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Feasibility of Eliminating the Use of Highly Enriched Uranium in the Production of Medical Radioisotopes

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Significant quantities of highly enriched uranium (HEU)—more than enough to make a Hiroshima bomb—are used annually as neutron target material in Canadian, European, and South African reactors to produce the short-lived fission products used in nuclear medicine. The most important of these fission products is ^{99}Mo, which decays into ^{99m}Tc, which is the most widely used medical radioisotope.

The U.S. supplies weapon-grade uranium to the Canadian radioisotope producer and might in the future provide it to the European producers as well. As a condition for receiving U.S. HEU, the 1992 Schumer Amendment to the U.S. Atomic Energy Act requires that a foreign producer cooperate with the United States in converting to low-enriched uranium (LEU) targets. Some smaller producers have already done so. The Canadian producer has asserted, however, that the cost of conversion would be too high. The 2005 Burr amendment therefore exempted radioisotope producers in Canada and Europe from the Schumer amendment's requirements but requested a National Academy of Sciences study of the feasibility of conversion, setting as a feasibility test that the production cost be increased by no more than 10 percent.

We show that paying for the conversion for the largest European production facility would increase the cost of ^{99}Mo production there by only a few percent. For the Canadian facility the production cost could be more than 10 percent but the increase in the cost of the final ^{99m}Tc-containing radiopharmaceutical would be only about 1 percent. It is also pointed out that savings in security could well dwarf the costs of converting to LEU if HEU were no longer present at the production and radioactive waste sites.

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INTRODUCTION

The most important nuclear material to keep away from potential nuclear terrorists is highly enriched uranium (HEU). If a terrorist group acquired about 50 kilograms of weapon-grade uranium (≥90-percent ^{235}U), it could cause a nuclear explosion using a simple gun-type device to assemble two sub-critical masses into a supercritical mass. This was the design used for the Hiroshima bomb. It cannot be used with plutonium because the high level of spontaneous neutron emission in plutonium would result in the chain reaction beginning before the supercritical mass was fully assembled. As a result the explosive power of a gun-type plutonium weapon would be reduced a thousand fold.

In the 1970s, recognizing the risks of nuclear proliferation and terrorism associated with civilian use of HEU, both the U.S. and Soviet governments launched programs to facilitate the substitution of non-weapon-usable low-enriched uranium (LEU, containing less than 20 percent ^{235}U) for HEU in civilian research-reactor fuel and in radioisotope production targets. This program is now international.[1] Its progress and limitations with regard to the conversion of research-reactor fuel have been discussed elsewhere.[2] This article discusses the issues associated with the use of HEU in the production of medical radioisotopes.

USE OF HEU FOR THE PRODUCTION OF MEDICAL RADIOISOTOPES

"Targets" of weapon-grade uranium placed in high neutron fluxes near the cores of high-powered research reactors, are the principal sources for the production of a number of short-lived fission products that have become important to modern medicine. In this article, we focus primarily on technicium-99m, which is currently used in about 80 percent of all nuclear-medicine diagnostic procedures worldwide.[3]

Technicium-99m (^{99m}Tc) has a 6 hour half-life and emits a gamma ray when it de-excites. Attached to various chemicals, it can be followed by its gamma emissions through the body and thereby can be used to examine the functioning of various organs. Its short half-life and lack of beta radiation minimizes unnecessary radiation doses. It is derived from molybdenum-99 (^{99}Mo), which has a half-life of 2.7 days and decays into ^{99m}Tc. ^{99}Mo is adsorbed onto the surface of a bed of small alumina particles in "generators" from which the ^{99m}Tc decay product is drawn off in solution.

