Estimating Plutonium Production at Israel's Dimona Reactor

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Abstract

Israel has used the Dimona reactor in the Negev Desert since the 1960s for unsafeguarded plutonium production. Estimates of cumulative historic production have been very uncertain, however, because the power level of the reactor is unknown, and there is a lack of detail about the reactor design. This analysis presents new estimates of historic plutonium production in Israel based on neutronics calculations for the Dimona reactor ("EL-102"), which is based on a modified version of the French EL-3. We estimate that cumulative production of plutonium to date is 800 ± 125 kg. The paper also includes a critical review of the 1986 testimony by the Dimona technician and whistleblower Mordechai Vanunu, which provided much of the basis for public discussion of the reactor's power and operation.

Background[1]

Israel launched its nuclear weapons program in the 1950s, building a plutonium-production reactor and associated reprocessing plant with French assistance at a secret nuclear center at Dimona in the Negev Desert. The site is home as well to other weapon-related activities, including the production of tritium and possibly also of enriched uranium (Figure 1).[2]

The most detailed revelations about the technical operations at Israel's nuclear facility at Dimona were published in a front-page article in the London-based Sunday Times in October 1986. That article was based on information supplied by Mordechai Vanunu, who was employed as a technician at Dimona from November 1976 until October 1985. Vanunu worked in various areas of the Dimona facility, in particular, where the irradiated fuel elements from the Dimona reactor are reprocessed to extract the contained plutonium, and where lithium is enriched in the isotope Li-6 in order to produce tritium via neutron irradiation of rods of Li-6 that are inserted into the core of the reactor and subsequently processed to extract tritium. Besides his notes about the operations at Dimona, Vanunu left Israel in January 1986 with about 60 color photographs that he had secretly taken within the facility, including models of weapons components. Some of the information that he revealed to the individuals who debriefed him in London, notably the journalist Peter Houman and his associates at the Sunday

Figure 1: Map of the Dimona site and reported designations and purposes of separate units. Based on drawings published in a 1961 U.S. government memo and in a 1989 book on the arms race in the Middle East.

Times, and the British scientist, Frank Barnaby, as well as a selection of the pictures, appeared in the article. More details from Vanunu's notes, as well as the complete set of pictures soon began to circulate, however, and these became the subject of intense scrutiny and speculation among both weapons experts and others who share a strong interest in Israel's nuclear activities.

Vanunu's data and subsequent analyses of it as well as new neutronics calculations for the reactor are the basis for this assessment of Israel's plutonium production. Vanunu also claimed that Israel was using lasers and centrifuges to enrich uranium at Dimona. Although he didn't have access to the areas of the plant where these activities were supposedly taking place, and thus couldn't supply further details, Israel's demonstrated expertise and interest in these technologies lend credence to Vanunu's claim. In addition to its potential use in nuclear weapons, Israel could have used enriched uranium to increase its production of tritium. Israel's need to offset the decay of its stock of tritium may help explain the continued operation of the Dimona reactor. For these reasons, the production of tritium and the possible production of enriched uranium are discussed briefly in the following.

Plutonium Production

The primary source of public information about French assistance to Israel in the construction of a plutonium production reactor and an associated reprocessing plant is Pierre Péan's book, *Les Deux Bombes.*[3] Péan notes that the reactor was of the EL-3 type, a heavy-water moderated and cooled research reactor that started operating at Saclay in 1957.[4] However, while the EL-3 was designed to achieve a high neutron flux for materials testing and used slightly enriched uranium fuel, the Dimona reactor—also designated EL-102—uses natural uranium and was designed to maximize plutonium production. An attractive feature of the EL-3 in this regard was that its design permitted a significant increase of the reactor power with a concomitant increase in plutonium production rate.[5]

