Comparison of Tritium Production Reactors

L.J. Wittenberg

October 1990

UWFDM-840

Presented at the 9th Topical Meeting on the Technology of Fusion Energy, 7–11 October 1990, Oak Brook IL.

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

Comparison of Tritium Production Reactors

L.J. Wittenberg

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

October 1990

UWFDM-840

Presented at the 9th Topical Meeting on the Technology of Fusion Energy, 7–11 October 1990, Oak Brook IL.

COMPARISON OF TRITIUM PRODUCTION REACTORS

Layton J. Wittenberg
Fusion Technology Institute
University of Wisconsin-Madison
Madison, WI 53706
(608) 263-1709

ABSTRACT

The characteristics of seven proposed tritium production reactors, two fissile, one accelerator, and four fusion designs, were examined. The fission reactors use near-term technology and are designed to meet current safety and environmental guidelines. Conversely, the fusion reactors require long-term research and development but appear to offer improved safety and environmental impact and, perhaps, much lower costs.

INTRODUCTION

The U.S. Department of Energy has initiated a New Production Reactors Program which will provide for the design, construction and operation of new facilities for the production of tritium and other special nuclear materials. The preliminary design phase of this mission is currently in progress, leading to construction and operation by the year 2000. Two reactor designs which are being developed utilize thermalized neutrons produced in fissile fueled nuclear piles to irradiate Li-6 in target assemblies. These two designs are the heavy water moderated reactor (HWR),[1] operating at low temperature, and the modular high temperature gas-cooled reactor (MHTGR)[2] which will operate at sufficiently high temperature to also provide excess electrical power generation.

Safety and environmental impact are high priority considerations in the design, construction, operation and eventual decommissioning of all the new production reactor design programs.[3] The Secretary of Energy has made the commitment that the new production reactors program will provide a level of safety and safety assurance that meets or exceeds that offered to the public by modern commercial nuclear power plants.

Currently, five conceptual designs of alternative concepts to fissile reactors have been proposed to supply neutrons for tritium production, with the caveat that longer times for research and development would be required than the proposed New Production Reactor Program. These include the Accelerator Production of Tritium (APT)[4] and four thermonuclear reactors which produce neutrons by the fusion of deuterium-tritium fuel. These fusion concepts include two magnetic confinement concepts, a tandem-mirror (TM)[5] and a tokamak (TOK),[6] and two inertially confined concepts initiated by laser drivers, an indirectly driven target design (ICF-TPR),[7] and a directly driven target design,[8] SIRIUS-T.

Each of the production reactor concepts will be described briefly and compared according to their technical operations, safety and environmental impact and projected cost of tritium produced. Such a comparison is difficult because the accelerator and fusion reactors are only conceptual designs; however, such a comparison is instructive to determine if the alternative concepts have improved characteristics which would justify their long-term research and development costs.

COMPARISON OF FISSION AND FUSION TRITIUM-BREEDING

Nuclear Reactions

Both fission and fusion reactors produce tritium by the absorption of nearly thermalized neutrons in lithium target materials, via the reaction $^6Li(n,\alpha)^3H$. In a fission reactor nearly 1.8 neutrons are supplied during the fissioning of ^{235}U which also produces ~200 MeV of energy (Table 1). Because 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 T atom releases ~250 MeV.

In a fusion reactor utilizing the nuclear reaction $^2H(^3H,n)\alpha$, one neutron is generated per fusion event with the release of 17.6 MeV of energy. In order to increase the production of tritium, this neutron bombards a ^9Be atom in a surrounding blanket to produce a neutron multiplication of ~2.3. These secondary neutrons react with Li to produce ~1.9 atoms of T with the release of 9.12 MeV. One T atom must be reserved as new fuel; consequently, in a fusion reactor with low neutron leakage, one net T atom is produced with the simultaneous production of ~28 MeV of energy (Table 1).