^{99}Mo is produced in about 6 percent of all fissions of ^{235}U.[4] Ninety-five percent of the global supply is produced by placing a "target" of HEU (usually weapon-grade) in or near a reactor core.[5] Very roughly 85 kg of HEU are being used for this purpose per year in Canada, Europe, and South Africa.[6] Less than five percent of the ^{235}U in the target is consumed and, in most cases,

Table 1: Reactors producing ^{99}Mo for major international distributors in 2005.[10]

Reactor/Country	Power (MWt)	Initial Operation (shutdown)	Percent of year operating	Distributor	Av/Peak production (% world demand)
NRU/Canada	135	1957	86	MDS-Nordion	40/80
HFR/Netherlands	45	1961	79	Mallinckrodt	20/30
				IRE	10/20
BR2/Belgium	100	1961	31	Mallinckrodt	5/15
				IRE	4/20
Osiris/France	70	1964	60	IRE	3/20
FRJ-2/Germany	23	1962 (2006)	57	IRE	3/10
SAFARI South Africa	20	1965	86	NTP	10/45
Other				Other	5/10
				Total	100/250

it is not recycled. The HEU in the waste is therefore still weapon-usable and has accumulated in the ^{99}Mo-producing countries in amounts that would be sufficient to make many Hiroshima weapons.[7] The gamma radiation dose rate from this HEU waste is not sufficient to make it self-protecting by international standards.[8]

The world's major ^{99}Mo production reactors are currently in Canada (^{99}Mo distribution by MDS-Nordion), Europe (Tyco-Healthcare/Mallickrodt in the Netherlands and the Institute for Radioelements [IRE] in Belgium), and South Africa (NTP) (see Table 1). Although the U.S. accounts for about half the global ^{99}Mo demand,[9] it currently does not produce ^{99}Mo.

U.S. EFFORTS TO ELIMINATE HEU TARGETS AND INDUSTRY OPPOSITION

The U.S. and Russia are the major international suppliers of HEU for use in research-reactor fuel and isotope-production targets. In 1992, the Schumer amendment was added to the U.S. Atomic Energy Act to help motivate foreign consumers of U.S. HEU to switch to LEU.

One of the requirements in the Schumer amendment is that, as a condition for the supply of U.S. HEU to foreign reactors, the operators of those reactors must make the commitment "that, whenever an alternative [LEU] nuclear reactor fuel or target can be used in that reactor, it will use that alternative."[11]

Small ^{99}Mo producers in Argentina and Australia are now using LEU targets and Indonesia's producer is converting to such targets.[12] The major producers, however, have been resisting conversion.[13]

Only one of the four major companies that distribute ^{99}Mo is currently importing U.S. HEU for targets, MDS-Nordion of Canada, which accounts for about 40 percent of global production of ^{99}Mo.[14] It imports about 20 kilograms

of weapon-grade uranium from the U.S. per year.[15] The European producers currently are using weapon-grade uranium that has either been acquired from another nuclear-weapon state (France, Russia, or the U.K.) or was exported by the U.S. prior to the Schumer amendment.[16] South Africa is using highly enriched HEU that it produced prior to 1991.

In 2005, a lobbying campaign sponsored by MDS-Nordion and Mallinckrodt resulted in the Burr Amendment in the National Energy Policy Act of 2005. This amendment exempts target HEU used by medical radioisotope producers in Canada, Belgium, France, Germany, and the Netherlands from the Schumer Amendment's requirements.[17] Some U.S. physician groups supported this exemption because they were persuaded that enforcement of the Schumer requirement would endanger U.S. radiopharmaceutical supplies.[18] As will be seen later, there is a question as to the future adequacy of world ^{99}Mo production capacity, but that is because of the aging of the production reactors—not the potential impact of converting the targets from HEU to LEU.

Supporters of the Schumer Amendment were unable to stop the Burr Amendment but were able to insert into it a requirement for a National Academy of Sciences study on "the feasibility of procuring supplies of medical isotopes from commercial sources that do not use highly enriched uranium."[17] The definition of "feasibility" includes an "average anticipated total cost increase from production of medical isotopes [of] less than 10 percent."

