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Managing the Plutonium Surplus: Applications and Technical Options

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TECHNICAL INTERPRETATION

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Abstract. This brief account of the workshop begins with a sketch of the report from the US National Academy Academy of Sciences (January 1994) "Management and Disposition of Excess Weapons Plutonium" and then moves to cite selected contributions from papers published in this volume and from the discussions among participants. The undoubted utility of weapon plutonium (W-Pu) and high-enriched uranium for the fabrication of nuclear weapons imposes the need to minimize the stocks of these materials and to bar unauthorized access, and leads to the "stored nuclear weapons standard" for the materials before disposition, and the "spent fuel standard" for the materials afterward. The burning of W-Pu as mixed-oxide ceramic fuel in power reactors of existing type was extensively discussed in the context of experience with recycling of the reactor-grade Pu (R-Pu) reprocessed from spent fuel from normal power reactors, as well as the direct disposal of W-Pu vitrified with fission-product waste. The third option of that report, disposition in deep boreholes also received attention. The utility of R-Pu for the fabrication of nuclear explosives then brought in the question of the eventual adequacy of the "spent fuel standard" for access to the W-Pu, and much attention was given to the status and plans for the use of plutonium in light-water power reactors and in fast (neutron) reactors. These latter were discussed both from the point of view of eventual use of the large amount of U^{238} that is not fissile in LWRs and as a means to treat and to burn (by fission) the plutonium and heavier elements (actinides) formed in LWRs. Accelerator-driven sub-critical reactors were discussed for waste treatment and as the basis of a thorium/U^{233} breeder cycle. Environmental implications of the existing 1000 tonnes of R-Pu largely in unprocessed spent fuel, and of the transport, processing and use of this plutonium were presented, as was the adequacy and cost of IAEA safeguards. Much attention was given and different points of view expressed with vigor regarding the economics of plutonium recycle in LWRs, and the relative merit of reprocessing and direct disposal of spent fuel. This Interpretation closes with recommendations for additional Advanced Research Workshops on criteria for nuclear waste isolation; on the economics of reprocessing and recycle; and on real-time accounting and safeguarding, especially as regards separated plutonium and high-enriched uranium.

THE REPORT OF THE U.S. NATIONAL ACADEMY OF SCIENCES

As the scientific organizer of the NATO Advanced Research Workshop on "Managing the Plutonium Surplus: Applications and Options," ably conducted at the Royal Institute of International Affairs, London, February 24-26, I am pleased to have the opportunity to provide this technical interpretation of the proceedings. Of course, no summary or interpretation can reproduce all of the detail in the submitted papers of this volume, nor should it do so. However, it may be valuable for an interested observer to note elements of agreement, disagreement, and needs and opportunities for future discussion and collaboration. That is the goal of this Scientific Interpretation.

The question of plutonium and nuclear power is lent additional interest and urgency by the astonishing events of the last few years. The end of the superpower confrontation have left the United States and the former Soviet Union with tens of thousands of nuclear warheads declared excess to current needs of the United States and Russian, and the START I and II agreements will bring the strategic inventories of each side to 3000-3500 warheads by the year 2003. In addition, tens of thousands of non-strategic warheads have been withdrawn from bases outside the United States and Russia, and as a matter of safety are also being demilitarized and dismantled. A report of the U.S. National Academy of Sciences "Management and Disposition of Excess Weapons Plutonium" was published in Washington January 24, 1994, the first day of the Workshop. Accordingly, the present author (one of the 16 members of the Committee on International Security and Arms Control which prepared the report) was responsible for its presentation to the Workshop, instead of Dr. Matthew Bunn, the Plutonium Study Director. The Executive Summary of that report is provided in the enclosed volume, but the briefing to the Workshop involved substantially more technical detail.

In brief, the CISAC report commissioned by the U.S. National Security Council and the Department of Energy concludes that these surplus nuclear weapons in the present political and social environment constitute a "clear and present danger". That danger is not so much that the weapons themselves will be used by the United States or Russia, nor that the weapons or the weapon materials may be used to rearm after substantial disarmament. On the assumption that those strategic warheads of the former Soviet Union still present in Belarus, Kazakhstan, and Ukraine will be transferred to Russia for dismantlement, the major problem is the proliferation of nuclear weapons to additional powers or to sub-national groups, by theft of the weapons themselves or by theft or unauthorized diversion of the fissile materials.

As a nominal amount of excess plutonium, the CISAC report considers 50 metric tons (MT) of weapon plutonium (W-Pu) and considers a nominal amount of W-Pu of 4 kg per nuclear warhead. Russian papers to the Workshop discuss a nominal amount of excess Russian W-Pu of 100 MT.

The theft of even 0.1% of this assumed Russian stock would correspond to 100 kg, and would be enough for some 25 nuclear weapons. For example, the implosion weapon used by the United States at Nagasaki in 1945 contained 6 kg of W-Pu. Accordingly, the CISAC report recommends extreme care for protection of the nuclear weapons and the extracted W-Pu and high-enriched uranium (HEU) of which there is contained in these weapons probably ten times as much as the amount of W-Pu.

HEU is also a proliferation hazard, although not the subject either of the CISAC report or of this NATO ARW.

It might be noted that the U.S. has contracted with Russia to purchase 500 MT of HEU, blended to form low-enriched uranium (LEU) appropriate for use in normal power reactors. It is the strong opinion of this author that stocks of HEU in the U.S. and in Russia ought as soon as the materials are extracted from weapons to be diluted to a 20% U^{235} content, which is essentially useless for nuclear weapons. This would retain flexibility for the future-- for the investment of that medium enriched uranium (MEU) as such in fast reactors, or for further dilution to form LEU-- and would reduce the cost and hazard of storage.

To return to the CISAC report, the authors strongly urge that the excess weapons and the W-Pu and HEU removed from them all be protected to the standard appropriate for storing nuclear weapons-- the "Stored Weapons Standard." The report recommends for the U.S. and Russia a regime of declarations of stockpiles of nuclear weapons and all fissile materials, the halt to the production of fissile materials for weapons, and cooperative measures to clarify and confirm these declarations, as well as agreed and monitored net reductions from these stockpiles.

The report recommends also a reciprocal regime of secure, internationally monitored storage of fissile material, with the aim of ensuring that the inventory and storage can be withdrawn only for non-weapons purposes.

Finally, there is recommended the long-term disposition of W-Pu to minimize the time during which plutonium is stored in forms readily usable for nuclear weapons, to preserve the material safeguards and security during the disposition process, and to result in a form from which the plutonium would be as difficult to recover for weapons use as the larger and growing quantity of plutonium in commercial spent fuel.

Thus, the disposition of the W-Pu should meet the "Spent Fuel Standard."

To achieve this, the first of two options favored for further work by the CISAC report is the fabrication of W-Pu into fuel for reactors of existing type, and the burning of this fuel to extract much of the fission energy from the W-Pu and at the same time to convert the W-Pu into an isotopic mixture of plutonium less desirable for use in weapons and also heavily contaminated with fission products.