While Péan's book was published in 1982, the fact that the Dimona reactor was patterned after the EL-3 had already been disclosed by the director of Dimona, Manes Pratt, to two American scientists, U. M. Staebler and J. W. Croach, Jr., during their one-day visit to the site in May 1961.[6] Specifically, Pratt told these visitors that the reactor design "is very much influenced by the French EL-3;" that the design calculations were done by the French, and that "natural uranium was selected as fuel for the reactor because of a desire to be able to produce as much as possible within their own borders." Pratt also gave them a summary of the reactor design parameters including the fact that there were three coolant loops, each of 13 MWt thermal capacity, which indicated that the reactor could operate at a power of 40 MWt instead of the specified 24–26 MWt.[7]

According to unnamed U.S. officials, the thermal power of the Dimona reactor was probably increased from about 40 MWt shortly after it went critical in December 1963 to about 70 MWt prior to 1977 when Vanunu began working at Dimona. This is consistent with Péan's information about the size of the cooling ducts and consistent with a statement attributed to Vanunu by Barnaby, which also claims that the reactor power was further increased "presumably to about 150 MWt" prior to his arrival.[8] The latter claim in turn is in rough agreement with an internally consistent set of data that Vanunu provided; namely, that (a) the ratio of plutonium to uranium in the dissolved fuel in the reprocessing plant was 0.0004;[9] (b) 36 kg of plutonium was extracted from the spent nuclear fuel per year,[10] and (c) about 10% of the plutonium contained in the metallic "buttons" was lost in weapon fabrication, but subsequently recovered and recycled back into buttons.[11]

The plutonium-uranium ratio implies a fuel discharge fuel burnup of about 450 MWd/ton. According to neutronics calculations, the effective plutonium production rate of this reactor is 0.96 grams per MWd for this fuel burnup (Figure 2).[12] Then, with 270 days/yr of operation, a plutonium production of 36 kg/yr from the spent fuel implies a reactor power of about 140 MWt,[13] i.e., somewhat lower but close to the value attributed to Vanunu. A power level of 140 MWt is used in the following

as a hypothetical maximum power level of the reactor. Such a large upgrade in reactor power from 40 MWt eventually to 140 MWt has been questioned on the grounds that it would require major modifications of the reactor itself as well as the associated heat exchangers and cooling towers. In addition, for a fixed burnup of the fuel, i.e., for a given amount of energy (and plutonium) produced per mass of fuel, increasing the reactor power requires a proportional increase in fuel throughput. Reportedly, the original design of the EL-102 had an inventory of about 8 tons of uranium.[14]

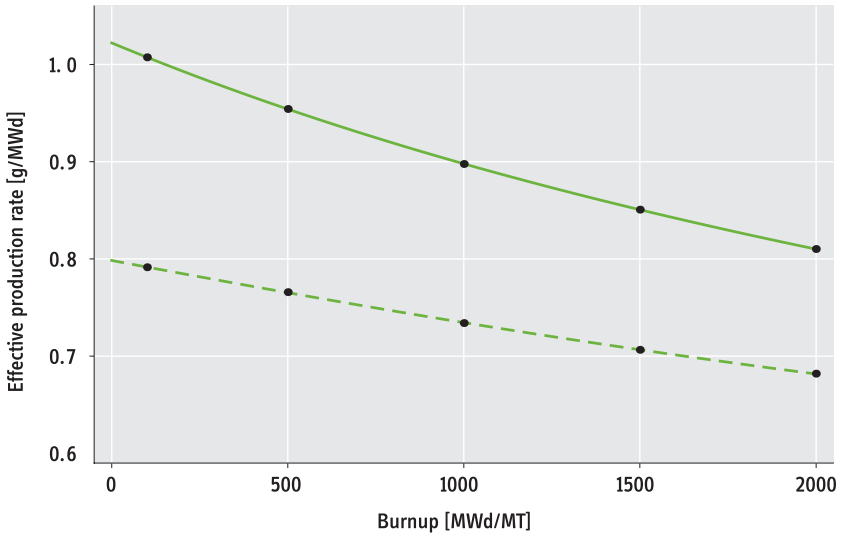

Figure 2: Effective plutonium production rate in Dimona ("EL-102"), a modified version of the French EL-3, using natural uranium (solid line) and slightly enriched uranium (1.0% U-235, dashed line). The use of slightly enriched uranium would increase the capability to produce tritium in the reactor while reducing the plutonium-production rate by about 20%.

