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Tritium Production Potential of Beam Research and Magnetic Fusion Program Technologies

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INTRODUCTION

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Regular replenishment of tritium in the nuclear weapons stockpile is essential to maintain our nuclear deterrent. Nuclear reactor facilities presently used for the production of tritium are aging, and their operation is being curtailed awaiting the repairs and upgrades needed to meet modern standards of safety and environment. To provide improved capability in the future, DOE plans to construct a new production reactor (NPR).

Alternatives to nuclear reactor methods for the production of tritium, mainly electrically-driven accelerator or fusion systems, have been proposed many times in the past. Given the critical national security implications of maintaining adequate tritium production facilities, it is clearly worthwhile for political decision-makers to have a clear and accurate picture of the technical options that could be made available at various points in the future.

The goal of this white paper is to summarize available technical information on a set of non-nuclear-reactor options for tritium production with a minimum of advocacy for any one system of implicit assumptions about politically desirable attributes. Indeed, these various options differ considerably in aspects such as the maturity of the technology, the development costs and timescales required, and the capital and operating costs of a typical "optimized" facility. For example, a concept that relies on relatively "unproven" physics and/or technology may, because of simplicity in scaling and/or its small modular nature, have a relatively low cost outlay requirement to prove its viability as a highly reliable production facility. Another factor to consider is the utility of the technology development for other purposes; e.g., fusion systems for tritium production can be a "stepping stone" to a commercial power station. For all these reasons, a single technical "figure of merit," such as the quantity

of tritium produced per unit of electricity consumed, is clearly inadequate as a basis for decision makers to understand the tradeoffs involved.

It is also important to distinguish the options proposed as *alternatives* to the NPR from those that — because of their more modular nature — might be suitable *backups* to the NPR. That is, small units that can be developed and demonstrated at reasonable cost could provide an “insurance policy” if problems are encountered in the NPR approval and construction process. Replication of these small units to produce the needed annual supply could then proceed with proven technology; minimum capital and/or operating cost of the ultimate deployment might be considered secondary to the initial outlays required for verification of the technology.

Five concepts based on technologies under present or past development or study in the Beam Research and Magnetic Fusion Program are assessed for their potential for tritium production. Three of the concepts are fusion based and two are based on high energy beams. The three fusion-based concepts are listed below, along with their proponent or reviewer:

- Linear Plasma (LP) - Fred Coengsen
- Tokamak Plasma (TP) - Ralph Moir
- Compact Torus Accelerator (CT-RACE) - Jim Hammer

The two beam-based concepts are:

- Electron Linear Accelerator (ELA) - Roy Hedtke
- Deuteron Linear Accelerator (d-LINAC) - J.D. Lee

The assessment of these concepts is limited in scope in that little effort has been allocated to this task. The amount of background material to draw on varies widely among the five concepts. The tokamak case is supported by a rather detailed study on its use as a tritium breeder; it also has a large research base developed over the years in the world's fusion

programs. At the other end of the spectrum is the CTF RACE case, which is based on a new concept of which R&D is just getting started with IR&D seed funds.

This white paper includes a section on each of the five concepts, describing some of the history of that concept and presenting major operating parameters and thoughts on R&D requirements. The paper also includes a section that discusses blanket and target R&D status and issues, and it concludes with a summary section.

LINEAR PLASMA-BASED TRITIUM PRODUCTION FACILITY

F.H. Coensgen, A.H. Futch, and A.W. Molvik

Concept

A schematic diagram of a 5 kg/yr tritium breeder is shown in Fig. 1. The system is simply a long fully ionized dense tritium plasma column confined radially by a linear magnetic field. An intense flux of 14-MeV neutrons is produced by transverse injection of 150 keV deuterons into the tritium plasma, which is sufficiently dense to essentially stop all of the beams. The trapped deuterium ions collide with tritium target ions, maintaining the D-T fusion reaction rate. The energetic ions are confined radially by the magnetic field and longitudinally by magnetic mirrors. Through collisions, the hot ions lose their energy to the plasma electrons, which in turn ionize and heat the tritium component and thus maintain the plasma target. All injected power is transported by electron thermal conduction along a solenoidal guide field to end regions, where it is absorbed in neutral tritium gas at high pressure. The high density tritium serves two functions: it is the source of tritium for the plasma column, and it prevents the erosion of the end walls by the hot plasma column. Ions entering the end chambers are cooled and either are recombined with electrons or reach the walls with energies below the thresholds for sputtering. Power loading at the walls is reduced to values that can be handled by conventional cooling technology. In principle, part of the energy can be recovered to reduce power consumption and thus lower operating costs. This option has not been evaluated and is not included in the estimates given below.