The second preferred option is the conversion of the plutonium, together with the highly radioactive fission products from which that plutonium was originally separated, into glass "logs" cast into stainless steel containers and eventually placed in a mined geologic repository. If the vitrification of high level waste goes forward as planned in the United States, it would appear to be relatively simple to add plutonium oxide to the melter as it is processing the HLW into glass for casting into the disposal cylinders.

Neither in the United States nor in Russia can the burning of W-Pu in reactors begin immediately, because of the lack of facilities for the fabrication of large amounts of fuel containing plutonium, and the process for adding W-Pu compounds during the vitrification activity needs to be perfected and licensed.

A third option that survived the analysis of the CISAC group is the emplacement of W-Pu in deep boreholes, sealed with bentonite clay.

THE CIVIL PLUTONIUM CONNECTION

There was no dissent at the Workshop with the need to carefully guard W-Pu and to dispose of it in a timely fashion. It was pointed out that national efforts to make nuclear weapons in the 1940s and 1950s involved many hundreds of scientists, engineers, and technical support people, and that it was not a trivial matter to utilize even weapon plutonium is a clandestine nuclear weapon. Nevertheless, the greater availability of materials of all kinds in the 1990s, ranging from simple insulated wire to switches to explosive components, to expert publications on the handling of plutonium, works in the opposite direction.

The choice by CISAC of the "Spent Fuel Standard" for reduced utility of the transformed weapon plutonium brings to the fore the question of how useful the plutonium derived from spent fuel can be for nuclear weapons. The CISAC report judges that it is the highly radioactive spent fuel or vitrified material, which then needs to be dissolved and chemically processed to separate plutonium, which constitutes the primary barrier to fashioning a nuclear explosive of spent fuel or of W-Pu dissolved in vitrified waste. The position of the CISAC report is similar to that taken by the author in the first paper in this volume, based on a paper by Mark [1]. which concludes that reactor plutonium can be used to fashion a powerful nuclear explosive and that the difficulties involved, although greater than those accompanying the use of W-Pu, are of the same kind and can be solved in the same fashion. Somewhat larger amounts of plutonium are required, in view of the somewhat lower fission capability of the chief non-weapon impurity in R-Pu (Pu^{240}), which, however, still has a smaller critical mass (required amount) than does weapon uranium. The two major further impediments are the increased heat generation by about a factor five over W-Pu, and a larger spontaneous neutron production by a factor 20 or so.

While it is not in the interests of international security to explain in detail how these barriers are to be overcome, the CISAC report concludes that an explosive fashioned with R-Pu could be assured of an explosive yield which would not fall below 1000 or 2000 tons of high explosive; the latter is 10% of the explosive yield that devastated Hiroshima and Nagasaki and perhaps 2000 times the explosive yield of the bombs that have caused substantial damage in recent years in the World Trade Center in New York or in the streets of London. The U.S. nuclear weapon development laboratories have recently made actual designs of weapons using reactor plutonium, which can produce very substantially higher explosive yield.

Data provided to the Workshop by William Walker and by N. Oi indicate that as of the end of 1992 there existed some 87 MT of separated R-Pu, with the largest holdings in France (16 MT), Russia (25 MT), and the U.K. (36 MT). However, this separated R-Pu is not necessarily owned by the nation in which it resides, since much of it has been reprocessed under contract to other nations. Total generation of R-Pu annually in civilian nuclear power plants is some 75 MT per year, and almost 1000 MT of R-Pu has been generated, although most of it still resides in the spent fuel.

To be precise, at a nominal burnup of uranium oxide fuel in a pressurized water reactor (measured after five years of removal from the reactor) the plutonium isotopes for burnup of 42 gigawatt-days per MT of fuel amount to Pu^{238} (2.7%), Pu^{239} (54.5%), Pu^{240} (22.8%), Pu^{241} (11.7%), and Pu^{242} (7.0%). The "fissile plutonium" is the sum of

the Pu^{239} and Pu^{241}, or about 66%. However, as we have discussed, the Pu^{240} is also readily fissionable in the spectrum of a fast neutron reactor or in the even "harder" spectrum of a nuclear weapon.

If nuclear weapons themselves are absolutely not available for theft or transfer, and neither is W-Pu or HEU, a nation might still choose to manufacture its own W-Pu in a small reactor, or to enrich uranium as did South Africa. To obtain 10 kg of W-Pu would require some 30 megawatt-years of operation of a reactor-- a fact which is well known and which is the basis for the extreme scrutiny by IAEA in applying safeguards to nuclear establishments which have been submitted for its monitoring.

Sub-national groups are unlikely to have the time or territory to operate reactors or to enrich uranium by conventional means, and it cannot be precluded that separated reactor plutonium would be sufficiently attractive to them to be the target of theft. And, of course, the "market" works well on the criminal side, in general, in that there are always willing intermediaries with no interest either in the creation of the material or in its ultimate use, but only in making a profit on what they claim they know best how to do-- steal or rob successfully.

There is already great attention in the international community to the Non-Proliferation Treaty (NPT) and to the requirements for IAEA monitoring of nuclear establishments to guard against the diversion of the reactor itself to the production (by short irradiation cycles, for instance) of W-Pu instead of R-Pu.

Not much detail has been presented about security measures in place for R-Pu, and security (as contrasted with accounting safeguards) is not a matter for the IAEA. No one at the Workshop took lightly the responsibility of guarding and accounting for separated Pu of any composition, or of the spent fuel from which it can be obtained.

DIRECT DISPOSAL OF SPENT FUEL

Spent fuel from power reactors of the boiling water or pressurized water types (BWR or PWR) is typically removed from the reactor after three years and placed into a "cooling pond" at the reactor. After a year or more, spent fuel is loaded into shipping casks and transported either to a reprocessing plant or to a facility where the cask (or a different one) is used to hold the very hot (both thermally and from the point of view of nuclear radiation) spent fuel for several decades, until the heat generation has diminished sufficiently to allow the economical placement of the disposal cask into the mined geologic repository. The allowable separation between casks and the amount of fuel in a given cask are both determined by the heat output, in order to avoid exceeding the allowable temperature of the rock.

The alternative, which is the plan to be used in France, Japan, and some other countries, involves chopping the fuel in the reprocessing plant, dissolving it, and separating plutonium, uranium, and fission products. In the process as practiced at COGEMA and which will be practiced at THORP (England), at Tokai (Japan), and eventually at Rokkasho-mura (Japan), the fission products after several years in holding tanks will be incorporated into molten borosilicate glass, which is cast into stainless steel canisters that are then welded closed and stored for some decades until their fission product heat release is low enough to allow their commitment to a mined repository. The reactor plutonium thus obtained (and perhaps the uranium) is recycled to a

light water reactor (LWR) or stored for use in a fast reactor. German utilities were formerly required to reprocess spent fuel, but direct disposal is expected to become an option for them as well in 1994.

