The Spent-Fuel Standard for Disposition of Excess Weapon Plutonium: Application to Current DOE Options

Panel to Review the Spent-Fuel Standard for Disposition of Excess Weapon Plutonium, Committee on International Security and Arms Control, National Academy of Sciences

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Committee on International Security and Arms Control

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PANEL ON IMMOBILIZATION/MOX ASSESSMENT

JOHN P. HOLDREN (*Chair*), Teresa and John Heinz Professor of Environmental Policy & Director, Program in Science, Technology, & Public Policy, Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, Cambridge, Massachusetts

JOHN F. AHEARNE, Adjunct Professor, Civil and Environmental Engineering, and Lecturer in Public Policy, Duke University; Sigma Xi, The Scientific Research Society, Research Triangle Park, North Carolina

ALLISON MACFARLANE, Senior Research Associate, Security Studies Program, Massachusetts Institute of Technology, Cambridge, Massachusetts

MARVIN M. MILLER, Research Affiliate, Center for International Studies, Massachusetts Institute of Technology, Cambridge, Massachusetts

ALBERT NARATH, President (retired), Energy and Environment Sector, Lockheed Martin Corporation, Albuquerque, New Mexico

WOLFGANG K.H. PANOFSKY, Professor and Director Emeritus, Stanford Linear Accelerator Center, Stanford University, Stanford, California

Study Staff

INTA BRIKOVSKIS, Director, Committee on International Security and Arms Control (until 12/98)

JO L. HUSBANDS, Director, Committee on International Security and Arms Control (from 12/98)

JOHN WILEY, Senior Program Officer, Board on Radioactive Waste Management

GEOFFREY FRENCH, Research Associate (until 11/99)

LA'FAYE LEWIS-OLIVER, Administrative Associate

COMMITTEE ON INTERNATIONAL SECURITY AND ARMS CONTROL

JOHN P. HOLDREN (*Chair*), Teresa and John Heinz Professor of Environmental Policy & Director, Program in Science, Technology, & Public Policy, Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, Cambridge, Massachusetts

JOHN D. STEINBRUNER *(Vice-Chair)*, Professor and Director, Center for International Security Studies at Maryland, School of Public Affairs, University of Maryland, College Park, Maryland

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PAUL M. DOTY, Professor Emeritus, Department of Molecular and Cell Biology; and Director Emeritus, Center for Science and International Affairs, Harvard University, Cambridge, Massachusetts (until June 1999)

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MATTHEW MESELSON, Thomas Dudley Cabot Professor of the Natural Sciences, Department of Molecular and Cellular Biology, Harvard University, Cambridge, Massachusetts

ALBERT NARATH, President (retired), Energy and Environment Sector, Lockheed Martin Corporation, Albuquerque, New Mexico

WOLFGANG K.H. PANOFSKY, Professor and Director Emeritus, Stanford Linear Accelerator Center, Stanford University, Stanford, California

C. KUMAR N. PATEL, Professor, Department of Physics and Astronomy, University of California, Los Angeles

JONATHAN D. POLLACK, Professor of Asian and Pacific Studies and Director, Strategic Research, Naval War College, Newport, Rhode Island

F. SHERWOOD ROWLAND, ex officio, Foreign Secretary, National Academy of Sciences, Washington DC

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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Milton Levinson, Menlo Park, CA
David G. McAlees, Bellevue, WA
Alexandra Navrotsky, University of California, Davis
John J. Taylor, Palo Alto, CA
Frank Von Hippel, Princeton University

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by, **Harold K. Forsen**, National Academy of Engineering, appointed by the NRC's Report Review Committee, who was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Executive Summary

BACKGROUND AND CHARGE TO THE PANEL

The concept of the "spent-fuel standard" was introduced, in the 1994 and 1995 reports of the NAS Committee on International Security and Arms Control (CISAC) on the disposition of excess weapons plutonium, as the criterion for judging the adequacy of resistance to theft and proliferation conferred by the intrinsic characteristics of the final plutonium form produced by a disposition option.[1] That standard held that plutonium in its final dispositioned forms should be roughly as difficult to acquire, process, and utilize in nuclear weapons as is the plutonium in typical spent fuel from civilian power reactors.

The 1994 and 1995 reports concluded that the two disposition methods most likely to be able to meet the spent-fuel standard in the near future are

(a) embodying the plutonium in mixed-oxide (MOX) fuel and irradiating this once through in civilian reactors of currently operating types ("the MOX option") and

[1]Committee on International Security and Arms Control, National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium*, Washington, DC: National Academy Press, 1994, 275 pp.; and Panel on Reactor-Related Options, Committee on International Security and Arms Control, National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options*, Washington, DC: National Academy Press, 1995, 408 pp.

(b) immobilizing the plutonium together with large quantities of fission products in a glass and/or ceramic matrix encased in steel ("the immobilization option").

The 1995 report argued further that, because both of these options face a combination of technical and institutional barriers that translate into uncertainties about the pace at which they could be implemented, the best chances for having at least one deployable option at an early date in both the United States and Russia would result from pursuing both options in parallel ("the dual-track approach") in both countries.

These CISAC recommendations have proven to be somewhat controversial in two main respects: the "dual track" approach (with some factions, in each country, favoring one or the other approach to the exclusion of the alternative, and some favoring different approaches) and the appropriateness and interpretation of the "spent-fuel standard" (including whether particular variants of the MOX and immobilization options meet it). The first issue has been settled, at least for the time being, by the recent U.S.-Russian Bilateral Plutonium Disposition Agreement: it specifies that Russia will disposition 34 metric tons of excess military plutonium entirely by the MOX route and that the United States will disposition the same amount, 3/4 by the MOX route and 1/4 by the immobilization route. The second set of questions—those connected with clarification and application of the spent-fuel standard—is the focus of the current report.

The charge to the Panel from the Office of Fissile Material Disposition in the U.S. Department of Energy (DOE) was, more specifically, to

(1) amplify and clarify the spent-fuel standard and the considerations to be taken into account in its application; and

(2) use the results of task (1) to determine whether the final plutonium forms produced by the two primary-candidate disposition options currently being pursued by DOE under the "dual-track" approach—"can-in-canister" immobilization of the plutonium together with high level radioactive wastes and once-through irradiation of the plutonium in mixed-oxide (MOX) fuel in commercial light-water or Canadian deuterium-uranium (CANDU) reactors—meet this standard.

The Panel was *not* asked to address: the proliferation and theft resistance of the steps that lead, under these disposition options, to the final plutonium forms; any questions related to geologic disposal or interim storage of these final forms except insofar as the properties of the final forms under such disposal or storage relate to assessing compliance with the

spent-fuel standard; or disposition alternatives other than the MOX and immobilization options described above. Important issues exist under all of these headings—some of them treated in the 1994 and 1995 reports—but we were not charged to revisit or explore them here, and the time and resources available for this study would not have permitted our doing so.

SUMMARY OF PRINCIPAL FINDINGS

As noted above, the spent-fuel standard holds that the final plutonium form produced by a disposition option should be approximately as resistant to acquisition, processing, and use in nuclear weapons as is the plutonium in typical spent fuel from once-through operation in a commercial light-water reactor (LWR). We have used, as a specific basis of comparison, 30-year-old spent LWR fuel irradiated to 33,000 megawatt-days per initial metric ton of heavy metal in fuel (MWd/MTHM).

Judgments about compliance with the spent-fuel standard should depend only on the intrinsic properties of the final plutonium form, not on the extent of engineered and institutional protections. Such protections are appropriate and necessary, both for ordinary spent fuel and for plutonium disposition forms meeting the spent-fuel standard, but they are not substitutes for the built-in barriers to which the spent-fuel standard relates. Meeting the spent-fuel standard should be regarded as a necessary but not sufficient condition for judging a disposition method satisfactory, and satisfactory disposition should be understood to be only one element of the needed comprehensive approach to managing the hazards of excess nuclear weapons and weapons-usable materials.

No mechanistically applicable formula can avoid the need for a multiplicity of informed judgments in the process of determining whether a specified plutonium disposition form meets the spent-fuel standard. We have attempted to systematize the process of making these judgments in a matrix framework that combines

(a) assessments of the relative importance, against a range of proliferation threats, of the various intrinsic barriers provided by dispositioned plutonium forms, with

(b) assessments of the performance of different dispositioned plutonium forms with respect to these barriers, compared with the performance of the reference LWR spent fuel.

We have applied this approach to address the spent-fuel-standard compliance of the final plutonium forms from four disposition options: spent fuel from the once-through irradiation in light-water-reactors, to

40,000 MWd/MTHM, of MOX fuel made with weapon plutonium (WPu-MOX); spent fuel from once-through irradiation in CANDU reactors, to 9700 MWd/MTHM, of WPu-MOX fuel; spent fuel from once-through irradiation in CANDU reactors, to 25,000 MWd/MTH, of WPu-MOX fuel in a configuration binding numerous CANDU-sized fuel bundles into a much larger agglomeration; and the current DOE can-in-canister configuration, in which unirradiated weapon plutonium is immobilized in ceramic pucks contained in steel cans, in a steel frame, in a steel canister filled with radioactive glass.

We have concluded that the LWR-MOX option is compliant with the spent-fuel standard; that the standard CANDU-MOX option is not compliant; that the compliance of the CANFLEX CANDU-MOX option is marginal; and that compliance of the reference can-in-canister option with the spent-fuel standard is contingent on the outcome of efforts to clarify this option's resistance against on-site attack and to improve its signatures aiding detection of separation activities.

We have concluded, further, that resolution of the vulnerability of the current can-in-canister configuration to on-site attack will require additional investigation. Defining the full details of the required effort was beyond the scope of the current study. But we are not recommending an open-ended R&D program. Rather, we suggest that a full scale-test be carried out involving an attack judged most likely to succeed by a group of independent subject-matter experts. The outcome of such a test would provide a basis for deciding what if any additional physical tests, modeling and simulation studies, and perhaps other analyses are required. We believe that such a testing and development program for the can-in-canister approach might well lead to identification of variants with sufficient resistance to attack to meet the spent-fuel standard, even if it turns out that the resistance of the current can-in-canister configuration is inadequate.

Charge to the Panel

At the request of the U.S. Department of Energy (DOE), the National Academy of Sciences formed in fall 1998, under the auspices of its Committee on International Security and Arms Control (CISAC), a Panel to Review the Spent-Fuel Standard for Disposition of Excess Weapons Plutonium. Under its charge, the Panel was to

(1) amplify and clarify the "spent-fuel standard" introduced in CISAC's 1994 and 1995 reports on the disposition of excess weapons plutonium[2] as the criterion for judging the adequacy of resistance to theft and proliferation conferred by the intrinsic characteristics of the final plutonium form produced by a disposition option; and
(2) use the results of (1) to determine whether the final plutonium forms produced by the two primary-candidate disposition options currently being pursued by DOE under the "dual-track" approach—"can-in-canister" immobilization of the plutonium together with high level radioactive wastes and once-through irradiation of the

[2]These studies were: Committee on International Security and Arms Control, National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium*, Washington, DC: National Academy Press, 1994, 275 pp. (hereinafter CISAC, 1994); and Panel on Reactor-Related Options, Committee on International Security and Arms Control, National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options*, Washington, DC: National Academy Press, 1995, 408 pp. (hereinafter CISAC, 1995).

plutonium in mixed-oxide (MOX) fuel in commercial light-water or Canadian deuterium-uranium (CANDU) reactors—meet this standard.

The Panel was not asked to address the proliferation and theft resistance of the steps that lead, under these disposition options, to the final plutonium forms, nor was it asked to address issues related to geologic disposal or interim storage of these final forms except insofar as the properties of the final forms under such disposal or storage relate to assessing compliance with the spent-fuel standard. Neither was the Panel asked to address compliance of final plutonium forms other than those of the two primary-candidate disposition options currently being pursued by DOE.[3] The consequent omission from consideration of other final forms, including some that have been proposed since the earlier CISAC reports on plutonium disposition, does not reflect any judgment by the Panel about whether these forms would meet the standard.

The Panel provided an Interim Report to DOE in July 1999, conveying preliminary findings relating mainly to the "can-in-canister" approach to plutonium immobilization and, more specifically, to the variant of this approach described in the documents and briefings made available to the Panel in the first part of 1999. The Final Report provided here updates and expands those preliminary findings in a number of respects, including consideration of the next iteration of DOE's can-in-canister design, further attention to MOX options, and expanded argumentation in support of the Panel's conclusions.

[3]The complete charge to the Panel may be found in Appendix A.

Background

CISAC's initial study of "Management and Disposition of Excess Weapons Plutonium" was the result of a 1992 request from General Brent Scowcroft, then the National Security Advisor to President Bush. The study was carried out under DOE sponsorship between late 1992 and mid 1995, following confirmation by the Clinton Administration of the mandate for this effort. The CISAC findings, which were presented in reports issued in January 1994 and July 1995[4], included the following:

- Besides the dangers well known to be associated with arsenals of nuclear weapons, the existence of surplus separated plutonium and highly enriched uranium (HEU) not embodied in nuclear weapons poses "a clear and present danger to national and international security."
- This danger consists of three elements — the risk that this material could be reincorporated into the nuclear arsenals of the states originally possessing it, the risk that it could be stolen for use in nuclear weapons constructed by other states or subnational groups, and the risk of impairment of nuclear-arms-control prospects by perceptions that the major weapons powers are retaining the material in directly weapons-usable form in order to keep open the option of reversing their post-Cold-War arms reductions.[5]

[4]CISAC, 1994 and CISAC, 1995.

[5]The third risk is of course related to the first one, but it is distinct in that harm arises in the form of reactions in other countries to the mere *possibility* of reincorporation of the

- It is more straightforward, in principle, to reduce the risks from highly enriched uranium than to reduce those from separated plutonium, because (a) HEU can be "blended down" isotopically (using abundant uranium-238) to an enrichment level unusable for weapons, but no such isotopic denaturing is practical for plutonium, and (b) the blended down HEU can be used as fuel for commercial nuclear reactors at a profit, while use of plutonium as reactor fuel under current conditions can only be done at an economic loss.[6]
- Politics and perceptions operate to link the fate of surplus nuclear materials in Russia with that of surplus nuclear materials in the United States. Reduction of Russian stocks of nuclear materials and improved transparency and protection for those that remain will only be agreed if the United States takes comparable steps.
- The needed comprehensive approach to this challenge would include: (1) a reciprocal regime of verified declarations and monitored reductions of U.S. and Russian stockpiles of nuclear weapons and nuclear-weapon materials; (2) secure and internationally safeguarded interim storage of the materials, allowing withdrawals only for non-weapon purposes; (3) development of satisfactory options for the long-term disposition of excess weapons plutonium in ways that make its re-use for weapons unlikely; and (4) pursuit of new international arrangements to improve security and accounting for all forms of plutonium and HEU, civilian as well as military, worldwide.
- Two key criteria for judging the adequacy of the approaches taken for the management and disposition of excess weapons plutonium are (a) that separated plutonium prior to final disposition be subject to the same high standards of security and accounting as are applied to intact nuclear weapons ("the stored nuclear-weapon standard") and (b) that the plutonium after disposition not be significantly easier to recover and use in nuclear weapons than is the plutonium in spent fuel from commercial power reactors ("the spent-fuel standard").