A reactor operated at 40 MWt for 270 days per year with an average fuel burnup of 450 MWd/ton would require 24 tons of fuel per year.[15] This is consistent with three annual core reloads and a 90-day exposure in the reactor.[16] One way to increase the power while maintaining the 90-day reloading schedule would be to increase the uranium inventory in the reactor. The design of the EL-102 could permit roughly a doubling of the fuel inventory to 40–45 tons without increasing the diameter of the vessel, consistent with a power up-rate to 70 MW. Beyond that, however, either the reactor vessel might have to be enlarged to accommodate still more fuel in the core, or the power per ton of uranium in the fuel—and therefore also the refueling rate—would have to be increased.[17]

Finally, higher power would also require a greater capacity to transfer heat from the fuel through the heat exchangers for release to the environment via the two cooling towers. These cooling towers are clearly visible and appear unchanged in satellite photos of the Dimona site taken since the 1970s. Indeed, the fact that no additional cooling towers are visible in the later image is often cited as evidence that the reactor power had not

been increased significantly during this period. However, both the heat exchanger and cooling-tower internals could have been upgraded, or an alternative cooling system may have been installed.

Nevertheless, doubts that the reactor power was upgraded to about 140 MWt persist, and several explanations of why the output of the reprocessing plant cited by Vanunu may not be an accurate indicator of the power level of the reactor have been suggested. One frequently cited explanation is that the plutonium production of about 36 kg/yr from spent fuel represents the surge-capacity of the reprocessing plant, i.e., the capacity when it was operated to process a backlog of irradiated fuel created by an extended shutdown of the plant, and that the steady-state production rate matches the assumed 70 MWt power level of the reactor during the period when Vanunu worked at Dimona. This scenario cannot fully explain, however, operation at such high throughput for the entire 8-year period that Vanunu worked there.

A plausible rationale for an increase in reactor power from 40 MW to 70 MW and possibly 140 MW during the 1970s and a subsequent decrease in power in the 1980s and 1990s is that, after the 1973 Yom Kippur war, Israel embarked on a major upgrade of the size and quality of its nuclear arsenal.[18] In particular, research and development was conducted on both two-stage thermonuclear nuclear weapons and battlefield weapons, e.g., nuclear artillery shells. However, while it is believed that the thermonuclear weapons have been incorporated into the arsenal, Israel apparently decided in the early 1980s not to produce and deploy battlefield nuclear weapons, and therefore reduced the production of plutonium while maintaining the level of tritium production required for thermonuclear weapons. If the Dimona reactor is operated today primarily for tritium production, Israel could be reprocessing its spent fuel and separating the plutonium, but not using it to make weapons.

Figure 3 illustrates various scenarios for the historic power level of the Dimona reactor. These scenarios can be used to estimate cumulative plutonium production in Dimona. As of 2010, the value could be as low as 465 kg if the reactor power never exceeded 40 MWt. This Scenario A is considered highly unlikely. The remaining four scenarios yield a total plutonium production of 800 $\pm$ 125 kg. Scenarios B, D, and E reflect various possibilities for reductions of reactor power starting in the 1980s. Evidence for such reductions might be obtained from historic satellite imagery of the cooling towers.

In the next two sections, we discuss briefly the production of tritium by neutron irradiation of lithium-6 (Li-6) targets in the Dimona reactor, as well as the possible production or acquisition of enriched uranium, which could be used to increase tritium production while decreasing the production of plutonium.[19] Indeed, the primary mission of the Dimona reactor today may be to satisfy Israel's continued need for tritium rather than to add to the existing plutonium stockpile. Overall, we find that the impact of using slightly enriched fuel at the conjectured levels, on the order of 1%, on plutonium production is well within the error margins specified here.