To get a little ahead of the discussion, reprocessing is necessary in a system of fast (neutron) breeder reactors, in which more plutonium is generated by capture of some of the fission neutrons on U^{238} than is burned to sustain the chain reaction. As a consequence, it is in principle possible to use almost all of the mined uranium ore, effectively fissioning the U^{238} through its transformation first into the Pu^{239}; but without reprocessing, the fission product burden would continue to increase in the reactor, and multiple reprocessing is therefore required. Twenty years ago there was much more optimism than there is now about the early advent of a breeder economy, providing good enough reason for the construction of reprocessing plants and exploratory fuel fabrication facilities that could use plutonium. But reprocessing and recycle of plutonium into LWRs is much more problematical, optional, and it can hardly be taken for granted that it is economically preferable to the "once through" or direct disposal approach.

There was considerable discussion about the economics, which are much influenced by capital costs of reprocessing and MOX fabrication facilities, whether such facilities exist and whether they can be operated near capacity, and the like. Indeed, support for the reprocessing and recycle option for LWRs is now largely based on "reduction of radiotoxicity" of waste going to geologic disposal, about which more will be said later.

Although it is strongly argued that any difference in cost between reprocessing and direct disposal is on the order of a few percent of the cost of electricity, and on the order of 5-10% of the fuel cycle cost, the author presented data from an unpublished international study which concludes that the "back end" of the fuel cycle costs 1.45 mill/kWh for reprocessing in comparison with 0.61 mill/kWh for direct disposal. These back-end costs are to be compared with the front-end cost of 4.13 mill/kWh for all of the charges involved in finding, mining, converting, enriching uranium and fabrication into LWR fuel. Fabrication of MOX with free plutonium is likely to be somewhat more expensive than the purchase of uranium oxide fuel ("UOX") but the costs of obtaining the plutonium for recycle tend to dominate the cost of fuel fabrication for a simple reason. Taking typical numbers from Bouchard, Table II, for a current UOX burnup of 42 GWd/t, the total Pu produced is shown as 34 kg/TWh(e), where the terawatt-hour refers to the electricity produced at an efficiency of about 30%. This yields about 10.2 kg Pu per MT of spent fuel-- just about 1% by weight.

Taking a nominal 7% total Pu content for MOX fuel in an unmodified LWR, we see that about 7 kg of UOX fuel needs to be reprocessed to provide the plutonium for one kg of MOX.

For all the reasons given previously, the cost of reprocessing is both debatable and difficult to define, but it is given (Suzuki, page 9) as $2x10^8$ yen/tSF, or about $2000/tSF for the years 2000-2020. This is for a substantial industry of 800 tSF/y (the size of COGEMA UP3 plant at La Hague). For the acquisition of one kg of MOX, some 5-7 kg of UOX needs to be reprocessed, contributing $10,000 to $14,000/kg MOX. If the cost of reprocessing is thus ascribed entirely to the plutonium resulting,

this component of the cost per kg of MOX is very much larger than any cost supplement or saving in fuel fabrication vs. the acquisition of UOX fuel.

As indicated, there was much discussion of such simple calculations, of the proper allocation of costs and benefits, and the like. Unfortunately, a report of the OECD Nuclear Energy Agency exhibited at the Workshop will only be published in April 1994, so no detailed presentation or analysis of that report was possible.

REPROCESSING VS. DIRECT DISPOSAL

Many participants argued that reprocessing and recycle of Pu in LWRs contributes to minimization of volume of radioactive waste, and to a reduced use of primary materials such as uranium ore. Indeed, the record of COGEMA, for instance, in reducing waste volume has been impressive, with the volume of "long-lived waste" generated in UP3 (in liters per MT of spent fuel) falling from a design of 3000 to a current 1400 to an expected 1000 in 1995 and about 500 in the year 2000. Nevertheless, the cost of the repository disposal is determined not by the volume but by the heat evolution; it is argued that it is the nature and durability of the waste formed that is important and not the volume. As for the saving of primary material or of the general commitment to recycling of materials, it is argued in opposition that the merits of recycle are exhibited in the economics, and that it does not benefit humanity but instead imposes a burden to do these things that are uneconomical. It is suggested that it is the business of governments and international organizations to set charges and taxes in such a way that free market competition results in an overall optimization, including environmental and resource goods.

As for resource extension and contribution to energy independence, if that is a goal to be valued in itself, additional tools are available to meet the goal of independence from denial of LEU shipment, for instance. This could be accomplished by the purchase of substantial amounts of surplus HEU from the United States or Russia, blended to MEU to eliminate its utility in nuclear weapons. Because of the very low cost of transport and storage of MEU in comparison with petroleum, it is indeed feasible and may even be a good financial investment to provide a multi-year supply of raw fuel for the entire set of a nation's LWRs.

"RADIOTOXICITY" AND OTHER CRITERIA FOR CHOICE OF WASTE AND PROCESS

Many of those involved in reprocessing argue that there is a major benefit in removing the actinides from the waste, so that the fission products that finally go to the repository in vitrified form pose less of a hazard of radioactivity than does the spent fuel itself. However, some who advance this reason for reprocessing and recycling of plutonium strongly oppose the argument that the separation and use of plutonium should be avoided because of the extreme radiotoxicity of plutonium, since they deny the likelihood that the material will be finally divided and brought into effective contact with a large number of humans. Yet the simple argument of reducing radiotoxicity of the vitrified waste (advanced by some of the participants) tends to ignore the pathways by which plutonium and the other actinides (elements beyond uranium in the periodic table) are actually transported from the waste to the biosphere.

Two aspects of such transport are important-- eventual water intrusion into an intact mined geological repository, on the one hand, and on the other, human intrusion with the recovery of the material and its careless disposal.

TOWARD A MORE UNIFIED CONSIDERATION OF NUCLEAR WASTE

Some of the participants pointed out that the transport of plutonium and other actinides from the geologic repository is limited by the very low solubility of the actinides in ground water and the strong absorption on rock and clay materials. Thus, Choi (Lawrence Livermore National Laboratory) notes that the radiation dose from contaminated water from the proposed U.S. repository is dominated by fission products. For instance, even in the early years (hundreds to thousands of years after deposition) the dose index (repository inventory multiplied by fractional dissolution rate multiplied by dose conversion factor) for Cs^{135} is ten times that for the amount of Pu^{240} or Am^{241} that are in the spent fuel (and Pu^{239} is significantly lower than Pu^{240}). Furthermore, the content of fission product I^{129} has twice the dose index of Cs^{135}, and Tc^{99} has four times the dose index of Cs^{135}.

Considering also that the half-life of Tc^{99} is 213,000 years, that of I^{129} is 15.7 million years, and that of Cs^{135} is 2.3 million years, from the point of view of transport by contaminated water there would be no significant reduction in the overall dose index at any time from the removal of actinides. Indeed, unless carefully managed, losses of actinides during reprocessing could well regard in much larger exposure to the biosphere than would leaching from a repository.

In any case, it follows that a total "radiotoxicity" (which leaves out the factor of "fractional dissolution rate" from the dose index), is an inadequate measure of the hazard of waste. A waste form with much higher radiotoxicity may be less hazardous if the material is present in a more concentrated form and thus is less available to transport by ground water.