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surplus weapons materials into the arsenals of its original possessors, even if the reincorporation does not occur.

[6]The difficulties encountered in implementing the "HEU deal", under which 500 metric tons of Russian HEU is to be blended down and sold to the United States over a period of 20 years for resale in the world nuclear-fuel market, shows that what is easier in principle may still not be easy enough in practice. See, e.g., Matthew Bunn, *The Next Wave: Urgently Needed New Steps to Control Warheads and Fissile Material*, A Joint Project of the Carnegie Endowment for International Peace and Harvard University, Washington, DC: Carnegie Endowment for International Peace, 2000 and references therein.

- The two disposition methods most likely to be able to meet the spent-fuel standard on a time scale reasonably commensurate with the urgency of the task are (a) embodying the plutonium in mixed-oxide (MOX) fuel and using this once through (without subsequent reprocessing) in civilian reactors of currently operating types, yielding a plutonium-bearing spent fuel destined ultimately for geologic disposal ("the MOX option") and (b) immobilizing the plutonium together with large quantities of fission products in a glass and/or ceramic matrix encased in steel—with mass, bulk, radiation field, and resistance to extraction of the contained plutonium comparable to the corresponding properties of spent-fuel bundles, and likewise destined ultimately for disposal in a geologic repository ("the immobilization option").
- Because both of these options face a combination of technical and institutional barriers that translate into uncertainties about the pace at which they could be implemented, the best chances for having at least one deployable option at an early date in both the United States and Russia would result from pursuing both options in parallel ("the dual-track approach") in both countries—including direct cooperation between the two countries on both options to maximize progress.

These CISAC findings had a substantial influence on subsequent debate and analysis on nuclear-materials policy inside and outside governments. Indeed, they are reflected to a considerable degree in the series of policy decisions on plutonium management taken by the U.S. and Russian governments since 1996,[7] up to and including the U.S.-Russian agreement on plutonium disposition concluded the June 2000 Summit between Presidents Clinton and Putin.[8]

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[7]See, e.g., Department of Energy, *Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives*, Washington, DC: Department of Energy, DOE-NN-007, January 1997, pp. 37-39; U.S.-Russian Independent Scientific Commission on Plutonium Disposition, *Final Report*, Washington, DC: Office of Science and Technology Policy, Executive Office of the President of the United States, September 1997 (available at http://ksgnotes1.harvard.edu/BCSIA/Library.nsf/atom); Department of Energy, *Record of Decision for the Surplus Plutonium Disposition Final Environmental Impact Statement*, Washington, DC: Department of Energy, 4 January 2000; and Department of Energy, Surplus Plutonium Disposition Final Environmental Impact Statement (3 vols. and summary), DOE/EIS-0283, Washington DC: Department of Energy, Office of Fissile Materials Disposition, November 1999.

[8]Executive Office of the President of the United States (Washington DC) and Office of the Press Secretary (Moscow), *Joint Statement Concerning Management and Disposition of Weapons-grade Plutonium Designated as No Longer Required for Defense Purposes and Related Cooperation*, 4 June 2000.

The largest controversies arising from the CISAC findings have been about the "dual track" recommendation (with some factions, in each country, favoring one or the other approach to the exclusion of the alternative) and about the appropriateness and interpretation of the "spent-fuel standard" (including whether particular variants of the MOX and immobilization options meet it). The first issue has been settled, at least for the time being, by the recent U.S.-Russian Bilateral Plutonium Disposition Agreement, which specifies that each country will disposition 34 metric tons of excess military plutonium as follows: the United States will disposition 25.5 metric tons via the MOX route and 8.5 metric tons by immobilization, and Russia will disposition all 34 tons via the MOX route. It is the second set of questions — those connected with clarification and application of the spent-fuel standard — which constitutes the focus of this new CISAC report.

Clarifying the Spent-Fuel Standard

We begin with a review of the definition and application of the spent-fuel standard in the initial CISAC study, before turning to issues raised subsequently and the challenge of making the standard easier to apply.

THE STANDARD AS ORIGINALLY CONCEIVED

CISAC's original formulation (CISAC, 1994, p. 34) held that "Options for the long-term disposition of weapons plutonium should seek to meet a 'spent-fuel standard' — that is, to make this plutonium roughly as inaccessible for weapons use as the much larger and growing stock of plutonium in civilian spent fuel." What was meant by the "inaccessibility" of plutonium in spent fuel was elaborated in a two-page box later in the same volume (CISAC, 1994, pp. 150–151) and further clarified in a passage in the successor volume (CISAC, 1995, p. 73) stating that the spent-fuel standard

> does *not* imply a specific combination of radiation barrier, isotopic mixture, and degree of dilution of plutonium. Rather, it describes a condition in which weapons plutonium has become roughly as difficult to acquire, process, and use in nuclear weapons as it would be to use plutonium in commercial spent fuel for this purpose. The rationale for the spent-fuel standard is, first, that the bulk, composition, and ionizing-radiation field of spent fuel pose very appreciable barriers to the theft or diversion of this material and extraction of contained plutonium for use in nuclear weapons and, second, that the existence in the world of many hundreds of tons of civilian plutonium in spent fuel means that there

> would be little security gain from special efforts to eliminate the weapons plutonium, or to render it much less accessible even than the plutonium in spent fuel, unless society were prepared to take the same approach with the global stock of civilian plutonium.

The terms "accessible" and "inaccessible" in short formulations of the spent-fuel standard, then, referred to the ease or difficulty of acquiring, processing, and using in weapons the plutonium that is embedded in typical spent fuel. A footnote to the above passage added this further important point about the time dimension of the standard

> Concerning the spent-fuel standard, we are aware that the accessibility of plutonium in commercial spent fuel is quite variable and increases with time as the fission-product radioactivity that provides the principal barrier to processing of the material for weapons use decays. An appropriate interpretation of what sort of spent fuel constitutes the standard follows from consideration of the situation that will exist at the time in the future when most of the surplus weapons plutonium at issue here is being processed for final disposition, say, between 2000 and 2030. There is likely to exist, in that period, upwards of 1,000 tons of civilian plutonium in spent fuel, ranging in age from freshly discharged to several decades old. If the inaccessibility of weapons plutonium is made comparable to that of civilian plutonium in the middle of this age distribution—that is, civilian plutonium in spent fuel 20–30 years old—the existence of the weapons plutonium in this form would not markedly increase the security risks already associated with the civilian spent fuel.

Dependence on intrinsic properties only

The CISAC reports also stressed that meeting the spent-fuel standard depends only on the *intrinsic* properties of the final plutonium form associated with a disposition option. "Intrinsic" means, in this context, the properties of the smallest plutonium-containing item that could be removed from an interim or final repository for the dispositioned form, or from a vehicle transporting plutonium in this form to such a repository, without a degree of physical processing likely to be impractical for anybody but the host state itself. (By "physical processing" we mean cutting, blasting, melting, dissolution, and the like. The determination of what would be "impractical" must take into account the amount of time likely to be available before the authorities discover the attempt and intervene.)

In the case of ordinary spent fuel itself, we would consider the relevant item to be the fuel assembly — an item removable intact from the reactor, or spent-fuel storage pool, or shipping task, but not further subdividable without a substantial amount of cutting (made more difficult, of course, by the radiation field associated with the item.) We do not include

the casks in which ordinary spent fuel would be shipped or stored as part of the 'intrinsic' barriers associated with such fuel, because the lid of such a cask can be removed by cutting or blasting in a matter of a few minutes.[9] Nor do we count as part of the 'intrinsic' barriers the other types of engineered and institutional barriers that may surround spent-fuel assemblies or other plutonium forms, including vaults, buildings, fences, alarms, guard forces, and so on.

It is, of course, the combination of intrinsic properties with additional engineered and institutional barriers that governs the overall proliferation resistance of a dispositioned plutonium form. The spent-fuel standard was not developed to describe overall proliferation resistance, but only to describe the *contribution* to overall proliferation resistance that should appropriately be sought from the intrinsic properties of the final plutonium form. The original CISAC formulations about this standard were intended to make clear that it should be regarded as (a) a necessary but not a sufficient criterion for adequate overall proliferation resistance of the final plutonium form and (b) a ceiling as well as a floor on what is worth achieving in this intrinsic-property contribution to proliferation resistance. Because these important points seem not to have been made entirely clear (or not to have been entirely accepted!),[10] we revisit them here.

- We believe the spent-fuel standard is a *necessary* condition for meeting convincingly the criterion that the existence of dispositioned plutonium should not constitute a significant addition to the security risks posed by plutonium in ordinary spent fuel (a form in which much more plutonium resides than in the military stockpiles). This is so in part, we think, because additional engineered and institutional barriers may not have as high a degree of reliability (or demonstrability of reliability) as the intrinsic

[9]Approaches in which ordinary storage and shipping casts and/or their contents have been modified to make the contents substantially more difficult to extract — as might be done to try to compensate for barriers to plutonium recovery from the items inside that were lower than those for ordinary spent-fuel assemblies — would need to be analyzed on a case-by-case basis. This would entail initially considering the entire object to be the "item" whose intrinsic resistance to attack must be assessed, and ultimately reaching a conclusion, based on analysis and comparison, as to whether this item's degree of resistance to attack, together with the properties of its contents, constitute compliance with the spent-fuel standard. That is just what has been done in this report for the can-in-canister immobilization option and the CANFLEX variant of the CANDU MOX option.

[10]See, e.g., Leonard W. Gray and Thomas H. Gould, Jr., *Immobilization Team Comments on Interim Report of NAS Panel Review of Spent-Fuel Standard for Disposition of Excess Weapons Plutonium*, Lawrence Livermore National Laboratory Report PIP-99-152, 28 October 1999.

barriers do (and indeed are certainly less reliable in Russia than in the United States), and in part because the imposition of intrinsic barriers sends a much stronger signal about the intention of the possessor state with respect to irreversibility of arms reductions than does the imposition of engineered and institutional barriers that, in many circumstances, would hardly impede the possessor state's recovery of the plutonium at all.

- At the same time, the spent-fuel standard is *not sufficient* because, as the original CISAC reports stressed, the intrinsic barriers to acquiring, processing, and using in weapons the plutonium embedded in typical spent fuel are not high enough for this material to be considered adequately "self protecting." Thus additional engineered and institutional barriers are appropriate for this material and for other plutonium forms with intrinsic barriers comparable to those of typical spent fuel. Indeed, society should plan to increase these engineered and institutional barriers against the weapons use of spent fuel and comparable material over time (including, eventually, by emplacement of the material in a monitored geologic repository), as the technological capacity to handle and reprocess this material becomes more commonplace and the radiation barrier to handling it becomes less daunting.
- The spent-fuel standard is a *ceiling* as well as a floor on what is worth achieving in the degree of proliferation resistance conferred by the intrinsic properties of dispositioned weapons plutonium. Achieving this much would eliminate the excess proliferation hazard represented by the weapons plutonium in comparison with the "background" hazard represented by the much larger stocks of civilian plutonium embedded in spent fuel. Spending additional time and money to bring the intrinsic-property proliferation resistance of dispositioned weapons plutonium to a higher level than that of plutonium in typical spent fuel would not significantly reduce proliferation risks overall. Indeed, incurring delays in disposition in order to reach a higher standard would add to those risks.

Intrinsic characteristics, we repeat, are only a part of adequate security. But they are an important part. That is why CISAC defined a spent-fuel standard, and why CISAC and we have emphasized that material that does not meet this standard, based on its intrinsic properties, cannot be made to meet the standard by increasing the engineered and institutional safeguards that are applied. If the spent-fuel standard is deemed to be satisfiable based on such engineered and institutional barriers as vaults and alarms and guards alone—no matter what the characteristics of the

plutonium form inside—then one could assert that pure plutonium ingots or even intact plutonium "pits" (nuclear-weapon cores) meet the spent-fuel standard, as long as the vault is strong enough, the alarm sensitive enough, the guards competent enough. By *reductio ad adsurdum*, this demonstrates the need for a criterion based on intrinsic properties alone. After all, no matter what engineered and institutional safeguards were applied, storing plutonium ingots or pits indefinitely in Russia would not be regarded by the United States as an adequate approach to the risks of reincorporation of the material into new Russian nuclear weapons—or its theft for incorporation into someone else's weapons—nor would this approach in either Russia *or* the United States be deemed, by others, an adequate indication of good intentions.

Further qualifications on the application of the standard

The 1994 and 1995 CISAC reports defining and elaborating the spent-fuel standard emphasized several further disclaimers about its application. We reiterate them here and associate ourselves with them.

- First, not only is a judgment on intrinsic properties of the final plutonium form insufficient (even though necessary) for concluding that the risks associated with the final form are sufficiently small, but consideration of the final form and the protection afforded it is not sufficient for reaching a judgment about the overall resistance of a disposition method to re-use of the plutonium in weapons. Resistance to acquisition and weapons re-use of the plutonium at earlier stages of the disposition process must also be taken into account. Typically, pursuit of increased resistance to proliferation in the final plutonium form entails additional handling and processing steps that add to proliferation risk. A judgment must be made that the gain at the end warrants the loss along the way.
- Second, actual resistance to acquisition and weapons re-use of the plutonium is not the only criterion for judging a disposition method satisfactory. Demonstrability of and perceptions about resistance are also important, as are timing, safety characteristics, environmental hazards, economics, tractability of institutional and regulatory requirements, domestic and international political acceptability, and influences on the proliferation resistance of nuclear-energy systems not directly involved in the disposition effort (which influences may be positive or negative[11]).

[11]See, e.g., CISAC, 1995, p. 256.

- Finally, getting to final disposition of excess weapons plutonium is not the only important part of managing the hazards of excess nuclear weapons and nuclear materials in the post-Cold-War world. The initial CISAC study and many others on this topic have emphasized the importance of de-activating, consolidating, inventorying, and dismantling excess weapons; consolidating and inventorying weapons-usable nuclear materials; storing and protecting all nuclear-weapon components and directly weapons-usable nuclear materials with the degree of diligence appropriate to intact nuclear weapons; blending down highly enriched uranium to levels not directly usable in weapons; subjecting all of these activities to a high degree of bilateral (U.S.–Russian) and eventually international monitoring and transparency; and increasing the attention given to improving the resistance of civilian nuclear-energy systems to the diversion of weapons-usable materials.[12] Defining and implementing standards for disposition of excess weapons plutonium is important, but it is not a substitute for and should not distract attention from these other steps.