Table 1. Fission and Fusion Tritium Breeding Reactions

Reactor	Reactions
Fission	n + ^{235}U = 2.5 n - 0.7 n (leakage + absorption) - 1 n (fission chain) + 200 MeV + fission products
	0.8 n + ^{6}Li = 0.8 T + 0.8 ^{4}He
Net Reaction, Nuclear	n + ^{235}U + ^{6}Li = 0.8 T + 0.8 ^{4}He + 200 MeV + fission products
Net Reaction, Thermal	~250 MeV/T atom
Fusion	D + T = n + ^{4}He + 17.6 MeV
	n + ^{9}Be = 2.3 n - 2.24 MeV (endothermal reactions) - 0.4 n (blanket absorption)
	1.9 n + ^{6}Li = 1.9 T - 1 T (fusion fuel) + 2 ^{4}He + 9.12 MeV
Net Reaction, Nuclear	D + T + ^{9}Be + ^{6}Li = 0.9 T + 2 ^{4}He + 24.5 MeV
Net Reaction, Thermal	27.2 MeV/T atom

(1)Adapted from Reference 9.

Thermal Energy Release

As noted above, the production of one atom of T in a fissile reactor releases ~9 times as much thermal energy as compared to a fusion reactor. If this thermal energy is not utilized, it must be released to the environment which may be detrimental to the proposed siting of a fissile reactor as opposed to a fusion reactor. The proposed tritium production reactors, in which no attempt is made to utilize the thermal energy, are water-cooled at <100°C, using low temperature technology, such as aluminum structures and Al-Li alloys as T breeder materials.

If the thermal energy for either a fission or fusion production reactor is utilized for power production, then the reactor temperature is increased to >300°C so that efficient high pressure steam can be formed for steam-electric power systems. The reactor components in this case must be designed for high temperature operation, using either steel or carbon structures and targets fabricated from either a Li ceramic compound or liquid Li.

Safety and Environmental Impact

All the production reactors are being designed to high safety standards and to minimize their environmental impact during routine operations and accidental events. All of the devices will be enclosed in containment structures which mitigate the release of tritium and other harmful radioactive products following an accident. During routine operations the integrity of the heat exchanger between the reactor coolant and the environmental heat sink is very important because tritium diffuses easily, particularly at high temperatures, through metals used to fabricate heat exchangers. In some of the designs, the reactor coolants may contain tritium which could leak or diffuse through this heat exchanger.

Because the fission reactors utilize ^{235}U fission as the neutron source for tritium production while the fusion reactors do not, the fission reactors must be designed for the containment of the fuel during normal and off-normal operation and for extended periods upon removal of the fuel from the reactor. Eventually, the spent fuel must be processed and the long-lived isotopes disposed of in safe repositories. By contrast, the fuel and fusion products from a fusion reactor are not long-lived radioisotopes. The metallic structure of a fusion reactor contains some long-lived radioisotopes, although some radioactive isotopes can be avoided by the choice of alternative structural materials. Model studies have shown that decommissioned fusion reactor structures can meet Class C waste disposal ratings which requires burial at only 5 m depth and monitoring for 500 years.

TECHNICAL ASSESSMENT OF PROPOSED TRITIUM FACILITIES

Brief technical aspects of each facility are summarized in Table 2.

Heavy Water Reactor (HWR)

The HWR utilizes fissile fuel with the neutrons moderated by D_2O at low temperature so that Al-Li targets can be used. These targets provide the following benefits: low permeability of tritium, low parasitic neutron capture, and low tritium solubility in the Al. The neutron capture cross-section of deuterium is small and the mass of D_2O is kept low so that the breeding of tritium is enhanced. The thermal power rating of the reactor is reported as 2500 MW. Although the tritium producing potential of this reactor has not been declassified, we can estimate from Table 1 that ~10 kg of T is produced per full power year (FPY). All the production reactors considered for this study have been rated at 70% availability, yielding ~7 kg of tritium per calendar year (CY).

