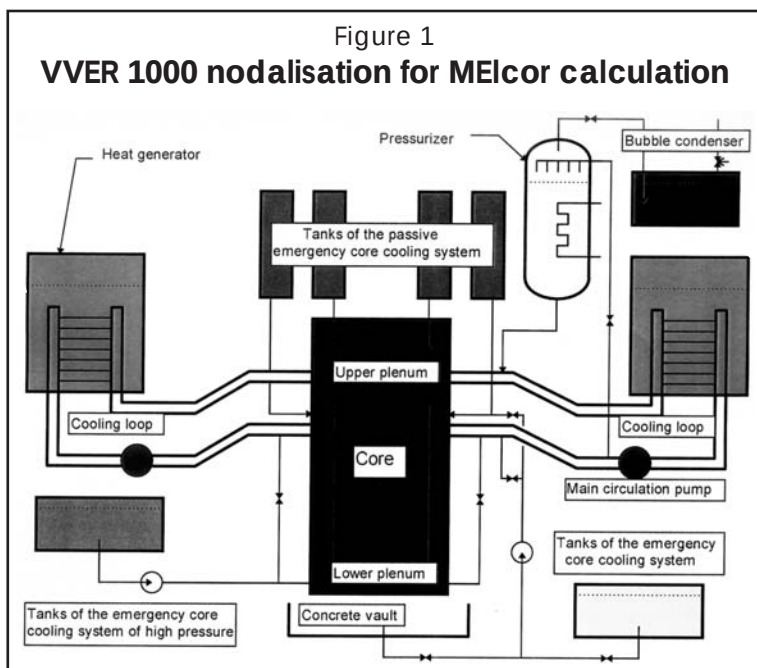
- model calculations of the possible activity of Pu-239 release into atmosphere resulting from the accident on VVER- 1000 reactor operating with fuel enriched by Pu-239;
 - calculation of the Pu-239 contamination density of the landscape, resulting from such an accident;
 - calculations of the population and personnel exposure doses resulting from Pu-239 release in an accident;
- The used base of information comprised:
- actual data on contamination levels of the environment objects by plutonium isotopes after the Chernobyl accident;
 - experimental data on plutonium isotope content in human body in the regions surrounding the Chernobyl NPP and fuel-processing plant “Mayak” in Chelyabinsk region;
 - modern dosimetry data on the radiation impact of plutonium isotopes on human body.

2. The model calculations of the consequences of major accidents at NPP's with PWR-type reactors are performed in IBRAE using the modified computer code “MELCOR”, which allows for specific features of the design of Russian reactors [1]. Figure 1 represents the nodalisation of VVER-100 used in the calculations with “MELCOR”. The basic scenario of the severe, accident on VVER-100 with Pu-239-enriched fuel was based on the event chain that gives the most severe consequences. The rupture of the main circulation pipe in one of four loops at the hot segment with equivalent diameter Du850 and bilateral outflow of coolant was chosen as an initial event. In addition, the presence of hidden defects in the plant equipment was assumed, namely: complete failure of power feeding from internal and external sources with respective failure of the emergency core cooling system (ECCS), and failure of the area spray system of steam condensation inside containment.

The calculations assumed that the fuel load at the moment of the accident was equal to 75,000 kg of UO₂ and 1,500 kg of

PuO₂. The fission products are released inside containment and then leak to the external space through the project leaking in the containment. The resulting chain of the accident events is represented in Table 3.

The rupture of a loop of the main circulation pipe is followed by the intensive coolant outflow into the reactor pit. At the beginning, the Outflow coolant is in the liquid state (water); later on, when the water level is reduced lower the edge of the emergency pipe, it turns into steam. The process is accompanied by the abrupt decrease of pressure and coolant level in the first circuit, and two seconds after the start of the accident, the emergency system is actuated. The reactor is shut down, and the run



down of the MCP starts. Further decrease of pressure should result in connecting the ECCS of high pressure and injecting of bore solution into reactor. However, owing to the mentioned hidden defects, it does not occur, and when the pressure decreases lower 5.9 Mpa, the passive tanks of ECCS are connected. The action of the tanks only slightly reduces the velocity of the level decrease in the reactor, and by the seventh second the drying of the core starts. Water is vaporized in the lower (poured) part of the core and outflows in the form of stream into the reactor pit, and then in the adjacent volume. Approximately 125 tons

Table 3
The Chain of Main Events of the Accident Process

Event	Time from the start of the calculation, s
The initial event - the rupture of the main circulation pipe	10.0
Actuation of the emergency protection system; start of the MCP run down	12.0
Connecting of tanks of the emergency core cooling system; start of bore solution injection into reactor	15.0
Start of core drying and hearing	17.0
Start of the steam-zirconium reaction with hydrogen release in the core	20.0
Cladding failure and start of the fission product release into the atmosphere	26.0
Devastation of the ECCS tanks	174.0
Start of the cladding meltdown	347.0
Complete vaporization of water from the reactor and start of heating of the core scrap at the reactor bottom	1300.0
Melting of the bottom of the reactor vessel and fall of the scrap into the reactor pit	1660.0
Complete vaporization of water from the reactor pit	25100.0

of water, from the total amount of 220 tons in the first circuit appear in the reactor pit, the rest amount spreads in the form of stream over other compartments of the reactor building.

Power removal from the dried part of the core is insufficient for the effective cooling of fuel rods, and by the 10th second from the accident start, the temperature of the upper part of fuel rods reaches the lower boundary of the stream-zirconium reaction (approximately, 1000 K). Hydrogen release and spreading over the plant compartments start. The reaction is accompanied by large heat production, which results in still more intensive heating of the core. Sixteen seconds after the start of the accident, when the cladding temperature reaches approximately 1300 K, cladding failure occurs, and gaseous fission products from the inter-rod space are released into the atmosphere. Further on, the release of the volatile fission products from the solid matrix is intensively developed, thus reducing the residual heat production in fuel. By the 337th second from the accident start, the rod temperature reaches the zirconium melting temperature, and the destruction of the core starts. The cells of the second, the most power-stressed zone are destroyed first, and several seconds later, the central zone is destroyed. The unmelted fuel tablets also fall down at the vessel bottom. The remaining water rapidly boils and cools the falling scrap. By this moment, the amount of water in the first circuit is sufficient for keeping the scrap at the bottom of the vessel poured. However, the water vaporization is enhanced, and approximately 1300 seconds later the start of the accident water is completely absent from the reactor vessel. The debris of two central zones heats the bottom, and it is melted 1600 seconds after the start of the accident. The melt appears in the reactor pit, and intensive vaporization of water from the pit and concrete destruction by the action of high temperature start. Further destruction of core occurs inside the reactor vessel, and only 5% of its total mass remain solid by the moment of the calculation end. The complete

vaporization of water from the reactor pit takes 25,000 seconds (or, approximately, seven hours).

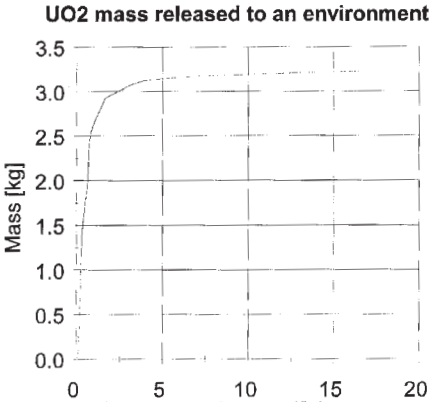
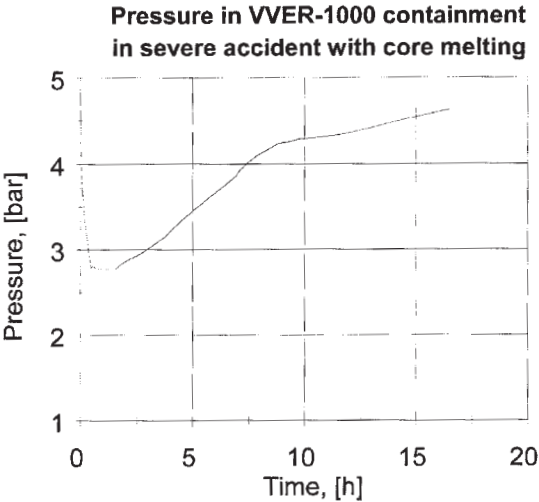
Figure 2 illustrates the thermohydraulic processes that occur in course of the specified scenario. It shows the time dependence of pressure inside the VVER-1000 containment and the value of mass of UO₂ released into environment.

3. Using the obtained parameters of the emergency release, we calculated the trajectory of propagation of the radioactive cloud and made a prediction of the probable radiation situation in the close proximity of the plant.

Such calculations are performed in IBRAE RAS on the basis of customary Gaussian models of the release propagation, which have shown good applicability within the distance of several kilometers from the release source (program code "TRACE" [1]), and on the basis of more complicated Lagrange models (program code "NOSTRADAMUS" [1]), which allows one to perform calculations for the distances of several hundred kilometers from the plant and accounts for changes in meteorological situation. The mentioned computer codes can predict the concentrations of radionuclides in the surface layer of the atmosphere; density of the territory contamination by radioactivity after the cloud pass; exposure doses of gamma radiation in the open air, and possible doses of external and internal radiation of people. The results of such calculations are intensively used in Russia when preparing and conducting practical games, Which emulate major radiation accidents, for assessment of the expediency of implementing various population-protecting measures (people housing, population evacuation, iodine prophylactics, etc.) in the region of the NPP, and for the analysis of the required and sufficient means and forces for such measures [2-4].

The performed calculation show that under usual weather conditions and within the specified accident scenario, the territory contamination density by Pu-239 at the distance 5 km from

Figure 2
**Thermohydraulic processes for the
specified accident scenario**



the NPP can reach 1.3 mBq/m², or 60 times larger than global average soil contamination density resulted from the nuclear weapons tests, according to estimates reported by the UN scientific Committee for Nuclear Radiation Effect.

4. In order to transform the territory contamination density to human exposure doses, we performed the analysis of actual and calculated data on people exposure doses by plutonium isotopes after the Chernobyl NPP accident. It was shown that 10 years later the accident, the ratio of the territory contamination density by Pu-239, 240 in kBq/m² and the annual effective exposure dose in μ Sv/year can reach 2.7, and 70 years after the accident this value could be the same density by Pu-239, 240 in this case is 0.66 mSv.

Table 4 displays the data on the comparison of radiation burden upon the population due to plutonium isotopes and other radionuclides for the occurred accidents (Chernobyl NPP and fuel plant "Mayak" in the Chelyabinsk region) and the accident described by the considered scenario.

In conclusion, we can emphasize that, if the post-accident contamination density of the territory at the distance 5 km from the NPP that uses Pu-239-enriched fuel would not exceed 1.3 kBq/m², then average cumulative people exposure doses resulting from the Pu-239 release would not exceed 0.86 mSv for 70 years of residence in the zone. This value is 1.2% of the exposure due to natural background for the same time interval. The dose for the personnel in the zones of intensive dust production can be 5-10 times large, but even in this case they are not dangerous for the human health. Thus, using the Pu-239-enriched fuel for the NPP with VVER-1000 reactors, even in the case of the severe accident with core meltdown would not aggravate the consequences of the accident for the population residing in the zone of the NPP.

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The Disposition of Weapon Grade Plutonium: Costs and Tradeoffs

William J. Weida



Abstract

This paper explores some of the economic issues surrounding a major area of expenditures now facing the nuclear powers: the disposition of weapon-grade plutonium either through 'burning' in nuclear reactors for power generation or by other means.¹ Under the current budgeting philosophy in the United States, programs managed by the Department of

Energy (DOE) tend to compete with one another for the total funds assigned to that agency. For example, in the FY1995 DOE budget a tradeoff was made between increased funding for nuclear weapons and reduced funding for site cleanup. No matter which disposition alternative is chosen, if disposition funds are controlled by the DOE in the US or by a government agency in any other country, disposition is likely to compete directly or indirectly with other alternatives for energy funding. And if they are subsidized by any government, research into plutonium as reactor fuel or the operations associated with such use are likely to consume funds that might otherwise be available to support sustainable energy alternatives.

When all costs are considered, final waste disposal costs will be incurred whatever disposal option is taken. These costs could potentially be offset by doing something profitable with

the plutonium prior to final storage, but this paper has shown that finding a profitable use for plutonium is unlikely. Thus, the more probable case is one where the costs of basic waste storage are increased by whatever costs are associated with the disposition option chosen. The factors most likely to significantly increase costs appear to arise from four areas:

- (1) The level of subsidization in the "profitable" parts of the disposition program.
- (2) Those items (such as reprocessing) that increase the volume of waste and thus, the cost of waste disposal.
- (3) The cost of security and its direct relationship to the number of times plutonium is handled or moved.
- (4) The cost of research and development of new and unproven methods of disposition.

Introduction

Over the last three years, the uneconomical aspects of burning plutonium have been made abundantly clear by a number of studies. In spite of this, of all the materials, systems, facilities, and laboratories involved in the design and operation of nuclear weapons, the most readily available assets for reuse are usually identified as being the plutonium from warheads. Over the last two years, quasi-private consortia have put considerable effort into convincing the US government to embark on such a program. These efforts have either

- (1) assumed that there was an economical way to burn plutonium for power,
- (2) proposed the construction and operation of new reactors specifically built to burn plutonium as part of a regional conversion plan for old nuclear weapon sites, or
- (3) claimed that even if power generation itself was uneconomical, it would still provide a way to dispose of the large

stocks of plutonium that was economically sound in the long run and was worthy of government support.

At the same time, other technical solutions for the plutonium problem have also been proposed. Many of these are transmutation techniques that would require large amounts of federal research and development money to construct facilities to turn plutonium into shorter-lived elements.² Others, such as shooting plutonium into the sun, are equally expensive. With the exception of the Integral Fast Reactor (IFR), which has also been marketed under category (2) above, transmutation has generally been proposed as a pure government research project.

