Gregory S. Jones[1]
June 2, 2016

U.S. Increased Tritium Production Driven by Plan to Increase the Quantity of Tritium per Nuclear Weapon

Introduction and Summary

Tritium is a vital component of every U.S. nuclear weapon. Due to the radioactive decay of tritium, continued production is required to maintain the U.S. nuclear weapon stockpile. The U.S. has begun a program to produce tritium by irradiating lithium in the commercial nuclear power reactor, Watts Bar 1. Using the data provided by this program I have calculated that currently the average U.S. nuclear weapon uses about 3.2 grams of tritium.

Buried in the Stockpile Stewardship Plan is the revelation that the U.S. intends to significantly increase the amount of tritium per weapon.[2] This change is intended to reduce the frequency with which the tritium reservoirs in the weapons are replaced and to help ensure weapon reliability in an era where there is no nuclear testing. I have estimated that the amount of tritium per weapon will be increased by roughly 50% to about 4.5 to 5.0 grams.

This increase in tritium per weapon will lead to a corresponding increase in the required production of tritium. This production increase plus the need to conserve uranium not encumbered by peaceful use requirements ("unobligated" low enriched uranium) will require the use of a second commercial nuclear power reactor to produce tritium. The U.S. plans to start tritium production at one of the two Sequoyah reactors in 2021. To keep this plan on schedule, the U.S. will need to start fueling this reactor with unobligated low enriched uranium in the spring of 2018.

Boosted Nuclear Weapons

Boosted fission weapons have hollow cores of fissile material. Just before detonation a tritium/deuterium gas mixture is inserted into this hollow space. The detonation of the weapon causes a fusion reaction. The energy output from this fusion reaction is small but the large number of high energy neutrons from this reaction significantly increases the efficiency of the fission reactions in the weapon. Instead of being used to increase the yield of the weapon, in most cases boosting is used to reduce the size and fissile content of a warhead while maintaining or even improving the yield.

As the British have pointed out, boosted fission weapons have another important property.[3] Implosion fission weapons that use plutonium are vulnerable to predetonation due to the

---

[1] This paper is the product of the author's personal research and the analysis and views contained in it are solely his responsibility. Though the author is also a part-time adjunct staff member at the RAND Corporation, this paper is not related to any RAND project and therefore RAND should not be mentioned in relation to this paper. I can be reached at GregJones@proliferationmatters.com

[2] "Fiscal Year 2016 Stockpile Stewardship and Management Plan, Report to Congress," March 2015, National Nuclear Security Administration and U.S. Department of Energy, p. 2-35.

[3] Lorna Arnold, *Britain and the H-Bomb*, UK Ministry of Defense, Palgrave, 2001.

neutrons from spontaneous fission. Even if such weapons contain only highly enriched uranium, they are still vulnerable to predetonation from neutrons produced by the detonation of other nearby nuclear weapons, which could be either defensive warheads or "friendly" weapons. Boosted fission weapons do not have this vulnerability and can be used to manufacture what the British term "immune warheads."

The British note that this immune property plus the small size and reduced fissile material content of boosted fission weapons makes them ideal primaries for two stage thermonuclear weapons. The U.S. has used boosted weapons since 1957 and all U.S. nuclear weapons, now and for the foreseeable future, will use boosted primaries.

U.S. Production of Tritium

The deuterium required for boosted weapons can be extracted from ordinary water but tritium only exists in trace amounts in nature and must be produced by either irradiating lithium in nuclear reactors or recovering the tritium produced in the moderator of heavy water nuclear power reactors. Since tritium has a half-life of 12.3 years, each year 5.5% of the tritium will decay away. Therefore, maintaining a supply of tritium requires continued production.

Starting in the 1940s the U.S. produced tritium by irradiating a lithium aluminum alloy in plutonium production reactors. The last of these reactors (the K reactor at Savannah River) was shut down due to safety concerns in 1988. The drawdown in the U.S. nuclear weapon stockpile at the end of the Cold War meant that there was no need to restart tritium production until after 2000.

In 1999 the Department of Energy decided that tritium would be produced using the commercial power reactor Watts Bar 1 operated by the Tennessee Valley Authority (TVA). This reactor started operation in 1996, has a 1,200 MWe output and uses an 18 month refueling cycle. Since electricity demand is highest in the summer and winter, these refuelings take place in the spring and the fall.

To allow higher fuel enrichments and thereby longer fuel cycles, Watts Bar 1 (like most light water reactors), uses boron containing burnable absorber rods to suppress excess reactivity at the start of a fuel cycle. To produce tritium this boron is replaced by lithium to create tritium-producing burnable absorber rods (TPBARs). Each TPBAR is irradiated for one fuel cycle (18 months). They are then removed and are sent to Savannah River where the tritium is extracted.