The concept presented here is an adaptation of a recently completed conceptual design

Figure 1: Linear Plasma-Based Tritium Production Facility

Table 1: Performance Parameters

Total length	2000 m	200 m
Reaction chamber length	1000 m	40 m
Unit size (kg T/yr)	18.0	5.0
Capital costs (1×10^9 \$)	2.5	1.6 ^a
Power required (MWe)	2000.0	1100.0
Operating and maintenance costs (1×10^6 \$)	100.0	70.0
Number of units to produce 5 kg T/yr	0.28	1.0
Q	0.7	0.3

^aBlanket and tritium recovery system not included.

1 of a compact high-fluence D-T neutron source for accelerated end-of-life testing of fusion reactor materials. Although this preliminary assessment serves to illustrate the main features of a linear plasma-based tritium breeder, it is not necessarily an optimized design. We believe that proper design choices for the breeder application will certainly reduce costs, perhaps by as much as a factor of two. We also point out that Q (the ratio of fusion power produced to power input to the plasma) increases with system length and that the cost per kg of tritium decreases for longer systems with higher output (see Table 1). In earlier studies of linear two-component plasma systems, Q values as high as three were predicted. At this level of performance, and with energy recovery, operating power requirements of the breeder could approach zero.

Similar values of Q are obtained in recent Soviet studies of long linear mirror systems. They discuss development of these systems for production of fissile fuel and tritium.

Physics and Technical Basis

The physics and technology data base for the breeder design has been developed in the magnetic fusion program over a considerable time span and has extensive verification. This data base was summarized by Molvik [2]. Except for the location of good field curvature at the ends instead of the middle, the breeder plasma design closely resembles that of the 2XHB experiment, which was operated at LLNL from October 1973 to October 1978 and which

demonstrated stable operation of a two-component plasma [3]. Notable among the achievements in that experiment was the demonstration of stable confinement of high- β plasmas using a minimum-B magnet in the central beam heated region. β is the ratio of plasma energy density to magnetic field energy density, and high- β is needed for economic operation of the breeder. Also, 2XHB experiments confirmed the theoretically derived conditions for control of high-frequency fluctuations (i.e., mirror mode microinstabilities). Recent work on MHD stability in axisymmetric systems, such as the breeder design, is reported by Molvik et al. [4]. Much of this work was carried out in a US/USSR collaborative effort on the Soviet Gas Dynamic Trap experiment at the Institute for Nuclear Physics, Novosibirsk, USSR. This experiment should test the ability of an axisymmetric system to reach high β with neutral beam injection in the near future.

The dominant heat loss is the electron thermal conduction from the hot plasma core to the gas target in each end cell. For a cylindrical plasma column, this power flow is given by

$$\text{flow power} = (4\pi a^2/l_c) \int K dT_e$$

where $K = 9.3 \times 10^{13} (T_e)^{5/2}$ W/m-keV with T_e expressed in keV. The coefficient of thermal conductivity was derived by Spitzer and Harm [5]. For a Gaussian radial profile, the fusion power is

$$\text{fusion power} = n_h n_w \langle \sigma v \rangle E_f \pi a^2 l_h / 2$$

where n_h and n_w are the peak densities of the hot and warm plasma, respectively; l_h is the length of the plasma column occupied by the hot ions; and a is the radial e-folding length of the plasma. Q is defined as

$$Q = \text{fusion power/flow power} = 1.47 \times 10^{-24} \langle \sigma v \rangle n_w n_h (l_c l_h R) (T_e)^{7/2}$$

for cgs units except T_e is expressed in keV. For a neutral-beam efficiency of 30%, the tritium production rate becomes

$$M_t/E = 12.7Q \text{ kg/GW-yr}$$

All technologies needed for the tritium breeder are within the state of the art. The 150-keV neutral beams will be demonstrated on JET in the spring of 1989 for a duration of 10-20 s. All components are essentially at steady-state. A longer lived cathode is desirable since present filaments are estimated to have a 2-week lifetime in steady-state operation. Superconducting magnets of 12-T fields were demonstrated during MFTF acceptance tests. The blanket technology is based on existing designs.

Development

We believe that a tritium breeder based on a linear plasma system could be an alternative or backup for a production facility, and we recommend a serious design effort be initiated at this time. Assuming favorable MHD stability can be proven in an axisymmetric linear system, we can build upon existing physics and technology facilities to develop a safe, reliable, continuously operating production facility as soon as possible, by means of a test section of a full-sized breeder constructed and tested following the design study. This test section would first be run using hydrogen to avoid neutron radiation and activation problems during development of continuous operation of neutral-beam systems, power removal and/or energy recovery, and remote-controlled operation and maintenance. All safety aspects of the facility would also be perfected and demonstrated in the hydrogen operation phases. Once reliability and safety are demonstrated, the test section would be operated as a tritium breeder to perfect blanket technology and tritium extraction. Based on our cost analysis of the intense neutron source, we estimate the construction cost of a 200-MW test section to be approximately \$250 M.

