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AN ICF TRITIUM PRODUCTION REACTOR*

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ABSTRACT

The conceptual design of an ICF tritium production reactor is described. The chamber design uses a beryllium multiplier and a liquid lithium breeder to achieve a tritium breeding ratio of 2.08. The annual net tritium production of this 532 MW_e plant is 16.9 kg, and the estimated cost of tritium is \$8100/g.

INTRODUCTION

A potential application for inertial confinement fusion (ICF) is the production of tritium to supply either civilian or military needs. (Also see Refs. 1 and 2.) LLNL and TRW have completed a conceptual design study of an ICF tritium production reactor (TPR). The fusion chamber is designed to maximize the tritium breeding ratio (TBR) and the only net product of the plant is tritium. The electric power produced is just sufficient to meet the power requirements of the driver and plant auxiliary system.

Many of the scientific and engineering developments required for ICF to be feasible as an energy source for electric power production are also required for the TPR. For example, both applications require technology to mass produce fusion targets and the availability of a driver with pulse rate capabilities of at least a few Hz. One major difference, however, is that the TPR can be economically attractive with a fusion energy gain that is an order of magnitude lower than required for electric power production. The fusion energy gain is defined as the product of driver efficiency and target gain. For this reason, the TPR may constitute an earlier application for ICF.

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Tritium is currently produced in fission reactors designed for, and dedicated to, that purpose. It is clear, however, that fusion offers several potential advantages over fission as a source of neutrons to produce tritium. One advantage is that for a given tritium production rate, a fusion reactor will produce an order of magnitude less thermal power than a fission reactor. This translates into a smaller, less expensive balance of plant and reduces the environmental impact from waste heat. Secondly, in a fission reactor, fuel reprocessing is required to recover the tritium that is produced. The fuel cycle facilities required for this can be quite expensive. In a fusion reactor, tritium can be removed continuously. Another advantage of producing tritium in a fusion reactor is that the safety and environmental concerns associated with fission and fission-products can be avoided.

CANDIDATE NEUTRON MULTIPLIERS

As an initial step in the conceptual design of an ICF tritium production reactor, we evaluated several candidate neutron multipliers. We compared three multipliers, Be, Pb and ²³⁸U, and a natural Li blanket.

The neutronics calculations were carried out in one-dimensional, spherical geometry using the TART Monte Carlo Code.³ The model consisted of a DT-target surrounded by a 1-m-thick breeding blanket with an inner radius of 2 m. A 14.1 MeV neutron source was uniformly distributed throughout the region of compressed DT with a density-radius product, ρR , of 3 g/cm². There was no structural material in the breeding blanket and no first-structural-wall. Leakage neutrons were added to the TBR to give the upper bound or potential TBR. The composition of the Be blanket was 90 vol% Be and 10 vol% ⁶Li. The Pb blanket contained the PbLi eutectic with 83 at% Pb and 17 at% ⁶Li. We ran three

cases for the ^{238}U multiplier; the blankets contained 25, 50 and 75 vol% ^6Li with the balance being ^{238}U . (This was necessary to reveal the tradeoff between neutron multiplication and neutron losses via the $^{238}\text{U}(n,\gamma)$ reactions.)

The TBR and fusion energy multiplication factors, M_f , are given in Table 1 for the six cases. Note that M_f is equal to $E_t/17.6$, where E_t is the total energy deposited in the system per DT reaction, including the fusion alpha particle energy of 3.5 MeV.

Table 1. Potential TBR and Fusion Energy Multiplication Factor for Six Blankets

Blanket	TBR ^a	M_f
Li (7.42 at% ^6Li)	1.78	1.20
Be (10 vol% ^6Li)	2.37	1.39
Pb (17 at% ^6Li)	1.73	1.19
^{238}U (25 vol% ^6Li)	2.00	9.80
^{238}U (50 vol% ^6Li)	2.52	8.18
^{238}U (75 vol% ^6Li)	2.30	5.76

^aIncluding neutron leakage

A uranium blanket with ~50 vol% ^6Li gives the highest TBR at 2.52. The Be blanket is a close second at 2.37, while ^7Li and Pb are comparable at 1.78 and 1.73, respectively. The uranium blankets, which rely on fast fission for neutron multiplication, have the highest values of M_f . The value of M_f decreases with increasing ^6Li fraction in the U blankets because the $\text{U}(n,f)$ rate is reduced due to competition for lower energy neutrons with ^6Li .

