MILITARIZATION OF CIVIL NUCLEAR REACTORS: TRITIUM FOR NUCLEAR WEAPONS

INTRODUCTION

Modern thermonuclear weapons utilize tritium, a radioactive isotope of hydrogen, to "boost" the nuclear yield of the fission explosive pit, or "primary", that generates the intense energy directed to ignite the fusion "secondary". The radioactive half-life of tritium is 12.3 years, and each year a given quantity of tritium will decrease by 5.5 percent. Thus, to maintain a given stockpile of tritium for weapons, the isotope must be continuously produced to replace the material lost to radioactive decay. Historically, this was done by the United States, France, and other nuclear weapon states by irradiating lithium targets in dedicated military production reactors and chemically processing the targets to extract the tritium.

In the United States, tritium was produced in the government-owned reactors at the Savannah River Site in South Carolina until the last operating reactor was closed in 1988 for safety reasons. Since 2003, the U.S. has been producing tritium for weapons by utilizing the neutrons generated by civil nuclear power plants—specifically, the two Watts Bar reactors in the state of Tennessee.[1584]

In March 2024, the French Government announced that, after the closure of its own tritium production reactors, it was partnering with the utility EDF to produce tritium for its nuclear weapons program at the Civaux dual-reactor nuclear station.[1585]

The program has not been approved yet by the French nuclear safety authorities. EDF is expected to submit a technical dossier in the fall of 2024 with a first test planned for 2025.[1586]

As there is hardly any information available on the French program, this chapter reviews the history of similar U.S. efforts, as well as the optics of using civil nuclear plants for military purposes.

1584 - The U.S. presumably also produced tritium for the United Kingdom's thermonuclear weapon stockpile under the Mutual Defense Agreement between the two countries. However, the U.K. stockpile, and tritium demand, are only a few percent of those of the U.S.

1585 - Ministère des Armées, "Déplacement du ministre des Armées à la centrale EDF de Civaux, le 18 mars 2024", Press Release (in French), Armed Forces Ministry, French Government, 18 March 2024, see https://www.defense.gouv.fr/sites/default/files/ministere-armees/18.03.2024%20D%C3%A9placement%20du%20ministre%20des%20Arm%C3%A9es%20%C3%A0%20la%20centrale%20EDF%20de%20Civaux%2C%20le%2018%20mars%202024.pdf, accessed 27 July 2024.

1586 - *Le Monde*, "L'armée française et EDF vont collaborer pour produire du tritium, indispensable aux armes de dissuasion nucléaire", with *AFP*, 19 March 2024 (in French), see https://www.lemonde.fr/planete/article/2024/03/19/nucleaire-l-armee-francaise-et-edf-vont-collaborer-pour-produire-du-tritium-indispensable-aux-armes-de-dissuasion_6222845_3244.html, accessed 22 August 2024.

TRITIUM DEMAND FOR NUCLEAR WEAPONS

Boosting occurs when a mixture of tritium and deuterium gas injected into the pit is compressed and undergoes fusion reactions, releasing high-energy neutrons that augment the rate of neutron generation within the pit compared to the rate due to fission neutrons alone. This process greatly enhances the efficiency, or fraction of the primary fuel (plutonium and/or highly enriched uranium) that undergoes fission. This allows for a reduction in the mass of the fuel and other primary components (reflector, high explosive) needed to generate a yield high enough (on the order of ten kilotons) to ignite the secondary. Tritium also renders nuclear fission weapons "predetonation-proof," allowing the utilization of fissile materials with higher spontaneous background neutron rates (such as reactor-grade plutonium[1587]) without any reduction in expected yield. Independent estimates of historical tritium requirements for thermonuclear weapons range from two to four grams per warhead on average.[1588] Some weapons (known as "dial-a-yield") can use variable amounts of tritium to adjust their explosive power. However, overall, the tritium demand has increased in recent years for the U.S. stockpile, presumably to increase performance margins.

