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Plutonium and Tritium Production in Israel's Dimona Reactor, 1964–2020

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ABSTRACT

Since the early 1960s, Israel has used the Dimona reactor in the Negev Desert for unsafeguarded plutonium production. Estimates of cumulative plutonium 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. As of December 2020, we estimate that the cumulative production of plutonium is 830 ± 100 kg. Israel continues to operate the Dimona reactor today, possibly to offset the decay of its stock of tritium. For these reasons, the production of tritium and the possible production of enriched uranium are also briefly discussed. Calculations suggest that the reactor could make on the order of 50–60 grams of tritium and support an arsenal of about one hundred advanced nuclear weapons. 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.

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Background

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.[1] The site is also home to other weapon-related activities, including the production of tritium and possibly of enriched uranium.

The most detailed revelations about the technical operations at Israel's nuclear facility at Dimona were first published in a front-page article in the London-based *Sunday Times* in October 1986.[2] 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, including, where the

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Figure 1. Two of the pictures taken by Vanunu inside Dimona in September 1985, showing mockup bomb components (left) and a control room of the Dimona plant (right). Vanunu shared these photos, along with his notes about the operation of the facility, with reporters for the London *Sunday Times*. A front-page story based on this information was published on October 5, 1986. By that time, Vanunu had already been kidnapped by Israeli intelligence agents and taken to Israel where he was tried in secret and sentenced to 18 years in prison. Source: Authors' archive via Frank Barnaby.

irradiated fuel elements from the Dimona reactor are reprocessed to extract the contained plutonium, and where lithium is enriched to produce tritium via neutron irradiation of dedicated target rods placed in the reactor. Vanunu left Israel in January 1986 with his notes about operations at Dimona and about sixty color photographs that he had secretly taken on two consecutive nights in the facility in September 1985 (Figure 1). 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 Times*, and the British scientist Frank Barnaby, as well as a selection of the pictures, appeared in the article.[3] More details from Vanunu's notes, as well as the complete set of pictures, soon began to circulate, and these became the subject of intense scrutiny and speculation among both weapons experts and others who shared an interest in Israel's nuclear activities.[4]

Today, there is broad agreement that the information Vanunu provided on the activities underway at Dimona between 1977 and 1985 was genuine and consistent. Unfortunately, multiple values for the reactor power and plutonium production rates have been quoted since. Most of these estimates were based on back-of-the-envelope calculations made by the authors contributing to the *Sunday Times* article. No attempts were made at the time to estimate tritium production rates at Dimona.

In the following discussion, we first develop an understanding of the situation at Dimona up until 1986, when Vanunu ended his stay at Dimona, followed by a discussion of possible scenarios since then. In particular, we seek to revise and update estimates for production rates and related characteristics of the reactor (including fuel enrichment and power

level) at the time of Vanunu's departure. New neutronics calculations enable a more complete analysis of Vanunu's data, resolve some inconsistencies in earlier reporting, and offer better estimates of historic and ongoing plutonium and tritium production at Israel's Dimona reactor.

Reactor model and neutronics calculations

An early source of public information about the design of the Dimona reactor is Pierre Péan's book, *Les Deux Bombes,* first published in 1982.[5] Péan's book not only drew attention to the fact that France provided extensive assistance to Israel in the construction of a plutonium production reactor and an associated reprocessing plant; it also noted that the reactor was of the EL-3 type, a heavy-water moderated and cooled research reactor that started operating at Saclay in 1957.[6] 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—designated EL-102 by the French—originally used natural uranium and was optimized for plutonium production.

Additional design specifications of the original Dimona reactor were later publicly released when the United States declassified reports on its inspections of Dimona in the early 1960s. One of these reports, *Notes on Visit to Israel*, a fourteen-page draft document from 1961 by Ulysses M. Staebler and Jesse W. Croach, Jr., has been the main source of information for the development of the reactor model used for this analysis.[7] The report lists, among some other relevant information, the dimensions of the fuel rod, the lattice spacing (pitch), the number of available grid positions, and the size of the reactor vessel or calandria (Figure 2 and Table 1).[8]

With the data from the 1961 U.S. document, one can estimate the total in-core uranium inventory of Dimona to about 8.5 metric tons. We considered this inventory and the quoted rod diameter (3.56 cm) as a basis for the original design of the Dimona reactor.[9] As we will see below, based on other information provided by Vanunu, one can infer a uranium inventory that must be about twice as high at the time when Vanunu was there (1977–1985). Assuming that it is not possible to simply add additional fuel assemblies in a reactor vessel of a given size, increasing the diameter of the fuel rods appears as the most straightforward way to increase the uranium inventory assuming that the fuel centerline temperature and other thermal-hydraulic constraints can be managed. In fact, Vanunu mentions a uranium-rod diameter of "two inches" in contrast to the 3.56 cm listed in the U.S. document. This difference would almost exactly double the uranium inventory. We therefore also examine such a modified design, which may have been adopted at some point when Israel sought to increase plutonium