Application of the standard to final plutonium forms in the initial CISAC study

The first volume of the CISAC plutonium study (1994) concluded that the two most promising plutonium-disposition options for meeting the spent-fuel standard and other disposition desiderata in a timely way were (1) fabrication of weapons plutonium into MOX fuel for once-through use in selected civilian power reactors of currently operating types and (2) immobilization of weapons plutonium by vitrification together with

[12]Besides the CISAC reports cited in Note 1, see, e.g., Frank von Hippel, "Fissile material security in the post-Cold-War world," *Physics Today*, June 1995, pp. 26-30; Graham Allison, Owen Coté, Richard Falkenrath, and Steven Miller, *Avoiding Nuclear Anarchy: Containing the Threat of Loose Russian Nuclear Weapons and Fissile Material*, Cambridge, MA: MIT Press, 1995; Matthew Bunn and John P. Holdren, "Managing military uranium and plutonium in the United States and the former Soviet Union," *Annual Review of Energy and the Environment*, vol. 22, 1997, pp. 403-486; U.S.-Russian Independent Scientific Commission on Plutonium Disposition, *Final Report*, Washington, DC: Office of Science and Technology Policy, Executive Office of the President of the United States, September 1997; Committee on Dual-Use Technologies Export Controls and Materials Protection, Control, and Accounting, National Research Council, *Proliferation Concerns: U.S. Efforts to Help Contain Nuclear and Other Dangerous Materials and Technologies in the Former Soviet Union*, Washington, DC: National Academy Press, 1997; and Committee on International Security and Arms Control, National Academy of Sciences, *The Future of U.S. Nuclear Weapons Policy*, Washington, DC: National Academy Press, 1997.

high-level radioactive wastes in glass logs of the approximate size and composition already selected for use in immobilizing high-level defense wastes at the Savannah River site of the U.S. nuclear-weapons-production complex. The second CISAC volume (1995) went beyond the "most promising" characterization to state flatly that current-reactor options using light-water or CANDU reactors and the then-envisioned heavy-log/vitrification-with-wastes option would both be able, if implemented, to meet the spent-fuel standard (CISAC, 1995, p. 10)[13]

> With respect to security of the final plutonium forms, the current-reactor options obviously meet the spent-fuel standard, and the Panel judges that the vitrification option meets this standard also. The plutonium in the spent fuel assembly would be of lower isotopic quality for weapon purposes than the still weapons-grade plutonium in the glass log, but since nuclear weapons could be made even with the spent fuel plutonium this difference is not decisive. Under typical assumptions, the radiological barrier presented by glass logs would be about three times smaller than that presented by a fuel assembly (but still very high), and the mass of a glass log—containing, coincidentally, about the same amount of plutonium as a fuel assembly—would be about three times greater. The difficulty of separating the accompanying materials would be roughly comparable in the two cases.

This conclusion, in which a MOX spent-fuel form containing about twice as much plutonium as typical spent fuel and a vitrified waste form with weapon-plutonium isotopics were both deemed to meet the spent-fuel standard, underlined CISAC's view that the standard should be understood to mean "roughly" as resistant to acquisition and use in weapons as is plutonium in typical spent fuel, not necessarily identical to typical spent fuel (which would then itself require more precise definition) in each characteristic that matters.

Questions about the Spent-Fuel Standard

The ambiguity inherent in judging whether a weapons-plutonium-disposition form meets a standard of "roughly" equivalent to typical spent

[13]The indicated comparison was between a 660-kg pressurized-water-reactor fuel assembly, irradiated to 40,000 megawatt-days per metric ton of heavy metal, and a 2,200-kg glass log of the type foreseen for production at Savannah River, containing 20 weight percent defense high-level wastes and 1.3 weight percent weapons plutonium mixed with the glass. Radiation doses from both were computed at the surface of the objects, 30 years after fuel-discharge and log production, respectively.

fuel in resistance to acquisition and use of the plutonium for weapons has naturally given rise to questions about whether particular forms meet the standard or not, as well as to calls for greater precision in the specification of the standard for use in making these determinations. Some have questioned whether any plutonium form in which the isotopic composition of the plutonium is that of weapons plutonium should be judged to meet the spent-fuel standard. Others have wondered by how much the plutonium concentration in MOX should be allowed to exceed the value typical for spent fuel arising from once-through use of low-enriched uranium before such MOX is deemed out of compliance with the standard. Still others have questioned at what point the combination of smaller fuel-assembly size and lower radiation barrier associated with CANDU fuel at the burnups typical for this reactor type would disqualify such fuel under the standard. And some have expressed worries that an overly strict interpretation of the spent-fuel standard in any or all of these cases could lead to degrees of delay in moving ahead with plutonium disposition, in the United States or Russia, that would increase proliferation dangers overall.[14]

Of particular concern to DOE and others interested in current U.S. plutonium-disposition plans is whether DOE's current design for the final plutonium form in the immobilization track in the dual-track option can reasonably be deemed to meet the spent-fuel standard. This design was developed subsequent to the 1995 CISAC report's determination that the then-current vitrification-with-wastes immobilization option and the once-through MOX option both meet the spent-fuel standard. In the new variant—called the "can-in-canister" approach—plutonium oxide is incorporated in ceramic pucks that themselves contain no fission products; the pucks are stacked in an array of cans suspended on a frame in a large steel canister; and molten borosilicate glass, bearing fission products, is poured into the canister to solidify around the cans and thus contain them in a massive, highly radioactive glass log. In the immobilization approach previously considered by CISAC, by contrast, the plutonium oxide would have been added directly to the fission-product-bearing molten glass with the aim of creating a more-or-less homogenous mixture of plutonium and fission products in the resulting highly radioactive glass log.

[14]Publications raising the questions mentioned in this paragraph are cited, and preliminary responses to the questions are provided, in John P. Holdren, John F. Ahearne, Richard L. Garwin, Wolfgang K. H. Panofsky, John J. Taylor, and Matthew Bunn, "Excess weapons plutonium: how to reduce a clear and present danger," *Arms Control Today*, November/December 1996, pp. 3-9. Virtually all of these questions were posed also in the briefings and public comment sessions arranged in connection with the meetings of this Panel (see Appendix B).

The can-in-canister approach was chosen by DOE in preference to the homogeneous plutonium-in-glass approach for several reasons.[15] It had become apparent that designing, testing, and implementing modifications to the Savannah River melter and the composition of its glass—required in order to enable addition of adequate quantities of plutonium directly to the melt while observing criticality constraints — would be technically difficult, costly, and likely to substantially set back the timetable for the already scheduled high-level-waste immobilization program at the Savannah River site. In particular, a change in glass composition from the original borosilicate glass to a lanthanide borosilicate glass would have been necessary to achieve the desired plutonium loading, but the processing temperature needed for the new composition (around 1475°C) was too high to allow incorporation of the cesium needed to provide the radiation barrier. (Cesium volatilizes above 1200°C.) It might also have been necessary to reduce the log size in order to maintain criticality margins, which not only would have entailed a new melter design but also would have reduced the resistance of individual logs to theft. Switching from glass to a homogeneous ceramic incorporating plutonium and cesium would entail producing all of this ceramic by hot isostatic pressing in hot cells, a considerable complication compared to the cold-press-and-sinter method, in glove boxes, which can be used if the ceramic contains plutonium but no fission products.

DOE's choice of the heterogeneous can-in-canister approach allowed staying with the original glass composition to contain the fission products, while gaining the improved performance of ceramic as the plutonium-containing material (including greater durability under repository conditions and greater ease of nondestructive assay for verification purposes) and avoiding criticality concerns attendant on adding multiple critical masses of plutonium to 1,700 kilograms of molten glass and fission products at a time. And leaving fission products out of the plutonium-bearing ceramic pucks in the can-in-canister approach allowed for lower manufacturing costs than would be entailed if the pucks themselves contained strong gamma-ray emitters

The most difficult question about the can-in-canister approach's meeting the spent-fuel standard is whether extraction of the plutonium from

[15]See, e.g., Office of Fissile Materials, Department of Energy, *Technical Summary Report for Surplus Weapons-Usable Plutonium Disposition*, Rev. 0, Washington, DC: Department of Energy, 1996; M. J. Plodinec et al., "Survey of glass plutonium contents and poison selection," in *Plutonium Stabilization and Immobilization Workshop*, Washington, DC: Department of Energy, 1995, pp. 229-239; and Leonard Gray and Malvyn McKibben, *An Analysis of Plutonium Immobilization Versus the "Spent Fuel Standard,"* Lawrence Livermore National Laboratory Report POP-98-073, August 1998.

the fission products in the heterogeneous pucks-in-glass arrangement is significantly easier than extracting plutonium from spent fuel. The corresponding questions about the MOX option's meeting the spent-fuel standard relate to whether the high residual plutonium concentration in spent light-water reactor (LWR) MOX or the relatively low mass and radiation field associated with spent CANDU MOX fuel assemblies would make these plutonium forms significantly more proliferation prone than typical spent fuel from lightly enriched uranium (LEU)-fueled LWRs. As preparation for addressing these questions, we proceed first to elaborate some ingredients of a systematic approach to applying the spent-fuel standard.

A SYSTEMATIC APPROACH TO CONSIDERING COMPLIANCE WITH THE STANDARD

Until now there has been no simple formula that can be mechanistically applied to determine whether the final plutonium form resulting from a disposition process is sufficiently close to typical spent fuel in the array of characteristics governing resistance to acquisition, processing, and use in weapons of the contained plutonium that it can be deemed to meet the spent-fuel standard. In the current study, we considered whether such a formula could usefully be constructed. We concluded that doing so is very difficult; neither are we convinced that it would even be desirable.

Many characteristics are germane; the importance of these characteristics relative to one another may vary with the type of threat that is deemed most important at a given time and place; the range of variation with respect to the relevant characteristics is substantial within the array of fuel types, degrees of irradiation, and ages since discharge in the global spent-fuel inventory; a final disposition form's departures from typical spent-fuel characteristics in the direction of lower resistance to proliferation in some respects may be offset by departures in the direction of higher resistance in other respects; and the benefit of trying to narrow a given "gap" between a characteristic of a final disposition form and the corresponding characteristic of typical spent fuel must be weighed against the delays and other increases of in-process proliferation risks that may result from this effort. In so complex a space of possibilities, it seems to us, the considered judgment of experienced people in answering the question, "How close to spent fuel is close enough?" will continue to be difficult to replace with a mechanistic formula.

We do think, however, that the needed judgments can usefully be informed by systematic comparison of the relevant quantitative and qualitative characteristics of candidate final plutonium forms, against those of typical spent fuel, in a matrix format that groups the characteristics by the

kinds of barrier against proliferation they confer and that indicates the relative importance of these different barriers against the main categories of proliferation threat. We employ such an approach here.

Interactions of threats and barriers

The three main classes of proliferation threats to which intrinsic barriers provided by final plutonium forms are germane are as follows:

(1) "Host-nation breakout" means that the country legitimately holding the dispositioned plutonium elects to recover it for re-use in its nuclear arsenal. This is likely to entail large amounts of plutonium (from several hundred to thousands of kilograms), no physical limitations on access to the dispositioned plutonium forms and the ability to transport them, high technical capabilities for separating the plutonium and employing it to make sophisticated nuclear weapons, high performance requirements for the weapons, and concerns with detection of the effort while it is underway ranging from negligible in the case of overt breakout to very substantial in the case that breakout is intended to be clandestine.

(2) "Theft for proliferant state" means that members of a subnational group and/or agents of a proliferant state—including, potentially, facility insiders —steal the material by stealth or force and transfer it to the state for use in nuclear weapons. Much smaller amounts of material are germane here (tens to perhaps one or two hundred kilograms); physical barriers to access and transport are important, in the context of limits on the time and technological capacities available to the thieves for dealing with these barriers; the technical capacities of the state receiving the material for processing it and employing it in nuclear weapons are likely to be moderately high albeit lower than in the "host-nation breakout" case; the performance requirements for the resulting weapons are likely to be moderate; and concerns with detection would be high in the theft and transport stages before the material is on the territory of the proliferant state and moderate to high thereafter.

(3) "Theft for subnational group" means that a subnational group steals the material by stealth or force and either tries to use it to make nuclear weapons itself or transfers it to another subnational group for this purpose. In this case the quantity of material of interest can be as small as one bomb's worth; the situation with respect to physical barriers to access and transport in relation to limits on the time and technological capacities available to the thieves are the same as in the "theft for proliferant state" category;

> the technical capacities available for processing and employing the stolen material in nuclear weapons are likely to be less than in the "proliferant state" case; the performance requirements for the resulting weapons are likely to be low; and concerns with detection would be high at all stages of the effort.

The indicated differences in the characteristics of these three types of threat give rise to differences in the relative importance of the various intrinsic characteristics of final plutonium forms as barriers against the threats.

We summarize our judgments on the interaction of threats and intrinsic barriers in Table 1, which arranges the characteristics of final plutonium forms according to the barriers these characteristics provide at different steps in the proliferation chain and indicates the relative importance of these barriers against the three classes of proliferation threats. The relative-importance ratings reflect a combination of the needs/capabilities of the threat groups with the nature of the barriers. We choose a scale of only four ratings—zero, low, moderate, and high—to reflect distinctions in relative importance without implying more precision than the complexity and judgmental character of these considerations permit.

The term "item" as used in Table 1, refers to the smallest embodiment of the final plutonium form that could be removed from a storage facility or transport operation without a degree of on-site physical processing (cutting, blasting, melting, dissolution, and so on) likely to be impractical for anybody but the host state itself. The term "technical difficulty" includes requirements for manpower and specialized knowledge, skills, and equipment, as well as an allowance for the amount of time likely to be required to complete a task with a given level of resources.

The detectability of an activity, which is an important barrier in cases where concealment is important to the proliferators, depends on resource and time requirements for the activity and on other signatures (e.g., thermal, chemical, nuclear) arising from the interaction of the intrinsic properties of the dispositioned plutonium form with the operations being carried out on it. Detectability also depends on the capabilities deployed to achieve detection. This underlines that, although Table 1 is intended to address the intrinsic properties of final plutonium forms and not the characteristics of the engineered and institutional protections supplementing these, there are interactions between intrinsic properties and the engineered and institutional protections (as, for example, in the relation between intrinsic properties related to detectability and the monitoring systems in place to achieve detection).