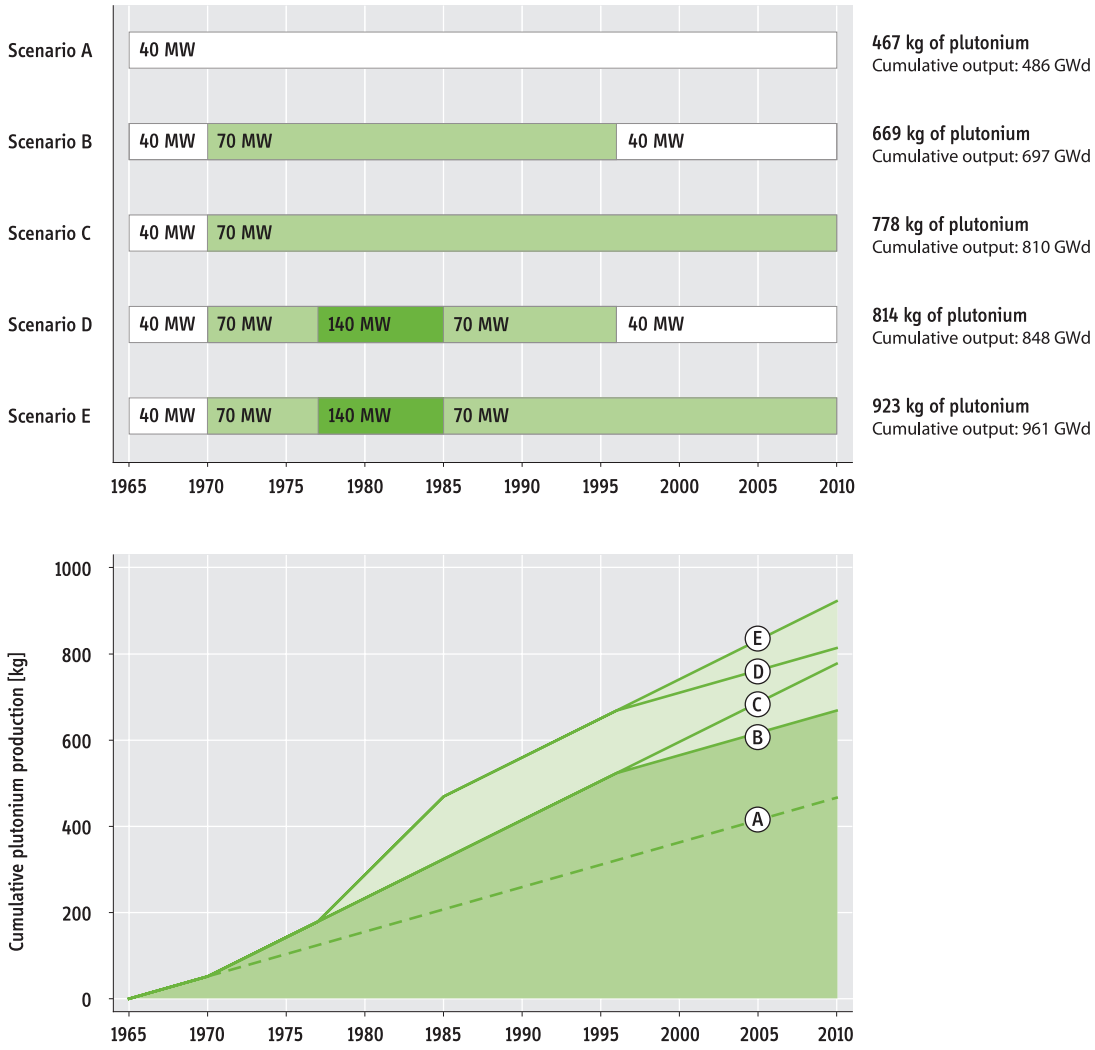

Figure 3: Scenarios of Dimona's historic power level, 1965–2010. The historic power level of the reactor is unknown, but an uprate to 70 MW by 1970 has been widely reported. A second power uprate may have occurred in the mid-1970s and would explain some observations made by Vanunu. Based on this information, five different scenarios are considered and illustrated above. Assuming a capacity factor of about 75% (270 effective full-power days per year), these scenarios can be used to estimate the total energy release (in GW-days thermal) and thereby the cumulative plutonium production at Dimona. Not including Scenario A, our estimate as of 2010 is about 800 $\pm$ 125 kg. If Dimona's power level never exceeded 40 MWt, cumulative plutonium production would be about 500 kg.

Production of Lithium-6 and Tritium

The lithium isotope, lithium-6 (Li-6), which constitutes about 7.5% of natural lithium, is utilized for two purposes in nuclear-weapon production: first, to produce tritium via neutron irradiation in a reactor for "boosting" the yield of a fission "primary" in a nuclear weapon and, second, as a source of fusion material in the "secondary" of a thermo-nuclear weapon, where it is combined with deuterium to produce lithium-6 deuteride.

According to Vanunu, in 1977, Israel built a pilot plant at Dimona to enrich Li-6 from its concentration of 7.5% in natural lithium to about 85%.[20] The product Li-6 was subsequently alloyed with aluminum and fashioned into small rods that were inserted into the core of the reactor. If all of this Li-6 was devoted to tritium production, about 40 kg of tritium could have been produced.[21] Assuming, rather arbitrarily, that: (1) Israel has about 100 weapons; (2) half of them are boosted; (3) they require a minimum of 4 grams of tritium to operate; and (4) the design life of the weapon before the need for replenishing the tritium is 12 years (i.e., one tritium half-life), then the initial tritium inventory for these 50 boosted weapons would be about $50 \times 4 \times 2 = 400$ grams, and the refueling requirement in the steady state would be about 20 g/yr.