Lithium aluminum alloy cannot be used since a nuclear power reactor must operate at high temperatures. Rather, the lithium is in the form of the ceramic lithium aluminate. From fall 1997 to spring 1999 thirty-two TPBARs were irradiated in Watts Bar 1 (during its second fuel cycle) as a test and no problems were discovered.

Due to the high temperatures in the reactor, the tritium would diffuse through many solid materials including the stainless steel that clads the TPBARs. However, tritium chemically reacts and is bound to zirconium. As a result the TPBARs contain a zirconium layer (in the form of Zircaloy) to act as a "getter" and retains the tritium in the TPBARs.[4] It was expected that about one gram (9,640 curies) of tritium would be produced in each TPBAR during the 18 month fuel cycle. Modeling indicated that about 0.5 curies of tritium would permeate out of each TPBAR during its irradiation. To be on the safe side, the Environmental Impact Statement (EIS) assumed that the tritium permeation would be 1.5 curies per TPBAR.[5]

Problems in the U.S. Tritium Production Program

In the fall of 2002 Watts Bar 1 was licensed to irradiate up to 2,304 TPBARs per fuel cycle. But almost immediately, concerns were raised about how the reactor might behave in an accident with this many TPBARs. In the fall of 2003 the license was amended to allow only 240 TPBARs per cycle. At the same time tritium production began with the loading of 240 TPBARs into Watts Bar 1 (See Table 1).

Over the course of this first irradiation a new problem was discovered. The tritium permeation was about 3.8 curies per TPBAR.[6] The radiation exposure to plant workers and the public resulting from this enhanced tritium release was not very large but the release exceeded the amount that was used to approve the EIS. The number of TPBARs irradiated per fuel cycle was kept at 240 while experts tried to figure out why the permeation was higher than predicted.

TPBARs using what was hoped to be an improved design were irradiated in fuel cycle 9 (spring 2008 to fall 2009) and this design improvement was used as the basis for changing the Watts Bar license to a maximum of 400 TPBARs per fuel cycle. However the tritium permeation was the same for the "improved" TPBARs (about 4 curies per TPBAR) as it had been for the old TPBARs. To date there is no explanation as to why the permeation has been significantly higher than predicted.

Despite the unresolved tritium permeation issue, due to the need for increased tritium production, the license for Watts Bar 1 was increased to a maximum of 704 TPBARs per fuel cycle as of May 2009. However the actual number of irradiated TPBARs increased slowly. Only 204 TPBARs were irradiated in cycle 10 (fall 2009 to spring 2011), 544 in cycles 11 and 12, reaching 704 in cycle 13 and the current cycle 14 (fall 2015 to spring 2017-see Table 1).

Since the tritium permeation problem could not be solved scientifically, it was solved administratively, i.e. the EIS was redone.[7] The revised EIS assumes that up to 2,500 TPBARs are irradiated per reactor using two reactors, one at the Watts Bar site and one at the Sequoyah

---

[4] The design of the TPBARs is described in the various Environmental Impact Statements on the tritium production program as well as "Description of the Tritium Producing Burnable Absorber Rod for the Commercial Light Water Reactor," TTQP-1-015, Revision 19, February 2, 2012.

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

[6] DJ Senor, "Recommendations for Tritium Science and Technology Research and Development in Support of the Tritium Readiness Campaign, TPP-7-084," PNNL-22873, Pacific Northwest National Laboratory, October 2013, p.7. Since tritium is produced by other processes in the reactor, this TPBAR permeation estimate has a plus or minus one curie uncertainty.

[7] "Final Supplemental Environmental Impact Statement for the Production of Tritium in a Commercial Light Water Reactor," U.S. Department of Energy and National Nuclear Security Administration, DOE/EIS-0288-S1, February 2016.

site.[8] The EIS also assumes that the tritium permeation could be as high as 15 curies per TPBAR. The EIS was approved in February 2016.

Note there are no plans to irradiate as many as 2,500 TPBARs in a nuclear power reactor and indeed the TVA has indicated that it does not know how it would operate a reactor with more than 2,304 TPBARs. The current licensing effort for Watts Bar 1 calls for the number of TPBARs irradiated per cycle to be increased to a maximum of only 1,792 TPBARs and the actual irradiation plans call for only a maximum of 1,504 TPBARs per fuel cycle. Nor is there any reason to think that the tritium permeation will be higher than about 4 curies per TPBAR. Rather the EIS values were chosen so that in the future the EIS will not be a constraint on tritium production.