The small contribution of actinide dose index relative to long-lived fission product dose index for spent fuel suggests also that it is largely irrelevant to criticize the recycle of actinides in LWRs because of the very substantial increase in radiotoxicity as a result.

Finally, it is important to consider in all cases something which is routinely ignored in most of the comparisons of waste forms and disposal, and that is the amount and availability of hazardous material present in the cycle at any time before ultimate disposition. Particularly in a growing nuclear energy economy, and with storage and processing times ranging from a few years to several decades, a very substantial fraction (or even the majority) of the radioactive material is present in spent fuel above ground, in holding tanks for solution of fission products, or the like. These stocks of hazardous material are not immune to accident or terrorist attack. Nor is it clear what would happen to them in the case of societal disruption by revolution or ethnic warfare. Clearly, it is inadequate to consider the hazard of ultimate disposal independent of minimizing the overall hazard from all parts of the cycle.

To minimize hazard from the entire cycle will be difficult, because of differing assessments of the likelihood of accident or disruption at various stages. Yet these aspects cannot be ignored, even though they are difficult to quantify.

ENERGY FROM NUCLEAR FISSION OVER THE VERY LONG RUN-- U^{238} AND TH^{232}

Major fast-neutron reactor programs (FNR) exist in Russia, France, and Japan, with a smaller FNR program more closely coupled to fuel reprocessing being explored in the United States-- the integral fast reactor, IFR. In order to avoid degrading the neutron energy by "moderation" by scattering on light-element materials in the structure or coolant, the FNR typically use liquid sodium as the heat transfer fluid, despite the great chemical reactivity of sodium with water and air. To avoid the design constraints imposed by the use of molten sodium, there is also under exploration in Russia an FNR cooled with molten lead.

As previously noted, from the very earliest days of consideration of nuclear energy through fission reactors, the Pu^{239}/U^{238} breeding cycle was very appealing. It was originally proposed that the breeder economy could expand rapidly by self-generated plutonium, and thus provide large amounts of electrical power by the consumption of U^{238} rather than the 0.7% U^{235} present in natural uranium. The potential resource extension goes far beyond the factor 140 represented by the relative abundance of U^{238} and U^{235}. Raw uranium at $50/kg contributes negligibly to the cost of electricity in an LWR. Uranium at $5000/kg would be no economic burden for an FNR that was otherwise an economical source of electrical energy. Thus, uranium could be obtained from seawater where there is a total stock at least 1000 times as much as the reasonably assured reserves of uranium in the ground.

Note that if uranium could be obtained from seawater at a cost of even $200/kg, it could still be used economically in the LWRs, but if the energy expended in the extraction exceeds the energy that can be produced at 30% efficiency from the fission of a portion of the 0.7% U^{235} content, the energy cycle can't be closed with an LWR. However, such a cycle would be a negligible drain on an FBR economy.

That is the attraction of a fast breeder reactor program. Thus far, the problem has been that FNRs have been substantially more costly than LWRs, although it is now argued by some that the cost of an LWR meeting all safety and environmental requirements has escalated to the point where an FNR may be competitive. Since there is no commercial FNR, it is very difficult to know whether this is true. Furthermore, it will be many decades before operating experience is obtained with demonstration commercial-quality fast reactors in a number of countries, as well as the lead cooled reactor.

A further constraint on the FNR has been the absolute dependence on plutonium recycle, with Pu^{240} fraction typically half as large as that in LWR spent fuel. The transport of spent fuel and especially of fresh recycle fuel then poses a potential proliferation hazard, since it is intermediate in quality between W-Pu and R-Pu from LWRs. In fact, the plutonium formed in the blanket of the FNR is "supergrade," with lower Pu^{240} content than W-Pu itself.

In the United States 30 years ago it was argued that it was urgent to reprocess LWR spent fuel in order to obtain the plutonium for investing in future fast breeder reactors, but it is now generally accepted that it is entirely appropriate to start a Pu-U fast reactor with enriched uranium-- typically 20% U^{235}. Three successive full cores of enriched uranium (perhaps ten year annual feed) could thus invest an FNR of con-

version ratio of 1.00 with the plutonium required to run it and its descendents forever, with reprocessing and recycle and the addition of depleted uranium. Thus some 15-20 MT of HEU equivalent would be required for each 1-GW(e) of fast reactor. If there is an additional 500 MT of Russian HEU available, that could eventually be used to invest some 35 fast reactors. If the world fast reactor population were to grow to 1000, the operation of such a population for 1000 years would require only about one million MT of uranium-- 1000 MT of natural uranium for each reactor. To obtain 20 MT of U^{235} for investing each of these reactors would require the enrichment of some 4000 MT of natural uranium for each reactor, or about as much U^{235} as is required to fuel the world's current 300 equivalent LWRs for about 70 years.

But with no shortage of uranium and enrichment capacity for the foreseeable future, supporters of the fast reactors claim that they can be used and should be used to burn up actinides, even those that are "non-fissile" (that is, those that do not undergo fission with thermal neutrons in an LWR). Such non-fissile isotopes can indeed be burned in fast reactors, but because of their substantial capture cross sections require about two neutrons to fission such a nucleus. In a thermal reactor, about three neutrons are required, since the non-fissile isotope must by definition first be converted by capture to one that can be fissioned in a thermal flux. But from the point of view of resource extension, whether or not one burns Pu^{240} does not contribute very much, and we have already discussed the inadequacy of the "radiotoxicity" index, despite the fact that fast reactors are often prescribed as a way of reducing the radiotoxicity of plutonium and of avoiding the enhancement of radiotoxicity by the recycle in LWRs.

What is the alternative, if one has already separated plutonium from spent fuel? It has been proposed by Sweden to put German spent MOX fuel into the Swedish mined geologic repository. In fact, Sweden has exchanged its commitment to COGEMA for the reprocessing of Swedish fuel and instead proposes to accept German MOX fuel after irradiation in German reactors, for disposition in the Swedish repository, although this has not yet been approved by the German government. This is of course also one of the principal options advocated by the CISAC report for the disposition of excess military plutonium-- the fabrication of MOX fuel, its burning in LWRs, and its commitment to the Yucca Mountain repository.

Most of the high level waste from plutonium production of the former Soviet Union has been either disposed of on the surface as in Lake Karachai, or injected into a series of wells some 800 m deep. In either case the fission product waste is not available for vitrification with the excess military plutonium. So excess Russian military plutonium could be fabricated into fuel for an LWR or an FNR, used to produce electrical power, and then be treated like civilian spent fuel. It could either go directly to the repository or could be reprocessed. There seems to be now general agreement that with the large stock of R-Pu already available in Russia and with the prospect of 100 MT of W-Pu becoming available over the next ten years (before any significant number of BN-800 FNR can be built) that it would save money and advance the fast reactor program most effectively to defer the construction of a reprocessing plant for BN-800 fuel until essentially all of the Pu had been fabricated and processed through reactors.

Note that the option proposed by CISAC for the processing of W-Pu as MOX in LWR of existing type in the United States does not depend upon a judgment of economic viability. It is estimated that there will be a net cost connected with this program of the order of $0.5-1.0 billion, compared with the operation of one or two reactors fueled with LEU and producing similar amounts of electrical energy over the same period.