In a more conservative approach to develop the breeder, the integrated physics design and power handling techniques could be verified first, using lower energy beams at lower power. Based on previous estimates, a pulsed 20-MW test facility could be constructed at LLNL using existing equipment for approximately \$10 M in about 1 year.

Cost Basis

To estimate construction and operating costs, we note that the size of the system is essentially proportional to the required power, which is estimated as outlined below. Costs are then obtained by scaling our estimates for the intense neutron source. For the 5-kg/yr facility, the estimated construction cost is \$1.6 B without tritium breeding blankets or extraction facilities. Operating costs are strongly dependent on power costs and energy recovery.

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A DRIVEN TOKAMAK FOR TRITIUM PRODUCTION

Ralph Moir

The potential for producing tritium from fusion neutrons absorbed in lithium is explored based on a study of a driven tokamak [1,2]. A steady-state neutral-beam-driven tokamak based on the present tokamak at Princeton, called TFTR, is predicted to generate about 10 kg/yr of tritium from 450 MW of fusion power. The 14 MeV neutrons produced in the fusion reaction are multiplied in the beryllium blanket, and tritium is produced in the Li-Al alloy blanket. The blanket structure is made of aluminum and is water-cooled at a temperature of less than 100°C. Figure 2 shows the production reactor and Fig. 3 compares the reacting plasma and magnets of the production reactor with those of TFTR, shown as an overlay for comparison.

A set of parameters for the production reactor called the Magnetic Fusion Production Reactor (MFPR) is given in Table 2, with TFTR "supershot" parameters achieved shown for comparison. The parameters are scaled up by a modest amount and are not very speculative, but as we have learned in the magnetic fusion program, progress doesn't come easily! The plasma volume for the MFPR is 3.5 times the TFTR volume; the density and the electron temperature are both twice that of TFTR.

A number of technologies have to be developed for a highly reliable production reactor based on the tokamak. Among these are divertors, magnets, remote handling equipment, blankets, and negative ion beams. The ongoing worldwide fusion programs will develop all of these component technologies but perhaps on a somewhat protracted timescale. If we

Figure 2: Evaluation view of the tokamak MFPR based on supershot-like plasma.

Figure 3: Size comparison of the MEPR (solid lines) and TFTR (dashed lines).

Table 2: Tokamak system parameters.

	MFPR	Best TFTR Supershots
Plasma major radius	3.9 m	2.5 m
Plasma minor radius	0.75 m	0.85 m
Plasma elongation	1.5	1.0
Maximum field at TF coils	9.8 T	9.6 T
Maximum field on plasma axis	5.0 T	5.2 T
Magnetic flux swing from solenoid	13 Wb	13 Wb
Neutral beam power, D ⁺	100 MW	15 MW
Neutral beam power, T ⁺	50 MW	15 MW
Neutral beam energy, D ⁺	250 keV	110 keV
Neutral beam energy, T ⁺	340 keV	120 keV
Plasma current	5.5 MA	1.6 MA
Pulse length	Steady-state	2 s
Electron density (peak)	1.6×10^{14}	8×10^{13}
Electron temperature (peak)	20 keV	9 keV
Ion temperature (peak)	35 keV	32 keV
Volume-ave. total beta	5%	1.5%
Frac. of total pressure in hot ions	1/3	1/3
Energy confinement time, τ_E	0.35 s	0.17 s
$N_e(o) \times \tau_E$ (cm ⁻³ s)	5.5×10^{13}	1.3×10^{13}
Z_{eff}	1.5	2.5
		<i>expected</i>
Fusion gain, Q	3.0	1.0
Total fusion power	450 MW	30 MW
Neutron wall loading (MW/m ²)		
Spatially averaged	1.4	0.20
At outboard midplane	1.65	0.25

Table 3: Capital Cost and Construction.

	Time	(1982\$)
Design/construct	6 yrs	\$1.4 B
Operate	2 yrs	
Upgrade	2 yrs	0.7
Tritium processing plant		0.1
		\$2.2 B

were to design and build the tokamak starting 2 years from now, we could not wait for many of the results that would naturally come along 10 years later. The driven tokamak is less demanding of these technologies and not very expensive and could be undertaken at a fraction (perhaps only 20%) of the \$2.2 B construction cost. The neutral beams 100 MW of 250 keV (D^+) and 50 MW of 340 keV (T^+) could be developed in ~ 5 years at a cost of $\sim$ \$40 M.

The power requirements are 560 MWe, of which 270 MWe is for the neutral beams and 220 MWe is for the toroidal field coils. The study [3] was done more than 8 years ago. Now superconducting magnets may be appropriate, in which case the power consumption comes down to 340 MWe. If we wanted to scale the power a factor of two down to 225 MW fusion, the beam power would be reduced by 135 MWe, bringing the total power consumption down to 205 MWe for 5 kg/yr of tritium production.

