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LA-4863-MS

AN INFORMAL REPORT

INDC(USA)-40/G

LASL Intense 14-MeV Neutron Source

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scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

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National Technical Information Service
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Price: Printed Copy $3.00; Microfiche $0.95

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An Informal Report
UC-20
ISSUED: June 1972

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by

Dale B. Henderson

*This work supported by the Division of Controlled Thermonuclear Research.

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ABSTRACT

At least two independent suggestions have been made to build a 14-MeV neutron source at 10^{14} to 10^{15} neutrons/cm^2-sec for materials damage studies related to fusion power reactors. Greater detail of the LASL suggestion is presented here than in our earlier report. A feasibility study is proposed in which such a 14 MeV source would be thoroughly investigated.

I. INTRODUCTION

The need for neutron sources suitable to study damage phenomena anticipated in fusion reactor structural materials has been, by now, well established. The latest estimate from the Scyllac group, for instance, is that the wall of a prototype pulsed D-T reactor would sustain a flux of 14.06 MeV neutrons equal to 2.7 x 10^{14} neut/cm^2-sec (at one pulse per second).[1] Other estimates span the range from 10^{14} to 10^{15} neut/cm^2-sec at 14 MeV. There are several anticipated and perhaps also some unexpected damage mechanisms which will be important at such fluxes and energies. The microscopic damage effects (transmutations to other metals, transmutation to helium and hydrogen, production of lattice vacancies and interstitials, etc.) will interact with the host material, with each other, and with effects due to the material temperature and stress fields in a very complicated way. The resulting effects of engineering interest - swelling, reduced ductility, enhanced creep rates, modified strength, etc. - are expected to be very important, but are impossible to predict from knowledge of the microscopic effects. It is for this reason that a neutron source is needed which can provide the correct flux and energy spectrum to samples which may be maintained at the appropriate temperature under the appropriate stress loading.

Such a source is quite obviously a variant of the Cockcroft-Walton D-T source, in continuous operation at a thousand times the present day maximum intensity, with enough room available close-in to locate the experimental samples. Such a source was proposed for fusion reactor application by Colombant and Lidsky[2] and then again in the present context at LASL by Dreicer and Henderson.[3]

The present report summarizes the ideas which underlay our earlier report with some improvements in the calculations. It also locates certain LASL expertise and facilities which could be brought to bear on a program to actually build such a source. These include extensive special experience with neutrons, hot high pressure hydrogen, fluid mechanics computation, accelerators, tritium, radiochemistry, and metallurgy. Finally, it suggests a short program which would establish the feasibility of the project, establish a reasonably firm design from among the possible variations, establish a good cost estimate including the location of suitable equipment available as government surplus, and work out a subsequent program which could be followed to the completion of the then proposed facility.

II. CONCEPT

The generation of 14 MeV neutrons from the DT reactions using a Cockcroft-Walton machine is a standard technique. In general a beam of deuterons is stopped in tritium-in-metal target such as developed at Los Alamos.[4] The specific yield from such targets is about 3×10^8 neutrons/joule and their intensity is limited by target heating. If one assumes that he might cool the target sufficiently well to retain the tritium loading at 3 kW/cm^2 (1.1 kW/cm^2 has been achieved),[5] the maximum source intensity is $(3 \times 10^8) \times (3 \times 10^3) \approx 10^{12}$ neut/cm^2-sec. The present idea is to use a windowless gas target in order to gain a factor of 10 in specific yield (neutrons/joule) and a factor of 100 in allowable beam power density. This is an old idea, mentioned as having been attempted without success in reference 5. Recently, however, a windowless gas target has been made to work at Los Alamos,[6] for a different application.