In this paper, comparisons between plutonium and other forms of nuclear power generation will be made using the general "industry model." In these comparisons, the costs associated with the wastes generated during the creation of nuclear power will not be explored because these costs are approximately identical no matter what kind of nuclear operations are undertaken. However, a full accounting of these costs would be necessary before any form of nuclear power generation is compared to coal, gas, hydroelectric, or solar generation schemes.

As a further issue, it should also be remembered that most nations are currently struggling with nuclear proliferation issues. Recent problems with North Korea have demonstrated that because plutonium is normally produced as a by-product of reactor operations, civilian nuclear power generation may be in fundamental opposition to proliferation goals in spite of international safeguards installed at most plants. Reactor grade plutonium is about 25% Pu240 as opposed to 6% in weapons-grade plutonium.³ However, the use of reactor-grade plutonium in a nuclear weapon was successfully demonstrated at the Nevada Test Site in 1962.⁴ Further, actually burning plutonium for power legitimizes the reprocessing of spent fuel and the possession of plutonium, both of which vastly complicate the proliferation issue. When evaluating any disposition option,

one should keep in mind that the major obstacle to building a bomb is getting plutonium. When that obstacle is overcome, the rest is much simpler.

The Economic Value of Plutonium

Value is normally established through a market mechanism in which a buyer and seller negotiate a price viewed as fair by each. At the present time, no market for plutonium has formed, due partially to a lack of demand, partially to plutonium's role as a heavily controlled substance, and partially to adverse public reaction over the shipment and use of plutonium. The only sizable market for civilian plutonium in recent years was one created by Japan's purchase of plutonium from France for future use in its breeder reactor program. Pricing in that market was not public, but Japan's unique lack of alternative energy sources make its determination of the value of plutonium inapplicable to most other countries. Further, adverse publicity generated by the plutonium shipments on the Akatsuki-maru in 1992-1993 are likely to prohibit similar purchases by Japan in the future—thus terminating the market. It is probable that there is another, illicit market for plutonium, but prices in this market are surely much higher than the actual value of plutonium because of the risk involved. Hence, neither previous experience nor the illicit market provide much guidance as to the actual value of plutonium.

If all costs of plutonium are considered, it would be some of the most expensive material ever created by man. Further, the true costs of reusing plutonium generated through dismantlement of nuclear weapons would also have to include:

The research costs accumulated in developing the materials.

The initial costs to extract uranium, to purify the materials and to make plutonium in reactors.

The cost to fabricate the materials into weapons.

The cost to maintain plutonium in weapons.

The cost to dismantle weapons and free plutonium for other uses.

And finally, the future costs of waste disposal would have to be included.

Accounting for the past costs of plutonium would make it too expensive for any alternative use and, whether legitimately or not, these costs are usually counted as the costs of doing business during the Cold War. As a result, alternative uses of plutonium are usually considered under the assumption that all past costs are sunk costs and future decisions are based only on the future costs of disposition.

Russian Perceptions of the Value of Plutonium

Russia's approach to valuing plutonium appears to be at least partially based on the costs expended to create it. Viktor Mikhailov, Russian Minister of Atomic Energy, has said that plutonium cost the Former Soviet Union six times as much to make as HEU so it is unacceptable to destroy it.⁵ He has also stated that "we have spent too much money making this material to just mix it with radioactive wastes and bury it."⁶

However, many Russians recognize that if plutonium has any real economic value, is only as a future energy source. The Director of the Obninsk Institute has acknowledged that plutonium does not have any economic value in the near term, but he noted that doesn't mean that the economy won't eventually change to favor the use of "products for future technology, which we cannot use today."⁷ In spite of this, Russian engineers are planning to use existing supplies of reactor-grade plutonium long before such use becomes economically viable—possibly to avoid the handling difficulties encountered as components of reactor-grade plutonium break down and become more radioactive over the next few years. This will allow Russia

to keep its weapons plutonium in storage for the next few decades.⁸

It is probable that the near-term attempts by Russia to use plutonium as reactor fuel are partially based on two perceptions—both of which affect assessments of value: first, such use allows more oil and gas to be exported, and second, shipping reactor fuel is easier than shipping coal, oil, or gas in a country as large as Russia. Viktor Mikhailov has proposed using part of the \$10 billion in hard currency Russia will generate by selling 500 metric tons of highly enriched uranium to the United States to help build new breeder reactors to produce more plutonium. Completing the first two reactors and a MOX factory to turn the plutonium into reactor fuel would cost \$2.5 billion, according to experts at the Institute of Physics & Power Engineering.⁹

Assuming these potential uses of plutonium do actually represent an assessment of its value instead of bureaucratic inertia or some other rationale, these assessments are clearly not universally accepted in Russia. Aleksei Yablokov, an adviser to President Boris Yeltsin and a former environment minister, claims it is not clear that existing nuclear reactors, let alone new ones, make economic sense when Russia could replace all its reactors with natural gas and coal-fired power plants for an estimated \$6 billion to \$7 billion. In contrast, he claims the International Atomic Energy Agency has stated that upgrading existing Russian reactors to Western safety standards would take between \$26 billion and \$120 billion.¹⁰

US Perceptions of the Value of Plutonium

As was the case in Russia, the US Department of Energy has usually calculated the value of US plutonium based on the costs to manufacture it. And as it was in the Russian case, the fallacy in the proposition that something is valuable if it is expensive to produce is obvious. Further, in a county such as the US which is not currently considering the use of reprocessing or breeder

technology, the prior costs used to value plutonium are neither market-based nor necessarily rational. As a result, all calculations of the value of US plutonium by independent sources have come to the same conclusion: the value is negative—at least for the foreseeable future.

As an added factor, when one evaluates the economics of plutonium burning in commercial reactors as a method of disposition, basic physical rules apply: first, reactors using plutonium generate approximately the same amount of power as they would if only uranium was used. Second, the quantity of material put into a reactor becomes the quantity of spent fuel generated by the reactor. Thus, only one cost comparison between plutonium and uranium is necessary to show if plutonium can be burned with an economic benefit and therefore, has a positive value:

(1) The costs of processing and fabricating reactor fuel—and whether these costs would be higher or lower when plutonium is used.

At prices of (\$20/kg) for natural uranium and (\$70/SWU) for separative work, low enriched uranium (LEU) costs about \$750/kg. This is about half the estimated cost of \$1300 - \$1600/kg for new MOX fuel. At these prices, disposing of 200 tons of plutonium would cost an additional \$1.5 billion over burning LEU (or \$2 - \$10 billion using a reasonable range of future LEU and MOX prices).¹¹

Also of interest is whether the costs of disposing of plutonium might be lowered by burning it in a reactor, or whether the overall costs of disposition can be reduced by simply disposing of plutonium without burning it. These disposition costs will be explored later in this paper, but with no operating market for plutonium, and with existing prices for plutonium that have been set by governments, it is fair to say that no one has established an economic value for plutonium. The lack of market information causes pricing problems that cascade through any

commercial operations when plutonium is introduced into a power-generating regime where market analysis and cost control govern which power sources are exploited.

The Nature of the Commercial Nuclear Industry In The United States

Since its inception, subsidies have been a way of life in the US nuclear power industry. A 1992 report found that over the period 1950 to 1990, 20% or \$96 billion of the \$492 billion (in 1990 dollars) spent to develop and obtain nuclear power was provided by the US federal government.¹² According to the DOE, of total subsidies to the energy sector provided by the federal government in 1992, nuclear energy received \$899 million of \$4.88 billion expended—or about 18%. However, while most other sources of energy (oil, coal, etc.) received either tax subsidies to lower prices or direct subsidies to encourage consumer use—both of which acted to stimulate demand for the product—nuclear energy received almost all of its subsidies (\$890 out of \$899 million) in Research and Development. In fact, in the US, nuclear energy received 44% of all energy R&D subsidies in 1992.¹³

Over the last forty years, funding of nuclear energy research has continued with little actual implementation of research results. As construction of new reactors in the US ceased—the last US commercial nuclear reactor was started in 1978—a few large companies stayed in the reactor research and development business without having to sell economically viable reactors. In such a situation, there has been no need for commercial products—instead, the emphasis has been on selling and maintaining large research and development programs. Each new research and development (R&D) proposal has been further removed from the last project private industry

and the public were willing to accept and fund. One result of this situation has been to create an industry interested in the development of sources of power, not the economics of producing power.

This helps explain the nuclear industry's continuing research into the use of plutonium burning reactors in the face of overwhelming evidence that such reactors would be economically unfeasible. As time has passed, the economic viability of even standard nuclear reactors has deteriorated. This is unlikely to improve in the future when plans to generate power from plutonium are proposed to take place. Evaluating the current status of nuclear power in the US, Shearson Lehman reports that: "Evidence suggests the average operating costs of nuclear power plants are now higher than those of conventional plants and other power supply alternatives."¹⁴ And Moody's investor's service has stated that:

"Given increasing competition from other types of generating facilities and renewed efforts via conservation and demand side management programs to reduce the need for new capacity additions, nuclear power's economics must be comparable with alternative fuel sources and energy efficiency and conservation options. In a deregulating environment, the pressure to maintain competitively low rates will compel utilities to select the most economic option. And given the challenges outlined above, we do not think that nuclear plants are likely to provide such economic benefits."¹⁵

The questionable ability of commercial nuclear reactors to compete with other power generators in the US has been further complicated by recent increases in the price of uranium. Many uranium producers ceased operations in the 1980s and the supply of down-blended Russian uranium available to western markets has been below expectations. Since January 1, 1996, the price of uranium has risen 18% to \$14.75 a pound, and prices have risen by 55% since the start of 1995. Uranium prices

peaked at \$40 in 1979 and were at \$5 per pound in 1991 when the industry's competitiveness problems began.¹⁶

Chow and Solomon estimated that thermal cycle plutonium use¹⁷ in commercial reactors will not be feasible until the price of uranium-bearing yellowcake reaches \$100/LB and they estimated that this will not occur for 50 years.¹⁸ They further projected that fast reactors will not be profitable until yellowcake prices reach \$220/LB in about 100 years.¹⁹ It should be noted that the costs of burning plutonium are always compared with the costs of burning highly enriched uranium (HEU) or low enriched uranium (LEU) in reactors. Since the inherent costs of regulation, operating efficiency, waste disposal, and contamination associated with nuclear operations are approximately the same for both uranium and plutonium operations, these costs are never discussed in this kind of comparison. However, these costs, as well as the increasing price of uranium, are all factors when a country, city, or power supplier considers the price of alternative nuclear and non-nuclear power sources. And in this type of comparison, the very factor that makes the cost of using plutonium compare favorably with the cost of using uranium—a sharp increase in the price of uranium—also makes it more likely that neither fuel will be competitive with non-nuclear methods of power generation.

Burning Plutonium

The economic realities of commercially operating breeder reactors have been faced by the US, Japan, Germany, and France over the last twenty years, and the result has been basically the same in all four countries.

The US:

The United States spent \$1.7 billion on a breeder reactor in

the 1970s and early 1980s when uranium was expensive and the number of nuclear power plants in the US and abroad was expected to continue to increase. As the price of uranium dropped from \$40 a pound in 1982 to a little over \$5 a pound in the early 1990s the US dropped its breeder reactor plans. The US canceled the Integral Fast Reactor research program several years ago and US experts continue to believe that there will a long-term glut of uranium.²⁰

France:

In France, Superphenix, the first commercial-scale fast breeder reactor, has had continuous problems since it began operations in 1986. Leaks in the liquid sodium coolant system have persisted, the reactor was shut down in 1990, and it operated only 174 days in eight years. France's Atomic Energy Commission (CEA) claimed the reactor could burn 200 kg of plutonium a year and in March, 1994, it said it will make modifications to achieve that goal. It has not said what these modifications will cost. The French government says it has abandoned the idea that the Superphenix will ever make money.²¹

The French civilian power industry owes bondholders billions of francs and the French government no longer guarantees nuclear bonds. An independent study by the International Project for Sustainable Energy Paths claims that the French nuclear power industry is "the world's most indebted corporation" and cites continual overestimation of demand and underestimation of costs. Official estimates of costs were based on an increase of 1.5% per year. In actuality, costs rose at 5-6% per year. Overall, government nuclear power costs have probably been underestimated by at least 60%.²²

Germany:

Construction of Germany's Kalkar breeder reactor was halt-

ed in 1986 before the reactor became operational. The entire project was abandoned in 1991 after total expenditures of over \$4 billion. In 1995 the 40 acre reactor site was sold to an amusement park developer from the Netherlands who plans to market it as the “Nuclear Water Wonderland.”²³

Japan:

Japan has delayed from 2010 to 2030 several breeder reactors and a large reprocessing plant. The delay was partly due to citizen pressure and partly due to the sharply increasing financial risks. The Monju breeder reactor was activated in March, 1994, at a cost of \$5 billion and has been so expensive to run that a second reactor has been delayed until the next century.²⁴ On December 8, 1995, Monju experienced a sodium leak in the piping of the secondary cooling system that did not involve the release of any radiation. The accident was the largest ever to occur in the piping of an operating reactor and also the worst in terms of the leakage rate.²⁵

The Japanese program is now about 30 years old. Early forecasts about how cheap this reprocessing/breeder program would be have been wildly wrong—Japanese breeder reactors are now estimated by some sources to be 5 to 15 times more expensive to run than conventional nuclear power plants.²⁶

Specific Cost Additions Arising from the Use of Plutonium in Commercial Reactors

The use of mixed oxide fuel (MOX) containing plutonium in Light Water Reactors (LWRs) is technically proven. Reactors that use LEU can have 1/3 of their core in MOX. Three US reactors of the System 80 type at the Palo Verde Nuclear Generating Station are pressurized light water reactors (PWRs) that could handle a full core load of MOX. Using these reactors, it would take 30 reactor years—or 10 years for all three reactors—to convert 50 tons of plutonium into spent fuel.²⁷

A National Academy of Sciences (NAS) study estimated that a new MOX fabrication facility would cost between \$400 million and \$1.2 billion and would take about a decade to complete.²⁸ The cost of MOX fuel fabrication is estimated to cost over \$2000 per kilogram of heavy metal, about six times the fabrication cost of LEU fuel.²⁹ At MOX fabrication costs of \$1300-\$2000 per kilogram, the cost of uranium would have to rise to \$123-\$245 per kilogram just to equal MOX fabrication costs even if the plutonium used was free.³⁰ In addition, it is not clear that the NAS study included the additional costs of security and handling that would be certain to accompany any plutonium processing or storage.