In 2004, the average price of the ^{99}Mo used per dose of ^{99m}Tc was about $7.50.[19] The average cost to hospitals of radiopharmaceuticals containing ^{99m}Tc in 2002 was $87 per dose.[20] Therefore, if the 10-percent criterion is applied to the production cost of the radioisotope, it corresponds to a requirement that the cost of radiopharmaceuticals be increased by less than 1 percent.

COMPARISON BETWEEN HEU AND LEU ^{99}Mo PRODUCTION PROCESSES

There appears to be no significant technical or safety reason not to replace HEU with LEU targets. G. F. Vandergrift from Argonne National Laboratory who provides technical support for replacing HEU with LEU targets, has examined the impact of conversion on production of: ^{99}Mo per target, ^{99}Mo extraction time, solution volume, solid-waste and plutonium production, and ^{99}Mo purity. His most important findings are as follows.[21]

Production Per Target

The dilution of the ^{235}U by four times as much ^{238}U in LEU in the target increases the total volume of uranium in the target. A typical target contains only about 15 grams of ^{235}U with a volume of about 1 cubic centimeter in a

target volume of hundreds of cubic centimeters, however. The quantity of ^{235}U is limited not by volume but by the rate at which the water flowing through and around the target can carry off the fission heat. Therefore, the addition of the ^{238}U can be easily accommodated.

Byproduct Plutonium Production

The added ^{238}U increases the amount of ^{239}Pu produced by neutron capture in the ^{238}U. Plutonium is a proliferation concern. The quantity of produced plutonium is still relatively small, however. For a case in which 0.5 percent of the ^{235}U in the target is fissioned, about 1 kg of plutonium would be produced for every 1,600 kg of weapon-grade uranium that otherwise would be in the waste.[22] For 5-percent ^{235}U fission, the ratio would still be less than 0.01.

Purity of the ^{99}Mo Product

For the same amount of purification, there will be more plutonium left in ^{99}Mo made with LEU. The product contains less than 1.6×10^{-14} grams of ^{239}Pu per Curie of ^{99}Mo, however.[23] The associated radiation dose to patients therefore would be less than one ten millionth of the dose from the ^{99m}Tc.[24]

COST OF CONVERSION FROM HEU TO LEU

The economic arguments made by the big producers against conversion to LEU targets have focused primarily on the costs of the conversion rather than the cost of operating with LEU targets thereafter. Because there appears to be no economic advantage to conversion, however, as long as conversion is not required, the big producers cannot be expected to volunteer to incur the costs and whatever risks there might be in going first.

Most of the public debate over conversion has involved the Canadian producer, MDS Nordion because it uses U.S.-supplied HEU for its ^{99}Mo production targets. The U.S. Nuclear Regulatory Commission licenses these exports. In 1999 and 2000, the NRC held public hearings on these exports because questions had been raised as to whether MDS-Nordion had been cooperating in good faith with the Argonne National Laboratory to convert to the use of LEU targets—i.e., complying with the Schumer Amendment.

MDS-Nordion currently uses the Atomic Energy of Canada Limited (AECL) *NRU* reactor at Chalk River, Ontario to irradiate its ^{99}Mo-production targets. The *NRU* is a multi-purpose reactor that began operations in 1957. An older reactor, the *NRX*, provided backup irradiation services until 1993, when it was permanently shut down. With the age of the *NRU* becoming an increasing concern, MDS-Nordion decided, for redundancy, to build two replacement reactors,

Maple 1 and *Maple 2*, which are to be fully dedicated to the production of ^{99}Mo and other fission products for radiopharmaceuticals.

Despite the requirements of the Schumer Amendment, however, the design of the new ^{99}Mo recovery facility associated with the *Maple* reactors was optimized for HEU targets.