When a current I_B of ions of one of the heavy hydrogen isotopes traverse a gas at density n_g of the other, most are simply slowed down, losing energy E as $dE = -n_g\ \varepsilon(E)\ dX$, where ε is the stopping power of the gas for the ion in units of (say) keV-barns. A small fraction will, however, produce neutrons N as

$$\begin{aligned} dN &= I_B\ n_g\ \sigma(E)\ dX \\ &= -I_B\ [\sigma(E)/\varepsilon(E)]\ dE, \end{aligned}$$

where σ is the cross section in barns. Standard data[7,8] for ε and σ are displayed for both the D^+ beam case: $T(d,n)\alpha$ and the T^+ beam case: $D(t,n)\alpha$ in Figs. 1 and 2. The differential yield, σ/ε in neutrons/joule, displayed in Fig. 3, is integrated to find the yield

$$Y = \int_{E_{in}}^{E_{out}} - [\sigma(E)/\varepsilon(E)]\ dE, \quad \frac{\text{neutrons}}{\text{ion}} .$$

The range or required target thickness is

$$R = \int_{E_{in}}^{E_{out}} - [1/\varepsilon(E)]\ dE, \quad \frac{\text{atoms}}{\text{cm}^2} .$$

The yield Y_0 and range R_0 for the case of a thick target ($E_{out} = 0$) are displayed in Figs. 4 and 5. [Note that we may equate the ion range and the target thickness or projected range since the difference is only $(m_e/3.5\ m_i) \approx 0.005\%$.][7]

As has already been alluded to, the experimental difficulties are most strongly dependent upon the beam and target power. Therefore the specific yield, Y_0/E_{in}, which is plotted in Fig. 6 is of special interest. Notice that there is no efficiency advantage to accelerating either species over the other: a maximum of 3×10^9 neutrons/joule is available either way. One chooses therefore to accelerate the tritium in order to minimize the tritium inventory and the associated costs and hazards. One further notes that the maximum is very broad; the range E_{in} = 250 keV to 370 keV has a specific yield within

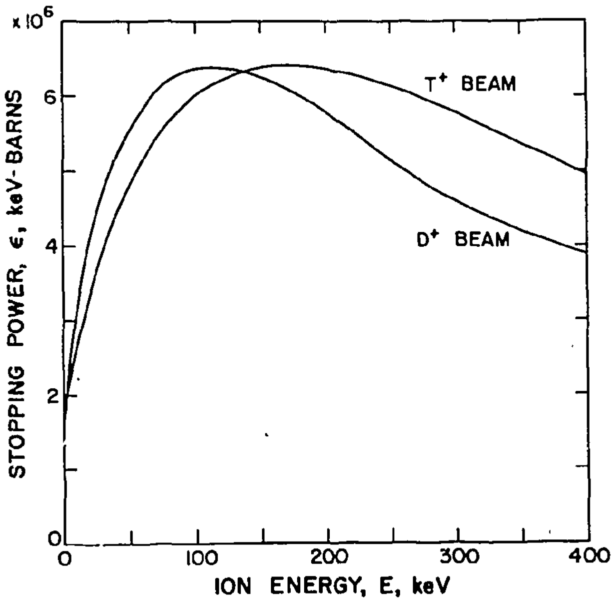

Fig. 1. Stopping power for D^+ in T_2 and for T^+ in D_2.

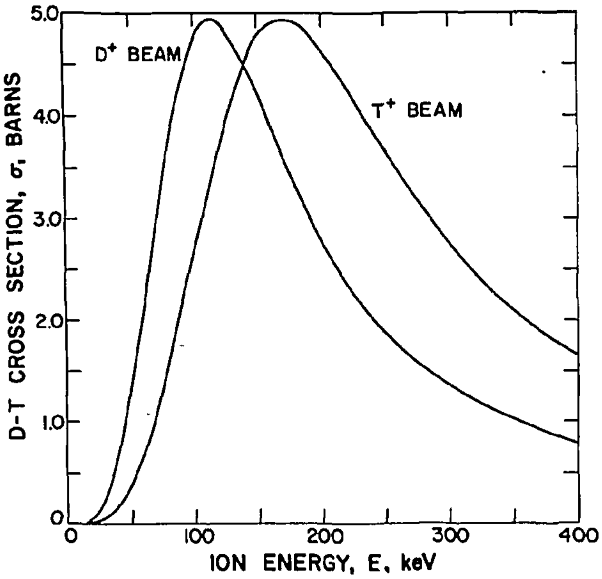

Fig. 2. Neutron production cross section.