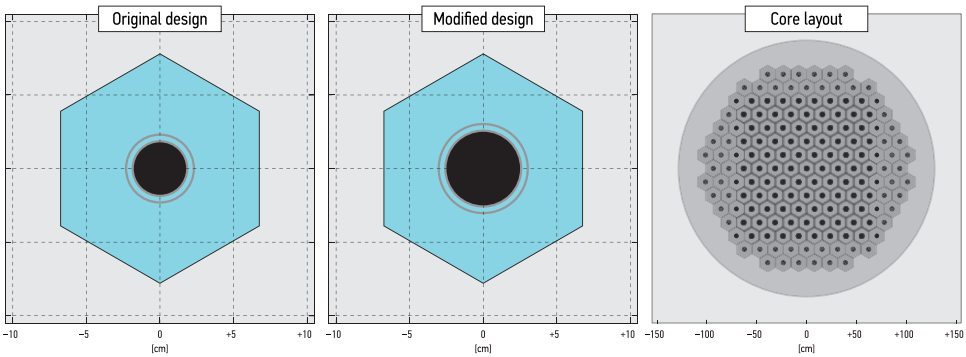

Figure 2. Original and modified unit cells of the Dimona reactor and possible core configuration. The uranium rod (shown in black) is centered in a hexagonal lattice; heavy water (shown in blue) is used for moderation and cooling. The original design shown on the left is based on the 1961 U.S. report, and the respective uranium inventory in the core is on the order of 8.5 metric tons; the modified design can accommodate almost 17.0 tons in the same vessel. The core configuration shown on the right has 163 assemblies, but up to 180 grid positions are available in the vessel. See table below for numerical values.

Table 1. Selected parameters relevant for a model of the Dimona reactor.

	Original design	Modified design
Uranium rod diameter	3.56 cm	5.00 cm
Cladding thickness	1.5 mm	
Fueled length	250 cm	
Lattice spacing	13.5 cm	
Number of elements in core	166–180	
Calandria diameter	257 cm	
Maximum uranium inventory	8,500 kg	16,800 kg

The parameters of the original design are based on values reported in a 1961 report by U.S. inspectors of the Dimona site.[7] The modified design essentially doubles the uranium inventory by using a fuel rod with a larger diameter based on Vanunu's observation that the fuel rods are "two inches" in diameter.

production. This modified design is shown in Figure 2 and included in Table 1.

To estimate plutonium and tritium production at Dimona, we have modeled and simulated the reactor with ONIX,[10] which couples the open-source Monte Carlo transport code OpenMC[11] with a depletion module to provide a full reactor-physics package. Figure 2 shows the unit cells of the original and the modified design used for all infinite-lattice simulations. Simulations for a range of power densities produced essentially identical results. We, therefore, used a constant value of 10 kilowatts per liter (of total unit-cell volume) for all cases studied below. Each calculation involved multiple Monte Carlo simulations with one million neutrons per cycle to compute neutron flux and reaction rates with minimal relative errors. Cross-sections, fission yields, and decay data are based on ENDF/B-VIII.0 nuclear libraries.[12]

This analysis focuses on neutronics calculations only. A separate analysis would be required to confirm that thermal-hydraulic constraints

can also be met, especially for those cases that consider the use of a fuel rod with a larger diameter combined with higher power levels of the reactor.

Plutonium production

Plutonium production in a reactor is primarily determined by the uranium enrichment of the fuel and the type and thermal power of the reactor. An attractive feature of the EL-3 in this regard was that its design permitted a significant increase of the reactor power with a respective increase in plutonium production.[13] When 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 U.S. inspectors during their one-day visit to the site in May 1961. 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." In addition to the summary of the reactor design parameters (summarized in Table 1), Pratt also confirmed that there were three coolant loops, each of 13 MW thermal capacity, which indicated that the reactor could operate at a power of about 40 MW (3×13 MW) instead of the specified 26 MW,[14] which are still listed in the IAEA database today.[15] In the following, we assume that Dimona never operated at a power level below 39–40 MW thermal.

For the production scenarios proposed below, we consider three distinct phases up until 1986, during which the mission of the reactor gradually expanded. Each of these original phases is characterized by specific design modifications and operational characteristics of Dimona. A summary estimating cumulative plutonium production at Dimona follows in a separate section toward the end.

Note that we explored numerous fuel options and operational parameters throughout this study, but only present those options here that we believe are most viable or plausible for each of the phases; in particular, all options have appropriate reactivity margins. The rationale for some choices, such as refueling rates and discharge burnup, will only become clearer once Vanunu's testimony is fully considered in Phase 3.

Phase 1: the early years (c. 1964–1970)

We assume that the reactor started up with a power level of 39–40 MW and the original fuel design based on natural uranium. Assuming that the reactor can be operated for 270 effective full-power days per year, the total

Table 2. Performance characteristics of different fuel designs and modes of operation.