Cost estimates for geologic repository disposal of spent fuel from commercial power reactors are about \$300,000 per ton of heavy metal (in 1988 dollars). However, the cost of disposal of a ton of plutonium would be higher because it must be diluted to make re-extraction difficult. Assuming a cost on the order of several million dollars per metric ton of plutonium, total disposal costs would range from \$100 million to \$300 million for 50 metric tons of plutonium.³¹

As was previously noted, the economics of plutonium burning have been investigated and rejected. Chow and Solomon looked at five options for using plutonium in reactors:³²

1. Use plutonium as fuel in existing fast reactors without reprocessing. Using weapon-grade plutonium in this manner would cost \$18,000/kg.
2. Use LWR's with 1/3 or partial MOX fuel without reprocessing. The cost for this is \$7,600/kg with weapon-grade plutonium.
3. Use LWR's with full MOX fuel loads without reprocessing. The cost for this is \$5,600/kg with weapon-grade plutonium.
4. Store plutonium for 20 or more years. Cost: \$3,800/kg.
5. Mix plutonium with waste and dispose of it as waste. Cost: \$1,000/kg in marginal costs over storing the waste alone—which would lead to costs of about \$4,800/kg.

None of these options has any commercial value. In the first three, the extra costs of handling plutonium because of its radioactivity, toxicity, and potential weapon use outweigh any benefits. Further, storage sites will not be ready until 2010 at the earliest, and when storage costs are taken into account, they raise the cost of burning plutonium in LWRs by \$4000 to \$10,000/kg. Because of these significant cost additions, the use of plutonium in civilian reactors creates no economic benefits.

Conversion as a Rationale for Plutonium Disposition in the US

One rationale for burning plutonium has been that even if a specific burning operation may not be economically viable, the use of the burning program as a tool of economic conversion³³ in a region or state justifies its implementation. A proposal of this nature raises the issue of whether a conversion program of similar impact be provided more cheaply.

The Triple Play Reactor, proposed for the Savannah River Site (SRS), and Project Isaiah, proposed for the old Washington Public Power System (WPPS) reactors around the Hanford site, have both been suggested as conversion programs where new or refurbished reactors would burn plutonium. Both programs have claimed they would be privately financed and, by implication, profit-making.

As a general principle, economic conversion is both site and sector based. On a site basis it preserves the local economic community by changing the base of economic support for the site. In an economic sector, it frees resources to be used in other ways for the benefit of the nation at large. Thus, the purpose of conversion is not to substitute one government-funded program for another, it is to change the economic base (the source of funds) for the region or sector. This cannot be achieved un-

less conversion generates economic benefits, and the Isaiah and Triple Play options demonstrate how the conversion approach to disposition has tried to adapt to the economic realities of plutonium burning.

The Isaiah Project

Proposed in 1993, this project involved burning plutonium in MOX and producing electricity by completing the WPPS #1 reactor at Hanford, WA and the #3 reactor at Satsop, WA. It has been claimed this would create 9,000 direct construction jobs, 2,500 permanent operations jobs and 13,500 secondary jobs in the region. Each plant would produce 1,300 MWe.³⁴

In 1993 dollars, completion costs for WNP-1 were \$1.7 billion and for WNP-2 they were \$1.6 billion. Operating costs were estimated at about \$21 million/year, and O&M costs at about \$123 million/year including the spent fuel disposal fee. When financing costs were included, the \$1.7 billion completion cost for WNP-1 rose to \$2.8 billion. However, private financing was supposed to cover all project completion costs and return \$4 billion to the Federal government.³⁵

While these financial arrangements sound promising, the poor economics surrounding this project were summed up by a clause in the Project Isaiah contract that stated that DOE would “enter into a long term contract.....[with] *a federal obligation to make debt service payments if revenues from the sale of steam [power is] not adequate.*”³⁶ (author’s italics)

Triple Play Reactor

The System 80+ “triple play” reactor was proposed by a quasi-private consortium to burn plutonium, produce tritium and generate electricity at the Savannah River Site. The triple play reactor is an advanced, pressurized light water reactor that would use a 100% MOX core and produce 1350 MWe. Two units would consume 100 metric tons of plutonium in 30 years

and would cost \$6.25 billion to build and deploy.³⁷ The reactor's Program Plan displayed considerable "uncertainty in costs" in MOX fabrication³⁸ and it proposed that the US federal government provide \$50 million in up-front financing.³⁹ The private consortium offered to pay back the \$50 million if DOE ultimately decided to proceed with the proposal at the end of the three-year study phase.⁴⁰

In addition, the Triple Play reactor required an extensive list of other subsidies:

The federal government had to provide a site and infrastructure at no cost to the consortium.⁴¹

The consortium pays disposal fees for waste, but then passes them through to the government, not to the consumer of the power.⁴²

The government supplies plutonium oxide, depleted uranium oxide, and the site lease, all at no charge, and it further agrees to sole-source irradiation services from the plant.

The "annual fees" required from the government were estimated at \$78 million for plutonium burning alone—about a 10% subsidy.

An annual fee would also be assessed for tritium production based on revenue losses and other factors.⁴³

The government shared liability for any increased costs due to regulatory changes or any other factors over which the consortium had no control.⁴⁴

Similar subsidies are likely to be required by project Isaiah because a majority of the proposed revenues from both projects are from electrical generation. An electricity-producing, plutonium-burning light water reactor is not economically feasible because of the additional facilities and security procedures required for plutonium handling. MOX fabrication will also add hundreds of millions of dollars to normal operating costs. Each of these factors increases the financial risk associated with the project.

In an October 10, 1995, DOE briefing on its 'Dual Track' strategy for producing tritium, Secretary O'Leary essentially abandoned the Triple Play option while proposing to "examine the policy and regulatory issues associated with purchase of a commercial reactor or irradiation service."⁴⁵ The cost of this option was estimated by the DOE to be between \$.2 billion and \$.45 billion⁴⁶—a cost to the US government that can be assumed to be less than the cost of subsidizing a Triple Play reactor. In 1988, the GAO estimated a total construction cost of \$.22 billion for converting the WNP-1 light water reactor at Hanford to produce tritium.⁴⁷ This would equate to a cost of about \$.29 Billion in 1995 dollars.

Disposition Requirements

Total Quantities of Plutonium

In 1991, the US had about 19,000 nuclear warheads and the Former Soviet Union (FSU) had about 32,000. Under START I and START II, the US and FSU agreed to reduce to 3,500 US and 3,000 FSU strategic warheads by 2003. Numbers of remaining tactical warheads may vary, but a good estimate would be about 1,500 US and 2,000 FSU tactical warheads. Thus, each side will have about 5000 nuclear warheads in 2003. About 2,500 warheads could be dismantled each year in the US, but only about 1,170 will be dismantled if parity is maintained with the FRS's rate of 2,250 per year.⁴⁸ The supply of plutonium available for reuse in the United States as of September, 1994, is shown in Table 1.

The outlook for Japanese plutonium inventories has changed considerably with the recent accident at Monju. Table 2 shows the Japanese plutonium inventory at the end of 1994. According to the long run supply and demand balance first presented by the Japanese Atomic Energy Commission in June,

1994, and revised in August, 1995, the annual supply of plutonium from the Tokai reprocessing plant is about 0.4 ton. This was short of the expected consumption of 0.6 ton by Monju, Fugen and Joyo, and this shortage was expected to be offset by plutonium imported from France. The Japanese government now says that plutonium stored for use in Monju will be used instead in Joyo, but the expected annual demand by Joyo and Fugen together is less than 0.2 tons. Thus, the total Japanese plutonium surplus in Japan and Europe could amount to around 25 tons by the turn of the century.⁴⁹

50 or more metric tons of excess weapon grade plutonium are now available in Russia.⁵⁰ While specific inventory breakdowns are not available for Russia, France, Great Britain, and

Table 1
US Plutonium Inventories and Locations

Site	Pu Inventory (in Metric Tons)	Pu in Wastes (in Kilograms)
DoD & Pantex	66.1	N / A
Rocky Flats	12.7	47
Hanford	11.0	1,522
Argonne Lab-West	4.0	2
Los Alamos	2.7	610
Savannah River	2.0	575
INEL	.5	1,106
Lawrence Livermore	.3	N / A
Others	.2	N / A
Oak Ridge	N / A	41
Nevada Test Site	N / A	16
TOTAL	99.5	3,919

Source: Secretary of Energy Hazel O'Leary, "Plutonium: The First 50 Years - United States Plutonium Production, Acquisition, and Utilization from 1944 to 1994," Department of Energy, Washington, DC, February 6, 1996.

Germany, based on the assumptions that there are less than 4 kg of plutonium in each warhead and that there are 20 metric tons of plutonium in the military inventories of other nuclear weapons powers, the global inventory of plutonium is approximately as shown in Table 3.

Aside from these inventories, the total amount of plutonium available for use in non-weapon applications is directly dependent on dismantlement of old warheads. The pit of a nuclear

Table 2
**Japan's Separated Plutonium Inventory
(as of end of 1994)**

Facility	Kilograms of Pu	Stockpiled(s) or in use/ready for use(u)*
Reprocessing plant	836	
As nitrate	710	s
Stored as oxide	126	s
Fuel Fabrication plant	3,018	
Stored as oxide	2,032	s
Under test or processing	948	u
Completed fuel	38	u
Reactor sites	498	
Joyo	6	u
Monju	15	u
Fugen	53	u
Critical assemblies	425	u
Overseas reproprocessors	8,720	
UK(BNFL)	1,412	s
France(COGEA)	7,308	s
Total	13,072	11,588(s)+1,484(u)

Takagi, Dr. Jinzaburo, Citizens' Nuclear Information Center, 1-59-14-302, Higashi-nakano, Nakano-ku, Tokyo 164, Japan, January 10, 1996.

*Attribution to u and s by Dr. Takagi.

weapon is composed of plutonium and weighs, on average, about 3-4 kilograms. The secondary is HEU that is over 90% U235 and weighs about 15 kg.⁵¹ Surplus US warheads contain about 50 tons of plutonium and up to 400 tons of HEU. Soviet Warheads contain about 100 tons of plutonium and more than 500 tons of HEU.⁵²

Beginning in October, 1992, the DOE set a dismantlement goal of 2000 warheads per year for the US. As Figure 1 shows, this goal has never been met, and, at the current pace, dismantlement work at Pantex is likely to continue for three or four more years. On January 19, 1994, the DOE announced a decision to increase pit storage at Pantex from 6,000 to 12,000 pits. As of May, 1995, there were 7239 pits stored at Pantex, meaning that there will be about 8500 pits stored in May of 1996. Given the remaining storage space—3500—it is likely that there is insufficient space for the remaining warheads scheduled for dismantlement and this can be expected to increase pressure to find some other means of disposing of these materials.⁵³

Table 3
Global inventies of plutonium

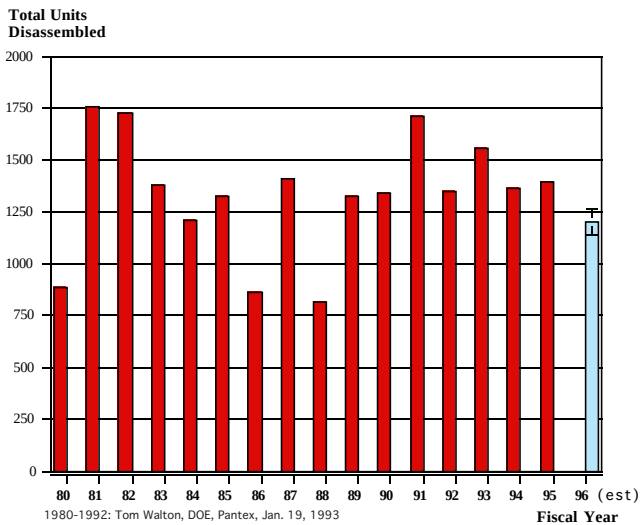
Source of Plutonium	Metric Tons
Military plutonium	248
Separated civilian plutonium	122
Unseparated plutonium in civilian spent fuel	532

Source: Makhijani, Arjun, and Annie Makhijani, *Fissile Materials In A Glass, Darkly*, IEER Press, Takoma Park, Maryland, 1995, p. 11.