Table 2. Tritium Production Reactors - Technology Assessment

	Fission Reactors		Accelerator Study	Magnetic Conf. Fusion		Inertial Conf. Fusion	
	HWR	MHTGC		Tandem Mirror	Tokamak	ICF-TPR	SIRIUS-T
Fuel	^{235}U-Fission		1.6 GeV, p-beam Pb (liq.) Target	D/T Fusion		D/T Fusion	
Tritium Production Reactions	Fission - n Thermal Moderator LiAl Breeder	Li Ceramic Batch Process	Spallation - n Thermal Mod. LiAl Breeder Batch Process	Fusion - n Be Multiplier LiAl Breeder Batch Process		Fusion - n Be Multiplier Liq. Li Breeder Continuous T_2 Removal	
TBR (net)[a]	0.8	0.8	40-50	0.67	0.52	1.08	0.90
Reactor Power, MWth	2500	2800	400	540	570	532	1410
Fission/Fusion Power, MWth	2500	2800	-	427	450	400	1000
Aux. Power Req'd., MWe	~50	(Produces 542 MWe)	900	355	560	(Power Self-Sufficient)	
Safety Issues	•Fission Products and Tritium Containment •Afterheat Removal		•Spallation Product Containment	•Tritium Fuel Cycle Containment		•Tritium Fuel Cycle Containment •Afterheat Removal	
Environmental Issues	•Fission Products Storage •Large Waste Heat Disposal		•Spallation Product Disposal; Waste Heat Disposal	•Waste Heat Disposal •Radioactive Structure Storage		•Lower Waste Heat Disposal •Radioactive Structure Storage	
Status	Proven	R&D for Tritium Breeder	Major R&D for p-beams + Pb Target	Requires Long-Term R&D for Fusion Technology			

(a)Tritium breeding ratio for each fission or fusion event, minus one neutron for fission chain or one tritium atom for fusion fuel, or number of neutrons produced per accelerated proton.

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 proposed 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.

The MHTGR uses a graphite-moderated, graphite-reflected annular core formed from prismatic graphite block and helium-cooled. The fuel consists of highly enriched uranium oxycarbide (UCO) microspheres which are coated with successive layers of pyrolytic graphite (PyC) and silicon carbide (SiC). These coated fuel particles are bonded together with a carbonaceous binder to form fuel rods which are sealed into channels machined in the prismatic fuel elements.

Enriched ^{6}Li aluminate microspheres which are coated with successive layers of PyC and SiC form the tritium production targets. Annular target compacts are formed from the coated target particles bonded with carbonaceous binder. These target compacts are stacked and sealed inside a cylindrical, annular graphite sleeve, which is inserted into the prismatic fuel block.

Each MHTGR module has a single loop heat transfer system that transfers heat from the reactor core to the steam system via a single helical-coiled steam generator with an integral superheater. Steam generated during normal operation is delivered to a single main turbine and condenser to produce a net output of 135 MWe per module. With the eight MHTGR modules at full power operation, the system would produce 2800 MW (thermal).

Accelerator Production of Tritium (APT)

The conceptual design of the APT facility consists of an accelerator system, a beam transport system, a target system, a tritium extraction system and a waste processing and handling system. In such a facility, a proton beam is accelerated to an energy of 1.6 GeV and a current of 250 mA by use of a radio-frequency current drive. These protons are focused on Pb targets to yield 40-50 neutrons per proton by spallation and evaporation reactions. These neutrons are moderated by water and subsequently captured in Li-Al fertile rods cooled by flowing water to maintain 90°C. The target rods are periodically removed and the tritium extracted in a separate facility. The use of lead for primary neutron production instead of a fissionable material provides lower decay heat with reduced safety concerns, as well as a lower amount of radioactive waste without the concern for the long-lived actinide wastes.

The APT target receives ~400 MW (thermal) and yields (6 to 7) × 10^{19} neutrons/s, giving a thermal energy to neutron yield ratio of ~40 MeV/neutron. The accelerator would require 900 MWe to drive the proton beam with an assumed efficiency of 44% for the conversion of electrical power to particle acceleration.

Magnetic Fusion Energy Reactors

Preconceptual designs have been investigated to utilize DT fusion reactions to produce neutrons by use of magnetically confined plasmas. Two confinement geometries were considered, namely, (1) the tokamak design (TOK) and (2) the tandem mirror design (TM).