	Phase 1	Phase 2	Phase 3
Rod diameter	3.56 cm	5.00 cm	5.00 cm
Enrichment level of fuel	0.71%	0.95%	1.50%
Lithium-6 loading	—	—	23 mg/kg
Target plutonium concentration	0.39 g(Pu)/kg(U)	0.39 g(Pu)/kg(U)	0.39 g(Pu)/kg(U)
Discharge burnup (ONIX)	396 MWd/t	375 MWd/t	454 MWd/t
Net plutonium production rate	0.98 g/MWd	1.04 g/MWd	0.86 g/MWd
Reactor power	39 MW	71 MW	86 MW
Energy release (270 EFPDs)	10,530 MWd	19,230 MWd	23,280 MWd
Uranium inventory	8,900 kg	17,100 kg	17,100 kg
Total plutonium production	10.3 kg/yr	20.0 kg/yr	20.0 kg/yr

We assume that the target plutonium concentration in the fuel is 0.39 g(Pu)/kg(U) for all cases. With this information and combined with ONIX calculations, we can determine discharge burnups, reactor powers, in-core uranium inventories, and total plutonium production rates that are consistent with Vanunu's observations and other information available about Dimona.

energy released is then at least 10,530 MWd. A typical discharge burnup could be on the order of 400–1,000 MWd/t, which is equivalent to a total uranium throughput of about 27 tons per year for the low-burnup case.[16] Based on the nominal uranium in-core inventory of about 8.5–9.0 tons (Table 1), this would require three refuelings per year. In other words, each batch of fuel remains in the core for a total of three months (90 days), leaving one month to discharge, refuel, and restart the reactor. As we will see below, these values (i.e., the discharge burnup of 400 MWd/t and the refueling frequency) are consistent with observations made by Vanunu later on. ONIX calculations show that total plutonium production for this set of parameters is on the order of 10 kg per year (Table 2, Phase 1).

Phase 2: accelerating production (c. 1971–1976)

In a second phase, Israel apparently made an effort to accelerate plutonium production beyond the original target value of about 10 kg per year. To do so, the reactor power would have to be increased. In fact, according to unnamed U.S. government specialists, the thermal power of the Dimona reactor was probably raised from 40 MW to about 70 MW thermal sometime in the early 1970s.[17] Here, we assume that Israel did not want to increase the refueling rate, i.e., for practical reasons, the operators wanted to maintain three-month irradiation cycles. Under this constraint, one option to operate the reactor at higher power would be to increase the discharge burnup of the fuel. Based on information from Vanunu's testimony, however, this is apparently not the strategy Israel decided to pursue; even in the 1980s, the discharge burnup of the fuel was remarkably low, producing weapon-grade or even super-grade plutonium.

The only other option is then to increase the in-core uranium inventory. As discussed above, we assume that increasing the diameter of the fuel rod

(e.g., from 3.56 cm to 5.00 cm) is the most straightforward way to do so given that other modifications of an existing reactor would be more difficult or impossible at that point. ONIX simulations show, however, that the modified fuel geometry illustrated in Figure 2 is no longer viable for use with natural uranium and requires slightly enriched fuel instead. Our calculations for this modified design suggest an enrichment level of 0.95% to guarantee a similar reactivity margin. The larger rod size and the lower deuterium to heavy metal (D/HM) ratio lead to significant changes in the neutron spectrum and the effective cross-sections of relevant uranium and plutonium isotopes. Surprisingly, despite the higher uranium-235 content in the fuel, the plutonium production rate remains very high and, in fact, is slightly greater than the original rate (Table 2, Phase 2). Specifically, increasing the reactor power from 39 MW to 71 MW thermal would almost exactly double the plutonium production rate to 20.0 kg per year for this phase of Dimona's history.

Phase 3: upgrading the arsenal (c. 1977–1986)

Finally, a possible third phase coincides with Vanunu's presence at the plant. Respective operations and processes are discussed in great detail in the Vanunu transcripts that were produced as part of the research for the *Sunday Times* article. Importantly, at that time and as reported by Vanunu, Israel had also begun tritium production at Dimona. A plausible rationale for these new activities is that, after the 1973 Yom Kippur War, Israel began to embark on a major upgrade of the size and quality of its nuclear arsenal.[18] In particular, research and development were conducted on both two-stage thermonuclear nuclear weapons and battlefield weapons, including miniaturized nuclear artillery shells. Boosting with tritium is key to both types of weapons. One or more possible nuclear weapon tests in the South Atlantic in September 1979 (Vela Alert 747)[19] would be consistent with such an effort to develop more sophisticated weapon types. Vanunu's time at the plant falls into this time period of maximum urgency and ambition.

The production of tritium, discussed in more detail below, involves the exposure of dedicated lithium targets in the reactor. These targets absorb neutrons and therefore require an additional reactivity margin, which can be provided by a higher uranium-235 content in the fuel. We have explored enrichment levels of up to 2.0%, but it appears that an enrichment of about 1.5% is sufficient to enable concurrent plutonium and tritium production at Dimona (Table 2, Phase 3). In fact, based on Vanunu's testimony, this is the scenario we have the most detailed information about. As

an example, it is discussed in slightly more detail here—also to support other assumptions made so far.