In 2000, MDS-Nordion officials stated to the U.S. Nuclear Regulatory Commission that only one design change would be required to adapt its new processing facility for LEU targets: increasing the capacity of its waste-calcining (drying and oxidizing) system. The MDS-Nordion officials also asserted, however, that the space that had been allocated in the new processing facility was too small to hold a larger capacity calciner. MDS-Nordion committed to try to adapt the recovery facility to LEU targets after it went into operation or, if that proved impossible, to build a new molybdenum-99 recovery line designed for LEU targets.[25]

In 2003, however, MDS-Nordion informed the Nuclear Regulatory Commission that conversion would not be feasible and that a new LEU processing facility would be too costly: (Cdn)$90 million ($77 million US).[26] There has been no independent confirmation of these claims because MDS-Nordion broke off its cooperation on conversion studies with Argonne National Laboratory.

The new Maple reactors were supposed to come on line in 2000 but were found to have safety defects related to both their design and construction. In November 2005, the Canadian Nuclear Safety Commission gave AECL an additional two years to bring the reactors into operation.[27] It also granted an interim extension of the NRU operating license to the end of July 2006 to allow preparation of an application to extend NRU operations until 2012.[28]

Subsequently, AECL took over project completion and operating costs for the *Maple* reactors and processing facility, relieving MDS-Nordion from a debilitating drain on its corporate finances. Because AECL is a "Crown Corporation," that is, wholly owned and subsidized by the Canadian government, this means, in effect, that the Canadian government has taken over the ownership and operation of the facilities, leaving MDS-Nordion with the role of distributing the radioisotopes. The reason given in the AECL press release was to "maintain Canada's position as market leader in a high-tech medical enterprise.[29]

A.A. Sameh has provided us with his estimate of the cost of converting the ^{99}Mo recovery facilities at Mallinckrodt's Radiochemical Center in Petten, Netherlands. Sameh developed the patented KfK ^{99}Mo recovery process used there and directed the Radiochemical Center from 1995 to 2004. He estimates the total conversion cost at about $10 million. Most of this expenditure would be required for construction of a hot-cell facility to optimize ("polish") the LEU process at production scale and obtain test data on the product for the European and U.S. pharmaceutical licensing agencies. Use of such a hot-cell facility would be necessary to avoid shutting down and using one of the production lines for the development and certification tests.[30]

IMPACTS ON RADIOISOTOPE AND RADIOPHARMACEUTICAL COSTS

In 2005, roughly 25 million diagnostic procedures using ^{99m}Tc were conducted worldwide.[31] Roughly 40 percent of global sales were delivered by MDS-Nordion—about 10 million doses (see Table 1). Charges of $0.5–1.6 per dose would pay off a $77 million investment in the new recovery facility in 30 years, assuming 6–21 percent fixed charge rates.[32]

This estimate is consistent with that which can be derived from information about the "extraordinary price increases" MDS-Nordion reported in 2000 that its customers had agreed to accept to help it defray the cost of building the new *Maple*-reactor complex—originally estimated at $140 million.[33] This price increase has been reported as being "an initial increase of about 40%" to pay for the cost for the *Maple* reactors and the associated ^{99}Mo recovery facility. At the time, ^{99m}Tc was being used in about 10 million procedures per year worldwide, MDS-Nordion controlled about 85 percent of the market and had estimated $50 million gross earnings per year from its ^{99}Mo sales—i.e., about $5 per dose.[34] A 40 percent price increase therefore would have been in the range of $2 per dose. This price increase is roughly in the same ratio to the $140 million estimated capital cost as our estimated $0.5–1.6 per dose price increase from a $77 million processing facility.

A $1 price increase per dose of ^{99m}Tc would be somewhat more than 10 percent of the current production cost for the associated ^{99}Mo but it would be less than 2 percent of the cost of the associated diagnostic procedure. The estimated impact of the $10 million conversion cost for Mallinckrodt Radiochemical Center would be lower. This facility supplies roughly 25 percent of the global market or about 6 million doses per year (see Table 1). A price increase of $0.12–0.35 would pay off the investment in 30 years with a 6–21 percent rate of interest. This price increase would be about 2–5 percent of the production cost of the ^{99}Mo and a few tenths of a percent of the cost of the associated radiopharmaceutical.

