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**氚生产综述**  
**AN OVERVIEW OF TRITIUM PRODUCTION**

**中国核情报中心**  
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# 氙生产综述

何开辉 黄锦华 冯开明  
(核工业西南物理研究院, 成都, 610041)

## 摘要

比较了裂变堆、加速器、聚变堆三种氙生产装置的不同特点。裂变堆特别是商用轻水反应堆使用较成熟的技术, 也满足当前安全和环境设计指导方针。相反, 加速器生产氙除了其高昂的成本外有很多的优点, 而聚变堆特别是以聚变中子源为基础的氙生产似乎能提供改进的安全和环境影响; 然而, 其成本有待进一步评估。

关键词: 氙生产 聚变中子源

# **An Overview of Tritium Production**

HE Kaihui HUANG Jinghua FENG Kaiming  
(Southwestern Institute of Physics, Chengdu, 610041)

## **ABSTRACT**

The characteristics of three types of proposed tritium production facilities, fissile type, accelerator production tritium (APT), and fusion type, are presented. The fissile reactors, especially commercial light water reactor, use comparatively mature technology and are designed to meet current safety and environmental guidelines. Conversely, APT shows many advantages except its rather high cost, while fusion reactors appear to offer improved safety and environmental impact, in particular, tritium production based on the fusion-based neutron source. However, its cost keeps unknown.

**Keywords:** Tritium Production, Fusion-based Neutron Source

## INTRODUCTION

Tritium is a radioisotope of hydrogen made in small quantities in nature by cosmic rays and decays at the rate of about 5.5% per year. To obtain the quantities required for national defense and civilian needs, it must be produced in nuclear devices or in accelerator. The United States had not produced tritium since 1988. Its Secretary of Energy announced in October 1995 a decision to pursue a "dual-track" strategy, funding both reactor- and accelerator-based systems for a three-years period, after that DOE would select the most promising method, and in 1998, the former was chosen for the production of tritium.

Safety and environmental impact are high priority considerations in the design, construction, operation and eventual decommissioning of all the new production facility design programs. So far three types of tritium production facilities have been reported. They are fissile type, accelerator production tritium (APT), and fusion type. In fissile type two reactor designs that were developed to utilize thermalized neutrons produced in fissile fueled nuclear piles to irradiate  ${}^6\text{Li}$  in target assemblies. These two designs are the heavy water moderated reactor (HWR)<sup>[1]</sup>, operating at a low temperature, and the modular high temperature gas-cooled reactor (MHTGR)<sup>[2]</sup>, operating at sufficiently high temperature to also provide excess power generation. In fusion type four thermonuclear reactors produces neutrons by the fusion of D-T fuel. These fusion concepts include two magnetic confinement concepts, a tandem-mirror (TM)<sup>[3]</sup> and a tokamak tritium production reactor (TTPR)<sup>[4]</sup>, and two inertial confinement concepts initiated by laser drivers, an indirectly driven target design, ICF-TPR<sup>[5]</sup>, and a directly driven target design, SIRIUS-T<sup>[6]</sup>. In Ref[7]., a brief comparison has been performed among HWR, MHTGR, TM, ICF-TPR and SIRIUS-T according to their technical operations, safety and environmental impact and projected cost of tritium produced. However, at that time, accelerator and fusion reactor were pre-conceptual designs.

Thus, our intention in this paper is to overview the various means of tritium production as possible as we can. Nevertheless, we mainly concern about the means of APT<sup>[8]</sup>, Commercial Light Water Reactor (CLWR)<sup>[9]</sup> and TTPR based on fusion neutron source. Such a comparison is difficult because of the subtle topic of costs. However, such a comparison is instructive to determine what decision is the most promising and is constructive to select or develop a means to the production of tritium suitable for our national military and civilian needs.

# 1 TECHNICAL COMPARISON

In order to compare the various tritium production facilities clearly and fully, several aspects of comparison are described in the following sections.