Annual Tritium Production Rate and Derived Tritium per Weapon

The 1999 EIS expected that a tritium production rate of no more than 3 kilograms per year would be required. It was anticipated that this high rate would only be needed if the tritium reserve was ever used or lost and needed to be replaced. The steady-state tritium production requirements (the rate needed to compensate for tritium decay and maintain a fixed tritium stockpile) would be significantly less and was considered classified.

The continued decline of the U.S. nuclear stockpile after 1999 presumably led to a reduced tritium stockpile and thereby a reduced required tritium production rate. In 2011 it was revealed that the required steady-state irradiation of TPBARs was about 1,700 TPBARs per fuel cycle.[9] At one gram per TPBAR, this would produce 1,700 grams of tritium per fuel cycle or about 1,130 grams of tritium per year. It is easy to calculate that the corresponding tritium stockpile would be about 20.1 kilograms.[10] Given that the U.S maintains a 5 year tritium reserve and currently has 4,717 nuclear weapons, the average amount of tritium per weapon is about 3.2 grams.

Though it seems to have attracted little attention, the Stockpile Stewardship Plan in 2015 revealed that the U.S. was planning to increase the amount of tritium contained in each weapon.[11] This increase would decrease the frequency with which the tritium reservoirs in the weapons would need to be replaced and would also increase the confidence in weapon performance since there is no longer nuclear testing. Given this increase in the amount of tritium per weapon and the continued low production of tritium up to now, tritium production is planned to increase substantially. This increased production will require irradiation of TPBARs at two reactors. The second reactor will be one of the two reactors at TVA’s Sequoyah site. The

---

[8] The TVA has operated two nuclear power reactors at the Sequoyah site since the early 1980s.

[9] “Supplemental Environmental Impact Statement for the Production of Tritium in a Commercial Light Water Reactor,” Public Scoping Meeting, October 20, 2011, National Nuclear Security Administration, Department of Energy, slide 8.

[10] The tritium stockpile is found by multiplying the annual production rate by the mean-life of tritium which is 17.8 years. The mean life is found by dividing the half-life by ln 2.

[11] “Fiscal Year 2016 Stockpile Stewardship and Management Plan, Report to Congress,” March 2015, National Nuclear Security Administration and U.S. Department of Energy, p. 2-35.

current scheduled tritium production until 2024 is shown in Table 1.[12] By 2025 it is anticipated that a production rate of 2,800 grams of tritium per fuel cycle (both reactors combined—about 1,870 grams per year) will be needed. Given that it has been found that only about 0.95 grams of tritium are being produced per TPBAR, rather than the one gram per TPBAR that had been anticipated, this will require the irradiation of about 1,504 TPBARs per fuel cycle per reactor.

The 2025 rate of tritium production is not an equilibrium rate but rather a higher rate to allow the expansion of the tritium stockpile.[13] As some point after 2025 the tritium production rate "may be reduced slightly" to a smaller steady-state rate.[14] If the 2025 tritium production rate were the equilibrium value then this would imply a total tritium stockpile of about 33.3 kilograms which works out to about 5.3 grams of tritium per weapon. A slight reduction in the production rate would imply a total tritium stockpile of around 30 kilograms and an average of perhaps 4.5 to 5.0 grams of tritium per weapon. These numbers indicate that the amount of tritium per weapon will be increased by about 50%.

The increase in the tritium production rate has already been delayed. Originally it was planned to irradiate 1,104 TPBARs in cycle 14 (starting in October 2015) at Watts Bar 1 and reach the maximum of 1,504 in cycle 15. However, the failure to complete the supplemental EIS until February 2016 meant that it was not possible to change the license at Watts Bar 1 (which currently limits the reactor to just 704 TPBARs per fuel cycle) in time for additional TPBARs to be loaded in October 2015. As a result the ramp-up in tritium production has been delayed one fuel cycle (18 months).

Need to Produce Tritium in a Second Nuclear Power Reactor

As recently as 2014, plans called for just using the Watts Bar 1 reactor to produce tritium but now a second reactor (one of the two at the TVA's Sequoyah site) will be used as well. There appear to be two reasons for this change. The first is the increased tritium requirement resulting from the increase in tritium per nuclear weapon discussed above. The second is the need to efficiently use "unobligated" LEU (low enriched uranium) required to fuel the power reactors.[15]

Unobligated LEU is fuel that has no peaceful use requirement. Unobligated uranium must be used to produce the tritium in the TVA reactors since the tritium is used in nuclear weapons. All LEU from foreign sources has a peaceful use requirement. A particular problem is the enrichment used to produce the LEU. The gaseous diffusion plant at Paducah, Kentucky produced LEU using U.S. developed technology but it was shut down in 2013. The 2014 bankruptcy of the United States Enrichment Corporation could mean that there will be no uranium enrichment capacity in the U.S. that does not rely on foreign technology.