Following the closure of its last dedicated tritium production reactor in 1988, the U.S. Department of Energy (DOE) sought to reinstate its production capacity by pursuing the development of a dedicated New Production Reactor (NPR). At the time, the option for the DOE to utilize commercial nuclear power reactors to produce tritium, either through leasing irradiation services or buying reactors outright, was thought to possibly violate the prohibition, under the 1954 Atomic Energy Act, on the use of special nuclear material produced in commercial reactors for "nuclear explosive purposes."[1589] In this case, the issue was tritium generation by neutrons released by the fission of plutonium that had been produced in the reactor core. However, the need for an expensive new tritium production reactor soon came into question when, in 1991, the U.S. decided to unilaterally dismantle most of its short-range (non-strategic) nuclear weapons, and then ratified the subsequent 1991 START I treaty, requiring the U.S. and Russia to reduce the number of long-range nuclear weapons in their stockpiles. This diminished the total tritium demand and allowed the need to be met by recycling tritium from dismantled warheads. Moving forward, the U.S. began to favor the option of utilizing existing power reactors, which would be quicker and cheaper to implement. All it took was a policy decision to go ahead.

The DOE estimated that it would need to produce 3 kilograms of tritium per year (an unclassified maximum level) to support a START I level stockpile (approximately 11,000 warheads, including reserves), which would have required tritium production to resume by 2005.[1590] For example, at 3 grams per warhead, the production requirement to make up an annual 5.5 percent loss of the START I stockpile of 33 kilograms would be 1.8 kilograms per year, after accounting

1587 - No country is known to currently use reactor-grade plutonium in its warheads.

1588 - See, for example, the derivation in Gregory S. Jones, "U.S. Increased Tritium Production Driven by Plan to Increase the Quantity of Tritium per Nuclear Weapon", 2 June 2016, see https://nebula.wsimg.com/08a60104185a91e6db9008fb929a0873?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1.

1589 - C. Lau and R.E. Rowberg, "The Department of Energy's Tritium Production Program", Congressional Research Service, 23 January 1997.

1590 - U.S. Department of Energy, "Final Environmental Impact Statement for the Production of Tritium in a Commercial Light-Water Reactor", DOE/EIS-0288, March 1999.

for process losses and other production-related factors. The additional makeup requirement to maintain a five-year reserve of about 12 kilograms would be about 0.65 kg per year, bringing the total production requirement to 2.5 kg per year. At the time, it was also anticipated that the follow-on START II agreement would reduce the number of warheads on each side by nearly 50 percent from the START I level and result in a proportional reduction in the annual tritium production requirement, pushing out the date for resumption to 2011. Although START II never went into force, the U.S stockpile continued to decline after 2001, and the Strategic Offensive Reductions Treaty (SORT), which did enter into force in 2003, eventually resulted in warhead levels decreasing to well below the START II level.

Nevertheless, the DOE was directed by the President in the 1996 Nuclear Weapons Stockpile Plan to support a START I stockpile level until the START II treaty was implemented, and the entry into force of SORT did not alter this requirement. Consequently, the DOE proceeded with plans to restart tritium production by 2005 by enlisting commercial light-water reactors for the task. It also continued to retain a backup option for years—the construction of a subcritical accelerator for tritium production—that was favored by powerful New Mexico senator Pete Domenici, but was never implemented.

TRITIUM PRODUCTION AT THE WATTS BAR NUCLEAR PLANT

In 1999, the DOE contracted with the Tennessee Valley Authority (TVA)—the only utility wholly owned by the federal government—to produce tritium in its Watts Bar-1 and Sequoyah-1 and -2 nuclear reactors. (Watts Bar-2 was unfinished at the time.) The approach involves replacing some of the boron-based burnable absorber rods that are used for reactivity control in light-water reactors with Tritium-Producing Burnable Absorber Rods (TPBARs) which contain lithium enriched in the isotope Li-6. As the reactor operates, neutrons are absorbed by the Li-6 nuclei, which then produce tritium and an alpha particle (helium nucleus). The tritium occurs as a gas that then reacts with metallic "getters," which trap the tritium in the form of a hydride. After one 18-month irradiation cycle, the TPBARs are shipped to a Tritium Extraction Facility at the Savannah River Site, where the recovered tritium is loaded into stainless-steel reservoirs for eventual insertion in weapons.

The substitution of TPBARs for burnable absorbers raises numerous safety concerns and imposes constraints on reactor operation. Some issues only emerged after the Watts Bar campaign began.[1591] In addition to increasing the radiological source term resulting from the in-core tritium inventory that could be released to the environment in the event of a core melt accident, the TPBARs reduce shutdown margins, necessitating core modifications such as a higher enrichment levels of the low enriched fuel.