TABLE 1
Intrinsic-barrier and threat characterization for final plutonium forms

Barrier	Importance of barrier against the threat		
	Host-nation breakout	Theft for a proliferant state	Theft for a subnational group
Barriers to acquisition of the Pu from its storage site			
Mass and bulk of item[a]	Zero to low[b]	Moderate	Moderate
(low) concentration of Pu in item	Zero to low[b]	High	High
Radiation hazard to acquirers	Low	Moderate	Moderate
Technical difficulty of partly separating Pu from bulk components of item on site[a]	Zero to low[b]	High	High
Thermal, chemical, and nuclear signatures aiding detection	Zero to moderate[b,c]	Moderate to high[c]	Moderate to high[c]
Barriers to separation of the Pu from diluents and fission products			
Technical difficulty of disassembly	Low	Low to moderate	Moderate
Technical difficulty of dissolution and separation	Low	Moderate to high	High
Quantity of material to be processed	Low to moderate[b]	Moderate to high	High
Hazards to separators	Low	Moderate	Moderate
Signatures aiding detection	Zero to moderate[b]	Moderate to high[c,d]	High[c]
Barriers to use of the separated Pu in nuclear weapons			
Deviation of isotopic composition from "weapons grade"	Moderate	Moderate	Low

[a] Barrier relates both to technical difficulty and detectability, which are themselves related (see text).
[b] Importance depends on whether breakout is open or clandestine.
[c] Importance depends on sensor capabilities.
[d] Importance depends on degree of proliferant state concern with detection.

Explanations of judgments in Table 1

The first set of intrinsic barriers comprises those that impede the *acquisition* of the plutonium—i.e., removal of the plutonium-bearing item from its place of storage or transport—including barriers to processing the item before it is removed in order to extract the plutonium from it or otherwise simplify its removal. In this category:

- The *mass and bulk of an individual item* would be barriers against the threat of host-nation breakout only in the case where the breakout was intended to be clandestine, in which case the item size might be expected to have some effect on the detectability of operations to remove the items from storage or divert them in transport. (We judge this to be of low overall importance in light of the relative ease with which a host country could probably overcome it.) If breakout was open, item size would be of no consequence to a host state (which would be well equipped to handle items of any mass and bulk). In the cases of theft for a proliferant state or a subnational group, the barriers posed by mass and bulk to ready removal of an item are more important—we rate them "moderate"—because of their effect on the character of the equipment needed to accomplish the theft (which affects, to some degree, the resources the thieves would need and the chance of their operation's being detected).
- The *concentration of plutonium in the item* is a barrier—the lower the concentration the higher the barrier—insofar as it affects the total mass of material (and thus the number of items) that must be acquired in order to obtain a given quantity of plutonium. As with item size, and for the same reasons, this factor would be of no consequence at the material-acquisition stage (although of some consequence at the processing stage, about which more below) to a state engaged in open breakout, and of only low consequence to a state engaged in clandestine breakout. But we believe it is of high importance in relation to theft for a proliferant state or a subnational group, because concentration even more than individual item size determines the scale of the entire theft operation (personnel and equipment), directly affecting both the resources the thieves would need to mobilize, the time required for the acquisition operation, and the chances of their being detected and thwarted in the course of it.
- The *radiation hazard to the acquirers of the plutonium* (as opposed to the radiation hazard to the processors, which is treated below) would be of low but not zero importance as a barrier to host-

nation breakout; such a state would be well equipped to minimize this hazard with shielding and remote-handling equipment. This barrier would be greater against theft for a proliferant state or a subnational group, but we rate it as "moderate" in importance rather than "high" for two reasons: first, even the highest radiation fields associated with spent fuel and other plutonium-disposition forms would not produce immediately incapacitating doses if the thieves took modest precautions; and, second, many potential thieves (and their bosses) might not give high priority to the avoidance of the kinds of doses that would be involved (either out of ignorance or out of willingness to bear the risk—or impose it on someone else—in exchange for expected high reward).

- The *technical difficulty of partly separating the plutonium from the bulk components of the item on site* would be of no importance in the case of open breakout by a host nation, which would face no difficulty in transporting the intact items to a processing site of its choice. The barrier would be a bit higher if the host-nation breakout was intended to be clandestine, since transporting the intact items to a processing site might be at least somewhat easier for other countries to detect than transporting more concentrated forms of plutonium would be. In the case of theft for a proliferant state or for a subnational group, however, it would be a *great* advantage for the thieves if the quantity and/or radioactivity of the material that needed to be removed from the site of the theft could be significantly reduced by operations that could be effected at the site without greatly prolonging the thieves' stay there or otherwise increasing the chance of their being detected in the act. This would ease substantially the thieves' subsequent problems of transport and concealment of storage and processing. Thus we rate the barriers against this as being of "high" importance.
- *Thermal, chemical, and nuclear signatures that would aid detection during the course of a theft and subsequent transport and storage* would be of no importance to a host nation engaged in open breakout. In the event the breakout was intended to be clandestine, however, such signatures could significantly affect the chance that other countries would detect the activity; thus we consider this barrier of "moderate" importance in this case (the highest of any of the barriers to host-nation breakout at the plutonium-acquisition stage). Sensitivity to detection during theft and subsequent transport and storage would be even greater in the cases of theft for a proliferant state or a subnational group, so we rate the barrier as "moderate to high" in these cases.

The second set of intrinsic barriers listed in Table 1 relate to the work of separating weapons-usable plutonium from the structure, diluents, and fission products accompanying the plutonium in the form in which it was acquired (that is, either its final dispositioned form or something derived from that by processing undertaken at the site of acquisition, as discussed above). In the case of host-state breakout, this activity could take place either clandestinely or openly, using old facilities or new ones constructed openly or clandestinely for the breakout purpose. In the case of theft for a proliferant state, this processing could be accomplished by the thieves before transfer of the material to the state, in which case it would likely be done on the territory of the state from which the material was stolen or, after smuggling it across one or more borders, on the territory of a third state. Or the thieves might manage to transfer the stolen items themselves to the proliferant state, whereupon the latter would do the subsequent processing in facilities on its own territory (in which case these could, again, be either open or clandestine, but more likely the latter). In the case of theft for a subnational group, this processing would most likely be in clandestine facilities, on whatever territory. The intrinsic barriers against these activities and the bases for our judgments about their relative importance are as follows:

- The *technical difficulty of mechanical disassembly of the plutonium-containing items* would be a barrier of only low importance in the context of host-nation breakout, inasmuch as such nations would have facilities adequate to handle this rather easily for any imaginable disposition form. It would also be of low importance to a proliferant state that is conducting this processing itself, since the technology for this mechanical disassembly step is not very demanding. If the processing were being done by the thieves before transferring the plutonium to the proliferant state, however, this barrier would be of moderate importance, as it would be in the case where a subnational group was the final recipient, because the relevant technologies/facilities would be harder for a subnational group to acquire and use (and hide) than for a state to do so.
- The *technical difficulty of dissolution of the plutonium-containing compounds and chemical separation of the plutonium from the other elements present* is, like the technical difficulty of mechanical disassembly, a barrier of low importance to a host nation (although not zero, insofar as the differences could be great enough to motivate the choice of one plutonium source over another if they were equally attractive—or equally difficult—in other respects). We judge the importance of this barrier to be "moderate to high" in the case of

theft for a proliferant state (depending on whether the processing is being done by the state or by the thieves themselves) and "high" in the case of theft for a subnational group. Although the relevant technologies for at least some disposition forms are well described in open literature, they are fundamentally more demanding for small states and subnational groups than are the mechanical-disassembly technologies.

- The *quantity of material to be processed* (which of course is related to the plutonium concentration, discussed separately above as a barrier to initial acquisition as opposed to a barrier to separation) is a barrier of low importance in the case of open host-nation breakout (although not of zero importance, because it increases time and cost in some combination). It is of moderate importance in the case of clandestine host-nation breakout, because its effect on the scale of the operation increases the chance of detection. We judge the importance of this barrier to be "moderate to high" in the case of theft for a proliferant state, depending on who is doing the processing and, in the event it is being done by the proliferant state, depending on the importance attached to concealment and on the sophistication of the facilities available to the particular state.
- The *radiation, criticality, and toxic hazards during the separation process* are barriers of only low importance in the case of host-nation breakout, because these nations have ample facilities and experience for minimizing these risks. Radiation and criticality are more important barriers in the cases of theft for a proliferant state or for a subnational group, because protection against these hazards during processing requires the development (and in some cases the concealment) of facilities and capabilities that the processing entities did not possess before. (Still, we do not rate these barriers "high" for proliferant-state processors because the needed capabilities are well within the means of most states, and we do not rate them "high" for subnational-group processors, even though their capabilities would generally be less than those of states, because such groups are likely to be willing to assume higher risks in these categories than states are.) Toxic hazards are not likely to be great enough to constitute more than a low barrier in any of the cases.
- *Detectability of processing operations* may be based on the scale of the required operations (including floor space, electrical power, specialized supplies, and the duration of the activities) and on chemical, nuclear, and thermal signatures from the specific operations involved. (Dissolution and separation of plutonium, for example,

can release effluents derived from the solvents involved, which are detectable remotely through technologies such as LIDAR (LIght Detection And Ranging), as well as releasing radionuclides that are detectable by various means. Chemical and radioactive "taggants" chosen for detectability may be deliberately added to disposition forms to raise this barrier. Infrared interrogation and observation of infrared emissions moreover, can determine whether or not known processing facilities are operating.) Of course, the importance of the detectability barriers depends on whether the activities are clandestine or open; it depends on whether discovery would necessarily be fatal to the enterprise (as it almost certainly would in the case of processing by a subnational group, might be in the case of processing by a proliferant state, and probably would not be in the case of clandestine host-state breakout); and it depends as well on the state of the sensor capabilities in relation to the strength of the signatures. These considerations in combination lead us to rate the detectability barriers as "zero to moderate" for the case of host-nation breakout, "moderate to high" in the case of theft for a proliferant state, and "high" for the case of the theft for a subnational group.

The last set of intrinsic barriers addressed in Table 1 are those against the utilization of the plutonium that the proliferators are able to separate for the fabrication of functional nuclear weapons. If it is assumed that proliferators in all categories will ultimately be capable of obtaining reasonably pure plutonium metal starting from the dispositioned forms—as we believe to be the case—then the main intrinsic barriers in this category are those associated with deviation of the plutonium's isotopic composition from "weapons grade."

The isotopic composition of the plutonium in the spent fuel is compared with that of weapons-grade plutonium in Table 2. The indicated differences lead to a neutron background nearly 7 times higher in the spent-fuel plutonium than in weapons-grade plutonium, a heat generation rate about 6 times larger, and a surface gamma-ray dose about 16 times higher.[16] These differences would produce additional difficulties for those who might choose to design, manufacture, and deploy nuclear weapons made from typical spent-fuel plutonium rather than from

[16]The unshielded surface gamma ray dose from reactor-grade plutonium is in the range of 20 rem/hour (see, e.g., CISAC, 1995, p. 270). This may be compared with the short-term dose that would be associated with a 50 percent chance of death within 30 days from acute radiation syndrome, which is in the range of 500 rem.

TABLE 2
Isotopic composition of plutonium in typical LWR spent fuel versus that in weapons-grade plutonium

	Isotope					
Type of plutonium	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Am-241
Typical spent-fuel plutonium from light-water reactors	1.3%	60.3%	24.3%	5.6%	5.0%	3.5%
Weapons-grade plutonium	0.01%	93.8%	5.8%	0.13%	0.02%	0.22%

Source: CISAC, 1995, p. 45.

weapons-grade plutonium—difficulties that account for the historical preference of nuclear-weapon states for using weapons-grade material. But, as emphasized in the previous CISAC plutonium reports and in other unclassified but authoritative studies, the differences do not preclude the design and construction of effective nuclear weapons from typical spent-fuel plutonium, at all levels of sophistication.[17]

We rate the barrier posed by isotopic deviations from weapons grade as "moderate" in importance for host-nation breakout in Table 1 mainly because recovery of weapons-grade plutonium from dispositioned forms would permit production of weapons from existing designs without new nuclear-explosive tests, whereas use of plutonium of different isotopic compositions would be likely to entail design modifications and, even if not, would probably require new nuclear-explosive tests to confirm that the change in isotopic composition had not unacceptably degraded performance. In the case of theft for a proliferant state we rate the barrier likewise as "moderate" in importance: such a state would probably prefer to avoid if possible the burdens posed by isotopic deviations for design, fabrication, and maintenance of nuclear weapons, but it would also probably have the capabilities to cope with these burdens in ways that achieved a level of weapon performance adequate for a proliferant state's initial purposes. We rate importance of the isotopic barrier as "low" in the case

[17]See CISAC (1994, pp 29-33), CISAC (1995, pp. 43-46), and Department of Energy, *Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives*, Washington, DC: Department of Energy, January 1997, pp. 37-39.

of theft for a subnational group because, although the weapon-related capabilities of such a group would probably be lower than those of a proliferant state, the subnational group would be likely to be much less concerned about deviations from ideal performance—inasmuch as a lower-than-expected yield would still mean an explosive force more than adequate for the likely purposes of such a group—and probably less concerned about radiation exposures to those making and handling the weapons.

Relative importance of threat categories

For purposes of deciding which characteristics of dispositioned plutonium forms are most germane to a determination of compliance with the spent-fuel standard, it might be thought useful to ask which of the three categories of threat is deemed to be of greatest concern. It is our view, however, that the answer to this question is likely to vary with time and with other circumstances. For present purposes, therefore, we give equal weight to the three threat categories.

It is to be emphasized that *none* of these three classes of threat to dispositioned plutonium will pose much danger of actually being carried out until a time in the future when sources of plutonium in much more convenient forms for proliferators have been considerably diminished compared to their abundance today. The countries of greatest potential concern in terms of host-nation breakout, for example, are Russia and the United States, which will have the largest quantities of dispositioned plutonium; but both countries are likely to retain, for some time to come, such large quantities of deployed and reserve nuclear weapons and reserve nuclear material, compared to any imaginable need, that it is difficult to envision any incentive for them to want to recover plutonium from the amounts they have declared excess and eligible for disposition. With respect to the "theft for proliferant state" and "theft for subnational group" threats, various military and civilian stocks of already separated plutonium and highly enriched uranium are likely to remain more attractive targets for proliferators than spent fuel or dispositioned plutonium forms would be for some years to come.

It is, nonetheless, important to move forward now with plutonium disposition—and, in that connection, important to determine the compliance of candidate approaches with the spent-fuel standard—both because disposition of excess plutonium is a process that will require decades under the best of circumstances (during which time it may be hoped that the stocks of warheads, separated plutonium, and highly enriched uranium will have been greatly reduced) and because, as the 1994 and 1995 CISAC plutonium reports emphasized, the barriers provided by pluto-

nium disposition against host-state breakout have arms-control and nonproliferation value through the signals they send (between the host states and to the rest of the world) about the intended irreversibility of nuclear arms reductions.

With these disclaimers, we conclude from the ratings in Table 1 that the characteristics that should receive the most weight in the determination of a disposition form's compliance with the spent-fuel standard are as follows.