Security Cost Savings

There could be a very large cost *saving* associated with using LEU targets—the elimination of the very high security costs associated with HEU transport and storage. It is puzzling that this factor has not been introduced into the debate at a time when the U.S. National Nuclear Security Administration (NNSA) is de-inventorying HEU-using facilities because of the associated huge post 9/11 increases in its security budget. The number of attackers (19) involved in the September 11, 2001 aircraft hijackings has required the NNSA to increase the size of the "design-basis threat" (DBT) that its guard forces are required to be prepared to defend against.

The estimated total cost per guard is $125,000 per year. For every attacker added to the design-basis threat against a facility where nuclear-weapon-useable materials are used, it would be necessary to add a guard to each of at least three posts for five shifts or a total of fifteen full-time guards. On this basis, the guard-force cost associated with a design-basis threat of 19 would be $36 million per year.[35] This dwarfs all the annual conversion charges discussed earlier.

We do not have sufficient information to make an analysis of the security cost savings that would result from conversion from HEU to LEU targets but it should be taken into account in future cost-benefit analyses such as the Congressionally mandated study by the National Academy of Sciences.

RELIABILITY OF ^{99}Mo SUPPLY

The redundancy of the ^{99}Mo supply has improved since the molybdenum-99 distribution networks have become global. If all the reactors were operating at full capacity, they could have supplied 250 percent of 2005 world demand. Taking into account the fraction of the year that each operates, they could produce on average 175 percent of 2005 world demand (see Table 1).

This excess capacity is fragile, however. In 2006, the ages of the production reactors ranged from 41 to 49 years. The *FRJ-2* shut down in 2006. If the NRU shut down, the combined production capacity of the remaining 4 reactors, if scheduled optimally, would drop to just 100 percent of world demand, which, has been increasing by 5–10 percent per year (see Table 1). It may be that some of the other reactors could increase their peak production capacities. The disciplined schedule of ^{99}Mo production can conflict, however, with other missions at multipurpose reactors. The high level of operation of the NRU, HFR, and SAFARI reactors reflect the fact that they are committed to be available to produce ^{99}Mo with only short interruptions. The other reactors currently operate as backup producers.

If the two dedicated 10 MWt *Maple* reactors come on line, they will alleviate the situation considerably. It has been proposed that Europe also build at least one new reactor dedicated to molybdenum-99 production in addition to the new multipurpose reactors that are being built.[36] In the U.S., there have been discussions of the possibility of using various Department of Energy or U.S. university reactors to provide a U.S. source of molybdenum-99 and proposals also have been made to build dedicated reactors.

Concerns about reliability of ^{99}Mo supply should not, however, be used as an argument for delaying conversion of ^{99}Mo production targets from HEU to LEU. Based on our analysis, conversion appears both technically and economically feasible.

CONCLUSIONS AND RECOMMENDATIONS

The major molybdenum-99 producers are currently using more than enough weapon-grade uranium each year to make a Hiroshima bomb. Very little of this HEU is consumed, and large stocks of weapon-grade uranium are accumulating at the associated waste-storage sites. All national governments should be concerned about this issue. The theft of HEU in any country represents a potential threat to all the cities of the world.

To date, only the U.S. government has been working seriously to persuade medical radiopharmaceutical companies around the world to convert to LEU targets. Canada's government, for example, which supplied a $100 million interest-free loan for the construction of the new *Maple* reactors and associated target processing facility[37] could have required MDS-Nordion to design the processing facility to be able to handle LEU as well as HEU targets, but did not, despite a 1997 exchange of diplomatic notes with the U.S. in which it committed to do so.[38] Now that AECL, a Canadian Crown Corporation, has bought the facilities, the Canadian government should be able to require that the facility be modified to accommodate LEU targets before it goes into production. Once the facility is in use, transitioning to LEU may become much more difficult if it is impossible to interrupt HEU-target processing for development and certification testing on LEU targets.