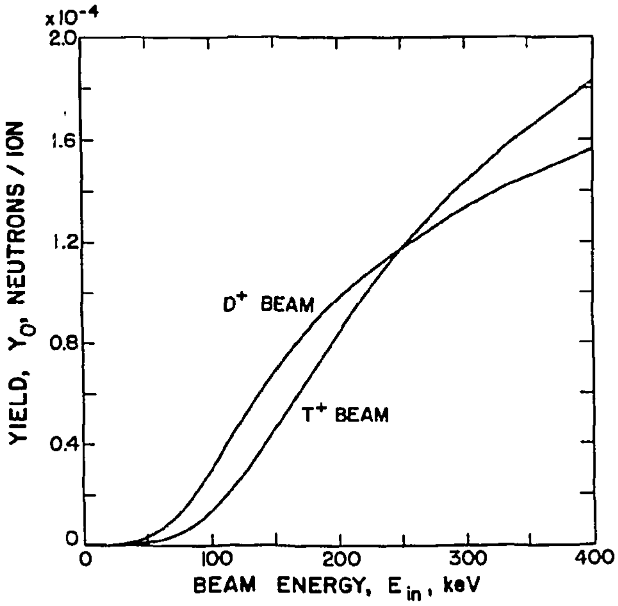

Fig. 4. Thick target yield.

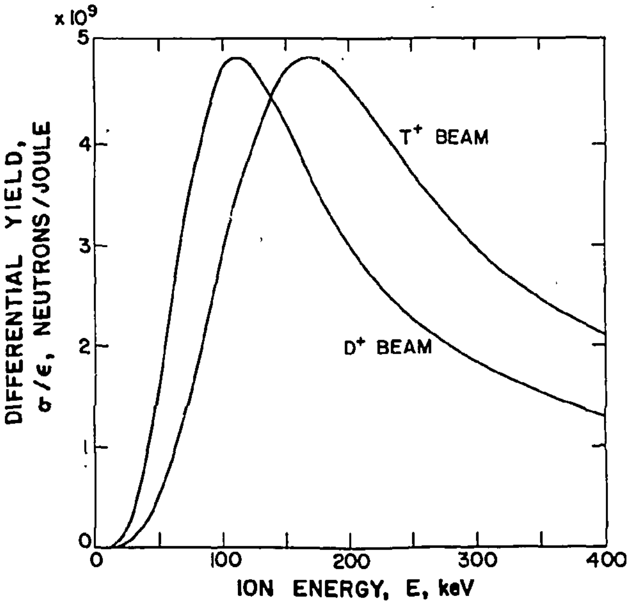

Fig. 3. Differential yield.

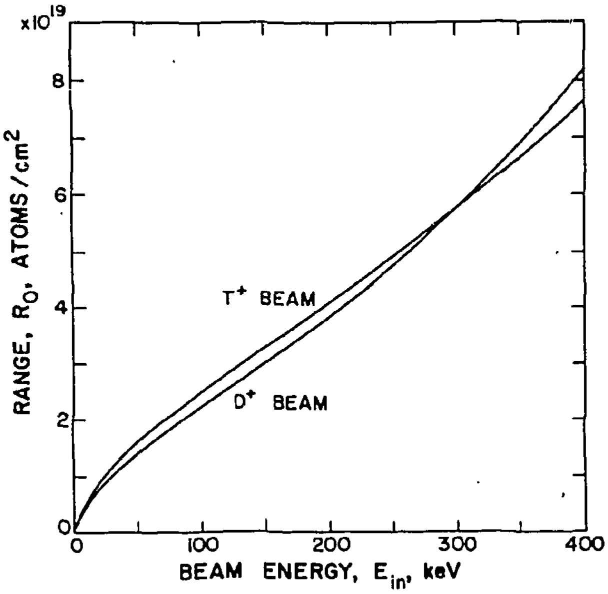

Fig. 5. Ion range for D^+ in T_2 and for T^+ in D_2.