(1) With respect to barriers to acquisition of the plutonium from its storage site: (a) the concentration of plutonium in the items that could be stolen, (b) the technical difficulty of partly separating the plutonium from the bulkier components of the item on site, and (c) the strength of the aids to detection of the items provided by their thermal, chemical, and nuclear signatures.
(2) With respect to barriers to subsequent separation of the plutonium from diluents and fission products: (a) the quantity of material that needs to be processed to obtain a weapon's worth of plutonium, (b) the technical difficulty of dissolution of the plutonium, (c) the technical difficulty of chemical separation of the plutonium from solution, and (d) the size of the aids to detection of these activities provided by their thermal, chemical, and nuclear signatures and the scale of the needed facilities.

Characteristics deserving somewhat smaller but still significant weight in the determination of compliance with the spent-fuel standard are the mass and bulk of the items that would need to be removed from the storage site, the radiation and criticality hazards associated with acquisition and processing of the material, and the deviation of the plutonium's isotopic composition from "weapons grade."

Evaluating Pu Disposition Forms Against the Standard

BASIS OF COMPARISONS

We believe the appropriate spent-fuel "item" for comparison with final weapons plutonium forms from disposition is the LWR fuel assembly — the array of fuel rods and spacers that is the smallest item that could be removed intact from a spent-fuel storage pool or shipping cask. Fuel assemblies for boiling-water reactors (BWRs) are typically 4 m long and .15 m on a side, with a mass of about 250 kg, and for pressurized-water reactors (PWRs) they are typically 4 m long and .25 m on a side, with a mass of about 670 kg. For purposes of comparison with plutonium disposition forms at a nominal 10 years after their creation, we will take "typical" spent fuel to be 30 years old, measured from the time of its discharge from the reactor. (That is, for a comparison in 2020 with a dispositioned plutonium form produced in 2010, we will use spent fuel that was discharged in 1990. For the United States, this would be about in the middle of the age distribution of the spent fuel that will exist in 2020.) We assume that typical spent fuel was irradiated in the reactor to 33,000 megawatt-days per metric ton of initially contained heavy metal (MWd/MTHM), which is typical of fuel discharged around 1990.[18] The pluto-

[18]A sense of the distribution of characteristics of the spent-fuel assemblies currently in inventory can be obtained from U.S. data, which show about 107,000 commercial LWR assemblies discharged between 1968 and 1994, some 60,000 of them from boiling-water reactors and about 45,000 from pressurized-water reactors. About 80 percent of the boiling-water reactor assemblies stored as of 1994 had experienced irradiation between 30,000 and

nium content would be about 2.5 kg for a typical BWR assembly and about 6 kg for a typical PWR assembly. The gamma-ray dose rate at the surface of a PWR assembly would be about 6,500 rem/hour; one meter from the surface of the assembly at its midpoint the dose rate would be about 800 rem/hour; for a BWR assembly the dose at one meter would be about 500 rem/hour.[19]

Spent fuel from plutonium disposition using the once-through MOX option with LWRs would be identical in physical dimensions and mass to the "reference" LWR spent fuel of the corresponding type. It would differ significantly in plutonium content (containing typically 2 to 3 percent by weight plutonium, compared to around 1 percent in the reference spent fuel), and the contained plutonium would differ somewhat in isotopic composition from that in the reference spent fuel. *By assumption* the spent MOX fuel would differ somewhat from the reference spent fuel in burnup and age since discharge (and therefore in radiation field), inasmuch as we assume the MOX fuel will be irradiated to 40,000 MWd/MTHM, and we compare such spent fuel at age 10 years in 2020 with the middle of the age distribution of spent LEU fuel extant in the United States at that time, aged about 30 years after irradiation to 33,000 MWd/MTHM.

The MOX option for plutonium disposition using CANDU reactors is considered here in two variants.

- The standard CANDU option is based on the fuel-assembly configuration in general use in commercial CANDU reactors, wherein the fuel assemblies measure about 0.5 m by 0.1 m, with a mass of 24 kg and irradiation to 9700 MWd/MTHM. At typical initial Pu loadings in CANDU MOX, the plutonium content in this spent fuel would be about 1.4 percent.
- The second option is the CANFLEX approach, which entails combining 40 slightly modified CANDU fuel assemblies (each containing 43 fuel pins as opposed to 37 in the standard CANDU

40,000 MWd/MTHM. About 85 percent of the pressurized-water reactor assemblies stored then had been irradiated to between 35,000 and 50,000 MWd/MTHM. See Energy Information Agency, *Spent Nuclear Fuel Discharges from U.S. Reactors: 1994*, Report SC/CNEAF/96-01, Washington, DC: Energy Information Agency, February 1996, and Carl Walter, "Uniform Descriptive Data," Lawrence Livermore National Laboratory unpublished report, May 1995.

[19]See CISAC (1995, pp. 270–273, and references cited therein). Because the gamma-ray doses from spent fuel and from dispositioned plutonium forms protected by fission products are dominated by 30-year half-life cesium-137 for the period between 5 years and 100 years from the discharge of the fission products from a reactor, knowing the dose rate at one time enables a straightforward calculation of what it would be at other times based on this half life.

> design) into a welded rack, which holds 20 tubes in two layers of 10, each tube containing 2 fuel assemblies. This item would have a mass of about 1000 kg. The CANFLEX variant also differs from the standard CANDU option in being irradiated to 25,000 MWd/MTHM, yielding a plutonium content of 1.8 percent. This approach was proposed in a 1995 study for DOE by Ontario Hydro, the operator of most of the Canadian CANDU reactors, but no further work on the concept has been done since that time.[20]

Although the CANFLEX approach is not yet a well developed option, we treat it here as a way of taking into account in a preliminary way the technical possibilities for increasing the proliferation resistance of standard CANDU MOX.

As indicated above, the can-in-canister approach to the immobilization track in DOE's two-track ("hybrid") program for disposition of excess weapons plutonium arose as a way to minimize the complications and delays that DOE feared would be imposed by the superposition of the plutonium-disposition mission on DOE's pre-existing program to immobilize defense high-level wastes at the Savannah River weapons production complex. The characteristics of the leading-candidate can-in-canister configuration as developed in the U.S. program as of December 1999 are summarized in Table 3. As discussed further below, this design is intended to be more robust against physical attack than the design discussed in this Panel's Interim Report.[21]

We note that the relevant question in addressing the compliance of the can-in-canister approach with the spent-fuel standard is whether the plutonium final form in the can-in-canister approach—where we take the relevant "item" for evaluation to be the 3 m (0.6 m, 2,500 kg canister—is approximately as proliferation resistant as the above-described typical LWR spent-fuel assemblies, *not* whether it is as proliferation resistant as the homogeneous plutonium-and-fission-product-bearing glass logs previously considered for the immobilization track.

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[20]The CANLEX approach incorporates a modification of the storage system now in use at the Darlington and Pickering CANDU plants, in which 48 tubes are stacked in a structure of four layers. Each tube, of thin stainless steel, contains two assemblies. The tubes are open, but covered with a wire mesh that allows IAE inspectors to verify that the IAEA seals are intact.

[21]Leonard W. Gray, Gregg Hovis, Robert Jones, and Michael Smith, *The Can-in-Canister—Then and Now*, Lawrence Livermore National Laboratory Report PIP-99-151, 28 October 1999; Leonard Gray and Thomas H. Gould, *Immobilization Team Comments on Interim Report of NAS Panel Review of Spent-Fuel Standard for Disposition of Excess Weapons Plutonium*, Lawrence Livermore National Laboratory Report PIP-99-152, 28 October 1999.

TABLE 3
Reference U.S. Can-In-Canister Configuration

Term	Description
Puck	Composition: DOE's Synroc ceramic incorporates plutonium into a crystal lattice, with pyrochlore, brannerite, zirconolite and actinide oxide as the principal plutonium-bearing phases and rutile as the primary non-plutonium bearing phase Size: 6.7 cm diameter by 2.5 cm height Mass: 0.5 kg, with 10.5 % Pu by weight, hence 52.5 g Pu
Can	Stainless steel cylinders holding 20 pucks each. Size: 7.6 cm diameter by 51 cm height Mass: 2.3 kg empty, 13.6 kg full, 1.05 kg contained Pu
Magazine	Perforated stainless steel tubes (the final design has not yet been selected) into which 4 cans are loaded on top of each other with glass surrounding each can in the magazine. Size: 8.3 cm diameter by 2.4 m height Mass: 6.4 kg empty, 60.8 kg full, 4.2 kg contained Pu
Rack	Welded stainless steel frame inside canister consisting of 7 vertical rods (2 cm diameter), 4 scalloped horizontal plates (0.6 cm thick) and a bottom plate into which 7 loaded magazines lock in place in an equally-spaced arrangement. Mass: 47–52 kg empty (range due to variation in base-plate designs), 472.6-477.6 kg full, 29.4 kg contained Pu
Canister	Stainless steel cylinder that contains rack. Loaded magazines are robotically inserted into rack inside canister. After loading of magazines, radioactive waste glass is poured into the void spaces in the canister. Size: 0.6 m diameter, 3 m height Mass: 500 kg empty, ~2500 kg full, 1523-1568 kg contained glass (depending on height of fill), 29.4 kg contained Pu
Requirements of disposition campaign	Disposition of 50 MT of Pu would require 1701 canisters Disposition of 17 MT of Pu would require 578 canisters Disposition of 13 MT would require 442 canisters

Sources: Plutonium Immobilization Project, Lawrence Livermore National Laboratory, "Plutonium Immobilization Project Baseline Formulation," UCRL-ID-133089, February 1999; L. Gray and T. Gould, *Immobilization Team Comments on Interim Report of NAS Panel Review of Spent-Fuel Standard for Disposition of Excess Weapons Plutonium*, Lawrence Livermore National Laboratory Report PIP-99-152, 28 October 1999; Letter report to Allison Macfarlane from L. Gray, dated December 1999.

COMPARISON MATRICES AND DISCUSSION

The matrix in Table 4 provides capsule descriptions and, where possible, quantification of the proliferation-resistance characteristics of the reference spent fuel and of three plutonium-disposition final forms—spent LWR MOX, spent CANDU MOX (conventional variant), and the current lead-candidate can-in-canister configuration. The characteristics are organized according to the classes of barriers to proliferation as presented in Table 1. In what follows, we elaborate on these comparisons barrier by barrier, characterizing each option's degree of match or mismatch with spent fuel, with respect to each barrier, as better than comparable, comparable, worse than comparable, or much worse than comparable. (By "better than comparable" we mean that the relevant barriers to proliferation are higher than for the reference spent fuel, and by "worse than comparable" we mean that the barriers are lower than for the reference spent fuel.) These evaluations are then aggregated in another matrix (Table 5) as a basis for our overall judgments about compliance with the spent-fuel standard.

Barriers to acquisition: mass and bulk of items

The mass and bulk of the canister—deemed barriers of moderate importance against acquisition of the plutonium from its storage site in the proliferant-state and subnational-group threat categories (Table 1)—are significantly larger than the corresponding characteristics of the reference (and LWR MOX) spent-fuel assemblies. In mass, the ratio is a factor of 4 to 10 (2500 kg vs. 250-670 kg). The "item" mass in the case of a standard CANDU fuel assembly, however, is a factor of 10 lower than the lightest reference fuel assembly and 100-fold lower than that of the can-in-canister configuration. The "item" size in the CANFLEX variant of CANDU is about 1,000 kg. (An important question, discussed separately below for both the can-in-canister and CANFLEX configurations under the heading of "resistance to energetic attack," is whether these structures are robust enough that dismantling them on site to reduce the mass and radiation field of what needed to be carried away would be impractical (for subnational groups) or more trouble than it is worth (for any proliferator).

With respect to this barrier, then, we judge the can-in-canister approach as better than comparable to typical spent LWR fuel, the LWR-MOX and CANFLEX-MOX options as comparable, and the standard CANDU-MOX option as much worse than comparable.

TABLE 4
Proliferation-resistance characteristics of final plutonium-disposition forms vs. those of typical commercial spent LWR fuel

Part A. Barriers to acquisition of the Pu from its storage site

	typical spent LWR fuel[a]	spent WPu MOX, LWR[b]	spent WPu MOX, CANDU[c]	reference can-in-canister
Mass of item	250-670 kg	250-670 kg	24 kg	2500 kg
Dimensions of item	4 m × 15-25 cm	4 m × 15-25 cm	0.5 m × 10 cm	3 m × 60 cm
Quantity of Pu in item	2.5-6 kg	5-23 kg	0.3 kg	29 kg
Radiation barrier[d]	500-800 rem/hr	950-1500 rem/hr	~50 rem/hr	500 rem/hr
Difficulty of on-site reduc-ion of mass & radiation	irrelevant: Pu homogeneously distributed in item	irrelevant: Pu homogeneously distributed in item	irrelevant: Pu homogeneously distributed in item	difficulty controversial—needs further investigation
Signatures aiding detection				
—thermal	~370 watts @ 30 years[e]	~770 watts @ 10 years[e]	~5 watts @ 10 years	~300 watts @ 10 years
—chemical	none	none	none	none
—nuclear	gamma, neutron, Cerenkov (if in spent-fuel pool)	gamma, neutron, Cerenkov (if in spent-fuel pool)	gamma, neutron, Cerenkov (if in spent-fuel pool)	gamma, neutron

continued

TABLE 4
Continued

Part B. Barriers to separation of the plutonium from diluents and fission products

	typical spent LWR fuel	spent WPu/ MOX, LWR	spent WPu/ MOX, CANDU	reference can-in-canister
Quantity of material to be processed	100 kg/kgPu	30-50 kg/kgPu	90 kg/kgPu	intact canister: 90 kg/kgPu pucks: 9 kg/kgPu
Process requirements for...				
—disassembly	sawing/chopping	sawing/chopping	sawing/chopping, for smaller item than LWR fuel	more complex procedure, for larger item than LWR fuel
—dissolution	hot nitric acid	hot nitric acid + 2nd step with catalyst	hot nitric acid + 2nd step with catalyst	specialized techniques[f]
—chemical separation	solvent extraction or ion exchange	solvent extraction or ion exchange	solvent extraction or ion exchange	ion exchange
Hazards to separators				
—radiation	large, until chemical separation completed	large, until chemical separation completed	moderate, until chemical separation completed	moderate, only until physical disassembly completed
—criticality	moderate, at all stages	moderate to high, at all stages	moderate, at all stages	high in solution
—toxics	moderate, at all stages	moderate, at all stages	moderate, at all stages	moderate, at all stages