## 1.1 The principles of various tritium production facilities

Both fusion and fission facilities produce tritium by the absorption of thermalized neutrons in lithium target materials, via the reaction  ${}^6\text{Li}(n,\alpha) {}^3\text{H}$ . From Table.1, it can be seen that in a fission event, nearly 1.8 neutrons are supplied during the fissioning of  ${}^{235}\text{U}$  that also produces approximately 200 MeV of energy, while 1 neutron is required to continue the chain reaction, only 0.8 neutron/fission is available to react with Li. Consequently, the production of one tritium atom release approximately 250 MeV. And in a fusion event, via the reaction  ${}^2\text{H}({}^3\text{H},n) \alpha$  and Be multiplication, one net T atom is produced with the simultaneous production of approximate 28 MeV of energy. Then, the production of one tritium atom in a fission facility releases approximate 9 times as much thermal energy as compared to a fusion facility. If this thermal energy is not utilized, it must be released to the environment that may be detrimental to the proposed siting of a fissile reactor as opposed to a fusion reactor.

**Table 1 Tritium production in fission and fusion events**

The type of reactor	Reactions
Fission reactor	$n+{}^{235}\text{U}=2.5 n-0.7 n(\text{leakage} + \text{absorption})-1 n(\text{fission chain}) +200 \text{ MeV}$ +fission products $0.8 n+{}^6\text{Li}=0.8 \text{ T}+0.8 {}^4\text{He}$
Net reaction, nuclear	$n+{}^{235}\text{U}+{}^6\text{Li}=0.8 \text{ T}+0.8 {}^4\text{He}+200 \text{ MeV}+ \text{fission products}$
Net reaction, thermal	$\sim 250 \text{ MeV/T atom}$
Fusion reaction	$\text{D}+\text{T}=\text{n}+{}^4\text{He}+17.6 \text{ MeV}$ $\text{n}+{}^9\text{Be}=2.3 n-2.24 \text{ MeV}(\text{endothermic reactions})-0.4 n (\text{blanket absorption})$ $1.9 \text{ n}+{}^6\text{Li}=1.9 \text{ T}-1 \text{ T}(\text{fusion fuel})+2 {}^4\text{He}+9.12 \text{ MeV}$
Net reaction, nuclear	$\text{D}+\text{T}+{}^9\text{Be}+{}^6\text{Li}=0.9 \text{ T}+2 {}^4\text{He}+24.5 \text{ MeV}$
Net reaction, thermal	$27.2 \text{ MeV/T atom}$

## Heavy Water Reactor (HWR)

The HWR utilizes fissile fuel with the neutrons moderated by  $\text{D}_2\text{O}$  at low

temperature so that Al-Li targets can be used. These targets provides the following advantages: Low permeability of tritium, low parasitic neutron capture, and low tritium solubility in the Al. The thermal power rating of this facility is reported as 2500 MW. If the plant availability is rated at 70%, this reactor yields about 7 kg of tritium per calendar year (CY).

#### **The Modular High Temperature Gas-Cooled Reactor (MHTGR)**

This production reactor concept utilizes 350 MW (thermal) modular high temperature gas-cooled reactors based upon designs for commercial MHTGR's. The MHTGR uses a graphite-moderated, graphite-reflected annular core formed from prismatic graphite block and helium-cooled. This concept design includes four modules combined into a production block that share a spent-fuel storage facility and other support facilities. Two production blocks (8 modules) are combined in the complete facility. With the 8 MHTGR modules at full power operation, the system would produce 2800 MW(thermal). If the plant availability is rated at 70%, this reactor yields about 7.8 kg of tritium per CY.

#### **Commercial Light Water Reactor (CLWR)**

A CLWR is a nuclear reactor designed and constructed to produce electric power for commercial use. Tritium can be produced during normal operation of a CLWR. The production of tritium in a CLWR is technically straightforward and requires no elaborate, complex engineering development and testing program. The process uses TPBARs (Tritium Production Burnable Absorber Rods) to absorb excess neutrons and help control the power in a reactor. Pressurized water reactors are well suited for the production of tritium because the TPBARs can be inserted into the non-fuel positions of the fuel assemblies. Tritium is generated within the TPBARs as they are irradiated during normal reactor operation. The neutron absorber material in the TPBARs would be enriched in the isotope  ${}^6\text{Li}$ , instead of the boron usually used in the burnable absorber rods. When the TPBARs are inserted into the reactor core, neutrons would be absorbed by the  ${}^6\text{Li}$  isotope, thereby initiating a nuclear process that would turn it into  ${}^7\text{Li}$ . The new isotope would then split to form  ${}^4\text{He}$  and tritium. The tritium then would be captured in a solid metal nickel-plated zirconium material in the TPBAR called a "getter."