Although tritium on a large scale, i.e., kilograms to tens of kilograms, has usually been produced in reactors dedicated to that purpose, smaller amounts can be produced by inserting Li-6 targets and/or substituting Li-6 for boron control rods in the core of reactors whose main purpose is the production of electricity or plutonium. To get a rough estimate of the capability of the Dimona reactor to produce tritium in this manner, it is assumed that small concentrations of lithium-6 can be added to the semi-permanent aluminum-sleeves enclosing the fuel rods in the Dimona reactor's core. Computer simulations show that up to 0.5 grams of lithium-6 can be loaded for every kilogram of uranium in the reactor, while still achieving the target burnup of 450 MWd/ton without loss of criticality and therefore without negatively affecting plutonium production in the reactor. Assuming a power level of 70 MWt and 270 effective full-power days per year, about 14 grams of tritium could be produced in this way per year. A more effective production strategy using dedicated lithium-rods might be able to increase this production rate to about 20 g/yr. The rate could be increased further with the use of slightly enriched fuel if a reduced plutonium production rate is accepted.

Production of Enriched Uranium

According to Vanunu, the production of enriched uranium at Dimona using gas centrifuges and lasers started in 1979 or 1980 and 1981, respectively. Supporting evidence for Israel's interest in centrifuges comes from centrifuge pioneer Gernot Zippe who revealed that, in the mid-1960s, he was persuaded to meet with Israeli scientists and

security agents who wanted information about centrifuge equipment suppliers, ostensibly to prevent acquisition of the technology by states hostile to Israel.[22] Zippe came to believe, however, that the requested information was for a centrifuge program of their own. By contrast with the secrecy surrounding the alleged centrifuge operation, Israeli research at Dimona on atomic vapor laser isotope separation was publicly acknowledged, although as in the case of centrifuge enrichment, there is no public information to support Vanunu's claim of the operation of a production plant.