Signatures aiding detection				
—scale of facilities	depends on item size, Pu concentration, Pu production rate, and other factors[g]	depends on item size, Pu concentration, Pu production rate, and other factors	depends on item size, Pu concentration, Pu production rate, and other factors	depends on item size, Pu concentration, Pu production rate, and other factors
—thermal	depends on quantity of material in process	depends on quantity of material in process	depends on quantity of material in process	depends on quantity of material in process
—chemical	emissions from processing materials (e.g., NOx)	emissions from processing materials (e.g., NOx)	emissions from processing materials (e.g., NOx)	processing-materials requirements smaller; taggants possible
—nuclear	fission products (e.g., Kr-85)	fission products (e.g., Kr-85)	fission products (e.g., Kr-85)	only from glass, unless taggants added

continued

TABLE 4
Continued

Part C. Barriers to use of the separated plutonium in nuclear weapons

	typical spent LWR fuel	spent WPu/ MOX, LWR	spent WPu/ MOX, CANDU[h]	reference can-in-canister
Deviation from WPu isotopics[h]	Pu-238 1.3% Pu-239 60% Pu-240 + Pu-242 30% Pu-241 + Am-241 9%	Pu-238 0.5-1.2% Pu-239 42-60% Pu-240 + 242 25-40% Pu-241 + Am-241 13-17%	Pu-238 <0.1% Pu-239 67% Pu-240 + 242 28% Pu-241 + Am-241 5%	Pu-238 <0.1% Pu-239 93.5% Pu-240 + 242 6% Pu-241 + Am-241 0.4%

[a]Ranges arise from difference between typical BWR and typical PWR fuel-assembly dimensions, the former being smaller. Fuel irradiation is taken to be 33,000 MWd/MTHM in both cases, and time is 30 years after discharge.
[b]Fuel irradiation for spent MOX fuel from weapon-plutonium disposition is taken to be 40,000 MWd/MTHM, and time is 10 years after discharge. Differences in irradiation and aging account for essentially all of the difference in radiation barrier between this spent WPu/MOX and the reference spent LWR fuel; the additional gamma dose from the much higher Am-241 content of the WPu/MOX amounts to only about 3 rem/hr 1 m from the assembly surface.
[c]Entries are for standard CANDU fuel with irradiation to 9700 MWd/MTHM and time 10 years after discharge. A variant with larger item size and irradiation to 25000 MWd/MTHM is described in the text.
[d]Radiation is in rem/hr 1 meter from item surface at mid-plane.
[e]For 500 kg fuel assembly.
[f]The processes for dissolution of the C-in-C ceramic pucks are classified.
[g]E.g., extent of provision for managing effluents and wastes affects facility size.
[h]For the CANFLEX CANDU option irradiated to 25000 MWd/MTHM, the weight fractions of the Pu isotopes are: Pu-238 <0.1%, Pu-239 42%, Pu-240 + Pu-242 48%, Pu-241 + Am-241 10%.

TABLE 5
Panel judgments on comparisons of final plutonium-disposition forms with typical commercial spent LWR fuel with respect to proliferation barriers.

Barrier importance ratings, from Table 1, are with respect to threats of host-nation breakout, theft for a proliferant state, and theft for a subnational group, respectively. (Importance scale is 0 = zero; L = low; M = moderate; H = high.)

	Barrier importance (from Table 1)	LWR-MOX	Standard CANDU-MOX	CANFLEX CANDU-MOX	Reference can-in-canister
Barriers to Acquisition					
Item mass and bulk	0-L / M / M	comparable	much worse	comparable	better
(Low) Pu concentration	0-L / H / H	worse	comparable	comparable	comparable
Radiation hazard to acquirers	L / M / M	comparable	worse	comparable	comparable
Difficulty of on-site reduction of mass & radiation	0-L / H / H	comparable	comparable	worse	much worse to comparable
Signatures aiding detection	0-M / M-H / M-H	better	worse	comparable	comparable
Barriers to Separation					
Technical difficulty of disassembly	L / L-M / M	comparable	comparable	comparable	better
Technical difficulty of dissolution & separation	L / M-H / H	comparable	comparable	comparable	comparable
Quantity of material to be processed	L-M / M-H / H	worse	comparable	worse	worse
Hazards to operators	L / M / M	better	worse	comparable	comparable
Signatures aiding detection	0-M / M-H / H	comparable	comparable	comparable	worse to comparable
Barriers to Utilization					
Isotopic composition	M / M / L	comparable	comparable	better	much worse

Barriers to acquisition: quantity of material to be acquired

The quantity of material that must be acquired to obtain a given quantity of plutonium—a matter of high importance in the proliferant-state and subnational-group threat categories—is about the same in the can-in-canister configuration as in the reference LWR spent-fuel assemblies, both of which have a plutonium concentration near 1 percent by weight. The plutonium concentration is about 30 percent higher in the CANDU MOX configurations and 2-4 times higher in the LWR MOX. For the can-in-canister, theft of a single 2500-kg item would bring 28 kg of plutonium. One would need to steal 4 to 10 of the correspondingly less massive (but similarly bulky) reference LWR spent-fuel assemblies to obtain a similar amount; and one would need to steal nearly 100 of the far less massive (and far less bulky) standard CANDU assemblies to get such a quantity. (We note that, at the 50-70 percent recovery factors that might be assumed for the processing efforts of subnational groups and proliferant states, the 28 kg of Pu in one can-in-canister item or 5-10 reference LWR spent-fuel assemblies would become 14-20 kg.)

With respect to this barrier, we judge the can-in-canister and CANDU-MOX options to be comparable to typical LWR spent fuel, and we judge the LWR-MOX option as worse than comparable.

Barriers to acquisition: hazard to acquirers from radiation

The radiation dose at one meter from the midplane of a 10-year-old canister—a barrier of moderate importance against acquisition of the plutonium from its storage site in the proliferant-state and subnational-group threat categories—would be about 500 rem per hour.[22] This is comparable to the 500-800 rem/hr range for 30-year-old spent LWR fuel. Ten-year-old spent LWR MOX would have a radiation field 2-3 times stronger (1000-1500 rem/hr) than the can-in-canister configuration, ten-year old CANDU MOX in the standard configuration a field about ten times weaker (~50 rem/hr). The corresponding field for the CANFLEX variant of CANDU is estimated as 700 rem/hr.

The conclusion that the radiation barriers of the can-in-canister and reference LWR spent-fuel assembly are comparable would not hold, however, if the radiation barrier associated with the can-in-canister configuration were significantly lower than the range just indicated as a result of

[22]This is calculated at 2018 assuming fill with 33 kilocuries of Cs-137 per canister in 2008 (Leonard Gray, private communication, December 1999).

lower-than-planned cesium-137 content in the waste-bearing glass. Such an outcome could result from the recently publicized shortcomings of the "in-tank precipitation" process that was to be used to separate cesium-137 and other fission products from the aqueous-phase (salt) defense high-level wastes stored at the Savannah River site (SRS), which were to be the source of the fission products in the glass for the can-in-canister approach.[23] It is now estimated that development and testing of an alternative process for extracting the fission products from these Savannah River wastes will require another 10 years, so that cesium-137 from Savannah River waste will not be available for addition to glass produced at that site before about 2010.[24]

A recent National Research Council review of the alternatives DOE has proposed to replace the failed "in-tank-precipitation" process produced the following recommendations that are relevant to judging the potential availability of separated cesium-137 at the SRS:[25]

- "…there are potential barriers to implementation of all of the alternative processing options. The committee recommends that Savannah River proceed with a research and development program … until enough information is available to make a downselection decision."
- "…that DOE hold good faith discussions with regulators to determine if the direct grout option [non-removal of cesium] is feasible should the other processing options prove impractical."

These findings indicate that the timely availability of separated SRS cesium-137 to support the can-in-canister proposal is by no means guaranteed. Given the importance of the radiation barrier to the proliferation resistance of dispositioned plutonium forms, it is essential that DOE take all necessary steps to ensure that an adequate approach to providing that barrier for the can-in-canister configuration can be implemented in a timely way.

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[23]U.S. General Accounting Office, "Nuclear Waste: Process to Remove Radioactive Waste from Savannah River Tanks Fails to Work," Report to the Ranking Minority Member, Committee on Commerce, House of Representatives, GAO/RCED-99-69, April 1999.

[24]Presentation to National Research Council staff by R. Schepens (DOE-SR) and S. Piccolo (Westinghouse Savannah River Co.) on June 7, 1999. Savannah River authorities are also considering a non-partitioning process in which untreated salt solution would be directly incorporated into a cement grout for on-site dispositioning in trenches. This approach would not make cesium-137 available for incorporation into glass.

[25]Committee on Cesium Processing Alternatives for High-Level Waste at The Savannah River Site, National Research Council, *Alternatives for High-Level Waste Salt Processing at the Savannah River Site,* Washington, DC: National Academy Press, 2000, p. 3.

With respect to this barrier, we judge the can-in-canister option to be conditionally comparable to typical LWR spent fuel (where the condition relates to the availability of sufficient cesium-137 to produce the indicated radiation field). We judge the LWR-MOX option and the CANFLEX variant of the CANDU to be comparable and the CANDU-MOX option to be worse than comparable.

Barriers to acquisition: difficulty of on-site reduction of mass and radiation

The technical difficulty of partly separating plutonium from the bulkier and more radioactive components of the disposition form at the site of a theft is a barrier we have rated "high" in importance against proliferant-state and subnational-group threats. In the case of the reference spent fuel and the LWR-MOX and standard CANDU-MOX spent-fuel forms, this barrier would be very high for anybody but the host state: the plutonium in all of these spent-fuel forms is more or less homogenously mixed with uranium oxide and fission products in the ceramic matrix of the spent fuel; and dissolution and separation at the site of the theft is out of the question in the proliferant-state and subnational-group cases because of the scale and complexity of the equipment that would need to be brought to bear and the time that would be required.

In principle, the fuel assemblies could be cut into smaller pieces at the site of a theft using shaped charges; this would reduce the size of the individual pieces that needed to be carried away (but not the total mass needed to acquire a given quantity of plutonium), and the smaller pieces would have somewhat lower radiation fields. For typical spent fuel and for the LWR-MOX and standard CANDU-MOX options, this would seem to fall into the category of "more trouble than it would be worth" to the proliferators. For the CANFLEX variant of CANDU-MOX, it is at least conceivable that breaking up the structure would be enough easier than fracturing fuel assemblies themselves to be considered worthwhile, so we rate CANFLEX as worse than comparable to typical spent fuel on this point.

There is a more serious question as to whether the can-in-canister configuration is vulnerable to some combination of thermal, explosive, and cutting attack to separate the plutonium-bearing cans from the canister and its radioactive glass at the site of a theft, so that the portable and only weakly radioactive cans could be carried away while leaving the bulk and radioactivity of the canister and glass behind. This question is of considerable significance, given the high importance attached, in the con-

text of the proliferant-state and subnational-group threats, to the difficulty of theft-site separation of the plutonium from the bulk and radiation barrier of the intact disposition form.

The Panel has encountered a range of opinions on this issue. The Lawrence Livermore National Laboratory group that has had the lead responsibility for developing the configuration has argued that their latest design is highly resistant to attack. In the Livermore view, a successful assault would necessitate multiple steps using shaped charges and/or saws, requiring more time than would plausibly be available at the site of theft by a group connected with a proliferant-state or subnational-group threat. The Lawrence Livermore group acknowledges that an earlier, less robust design might have been vulnerable to such theft-site attack, but believes the new variant is not.

A group at the Sandia National Laboratory was tasked with performing a "Red Team" exercise to try to determine how the earlier design might most effectively be attacked, and this group made a case that use of linear shaped charges by knowledgeable attackers might separate the plutonium-bearing cans from the radioactive glass and canister quite quickly.[26] This "Red Team" finding was an important basis for the conclusion, in our interim report, that the comparability of the can-in-canister approach with spent fuel with respect to this important aspect of proliferation resistance could not be determined without a substantial program of analysis and actual testing, which we recommended be undertaken.

In a commentary on our interim report,[27] the Livermore group noted that our conclusion on this point related to a can-in-canister design that had since been superseded, and they noted that a subsequent brief review of the current design by a subset of the original Sandia "Red Team" had concluded that "there have been numerous steps and decisions that are consistent with establishing high levels of proliferation resistance and reducing the potential for proliferation vulnerabilities". But this "quick-look" assessment was not supported by either detailed analysis or by actual tests, and, accordingly, it was unable to establish whether the

[26]See, e.g., Leonard Gray and Malvyn McKibben, *op. cit.*; S. Cochran, W. Dunlop, T. Edmunds, L. MacLean, and T. Gould, *Fissile Material Disposition Program Final Immobilization Form Assessment and Recommendation*, Lawrence Livermore National Laboratory Report UCRL-ID-128705, October 1997; J. Hinton, R. Barnard, D. Bennett, R. Crocker, M. Davis, G. Harms, L. Kruse, J. Milloy, W. Swansiger, K. Ystesund, H. Groh, E. Hakkila, W. Hawkins, and E. Hill, *Proliferation Vulnerability Red Team Report*, Sandia National Laboratory Report SAND97-8203, October 1996.

[27]Leonard Gray and Thomas H. Gould, *Immobilization Team Comments on Interim Report of NAS Panel Review of Spent-Fuel Standard for Disposition of Excess Weapons Plutonium*, Lawrence Livermore National Laboratory Report PIP-99-152, 28 October 1999.

design's resistance to physical attack had been increased enough to render success in such an attack implausible. Indeed, the second Red-Team analysis again reaches the conclusion that the vulnerability of the design to on-site energetic disassembly would need to be investigated through further engineering analysis and actual testing in order to establish high confidence that attacks of the sort a proliferant state or subnational group might mount would not succeed.[28]

We persist in our view, therefore, that a more extensive program of investigation, including actual tests, is required to clarify this important matter. In particular, such a program should be designed to shed light on which are the plausible ones among a number of conceivable outcomes of energetic attack on the can-in-canister configuration—outcomes which have quite different implications for judgments about the comparison with spent fuel. The possibilities include the following:

(1) The attack might succeed in cutting the canister in such a way that it separates cleanly, leaving the rack and all or most of the glass intact. In this case the mass of the object to be carried away is reduced only by the mass of the canister (~500kg), hence remains about 2,000 kg (still much more than LWR fuel assemblies). The radiation barrier is not changed significantly in this scenario, moreover, and the exposed glass with its presumably fractured surface and the loss of shielding provided by the canister would actually increase the difficulty of handling. If this were the only plausible outcome, we would judge the can-in-canister configuration to be comparable to spent fuel with respect to the barrier it poses to energetic on-site attack.

(2) The attack might, in addition to removing the canister, cause sufficient fracturing of the glass that a large fraction falls from the rack assembly in small pieces. In addition to further reducing the weight of the object to be carried away by up to the total mass of glass in the canister (~1,300 kg) such an attack would also lower the radiation barrier proportionally. If this were a likely outcome of energetic attack, and if the reduction of the mass and radiation barrier were great enough, we would judge the can-in-canister configuration to be worse than comparable to spent fuel with respect to the barrier it poses against on-site reduction of mass and radiation.