#### **Accelerator Production Tritium (APT)**

In APT, tritium is made by capturing neutrons in  ${}^3\text{He}$  (helium gas). To supply the neutrons, protons are energized in a linear accelerator and used to bombard a heavy-metal target made of tungsten or lead, creating neutrons in a process known

as "spallation." The resulting neutrons are moderated by collisions with lead and water, increasing the efficiency of their capture in the helium gas flowing through the target to make tritium. The tritium is extracted from the gas continuously, providing supply to the stockpile. In general, producing tritium through neutron capture on  $^3\text{He}$  is as following:

- (1) Protons are accelerated to 1700 MeV in the accelerator and directed into the target/ blanket;
- (2) High-energy protons cause nuclear spallation reactions in tungsten or lead ;
- (3) Spallation produces 47 neutrons per proton at 1700 MeV ;
- (4) Neutrons slow down in collisions with lead and water ;
- (5) Neutrons are absorbed by  $^3\text{He}(n, p)$ , producing tritium:  $^3\text{He}+n\rightarrow\text{T} + p$ .

#### **Magnetic Confinement Fusion Facility**

Conceptual designs have been reported to utilize DT fusion reactors to produce neutron by use of magnetically confined plasma. Two confinement configurations were considered: a Tokamak Tritium Production Reactor (TTPR) and the Tandem-Mirror design (TM). The TTPR concept is based on physics and technology that either exists or is being developed and will be tested under integrated, prototypical conditions in the International Thermonuclear Experimental Reactor (ITER).

The neutron produced in either of these facilities are emitted randomly from the plasmas and penetrate into a blanket structure containing a Be neutron multiplier. These neutron are absorbed in Li breeder materials to generate tritium. When the neutron losses, parasitic captures and one T atom is reserved for refueling were taken into account. The TM had an excess of 0.67 and the TTPR 0.52 T atoms/incident neutron. The fusion power is 450 MW for the TM producing 10.8 kg of tritium per CY (plant availability is 70%). The TTPR can provide 2.0 kg/a tritium for weapons replenishment operating at a fusion power level of 500 to 1000 MW and at a plant factor of 10% to 25%<sup>[12]</sup>. No structural component should need to be replaced because of radiation damage during the 40-years lifetime of the TTPR.

#### **Inertial Confinement Fusion Facility**

Two conceptual designs have been proposed for the production of tritium by neutrons released from inertially confined fusion reactions, namely the Inertial Confinement Fusion-Tritium Production Reactor (ICF-TPR) and the reactor study "SIRIUS-T" . Both of these devices use laser beams to compress small, spherical targets of D/T solid to very high density and heat the compressed fuel to high temperatures in order to initiate the thermonuclear reaction. Both of these two

designs use beryllium in a surrounding chamber to multiply the neutrons. These neutrons are captured in a flowing stream of liquid lithium to produce tritium. The tritium in the lithium is extracted outside the reaction chamber. Table 2 summarized the brief technical aspects of each type of facilities.

**Table 2 Technology comparison of tritium production facilities**

	Fission facility	Fusion facility	Accelerator
Fuel	$^{235}\text{U}$	D-T fusion	1700 MeV P-beam W/Pb target
Tritium production reactions	Fission-n Be multiplier	Fusion-n Be multiplier	Spallation-n
TBR(Net) <sup>1)</sup>	0.8	0.5~1.1	40~50
Reactor power, $\text{MW}_{\text{th}}$	$\geq 2500$	400~1000	400
Safety issues	Fission products & tritium containment Afterheat removal	Tritium fuel cycle containment Afterheat removal	Spallation product containment
Environmental issues	Fission Products Storage Waste heat disposal	Waste heat disposal Radioactive structure storage	Spallation product isposal Waste heat disposal
Status	Proven	Still requires R&D for fusion technology	P-beam current is too low

Note: 1) TBR, tritium breed ratio

## 1.2 The characteristics of structures of various tritium production facilities

### ICF Facilities

In inertial confinement facilities, the shape of the reaction chamber is influenced by the type of target. The ICF-TPR uses an “indirect-drive” target which requires only two laser beams from opposite directions. Consequently, this chamber is cylindrical, 6 m OD by 9 m high. By contrast, SIRIUS-T uses a simple target design in which the D/T “ice” is contained in a thin shell. This target to “ignite” the target must be illuminated very symmetrically, which requires 92 laser beams. So the direct-drive chamber is therefore a sphere of 4 m ID, composed of hexagonal and



pentagonal modules, which accommodate the 92 beams.