Our idea is to design (2 yr) and build (4 yr) the tokamak and to operate it for a period of perhaps 2 years, after which time we assume a 2-year upgrade of components to a state of high reliability. This is illustrated in Table 3.

A production reactor could be operational ~ 10 years after a clear decision to proceed. A fair amount of development could proceed in parallel. The upgrade, which would include the reliable breeding blankets and all highly reliable components such as long-lived neutral beams, would proceed only if the operation achieved the necessary performance, as shown in Table 2. The operating cost has been estimated and is shown in Table 4.

Table 4: Operating Costs.	
Reactor O&M	\$30 M/yr
Process plant	10
Blanket replacement	20
Electricity (\$0.045 kWh)	\$95 M/yr
	\$185 M/yr

The Academy of Science and Engineering conducted a study of the tokamak as a tritium producer [3]. Their conclusion is reproduced here:

Because the tritium-breeding fusion reactor offers promising features of yield, cost, and technology, officials in the U.S. Department of Energy concerned with the capability and security of tritium production should undertake a program that analyzes and periodically reassesses the concept, including design studies, experimentation, and evaluation as fusion development proceeds.

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COMPACT TORUS ACCELERATOR CONCEPT

Jim Hammer

The compact torus accelerator ¹ is a device that accelerates magnetically confined plasma rings (compact toroids) to high velocities ($> 10^8$ cm/sec) and focuses them to high power and energy densities. The accelerator is shown schematically in Fig. 4. The essential elements are a magnetized coaxial plasma gun for forming the compact torus, a compression/acceleration stage where the torus is confined between conducting coaxial electrodes and accelerated by $\mathbf{J} \times \mathbf{B}$ forces, a focusing stage, and a converter where deposition of the compact torus kinetic energy results in neutron production. The coaxial gun and accelerator have separate power supplies (usually fast capacitor banks). The accelerator is distinguished from other types of plasma accelerators by the magnetic confinement of the accelerated plasma. This allows acceleration over many ring diameters to high velocities and high kinetic energies such that the torus can then be focused to high energy densities. The magnetic confinement of the accelerated plasma is also an advantage in the choice of conversion schemes for neutron production.

For the purposes of scoping this concept, we will assume that a converter of the MICE (magnetically-insulated inertial confinement fusion) ² type is employed. An accelerator of ~ 10 m length would be required to inject a compact torus of ~ 2 MJ energy into the converter. In the MICE case, the accelerated torus is focused to a size of several centimeters, a magnetic field strength of a few megagauss, and injected into a fluid-walled chamber (e.g., lithium-lead) of similar dimensions (Fig. 5). The chamber contains fusion fuel (deuterium, tritium) in the form of a pellet or gas cloud. The high velocity of the torus ($\sim 10^8$ cm/s)

Figure 1: Compact torus neutron generation follows the four phases of acceleration.

Figure 5: MJCF convertor chamber.

impacting the fuel heats the fuel to fusion temperatures of ~ 10 keV. The plasma of the injected torus could also be deuterium and/or tritium. The magnetic field suppresses electron heat loss to the wall so that confinement of the hot plasma and thermonuclear neutron production is limited by the inertial disassembly of the liquid wall ($\tau_{burn} \sim 1 \mu s$). The degree of magnetic confinement required is quite modest since the burn time is less than the Bohm confinement time, the shortest transport time usually applicable to a magnetically confined plasma. Because of the simple geometry (no coils, etc.), it should be possible to almost completely surround the impact chamber with breeding material (lithium with a beryllium neutron multiplier) such that a breeding ratio of unity is approached; i.e., two tritons produced for each triton consumed in a fusion reaction.

The compact torus accelerator concept has been demonstrated at the 20-40 kJ level with ring velocities $< 3 \times 10^8$ cm/s on the RACE [3] (Ring ACceleration Experiment) device at LLNL. The concept evolved from magnetic fusion studies of the spheromak-type of compact torus at LLNL. The earlier experiment (Beta II) [4] also used a magnetized coaxial plasma gun (a Marshall-type gun with an embedded B_r , B_z field from a solenoidal magnet) to form the torus, which was subsequently trapped in a flux-conserving metal shell for confinement studies. The compact torus field structure is characterized by a dipole-like B_r , B_z field encompassing an azimuthal B_θ field, in many respects similar to the tokamak magnetic confinement device. The fields are produced by currents flowing within the plasma and image currents in nearby conductors, so the compact torus is not tied to an external coil structure and may be translated axially. The "portability" of the torus and its long lifetime (100's of μs) led naturally to the concept of an accelerator employing the torus to confine plasma over long throw distances, allowing higher velocities and ultimately higher power/energy densities than can be otherwise achieved. A variety of applications are conceived for the device, including an injector to fuel or drive current in tokamaks, an intense pulsed x-ray source, a high-power microwave generator, a fast-opening switch for pulsed power applications [5], a

high-gain MCF driver (at ~ 80 MJ torus energy) [6], and, at very high power densities, as an ion beam driver for inertial confinement fusion [7].