[28]Andre Cygleman, "Report on the Red Team Revisit of Proliferation Resistance for the Fissile Material Disposition Program," Briefing Charts for the National Academy of Sciences Panel on MOX/Immobilization Assessment, U.S. Department of Energy Office of Fissile Materials Disposition, 13 June 2000.

(3) The attack might, additionally, lead to a separation of the magazines from the rack, either as a consequence of the initial energetic event or possibly by a subsequent destruction of the latches. Since the volume of glass trapped inside the magazines is small, the residual radiation barrier would cease to be a significant factor. If this were a likely outcome of energetic attack, the can-in-canister configuration would clearly be less than comparable to spent fuel with respect to the barrier against such attack. A worse outcome still—the separation of individual plutonium-bearing cans from the magazines—would render the configuration much worse than comparable to spent fuel on this score.

(4) It is conceivable that, to be successful in removing both canister and glass, an attack would have to be so energetic that it would also breach the cans and shatter the ceramic pucks in such a way as to make collection of a sufficient quantity of the plutonium-bearing ceramic impractical. (It is this scenario that the Lawrence Livermore group regards as most probable.) If this were the only plausible outcome—or if this and (1) were the only plausible two—we would judge the can-in-canister configuration comparable to spent fuel with respect to the barrier against on-site energetic attack.

There is, unfortunately, no adequate basis at present for deciding which outcomes in this wide range are the plausible ones.

With respect to resistance to energetic on-site attack to reduce mass and radiation, therefore, we conclude that the can-in-canister configuration could be anywhere from comparable to much worse than comparable to typical spent fuel, with the determination of where in this range it falls requiring design and completion of a program of analysis and testing to resolve this question. The LWR-MOX and standard CANDU-MOX options are comparable to typical spent fuel with respect to this barrier, and the CANFLEX variant of the CANDU-MOX option is worse than comparable.

Barriers to acquisition: signatures aiding detection

As noted above, detectability of attempts to acquire, transport, and process dispositioned plutonium forms is a matter of the interaction of intrinsic properties of these forms with engineered and institutional elements of detection. The engineered and institutional elements include national and international materials accountancy and control measures

applied at the storage site, monitoring measures applied to transport, and remote sensors, deployed by either the host state and/or other countries, that can detect the presence of distinctive nuclear, chemical, and thermal signatures associated with diversion, transport, and plutonium extraction.

The signatures themselves arise from the intrinsic characteristics of the disposition form and the nature of the processes for acquisition, transport, and processing that are dictated by these characteristics. The intrinsic characteristics of final disposition forms are of course influenced by a variety of choices made in designing and producing these forms (such as the burn-up of MOX fuels and the composition of the ceramic and/or glass forms used in immobilization approaches), and these choices may include the use of additives intended to enhance signatures aiding detection, as discussed further below.

We treat in the remainder of this subsection the detection of acquisition of the plutonium-containing items. Detection of the processes for separation of plutonium from these is discussed later.

The approximately 3-fold higher concentration of plutonium in LWR-MOX compared to typical spent fuel does not give rise to any significant differences in the signatures associated with diversion and transport of LEU or MOX fuel assemblies from storage or transport. The higher burnup and lower age of the LWR-MOX fuel gives rise to somewhat stronger thermal and nuclear signatures, however. The thermal and nuclear signatures of the CANFLEX CANDU-MOX option would not differ significantly from those of typical LWR fuel, inasmuch as the CANDU-CANFLEX burnup is about three quarters of that for our reference LWR fuel and age of the fuel since discharge is less. The standard CANDU-MOX spent fuel would generate weaker thermal and nuclear signatures by virtue of its considerably lower burnup and smaller item size.

The intrinsic characteristics of intact canisters aiding detection of attempts to remove them from the storage site and transport them elsewhere—external gamma and thermal radiation fields, as well as size and mass—are comparable to those of spent LEU fuel assemblies. As discussed earlier, however, partial or complete separation of the plutonium-bearing cans from the canister at the storage site may be feasible. On the one hand, this would give rise to additional signatures that could facilitate detection, e.g., loud blasts if explosive charges were used, and the potential release of volatile cesium in the case of attempts at thermal separation. On the other hand, if separation is successful, it would make transport off-site less detectable.

With respect to signatures aiding detection of plutonium acquisition, then, we judge the CANFLEX CANDU-MOX option and

the can-in-canister option to be comparable to typical LWR spent fuel, the standard CANDU-MOX option to be worse than comparable, and the LWR-MOX option to be better than comparable.

Barriers to separation of plutonium: technical difficulty of disassembly

We separate, from the question of vulnerability to attack on the "item" at the site of a theft in order to reduce the mass and radiation field of what must be carried away, the question of the relative difficulty of mechanical disassembly of the item in order to isolate the plutonium-containing compound for subsequent chemical processing at a facility dedicated to the task of plutonium extraction and purification. And, in order not to "double count" the possibility that the plutonium-containing cans in the can-in-canister configuration might prove to be separable from the canister, frame, and radioactive glass by energetic attack at the site of a theft, we assume for this next discussion that the item to be dealt with at the plutonium-extraction facility is, in the can-in-canister case, an intact canister.

In the case of spent LWR fuel, the disassembly step involves sawing and chopping operations that are conducted under water because of the intense radiation field. The technology for this is well established, widely known, and not difficult to replicate. The technology for and associated difficulty of this step would not differ in any significant way if the items to be operated upon were LWR-MOX, or standard CANDU-MOX, or CANFLEX-MOX fuel assemblies.

In the case of the can-in-canister configuration, mechanical disassembly would likewise need to be carried out with heavy shielding, probably most conveniently under water. The actual process of disassembly would be more complex and difficult than for spent-fuel assemblies, however, inasmuch as the can-in-canister system is a considerably larger, sturdier, and more complex object. Disassembly would entail penetrating and removing the canister itself, removing the radioactive glass from around and between the cans containing the plutonium, and removing the cans from their frame and opening them to extract the pucks. In contrast to the widely known technology for disassembly of spent fuel, some effort would have to be devoted to working out how to handle this corresponding job for the can-in-canister option.

With respect to this barrier, then, we judge the can-in-canister option to be better than comparable to typical LWR spent fuel. The LWR-MOX and CANDU-MOX options are comparable to LWR spent fuel in this respect.

Barriers to separation: technical difficulty of dissolution and chemical separation

In the case of spent LWR fuel, the steps following sawing and chopping begin with immersing the pieces in hot nitric acid in order to dissolve the uranium-oxide ceramic and the plutonium and fission products it contains. Then plutonium and uranium together are separated from the fission products during a first solvent-extraction step. Both the dissolution and the first solvent extraction must be carried out behind shielding to protect the operators from the high radiation field emanating from the fission products. Once these "hot" steps are complete, "cold" operations requiring little or no shielding begin: first the uranium and plutonium are separated from each other with a further solvent-extraction step, and then the plutonium product is "cleaned up" with ion-exchange techniques. None of these dissolution and separation steps would be made either appreciably easier or appreciably more difficult by the higher plutonium concentration in LWR-MOX and CANDU-MOX spent fuel.

In the case of the can-in-canister configuration, we assume in order to avoid double counting of difficulties that mechanical disassembly operation has succeeded in completely separating the ceramic pucks from the rest of the item, so that the input to the dissolution operation is pucks alone. Because the radiation field from the pucks would be far less intense than that associated with the high concentrations of fission products in the glass that has now been removed (and in the comparison spent fuel), the dissolution step could proceed with little shielding. It would begin with grinding the pucks to a powder to ease dissolution. Dissolution itself would not be as straightforward as for spent fuel, however, because the ceramic used in the pucks does not dissolve in hot nitric acid. A proliferator would need to seek out alternative processes (for which task there is considerable relevant information available in the open literature, but no cookbook-style recipe as for spent fuel). Once the ceramic is in solution, the final step would be chemical separation of plutonium from the other constituents of the ceramic, including uranium (which is a constituent of the pucks intended to address long-term criticality issues in the repository). The separation step may be accomplished via an ion-exchange process, although this will be complicated by the presence of uranium.

In our judgment, the reduction in technical difficulty of dissolution and separation associated with the reduced shielding requirements for the can-in-canister case, compared to those for typical spent fuel, is substantially offset by the greater difficulty the proliferators would face in mastering the chemistry for these steps.

With respect to technical difficulty of dissolution and separation,

therefore, we conclude that the can-in-canister approach is comparable to typical spent fuel. More obviously, the LWR-MOX and CANDU-MOX options are also comparable in this respect to ordinary LWR fuel.

Barriers to separation: quantity of material to be processed

Distinct from the question of the quantity of material that must be acquired in the first place to obtain a given quantity of plutonium, which was discussed above under "barriers to acquisition", is the question of the quantity of material that must be passed through the various processing steps. Leaving aside, so as to avoid double counting, the possibility that much of the mass of the can-in-canister configuration could be removed by energetic attack at the site of a theft, the comparison of the mass of material per kilogram of contained plutonium entering the mechanical-disassembly step would be the same as the comparison given above for the masses of material that must be initially acquired — that is, the can-in-canister and standard CANDU-MOX cases are comparable to typical spent fuel, and the LWR-MOX case and CANFLEX CANDU-MOX cases are worse than comparable.

For the can-in-canister case, the quantity of material needing to be handled goes down by about a factor of 10 following mechanical disassembly, the large mass of the radioactive glass and steel structure having been removed at that step. The throughput of material per quantity of contained plutonium is, correspondingly, about 10 times smaller at the dissolution and chemical-separation steps than for the case of typical spent fuel, and 3 times smaller than for LWR-MOX. This deviation is only moderately offset by the smaller anticipated recovery factor of plutonium from the can-in-canister ceramic than from spent fuel: a well run spent-fuel reprocessing operation can recover 85 to 90 percent of the contained plutonium, compared to a Livermore Lab estimate of just over 70 percent as the upper limit for recovery from the can-in-canister ceramic (based on getting 80 percent of the contained plutonium into solution and then losing 10 percent of that in the separation, purification, and conversion-to-metal steps).[29]

With respect to quantity of material to be processed, we judge the standard CANDU-MOX option to be comparable to typical spent fuel and the CANFLEX CANDU-MOX, LWR-MOX, and can-in-canister options to be worse than comparable.

[29]See Gray and Gould, October 1999, cited at Note 9.

Barriers to separation: hazards to operators

The radiation, criticality, and toxic hazards to the operators of the processes used to separate plutonium from the dispositioned form—considered separately from the radiation hazards to those acquiring the plutonium-containing items from storage or transport—were rated in Table 1 and the accompanying discussion as being of low importance against the threat of host-nation breakout and moderate importance against the proliferant-state and subnational-group threats. As also indicated earlier, the toxic component of these hazards is not sufficient to constitute a significant barrier, and we do not consider it further here. Radiation and criticality would be the proliferators' main concerns in the category of hazards of separation.

As noted just above, in the reference case of reprocessing ordinary spent fuel, a high radiation field from the fission products accompanies the plutonium through the dissolution and first solvent-extraction steps. The need for shielding against this field complicates the technical work, as considered above in our discussion of the "technical difficulty of separation" barrier, and it poses a risk of health-damaging or even fatal doses of radiation to the operators in the event of mistakes or in the event of a need for "hands on" repairs during processing. Inasmuch as this hazard is dominated by the fission products rather than by the plutonium, uranium, and other heavy isotopes present, its variations among different spent-fuel forms depend mainly on the fuel's burnup and its age since discharge. The fission products in spent-fuel from the LWR-MOX option, which we assume will have a burnup of 40,000 MWd/MTHM and which we are evaluating at 10 years past discharge, would be generating about twice the radiation field of our designated "typical" spent fuel with its burnup of 33,000 MWd/MTHM and an age of 30 years since discharge. The fission products from CANDU-MOX fuel irradiated to 9700 MWd/MTHM and aged 10 years would generate a field about half as intense as that from our "typical" LWR fuel;[30] and those from the CANFLEX CANDU-MOX option (where the assumed burnup is 25,000 MWd/MTHM) would be about 20 percent more intense than that from the "typical" LWR fuel. In all these cases, the concentrations of the fission products in solution would be similar, as the processing geometries involved presumably would be, so no significant differences in the radiation fields are to be expected from these factors.

[30]Prior to mechanical disassembly and dissolution, the radiation field from CANDU-MOX is smaller than that of "typical" LWR fuel by a larger factor than this (in the range of 10 to 15), where the additional shortfall comes from geometry in the form of the CANDU fuel assemblies being much smaller.

In the case of the can-in-canister option, the high radiation hazard arising from the fission products persists in the course of processing only up to the point where the plutonium-containing ceramic pucks are extracted from the surrounding fission-product-containing glass. The subsequent dissolution and separation steps entail much smaller shielding requirements—and lower radiation hazards in the event of mistakes or hands-on maintenance needs—because the fission products are gone. This part of the "hazards" barrier, then, is significantly lower for the can-in-canister option than for the reference spent fuel and for all of the MOX options.

As for criticality, this hazard arises mainly from the possibility that plutonium in solution will find itself in a combination of concentration, geometry, and diluent properties that allow formation of a critical mass.[31] The high flux of neutrons from criticality would constitute a potentially deadly radiation hazard, and the energy release could be enough to damage or destroy the processing equipment. The main variable among the disposition options, with respect to this hazard, is the plutonium concentration in solution. In order to avoid discussing the chemistry of dissolution and separation in excessive detail, we assume here that the concentration of plutonium in solution is proportional to the plutonium concentration in the items dissolved. If this were so, then the relevant concentration for the CANDU options would be 30 percent higher than in the case of our designated "typical" LWR fuel, and the concentration for the LWR-MOX option would be about 3 times higher. In the case of the can-in-canister option, since only the plutonium-containing pucks and not the initially surrounding glass must be dissolved, the concentration of plutonium in solution would be about 10 times that for typical spent fuel.

Thus, the criticality hazard experienced by the operators of plutonium recovery processes in the can-in-canister case would be much better than comparable to that associated with reprocessing typical spent fuel, while the radiation hazard would be much worse than comparable. If these two hazards are given similar weight, then these differences substantially offset each other in the overall evaluation of comparability with respect to the barrier of "hazards to the operators," and can-in-canister approach comes out "comparable" in this respect. The LWR-MOX option is better than comparable with respect to criticality and comparable with respect to radiation, and we rate it better than comparable overall. The CANFLEX CANDU-MOX option comparable in both criticality and radiation, hence comparable overall; and the standard CANDU option is com-

[31]There is also a possibility of this occurring after the plutonium has been extracted from solution—that is, when it is in the form of plutonium oxide or plutonium metal—but the criticality hazard once this stage is reached does not differ among the disposition options from which the plutonium was obtained and so will not be discussed further here.

parable in criticality and worse than comparable in radiation, hence rated worse than comparable overall.