Europe should not repeat Canada's mistake. Euratom, the European Union's nuclear regulatory agency, should require that any new molybdenum-99-production facility in Europe be designed to use LEU targets and require peer-reviewed feasibility studies on the conversion of existing facilities. South Africa should do so as well. The costs of these initiatives would be trivial in comparison to the potential consequences of a theft of some of the HEU.

NOTES AND REFERENCES

1. Information about the Reduced Enrichment Research and Test Reactor program may be found at http://www.rertr.anl.gov.

2. "A comprehensive approach to elimination of highly enriched uranium from all nuclear-reactor fuel cycles" by Frank von Hippel, *Science & Global Security*, 12 (2004), 137; and "Global Cleanout: Reducing the Threat of HEU-Fueled Nuclear Terrorism," Alexander Glaser and Frank von Hippel, *Arms Control Today* (January/February 2006) 1–18.

3. "Production of Mo^{99} in Europe: Status and perspectives," H. Bonet, B. David, and B. Ponsard, 9th *International Topical Meeting on Research Reactor Fuel Management, Budapest, Hungary*, April 10–13, 2005, available at http://www.euronuclear.org/pdf/RRFM2005-Session1.pdf. Other fission products used in medicine are ^{131}I (8.0-day halflife), ^{133}Xe (5.2 days), and ^{89}Sr (50.5 days), "Nuclear Medicine Facility Survey, SNM 2003: Survey Reporting on 2002 Cost and Utilization" by Denise Merlino, *Journal of Nuclear Medicine Technology*, 32(*4*), (December 2004): 215.

4. Most of this ^{99}Mo comes from the decay of the short-lived fission products, ^{99}Y(1.47 seconds) and ^{99}Zr(2.2 seconds), *Evaluation and Compilation of Fission Product Yields 1993*, T. R. England and B. F. Rider, Los Alamos National Laboratory, LA-UR-94–3106, ENDF-349 (1994), http://ie.lbl.gov/fission.html

5. "Production of Mo^{99} in Europe: Status and perspectives," *op. cit.*

6. *RERTR program project execution plan*, U.S. Department of Energy, National Nuclear Security Administration, February 16, 2004, Table B5.

7. Recycling the HEU (as well as conversion to LEU) was seriously investigated at Mallinckrodt's Radiochemical Center at Petten, Netherlands around 2000, "Production of fission Mo-99 from LEU uranium silicide target materials" by A. A. Sameh, Radiochemical Center Mallinckrodt Medical, presented at *2000 Symposium on Isotope and Radiation Applications*, May 18–20, 2000, Institute of Nuclear Energy Research, Taiwan.

8. The IAEA standard for self-protection is a radiation dose of one Sievert (100 rems) per hour at a distance of one meter, *The physical protection of nuclear material and nuclear facilities*, International Atomic Energy Agency, INFCIRC/225/Rev.4. Five Sieverts is a median lethal dose. The canisters of HEU-containing waste that are shipped from Mallinckrodt's Petten facility to the Netherlands interim radioactive-waste storage facility two years after target irradiation contain 0.4 kg of HEU each and have an unshielded dose rate at one meter of 0.1 Sievert/hour, personal communication, Fred Wijtsma, Director, High-flux Reactor, Petten, Netherlands, June 1, 2006.

9. Marvin Burns, Bio-Tech Systems Inc. personal communications, December 2005.

10. "Production of Mo^{99} in Europe: Status and perspectives," *op. cit.* Years of initial operation from *Nuclear Research Reactors in the World* (IAEA, 2000).

11. Atomic Energy Act (42 U.S.C. 21 *et seq.*) Chapter 11, Section 134. Other requirements set by the Schumer Amendment are that a reactor operator can only request HEU if no LEU fuel or target suitable for use in the reactor is available and if suitable LEU fuel or targets are under development.