The transcripts describe, in particular, the purpose and technical parameters of each unit of the reprocessing plant ("Machon 2") located underground, next to the reactor. For our purposes, the following quote is the most relevant one:

> *"UNIT 14: Here the fluid is concentrated to 450 grams/litre of uranium with 170/180 mgms/litre of plutonium. It is then sent to Unit 15. Here the flow rate is at 150/175 per cent of standard production — 20.9 litres/hour.*

The nominal flow rate can be used directly to determine the annual plutonium production at Dimona at the time. Vanunu states that the reprocessing plant routinely shut down for maintenance during a four-month maintenance period from July through October each year. That leaves a total of 242 days of operation per year. The transcripts also suggest that the facility was operated continuously ("around the clock"); in fact, at least for some time, Vanunu was working the night shift from 11:30 p.m. to 8:00 a.m. With these assumptions, the annual plutonium production can be estimated to:

$$(0.175\ \mathrm{g/l}) \times (20.9\ \mathrm{l/hr}) \times (24\ \mathrm{hr/day}) \times (242\ \mathrm{days/yr}) \approx 21.2\ \mathrm{kg/yr}$$

For simplicity and allowing for some interruptions, in the following, we assume the nominal production rate was 20 kg per year during Vanunu's time at the site, i.e., the same it was in the previous phase but now achieved while also making tritium in the reactor.

Based on Vanunu's quote, we also can specify the plutonium concentration in the uranium fuel upon discharge:

$$0.175\ \mathrm{g(Pu)}/0.45\ \mathrm{kg(U)} \approx 0.39\ \mathrm{g(Pu)/kg(U)}$$

With these reference values, the total uranium throughput is also determined:

$$(20000\ \mathrm{g(Pu)/yr})/(0.39\ \mathrm{g(Pu)/kg(U)}) \approx 51300\ \mathrm{kg(U)/yr}$$

Vanunu states that the fuel remains in the reactor for three months (90 days), which would correspond to three annual reloads. The in-core uranium inventory would therefore be on the order of (51.3 tons/3) = 17.1 tons, which is nearly perfectly consistent with the modified fuel design introduced above (Table 1) and other assumptions made for the earlier phases.

The target concentration of plutonium in the uranium (0.39 g/kg) can also be used to determine the discharge burnup of the fuel using neutronics

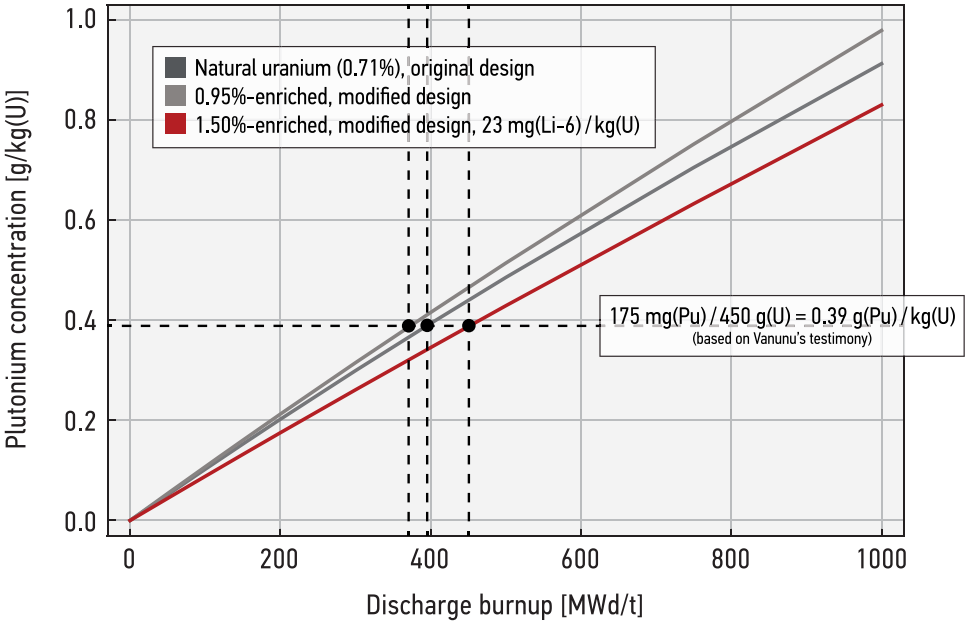

Figure 3. Plutonium concentration in the fuel as a function of discharge burnup. Vanunu stated that, after the dissolution of the fuel, the plutonium concentration is 0.39 g per kg of uranium. This information can be used to determine the discharge burnup for different fuel designs and enrichment levels, including those proposed for earlier phases of operation. All results are based on ONIX infinite-lattice calculations.

calculations. Figure 3 shows the main results of the ONIX calculations, which have been used to calculate the plutonium concentration in the uranium for the different fuel geometries and enrichment levels proposed. Accordingly, the discharge burnup is about 454 MWd/t for the modified design using 1.5%-enriched fuel and lithium targets to enable tritium production (Table 2, Phase 3). For reference purposes, the fuel and design options for Phases 1 and 2 are also shown.