The net tritium production rate per unit of thermal power is proportional to $(\text{TBR}-1)/M_f$; in Fig. 1 we show values of this quantity normalized to the result for Be. For a given size thermal plant, the Be blanket will produce 1.5, 1.6 and 4.4 times more net tritium than Li, Pb and ^{238}U blankets, respectively. This should translate into cost savings and a lower cost per gram of tritium. Therefore, Be was selected as the neutron multiplier for the ICF TPR design study.

The 5-cm-thick Li fall, which protects the Be structures, is also supplied by a reservoir of Li at the top of the chamber. The Li from the fall enters a common pool at the bottom of the chamber. Li at 400°C is removed from

Fig. 1 Net tritium production per unit of thermal power normalized to Be.

this lower pool and circulated through heat exchangers and returned to the top of the chamber. A small slip stream is circulated through a molten-salt extraction system for tritium recovery.⁴ The design of the chamber is described in more detail in a companion paper.⁵

BERYLLIUM / LITHIUM SYSTEMS

Having selected Be as the most efficient neutron multiplier, the question now becomes: "How can we most effectively incorporate Be in the reaction chamber to maximize the TBR?" First of all, to take full advantage of the ability of high-energy neutrons to produce $(n,2n)$ reactions in Be, the Be must be located inside the structural wall of the chamber. Neutronic studies were also carried out to quantify the dependence of the TBR on:

- 1) the Be volume fraction in the blanket,
- 2) the thickness of the protective Li fall, and
- 3) the steel volume fraction.

We found that the TBR was only slightly dependent on the Be volume fraction. Reducing the Be fraction from 90 to 45 vol% reduced the potential TBR from 2.37 to 2.21.

The iron fraction in the Be/Li blanket is an important consideration. The TBR decreases as the Fe fraction increases due to parasitic absorption. For a blanket with 75 vol% Be, a variable vol% Fe, and the balance natural Li, the potential TBR is reduced from 2.34 to 2.06 as the Fe fraction is increased from 0 to 10 vol%. This is shown in Fig. 2.

Fig. 2 The potential TBR decreases with increasing Fe fraction in the Be/Li blanket.

CHAMBER DESIGN

The TPR chamber design is shown in Figures 3 and 4. The fusion target is surrounded by an array of Be columns (only half of the array is shown). These 6-m-high columns are made up of individual blocks, 50-cm high and 30 cm in diameter, and are held together by steel fastening bands. A dense array of coolant channels is machined into each block. Li coolant is supplied at the top of the chamber, flows down through the Be columns and exists at the bottom of the chamber. The columns are attached to the top and bottom plates in such a way as to tolerate radiation-induced swelling and the vibrations resulting from each fusion pulse.

In order to use Be inside the chamber, it must be protected from direct exposure to x-rays and debris from the target. A Li fall, placed between the target and the Be, can provide this protection. Adding a protective Li fall reduces the TBR only slightly. With a 15-cm-thick fall, the potential TBR is reduced from 2.34 to 2.22.

In summary, to maximize the TBR, the chamber design should seek to maximize the beryllium volume fraction, minimize the steel fraction, and minimize the protective fall thickness.

TWO-DIMENSIONAL NEUTRONICS

Detailed, two-dimensional neutronic studies were carried out for the chamber illustrated in Figures 3 and 4. The Be/Li blanket was composed of 72 vol% Be, 25 vol%

Fig. 3 The chamber design for the TPR uses a Be multiplier and a Li breeder.

Fig. 4 Cross-sectional view of the chamber. An array of Be columns surrounds the fusion target.

Li, and 3 vol% Fe. Structural support plates, structures in the upper and lower Li pools, and neutron leakage through the beam ports were accounted for in these studies.

We found a TBR of 2.08 with ${}^6\text{Li}(n,T)\alpha$ and ${}^7\text{Li}(n,n'T)\alpha$ contributions of 1.89 and 0.19, respectively. The Be/Li blanket accounts for 69% of the total, the Li fall produces 17% and the inlet and outlet pools contribute 13%. The total energy deposited in the chamber (including the alpha particle energy) is 23.4 MeV. This gives a fusion energy multiplication factor, M_f , of 1.33.