Another possible source of enriched uranium was NUMEC, a nuclear fuel facility in the United States near Pittsburgh. The allegation that hundreds of kilograms of weapon-grade uranium were secretly transferred from the NUMEC plant to Israel in the 1960s, with the cooperation of the plant's owner, Zalman Shapiro, has been the subject of intense investigation and speculation.[23] Besides being used directly in weapons, the enriched uranium could have been blended with natural or depleted uranium and used in the Dimona reactor to increase the production of tritium, as noted above, or to decrease the amount of fresh fuel required for operating the reactor.

The use of enriched instead of natural uranium to increase tritium production would cause a decrease in the production of plutonium by about 30%, which can be estimated from the reduced production rate of about 0.77 g/MWd for fuel enriched to 1% compared to 0.96 g/MWd for natural uranium (Figure 1).[24] This might be the favored mode of operation if the goal was to maintain the tritium inventory for the existing stockpile rather than to produce plutonium for more weapons. Enriched uranium could also be used for blending with irradiated and slightly depleted uranium so that it can be recycled back into the reactor.[25]

Conclusion

Israel neither affirms nor denies its possession of nuclear weapons; indeed, beyond the existence of the Dimona reactor, the government refuses to disclose any information about its unsafeguarded nuclear activities. Thus, despite the revelations of Mordechai Vanunu, there remain large uncertainties in independent estimates of Israel's inventory and its current rate of production of plutonium and tritium for weapons. As of 2010, Israel is estimated to have produced a total of 800 $\pm$ 125 kg of weapon plutonium. If all this plutonium has been incorporated into weapons, it would be equivalent to about 160 weapons, assuming that each weapon contains 5 kg of plutonium.

The fact that other analyses of Israel's plutonium production have led to similar estimates of its weapons stockpile[26] has led to the conjecture that Israel already has enough plutonium to satisfy its national security needs, and could adhere to a fissile material cutoff treaty (FMCT), even while continuing to operate the Dimona reactor to produce tritium, which has a 12-year half-life and must be replenished regularly in weapons. Indeed, tritium production isn't banned under an FMCT, and the fact that

plutonium isn't being separated from the spent fuel in the existing reactor or in a separate dedicated tritium production reactor or accelerator could be verified remotely, e.g., by the absence of Kr-85 emissions.

Israel's principal official objection to an FMCT is that it would allow uranium enrichment and plutonium production, albeit under safeguards, in other states of the region. However, it would also object to other arrangements that ban any uranium enrichment or reprocessing in the Middle East, but allow it to continue to produce tritium because the latter would be incompatible with the pretense that Israel isn't a nuclear weapon state.

Endnotes

[1]An earlier but more extensively referenced version of this article appeared in *Global Fissile Material Report 2010: Balancing the Books,* International Panel on Fissile Materials, December 2010, www.ipfmlibrary.org/gfmr10.pdf.

[2]We focus in the following on plutonium production; for additional details, see *Global Fissile Material Report 2010, op. cit.* The map is based on drawings published in U. M. Staebler and J. W. Crouch, Jr., *Notes on Visit to Israel,* Draft, 23 May 1961, available at www.gwu.edu/~nsarchiv/israel/documents/first, mirrored at www.ipfmlibrary.org/sta61.pdf, and Frank Barnaby, *The Invisible Bomb,* I. B. Tauris, London, 1989., Appendix III, p. 213.

[3]Pierre Péan, *Les Deux Bombes,* Fayard, Paris, 1982.

[4]For a detailed description of the EL-3, see G. B. Melese, "France's New High-Flux Research Reactor," *Nuclear Engineering,* 3 (24), March 1958, pp. 115–120; and: J. Robert, J. Hainzelin, and V. Raievski, "The EL-3 Reactor," A/CONF. 15/P/335 Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958, www.ipfmlibrary.org/rob58.pdf.

[5]G. B. Melese, *op. cit.,* p. 115.

[6]U. M. Staebler and J. W. Crouch, Jr., *op. cit.*

[7]To this date, the IAEA lists the Dimona reactor (IRR-2) with a power level of 26 MWt.