Projected Performance Parameters

Projected parameters for a tritium production technology based on the compact torus accelerator are shown in Table 5. The production parameters shown in Table 5 correspond to an accelerator with the parameters shown in Table 6.

Table 5:		
Capacity kg/yr	Electric Power Required per unit (GW)	Direct Cost per unit (\$ B)
0.027	0.0067	< 0.013 ^a
# Units for 5 kg tritium	kg-tritium per GWY	Direct Cost \$ B/kgT/yr
265 ^b	1	< 0.69 ^a

^aDriver only

^b 70% capacity factor

There are numerous uncertainties in the projections shown in Tables 5 and 6. The physics of scaling the accelerator from the RACE scale (0.26-MJ full driver bank energy) to the 6-MJ level and to the requisite energy densities have yet to be demonstrated. While the neutron-conversion scheme places modest demands on the magnetic confinement properties of the torus, as noted above, the production of the thermonuclear neutrons at the required level must also be demonstrated.

Table 6:	
Driver bank energy	6 MJ
Compact torus energy (kinetic & magnetic)	2 MJ
Compact torus velocity	$> 10^8$ cm/s
Volume of focused torus/converter chamber	27 cc
Accelerator length	~ 10 m
Rep rate	1 hz

On the engineering side there are a number of development issues. Repetition of the

driving bank at 1 Hz will require pulse-power technology development. In the cost figure included in Table 5, the driving bank was costed at \$2/joule to allow for the estimated increase in costs due to rep-rating (non-rep-rated banks of the requisite type are typically \$0.50-\$1/joule). The driving bank is assumed to dominate the cost. Survival of accelerator electrodes for $> 10^7$ pulses is also a development issue.

Since the scheme employs deuterium-tritium fusion at low burn-up fraction, a high tritium recycling efficiency will be necessary. Also, a converter chamber/blanket design that can withstand the pulsed loading must be designed.

The unique feature of the concept which may offset the many technical uncertainties is the high degree of modularity. This would allow construction of a full-scale prototype unit at low cost (few $\times$ \$10M for the accelerator and driver bank), given success of the research and development program. The small size of the unit should also speed the research phase. The existing program plan for compact torus accelerator research at LLNL calls for 2 additional years of experimentation on RACE at a level of \$2.5M/year, followed by a 3-year research program on a 2-MJ RACE upgrade at \$3.5M/year. The RACE upgrade accelerator is projected to produce compact energies and power densities within a factor of three of the requirements for a tritium production module as outlined in Tables 5 and 6. The physics research phase could be accelerated by overlapping the upgrade construction with the final year of RACE operations and possibly by increasing the RACE upgrade energy to the 6-MJ level. A development program studying driver bank rep-rating issues and design of the converter chamber would need to be carried out in parallel to allow construction of a prototype unit in the mid 1990's.

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ELECTRON LINEAR ACCELERATOR PRODUCTION OF TRITIUM

Roy Hedtke

Basic Concept

Current Department of Defense (DOD) programs are funding the development of very high-average-power electron induction accelerators. For this reason, it is appropriate to examine the potential of this technology for tritium production.

The basic concept is simple. Electrons are injected into the accelerator with a given amount of energy (on the order of 3 MeV) and accelerated through induction cells to whatever end energy is desired. The current design of the induction cell allows a gap potential of 100 to 300 kV per cell. When the electron beam has been accelerated to its end energy, it must be transported somewhere, in this case to the target area. In the target area the beam passes through several layers of differing materials (tungsten) to produce first bremsstrahlung radiation and then a stream of neutrons which gets multiplied in beryllium; finally, the neutrons are directed onto a lithium target to produce a triton and an additional neutron. Conceptually, the idea is relatively simple. Figure 6 contains a sketch of this idea.

Historical Evolution

Developmentally, the electron accelerator has received much recent attention (late 1970's on) at LLNL as a result of DARPA's funding of the *Charged Particle Beam Program*. The successes at the Advanced Test Accelerator and other test beds led to the *Free Electron Laser (FEL) Program*. These programs stressed high-average-power, high-current, pulsed

Figure 6: Conceptual drawing of electron linear accelerator.

accelerators for weapons applications. The typical accelerator envisioned for the production of tritium will necessarily be a high-average-power cw machine. The results of these programs have a synergistic effect on any efforts to develop a machine for tritium production. In spite of many reports on electron linacs, our research indicates that electron accelerators have *not* previously been seriously considered for producing tritium, except as they may apply to some fusion programs. Little or no developmental work has been completed in the area of targets for tritium production since the mid 1970's. The bulk of that work focused on the use of fertile and other high-Z materials to produce copious amounts of neutrons. The least developed facet of this concept is the target portion.