After irradiation for one 18-month cycle, each TPBAR, on average, was estimated to produce just under 1 gram of tritium (but the average yield was originally expected to be as low as 0.75 gram per TPBAR, factoring in process loss). To meet the original tritium production goal

1591 - Dave Senor, "Recommendations for Tritium Science and Technology Research and Development in Support of the Tritium Readiness Campaign, TTP-7-084", PNNL-22873, Pacific Northwest National Laboratory, commissioned by the U.S. Department of Energy, October 2013, see https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-22873.pdf.

of 3 kilograms per year, the DOE anticipated that it might have to load up to 6,000 TPBARs each cycle. This would require multiple reactors because at the time it believed that the safety limit was 3,400 TPBARs for a single unit. However, during the first production cycle at Watts Bar-1 in 2003, when only 240 TPBARs were loaded, it was discovered that the permeation rate of tritium into the reactor coolant was nearly ten times higher than predicted.[1592] Although the amount released was only a small fraction of the total inventory in the TPBARs, it exceeded the NRC's regulatory limit for annual tritium release in wastewater. This caused the NRC to impose a limit of no more than 704 TPBARs in a single reactor and triggered additional research and development work to improve tritium retention in the TPBARs (which has been unsuccessful).

Thus, for several subsequent cycles, the number of TPBARs loaded into Watts Bar-1 was well below the original number that DOE said was needed to maintain a START I-sized stockpile. Although the DOE could have also used the two Sequoyah reactors, there apparently was no need to do so. Due to the stockpile reductions that were taking place at the same time,[1593] the reduced level of tritium production apparently was tolerable, presumably with some drawdown of the 5-year reserve. However, by 2015, the DOE had raised the production requirement to 1,700 grams of tritium per 18-month cycle, or 1,130 grams per year, which required a ramp-up. At the declared level in 2015 of 4,571 warheads, assuming 3 grams per warhead, the annual makeup requirement would be about 1 kilogram per year including replenishment of the reserve, requiring about 1,500–2,000 TPBARs per 18-month cycle, or more than twice the 704 that were loaded in Watts Bar-1 that year.

Also in 2015, the public version of the Stockpile Stewardship and Management Plan that the DOE provides to Congress stated that the stockpile demand for tritium would further increase to 2,800 grams per cycle by 2025. Although the reasons for this were not disclosed, it has been posited that increasing the amount of tritium supplied to each warhead would allow the tritium reservoirs to be replaced less frequently and would increase weapon performance margins.[1594] Another possibility is that the DOE may want to retain additional tritium as a hedge in the event that it wants to increase the size of the stockpile. Accordingly, the TVA applied to the NRC for license amendments to increase the maximum number of TPBARs in Watts Bar-1, as well as to expand tritium production to Watts Bar-2. In 2023 TVA loaded 1,792 TPBARs in Watts Bar-1, the maximum licensed limit, and 1,104 in Watts Bar-2.

However, while the licensed limit of 1,792 TPBARs in both Watts Bar units would appear to be more than sufficient to meet the DOE's 2,800 gram per cycle objective, the DOE requested another increase in the TPBAR limit. In April 2024, the NRC granted a license amendment to TVA authorizing an increase in the TPBAR loading in each core to 2,496, for a total of nearly 5,000 TPBARs per cycle. If fully utilized, this quantity would represent a tritium production rate 70 percent greater than the stated DOE objective, and three times the original rate per warhead needed to support a START I stockpile. This oversupply may be needed to compensate

1592 - Dave Senor, "Commercial Light Water Production of Tritium: Update and Path Forward", PNNL-SA-94431, Tritium Focus Group, Pacific Northwest National Laboratory, 23 April 2013, see https://www.energy.gov/sites/prod/files/2015/08/f26/Comml%20Light%20Water%20Prod%20of%20Tritium.pdf.

1593 - National Nuclear Security Administration, "Transparency in the U.S. Nuclear Weapons Stockpile", U.S. Department of Energy, 2024 see https://www.energy.gov/nnsa/transparency-us-nuclear-weapons-stockpile.