The increased enrichment level of the fuel (1.50% *vs.* 0.95% compared to the version without lithium) leads to a decreased rate of plutonium production. To maintain the total production target of 20 kg per year, the power of the reactor has to be increased further from 71 MW to 86 MW thermal (Table 2).

Power upgrades from 40 MW to 70 MW and eventually to almost 90 MW have 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.[20] The cooling towers are clearly visible and appear unchanged in satellite imagery of the Dimona site taken since the early 1970s (Figure 4). However, both the heat exchanger and cooling-tower internals could have been upgraded, or an alternative cooling system may have been installed. Based on the publicly available information, it is difficult to conduct a conclusive analysis one way or another. Here, we simply

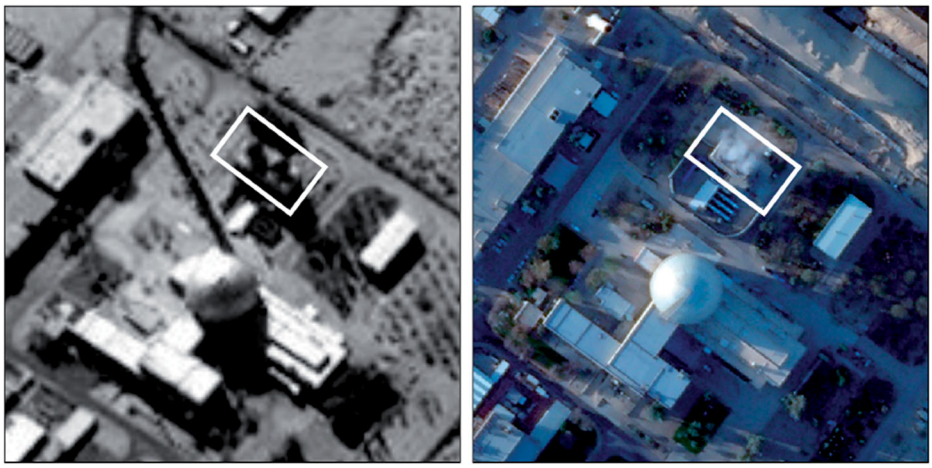

Figure 4. The Dimona reactor (31.0011 N, 35.1445 E) in 1971 and 2021. The cooling towers of the Dimona reactor are clearly visible and identifiable in satellite imagery. Comparison of declassified Corona imagery taken in 1971 (KH-4 Mission 1115-2, September 29, 1971) with imagery from 22 February 2021 suggests that no new cooling towers have been added between those dates. Coincidentally, the steam visible in the 2021 imagery also confirms that the reactor is still operational. Credit: public domain (left) and Planet Labs Inc. (right).

assume that such upgrades have indeed been possible. The results we report should be understood with this limitation in mind.

We also note that one could derive an even higher plutonium production rate from the transcripts. First, Vanunu mentions flow rates that are substantially above nominal, reaching up to 35 liters per hour for Unit 14. Second, Vanunu comments on the mass and number of plutonium buttons produced per week. This information would be consistent with a production rate of 35–40 kg of plutonium per year, a number that was also reported in the *Sunday Times* article.[21] Based on our analysis, however, we conclude that it is most likely incorrect. In particular, it is possible that, unknowingly to Vanunu, button production also included already existing plutonium that was "recycled" for the manufacture of new weapons while Israel was upgrading its weapon designs. Moreover, as the discussion above suggests, a production rate of 35–40 kg/yr would require even higher uranium inventories and reactor power levels, both of which can be considered impractical based on the original design specifications of the reactor.

Before we proceed to an estimate of the total amount of plutonium produced at Dimona between 1964 and 2021, we briefly discuss the production of tritium by neutron irradiation of lithium-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 at the expense of plutonium production.[22]

Lithium-6 and tritium production

Lithium-6 serves two purposes in the production of nuclear weapons. First, it is used to make tritium via neutron exposure in a nuclear reactor. During the implosion sequence of a nuclear weapon, this tritium (along with deuterium) is used to boost the fission chain reaction in the "primary" of the weapon, which increases the explosive yield of a given design or reduces the amount of fissile material needed for this weapon component. Second, lithium-6 is also used as a source of fusion material in the "secondary" of a thermonuclear weapon, where it is combined with deuterium to produce lithium-6 deuteride (LiD). Naturally occurring lithium only contains about 7.5% of lithium-6, and the isotope must therefore be enriched before it can be used efficiently for weapon purposes. To do so, according to Vanunu, in 1977, Israel built a pilot plant at Dimona to enrich lithium-6 to about 85%.[23] The part of the product dedicated to tritium production was subsequently alloyed with aluminum and fashioned into small rods that were inserted into the core of the reactor.