The Costs of Transmutation and Other Non-Burning or Technical Fixes

Complete elimination of plutonium is only possible through two means: first, wait until the natural radioactive decay destroys it—this would take thousands of years. Second, transmute plutonium by using some technique to bombard its nuclei and split them into fission products. Option two can only occur through a nuclear reaction in a reactor or in a particle accelerator.⁵⁴ Most elements created by transmutation would have much

Figure 1
**Dismantlement Rates for Nuclear Warheads
At The Pantex Plant, Amarillo, Texas**



shorter half-lives than plutonium. Thus, the potential benefits of transmutation could be:

1. A reduced volume of material.
2. Reduced radioactive life of materials.
3. Less risk of human intrusion into storage areas.⁵⁵

Most transmutation techniques require reprocessing and, hence, are likely to be unacceptable in the US on the basis of both proliferation and waste generation concerns.⁵⁶ DOE's own studies show that in the US

"Over a period of 40 years, [reprocessing] plants generated 105 million gallons of highly radioactive and hazardous chemical waste."⁵⁷

"The high-level waste generated in chemical separations contains almost 99 percent of all radioactivity present in by-products and waste generated by nuclear weapons production."⁵⁸

In fact, the US Government Accounting Office (GAO) has noted that "the reprocessing and separating of the waste are more difficult technical problems than transmuting the long-lived elements from the waste."⁵⁹

Waste transmutation would take many billions to develop and is not possible before 2015.⁶⁰ DOE believes it is not economically justifiable since a waste repository would still be needed. A complete transmutation system of the kinds shown in Table 3 includes a reactor or accelerator to transmute reprocessed fuel, a spent fuel reprocessing and waste separation facility, a fuel fabrication facility, and storage facilities for spent fuel and residual wastes.⁶¹

In addition to the transmutation techniques shown in Table 3, the following proposals have been subjected to enough investigation to either allow the estimation of costs or to identify similar process for which costs are generally known:

Table 4
Potential transmutation technologies

Potential Programs	Sponsor	Units & Time To Destroy 90% Of LWR Actinide Waste Expected in 2010	Schedule/ Cost(\$1993)	Destroys Actinides	Destroys Fission Products
Advanced Liquid Metal/ Integral Fast Reactor (ALMR/ IFR)	DOE, GE Argonne	19 Units and 200 years Ops Cost: \$32 B	\$5B (1 reactor) +4 B/ Unit for remainder Start: 2015 Operate: 200 yr.	Yes	No
Accelerator Transmutation Project (ATW)	LANL	19 Units 40 years	Develop: \$5B Start: 2016 Total: \$120B	Yes	Some Including Pu and U
Phoenix Accelerator Pu nor U	Brookhaven National Lab	1 or 2 units 25 years	Develop: \$29B Development Time: 15-20 yr.	Yes	Some Neither
Particle- Bed Reactor (PBR)	Brookhave National Lab	20-70 Units 40 years (150 yr. for Pu)	Develop: \$1.3B Development Time: 16 yr. No cost estimate	Yes	Yes
Clean Use Of Reactor Program (CURE)	Hanford / Westinghouse		Rsch: \$74-160 M No cost estimate	No	Yes

Source: *Developing Technology to Reduce Radioactive Waste May Take Decades and Be Costly*, GAO/RCED-94-16, United States General Accounting Office, Washington, DC, December, 1993

1. Monitored Surface Storage

In 1990, a monitored storage facility for 50 tons of plutonium had an estimated capital cost of \$170 million (1990 dollars) with an operating cost of \$28 million per year.⁶² Preliminary estimates by Fetter were that storing plutonium would cost about \$1 per gram per year. Thus, storing 200 metric tons would cost roughly \$200 million per year for a net present value cost of \$2 billion.⁶³

In 1994, civilian plutonium reprocessors charged between \$2 and \$4 per gram for storing separated plutonium. At these prices, storing 50 metric tons of plutonium for a decade would cost from \$1 to \$2 billion.⁶⁴

2. Deep Geologic Disposal/Seabed Disposal

The cost is essentially that for vitrification and for burial in Yucca Mountain—i.e., the cost of both operations. See the vitrification option below.

3. Launching Plutonium Into the Sun

A 1982 NASA study estimated the cost of this option at \$200,000 per kilogram of plutonium. Several hundred kg could be handled at a time. This is probably not feasible due to public fears about the potential for a crash and resulting dispersion of plutonium from one of the rockets.⁶⁵

4. Underground Nuclear Detonation

In one Russian proposal, 5000 warheads would be destroyed in a single explosion of a 100-kiloton warhead. A US option proposed using small shafts to destroy 5 warheads at a time (about 3000 detonations would be required.) Even if one destroyed 50 warheads at a time, 300 detonations would be required—almost half of the 730 US underground tests conducted to date.⁶⁶ The costs of this option would be similar, although not identical, to the costs to conduct underground tests of nuclear weapons which ranged from \$20 million to \$60 million per test.

Sixty-three past US underground tests involved more than one explosive device, and one test used six devices.⁶⁷ Thus, the technical aspects of this option are fairly well known. Costs would be lowered to the extent that the extensive telemetry and experiment design required for successful underground tests would not be required. However, costs would be increased to the extent that underground pollution of aquifers and other resources occurred.

5. Vitrification

By 1994, the DOE had spent over \$1 billion trying to vitrify liquid wastes and had not yet succeeded. However, plutonium may not share these problems and it could be formed into blocks weighing thousands of pounds to make theft more difficult.⁶⁸ However, while vitrification of plutonium alone is an option, it is unlikely to present a sufficient barrier to reuse.⁶⁹ For this reason, prior to vitrification, plutonium will most likely be mixed with other materials that would make repurification more difficult.⁷⁰

There are three general vitrification options with potential for plutonium disposition:

1. Vitrification of plutonium mixed with gamma-emitting fission products so the resulting glass logs meet the spent fuel standard.⁷¹ These fission products have much shorter half-lives than plutonium. For example, the half-life of Cesium 137 is only 30 years as opposed to 24,000 years for plutonium. Thus, the mix would become less resistant to proliferation over time. This is likely to take longer since vitrification plants are not prepared for this task.⁷²
2. Vitrification of plutonium with depleted uranium or some other alpha-producing element.
3. Vitrification of plutonium with a non-radioactive element, such as europium, that would render the mixture unsuitable for weapons without reprocessing.⁷³

According to one proposal, the US could incorporate high level waste (HLW) like plutonium into 25,000 tons of glass at a rate of about 1000 tons of glass per year. This would allow the disposal of 100 tons of plutonium in five years if the glass contained only 2% plutonium. A recent analysis by Pacific Northwest Laboratories estimates the total additional cost at \$100 million to convert 100 tons of plutonium metal to oxide and mix it with other HLW—ten times cheaper than storage, and ten to fifty times cheaper than MOX.⁷⁴ One could also place a barrier to misuse by subnational groups by making the canisters in which vitrified plutonium is stored highly radioactive.⁷⁵

Critics note that vitrification leaves weapon-grade plutonium in a recoverable form that is not isotopically contaminated and has a low probability of going critical in storage. Plutonium is relatively insoluble in water, but boron, which is the medium that absorbs neutrons, is not. Thus, they claim vitrified waste stored in the presence of water could go critical.⁷⁶ However, the MIT engineering group that has performed the research on the “clean glass” borosilicate vitrification option found that extracting the plutonium from this medium would present a formidable barrier to subnational groups. Further, tests conducted by this group show the borosilicate glass to be quite durable in the presence of water.⁷⁷

6. Mix and Melt

Proponents of this method, such as Argonne National Laboratory, claim that reactor grade plutonium cannot easily be used to make weapons because it has 5 times the isotopic contamination of weapons grade plutonium, its radioactivity makes it more difficult to work with, and weapons made from this material would have an unpredictable yield.⁷⁸

The mix and melt alternative proposes to melt plutonium together with spent fuel resulting in a mix that is too isotopically contaminated to easily make weapons without a time-consum-

ing and expensive process. After this procedure is performed, the separation of isotopes would be so difficult that anyone who could do it would likely prefer to use “fresh” weapons grade plutonium instead.⁷⁹ The cost of this option would probably be similar to the \$4 billion cost of the pyroprocessing reprocessor recently proposed as part of the US Integral Fast Reactor project.

Wolfgang Panofsky, chair of the NAS Plutonium Study, notes that the mix and melt process, as a variant of pyroprocessing, is largely unproved and would require a plant capable of handling over 2000 tons of heavy metal and 50 tons of plutonium—a plant that would be a giant reprocessing facility that has undergone neither engineering development nor any aspect of the regulatory process. The reactor grade plutonium in question is of approximately the same isotopic concentration of Pu239 as weapon grade plutonium. Further, no proposal for decreasing the isotopic concentration of Pu239 makes it less desirable to terrorists since “it has been amply and convincingly documented that, while reactor-grade plutonium has not been the material of choice for past weapons builders, an explosive device with an assured yield of one to two kilotons could be built from reactor-grade plutonium by relatively elementary methods.....In the hands of a terrorist or proliferator such devices would be formidable indeed.”⁸⁰

7. Burning plutonium in unconventional matrices

This solution has been proposed by members of the Nuclear Engineering Department of the Centro Studi Nucleari Enrico Fermi in Italy. Japan, Russia, and Switzerland are considering the unconventional matrix approach for their PWRs, as is Canada in its D₂O reactor.

One of the authors of the proposal has noted that the economic implications of this proposal are not markedly different from those for burning MOX. Discharged fuel would not under-

go reprocessing or chemical treatments, leading to a one-time pass through only. The inert matrices have not undergone systematic testing and the development of these fuels still remains to be accomplished.⁸¹

Conclusion

Several studies on alternatives for disposition of plutonium have noted that due to potential proliferation problems and the danger these pose for all people, disposition issues should be decided based on expediency and safety, and economic considerations should not play a major role in this process.⁸² However, a student of the military budgeting process or the budget considerations surrounding a major infectious disease such as AIDS will realize that there is no precedent for real-world decisions—even those that concern threats to large numbers of people—being made in an environment free of economic considerations. In fact, in making such decisions it is not unusual for economic costs and benefits to be considered first, not last. For this reason, it is necessary to identify those factors involved in the disposition area that will create common costs across all options, and to specify those areas where specific factors are likely to be major cost drivers that could discriminate between the various disposition options.

This paper has shown that burning plutonium in power generating reactors is not economical at the present time and is unlikely to become economical at any time in the near future. As the recent National Academy of Sciences study stated,

“Exploiting the energy value of plutonium should not be a central criterion for decision making, both because the cost of fabricating and safeguarding plutonium fuels makes them currently uncompetitive with cheap and widely available low-enriched uranium fuels, and because whatever economic value

this plutonium might represent now or in the future is small by comparison to the security stakes.”⁸³

However, even if burning plutonium is not economical, is it still cheaper than other methods of dealing with or disposing of plutonium? This question incorporates both proliferation risk and economics, and the following framework is suggested as a way in which it might be considered:

First, it is obvious that increased handling of plutonium leads to increased costs and increased proliferation risks.

Second, any proposal to burn plutonium in reactors to reach a spent fuel standard might also be accomplished more simply and cheaply by mixing plutonium with waste to a spent fuel standard to start with.⁸⁴ As an isotopically different element, plutonium can always be chemically separated from spent fuel whether it was generated inside a reactor or simply mixed with existing spent fuel, although the difficulty associated with this operation can be increased by adding other elements to the mix.

Third, waste storage costs, irrespective of the method of storage chosen, are based on volume and radioactivity and will be the same for all burning and non-burning options. In any process that requires putting material in a reactor, whether for power generation or simply to dispose of the material, the volume of material will remain constant throughout the process and the radioactivity of the spent fuel will be approximately the same for storage considerations. The only exception to this rule occurs when reprocessing is involved. Then both waste volume and costs rise dramatically. And fourth, for transmutation, costs are altered because one is handling hotter material for relatively shorter periods of time—but these time periods are still so extensive that discounted cost comparisons between alternatives cannot show significant differences. In addition, transmutation technologies still require reprocessing and they still must absorb the cost of research and development. Other options do not have either of these negatives.

Viewed in this light, final waste disposal costs will be incurred whatever disposal option is taken. These costs could potentially be offset by doing something profitable with the plutonium prior to final storage, but this paper has shown that finding a profitable use for plutonium is unlikely. Thus, the more probable case is one where the costs of basic waste storage are increased by whatever costs are associated with the disposition option chosen. The factors most likely to significantly increase costs are the major cost drivers that create differences among the various options for plutonium disposition. At this point, major costs of plutonium disposition appear to arise from four areas:

- (1) The level of subsidization in the "profitable" parts of the disposition program.
- (2) Those items (such as reprocessing) that increase the volume of waste and thus, the cost of waste disposal.
- (3) The cost of security and its direct relationship to the number of times a material is handled or moved.
- (4) The cost of research and development of new and unproven methods of disposition.

These four costs outweigh all other costs of disposition by many orders of magnitude and, as a result, minimizing their impact should be the major consideration in choosing among disposition options.

NOTE

¹For example, see

Chow, Brian G. and Kenneth A. Solomon, *Limiting the Spread of Weapon-Usable Fissile Materials*, National Defense Research Institute, RAND, Santa Monica, CA, 1993, and *Management and Disposition of Excess Weapons Plutonium (Pre Publication Copy)*, Committee on International Security and Arms Control, National Academy of Sciences, National Academy Press, Washington, DC, 1994.

"Burning" is the techno-slang word for using plutonium in nuclear reactors by mixing it with uranium to form a mixed oxide fuel (MOX) that can be burned in light water reactors (LWRs).

²Elements with half-lives of 50 to 100 years instead of the 24,000 years possessed by plutonium.

³von Hippel, Frank, "Fissile Material Security In The Post-Cold-War World," *Physics Today*, June, 1995, p. 32.

⁴Makhijani, Arjun, and Annie Makhijani, *Fissile Materials In A Glass, Darkly*, IEER Press, Takoma Park, Maryland, 1995, p. x.

⁵Garwin, Richard L., *Critical Question: The Value of Plutonium*, presented at Cornell University, October 1, 1993.

⁶Wald, Matthew L. And Gordon, Michael, "Russia And US Have Different Ideas About Dealing With Surplus Plutonium," *New York Times News Service*, New York, August 19, 1994.

⁷Ibid.

⁸Ibid.

⁹Ibid.

¹⁰Ibid.

¹¹Fetter, Steve, *Control and Disposition of Nuclear Weapons Materials*, Working Papers of the International Symposium on conversion of Nuclear Warheads for Peaceful Purposes, Rome, Italy, June 15,16,17, 1992, pp. 144-148.