The neutrons produced in either of these devices are emitted randomly from the plasmas and penetrate into a blanket structure containing a Be neutron multiplier (Table 1). The neutrons are absorbed in Li breeder materials to yield tritium. When the neutron losses, parasitic captures and one T atom is reserved for refueling were considered, the TM had an excess of 0.67 and the TOK 0.52 T atoms/incident neutron. Both the TOK and the TM fusion reactor concepts utilized ^{6}Li-Al alloys as the tritium breeding materials with the targets cooled and moderated by water at <100°C.

The fusion power is 450 MW for the TM and 427 MW for the TOK producing 10.8 and 9.1 kg of tritium per CY. All the current drive for the plasma has to be supplied by external power sources which requires 355 MWe and 560 MWe for the TM and TOK, respectively.

Inertial Confinement Fusion

Two preconceptual 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)[7] and the reactor study[8] "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 designs use Be 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 of the reaction chamber. The moderation and capture of neutrons in the lithium and the structure produces thermal energy which is also transferred by the lithium to a steam-electric turbine outside of the reactor. The electrical power generated is used solely to provide power to the laser and other auxiliary systems.

The shape of the reaction chamber is influenced by the type of target. For instance, 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. For this target to "ignite" the target must be illuminated very symmetrically, which requires 92 laser beams. The direct-drive chamber is therefore a sphere of 4 m ID, composed of hexagonal and pentagonal modules, which accommodate the 92 beams.

Following the target ignition, the nuclear fusion reactions continue until the inertia in the compressed target has been exceeded and the target disintegrates, hurling x-rays, α-particles, unburned fuel and target debris throughout the chamber. Two different techniques have been used in order to attenuate these photons and particles before they impact the first structure surrounding the target, because this structure would be severely damaged. In the ICF-TPR, which is cylindrical, a fall of liquid Li, ~5 cm thick, extends from the top to the bottom of the chamber at 1.5 m from the target and protects the breeding blankets behind the fall. In the SIRIUS-T spherical chamber, xenon gas at a pressure of 133 Pa is used to protect the first structure. In a chamber of 4 m radius, all the photons and debris (but not the neutrons) are stopped before impacting the first structure. The shock wave of Xe gas at this low pressure is small; however, because all the x-ray and ions are attenuated by the Xe, it reaches a high temperature. This thermal energy is then re-radiated to the first wall at a sufficiently slow rate so that the first wall shield, a graphite composite, can withstand the thermal shock.

The tritium breeder blankets were approximately the same thickness, 1.5 m for the ICF-TPR and 1.0 m for SIRIUS-T. The ICF-TPR breeder used Be as a structural material with very little steel which gave 2.08 tritium atoms/incident neutron, or a excess tritium yield of 1.08 per fused T atom in the target. The SIRIUS-T breeder used a vanadium alloy as a structural material with a somewhat smaller amount of Be which gave an overall ratio of 1.90 tritium atoms/incident neutron or 0.90 T atom per T fused in the target.

The tritium production rate in an ICF chamber is a function of the rate of target "burns" and is limited by the rate of debris removal from the chamber and is not constrained by the repeatability of the laser system. For the ICF-TPR the target ignition rate is 2 Hz producing 400 MW of fusion power and 16.9 kg of tritium/CY at 70% availability. For SIRIUS-T the ignition cycle is 10 Hz, producing 1000 MW of fusion power, and 33.3 kg of T/CY at 70% availability.

The technical status of these fusion production reactor concepts places them in the long-term time frame for potential use in the years 2010-2020. In the near-term research and development tasks related to the required laser power, target testing and laser-target interactions will be conducted.

Safety and Environment Impact

The salient features of each reactor in regard to safety (accidents) and environmental impact are summarized in Table 2.

ECONOMIC ASSESSMENTS OF TRITIUM PRODUCTION REACTORS

This task is difficult because the costing information was supplied by diverse groups and the level of detail varied. The HWR, the MHTGR and the APT followed the NPR capacity cost evaluation guidelines[10] supplied in 1988. The fusion reactors were costed by their designers without any guidelines and would be very difficult to reevaluate. For this comparison, the NPR guidelines were used, as defined below, and the missing fusion reactor cost items were added as noted in Table 3.