### **MCF Facilities**

The most representative MCF facility is the Tokamak Tritium Production Reactor (TTPR) II<sup>[12]</sup> designed by Prof. W. M. Stacey staff. The design concept for a fusion neutron source-based tritium production reactor is using liquid Li as coolant and tritium breeder and using V-4 Cr-4 Ti as the structural material. The fusion neutron source is developed on the physics and technology that will be developed in ITER. In the design concept, the tritium production reactor has a toroidal configuration. The toroidal tokamak plasma is surrounded by a first wall, behind which is located the TPA (Tritium Production Assembly) (or blanket), followed by a vacuum vessel and a primary shield, and then the toroidal field (TF) magnets. The TPA was subdivided toroidally into 68 sectors, with the Li flowing radially inward at the top/bottom, flowing poloidally, and then exiting radially at the bottom/top.

### **The APT Facility**

In recent designs, the APT facility is made up of the following components:

(1) Injector The proton beam begins in the APT injector. This beam is formed by ionizing hydrogen atoms and accelerating them to form a low-energy proton beam.

(2) Accelerator The protons are accelerated to the necessary energy before being transported to the target region. Proton energy for the Strategic Arms Reduction Treaty II (START-II) tritium production requirement is about 60% the value of that for START-I.

(3) Tritium Production At the high-energy end of the accelerator, the beam is expanded to distribute protons evenly. The expanded proton beam strikes a tungsten or lead target to produce neutrons through spallation. Neutrons are then slowed and finally captured in <sup>3</sup>He to produce tritium. The APT target/blanket will operate at low temperature and pressure, and has a minimal inventory of tritium.

(4) Tritium Separation The tritium produced in the target/blanket is recovered and purified. The technology for this process has been successfully demonstrated at full scale. In addition, the process has been designed and tested to prevent release of radioactive tritium to the environment.

## **1.3 Advantages and disadvantages**

### **CLWR**

The CLWR Project provides a highly reliable, technically mature, robust and cost-effective solution for the earliest delivery of tritium gas.

The replacement of burnable absorber rods with TPBARs should have few impacts on the normal operation of the reactor. The normal power distribution within the core and reactor coolant flow and its distribution within the core would remain within existing technical specification limits. Some tritium is expected to permeate through the TPBARs during normal operation, which would increase the quantity of tritium in the reactor's coolant water system. Since tritium is a type, or isotope, of the hydrogen atom, once the tritium is in the reactor's coolant water system, it could combine with oxygen to become part of a water molecule and could eventually be released to the environment.

With respect to construction impacts associated with tritium production, use of an existing CLWR would have the least impact on the natural environment. Completion of an unfinished reactor would have positive socioeconomic impacts, as would the APT, using existing CLWR would have no socioeconomic impacts. For all alternatives, the environmental impacts associated with construction are considered small.

#### **APT**

APT is a very safe and environmentally benign system. The fundamental reason for this is that neutrons are produced by the spallation process rather than by nuclear fission. APT will produce the required neutrons without fissile materials or a nuclear chain reaction, avoiding the production of long-lived radioactive products such as plutonium or neptunium. Additionally, the constant extraction of tritium from the blanket not only provides tritium to the stockpile quickly, but also avoids any radioactive buildup. In brief, the advantages of APT are summarized in the following:

- No fissile materials
- No spent nuclear fuel produced
- Produces very little low-level and no high-level radioactive waste per year
- No chance of a criticality accident
- Minimal environmental effects
- No nuclear proliferation issues
- Engineering simplicity provides inherent safety advantages
- Constant extraction of tritium
- Immediate shutdown
- Easily scaled to stockpile needs