2% of the optimum at 305 keV. LASL has obtained a 0 to 270 keV - .2 amp d.c. power supply, valued at $1.8 M, from DoD surplus for this project. For this reason we shall adopt E_{in} = 270 keV in the following.

Because tritium is so hazardous, 10^4 curies/gram, and expensive,[9] $.75/curie = $7,500/gram, and because the beam passes quite a lot of it (10 amp-hours ≈ 1 gram), it is appealing to use an "almost thick" gas target from which triton beam is excited with sufficient energy for separation but not for further neutron production.

Some of the characteristics of an "almost thick" target for E_{in} = 270 keV are plotted in Fig. 7. Here one may distinguish between specific yields per beam joule and per deposited-in-the-gas joule since the two are no longer equal: a

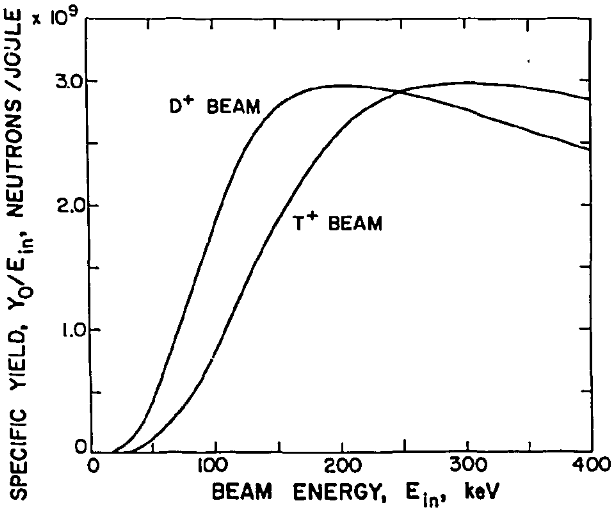

Fig. 6. Specific yield for thick target.

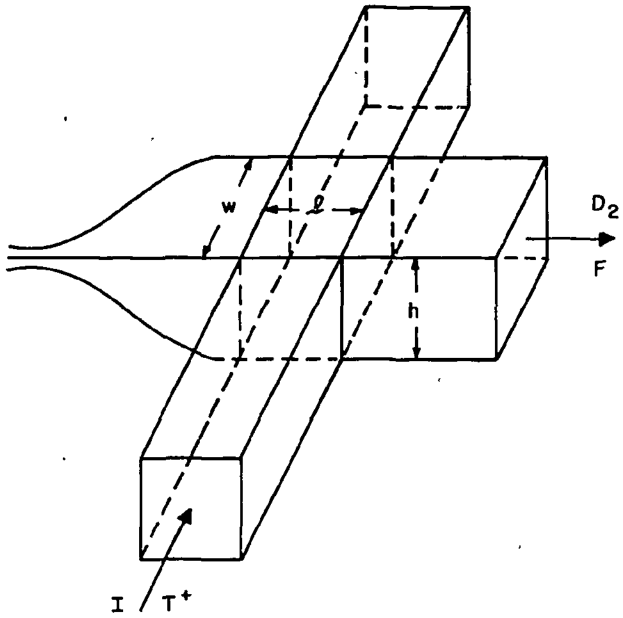

Fig. 8. Sketch of reaction volume.