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5. Discussions with key laboratory personnel and other library research.

Performance Parameters

The electron linear induction accelerator has nominal operating characteristics of 100 to 150 MeV, a beam current of 10 to 5 kA, a pulse width of 50 ns, and a repetition frequency of 10 to 20 kHz. These characteristics do not represent an optimized accelerator design. Much study would have to go into such a design before it could be considered optimized. These parameters correspond to an accelerator with an average power of 500 to 750 MW. That is approximately two to three times greater than the average power of the accelerator for the FEL system at White Sands Missile Range (WSMR), New Mexico. With operating characteristics such as these, one accelerator will produce approximately 400 g of tritium per year, assuming a tungsten target for neutron production with a slight neutron multiplication. Table 7 lists tritium production rates for a 750-MW machine with various neutron-producing targets and neutron multiplication factors. Multiplication factors of two are reasonable, and a factor of five may be achievable in beryllium. Research indicates that neutron multiplication would be at least an order of magnitude higher in a fissile material such as uranium. The remaining key performance parameters, for the baseline case, are contained in Table 8. The parameters listed in the table are very sensitive to average power and multiplication factor. The assumptions made about a plant's reliability will also drastically affect estimates of tritium production. The baseline case is based on a single point design, rather than a broad

Table 7: Tritium production rates for various target materials.

Target Material	Neutron Multiplication Factor			
	1	2	3	4
	Yield (g-T/yr)	(assumes 1 yr (of cw operation))		
Uranium	411	824	1236	1647
Tungsten	279	559	838	1117
Aluminum	69	137	206	275
Beryllium	42	83	125	166

study of the problem. An optimization of the accelerator configuration would undoubtedly result in a machine with different operating parameters.

WSMR Machine Performance

An interest was expressed in the amount of tritium that the WSMR device could produce in 1 year. Using the stated pulse format, assuming we could use this number of pulses per day for 200 operating days per year, we would produce 0.022 g T/year. It makes no difference how the 630,000 pulses are used, for 100 seconds at full PRF or whether the rep rate is lowered and the pulses expended over a period of 6 hours. The fact that the WSMR device is pulsed, plus its lower average power, accounts for its small amount of tritium production.

Level of Design Optimism

The 750 MW of average power is considered very optimistic for a near-term accelerator, especially considering that the accelerator would have to run continuously. The Army machine at WSMR is designed to operate in a pulsed mode for no more than 100 seconds. Most accelerator experts would agree that operating continuously at this high-average power with a reliability of 70% for 1 year is not a near-term goal (achievable in 5 to 10 years). In order to produce sufficient neutrons the average power must remain high. The results from the neutron yield calculation are viewed as conservative. They are based on established rules

Table 8: Key performance parameters (theoretical).

Parameter	Baseline Concept
Average E-beam power	750 MW
Target composition	Tungsten - Beryllium
Multiplication factor	1.5
Neutron production	2.65×10^{18} n/s (ave)
Tritium production per year	0.41 kg
Number of units to produce 5 kg T/yr	$\sim 12^a$
Power requirement per system	~ 1070 MWe
Direct capital cost per system	$\sim \$540$ M
O & M costs per year	$\sim \$15$ M

^a Assumes a capacity factor of 70%.

for neutron production derived from theoretical computations and experiment. The baseline neutron multiplication factor is also considered conservative.

From an engineering standpoint, the target system is the major problem. To date, little or no work has been completed on a target system concept. It is anticipated that the high average power of this accelerator will create extremely difficult thermal management problems in the target system. The two major problem areas will be heat removal in the target itself and the design of a window to maintain vacuum and radioactive isotope integrity. The solution to these problems is not anticipated to be near-term. Therefore, the conceptualized target system is seen as very optimistic.

Finally, the target cost data needs additional work. The figures assumed for the target system were extrapolated from a 1976 report on the MTA project which used a deuterium accelerator to convert fertile to fissile material. These costs were then converted to 1988 dollars. There is little confidence in the accuracy of these costs.

Developmental Status

Since the inception of the FEL program (last 4 to 5 years), approximately \$50 million has been invested in accelerator development and the ETA II (Experimental Test Accelerator II) project. Accelerator technology has reached a level of maturity which permitted the FEL program, in conjunction with TRW, to compete for the Ground Based Free Electron Laser Technology Integration Experiment (GBFELTIE) at WSMR. It is estimated it will cost an additional \$62 million and take 294 man-years of effort to develop this accelerator and provide a prototype at WSMR. The accelerator in the tritium production device will be two to three times more powerful than the WSMR device. However, any progress made in the development of the WSMR accelerator would be applicable to the tritium production machine. By comparison, the target system is not mature at all. We cannot begin to anticipate the costs and required level of effort without much more work.