## TTPR

As stated by Prof. W.M.Stacey that it seems that there are three intrinsic advantages of developing a fusion-based neutron source tritium production reactor over an accelerator-based one. Firstly, a fusion-based neutron source is a volumetric source with a large surface area available for locating tritium production assemblies (TPAs) in a high neutron flux, whereas an accelerator-based neutron source is essentially a localized source with a limited surface area available for locating TPAs in a high neutron flux. As a consequence, the high-neutron-flux volume should be much greater for a fusion neutron source than for an accelerator neutron source. Secondly, the development of most of the physics and technology needed for a fusion neutron source has been carried out by an international collaboration in support of the ITER, whereas the accelerator development would require a substantial additional research and development (R&D) program solely for the purpose of building the neutron source for a tritium production reactor. Finally, the experience gained in building and operating a fusion-based tritium production reactor would be directly applicable to the development of the fusion reactors for electrical energy production, as well as to the build of the fusion-based neutron source for other application, whereas the experience gained in building and operating an accelerator-based tritium production reactor would seem to be directly applicable only to building other accelerator-based neutron source facilities.

Remarkably, in this design concept, any combination of power level, plant factor (PF), and TBR with the same product  $P_{\text{fus}} \times \text{PF} \times \text{TBR} = 120$  will accomplish the objective of producing 2 kg/a excess tritium (e.g., 750 MW, TBR=1.5, and 11% plant factor). Therefore, the design concept has a high probability of meeting its objective.

## 2 ECONOMIC ASSESSMENTS OF TRITIUM PRODUCTION FACILITIES

It is difficult to do this task because different design concept has its own costing information, let alone the level of detail of each design. Relative ripe design concepts, e.g. the HWR and the MHTGR, following the NPR capacity cost evaluation guidelines<sup>[10]</sup> supplied in 1988. And some of the fusion reactors were costed by their designers, and in TTPR concept design, the designers didn't make a cost estimate<sup>[11]</sup>. Nevertheless, Prof. L.J.Wittenberg used NPR guidelines compares

the costs of different reactors<sup>[7]</sup>. So in this paper only economic assessments of APT and CLWR are made using information from U.S. DOE. Cost is determined in terms of investment cost and life cycle cost.

The investment cost remaining (FY 1999-2008) to develop, design, construct, and startup the APT facility, size to meet START I tritium requirements, would be \$3.4 billion. The investment cost remaining to establish capabilities to produce tritium through irradiation services with existing commercial reactors and to design, construct, and startup the TEF (Tritium Extraction Facility) would be 580 million. This investment cost would increase by \$1.2~1.8 billion if finishing an incomplete reactor is included. The annual operating cost of APT would be \$135 million when meeting START I requirements. The annual operating cost to produce START I quantities of tritium using existing reactors would be \$20~60 million. D&D costs for the APT would be \$260 million. For the reactor alternative, DOE would be liable only for D&D of the TEF at \$8 million. Life-cycle cost for the APT is estimated to be \$9.2 billion. Life cycle cost for the use of commercial reactors is estimated to be \$1.2 billion to \$2.9 billion, depending on the investment-revenue combination. The present discount value of the APT alternative, using a 3.6 percent discount rate, would be \$5.2 billion. The present discount value of the commercial reactor alternative would range from \$880 million to \$2.0 billion, depending on the investment and fuel enrichment strategies. All costs discussed above refer to constant FY 1999 dollars.

### 3 RESULTS AND CONCLUSIONS

A relatively detailed comparison of the characteristics of three types of proposed tritium production facilities, fissile type, accelerator production tritium (APT), and fusion type, has been made. Different facility has its own specific advantages. The fissile reactors use comparatively mature technology and are designed to meet current safety and environmental guidelines. Using existing CLWR to produce tritium would involve insignificant socioeconomic impact, while operation of a newly completed reactor and the APT would have the greatest positive socioeconomic impacts. At the same time, utilizing the commercial reactor would cost significantly less than the APT in terms of investment cost, operating costs, D&D costs, and life cycle costs. Although TTPR was not estimated, fusion reactors appear to offer improved safety and environmental impact, in particular,

tritium production based on the fusion-based neutron source.

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