THE U^{233}/TH^{232} BREEDING CYCLE

This is a cycle that operates (almost) on thermal neutrons, although the conversion ratio is not large enough to compensate for parasitic losses of neutrons to fission products, structure, and leakage in a useful reactor. As a consequence, the group at Los Alamos has proposed supplementing the neutron economy to the extent of about 5% by spallation neutrons from a proton accelerator of some 1000 MeV beam energy, and the LANL group proposes also to use the flexibility of such a system to burn up the long-lived fission products from the LWR power producers.

More recently, Carlo Rubbia (CERN) has proposed breeders of this type, but specifying operation at a flux density of $2x10^{14}$ or lower, compared with about ten times that value for the LANL approach. In this way, the CERN group allows the Pa^{233} to decay in large part to U^{233} rather than parasitically capturing a neutron, thus improving the neutron economy.

Further differences between the two approaches is that LANL now specifies a molten salt system with fluid fuel and graphite moderator, while the CERN approach uses a much more conventional system with solid fuel.

Although Carlo Rubbia was unable to attend the NATO ARW, his proposal has been studied and note taken of one of the principal advantages claimed for this approach-- namely, the very small amount of actinide production compared with the Pu^{239}/U^{238} cycle. However, the addition of perhaps 3% U^{238} to the Th^{232} to prevent weapon use of the separated U^{233} will indeed lead to substantial production of Pu^{239}.

As energy producers, these proposals need to compete on projected economics and environmental aspects. Similarly, if the transmutation of long-lived fission products instead of sending them to the repository as spent fuel or vitrified high-level waste is to be a major benefit of the program, it needs to show an economic benefit in comparison with the alternative, or an environmental and health benefit.

The claimed immunity from criticality accidents, in view of the operation at reproduction factor of 0.95 instead of 1.00, may be addressing a problem that is not regarded as very serious, in view of the fact that current reactors operate with a prompt k of some 0.993 (with a delayed neutron fraction of 0.7%).

Plutonium reactors with non-fertile fuel will operate with a delayed neutron fraction of 0.2-0.3%, and so with a prompt k on the order of 0.997. It would seem that at least one interesting design point for an accelerator-driven sub-critical assembly would be to drive a sub-critical reactor with a prompt k of 0.99, thus providing MORE margin against criticality incidence than is available in current reactors, and reducing the accelerator power by a factor 5 in comparison with operation at $k = 0.95$.

Furthermore, a shortage of neutrons is not exactly the situation that we'll obtain for the next three or four decades, with the surplus of W-Pu and HEU from weapon

dismantlement, so that the role of such accelerator-driven systems in the near term is unclear (and of course they're not available in the near term) and it is no more clear in the long term. Nevertheless, exploratory work on the U^{233}/Th^{232} cycle would be valuable for its prospects and also for the insight it will give on the Pu^{239}/U^{238} cycle as practiced either in sodium-cooled or lead-cooled reactors. The on-line processing of the molten fluoride salt of beryllium and lithium (and the contained fuel and fission products) is less widely known than the Purex aqueous process for oxide fuel. Of course, if it proves to have economic and environmental and health superiority, it would be a welcome addition to the technological stockpile.

ENVIRONMENTAL IMPACTS AND CONSTRAINTS

The Workshop was shown the status of some plutonium process wastes associated with the military program. All agree that plutonium is a hazardous material and that it should be kept apart from the biosphere.

However, proven long-term repositories for spent fuel or for vitrified waste are not yet available, and the cost and quantitative aspects of transport of waste to the biosphere are still matters of analysis and experiment. So while almost 1000 tons of civil plutonium is already present in spent fuel and nearly 100 MT of R-Pu is available in separated form, the details and cost of ultimate disposal are still unknown.

COSTS OF TRANSPORT AND SAFEGUARD REGIMES

The additional cost of building either a complex or a simple building complex to facilitate safeguard application by the IAEA is not large-- probably less than 1%, it was suggested. However, the IAEA does not currently have the budget to adequately safeguard the large number of nuclear energy establishments in the nuclear weapon states, as well as the ones on which it is currently applying safeguards. Not only an increase in budget and personnel for the IAEA would be necessary, but it would also be helpful to have additional measures provided in the nuclear energy facilities and approved by the IAEA that would obviate the need for most continued presence of IAEA inspectors.

RECOMMENDATIONS FOR FURTHER WORK.

Much interest was expressed at the workshop in the utility of collaboration among all those concerned, especially with the Russian nuclear industry, on the criteria for waste isolation. Thus, radiotoxicity alone is inadequate, although it is the historical approach, and something that takes into account the mechanism of migration from a geological repository to the biosphere, such as Dose Index, might be a better indicator of the hazard. There seems to be a willingness to share analyses and computer codes for such purposes, and that can only be good. Furthermore, the question of repository cost as a function of volume of the waste to be disposed is of some interest and urgency. If the heat evolution is unchanged, what is the value of reduced volume? This question of criteria for waste isolation would seem to be a good topic for a further NATO Advanced Research Workshop.

It was indicated at the London ARW that the publication of the OECD Nuclear Energy Report on reprocessing economics is expected April 1994. Although this is the product of a group of experts from the individual countries, the text of the various drafts has not been publicly available, and the utility of the NEA report would be enhanced by a NATO ARW focusing on the analyses and their interpretation. This would, of course, involve groups and individual analysts who had no part in the development of the NEA report, together with those who were involved.

A third NATO ARW as well as the desirability of other cooperative work, would seem to be in order on real-time material accounting and safeguarding, especially as applied to weapon material and HEU. The traditional IAEA safeguards, which are to provide "timely warning" of diversion, and the confidential nature of IAEA activities seem neither optimum nor adequate for safeguarding these materials that are more quickly useful in nuclear weapons. But before looking at safeguards, the individual nations responsible for such materials could well develop a modern, efficient, and economical system for accounting for and managing their own stocks.

Finally, the question of breeder reactors is important as a contender for long-term energy supply. But one could well have a three-day NATO ARW on the various types of breeder reactors and their intercomparison, allowable fuel costs, and the like, without touching the very important competition with renewable resources, fusion, and energy conservation for the long term. Perhaps a NATO ARW on breeder reactors would be in order, followed in about a year by a more general NATO ARW on the broader question of long-term energy needs and options.

CONCLUSION

I should add the summary with which I concluded my remarks at the last session of the Workshop: Among all the discussion, agreement, and controversy at this Workshop, the common ground is analysis with economic, environmental, and security components, and it is both important and urgent that scientists and technologists interested in nuclear energy learn such techniques and standards and also involve the professionals from those fields.