¹²These figures significantly understate the current estimates of the costs to bury nuclear wastes and decommission reactors. Source: Komanoff Energy Associates, *Fiscal Fission: The Economic Failure of Nuclear Power*, 270 Lafayette, Suite 400, New York, NY, December, 1992.

¹³*Federal Energy Subsidies: Direct and Indirect Interventions in Energy Markets*, SR/EMEU/92-02, Energy Information Administration, US Department of Energy, Washington, DC, November, 1992, p. 7.

¹⁴*Electric Utilities Commentary*, "Are Older Nuclear Plants Still Economic?", Insights from a Lehman Brothers Research Conference," vol. 2, no. 21, May 27, 1992, p. i.

¹⁵*Nuclear Power*, Moody's Special Comment, Moody's Investors Service, New York, NY, April, 1993, p. 7.

¹⁶ Heinzl, Mark, "Uranium Prices Rise on Scarcity, Steady Demand," *The Wall Street Journal*, February 26, 1996.

¹⁷Reprocessing plutonium and U from spent fuel and using plutonium-bearing mixed-oxide (MOX) fuel in thermal nuclear power plants.

¹⁸Chow and Solomon, Op. Cit., pp. xvi, xvii.

¹⁹Ibid., p. xvii.

²⁰Wald, Op. Cit.

²¹Rothstein, Linda, "French Nuclear Power Loses its Punch," *The Bulletin of the Atomic Scientists*, July-August, 1994, pp. 8,9.

²²Ibid.

²³"A Great Fixer-Upper," *The Bulletin of the Atomic Scientists*, Vol. 52, No. 2, March / April, 1996, p. 8.

²⁴Sanger, David E., Japan, "Bowing to Pressure Defers Plutonium Projects," *The New York Times*, February 22, 1994.

²⁵Takagi, Dr. Jinzaburo, Citizens' Nuclear Information Center, 1-59-14-302 Higashi-nakano, Nakano-ku, Tokyo 164, Japan, January 10, 1996.

²⁶Sanger, Op. Cit.

²⁷Makhijani and Makhijani, Op. Cit., p. 26-27.

²⁸*Management and Disposition of Excess Weapons Plutonium*, Op. Cit., p. 159-160.

²⁹*Nuclear Fuel*, January 26, 1992.

³⁰Feiveson, H.A., *Plutonium fuel: An Assessment*, OECD, Paris, 1989, p. 69.

³¹Makhijani and Makhijani, Op. Cit., p. 66.

³²Chow and Solomon, Op. Cit., pp. xxi, xxii.

³³Conversion programs attempt to replace an obsolete or formerly federally funded economic base in a community or region with a new industry or base that does not rely on the old funding sources. In the case of nuclear plant locations, conversion programs have proposed to replace older DOE plants with new, privately-funded nuclear facilities.

³⁴Letter from Robert Wages, President, OCAW, to Elmer Chatak, President, Industrial Union Department, November 3, 1993.

³⁵Letter from John R. Honenkamp, SAIC, to Dr. Matthew Bunn, National Academy of Science, November 9, 1993.

³⁶Communication from Lauren Dodd, Battelle Institute, "The Isaiah Project," Pacific Northwest Laboratories, October 1, 1993.

³⁷*Program Plan for deployment of a System 80+ Multi-purpose Nuclear Facility at Savannah River Site*, System 80+ Team, Savannah River Site, Aiken, SC, March 31, 1994, pp. 1-12.

³⁸Ibid., p.8.

³⁹Ibid., p.9.

⁴⁰Personal communication between Brian Costner and George Davis of ABB combustion Engineering in May, 1995.

⁴¹*Program Plan for deployment of a System 80+ Multi-purpose Nuclear Facility at Savannah River Site*, Op. Cit., p.68.

⁴²*Ibid.*, p.70.

⁴³*Ibid.*, p.75 and personal communication between Brian Costner and George Davis of ABB Combustion Engineering in May, 1995.

⁴⁴*Ibid.*

⁴⁵O'Leary, Hazel, Briefing on Dual Track Strategy, Department of Energy, October 10, 1995.

⁴⁶*Ibid.*

⁴⁷GAO, 1988 and Barker, Rocky, "Experts Weigh Four Designs," *The Idaho Falls Post Register*, April 24, 1988.

⁴⁸Chow and Solomon, Op. Cit., pp. 9,10.

⁴⁹Takagi, Op. Cit.

⁵⁰*Management and Disposition of Excess Weapons Plutonium*, Op. Cit., p. 1.

⁵¹von Hippel, Frank, and Marvin Miller, Harold Feiveson, Anatoli Diakov, Frans Berkhout, "Eliminating Nuclear Warheads," *Scientific American*, August, 1993, p. 46.

⁵²*Ibid.*, pp. 46-47.

⁵³Norris, Robert S. and Arkin, William M., "US Nuclear Weapons Stockpile, July 1995," *The Bulletin of the Atomic Scientists*, Vol. 51, No. 4, July-August, 1995, pp. 78-79.

⁵⁴*Developing Technology to Reduce Radioactive Waste May Take Decades and Be Costly*, GAO/RCED-94-16, United States General Accounting Office, Washington, DC, December, 1993, p. 11.

⁵⁵*Ibid.*, p. 10.

⁵⁶Makhijani and Makhijani, Op. Cit., p. 98-100.

⁵⁷*Estimating the Cold War Mortgage—The 1995 Baseline Environmental Management Report*, US Department of Energy, Office of Environmental Management, DOE/EM-0232, March, 1995, pp. B.4 to B.5.

⁵⁸*Ibid.*, p. B.5.

⁵⁹*Developing Technology to Reduce Radioactive Waste May Take Decades and Be Costly*, Op. Cit., p. 13.

⁶⁰*Ibid.*, p. 3.

⁶¹*Ibid.*, p. 4,5.

⁶²Bloomster, C.H., P.L. Hendrickson, M.H. Killinger, and B.J. Jonas, *Options and regulatory issues related to disposition of fissile materials from arms reduction*, PNL-SA-18728, Pacific Northwest Laboratories, US Department of Energy, Washington, DC, 1990, pp. 12-13.

⁶³Fetter, Op. Cit.

⁶⁴*Management and Disposition of Excess Weapons Plutonium*, Op. Cit., pp. 126-127.

⁶⁵International Physicians for the Prevention of Nuclear War and The Institute for Energy and Environmental Research, *Plutonium—Deadly Gold of the Nu-*

clear Age, International Physicians Press, Cambridge, MA, 1992, pp. 130-138.

⁶⁶Ibid., pp. 130-138.

⁶⁷"Known Nuclear Tests Worldwide, 1945-1994," *The Bulletin of the Atomic Scientists*, Vol. 51, No. 3, May/June, 1995, p. 70.

⁶⁸For a discussion of potential problems and benefits associated with vitrification, see comments by Wolfgang Panofsky, Kevin Wenzel et al, and Alex DeVolpi in "Letters," *The Bulletin of the Atomic Scientists*, vol. 52, no. 1, January/February, 1996.

⁶⁹Makhijani and Makhijani, Op. Cit., p. 4.

⁷⁰Wald, Matthew, "Encase Excess Plutonium in Glass, US Urged," *The New York Times*, November 17, 1994.

⁷¹The spent fuel standard proposes to make plutonium as difficult to retrieve as it would be if it was in the form in which it exists in nuclear reactor fuel that has been irradiated (used) to the extent that it can no longer effectively sustain a chain reaction and thus, has been removed from the reactor for disposal. This irradiated fuel contains fission products, uranium, and transuranic isotopes.

⁷²Makhijani and Makhijani, Op. Cit., p. 88.

⁷³Ibid., p. 4.

⁷⁴Fetter, Steve, *Control and Disposition of Nuclear Weapons Materials*, Op. Cit., pp. 144-148.

⁷⁵Makhijani and Makhijani, Op. Cit., p. 89.

⁷⁶DeVolpi, Alex, "Fast finish to plutonium peril," *The Bulletin of the Atomic Scientists*, Vol. 51, No. 5, September/October, 1995, p. 20-21.

⁷⁷Wenzel, Kevin W.; Sylvester, Kory W.; Cerefice, Gary, "Reply to 'Fast finish to plutonium peril'," *The Bulletin of the Atomic Scientists*, Vol. 52, No. 1, January-February, 1996, pp. 59-60.

⁷⁸DeVolpi, Op. Cit.

⁷⁹Ibid.

⁸⁰Panofsky, Wolfgang K.H., "No Quick Fix For Plutonium Threat," *The Bulletin of the Atomic Scientists*, Vol. 52, No. 1, January-February, 1996, pp. 3, 59.

⁸¹Letter from Carlo Lombardi, Dipartimento Di Ingegneria Nucleare, Centro Studi Nucleari Enrico Fermi, to William Weida, November 30, 1994.

⁸²For example, see Makhijani and Makhijani, Op. Cit.

⁸³*Management and Disposition of Excess Weapons Plutonium*, Op. Cit., p. 3,4.

⁸⁴For a discussion of potential problems and benefits associated with "mix and melt" approaches to plutonium disposition, see comments by Wolfgang Panofsky, Kevin Wenzel et al, and Alex DeVolpi in "Letters," *The Bulletin of the Atomic Scientists*, vol. 52, no. 1, January/February, 1996.

Utilization of Excess Weapon Plutonium: Scientific and Technological Aspects of the Conversion of Military Capacities for Civilian Use and Sustainable Development

*Hans-Peter Winkelmann**



1. The Imperatives of Scientific and Technological Aspects of Conversion of Military Capacities for Civilian Use and Sustainable Development

Throughout history there has always been some reduction in military production in times of détente following wars. However, the end of the Cold War, in the aftermath of one of the biggest military build-ups and arms races ever, has left in its wake problems of unexpected magnitude: Threats to nations or to the world community are no longer limited to military aggression. While the decline of a military threat in the recent years resulting from the East-West détente is evident, the increasing environmental degradation caused by the high status of existing military potentials continues to be a source of deep global concern - despite all disarmament efforts.

Military activities have caused such formidable damage to the environment and to human health that their consequences will be felt for decades and, in instances of forms of radioactive

contamination, for much longer. Unfortunately, hardly any of the world's nations are devoid of contaminations caused by military activities, devastated landscapes, polluted groundwater and injured biota. Furthermore, damage has been spread throughout the oceans and atmosphere. The catastrophic nature of environmental contamination becomes more apparent as additional sites of contamination are discovered in the course of the ongoing disarmament process and as the effects of the damage at known areas manifests itself fully. The true extent of the environmental damage resulting from military activities during the Cold War is both massive and only now becoming apparent. The seepage of chemical or radioactive contamination into water systems and the corrosion of containers dumped at sea, containing chemical weapons or radioactive material are but two examples of problems that grow more serious with the passage of time. The scope of the problem and the technological needs can only be hinted at. A particularly important concern is the large number of nuclear weapon test areas that witnessed many of above-ground nuclear explosions and subjected surrounding populations to decades-long exposure to high levels of radioactivity. Thus, pollution from radioactive waste stored on land and at sea is a subject of great concern. There are many areas where nuclear waste has been stored in disregard of internationally accepted standards established to prevent environmental damage. The location and assessment of such sites is particularly urgent. In the first place, efforts must focus on pollution from radioactive materials, primarily those affecting oceans and waterways. In this context, problems of radioactive contamination arising from the accidental loss and decommissioning of nuclear submarines have received considerable public attention in the recent past. It is necessary to assess the effects on the marine and human environment of present levels of radioactivity, including the risks of increased levels of contamination owing to corrosion.

In dealing with the environmental legacy of the Cold War the dimensions of the effort needed to correct these problems is truly massive. A comprehensive and fast solution is beyond the economic means of today's society. Even spread over several generations, satisfactory clean-up can only be managed by prioritizing the problems, tackling or containing those that are most urgent and developing much more cost-effective technologies as soon as possible. International cooperation to share experience and resources, and to plan for the necessary efforts is imperative not only because of their similar nature and trans-boundary character. In the long range, alternative technologies, capable of drastically reducing clean-up costs, will have to be developed in order to bring the whole problem within affordable financial resources. International cooperation is needed to speed up the development of these technologies and to use the best efforts of the cooperation partner scientists.

The end of the Cold War and the evident decline of military threats between major powers of the world on one hand, and the wide spectrum of increasing environmental concerns including that are defence-related underscore the need for conversion of military scientific and technological capacities as an effective strategy to accompany national and international disarmament efforts and as a contribution to a development path in harmony with the natural carrying capacity of our planet. For the first time, the need to transform large-scale scientific, technological and industrial capacities formerly devoted to military purposes has become a worldwide issue affecting all nations, major powers as well as many smaller countries.

At the same time, the challenges of global environmental change have led the world community to adopt - at the United Nations Conference on Environment and Development - the new paradigm of sustainable development. Sustainable Development has broadened the traditional understanding of security: Global environmental change as the main destabilizing ef-

fect is also perceived as a vital risk to nations. In addition, environmental concerns are often blocking the dismantlement of nuclear weapons or their transport or dismantlement sites resisted by local populations and political bodies.

The question of how to respond to the need to transform large-scale scientific, technological and industrial capacities designed to serve the military-industrial complex by redirecting them towards environmental protection and accelerating the development process has increasingly become part of the discussion of a new understanding of "security".

The new understanding of security, the industrial restructuring for sustainable development, the human resources issues, the cleaning up of the Cold War legacy and developing timely alternative use plans for military facilities constitute the framework for the issues of concern. This framework should be looked at more detailed in the following.

2. The Framework of Scientific and Technological Aspects of Conversion

The scientific and technological aspects of the conversion of military capacities for civilian use and sustainable development concerning the utilization of excess weapon plutonium consist of the following main issues:

- 1. The new understanding of "security":** Threats to nations are not simply military threats. Today, the future of nations is equally threatened by global environmental change and economic or social instability.
- 2. Industrial restructuring for sustainable development:** Conversion of the military-industrial complex into clean, market- and consumer-oriented production facilities is part of overall efforts of industrial restructuring in the pursuit of sustainable development.