Developmental Issues

Drivers

There are three major issues with the driver. The first issue involves attaining higher average power. Since neutron production scales with average power, the best method of increasing tritium production is to increase average power. Average power is dependent on beam energy, beam current, and pulse width and PRF. Raising beam energy alone will not accomplish much. This leaves the current and pulse format. Higher current creates even greater problems in beam transport, but the pulse format offers a means of increasing average power. The WSMR machine will have a PRF between 6 and 10 kHz. A higher rep rate (such as our machine will have) requires multiplexing of two pulsed power trains. This, in turn, will raise costs dramatically, but it will increase average power. The second issue is that of accelerator efficiency. With this machine's huge power demand, either the accelerator must become more efficient or we must learn how to recoup and reuse the thermal power. Finally, we

must make the transition from pulsed-power machines to reliable cw machines. The third issue, of accelerator reliability and cw operation, encompasses the first two issues and will probably be the most difficult problem.

Targets

The two most stressing issues with the target are thermal management within the target/pit area and development of a suitable window design. A third issue is that of enhanced neutron production and neutron multiplication with low-Z materials. We need to produce more neutrons from materials which tend to activate less. Finally, extraction of tritium from the target area is seen as a developmental issue. We desire safer and more efficient means of tritium extraction.

A DEUTERON LINAC FOR TRITIUM PRODUCTION

J.D. Lee

The potential for producing tritium with a deuteron linac (d-LINAC) is explored by adapting the results of a 1976 study that assessed the potential for producing fissile materials [1]. The 1976 study had as its origin the MTA project.

For this example an Alvarez linac produces 0.25 A of 500 MeV deuterons which are then used to produce tritium in a target assembly. Parameters for the 500 MeV linac are listed in Table 9. The target consists of a primary Li target surrounded by a Be and Li secondary target. In the 1976 study the secondary was U and/or Th. The primary Li target is 1.8 m in depth and produces two 105 MeV average energy neutrons per 500 MeV deuteron. The Be-Li secondary, proposed here for tritium generation, supports multiplication of the high energy neutrons and ${}^6\text{Li}(n,\alpha)\text{T}$ plus ${}^7\text{Li}(n,n'\alpha)\text{T}$ reactions. Each 105-MeV neutron is taken to produce 6.25 tritons based on energetics scaled from 14-MeV neutron calculations with Be-based blankets [2]. Light-element targets are proposed because their lower power density and generation of activation products would simplify target thermal design and waste management compared with the use of heavy elements. A water-cooled Be primary and Be - LiAl secondary target should also be considered because it would eliminate the need to handle liquid lithium and would utilize Savannah River target technology.

An elevation view of how a d-LINAC tritium production accelerator might look is shown in Fig. 7

Figure 7: d-LINAC Case

Table 9: General parameters for 500-MeV, 0.25-A beam (cw) deuteron Linac.

Beam power (MW, cw)	125
Injection energy (keV)	750-800
Normalized emittance (inject: cm-mrad.)	0.84π
Minimum bore radius (cm)	2.25
Linac frequency (MHz)	50
Average axial E-field (MV/m)	1
Acceleration rate (MeV/m)	0.62-0.74
Stable phase	30°
Drift-tube quadrupole sequence	N - 1 (. . .)
Integrated quadrupole strength (kG)	15.7
Total rf power (MW)	172
Number of cavities	101
Linac length (m)	780
Total power input (MW at 60 Hz)	290
Injector	1
Quadrupoles	2
rf system	265
Auxiliary power (cooling, vacuum, control)	22

Key performance and economic parameters for this d-LINAC case are estimated to be:

Accelerator deuteron energy and current	500 MeV, 0.25 A
Tritium production rate	3.1 kg/yr
Accelerator electrical power input	290 MW
Capital cost, direct	\$422 M
O & M costs per year (excluding electricity and tritium processing)	\$18 M

R&D Status and Issues

In 1976, when electronuclear breeding of fissile fuels with a 500-MeV d-LINAC was investigated, the following accelerator R&D issues were listed:

- CW beam-current injection development is needed.
- Alternative accelerator structures should be assessed to determine if there may be more cost-effective options.
- RF tube development could increase efficiency from 50% to 65-70%.

In the target performance area the following R&D is needed:

- Theoretical and experimental verification of beam-target interaction.
- Performance (T/d) vs waste generation in light vs heavy secondary targets.

The time and cost associated with addressing the R&D needed to demonstrate the reliable operation of a d-LINAC based tritium production facility has not been determined.

References

1. C.M. Van Atta, et al., "The Electronuclear Conversion of Fertile to Fissile Material," Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52144 (1976).
2. R.W. Moir et al., "Study of a Magnetic Fusion Production Reactor," Lawrence Livermore National Laboratory, Livermore, CA, UCRL-94408 (1986).