Although tritium production on a large scale has usually been carried out in dedicated reactors, smaller amounts can be produced by inserting lithium-6 targets or by substituting lithium-6 for boron control rods in the core of reactors whose main purpose is the production of electricity or plutonium. According to Vanunu, this is the strategy pursued at Dimona, where

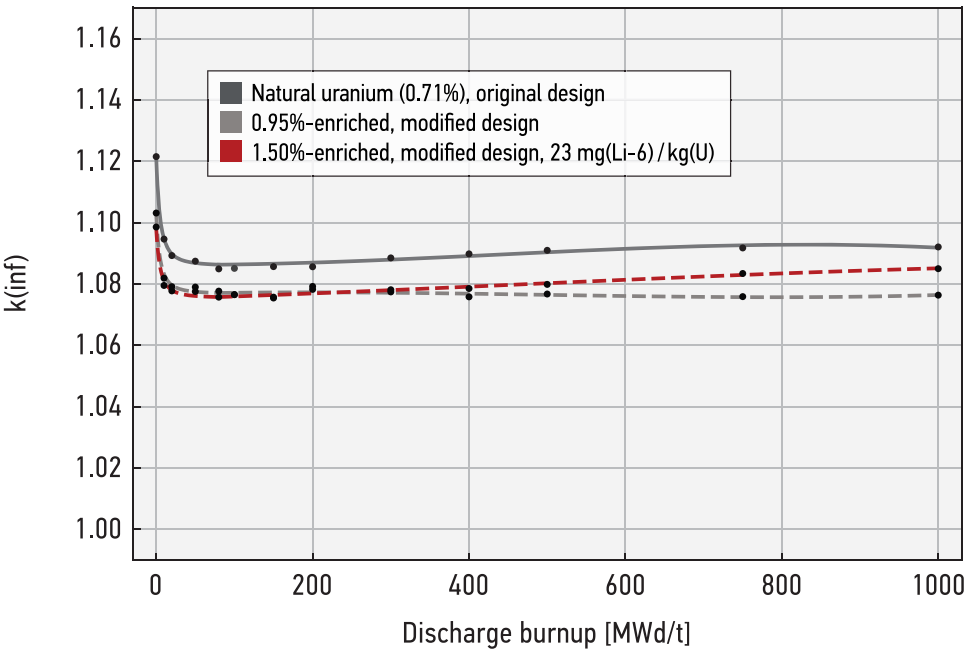

Figure 5. Infinite multiplication factor *vs.* burnup for the fuel designs listed in Table 2. The cases using the modified design have been optimized such that they are close to the reactivity margin of 8–9% of the original design of Dimona. All results are based on ONIX calculations.

"lithium sticks" are irradiated in the reactor core. To get a rough estimate of the capability of the Dimona reactor to produce tritium in this manner, for simplicity, we add small concentrations of lithium-6 to the semi-permanent aluminum sleeves enclosing the fuel rods.

ONIX simulations show that operating the reactor with 23 mg of lithium-6 for every kilogram of uranium requires an enrichment level of about 1.5% to match the reactivity margin of the original design (Figure 5). Additional ONIX depletion calculations for the lithium targets show that this design produces about 2.42 mg of tritium per MWd at a discharge burnup of 454 MWd/t. Assuming that the reactor operates at 86 MW for 270 days per year (23,280 MWd, see Table 2), annual tritium production is on the order of 56 grams:

$$(23280\ \text{MWd/yr}) \times (2.42\ \text{mg/MWd}) \approx 56\ \text{g/yr}$$

This particular production rate is based on the assumption that the lithium targets are loaded and discharged along with the uranium fuel every 90 days; to reduce lithium requirements, however, the targets could be exposed for a longer period of time. For example, if the targets stayed in the core for three cycles, i.e., for one year, the effective tritium production rate would drop to 47–49 grams per year.[24] Tritium production can be further increased with higher fuel enrichment and lithium loadings, but may then also require another increase in reactor power.

Production rates on the order of 50–60 grams per year appear consistent with Israel's tritium requirements. If we assume that Israel has a stockpile of about 100 nuclear warheads and that there are on average about 10 grams of tritium per warhead,[25] then the total tritium inventory would be on the order of about 1 kg. Tritium has a half-life of 12.3 years, which is equivalent to a decay rate of 5.5% per year. With these assumptions, Israel would therefore need a supply of 55 grams of tritium per year to offset natural decay.

One can verify with a simple back-of-the-envelope calculation that the tritium production estimate of 50–60 grams is consistent with the overall neutron balance in the system. In a reactor operated at 86 MW thermal, about 2.68×10^{18} fission events release 6.6×10^{18} neutrons per second or about 250 mol per year. ONIX calculations show that using 1.5%-enriched fuel (without lithium) provides an extra reactivity margin of about 10% compared to the reference design with 0.95%-enriched fuel. Ideally, this extra margin is available for capture in the lithium targets: 0.1×250 mol of neutrons can therefore be used to make 25 mol of atomic tritium with a total mass of 75 grams. This is an upper limit and quite consistent with the results we find in the neutronics calculations.