3. **Human Resources Issues:** In countries where the military sector (industry, national R&D institutions, and the armed forces themselves) is particularly important as compared to overall economic activity, unemployment - including that of scientific and technological staff - resulting from disarmament, could lead to an outflow of skills to nations still expanding military R&D and production.
4. **Cleaning up of the Cold War legacy:** Abandoned military sites and facilities are often among the worst areas struck by toxic waste pollution. Military activities have caused such formidable damage to the environment and to human health that their consequences will be felt for decades and, in instances of forms of radioactive contamination, for much longer. This is task which requires scientific and technological inputs. Closely related to this aspect of conversion is the environmentally sound disposal of existing military hardware and surplus weapon systems including nuclear weapons.
5. **Developing timely alternative use plans for military facilities:** This is part of the development strategies in economies heavily dependent on the presence of such facilities. It is essential to avoid large-scale unemployment initiating brain-drain and to secure public support for conversion measures. It requires also scientific and technological assessment and economic projection.

The notion to diversify resources traditionally devoted to the military and released in the process of disarmament to address such risks is intriguing. Scientific and technological aspects, including the conversion of military research and development (R&D) with the objective to develop environmentally sound technologies are of particular interest in this context.

Such a "trade-off" has been termed in a broad discussion the "peace-dividend". Different terms are being used to describe the process of conversion, for example "reinvestment", and

strategies to utilize the expected peace dividend for sustainable development efforts. Such a pay-off as it is implied in the objective of the utilization of excess weapon plutonium cannot simply be described in financial terms. While the release of actual financial resources from military to civilian endeavours is questionable, the peace-dividend essentially exists in terms of human resources as disarmament is freeing scientific and technical resources to pursue profitable R&D, and in terms of a long-term economic impact resulting from the restructuring of production from a narrowly-based military one to a more efficient production serving a broader civilian market. The issue is after all, how it can be achieved to count the civilian utilization of excess weapon grade plutonium under such understanding of conversion for sustainable development.

Closely related to this aspect of conversion is the environmentally sound disposal of existing military hardware. Such conversion for sustainable development is an exercise where tremendous short-term costs have to be balanced against long-term benefits. Cleaning up the Cold War legacy is in particular costly and a complex venture when it is connected with the dismantlement of nuclear weapons. There are various options for how to solve the disposal problems of these materials, each involving different cost levels for realization and eventual economic and political benefits. In the search for an optimal method of conversion of weapon-grade plutonium it is necessary to bear in mind the grave potential hazards of storing plutonium even during a limited period of time, both in respect to the environment and human health, as with respect to non-proliferation and the prevention of terrorism. In terms of the discussion on conversion it should be clearly distinguished between the civilian utilization of excess weapon plutonium and nuclear disarmament.

3. Nuclear Disarmament: The Role of the Military for Clean Up, Management and Prevention as the Major Option

Therefore it should be taken into consideration that modern military establishments have developed highly sophisticated techniques and technologies that could be applied by the military in an active conversion role to protect, restore and improve the environment. Military establishments can assist in achieving these objectives by contributing their technical expertise, advanced equipment and communications and surveillance systems. The range of scientific and technological areas which could be used for such purposes include the handling and disposal of highly radioactive substances as well as the destruction of weapons.

The high pace of nuclear disarmament, on the one hand, and the unpreparedness of the current nuclear fuel cycle to adopt and process such large quantities of new nuclear materials, as well as the actual lack of demand for these materials lead to the need for a political decision on the management of the nuclear disarmament process. It is in this context that a conversion policy to manage effectively the nuclear disarmament process in full compliance with all international norms and safety standards is of utmost importance. Therefore the need for a close international cooperation on this issue is evident. Such a decision would provide additional time for a reexamination of all options and should include a new role for the military sector in the overall nuclear weapons safety, security and dismantlement process. This prospective to concentrate on nuclear disarmament instead of real conversion for civilian application could lead, in a first step, to a safer world and in it, to a sustainable future.

I would like to underscore that the military sector, including military R&D and parts of the armed forces, are ideally suited for dealing with these and other defence-related environmental

problems. What is needed now in terms of dealing with the nuclear disarmament management is the development of an overall prioritized plan of action that will result in a systematic assessment of the problem, an analysis of associated risks, a selection of clean-up technologies and the development of a rational basis for deciding on the order in which problems should be addressed. It would be not needed to establish a new international agency or the allocation of huge resources in any one centralized body. But is it indispensable to create coordinated, inter-governmental efforts, relying heavily on existing agencies and appropriate organizations, to share experiences and resources and to develop a rational plan to deal with this pervasive threat to the security of us all. This would be the most pressing recommendation which should be forwarded to the forthcoming G-7 Summit on Nuclear Safety in Moscow from the environmental point of view associated with the scientific and technological aspects of the conversion military capacities related to nuclear disarmament for civilian use and sustainable development.

4. Conclusions for Sustainable Development

All the main issues and problems mentioned above have severe consequences for the entire nuclear disarmament management process. Such problems of the nuclear disarmament management which are linked to sustainable development are part of chapter 22 of the Agenda 21 which is entitled "Safe and Environmentally Sound Management of Radioactive Wastes". The programme area *Promoting the safe and environmentally sound management of radioactive wastes* has the objective to ensure that radioactive wastes are safely managed, transported, stored and disposed of, with a view to protecting human health and the environment, within a wider framework of an interactive and integrated approach to radioactive waste management and

safety. Special emphasis is laid on the international and regional cooperation and coordination of states and, in cooperation, with international organizations as the main basis for action. The particular objectives of such measures are to promote policies and practical measures to minimize and limit, where appropriate, the generation of radioactive wastes and provide for their safe processing, conditioning, transportation and disposal. The further aim is also to promote the safe storage, transportation and disposal of radioactive wastes, as well as spent radiation sources and spent fuel from nuclear reactors destined for final disposal, in all countries by facilitating the transfer of relevant technologies and/or the return to the supplier of radiation sources after their use, in accordance with relevant international regulations or guidelines. With regard to the scientific and technological means the chapter 22 of the Agenda 21 suggests to promote research and development of methods for the safe and environmentally sound treatment, processing and disposal, including deep geological disposal, of high-level radioactive waste as well as to conduct research and assessment programmes concerned with evaluating the health and environment impact of radioactive waste disposal.

The Proliferation Risks of Plutonium Mines¹

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Abstract²

Several recent observers have called attention to the risk that mined geological repositories, the planned destination of at least some of the plutonium recovered from nuclear warheads and additionally of a large fraction of the world's spent commercial fuel, could eventually become low-cost sources of fissile material for nuclear weapons. This paper argues that the risk of these so-called "plutonium mines" as a source of weapons-usable material depends on the accessibility of plutonium in repositories relative to other sources of fissile material. A preliminary analysis suggests that the range of circumstances under which plutonium mining will be significantly more attractive than alternative routes to fissile material are fairly narrow. Furthermore, the proliferation risks of alternatives to spent fuel disposal in repositories, in particular schemes to partition the pluto-

1. This talk is based on a paper in preparation by Edwin Lyman and Harold Feiveson, "The Proliferation Risks of Plutonium Mines".
2. Note: This Abstract is slightly different than the one submitted to the conference three weeks ago. In that Abstract and in the fuller paper from which this talk is derived, there is introduced the concept of a "Materials Production Standard" - namely, that the proliferation risks posed by geological disposal will be acceptable if one can demonstrate, under a number of reasonable scenarios, that the recovery of plutonium from a repository is likely to be as difficult as new production of fissile material. But for this shorter version, it seemed simpler to cut out discussion of the new standard.

niun in the spent fuel and to burn it in reactors or accelerators, appear greater and far more immediate than the risks of repository mining. Nevertheless, the risks of such mining are significant enough that safeguards should be maintained on spent fuel repositories indefinitely, even after the repositories are closed and the contained spent fuel made “irretrievable”.

Introduction

The U.S. appears committed to convert surplus plutonium recovered from dismantled warheads to a form meeting the “spent fuel standard” - that is, to a form similar to spent fuel from commerciale reactors. This would be done either through immobilization of the plutonium in soe waste form (such as vitrified high-level waste) or by burning the plutonium in the form of mixed-oxide (MOX) fuel in reactors to produce spent MOX fuel. Presumably then the resulting waste would be disposed of as would commercial spent fuel. For the U.S. (along with some other countries, including Sweden and Canada), the intention has been to dispose of this spent fuel, after some period of retrievable storage, by emplacing it into mined geological repositories. After this period, all access tunnels and ventilation shafts will be backfilled and sealed, and all supporting facilities will be decommissioned and dismantled. The repository will then be considered “irretrievable”, in the sense that recovery of the emplaced material would require much greater cost and effort.

But is a mined geological repository a safe destination for the recovered plutonium (and for the spent fuel from commercial reactors)? Some analysis think not. They fear that the repositories will become over time “plutonium mines” because of three factors. First, the penetrating radiation barrier that renders spent fuel extremely hazardous to handle will decay to a very long level after few centuries of cooling, so that the materi-

al can be acquired and reprocessed at much lower cost than spent fuel of more recent vintage. Second, the time and effort necessary to recover the fuel from the repository will decrease as mining technologies improve. Third, the isotopic quality of the plutonium in commercial spent fuel will approach (although never reach) that of "weapons-grade" with time.¹

It is the purpose of this paper to examine such claims and whether the prospect of future "plutonium mines" really poses an unacceptable long-term risk.

Standard of Comparison

The critical question in defining the risks of plutonium mining is how much easier (if at all easier) will such mining be compared to other ways in which countries can acquire fissile material. This comparison depends foremost on the future of commercial nuclear power. If a country has an operating nuclear fuel cycle, it will always have a ready supply of spent fuel available, either in retrievable storage or in the reactor cores. (If the nation, as well, operates commercial reprocessing plants or contracts for reprocessing, it will also process stockpiles of separated plutonium and, if it has its own reprocessing plant, the ability to reprocess quickly any spent fuel). Under these circumstances, it seems likely that spent fuel in a sealed geological repository would be relatively unattractive with respect to both state-sponsored and sub-national diversion, assuming that repositories were safeguarded at a level consistent with other stages of the fuel cycle.

The relative attractiveness of spent fuel in a repository would be greatest in the context of a "nuclear-free" future, in which nuclear power had been phased out and neither operable reactors nor retrievable spent fuel storage facilities existed. In this case, the only means of acquiring spent fuel other than min-

ing the repository would be the construction and operation of production reactors and associated front-end facilities (e.g. uranium mining and fuel fabrication) from scratch. For both repository mining and new production, it will still be necessary to reprocess the spent fuel to obtain the plutonium.

Alternatively, a proliferant could seek to acquire weapons-usable material by enriching natural uranium, bypassing the spent fuel route altogether. How difficult this alternative would be in the hundreds or thousands of years in which the security of a repository might be an issue is a crucial, but undecidable, question. For clarity of presentation, we disregard the enriched uranium route to weapons-usable fissile material, and focus exclusively on the plutonium route in a non nuclear world. Can plutonium be acquired more readily through new production or through mining a repository?

Resources Needs for New Production

The development cost of a dedicated plutonium production capability from scratch depends on the size of program desired. Consider three categories of plutonium production (all costs are given in 1992 dollars):

i) A “minimum acquisition” plutonium program, based on a gas-graphite production reactor rated at 30 MW-thermal (MWt) and capable of producing around 10 kg of plutonium per year. This program is estimated to require a capital cost of \$120-\$300 million, of which \$35-\$100 million is the construction cost of the reactor¹. The average cost of the reprocessing component is \$15 - \$40 million, or about 12% of the total. The time for construction of this project is estimated to be 3-4 years, with a crew of 100.

ii) An “intermediate acquisition” program capable of producing around 100 kg of plutonium per year. One program, based on a 400 MWt reactor, was estimated to require a capital

investment in the range of \$1-2 billion, including \$400 million to \$1 billion for the reactor alone, with a cost overrun of up to 100% possible in the event of delay. The construction time for this reactor is estimated to be 5-7 years, requiring a staff of 200-300², although the time could be shortened through a crash effort. The cost of the reprocessing plant in this case was not given; scaling from the previous example (40% of the reactor cost) yields a value of \$160-\$400 million.

iii) A “maximum acquisition” plutonium program, in which the desired production rate is limited only by the resources available. For example, during the Cold War, multiple 2150 MWt reactors were constructed at the Savannah River Site, each capable of producing about 600 kg of plutonium per year. Today, total capital costs of such a reactor would be between \$1.5-3.0 billion; and a large reprocessing plant might cost an additional \$1 billion.

Characterization of a Mined Repository

No geological repository has been fully designed, let alone built. However, authorities in the U.S., Sweden, and Canada have developed conceptual designs which can be used to describe a “nominal” repository. In particular, repository designs, which have been developed by the U.S. Department of Energy for Yucca Mountain, and by Atomic Energy of Canada Limited (AECL), can be used for this purpose¹.

We may imagine the repository to consist of two principal parts:

- above-ground facilities, for unloading and packaging fuel for final disposal, for crushing rock to be used as backfill, for mixing concrete for vault seals, for handling and storing low-level radioactive wastes, and for various administrative and service functions;

- an underground vault, consisting of a series of tunnels about 300-1000 meters below ground, capacious enough to allow various heavy equipment to move.

A small number of shafts or ramps would connect the two parts of the repository.

In general, we may imagine two periods of concern after the repository is built:

- a pre-closure transition of 50-100 years before the repository is closed, during which period spent fuel would be placed into the repository;
- the period after the repository is closed.