12. "Facts and myths concerning ^{99}Mo production with HEU and LEU targets," G. F. Vandergrift, Argonne National Laboratory, *Proceedings of the International Conference on Reduced Enrichment for Research and Test Reactors, Boston, MA, Nov. 7–10, 2005*.

13. See, e.g., *DOE Needs to Take Action to Further Reduce the Use of Weapons-Usable Uranium in Civilian Research Reactors*, U.S. Government Accountability Office report, GAO-04-807 (2004), 2.

14. "Production of Mo^{99} in Europe: Status and perspectives," *op. cit.*

15. Nuclear Regulatory Commission (NRC), "Briefing on proposed export of high enriched uranium to Canada," June 16, 1999, public hearing transcript, http://www.nrc.gov/reading-rm/doc-collections/commission/tr/1999/19990616a.html, 15. After September 11, 2001, the NRC stopped making such information public but recently, in response to a request from Alan Kuperman of the Nuclear Control Institute, made public the fact that the U.S National Security Administration had requested a license to export 15.5 kg of 93 percent enriched HEU to Canada for use in ^{99}Mo-production targets. However, the NRC refused to make public Canada's annual requirements for this purpose because the applicant considered that "proprietary information," letter to Alan Kuperman from NRC chairman Nils J. Diaz, April 26, 2006, www.nci.org/06nci/06/NRC-HEU-export-licenses-2006-Response-May-AK.PDF.

16. As of the beginning of 1993, Euratom had 13.7 tons of HEU originally exported from the U.S., *Plutonium and highly enriched uranium 1996* by David Albright, Frans Berkhout, and William Walker, (Oxford University Press, 1997), Table 8.1. Euratom

does not inform the U.S. of transfers of this material within the EU when it is no longer needed for its original purpose, such to fuel a critical facility.

17. National Energy Policy Act of 2005, Sec. 630.

18. "Bomb-grade bazaar," Alan J. Kuperman, *Bulletin of the Atomic Scientists*, (March–April 2006).

19. Total U.S. ^{99}Mo sales in 2004 were $150 million for 20 million doses of ^{99m}Tc, Marvin Burns, Bio-Tech Systems Inc. personal communications, December 2005.

20. Calculated from Table 4 of "Nuclear Medicine Facility Survey, SNM 2003: Survey Reporting on 2002 Cost and Utilization," *op. cit*. The average charge for four ^{99m}Tc-containing drugs to Medicare between July 1, 2003 and June 30, 2004 was $78 per dose, *Medicare: Radiopharmaceutical Purchase Prices for CMS Consideration in Hospital Outpatient Rate Setting*, Government Accountability Office, letter report to the Secretary of Health and Human Services, July 14, 2005, Table 1.

21. When no other reference is provided, our source is "Facts and myths concerning ^{99}Mo production with HEU and LEU targets," *op. cit.*

22. "Preliminary investigations for technology assessment of ^{99}Mo production from LEU targets," G. F. Vandegrift et al., *Proceedings of the 1986 International Conference on Reduced Enrichment for Research and Test Reactors*, Gatlinberg, Tennessee, November 3–6, 1986, Table 1.

23. One Curie (Ci) of ^{239}Pu has a mass of 16 grams.

24. Because of the difference in half-lives, 1 Ci of ^{99}Mo would produce 11 Ci of ^{99m}Tc. We assume that only 2.4 of these 11 Ci are used, however. The standard dose of ^{99m}Tc is 24 mCi ["Nuclear Medicine Facility Survey, SNM 2003: Survey Reporting on 2002 Cost and Utilization," *op. cit.*]. One dose of ^{99m}Tc would be associated with less than 1.6×10^{-16} grams of ^{239}Pu. The effective dose from inhaling this much ^{239}Pu is 2.4×10^{-11} Sieverts (Sv), "The hazard from plutonium dispersal by nuclear-warhead accidents," Steve Fetter and Frank von Hippel, *Science & Global Security 2* (1990): 21. The average effective doses from ^{99m}Tc procedures are in the range of 1–10 mSv, *Sources and Effects of Ionizing Radiation*, U.N. Scientific Committee on the Effects of Atomic Radiation (UN, 2000), Annex D, Table 42.