Use and possible production of enriched uranium

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.[26]

According to Vanunu, the production of enriched uranium at Dimona using gas centrifuges and lasers started between 1979 and 1981. 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 the acquisition of the technology by states hostile to Israel.[27] 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.

Enriched uranium could be used directly in weapons. More relevant for Israel, however, could be its use as slightly enriched reactor fuel for the Dimona reactor to accelerate plutonium production (Phase 2) and to enable concurrent tritium production (Phase 3).

If Israel deployed a domestic enrichment capability to make slightly enriched fuel for the Dimona reactor operated at a power level of about 70 MW and using 0.95%-enriched fuel during Phase 2, the capacity of the plant would have to be on the order of 11,000 SWU/yr if natural uranium is used as feedstock;[28] similarly, about 47,000 SWU/yr would be needed in Phase 3 to enrich the same amount of fuel to 1.5%. A much smaller capacity would be sufficient if recycled uranium is used as feedstock. In our reference case for Phase 3 (1.5% initial enrichment, 454 MWd/t), the fuel is discharged with a residual uranium-235 content of 1.45%. Re-enriching this material to 1.5 or 1.6% would only take 770–2,500 SWU/yr depending on the depletion level of the tails.[29] These enrichment capacities are very small compared to commercial requirements, and a plant of this size could easily be accommodated somewhere on the Dimona site.

Another early, possible source of enriched uranium was NUMEC, a nuclear fuel facility in the United States near Pittsburgh, Pennsylvania. The allegation that hundreds of kilograms of weapons-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.[30] For example, one could blend 300 kg of weapons-grade uranium (93% uranium-235) with natural uranium to obtain 115 tons of 0.95%-enriched uranium. In other words, based on the estimated annual uranium throughput of 51.3 tons, this blended

Table 3. Plutonium production scenarios and inventories.

Time period	Power	Fuel	Production rate	Cumulative production
1964–1970	39 MW	Natural uranium	10 kg/yr	70 kg
1971–1976	71 MW	0.95%-enriched	20 kg/yr	120 kg
1977–1986	86 MW	1.50%-enriched	20 kg/yr	200 kg
1987–2020	86 MW	1.50%-enriched	20 kg/yr	680 kg
Maximum lifetime production, 1964–2020				1,070 kg
Reduced production scenario 1 (50% since 1997, −240 kg)				830 kg
Reduced production scenario 2 (50% since 1987, −340 kg)				730 kg

If Dimona operated since 1977 at 86 MW while maximizing both plutonium and tritium production, up to 1070 kg of plutonium could have been produced by the end of 2020. Most likely, this exceeds by far the requirements of Israel's stockpile of nuclear weapons. It is possible that the parameters of reactor operation have been adjusted sometime in the past (e.g., in 1987 or 1997) to meet tritium requirements while de-emphasizing plutonium production. In this case, lifetime plutonium production could be significantly lower today. See text for further details.

material would provide enough fuel to operate Dimona for more than two years at the time when it used fuel of that enrichment level.

Estimating total plutonium production

The main purpose of this article is to provide an updated assessment of plutonium production at the Dimona site. Based on the preceding discussion, there is strong evidence that the power level of the reactor was raised over time, possibly in multiple steps, while operation moved from natural uranium (Phase 1) to slightly enriched uranium fuel to accelerate plutonium production (Phase 2) and finally to also enable concurrent tritium production (Phase 3). Based on this general scenario and the respective calculations discussed in this article, we can assemble a tentative complete history of plutonium production at Dimona. Results are summarized in Table 3.

Based on Vanunu's testimony and other information available about the original design of the reactor, we have a rather consistent picture of operations at Dimona up until 1986. We have no new information about Dimona's characteristics since 1986, however. Satellite imagery from 2021 confirms that the reactor is still operating today (Figure 4), though not necessarily continuously or at maximum power. While it is believed that boosted primaries and thermonuclear weapons have been incorporated into the arsenal in the late 1970s or early 1980s, Israel apparently decided not to produce and deploy battlefield nuclear weapons and therefore may have reduced the production of plutonium while maintaining the level of tritium production required for its stockpile of thermonuclear weapons. Overall, it is plausible to assume that, perhaps as early as 1987, Israel had largely met its plutonium requirements. Unless the reactor has been completely redesigned and uses fuel with much higher enrichment today, it would be

difficult to reduce the power level of Dimona significantly, while maintaining tritium production rates of 50–60 grams per year. 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.