During the pre-closure period, the spent fuel packages would be placed in containers and then sent underground for emplacement in the storage areas by a transporter truck. In the Canadian design, the vault would be filled room by room. After each room is filled (in the AECL design requiring about one month), it is backfilled with mixtures of clay, and sand.

Once the vault is filled, the surface and subsurface facilities will be dismantled; the tunnels, shafts, and exploratory boreholes will be sealed; and the secondary wastes disposed. Seals will be backfilled with clay and concrete and rock. In the final closure step, measuring instruments would be removed from exploratory boreholes and the boreholes would be sealed. Conceivably, the vault location could be identified with on-site markers.

Resources and Time Required for Repository Mining

Retrieval of spent fuel from a closed repository would entail assembly of the necessary equipment on-site, construction of new surface support and material handling facilities, the drilling of new shafts into the geologic formation, and the use of grappling and other equipment to extract the spent fuel. We

may imagine that the repository is filled either with canisters containing something like 5 kilograms of plutonium per canister, as in the Canadian design, or with casks, containing perhaps 100 kilograms of plutonium per cask, as in the Yucca Mountain concept. A "minimum acquisition" program would require the recovery of 2 canisters per year on one cask per decade. An "intermediate acquisition" would require the recovery of 20 canisters or one cask per year.

For the extraction of from a few to several canisters to one or two casks, corresponding to the first two levels of diversion introduced above, the most direct way to recover material might be to drill a tunnel to level of repository, contact a canister or cask, and then somehow bring the spent fuel to the surface. For the extraction of some substantial number of canister or casks, it might be more efficient to reexcavate a part of the repository through the drilling of large shafts or trenches in which large equipment could be introduced into the repository much as the case when the repository was first filled.

Let us consider first the effort to obtain small amounts of spent from a Canadian-type repository utilizing canisters containing about 5 kilograms plutonium per canister. Assuming that the driller had a general but not precise map of the burial spots, he would, in all likelihood, have to dig several tunnels to hit a canister. In a study done for the International Nuclear Fuel Cycle Evaluation (INFCE) in 1979, the authors estimated that it might take on the order of twenty one-meter diameter holes to recover a single canister. After contact, the canister would have to be attached and hoisted through the shaft or tunnel. For a nominal tunneling cost of \$3000-5000 per meter and tunnel length of 2-4 kilometers, a single tunnel drilled might cost \$6-20 million. Twenty such tunnels would then cost \$120-400 million, comparable to the cost of a small production reactor scenario. At a rate of billing of (say) 20-50 meters per day, and assuming that the tunnels are drilled in parallel, it might take a few months to contact

and extract a canister. This is consistent with the INFCE study which concluded that the "recovery of one of a few canisters might be accomplished using ten drilling rigs in two months time; more probable recovery times are six months or longer"¹.

For recovery of spent fuel from a repository similar to Yucca Mountain, the direct tunnel approach would be far more difficult. The nominal waste cask envisioned for Yucca Mountain weighs 40 tons, with diameter about 1.7 meters and length about 5.2 meters. In this case, the tunnel drilled would have to be much bigger than one meter diameter, of course; and the grappling equipment needed to bring up the cask, or alternatively open it and remove the fuel assemblies, would be formidable. Again, it might be necessary for the driller to drill many tunnels before hitting a cask. Given time for initial preparation, bringing drilling equipment to the site, and then the actual drilling and extraction of the spent fuel, an effort of many months to a year or more and a cost of several hundred million dollars would probably be required.

For a massive reentry into a repository, reexcavation of the repository would probably be the preferred mode, with the diverter excavating out very large shafts and trenches and emplacing specialized equipment and transporters down into the repository. This would involve a very substantial mining operation. Large underground mining operations today typically require capital investments on the order of a few hundred million to well over one billion dollars (with the higher figure reflecting isolated sites and/or difficult climates), and development times of 2-5 years before production can begin². Excavation of a spent fuel repository would require a similar level of investment. For example, the development costs of the original (1988) design of the Yucca Mountain repository include \$200 million for preparation of the site, \$320 million for constructing the shafts and ramps, initial excavations at the repository level, and underground service systems, and \$510 million for construction of

surface facilities, for a total of over \$1 billion (all costs in undiscounted 1992 dollars).

Although the advance rates of modern drilling methods can be quite high, on the order of 50 meters per day, the minimum time necessary to gain access to a repository will probably be determined by the significant effort involved in the on-site assembly and preparation of equipment. For example, the tunnel boring machine (TBM) being used to drill Exploratory Studies Facility (ESF) at the Yucca Mountain site was brought there in 52 separate truckloads. One engineer has estimated that one to two years would be needed to assemble a large TBM and auxiliary equipment, and to prepare a platform to launch the drilling.

Although the effort and time required to excavate a repository would thus not be trivial, once completed, the rate of removal of spent fuel from a repository could be on the order of the rate of emplacement. This could be quite high. For example, the rate of loading of the planned Yucca Mountain repository is currently anticipated to be 3000 tHM of spent fuel a year. Assuming equal rates of retrieval and emplacement, a large mining operation could produce 25 tonnes of plutonium per year. More than forty large Savannah River-type reactors would have to be built to attain a level of production equivalent to the mining route, at a much greater capital cost. Therefore, current repository designs would allow accumulations of plutonium equivalent to a rate of thousands of nuclear weapons per year. However, it remains to be determined whether this scenario is sufficiently credible to warrant concern.

Comparison of Mining and Production

No reliable and precise comparison between the production and mining routes to the acquisition of weapons useable material is possible over the hundreds or thousands(1) of years in

which repository spent fuel must be a concern and during which period one must expect both mining and fissile-material production technologies to improve markedly. Moreover, aside from the vast uncertainties in future technology, other factors frustrate any exact comparisons, for example: How many tunnels will be necessary to contact a cask? Once a cask is contacted, will it be relatively easy to contact another cask nearby? Once the major capital investments in reactors or drilling rigs are made, what be the relative marginal effort required to obtain a continuing stream of fissile material?

However, despite all these and other uncertainties, the above analysis suggests that for the "minimum" and "intermediate" acquisition scenarios, both the spent fuel mining and the new production route would require capital investments up to several hundred million dollars, and a development time of six months or more. It may be that, in some circumstances, the mining path will be quicker and cheaper, and since commercial spent fuel in a repository will be approximately ten times more concentrated in plutonium than production-reactor spent fuel, the separation of plutonium from the fuel could be done more rapidly. Spent MOX fuel fabricated from weapon-grade plutonium would be still more concentrated in plutonium. Nevertheless, mining will require substantial resources and activity, allowing the possibility of effective safeguards, a subject which is addressed after the next section. For a very large acquisition of weapon-useable material, reexcavation of a depository would appear to provide a more efficient route than the construction of new production reactors. But again such an effort would be highly visible and would allow effective safeguards or internationalization of the repository.

The Attractiveness of Aged Spent Fuel

Relatively fresh spent fuel is strongly self-protecting from casual appropriation and processing. For example, assuming a nominal cooling period of 10 years and fuel burnup of 40 Mwd/kg burnup, the dose rate perpendicular to a PWR fuel assembly at the center is about 4,000 rem/h at 1 meter, about 300 rem/hr at 5 meters. Since the LD-50 dose is 450 rem², the spent fuel must be handled and processed remotely behind heavy shielding. Specialized equipment, such as shielded machines with grappling hooks, casks to place the fuel assemblies, and transporters strong enough to convey the casks are required to remove the fuel from reactor storage pools. In addition, once the spent fuel assemblies are obtained, many of the key steps to separate the plutonium will also have to be done remotely behind shielding. The equipment requirements are, therefore, extraordinarily daunting for terrorist groups and represent a hurdle even for states.

Unfortunately, however, the “self-protecting” field of penetrating radiation emitted by spent fuel decreases steadily with time, and effectively disappears after several hundred years of cooling. Thus, in about 300 years, both the total radioactivity and gamma and x-ray activity of the spent fuel will have decreased by a factor of one thousand.¹ After this period, the handling of spent fuel, once obtained, will be possible without heavy shielding; and the processing of the spent fuel will be possible in a glovebox facility, rather than in a shielded, remotely-operated reprocessing plant.

These potential attractions of aged spent fuel, however, do not appear overwhelming. First of all, it is evident that many states already have the capacity to handle and process fresh spent fuel. They have routine access to the specialized equipment required; and several of these countries already remove the fuel assemblies and transport them to reprocessing or away-from-

reactor stores. Similarly, countries with reprocessing plants already in place would be able to separate the plutonium from the spent fuel readily.

If a proliferant did not have access to an already constructed separations plant, it would have to construct one. Facility requirements would depend strongly on the scope of plutonium production the proliferant was undertaking and its overall industrial sophistication. But, in general, the scale of the separations endeavor would not have to be great. Each half-ton fuel assembly from a PWR contains about one bomb's worth of material; so a plant capable of reprocessing one fuel assembly per week could in a short period assemble material for tens of bombs. The lead-time necessary to construct a separations plant of this capability has been estimated to be from six months to four years.²

The barrier to spent fuel processing is even less if a country is dealing with fuel from a new production reactor, rather than a commercial reactor. The burnup of spent fuel from dedicated gas-graphite weapons-grade plutonium production reactors is typically quite low, below around 800 Mwd/t. This is around fifty times smaller than the typical burnup of commercial fuel.

For low and intermediate production rates, low-burnup fuel can be processed in small, rudimentary reprocessing cells known as "caves", provided the operators are willing to accept high but not debilitating radiation doses. These cells, which date from the 1950s, utilize primitive, mechanically operated remote-handling devices known as ball-joint manipulators. The difference in cost between a small cave and a glovebox facility would probably not be great enough to influence the decisions made by a proliferant group.¹

At higher production rates, small, locally-shielded caves would no longer be feasible for reprocessing production-reactor fuel, and larger plants, utilizing remote operation and maintenance, would have to be employed. Thus the comparative at-

tractiveness of repository-grade spent fuel is maximized under these circumstances. However, at high production rates, the cost of a facility for reprocessing spent fuel would increase as well, because of the need to provide greater containment of alpha particles and to mitigate the increased risk of a criticality accident.

Over time, because the half-lives of Pu-240, Pu-241, and Pu-238 are 6540 years, 14.4 years, and 87.7 years respectively, compared to 24,100 years for Pu-239, the fraction of Pu-239 in the plutonium in a repository will gradually increase, making the plutonium slightly more weapon-grade. But the change is indeed very slight, the Pu-239 fraction increasing from about 58% for spent fuel one-year out of reactor to just under 70% in 1000 years.² Not only is the change in isotopic quality slight, but several sources have now confirmed that reactor-grade plutonium could be used to make both crude nuclear devices such as may be sought by terrorist groups or sophisticated nuclear weapons.³

Detectability and The Role of Long-Term Safeguards

The safeguards aspects of spent fuel disposal in repositories have been examined by the IAEA over the last several years, with particular reference to the question of whether safeguards on spent fuel could ever be terminated. Under INFCIRC/66 and INFCIRC/153 guidelines, safeguards on fissile material cannot be terminate unless by determination by the Agency that the material is no longer usable for any nuclear activities or has become “pratically irrecoverable” due to lack of access to the material. Before closure of a repository, the plutonium in the spent fuel would clearly not be irrecoverable and safeguards would have to be applied. Various studies have examined how this might be done through application of containment and surveil-

lance and materials-accountancy measures at a repository site. Prior to closure, these measure should be as effective at a repository as elsewhere in the fuel cycle.

An advisory Group Meeting on safeguards related to final disposal of spent fuel and nuclear wastes, held at the IAEA in 1988, found that spent fuel does not qualify as being "pratically irrecoverable" at any point, even after closure of a repository, and recommended that the IAEA should not terminate safeguards on spent fuel.¹ The IAEA has been reexamining this question, and is expected to formally determine that safeguards must be maintained on repositories containing spent fuel.²

Although the maintenance of long-term safeguards on spent fuel repositories is inconsistent with one of the fundamaental goals of geologic disposal - namely, that a repository, after it is scaled, should not require active monitoring for any purpose - the IAEA determination to maintain safeguards does appear warranted. Mining a repository would not be a quick of quiet operation, but if could be done; and, therefore, it is reasonable that it be kept under safeguards. Safeguards could be strenghtened if the repositories were also put under international ownership, so that no nation had carte blanche to access them.

The safeguards challenge must be considered in some perspective. As already noted, the threat posted by mining of a geologic repository is maximized in the context of a "nuclear-free" world in which there are no operating nuclear reactors or retrievable spent fuel storage facilities. However, if once assumes menas for detecting clandestine production is in place, then it is sensible to assume as well that such techniques could be extended quite simply to safeguard geologic repositories. Indeed, the task of minitoring a series of known sites would be far more straightforward than the task of verifying the absence of clandestine activities, which could occur anywhere (and in particular, in industrial areas where the vusual and thermal signals could be camouflaged). This suggests that in the presence of a

monitoring regime, clandestine production would be more likely to escape detection than repository mining.

Alternatives

Comparison to alternative ways for a country to acquire spent fuel is one standard of comparison to evaluate risks of plutonium mining. But there is another standard of comparison which should be kept in mind. If the spent fuel is not put into a repository, it will have to go somewhere else, and the ensuing risks of that somewhere else will have to be considered. Disregarding exotic or underdeveloped alternatives, such as shooting plutonium and high-level waste separated from spent fuel to the sun, deep bore-hole emplacement, and sub sea-bed disposal, there appear but two practical long-term alternatives to geological repositories for the disposal of spent fuel:

- (1) Indefinite, monitored, retrievable storage of spent fuel.
- (2) The partition of plutonium from other constituents in spent fuel and its transmutation in a reactor or accelerator, with the high-level waste treated and then sent to a geological repository. The spent fuel created by burning the plutonium would be reprocessed repeatedly with the plutonium (and other actinides) gradually burnt-down. The repeated reprocessing and recycling is termed "partition and transmutation" (P-T). (A truncated process, in which separated plutonium is fashioned into mixed-oxide (MOX) or other reactor fuel and recycled only once or twice rather than repeatedly, would reduce the value of plutonium in spent fuel. But this would merely delay the spent fuel disposition choices, since the spent MOX or metallic reactor fuel would have to be disposed).