1594 - Gregory S. Jones, "U.S. Increased Tritium Production Driven by Plan to Increase the Quantity of Tritium per Nuclear Weapon", 2016, op. cit.

for potential uncertainties in the production chain that significantly reduce the nominal likelihood of DOE, as the end user, actually receiving the tritium it requires.[1595]

Despite years of attention to the issue, DOE does not seem to have been able to reduce the tritium permeation problem from TPBARs. To meet the NRC's wastewater tritium discharge limit with a significantly greater number of TPBARs in the core, TVA needs to employ a mobile demineralizer to further treat the effluent or dilute it prior to discharge.[1596]

NONPROLIFERATION CONCERNS

The isotope tritium occupies a gray area in nuclear nonproliferation law and policy. Because it is not itself a fissionable material that can sustain a chain reaction (despite some who claim that it is possible to build a pure fusion bomb), nor can it be used as a source of nuclear explosive material, it is not subject to international safeguards. Moreover, it is not classified as "special nuclear material" in domestic laws such as the U.S. Atomic Energy Act (AEA). On the other hand, it defies common sense to argue that the production of tritium for nuclear weapons can be classified as "peaceful use," regardless of whether it can be used directly to fuel a nuclear weapon. And the production of tritium for weapons using commercial facilities violates the principle that civilian and military nuclear activities should remain fully separate.

In 1998, a U.S. Government interagency review concluded that the production of tritium in commercial light-water reactors was not prohibited by the AEA and was acceptable from a nonproliferation perspective because the U.S. had never fully separated civil and military nuclear activities.[1597] The review also argued that the use of reactors owned by the Tennessee Valley Authority, which is a U.S. Government agency, mitigated the dual-use nature of the program. It did take the position though that tritium production could not be carried out using imported materials, equipment, or technologies that had "peaceful use" obligations. U.S. policy also excludes the production of tritium using "encumbered" nuclear materials that were declared excess for weapons use after the end of the Cold War, specifically: stockpiles of around 47 metric tons of excess plutonium and 374 metric tons of highly enriched uranium (HEU). This means, in particular, that low-enriched uranium produced from blending down HEU from excess Cold War weapons that had been declared for peaceful use could not be used as fuel for a commercial reactor that was concurrently producing tritium.

These constraints have proven to be problematic given the limited amount of unobligated and unencumbered enriched uranium available in the United States. The U.S. stopped enriching uranium in government-owned facilities using U.S. technologies in 2013, and the sole domestic industrial-scale enrichment facility is owned by URENCO, an international consortium that is under peaceful use obligations. Consequently, TVA has been only able to utilize Low Enriched Uranium (LEU) fuel derived from blended-down unencumbered HEU from a dwindling

1595 - E.F. Love, M.L. Stewart et al., "Tritium Production Assurance", Tritium Focus Group, Pacific Northwest National Laboratory, 11 May 2017, 5 June 2017, see https://www.energy.gov/sites/prod/files/2017/06/f34/May%2011%20-%20Stewart%20-%20Tritium%20Production%20Assurance.pdf.

1596 - U.S. Nuclear Regulatory Commission, "Tennessee Valley Authority; Watts Bar Nuclear Plant, Units 1 and 2; Environmental Assessment and Finding of No Significant Impact", 16 February 2024, see https://www.nrc.gov/docs/ML2400/ML24009A172.pdf, accessed 22 August 2024.

1597 - Department of Energy, "Interagency Review of the Nonproliferation Implications of Alternative Tritium Production Technologies Under Consideration by the Department of Energy", United States Government, report to the U.S. Congress, July 1998.

stockpile that the U.S. has retained for military purposes, including production of fuel for naval reactors. After scouring the nuclear weapons complex for HEU scrap that no one else wanted, the DOE now says it can provide sufficient fuel to the TVA reactors to produce tritium until 2044.[1598] However, after that date, it will have to find another source. The DOE is currently sponsoring work on two different U.S.-origin centrifuge technologies with the ultimate goal of producing unobligated enriched uranium for a range of military purposes, including tritium production.

IMPLICATIONS FOR FRANCE

There is little public information at this time regarding the weapons tritium production program that has been proposed for the Civaux reactors in France. However, the scale of the effort is likely to be much smaller than the U.S. program at the Watts Bar plant. The active French nuclear stockpile is estimated at around 300 warheads, or less than one tenth of the active U.S. stockpile. Assuming France employs similar TPBAR technology to the U.S. and that its weapons use similar quantities of tritium, the core TPBAR inventory at Civaux would be far lower than the inventory planned for the Watts Bar reactors and would likely be below the maximum that the U.S. NRC approved to control tritium permeation into the coolant. The impact of the TPBARs on reactor operation would also be lower and may not necessitate the same types of adjustments that were made at Watts Bar.