BLANKET AND TARGET R&D STATUS AND ISSUES

Maximizing tritium production, thermal management, material lifetime and replacement, activation product generation, tritium handling—all must be satisfactorily addressed in the design of any blanket or target.

The tritium breeding blankets proposed for the Linear Plasma and Tokamak Plasma fusion cases are based on mostly demonstrated technology, namely the Savannah River water-cooled LiAl target and tritium extraction technologies. Designs (conceptual) for both the linear and tokamak cases were addressed in some detail in Ref. [1] and [2]. There are some uncertainties in the achievable tritium breeding ratios ($\pm 15\%$) and material lifetimes, but these uncertainties can be accommodated for by a modest increase in size and cost. In short, a major R&D program is not required; only a modest ($< \$50\text{M}$) design and testing effort is needed.

The breeding blanket for the Compact Torus (CT/RACE) fusion concept will require an R&D program. This is because the concept is new and radically different from those examined in the past. Development will be especially challenging because the blanket must provide confinement for the plasma magnetic field as well as breed tritium. The target tritium handling system will likely have to deal with the unburned D-T fuel along with that produced in the blanket. *Such an R&D program should be relatively short-term and of modest cost ($\sim \$50\text{M}$) because of the small size of the CT/RACE concept, but its outcome is more speculative.*

Tritium breeding targets for the accelerator-driven concepts will require some R&D as outlined in the sections on those cases. It may also be possible to use Savannah River-based target technology, along with beam sweeping, for the accelerator cases as well.

References

- [1] R.W. Moir et al., "Study of a Magnetic Fusion Production Reactor," Lawrence Livermore National Laboratory, Livermore, CA, UCRL-94408 (1986).
- [2] J.D. Lee, "Tritium Breeding Analysis of a Tokamak Magnetic Fusion Production Reactor," Lawrence Livermore National Laboratory, Livermore, CA, UCRL-100019 (1988).

SUMMARY AND CONCLUSIONS

To help give some perspective to the five potential tritium-producing concepts described above, Fig. 8 compares their estimated performance in terms of unit capacity, electrical power requirement, and cost. It also lists normalized performance in terms of the number of units required to produce 5 kg/y, the tritium produced per unit of electric energy (kg/GWY), and the direct capital cost per unit capacity (\$B/kg/y). The five concepts examined vary significantly in these figures of merit. As is normally the case, economy of scale prevails, and the tokamak with its large capacity of 13 kg/y has the lowest cost in terms of construction and electricity per unit of tritium production capacity. The CT/RACE concept is by far the smallest of the five in size as well as capacity, and a production facility based on CT/RACE would come closest to our desired ideal of a small, modular system. The CT/RACE concept is also the most speculative of the five but an R&D program through full-scale demonstration should, by virtue of its small size, be much less costly in time and money than the others.

With respect to the two accelerator cases considered, the d-LINAC has the potential for relatively good performance, and its uncertainties and required R&D program appear to be modest. The performance potential of the electron linac case was found to be very low.

It should be pointed out that fission-based systems have a proven record of reliable operation that make them the logical choice in the near term and that will be hard to match even with mature fusion or accelerator technologies. However, in view of the concern that even new fission production reactors could be subject to unforeseen shutdowns in the future, development of non-fission production methods (as backups or in addition to NPR's) would enhance the overall security of tritium supply. Fusion-based tritium production does have potentially significant inherent advantages over fission in that the amount of nuclear energy

released per triton produced is about six times lower, and the activation and after-heat levels can be much lower. These advantages arise from the fact that a DT fusion reaction produces a 14 MeV neutron and a 3.6 MeV alpha, compared to a fission reaction event which produces 200 MeV and activated fission products. Both events produce about 0.7 net tritons. These advantages were highlighted by the recent NRC study and could result in real and/or perceived safety advantages. Accelerator-based systems should have similar advantages.

Concept	Unit Performance			Normalized Performance		
	Capacity (kg/yr)	P(el) Req. (GWel)	Direct Cost (B\$)	# Units for 5 kgT per year ^a	T/E(el) (kg/GWY)	Direct Cost (B\$/kgT/yr)*
e-LINAC	0.41	1.1	0.54**	18	0.40	4.3**
d-LINAC	3.1	0.29	0.42	2.3	11	0.19
Linear Plasma	5	1.4	1.6	1.4	3.6	0.46
Tokamak Plasma (PPPL/LLNL)	13	0.56	1.7	0.55	23	0.19
RACE, CT	0.027	0.0067	≥0.013**	265	4	≥0.69**

* @ 70% capacity factor

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** Driver only, blanket-target systems not included

Figure 8: Comparison of potential tritium production technologies.