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INTRODUCTION

The purpose of this presentation is to interpret the 1993 paper Mark [1] which addressed directly "the question of whether a terrorist organization or a threshold state could make use of plutonium recovered from light-water-reactor fuel to construct a nuclear explosive device having a significantly damaging yield." Carson Mark was Director, Theoretical Division, Los Alamos National Laboratory, 1947-1972 and has remained involved with that Laboratory since stepping down as head of the weapons design effort and since his retirement. I will discuss some of the technical analysis of [1] but want first to reproduce the conclusions of that paper:

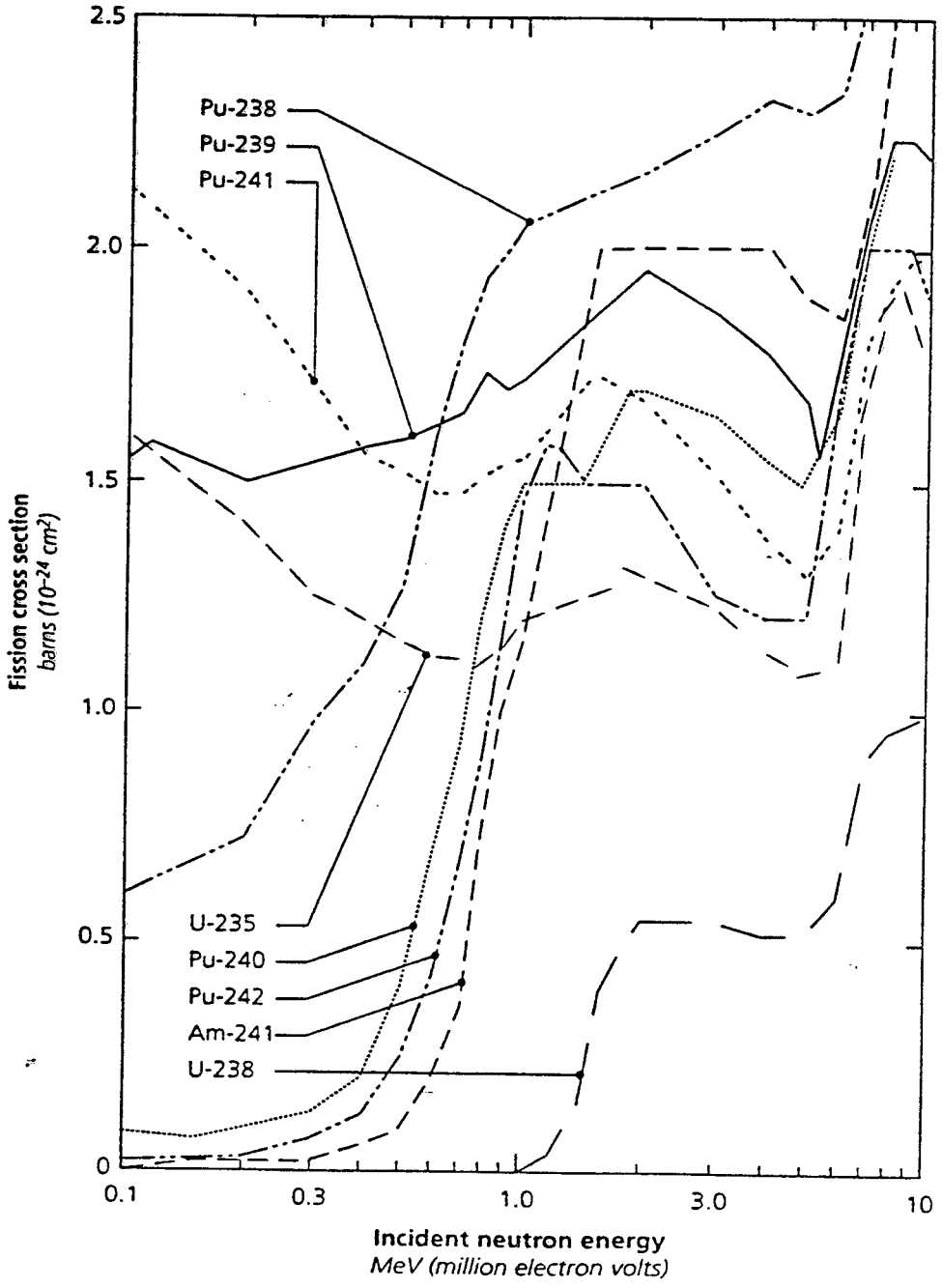
- *Reactor-grade plutonium with any level of irradiation is a potentially explosive material.*
- *The difficulties of developing an effective design of the most straightforward type are not appreciably greater with reactor-grade plutonium than those that have to be met for the use of weapons-grade plutonium.*
- *The hazards of handling reactor-grade plutonium, though somewhat greater than those associated with weapons-grade, are of the same type and can be met by applying the same precautions. This, at least, would be the case when fabricating only a modest number of devices. For a project requiring an assembly line type of operation, more provisions for remote handling procedures for some stages of the work might be required than would be necessary for handling weapons-grade material or for handling a limited number of items.*
- *The need for safeguards to protect against the diversion and misuse of separated plutonium applies essentially equally to all grades of plutonium.*

The fourth conclusion follows from the first three, on which I concentrate. The second conclusion is most delicate to discuss, because it is most closely connected with the design of nuclear weapons, and our purpose is to prevent rather than facilitate the misuse of civil plutonium in nuclear weapons.

PLUTONIUM USELESS IN A NORMAL REACTOR CAN BE USED IN A NUCLEAR EXPLOSIVE

Thus I begin with the assertion that "reaction-grade plutonium with any level of irradiation is a potentially explosive material." As taught by Serber [2], a nuclear weapon involves a chain reaction multiplication of fast neutrons in plutonium or uranium metal or other material subject to fission by neutrons in the energy range of about an MeV or more. The fission cross section of U^{238} rises to about 0.5 barns at about 2.0 MeV, but no amount of U^{238} will provide a self-sustaining chain reaction even for fast neutrons, because the likelihood that one neutron will generate by fission more than the neutron required to replace it is not enough to compensate the probability that the original fast neutron will be lost to the desired energy range by so-called "inelastic scattering."

Figure: The neutron cross-section for fission of the principal plutonium and uranium isotopes (and americium-241, a decay product of Pu^{241}) against neutron energy. (Reproduced by permission from Fig. 2 of [1]).



EXPLOSIVE PROPERTIES OF VARIOUS TYPES OF PLUTONIUM

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Abstract. The theft of nuclear weapons or of weapon-grade plutonium is likely to be the preferred approach to weapons acquisition by a nation or terrorist group, but the acquisition of "reactor grade" plutonium from spent power reactor fuel is also a feasible route to nuclear explosives. The analysis interprets and agrees with the 1993 paper by Carson Mark which emphasizes the fact that reactor-grade Pu can be used in nuclear explosives and the reasons for that conclusion, and that Pu from power reactors must be protected in a fashion similar to the protection afforded weapon-grade material.