Pretty clearly, the first alternative would allow more ready access to spent fuel than an underground geological repository. What about the second?

Partition and Transmutation

Partition and transmutation systems have been described and analyzed recently by the Lawrence Livermore National Laboratory¹ and by the Panel on Separations Technology and Transmutation Systems (STATS panel) of the National Research Council.² Both reports drew on earlier work by Thomas Pigford and collaborators.³ Both the Livermore study and the STATS panel consider a range of concepts, including the Integral Fast Reactor program developed at the Argonne National Laboratory, the PRISM fast reactor concept developed by General Electric, and accelerator concepts developed by Los Alamos National Laboratory and Brookhaven National Laboratory.

In all the cases, partition and transmutation operations are designed to burn a large part of the plutonium (and other actinides) in spent fuel, with the produced high-level wastes, containing most of the fission products, after they were vitrified or otherwise treated, sent to a geological repository. The proliferation risks of P-T compared to a spent fuel repository then involve a weighting of the reduced risks of plutonium mining in a repository and the increased diversion risks associated with the above-ground processing and recycling.

This processing and recycling would have to be on a grand scale indeed. For example, consider what would be involved in treating U.S. spent fuel - approximately 2000 tonnes of heavy metal per year. Reprocessing of the fuel would require the equivalent of three plants the size of the THORP reprocessing plant in Great Britain (whose capacity is 700 tonnes of heavy metal per year). Since there are about 10 kg per tonne of transuranics in the LWR spent fuel, the reactor or accelerator deployment will have to be able to handle 20 tonnes of transuranics per year. Assuming for specificity a fast breeder reactor of capacity 1.4 GWe, with a conversion ratio of 0.76 and lifetime of 40 years (the PRISM reactor with the lowest practical conversion factor), such a reactor

could fission in its lifetime about 37 tonnes of transuranics.¹ Since, over forty years, the LWRs will generate about 800 tonnes of transuranics, the transmutation effort will involve some 20 reactors. After 40 years, the job won't be finished because the transuranic inventories in the reactors will still be substantial and will have to be burned down still further. Depending on how completely one wishes to destroy the transuranics, the transmutation effort could take from hundreds to thousands of years.²

This scale of activity would be extremely difficult to safeguard and physically-secure. Even where separations technologies can be implemented such that the plutonium nominally stays mixed with most of the other actinides and thus would not be weapons-usable (such as is promised by the pyroprocessing technique developed at Argonne National laboratory), it would almost certainly always be possible for a country to reconfigure the separations process to allow the separation of plutonium.² Safeguards would have to be applied in perpetuity as with safeguards on spent fuel repositories. So, even if the long-term risks of plutonium mining in a repository are significantly reduced through P-T, they may be overwhelmed by the short and medium-term risks of processing and recycling.

Transmutation of already separated weapon-grade plutonium, of course, would not require the reprocessing step. But the "spent fuel standard" implies that extraordinary efforts to dispose of weapons plutonium are not justified unless simultaneous efforts are undertaken for the disposal of commercial spent fuel.

Even if the risks of repository mining do not look excessive compared to P-T or on the basis of an MPS, they may be large enough to justify a serious reinvestigation of other permanent storage solutions, such as deep borehole or sub sea-bed.¹

Conclusions

Although the diversion scenarios examined do not cover all possibilities, they do suggest that the range of assumption under which a repository will look attractive compared to other routes to plutonium acquisition is extremely narrow. It is true that after a couple of hundred years cooling, repository spent fuel will become less self-protecting than relatively fresh production-grade spent fuel. However, this fact does not mean that repository spent fuel will be valuable to mine.

In circumstances where a country has a working nuclear fuel cycle, mining a repository is not likely to look attractive compared to more direct ways to obtain weapons usable material. In a nuclear-free world, for small and intermediate acquisition programs, repository mining might be quicker and cheaper than the production route, although give uncertainties in technology advances in the next several hundred years, it is hard to make any definitive comparison. At a minimum, it seems likely that mining will take at least several months and will be readily detectable if there are reasonable safeguards applied at the repository sites.

Mining a repository might look attractive to a country contemplating a large scale breakout if it did not already have access to many power reactors. In this case, the quantity of plutonium in a repository would be the main attraction, not so much the cooler fuel; for in the time necessary to establish a mine at a repository or to obtain large quantities of spent fuel from an ongoing civilian power program, a country would probably want to construct a large, heavily-shielded reprocessing plant even for fuel cooler for several hundred years or more.

If anything, comparing the risks on mining a spent fuel repository to those of new production probably overvalues the repository as a plutonium mine. This is first of all because the construction of new production reactors and reprocessing

plants is an appropriate standard of comparison, an appropriate standard only for instances where there is no ready access to an operating nuclear fuel cycle. For proliferants with access to operating reactors, other fuel-cycle facilities, and /or inventories of spent fuel in monitored, retrievable storage, the acquisition of plutonium would be much more direct and inexpensive.

Secondly, if the spent fuel accumulated in a nation's civilian power program is not put into a repository, it will likely instead be put either into monitored, retrievable facilities or processed in a P-T program. Each of these alternatives will allow plutonium to be mined more readily than would a repository.

For these reasons, recent suggestions to scale back efforts to develop a spent fuel repository in the United States are to be regretted. A scale-back would send a strong signal to other countries now contemplating what to do with their spent fuel. If could, in consequence, delay for decades the movement of spent fuel out of retrievable storage in this country and abroad, and lead also to partition and transmutation activities, with all their attendant hazards.

It seems likely that disposal of spent fuel in a mined repository in tuff of granite can be made an acceptable long-term option, at least with respect to plutonium mining. Under this option, by necessity, the fuel will be retrievable for some period; and although most repository schemes envision the repository to be closed, and the fuel made practically irretrievable, in 50-100 years after the repository is first opened, that decision could itself be changed over time, with the closure of the repository delayed still longer if doubts persisted concerning the long-term safety of geologic disposal. In the pre-closure period, a mined geological repository will effectively constitute a monitored, retrievable store - but one underground.

No matter how the competition among repository disposal, long-term storage, and partition and transmutation is finally decided, it is critical to recognize that, no matter what is done

with spent fuel, all countries with nuclear power programs will have access to spent fuel containing substantial quantities of plutonium. A one gigawatt-electric reactor will contain an in-reactor inventory of plutonium of about 600 kilograms and will discharge about 200 kilograms per year. Even if spent fuel was removed from reactor site after a very short period after discharge (say two years), a country with a single 1 gigawatt reactor would have continually on hand something like 1 tonne of plutonium in its spent fuel, enough for perhaps 200 warheads. By the time the country had built a reprocessing plant, it would thus have a substantial backlog of spent fuel from which to produce plutonium, and in the future it would be able to produce about 200 kilograms of plutonium per year. Resolution of the quandary of what to do with the long-term disposal of spent fuel can reduce pressures for reprocessing and it could speed the emplacement of spent fuel underground; but it cannot choke off the route to nuclear weapons through civilian nuclear programs based on current reactor types.

Bowman and Venneri Hypothesis.

Finally, a brief comment may be made on another objection to a geologic repository which has recently been advanced. This is the hypothesis by two Los Alamos scientists, Charles Bowman and Francesco Venneri, that plutonium in glass or other medium underground would eventually become susceptible to criticality and explosive events long after emplacement in a repository.¹

... subcritical fissile material underground might reach criticality that is autocatalytic or self-enhancing. This criticality could come about upon dispersion into the surrounding medium by either natural or unnatural process, or by the fissile material being carried to other sites where it can collect into different autocatalytic critical configurations. Underground, where

the material is confined and there is an abundance of moderating medium around it, the consequences of such supercritical excursions could range from modes energy releases to the generation of explosive nuclear yields up to a few hundred gigajoules [about 100 tonnes] of high explosive equivalent from a single event... In varying degrees, all categories of waste containing fissile material appear to be susceptible to these criticality excursions, including vitrified weapons plutonium, research reactor and DOE spent fuel, commercial and MOX spent fuel.

The B/V hypothesis is now under challenge from several quarters and yet may be shown to be inconsequential. For example, it might be that waste forms could be developed which preclude criticality. But I would like to focus on the extremely long time frames involved. The B/V excursion couldn't occur until the canister shell loses integrity (hundreds to thousands of years), the nuclear poisons such as boron leach away (thousands to tens of thousands of years), and the underground fissile material gets concentrated through some mechanism. Such a mechanism is more likely for the decay product of plutonium - uranium-235 - so that it may be that the explosive excursion could only happen after much of the plutonium has decayed to U-235. This would put the time of concern a couple to a few plutonium half-lives away or (say) 50-100 thousand years. The B/V analysis is not invalidated by the long time frames involved, and may, in fact, suggest some useful fixes in repository geometry or in materials packaging. But, it would be foolish to let a speculative risk many thousands of years in the future or longer determine in any fundamental way how we dispose of weapons plutonium over the next few decades.

This is exactly the conclusion to draw also, I believe, on the speculative and distant risk of plutonium mining.

NOTE

¹See, for example, Johan Swahn, "The Long-term Predicament", Technical Peace Research Group, Institute of Physical Resource Theory, Chalmers University of Technology, Goteborg, Sweden 1992; and Pers Peterson, "Long-term Safeguards for Plutonium in Geologic Repositories, *Science & Global Security*, Spring 1996 (in press).

¹U.S. Congress, Office of Technology Assessment (OTA), *Technologies Underlying Weapons of Mass Destruction*, OTA-BP-ISC-115, U.S. Government Printing Office, Washington, D.C., December 1993, 156.

²*Ibid*, 158

¹AECL, *Environmental Impact Statement on the Concept for Disposal of Canada's Nuclear Fuel Waste*, AECL-10711, COG-93-1, September 1994; TRW Environmental Safety Systems, "Strategy for Waste Containment and Isolation for the Yucca Mountain Site", October 9, 1995.

¹"Safeguards for Geologic Repositories", Prepared for Working Group 7 of the International Nuclear Fuel Cycle Evaluation, by the U.S. Delegation, IN-FCF/DEP/WG.7/18, September 1979, pp 18-19.

²W. Peters, *Exploration and Mining Geology*, 1987, 162.

¹W.R. Lloyd, M.K. Sheaffer, and W.G. Sutcliffe, "Dose Rate Estimates from Irradiated Light Water Reactor Fuel Assemblies in Air", UCRL-ID-115199, January 31, 1994.

²The LD-50 is the dose rate expected to be fatal to 50 percent of the exposed population.

¹Swahn, 69, 147. The factor of one thousand in 300 years is due principally to the passage of ten half-lives of Cs-137.

²Memorandum from D.E. Ferguson to F.L. Culler, *Simple, Quick Processing Plant*, Oak Ridge National Laboratory, August 30, 1977.

¹After two years of cooling, each tonne of uranium gas-graphite reactor fuel, irradiated to a burnup of 800 MWD/t, will contain about 720 grams of weapons-grade plutonium and about 4000 curies (Ci) of hard (greater than 0.4 MeV) gamma activity. In order to produce 100 kg of plutonium per year, about 0.5 tonnes of fuel would have to be reprocessed per day (assuming 80% plant availability). This quantity of fuel could be subdivided into five batches per day, each containing about 400 Ci of hard gamma activity. The unshielded exposure from a point source of this strength at a distance of 50 cm is over 5 Gy/hr; to reduce this to (say) 1.5 mGy/hr, a target value that a proliferant could conceivably tolerate, would require attenuation by a factor of 3300. This can be achieved with 8 cm of lead or 15 cm of dense lead glass. These dimensions are well within the constraints of process cells of the type described.

²Swahn, 131.

³See, for example, National Academy of Sciences, *Management and Disposi-*

tion of Excess Weapons Plutonium, National Academy Press, Washington, D.C. 1994, Box: "Reactor-grade and Weapons-grade Plutonium in Nuclear Explosives".

¹International Atomic Energy Agency, Advisory Group Meeting on Safeguards Related to Final Disposal of Nuclear Material in Waste and Spent Fuel, STR-243 (Rev. 1), Vienna, 1988. Also see A. Fattah and N. Khlebnikow, "International Safeguards Aspects of Spent Fuel in Permanent Geological Repositories", *Journal of Nuclear Materials Management*, October 1990/January 1991.

²G. Seneviratne, "IAEA Developing Safeguards Conditions for Vitrified Waste Repositories", *Nuclear Fuel*, September 12, 1994, 9.

¹Lawrence Rampsott, et al. *Impacts of New Developments in Partitioning and Transmutation on the Disposal of High-level Nuclear Waste in a Mined Geologic Repository*, UCRL ID-109203, Lawrence Livermore National Laboratory, Livermore, CA, March 1992.

²National Research Council, *Report of the Panel on Separations Technology and Transmutation Systems*, 1995.

³See, for example, Thomas H. Pigford, "Actinide Burning and Waste Disposal", Invited Review for the MIT International Conference on the Next Generation of Nuclear Power Technology", UCB-NE-4176, University of California Berkeley, October 5, 1990.

¹Rampsott, et al, p. 4-3.

²Rampsott, et al, p. 4-21.

³Edwin Lyman, "Interim Storage Matrices for Excess Plutonium: Approaching the Spent Fuel Standard Without the Use of Reactors", Research Report 286, Center for Energy and Environmental Studies, Princeton University, August 1994.

¹Swahn, op cit, argued in his pioneering study that serious attention be given to deep borehole emplacements.

¹See Charles Bowman and Francesco Venneri, "Underground Supercriticality from Plutonium and Other Fissile Material", and several critiques, in *Science & Global Security*, Vol. 5, No. 3, 1996.