25. "Briefing on proposed export of high enriched uranium to Canada," July 10, 2000, Nuclear Regulatory Commission, public hearing transcript, http://www.nrc.gov/reading-rm/doc-collections/commission/tr/2000/20000710b.html

26. "Nordion headed for a showdown with the U.S.?" Daniel Horner, *Nuclear Fuel*, March 15, 2004.

27. The principal safety design problem is a positive power coefficient of reactivity, i.e., if the power increases, the reactivity increases—which further increases the power. As of November 2005, the cause of this problem was still not understood, "Application for the renewal of the operating license for the MAPLE reactors at the Chalk River Laboratories: Record of proceedings, including reasons for decision," Canadian Nuclear Safety Commission, November 24, 2005, http://www.nuclearsafety.gc.ca/eng/commission/pdf/2005-10-18-Decision-AECL-MAPLE-e.pdf.

28. "Application to continue operation of the National Research Universal (NRU) reactor beyond December 31, 2005: Record of proceedings, including reasons for decision," Canadian Nuclear Safety Commission, November 24, 2005, http://www.nuclearsafety.gc.ca/eng/commission/pdf/2005-10-18-Decision-AECL-NRU-e.pdf.

29. "AECL and MDS enter into long-term supply agreement for medical isotopes," AECL news release, February 22, 2006, http://www.aecl.ca/NewsRoom/News/Press-2006/060222.htm

30. Sameh assumed that the highly enriched UAl_3, targets used at Petten would be replaced by 20-percent enriched U_3Si_2 targets, A. A. Sameh, private communications, January 2006. If the hot cells at the Petten HFR could be use to polish the LEU process, the cost of conversion would be only perhaps $1 million.

31. "Production of Mo^{99} in Europe: Status and perspectives," *op. cit.*

32. We have used the following approximation to the mortgage formula: Annual payment = iC/[1 −exp(-iT)], where C is the cost of the facility, *i* is the interest rate, and T is the payback period in years. The range of annual fixed charge rates considered come from an analysis of spent-fuel reprocessing economics in which a 5.8 percent charge rate was obtained for a government-owned plant and 20.8 percent for a private venture, *Nuclear Wastes: Technologies for Separations and Transmutation* (National Academy Press, 1996), Table J-5.

33. NRC, "Briefing on proposed export of high enriched uranium to Canada," June 16, 1999, public hearing transcript, 15, *op. cit.* By 2003, MDS-Nordion had spent $304 million on its new ^{99}Mo production complex, *MDS Inc*, Veritas Investment Research, July 2004, 2.

34. *Evaluation of medical radionuclide production with the accelerator production of tritium (APT) facility*, Kenneth M. Spicer *et al*., Medical University of South Carolina, University of South Carolina, and Westinghouse Savannah River Co, 1997, 12, 46.

35. *U.S. Nuclear Weapons Complex: Homeland Security Opportunities*, Project on Government Oversight, May 2005, http://www.pogo.org/p/homeland/ho-050301-consolidation.html, 15. This report cites (on p. 9) a NNSA estimate that the new DBT will require adding about 100 guards around the clock at each of seven facilities.

36. "Production of Mo^{99} in Europe: Status and perspectives," *op. cit.* Germany brought the 20-MWt *FRM-II* research reactor on line in 2004 and France is constructing a new 100-MWt *Jules Horowitz* materials test reactor, which is expected to go into operation in 2014. But radioisotope production will be at most a backup mission for these reactors.

37. MDS-Nordion, *Annual Information Form for the period ending October 31, 2005*, http://www.mdsinc.com/reports/2005_engaif.pdf, 11.

38. Cited in "Bomb-grade bazaar," *op. cit.*, endnote 13.