U^{235} (or highly enriched uranium, HEU, typically 94% U^{235} and 6% U^{238}) can be used to make nuclear weapons, either by the "gun assembly" method used for the bomb exploded at Hiroshima and in some artillery shells, or by the implosion method that must be used for plutonium nuclear explosives. It is conventional to characterize nuclear explosive materials by the bare-sphere critical mass, being that amount of material at normal metallic density for which a set of fission neutrons just reproduces itself in a succeeding generation. Thus, in reactor parlance the bare-sphere critical mass of the weapon designer has a reproduction factor k of 1.000 for prompt neutrons. For amounts of material significantly in excess of the critical mass, the time required for the neutron population to double is extremely short, on the order of the very short neutron lifetime of about 10^{-8} seconds; in addition, because of the phenomenon of delayed neutrons, one could not gradually accrete more than about 0.99 bare-sphere prompt critical masses.

Even that would be exceedingly dangerous, because the reflection of neutrons from neighboring materials can make the mass which is subcritical for a bare sphere supercritical on prompt neutrons. Mark indicates that by the use of a neutron reflector a few inches thick, the critical mass of the fissile material can be reduced "by a factor two, or so, below the bare critical mass." In addition to differing substantially in fission probability vs. energy as indicated in the Figure, the various fissionable materials differ also in the number of neutrons liberated per fission and in the average energy per neutron. The bare critical masses of Table 1

Table 1: Various properties of plutonium isotopes (and americium-241). (Reproduced by permission from Table 2 of [1]).

Isotope	Half-life[a]	Bare critical mass	Spontaneous fission neutrons	Decay heat
	years	*kg, α-phase*	$(gm\text{-}sec)^{-1}$	*watts* kg^{-1}
Pu-238	87.7	10	$2.6 \cdot 10^{3}$	560
Pu-239	24,100	10	$22 \cdot 10^{-3}$	1.9
Pu-240	6,560	40	$0.91 \cdot 10^{3}$	6.8
Pu-241	14.4	10	$49 \cdot 10^{-3}$	4.2
Pu-242	376,000	100	$1.7 \cdot 10^{3}$	0.1
Am-241	430	100	1.2	114

a. By α-decay, except Pu-241, which is by β-decay to Am-241.

may be compared with the bare critical mass of 52 kg of high-enriched uranium (94% U^{235} and 6% U^{238}). Pure Pu^{239} has a critical mass of about 10 kg for alpha-phase material of density 19.6 g/cc, as do Pu^{238} and Pu^{241}. Pu^{240}, according to Table 2 present as 24.3% of the Pu in reactor-grade Pu recovered from LEU reactor fuel that has released 33 MWD/kg and been stored for ten years prior to reprocessing, in pure form has a critical mass of about 40 kg. The critical mass of reactor-grade plutonium is 13 kg.

something like the maximum yield available with that assembly. It there were no neutron at all during the assembly, the material would disassemble without any nuclear explosion. For this reason, both the implosion weapon and the gun-type weapons contained "initiators" which would allow contact of alpha-emitting Po^{210} with beryllium as the shock or the motion reach the-initiator, so as to provide with high probability several neutrons to initiate the chain reaction.

Premature initiation by a spontaneous fission neutron, a neutron from cosmic rays, or by an improperly functioning initiator would lead to a chain reaction that could produce energy densities greater than that corresponding to the assembly velocity of the material, and if injected at a "worst instant" would lead to a minimum yield from that assembly. The worst instant is something like the moment of criticality, and this minimum yield is called the "fizzle yield." The fizzle yield for the first implosion weapon was apparently on the order of one kiloton and Mark quotes from 1945 correspondence of Robert Oppenheimer and General Leslie Groves to infer that the probability was 88% that this assembly would survive long enough without a chain being initiated so that it would provide the nominal yield of 20 kt; about 94% that it would have a yield greater than 5 kt, and about 98% that it would provide a yield in excess of one kt. Mark then points out that if the neutron source is multiplied n-fold, the probability of surviving to produce the nominal yield would be only 0.88 to the n-th power, and so on.

The spontaneous fission neutron rate from super-grade Pu is given by Mark as some 20/g-sec, from weapons-grade material as 66/g-sec, and from reactor grade some 360/g-sec. Mark also estimates the probability, based on the Oppenheimer letter, of achieving various yields in an assembly system twice as rapid as the first implosion system ("Trinity") as a function of the spontaneous fission rate. If one were to assume that Trinity used the super grade material and that the comparison was with reactor-grade material, the neutron source would be some 20 times larger. In the Trinity assembly, this larger neutron source would then correspond not to 88% probability of achieving nominal yield of 20 kilotons but only about 8%; however, according to Mark the probability of achieving a yield above 5 kt would be 29%, and 67% above 1 kt.

In the implosion system that assembles twice as rapidly, the probability of achieving the nominal yield of 20 kt would be 28%, with a 54% probability above 5 kt. Of course, the nominal yield from the more rapid assembly could be larger than that assumed here. So it is clear that there are very substantial probabilities of achieving essentially nominal yield from fissile assemblies made with reactor plutonium.

In an Appendix to Mark [1], Princeton physicists Frank von Hippel and Edwin Lyman, on the basis of a simplified model, present actual calculations of the probabilities of different yields, assuming a linear growth of the neutron multiplication rate k from unity at the time of criticality to 2 at the time of maximum supercriticality. The results are similar to those used as examples by Mark.

INCREASED DECAY HEAT FROM REACTOR-GRADE PLUTONIUM

The presence of temperature sensitive materials like high explosive in proximity to the plutonium core is a problem that must be managed by the designer. The problem is

worsened by the fact that more fissile material will probably be required for a reactor grade than for a weapon grade explosive (perhaps a factor two), but also that the decay heat of reactor-grade material is greater by about a factor four (10.5 W/kg in comparison with 2.3 W/kg). Thus if the interior of the explosive were fairly warm in a normal nuclear weapon (say 20 C above ambient temperature) that of a weapon made with reactor-grade material might have a temperature rise some ten times greater-- 200 C-- which would be unacceptable. Clearly this is a dominant problem for the weapon designer, and Mark quotes an example in which a crude nuclear explosive containing perhaps 8 kg of reactor-grade plutonium would emit nearly 100 watts of heat-- much more than the 9 watts emitted from the approximately four kilograms of weapon-grade plutonium taken by a recent report the US National Academy of Sciences as the plutonium content of a nominal nuclear warhead [3]. Mark points out that the thermal conductivity of aluminum is about 1000 times greater than that of high explosive, so that a "thermal bridge" of about one square centimeter cross section could cut in half the temperature increase induced by the reactor-grade plutonium. Other approaches to the problem include delaying the mechanical assembly of the fissile material into the explosive until shortly before the device is to be detonated.

RADIATION EMITTED FROM REACTOR-GRADE PLUTONIUM IN EXPLOSIVES

Here the external dose is dominated by the gamma ray emitted in the decay chain of Pu^{241}, which decays with a half-life of 14.4 years to americium (Am^{241}) which itself decays with a half-life of 430 years. Although Pu^{241} has a much shorter half-life and thus has a much higher decay rate per gram, the decay heat associated with 1 kg of Pu^{241} is only 4.2 W, while that associated with 1 kg of Am^{241} is a much larger 114 W. Rather than a decay heat in the ratio of the decay rate (lower by a factor 30 for Am^{241}), the decay heat for Am^{241} is larger by about a factor 30. This discrepancy arises because the decay of Pu^{241} is by a very low-energy beta emission, while that of Am^{241} is by alpha decay. Rather than calculate from first principles the acceptability and effects of the emitted gamma radiation, it is simpler (as done by Swahn [4]) simply to note that the dose rate from reactor grade plutonium is about six or so times larger than that from the weapons grade material. Mark and Swahn make the point that nuclear weapons fabricated with weapon-grade material are handled routinely by individuals who spend many hours in close proximity to them, so that the six times as intense radiation of a device made with reactor grade material would be little inhibition to an individual who was required to deal with only one or a few such devices.