TPR PLANT PARAMETERS

One criterion we adopted for the design was that the plant should break-even in electric power production. For an ICF plant, the criterion for electric self-sufficiency can be written as

$$GM_f \eta_t \geq 1/\eta_d$$

where G is the target gain, η_t is the thermal conversion efficiency, and η_d is the driver efficiency. The driver efficiency was conservatively assumed to be 3%, and the plant thermal efficiency was estimated at 36%, consistent with the 400°C Li outlet temperature. With $M_f = 1.33$, the above criterion is met if the target gain is greater than 70.

The driver energy required to achieve this gain is estimated from the target gain versus driver energy curves shown in Fig. 5. We used the conservative gain band as our basis. The selected design point is a driver energy of 2.7 MJ and a target gain of 74. This gives a target yield of 200 MJ.

The chamber pulse repetition rate is limited by the time required to reestablish the protective Li fall and condense the Li which is vaporized on each pulse. Based on these considerations, we selected a pulse rate of 2 Hz, which results in a fusion power of 400 MW.

The plant thermal power is 532 MW_t. Heat is transferred from the Li primary coolant to a sodium intermediate loop. The heated sodium is then used to produce steam at 350°C and 6 MPa. The thermal conversion efficiency is 36%, giving a gross electric power production of 192 MW_e. The driver consumes 180 MW_e and the auxiliary power requirements of the plant consume the remaining 12 MW_e. It should be noted that beyond the Li/Na heat exchanger, the plant uses standard liquid metal breeder technology.

The plant parameters are summarized in Table 2. The net tritium production rate at a 70% capacity factor is 16.9 kg/yr. The unit cost of tritium, \$8100/g, is derived in the next section.

Fig. 5 The selected design point for the TPR is based on the conservative gain band.

Table 2. Reference Parameters for the TPR

Driver energy	$E_d = 2.7 \text{ MJ}$
Driver efficiency	$\eta_d = 3\%$
Target gain	$G = 74$
Repetition rate	$\omega = 2 \text{ Hz}$
Fusion power	$P_f = 400 \text{ MW}$
Energy multiplication	$M_f = 1.33$
Thermal power	$P_t = 532 \text{ MW}_t$
Conversion efficiency	$\eta_t = 36\%$
Gross electric power	$P_g = 192 \text{ MW}_e$
Driver power	$P_d = 180 \text{ MW}_e$
Tritium breeding ratio	$\beta = 2.08$
Net production rate (at 70% capacity factor)	$m_T = 16.9 \text{ kg/yr}$
Total capital cost	$C = \$1.96 \text{ B}$
Cost of tritium	$U = \$8.1 \text{ k/g}$

COST ESTIMATES

We estimated the cost of the TPR based on a costing study for an ICF fusion demonstration facility that was carried out by the architect-engineering firm of Burns and Roe⁶. The costs are representative of a one-of-a-kind type facility and are, therefore, much higher than the expected cost of full-size commercial power plants in a mature ICF technology. Reference 6 includes cost estimates for 600 and 850 MW_t plants that use liquid Li as the primary coolant and sodium as the intermediate coolant. As such, the plant designs are quite similar to the TPR. Where appropriate, costs were scaled from the 600 MW_t plant to a 532 MW_t size plant for the TPR.

The direct capital costs in January 1983 dollars are given in Table 3. The miscellaneous plant equipment cost includes \$32 M for a Be recycle plant. The total reactor plant cost is \$540 M. We must also add the cost of the driver and target factory. The driver cost is estimated at \$550 M. This is based on \$250 M per MJ and a scaling as $E_d^{0.8}$, where E_d is the driver energy in MJ.⁷ The target factory cost is estimated at \$100 M direct. This brings the total direct capital cost to \$1190 M. Including a contingency factor (20%), engineering costs (25%), interest and escalation during construction, gives a total capital cost of \$1960 M in 1983 dollars.

Table 3. Direct Capital Cost for the TPR

Item	Cost (\$M)
Reactor plant	
Land	3
Structures and site facilities	122
Reactor plant equipment	230
Turbine plant equipment	50
Electrical plant equipment	63
Miscellaneous plant equipment	43
Special materials (beryllium)	29
Total reactor plant	540
Driver	550
Target factory	100
Total direct capital cost [†]	\$1190M

To estimate the cost of tritium, the annual costs are divided by the annual tritium production. Financing was assumed to be 100% government bonds with a real cost (excluding inflation) of 3%/yr. The plant life is taken as 30 years and taxes were excluded, as would be appropriate for a government-owned

facility. The levelized cost of capital is \$100 M/yr including retirement of the debt. Operation and maintenance costs are estimated \$36 M/yr and Be make-up adds less than \$1 M/yr. For the annual tritium production rate of 16.9 kg/yr at 70% capacity factor, the cost of tritium is \$8100/g. This is about a factor of 2-3 lower than the cost of tritium from future fission-based tritium production reactors.⁸