It is therefore plausible to consider several, simple post-1986 scenarios that de-emphasize plutonium production. Most importantly perhaps, once the plutonium is no longer needed for weapons, the discharge burnup of the fuel could be increased significantly. Indeed, as Figure 5 already suggests, there remains a large reactivity margin beyond 1,000 MWd/t. In fact, additional ONIX calculations show that the fuel could be irradiated up to about 5,000 MWd/t. In that case, the plutonium is no longer weapons-grade (about 86% plutonium-239); such a strategy would, however, save significant uranium resources and use the lithium targets much more efficiently. Net plutonium production would drop by about 20–25% from the reference value of 0.86 g/MWd to about 0.68 g/MWd. As a lower bound, we arbitrarily assume that plutonium production could have decreased by 50% to 10 kg per year once tritium production became the primary mission of Dimona. Table 3 includes two such alternative scenarios: one in which plutonium production dropped in 1997, i.e., a few years after the end of the Cold War, and one in which it dropped in 1987 already. For reference purposes, we also consider the case where plutonium production has remained at the nominal level of 20 kg/yr reported by Vanunu for 1985.

As there are no obvious removals from the stockpile—besides one or more possible nuclear weapon tests in 1979, which may have consumed 10–20 kg of plutonium—the upper limit of Israel's plutonium inventory is on the order of 1,000 kg today. Unfortunately, it is not possible to choose a most likely alternative production scenario based on the information we have available. Neither is it possible to assign definitive error bars to our estimates. With these caveats in mind and based on the data summarized in Table 3, we choose 830 ± 100 kg as an estimate that broadly captures the range of the scenarios we considered.

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. Here, we have developed a

new estimate that is based on extensive neutronics calculations and distinguishes different phases of Dimona's history and operation. We have placed a particular emphasis on Vanunu's 1986 testimony in an attempt to resolve some inconsistencies in earlier reporting.

Overall, as of December 2020, we estimate that Israel produced a total of 830 ± 100 kg of plutonium at Dimona. If all this plutonium were used for weapon purposes, it could be equivalent to about 150–190 warheads, assuming that each device contains on the order of 5 kg of plutonium. This by far exceeds the independent estimates of Israel's current nuclear arsenal of 80–85 weapons.[31] Based on this finding, one can assume that, for the past two or three decades, the Dimona reactor may have been used primarily for tritium production and that maximizing plutonium output has not been a priority; in fact, plutonium could be a mere by-product today. If this assessment is correct, Israel could in principle adhere to the provisions of a possible Fissile Material Cutoff Treaty today. The fact that plutonium is not being separated from the spent fuel of the original or another reactor onsite could be verified non-intrusively, e.g., by confirming the absence of krypton-85 emissions from the site.

Meanwhile, satellite imagery from February 2021 confirms that the Dimona reactor remains operational. No other plutonium production reactor has been operated longer than this reactor in the Negev Desert. While Israeli officials insist that the reactor is safe, it is very likely that at some point in the next few years the reactor will either require significant modernization or will have to be shut down and possibly replaced if Israel seeks to maintain its current nuclear arsenal. This presents an opportunity to engage Israel on the issue of the future of its nuclear program.

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8. A calandria is a vessel through which tubes pass. Heavy-water moderated reactors often use this design, and the Canadian CANDU reactors are the most prominent example of a power reactor using a calandria and allowing online refueling.
9. Unfortunately, from these documents, it is not clear if the U.S. visitors were able to confirm at least some of these values or if they were simply reported to them.
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16. All tons are metric tons.
17. The possible power increase to 70 MW thermal ("perhaps, in 1972") was first reported in Leonard S. Spector and Jacqueline R. Smith, *Nuclear Ambitions: The Spread of Nuclear Weapons 1989–1990* (Boulder, CO: Westview Press, 1990), 160.
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20. In addition, the postulated larger diameter of the modified fuel rod would further increase hydraulic resistance and most likely require more powerful circulation pumps. We assume, however, that such modifications would not be visible in satellite imagery.
21. A plutonium production rate of about 40 kg/yr can be inferred from the transcripts as follows: According to Vanunu, nine buttons are fabricated per week over an eight-month period per year (242 days, 34.6 weeks), each button containing 130 g of plutonium. This corresponds to a production rate of 40.45 kg/yr. Similarly, the *Sunday Times* article stated: "Plutonium production rates amount to 40 kilograms a year, enough to build 10 bombs."

22. 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.*
23. See Barnaby, *The Invisible Bomb*, 38–40, *op. cit.*
24. This drop is due to *in-situ* tritium decay as well as depleting quantities of available lithium-6 with irradiation time.
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26. R. Scott Kemp, "*Nonproliferation Strategy in the Centrifuge Age*" (PhD diss., Princeton University, June 2010). See, in particular, "Centrifuge Program Dossiers: A Rogues Gallery?" (Chapter 3).
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28. This estimate is based on the following assumptions: Natural uranium is enriched to 0.95% uranium-235 with a tails depletion level of 0.3%. Total production is 51.3 tons per year.
29. For example, it would only take about 770 SWU/yr to re-enrich 51.3 tons of 1.45%-enriched feedstock to 1.50% uranium-235 for a tails depletion level of 0.71%. In practice, of course, these re-enrichment scenarios would have to factor in the availability of reprocessed uranium.
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