ARE THE CONCLUSIONS REASONABLE?

It is desirable to submit the conclusions quoted at the beginning of this report to a test of reason, and it is often asked why no nation has built a large (or even small) nuclear arsenal on the basis of reactor grade rather than weapon grade plutonium, if weapon fabrication with reactor grade Pu is as simple as one might infer from the discussion.

Swahn [4, p. 63] quotes the US Government Energy Research and Development Agency (the predecessor to the current Department of Energy, and the government

Table 2: Approximate isotopic composition of various grades of plutonium. (Reproduced by permission from Table 1 of [1]).

Grade	Isotope				
	Pu-238	Pu-239	Pu-240	Pu-241[a]	Pu-242
Super-grade	–	.98	.02	–	–
Weapons-grade[b]	.00012	.938	.058	.0035	.00022
Reactor-grade[c]	.013	.603	.243	.091	.050
MOX-grade[d]	.019	.404	.321	.178	.078
FBR blanket[e]	–	.96	.04	–	–

a. Pu-241 plus Am-241.
b. N.J. Nicholas, K.L. Coop and R.J. Estep, *Capability and Limitation Study of DDT Passive-Active Neutron Waste Assay Instrument* (Los Alamos: Los Alamos National Laboratory, LA-12237-MS, 1992).
c. Plutonium recovered from low-enriched uranium pressurized-water reactor fuel that has released 33 megawatt-days kg^{-1} fission energy and has been stored for 10 years prior to reprocessing (*Plutonium Fuel: An Assessment* (Paris: OECD/NEA, 1989), Table 12A).
d. Plutonium recovered from 3.64 percent fissile plutonium mixed-oxide (MOX, uranium-plutonium) MOX fuel produced from reactor-grade plutonium and which has released 33 megawatt-days kg^{-1} fission energy and has been stored for 10 years prior to reprocessing (*Plutonium Fuel: An Assessment* (Paris: OECD/NEA, 1989), Table 12A).
e. FBR = Fast-neutron plutonium Breeder Reactor.

Although Mark terms Pu^{240} "... a more effective fissionable material than weapons-grade uranium in a metal system" he would not suggest that it is preferred over U^{235}, for reasons which will now become evident.

He then discusses the problems of "pre-initiation" and of heat, and that of the gamma radiation of the decay products of Pu^{241}.

PRE-INITIATION

The sub-critical mass must be brought by change of configuration to a supercritical state, which is accomplished for a gun weapon by the physical movement of the projectile into the matching receptacle. For an implosion weapon, much more rapid motion of the fissile material is achieved by the use of high explosive, so that the "assembly" of the supercritical mass happens in a time which must be of the order of tens of microseconds. As emphasized by Serber and Mark, this was necessary for the use of plutonium in nuclear weapons because of the significant number of neutrons emitted by this material as a result of the spontaneous fission of the small amount of Pu^{240} (about 6% in weapons-grade plutonium). Although Pu^{239} contributes about 22 spontaneous fission neutrons per kg-sec, Pu^{240} contributes some 10^6 spontaneous fission neutron/kg-sec. The likelihood of a ten microsecond interval passing without a neutron injected by the decay from 10 kg of Pu^{239} is very high; however, the 6 kg of weapon plutonium of the Trinity bomb contributes (by virtue of the 6% Pu^{240} content) about 0.36 neutrons per microsecond (about 0.12 per microsecond if it was "super grade") so about four neutrons per ten microsecond interval.

As the reproduction factor k gradually increases from a value below unity to its maximum during the implosion, a neutron injected at the optimum time would lead to explosive disassembly at about the time of maximum k, which would correspond to

agency responsible for nuclear weapons) in briefings held at a meeting of the Atomic Energy Forum/American Nuclear Society in 1976:

> *It is sometimes asserted that fabricating a weapon from the plutonium contained in spent fuel from a power reactor is difficult if not impossible for all but industrial states with sophisticated technology at their disposal. In fact, although reactor grade plutonium is more difficult to work with than plutonium produced specifically for nuclear weapons, it can be made into a powerful nuclear explosive. The basic arguments against the usefulness of reactor grade plutonium in nuclear weapons are that it is highly radioactive, hence difficult to handle, and that it contains isotopes which spontaneously fission, releasing neutrons that would cause pre-initiation of the chain reaction before the nuclear device was assembled. The result would be little or no nuclear yield.*
>
> *In answer to the first point, although plutonium of any isotopic composition is inherently difficult to handle, many nations have developed techniques and equipment to work with plutonium in the course of recycling spent reactor fuel. With only a marginal increase in difficulty, nations so inclined could adapt these same methods to handling plutonium in the fabrication of nuclear explosives. As to pre-initiation, it is more likely to occur in a device using plutonium with a large content of isotopes that spontaneously fission, but a device specifically designed to use reactor grade plutonium could produce a powerful nuclear explosion. All grades of plutonium must be considered strategically important and dangerous.*

There is no doubt that weapon grade material is preferable, in being somewhat easier to handle and for a pure fission explosive providing greater likelihood of a higher and more stable yield. It is probably also cheaper to produce weapon grade material in either small or large quantities than reactor grade material, if the costs of production are all ascribed to the nuclear material itself. Of course, a nation with a well-developed nuclear power program automatically acquires large amounts of spent fuel, on the order of 200 kg per year of operation of a plant rated at 1000 megawatts electric, enough for 20 or more nuclear weapons each year. But if the task is a high-priority program to make nuclear weapons, it is far cheaper to operate a reactor without the additional complications of high pressure and temperature required to make electrical power, and simply to discard the heat at low temperature into cooling water or cooling air. Indeed, one needed to produce the first plutonium with a reactor built with natural uranium, thus far with either heavy water or graphite moderator, although other materials could be used. So it is a matter of simplicity, predictability, and cost for an overt program, all of which lead to the decision to use specially produced weapon grade Pu.

For a terrorist group or a nation that wishes to acquire a few nuclear weapons but lacks the competence or the time to build and operate production reactors, the theft of weapon grade material or of actual weapons is likely to be the preferred path, but reactor-grade material is also a feasible approach to the manufacture of nuclear weapons. Indeed, it is a fantasy to believe that one can actually calculate the effects in warfare of a nuclear weapon even with a precisely assumed yield, so that a variation by a factor ten in actual yield by virtue of pre-initiation in an explosive made from reactor grade material would appear to have very little impact on the influence of the existence of a terrorist explosive.

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