INVESTMENT CAPITAL

Direct Capital Costs: The total capital costs include all the structures and the equipment installed, as given by the authors of each design.

Indirect Cost: The project management cost is set at 10% of the Direct Capital Costs. The contingency cost is determined as a percent of Direct Capital Cost. This contingency cost reflects an assumption of the maturity of the system to achieve a completed plant which has a 50/50 probability of producing the required production on the required schedule.

Spares and Fission Fuel: This category includes extra parts or equipment which are purchased at the time of construction and the initial fuel core for the fission reactors. For the SIRIUS-T fusion reactor extra Be was purchased for recycle but this cost was included in the Direct Capital Cost.

Operational Costs: This category is given on an annual cost basis.

Cost of Capital: This represents the annual payback of the investment plus interest over the 40 year assumed lifetime of the plant. The long-term "real" interest rate was judged to be 4% and used in this study.

Operation and Maintenance: This line includes the operational staff expenses and expendable items for operation of (1) the reactor, (2) the tritium plant, and (3) waste management. A separate line is used for general site management.

Contingency: This category reflects the maturity of the design and is highest for the APT and the 4 fusion reactor designs.

Capital Upgrade: The NPR cost evaluation study recommends at least 1% of direct capital be used each year for upgrading the facility.

Target Purchase: The designers of SIRIUS-T proposed that fuel targets be purchased as an annual operational cost @ 15¢ per target while the ICF-TPR constructed a 100 $M facility to accomplish this task.

Electric Power: For the designs which were not self-sufficient in electrical power, this power is purchased from a power grid at costs which varied from 28 mills/kWh for the TM and TOK up to 56 mills/kWh for the APT and depended upon the site selection.

Inflation: The total operational costs were compared in 1990 dollars by use of the consumer price index from the original date of each design to CY 1990.

Cost Comparison: The cost per gram of tritium obtained when the annual cost of operation was divided by the proposed annual production of tritium.

RESULTS AND CONCLUSIONS

A meaningful comparison is obtained when the alternative facilities are compared with the HWR, which is an existing technology, and shows the following: (1) the cost of tritium from a new HWR will be ~3 × the current selling price of $29,000/g, (2) the MHTGR supplies tritium at a 45% lower cost, because of the sale of electricity, (3) the APT cost is a factor of 160% higher, (4) the magnetic fusion facilities are ~36 to 50% of the cost, and (5) the two ICF facilities are ~10 to 12% of the cost of tritium as compared to the HWR.

The HWR is based upon existing technology, it provides tritium at a reasonable cost, and it can be built within a ten-year time frame. The MHTGR produces tritium at a significantly lower cost and, also, electrical power which may be valuable at the chosen site; however, the containment of the tritium in the target assemblies during irradiation and the processing of the targets to release the tritium must be demonstrated within the proposed time schedule.

The APT requires major developments in the RF accelerator design, beam propagation, spallation physics and target development. In addition, the cost of tritium appears to be high.

For the long-term supply of tritium and other special isotopes which can be produced by neutron irradiation, the four fusion reactors should be considered. Their advantages are: (1) the amount of waste heat for disposal is only 15% as compared to the fissile reactors, (2) the radioactive wastes are not as hazardous (no actinides) and require much reduced internment facilities, (3) the radioactive heating of the fusion reactors at shutdown is much less than in the fission reactors which reduces the potential for post-accident melting and vaporization of the reactor components, (4) especially the ICF designs are able to support their own power requirements, and (5) the unit cost of tritium is significantly lower. Admittedly, the costs for a fusion reactor contain many tenuous assumptions. These costs should be viewed as indicators rather than as absolute values until a new costing model[11] for fusion reactors which is being developed is accepted.