In summary, with respect to the barrier of hazards experienced by the operators of plutonium-recovery processes, we judge the can-in-canister and CANFLEX CANDU-MOX options to be comparable to typical spent fuel, the LWR-MOX option to be better than comparable, and the standard CANDU-MOX option to be worse than comparable.

Barriers to separation: signatures aiding detection

Comparable amounts of radioactive and chemical effluents are released to the environment as a byproduct of the mechanical/chemical (PUREX) process ordinarily used to extract plutonium from either LWR spent-fuel form. The higher concentration of plutonium in LWR-MOX compared to typical spent fuel implies that a smaller processing facility could be used to produce plutonium at the same rate in the case of MOX. On the other hand, dissolution of higher concentrations of plutonium is more difficult, requiring a secondary dissolution step, which in turn generates additional chemical effluents. Based on these considerations, we judge that LWR-MOX is comparable to typical spent fuel with respect to signatures aiding detection, as are the standard and CANFLEX CANDU-MOX options.

The signatures comparison is more complex in the case of the can-in-canister approach. The radioactive and chemical signatures available for detecting the separation of the ceramic pucks from the glass and the subsequent processing of the former to extract the contained plutonium are different from those available in extracting plutonium from spent fuel using the PUREX process. The three main differences are: the absence, in the case of the can-in-canister approach, of detectable fission products such as the noble gas Kr-85, released during reprocessing of spent fuel; the need to use processes other than PUREX to separate and dissolve the ceramic and extract the contained plutonium; and the higher concentration of plutonium in the ceramic pucks compared to that in typical spent fuel, which, all else equal, will reduce the scale and/or duration, and hence the detectability, of extraction operations.

Taking these differences into account, we judge that the detectability of processing to extract plutonium in the case of the can-in-canister option would never be better, and in most cases would be worse, than for typical spent fuel across the range of diversion scenarios involving the host state, proliferant states, and subnational groups. The detectability of processing in the case of the can-in-canister option can be increased, however, either

directly (by the addition of various infrared active chemical "taggants" to the canister that would be released when it is disassembled) and/or indirectly (by adding constituents to the ceramic that would complicate the chemical processing and thus increase the scale and duration of emissions). Our preliminary survey of such signature enhancement techniques has indicated a wide variety of possibilities. While these require further analysis with regard to technical feasibility and cost, we judge this to be a promising option for increasing detectability. We also note that detection of a chemical taggant in the vicinity of a storage site could alert authorities that a canister had been disrupted on site; this detection possibility, if coupled with adequate response times of security forces, could reduce somewhat the concerns about vulnerability of the can-in-canister configuration to such on-site attack.

With respect to signatures aiding detection of plutonium separation, we judge that the LWR-MOX and CANDU-MOX options are comparable to typical spent fuel. We judge the can-in-canister option worse than comparable on this criterion, although there is a high likelihood that it could be made comparable through the use of additives to increase detectability, and possibly it could be made better than comparable in this way.

Barriers to utilization: deviation of isotopic composition

The "reactor-grade" plutonium in typical spent fuel differs from "weapons-grade" plutonium in having a higher neutron background (deriving mainly from the higher Pu-240 and Pu-242 content), a higher heat-generation rate (deriving mainly from higher Pu-238 content), and a higher surface gamma-ray dose (deriving mainly from higher Pu-241 and Am-241 content). As indicated earlier, these differences present additional difficulties to the designers, producers, and handlers of nuclear weapons made with reactor-grade plutonium, compared to those encountered when weapons-grade plutonium is used. The barriers posed by these difficulties for the utilization in weapons of plutonium of isotopic composition differing from weapons grade are not insurmountable; for reasons explained above, we have rated them as "moderate" in importance against the host-nation and proliferant-state threats and "low" in importance against the subnational-group threat.

As seen in Table 4, the plutonium in the LWR-MOX option has about the same Pu-240 + Pu-242 content as plutonium in the reference spent fuel, a Pu-238 content ranging from less than half as great to about the same, and a Pu-241 + Am-241 content ranging from 50 percent greater to twice as high; on balance, we rate the isotopic barrier of the LWR-MOX

option as comparable to that of typical spent fuel. The standard CANDU-MOX option is likewise comparable to typical spent fuel in this respect, with Pu-240 + Pu-242 concentration in the same range, Pu-238 content considerably smaller, and Pu-241 + Am-241 content about 50 percent lower. The CANFLEX-CANDU option has Pu 240 + Pu-242 content about 50 percent higher than that in typical spent fuel, considerably smaller Pu-238 content, and Pu-241 + Am-241 content about the same; we rate this as better than comparable to typical spent fuel. In the case of the can-in-canister option, the isotopic composition of the contained plutonium is unaltered from that of the weapons plutonium provided to the process; we rate this as much worse than comparable to typical spent fuel.

In summary, with respect to the isotopic barrier to utilization of the plutonium in nuclear weapons, we judge the LWR-MOX and standard CANDU-MOX options to be comparable to typical spent fuel, the CANFLEX-CANDU option to be better than comparable, and the can-in-canister option to be much worse than comparable.

Overall judgments on comparability and compliance

Table 5 summarizes our judgments on the comparability, with typical commercial spent LWR fuel, of the four disposition forms—LWR-MOX, standard CANDU-MOX, CANFLEX CANDU-MOX, and the reference can-in-canister configuration—in respect to all of the proliferation barriers considered here. The relative-importance ratings of these barriers against the three classes of threats are indicated (from Table 1) in the first column. In the remaining columns, each disposition form is rated on each barrier as being "comparable" to typical spent fuel, "worse than comparable", "much worse than comparable", or "better than comparable". (Again, 'worse' means a lower barrier to proliferation than provided by the reference spent fuel, and 'better' means a higher barrier to proliferation.) We found no instance in which a rating of "much better than comparable" was warranted.

Our judgments on compliance with the spent-fuel standard are then based on "summing," in a manner of speaking, the departures from comparability for each disposition option. Thus:

- *The LWR-MOX option* is worse on Pu concentration and quantity of material to be processed; better on signatures aiding detection of acquisition and hazards to operators; and comparable on the remaining seven barriers. The importance ratings of the two barriers on which LWR-MOX is worse than reference spent LWR fuel

are only slightly higher than the importance ratings of the two barriers on which it is better. (The average of these differences is about half a level, that is, half of the difference between "low" and "medium" or between "medium" and "high.") The magnitude of the net deviation from reference LWR spent fuel in importance-weighted barriers to acquisition, separation, and utilization of the contained plutonium is small, well within the spent-fuel standard's requirement that the plutonium be "roughly as difficult to acquire, process, and use in nuclear weapons" as that in the reference spent fuel. **Accordingly, we judge the LWR-MOX option to be compliant with the spent-fuel standard.**

- *The standard CANDU-MOX option* is much worse on item mass/bulk; worse on radiation hazard to acquirers, signatures aiding detection of acquisition, and hazards to operators; and comparable on the remaining seven barriers. The "worse" and "much worse" performances are uncompensated by any "better" performances, and they occur in barriers with importance ratings averaging near "moderate" and extending to "moderate to high". The magnitude of this net deviation from reference spent LWR fuel in importance-weighted barriers to acquisition, separation, and utilization of the contained plutonium is too large, in our judgment, to meet the spent-fuel standard's requirement of "roughly as difficult…" **Accordingly, we judge the standard CANDU-MOX option to be noncompliant with the spent-fuel standard.**
- *The CANFLEX CANDU-MOX* option is worse on difficulty of on-site reduction of mass & radiation; worse on quantity of material to be processed; better on isotopic composition; and comparable on the remaining eight barriers. The importance ratings of the two barriers on which this option is worse than reference LWR spent fuel are significantly higher than the importance rating of the barrier on which it is better, which means that the one "better" performance does not fully compensate even the less important of the two "worse" performances; the more important of the "worse" performances, which is completely uncompensated, entails "high" importance ratings against two of the three classes of threat. The magnitude of the net deviation from reference LWR spent fuel in importance-weighted barriers to acquisition, separation, and utilization is not as great as in the case of the standard CANFLEX CANDU-MOX option, but it is enough to render this case a close call. **We judge the compliance of the CANFLEX CANDU-MOX option with the spent-fuel standard to be marginal.**
- *The reference can-in-canister option* is much worse on isotopic composition; worse on quantity of material to be processed; better on

item mass/bulk and technical difficulty of disassembly; and comparable on five other barriers. It could be from much worse to comparable on difficulty of on-site reduction of mass and radiation (this evaluation depending on the outcome of a recommended program of analysis and testing), and from worse to better on signatures aiding detection of separation (this evaluation depending on the outcome of investigation of the potential of additives to enhance these signatures). Taking into account the importance ratings of the barriers involved, the two "better" performances could be deemed to compensate for enough of the "worse" on quantity of material to be processed and the "much worse" on isotopic composition to permit a judgment of compliance with the spent-fuel standard *if* analysis and testing showed performance to be comparable with respect to difficulty of on-site reduction of mass & radiation *and if* it proved possible, using additives, to make the signatures aiding detection of separation at least comparable to those for typical LWR spent fuel. **Accordingly, we judge the compliance of the reference can-in-canister option with the spent-fuel standard to be contingent on the outcome of efforts to clarify this option's resistance against on-site attack and to improve its signatures aiding detection of separation activities.**

Alternatives to the Reference Can-in-Canister Configuration

In the event that the current can-in-canister configuration were to be found noncompliant with the spent-fuel standard, there are other modifications to this approach to plutonium immobilization that could and should be considered as potential remedies. The possibilities, beyond the use of additives to increase detectability of processing as already discussed above, include the following:

- *Further modification of the frame-and-can arrangement to increase resistance to cutting and/or explosive attack.* Considerable efforts along these lines have already been made, but further advances may be possible.
- *Addition of materials to the puck composition to increase the difficulty of chemical extraction of the plutonium.* Some of the materials that pose the greatest difficulties in this respect are already part of the current composition, and have been taken into account in our evaluation, but further ingenuity in complicating the mix may be possible.
- *Reduction in the concentration of the plutonium in the ceramic.* This is technically easy but would, obviously, increase the amount of

plutonium-bearing ceramic material to be produced and the quantity of radioactive glass and number of canisters to be provided for disposition of a given quantity of plutonium.

- *Addition of cesium directly to the ceramic.* This measure would extend the main radiation barrier into the chemical dissolution and separation steps, corresponding to the situation with spent fuel. This would complicate (and increase the cost of) the puck-production process, but the gain in proliferation resistance might be worth it.
- *Replacement of pucks with pellets.* Instead of pucks, the plutonium-containing ceramic could be formed into pellets or marbles, which could be placed in a wire mesh for loading into the canister or added to the molten glass as it is being poured. These modifications would require surmounting certain difficulties, but the resulting more homogeneous distribution of ceramic in the glass would make it more difficult for thieves to separate the plutonium-containing material at the site of the theft.

All of these possibilities have been considered in at least a preliminary way by DOE and its contractors. All of them pose difficulties as well as offering potential for increased proliferation resistance. To investigate these trade-offs would have been beyond our mandate, and we have not done so. But we believe all these approaches would be worth revisiting in the event that the current configuration is ultimately judged noncompliant with the spent-fuel standard. Some combination of them—and perhaps others not mentioned here—might suffice to bring the can-in-canister option into compliance.[32]

[32]Some of these approaches would undoubtedly increase costs, but we would reiterate in this connection the emphatically stated view of the previous CISAC plutonium reports that security is primary in this matter and cost secondary (unless and until costs become high enough to prevent taking the steps that security requires).

Appendix A

Charge to the Panel

The National Academy of Sciences will convene a committee of experts to conduct a 14-month study to

(1) amplify and clarify the "spent-fuel standard" introduced in the Academy's 1994 and 1995 reports on disposition of excess weapons plutonium as the criterion for judging the adequacy of resistance to theft and proliferation conferred by the characteristics of the final plutonium form produced by a disposition option;
(2) use the results of part (1) to determine whether the final plutonium forms produced by the two primary disposition methods being implemented by the Department of Energy under the hybrid approach adequately meet the spent-fuel standard.

In Task 1 the study will review efforts made in the 1994-1995 NAS reports and subsequently to quantify the spent-fuel standard, and it will suggest appropriate metrics for determining whether a given immobilization end-product or spent-fuel form adequately meets the standard.

The two disposition options for which the final plutonium forms will be analyzed under these metrics are

(a) "can-in-canister" immobilization of the plutonium in combination with high-level radioactive wastes, and
(b) once-through irradiation of the plutonium in mixed-oxide (MOX) fuel in commercial LWR or CANDU reactors.

The study will not address the proliferation and theft resistance of the steps that lead, under these disposition options, to the final plutonium forms, and it will not address issues related to geologic disposal or interim storage of these final forms except insofar as the properties of the final forms under such disposal or storage relate to assessing compliance with the spent-fuel standard.

Appendix B

Panel Meetings, Briefings, and Consultants

MEETINGS AND BRIEFINGS

November 23, 1998: Harvard University, Cambridge, MA; committee bias and potential conflict of interest review in accordance with NRC procedures, scope of the study, sources of information, study timeline, and preliminary dates for future meetings (closed sessions only).

December 18–19, 1998: Livermore, CA (day 1) and Stanford, CA (day 2); overview of the can-in-canister option, physical and chemical aspects of the proposed final form, process summary (open session, day 1); initial discussion of issues related to conclusions and recommendations (closed session, day 2); briefers Leonard Gray and Thomas Gould (Lawrence Livermore National Laboratory).

January 15–16, 1999: Washington, DC; general discussion, overview and status of DOE Materials Disposition program, public comments (open session); review of public comments, status of project and interim report (closed session); briefers Laura S. H. Holgate and Howard Canter (DOE Office of Materials Disposition).

February 15, 1999: Harvard University, Cambridge, MA; plans and assignments for drafting interim report (closed sessions only).

July 7-8, 1999: Cambridge, MA; public comments (open session); discussion of response to review of the interim report (closed); discussion of the

issues for the Panel's final report, including the schedule and work plan (closed).

September 24-25, 1999: Washington, DC; public comments on interim report (open session); discussion of comments received regarding the interim report and Panel members' assignments for the final report (closed session).

December 3, 1999: Washington, DC; update of events and issues since the last meeting; content of the final report; plans for completion of the final report (closed session).

June 13, 2000: Washington, DC; meeting with Laura Holgate and Andre Cygelman (classified, closed session at DOE HQ); discussion of draft final report and plans for its completion (closed session).

CONSULTANTS

Matthew Bunn
Earl Wheelwright
Raymond Wymer