[8]Barnaby, *op. cit.,* p. 28.

[9]Transcripts, unpublished, "Unit 14: Here the fluid is concentrated to 450 grams/litre of uranium with 170/180 mgms/litre of plutonium."

[10]Transcripts, *op. cit.,* The net production rate of 36 kg/yr at Dimona can be computed as follows: the reprocessing plant operates nonstop for 242 days per year. The flow rate in one particular section of the plant (Unit 14) averages 35 liters per hour, and the process solution contains 170–180 milligrams of plutonium per liter. This yields 34.6–36.6 kg/yr or about 35.6 kg/yr on average.

[11]Vanunu did not state explicitly that there was a loss of about 10% to scrap, but this figure is consistent with a plutonium extraction rate from the spent fuel of 36 kg/yr and a button production

rate of 40 kg/yr cited in Barnaby, *op. cit.,* p. 31. The button production rate of 40 kg/yr can also be inferred from the Transcripts, *op. cit.:* accordingly, 9 buttons are fabricated per week during 8 months per year (242 days, 34.6 weeks), each button containing 130 grams of plutonium. This corresponds to a button production rate of 40.45 kg/yr. The transcripts incorrectly compute a rate of 32 kg/yr from this data.

[12]More precisely, in our simulations, a plutonium-uranium ratio of 0.0004 corresponds to a burnup of 415 MWd/ton, see *Global Fissile Material Report 2010, op. cit.*, Appendix B.

[13](36 kg)/(0.00096 kg/MWd × 270 d) = 138.9 MW.

[14]U. M. Staebler and J. W. Crouch, 1961, *op. cit.*

[15](40 MW x 270 d)/(450 MWd/ton) = 24 tons.

[16]Both the transcripts and Barnaby, *op. cit.,* specify an in-core residence time of "three months."

[17]Increasing the refueling rate appears more realistic, but would be inconsistent with Vanunu's observation that the fuel remains in the reactor for three months. One possibility is that the fuel was shipped to the reprocessing plant only every 90 days, but was unloaded from the reactor more frequently, e.g., every 45 days for the 140 MW scenario.

[18]Avner Cohen, *The Worst Kept Secret: Israel's Bargain with the Bomb,* Columbia University Press, 2010, pp. 81–84.

[19]Additional information about these operations as well as a discussion of the possible production of tritium by stripping it from the reactor heavy water moderator/coolant can be found in *Global Fissile Material Report 2010, op. cit.*

[20]See Barnaby, *op. cit.,* pp. 38–40.

[21]This assumes that only about 50% of the lithium (85 kg) can be transmuted into tritium due to the loss of structural integrity beyond that point of the Li-6 targets due to gas pressure. Note that 85 kg of lithium-6 when fully converted via Li-6 + n → He-4 + T would result in the production about 42.6 kg of tritium because, per atom, tritium weighs half as much al Li-6. See, e.g., Warren Stern, *Nuclear Weapons Material Control: Verification of Tritium Production Limitations,* Master's Thesis, MIT Department of Nuclear Engineering, January 1988, p. 53.

[22]Stephanie Cooke, *In Mortal Hands: A Cautionary History of the Nuclear Age,* Bloomsbury, 2009, pp. 231–232.

[23]For a recent discussion, see Victor Gilinsky and Roger J. Mattson, "Revisiting the NUMEC affair," *Bulletin of the Atomic Scientists,* March/April 2010.

[24]For example, plutonium production at 70 MWt would drop from 18.1 kg to 14.5 kg per year.

[25]The reprocessed uranium from irradiation of natural uranium fuel contains about 0.66% U-235 instead of the 0.72% in natural uranium, which is still sufficient for operation at the desired fuel burnup. Recycling uranium a second or third time, however, may require blending with enriched uranium.

[26]See Cohen, *op. cit.,* Table 1, p.xxvii.