Using just one reactor to produce large amounts of tritium introduces inefficiencies. The Watts Bar 1 reactor contains 193 fuel assemblies, which in normal operation remain in the reactor for

---

[12] "Fiscal Year 2017 Stockpile Stewardship and Management Plan, Report to Congress," March 2016, National Nuclear Security Administration and U.S. Department of Energy, p. 3-12.
[13] "Tritium and Enriched Uranium Management Plan Through 2060, Report to Congress," October 2015, U.S. Department of Energy, pp. 9-12.
[14] *Ibid.*, p. 11.
[15] *Ibid.*, pp.10-11.

three fuel cycles (4 ½ years). At each refueling about 64 assemblies (one-third of the core) are removed and 64 fresh fuel assemblies are added. The TPBARs must be used in fresh fuel assemblies and the maximum number of TPBARs per assembly is 24. Therefore under normal operation a maximum of 1,536 TPBARs can be irradiated each fuel cycle. The irradiation of 2,500 TPBARs would require over one hundred fresh fuel assemblies each refueling, which would mean replacing over one half the core. Some fuel assemblies would be in the reactor only two fuel cycles and some only one fuel cycle instead of the normal three. In addition the amount of tritium produced per TPBAR is estimated to be only 0.85 grams instead of the current 0.95 grams if as many as 2,300 TPBARs are irradiated per fuel cycle.

By limiting the number of TPBARs irradiated per cycle in each reactor to just 1,504 as is currently planned, it will be possible for the fuel assemblies to remain in each reactor for the full three cycles while still producing 0.95 grams per TPBAR. The U.S. Department of Energy has identified options that could provide enough unobligated LEU to run two reactors until 2041.[16] Unobligated LEU must be used to fuel a reactor for two fuel cycles before it starts irradiating TPBARs in order to clear the reactor of obligated LEU. For a reactor at the Sequoyah site to start irradiating TPBARs in the spring of 2021, that reactor will have to start being fueled with unobligated LEU in the spring of 2018 (only two years from now).

Conclusions

The U.S. is currently using the commercial nuclear power reactor Watts Bar 1 to produce tritium by irradiating lithium. This program has suffered significant delays mainly due to an unexpectedly high tritium permeation rate from the TPBARs. Efforts to reduce this high permeation rate have failed and the problem has been solved administratively by revising the EIS. Using the data provided by this program I have calculated that currently the average U.S. nuclear weapon uses about 3.2 grams of tritium.

Buried in the Stockpile Stewardship Plan is the revelation that the U.S. intends to significantly increase the amount of tritium per weapon. This change is intended to reduce the frequency with which the tritium reservoirs in the weapons are replaced and to help ensure weapon reliability in an era where there is no nuclear testing. I have estimated that the amount of tritium per weapon will be increased by roughly 50% to about 4.5 to 5.0 grams.

This increase in tritium per weapon will lead to a corresponding increase in the required production of tritium. This production increase plus the need to conserve unobligated LEU will require the use of a second commercial nuclear power reactor to produce tritium. The U.S. plans to start tritium production in 2021 at one of the two Sequoyah reactors. To keep this plan on schedule, the U.S. will need to start fueling this reactor with unobligated LEU in the spring of 2018.

---

[16] *Ibid.*, pp.12-22.

Table 1

Actual and Projected TPBAR Irradiation

Approximate fuel cycle dates	Reactor	Number of TPBARs irradiated
Fall 2003 to Spring 2005*	Watts Bar 1	204
Spring 2005 to Fall 2006	Watts Bar 1	204
Fall 2006 to Spring 2008	Watts Bar 1	204
Spring 2008 to Fall 2009	Watts Bar 1	368
Fall 2009 to Spring 2011	Watts Bar 1	204
Spring 2011 to Fall 2012	Watts Bar 1	544
Fall 2012 to Spring 2014	Watts Bar 1	544
Spring 2014 to Fall 2015	Watts Bar 1	704
Fall 2015 to Spring 2017	Watts Bar 1	704
Spring 2017 to Fall 2018	Watts Bar 1	1,104
Fall 2018 to Spring 2020	Watts Bar 1	1,504
Spring 2020 to Fall 2021	Watts Bar 1	1,504
Spring 2021 to Fall 2022	Sequoyah**	400
Fall 2021 to Spring 2023	Watts Bar 1	1,504
Fall 2022 to Spring 2024	Sequoyah	800
Spring 2023 to Fall 2024	Watts Bar 1	1,504

*This is the sixth fuel cycle for Watts Bar 1. The current fuel cycle (fall 2015 to spring 2017) is the fourteenth fuel cycle.
**It has not been determined which of the two Sequoyah reactors will be used.