We also investigated the sensitivity of this cost to uncertainties in the cost estimates, the driver efficiency, and the target gain. The results are shown in Table 4. As indicated, the cost of tritium is relatively insensitive to large variations in cost and performance. For example, increasing the laser cost per MJ by 50% increases the cost of tritium by only 17%. Reducing the laser efficiency from 3 to 1.5% increases the cost by 23% since the plant must now purchase 180 MW_e of electric power (purchase price = 2.8¢/kWh). Increasing the driver efficiency to 6% reduces the cost of tritium by 9% as a result of being able to sell 90 MW_e of power at 2.3¢/kWh. Also shown is the effect of improved or degraded target performance. In both cases, the yield is held constant at 200 MJ. With the degraded gain, the cost of tritium increases 23% as the result of a higher capital cost for the laser and increase power consumption (87 MW_e purchased). With the improved target gain, the cost of tritium is reduced by 24% due to a less expensive laser and the sale of 93 MW_e.

Table 4. Sensitivity of Cost of Tritium to Changes in Plant Cost and Performance

Variation		Tritium Cost
Laser cost/MJ	±50%	±17%
Target factory cost	±100%	±6%
Be factory cost	±100%	±2%
Laser efficiency	= 1.5%	+23%
	= 6.0%	-9%
(baseline	= 3.0%)	
Target gain	= 50 at 4 MJ	+23%
	= 150 at 1.3 MJ	-24%
(baseline	= 74 at 2.7 MJ)	

With a combination of degrading factors; namely, increasing the laser cost per MJ by 50%, reducing the laser efficiency to 1.5%, increasing the target factory and Be plant cost by 100% and achieving the lower target gain ($G = 50$ at 4 MJ), the cost of tritium increases by 84%. On the other hand, with a combination of improvements, (laser cost per MJ reduced by 50% laser efficiency increased

to 6%, target factory and Be plant costs negligible, and $G=150$ at 1.3 MJ), the cost of tritium is reduced by 45% to \$4500/g.

CONCLUSIONS

We conclude that an ICF TPR has the potential for exceptional performance. The Be/Li blanket, which allows us to achieve a TBR greater than 2.0, appears to be feasible. This concept achieves a very high tritium production rate per unit of thermal power. We estimate that it will produce low cost tritium with first generation technology and that performance improvements will reduce the cost even further.

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REFERENCES

1. J. H. PENDERGRASS and D. J. DUDZIAK, "Tritium and Plutonium Production as a Step Toward ICF Commercialization," Proc. IASTED International Symposium, Acta Press, Anaheim, CA, p. 34 (1983).
2. W. W. SAYLOR, J. H. PENDERGRASS, AND D. J. DUDZIAK, "A 'FIRST STEP' Toward ICF Commercialization," Trans. ANS Summer Meeting, TRANSO 46 1-877, 46 p. 241 (1984).
3. E. F. PLECHATY and J. R. KIMLINGER, "TARTNP: A Coupled Neutron-Photon Monte Carlo Transport Code," UCRL-50400, Vol. 14, LLNL (1975).
4. W. F. CALAWAY, "Electrochemical Extraction of Hydrogen from Molten LiF-LiCl-LiBr and Its Application to Liquid-Lithium Fusion Reactor Blanket Processing," Nucl. Technol., 39, 63 (1978).
5. T. J. MCCARVILLE, et al, "An ICF Reactor Cavity to Maximize Tritium Breeding," TRW, presented at the Sixth Topical Meeting on the Technology of Fusion Energy (March 1985).
6. W. G. STEELE, et al, "An Assessment of Technical Risks and R&D Requirements for Inertial Confinement Fusion," TRW-FRE-010, TRW (1985).
7. D. H. BERWALD and W. R. MEIER, "Reactor Systems Modeling for ICF Hybrids," Proc. Fourth Topical Meeting on the Technology of Controlled Nuclear Fusion, p 1487 (1981).
8. I. O. BOHACHEVSKY AND T. G. FRANK, "Production of Tritium in Low-Pellet-Gain ICF Facilities," LA-9657-MS, LASL (1983).