France may also need to confront the policy question of whether uranium imported into France under "peaceful use" obligations, e.g. from Australia or Canada, can be used for co-production of tritium for weapons. If France concludes that it cannot be used, that would impose constraints on the source of the uranium fuel used at Civaux.

1598 - U.S. Department of Energy, "Fiscal Year 2024 Stockpile Stewardship and Management Plan: Report to Congress", November 2023.

SMALL MODULAR REACTORS (SMRs)

The gap between hype about Small Modular Reactors (SMRs) and reality continues to grow. The nuclear industry and multiple governments are doubling down on their investments into SMRs, both in monetary and political terms. In addition to individual governments, there are also multilateral efforts being launched, including the European Industrial Alliance on Small Modular Reactors set up by the European Commission with the aim of accelerating "the development, demonstration and deployment of Small Modular Reactors (SMRs) in Europe by the early 2030s."[1599] The Alliance's stated ambition is to "have at least 150 GW of nuclear capacity installed by 2050."[1600] Nuclear regulatory agencies in the United States, the United Kingdom, and Canada are trying to "facilitate resolution of common technical questions to facilitate regulatory reviews" of advanced reactors and SMRs.[1601]

At the same time, the reality is far more somber. As documented below, SMR projects continue to be delayed or canceled. Some mainstream news outlets are warning that costs for nuclear projects in general and SMRs in particular are surging.[1602] This is apparent in the few available cost estimates, especially when weighted by the electrical power generation capacities of SMRs.

This chapter provides updates on programs in all those countries developing their own SMR designs. In addition, there are countries that have expressed verbal interest in importing SMRs. These are discussed only in the context of agreements or contracts with the countries interested in exporting SMRs.

ARGENTINA

Argentina's CAREM (Central Argentina de Elementos Modulares) is currently the oldest pursued SMR design, passing the milestone of being under construction for a decade in February 2024. Under development by the National Atomic Energy Commission (CNEA) since the 1980s,[1603] the 25 MW CAREM was "scheduled to begin cold testing in 2016 and receive

1599 - Alfie Shaw, "European Commission launches industrial alliance for SMRs", *Power Technology*, 8 February 2024, see https://www.power-technology.com/news/eu-launches-smr-industrial-alliance/, accessed 13 February 2024; and Directorate-General for Energy, "Commission to ally with industry on Small Modular Reactors", European Commission, 9 February 2024, see https://energy.ec.europa.eu/news/commission-ally-industry-small-modular-reactors-2024-02-09_en, accessed 15 February 2024.

1600 - Thierry Breton, "Driving decarbonisation and resilience with nuclear energy", Internal Market Commissioner, European Commission, 28 November 2023, see https://ec.europa.eu/commission/presscorner/detail/en/speech_23_6156, accessed 12 August 2024.

1601 - U.S. NRC, CNSC and ONR, "Memorandum of Cooperation on Advanced Reactor and Small Modular Reactor Technologies Among the United States Nuclear Regulatory Commission, the Canadian Nuclear Safety Commission and the United Kingdom Office for Nuclear Regulation", 12 March 2024, see https://www.nrc.gov/docs/ML2406/ML24066A026.pdf, accessed 12 August 2024.

1602 - Jonathan Tirone, "Mini Reactor Cost Surge Threatens Nuclear's Next Big Thing", *Bloomberg*, 30 June 2023, see https://www.bloomberg.com/news/articles/2023-06-30/mini-reactor-cost-surge-threatens-nuclear-s-next-big-thing, accessed 2 July 2023.

1603 - Dario F. Delmastro, "Small modular reactors (SMRs): The case of Argentina", National Atomic Energy Commission and Universidad Nacional de Cuyo, in "Handbook of Small Modular Nuclear Reactors", ed. by Daniel T. Ingersoll and Mario D. Carelli, *Woodhead Publishing*, November 2020, see https://www.sciencedirect.com/science/article/pii/B978012823916200014X, accessed 7 August 2023; and U.S. House of Representatives, "Oversight review of South American science, space, and technology: report to the Committee on Science, Space, and Technology, U.S. House of Representatives, One Hundredth Congress, second session", U.S. Government Printing Office, 1988.