The development costs needed for a fusion TPR might be considered, but would be difficult to quantify. For instance, if $10 million/yr for 20 years were spent for the tritium production components in the development of the SIRIUS-T reactor, and this investment at 4% interest rate were charged to the eventual tritium product, its cost would increase by only $500/g. The spending of larger

Table 3. Economic Assessment of NPR's (in Million $U.S.)

Categories	HWR	MHTGR	APT	TM	TOK	ICF-TPR	SIRIUS-T
Design Year	1988	1988	1989	1982	1982	1985	1986
Direct Capital	2970	3107	3380	1115	1095	1190	1413
Indirects							
Project Management	296	315	340	112	110	119	141
Contingency Risk/$	9%/294	24%/741	30%/1120	30%/336	30%/330	30%/357	(30%)423
Spares and Fission Fuel	66	245	280	[a]	-[a]	-[a]	-[b]
Total Investment	3626	4408	5120	1563	1535	1666	1977
Annual Costs							
Capital	183	223	259	79	78	84	100
O&M, Plant + T Fac.	255	225	155	66	66	37	70
General Support	168	168	130	55**	55**	31**	58**
Contingency (Risk/$)	0.5%/2	8%/32	15%/40	17	15%/17	15%/10	15%/19
Capital Upgrade	38	24	140	17	21	12**	30
Target Purchase	-	-	-	-	-	-[c]	35
Electric Power	9	271*	335	61	96	-[d]	-[d]
Total	655	401	1059	284	333	174	296
$/1990	708.5	434	1101	391	442	207	346
Production, T (kg/CY)	7	7.8	6.8	10.8	9.1	16.9	33.6
Tritium Cost, $/g	101,000	55,600	162,000	36,200	48,600	12,300	10,300

*Revenue, **Amounts added by author

[a]Not available, [b]Included in direct capital, [c]Target facility included during construction, [d]Power self-sufficient

amounts of money to drive the fusion program specifically for tritium production might be an option; however, in this case, the development costs would need to be amortized amongst all fusion reactors built for any purpose.

In summary, long-term support is economically and environmentally justified to develop the technology and test these fusion reactor concepts.

ACKNOWLEDGEMENT

The author wishes to thank several reviewers for their helpful comments. Support for this research has been provided by the Inertial Fusion Division, Office of Research and Advanced Technology, U.S. Department of Energy.

REFERENCES

1. J.J. Jicha, Jr., "Heavy-Water Program: Technical Requirements, Conceptual Design Phase Process, and Reactor Characteristics," Trans. Amer. Nucl. Soc., 61, 153 (1990).

2. J.D. Nulton, "The Modular High-Temperature Gas-Cooled Reactor - A New Production Reactor," Trans. Amer. Nucl. Soc., 61, 153 (1990).

3. K.A. KLEIN, "New Production Reactor Safety," Trans. Amer. Nucl. Soc., 61, 154 (1990).

4. "Accelerator Production of Tritium," DOE/S-0074, Energy Research Advisory Board to the United States Department of Energy (1990).

5. J.D. LEE, "Economic Analysis of a Magnetic Fusion Production Reactor," J. Fusion Energy, 6, 59 (1987).

6. J.D. LEE, "Tritium Breeding Analysis of a Tokamak Magnetic Fusion Production Reactor," J. Fusion Energy, 8, 89 (1989).

7. W.R. MEIER, T.J. McCARVILLE, D.H. BERWALD, J.D. GORDON, and W.G. STEELE, "An ICF Tritium Production Reactor," Fusion Technology, 8, 1208 (1985).

8. I.N. SVIATOSLAVSKY et al., "SIRIUS-T, An Advanced Tritium Production Facility Utilizing Symmetrically Illuminated Inertial Confinement Fusion," this conference.

9. W.A. LOKKE and T.K. FOWLER, "Stockpile Tritium Production for Fusion," UCRL-94003, Lawrence Livermore National Laboratory (1986).

10. "New Production Reactors Capacity Cost Evaluation," DOE DP-0052, Oak Ridge National Laboratory (1988).

11. J. DELENE, "Updated Comparisons of Economics of Fusion Reactors with Advanced Fission Reactors," this conference.