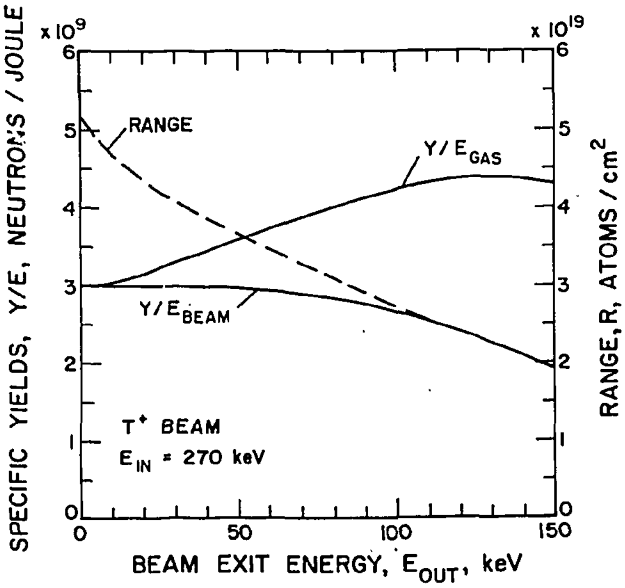

Fig. 7. Specific yield for almost thick target.

significant fraction of the beam energy passes through and the range (more properly thickness) is reduced. For instance E_{out} = 50 keV would provide an energetic triton beam for separation but would reduce the yield by only 0.7%. The range would be reduced 30% and the specific yield per deposited-in-the-gas joule increased 21%.

If it should turn out that the gas target thickness and power capability are much more difficult and expensive than beam intensity and power, then it might be advantageous to use a significantly thinner target. That is, to go some way toward optimizing the yield per target joule at the expense of the yield per beam joule. For the present, however, we shall continue with the "almost thick" target.

III. GAS TARGET

The model thus far consists of a triton beam at 270 keV incident upon a deuterium target of thickness R = 3.63×10^{19} atoms/cm^2 = 1.82×10^{19} molecules/cm^2. The beam exits at 50 keV yielding 1.26×10^{-4} neutrons/triton or 2.93×10^9 neutrons/beam-joule or 3.59×10^9 neutrons/gas-joule.

The target is sketched in Fig. 8 as two crossed beams: a T^+ current I and a D_2 current F. The reaction volume is sketched as a solid rectangle w x ℓ x h, not to indicate that such a geometry would be used, but because the computation is simplified. The neutron production will be

$$N = 1.26 \times 10^{-4}\ I_B$$

$$= 0.787 \times 10^{15}\ I, \text{ neutrons/sec}$$

for I in amps.

The flux at the top and bottom (Fig. 8) surfaces $w \times \ell$ will be approximately

$$f \approx \frac{N}{4\pi (h/2)^2} = 2.5 \times 10^{14}\ I/h^2,$$

where all dimensions are assumed to be in centimeters. The required gas target has a thickness of

$$R = w \times n_g = 1.82 \times 10^{19}\ \text{molecules/cm}^2$$

and contains $1.82 \times 10^{19} \times \ell \times h$ molecules.

The problem of heat addition to flow in constant area duct is simply solved, but the derivation is too lengthy to reproduce here.[10] The density n, speed v, pressure p, and temperature T on the upstream (denoted 1) and downstream (denoted 2) sides of the heating zone are, however, simply related in terms of the Mach numbers M_1 and M_2:

$$\frac{n_1}{n_2} = \frac{v_2}{v_1} = \left(1 + \frac{1}{\gamma M_1^2}\right) \Big/ \left(1 + \frac{1}{\gamma M_2^2}\right) ,$$

$$\frac{p_2}{p_1} = \frac{M_1^2}{M_2^2} \frac{v_2}{v_1} ,$$

$$\frac{T_2}{T_1} = \frac{M_1^2}{M_2^2} \frac{v_2^2}{v_1^2} ,$$

where γ is the ratio of specific heats and equals 1.4 here. Notice that if the flow remains fairly supersonic ($M^2 \gg 1$), then the density and flow speed are only slightly affected by the heat addition while the pressure and temperature are increased approximately as $(M_1/M_2)^2$.

The Mach number is reduced in proportion to the relative enthalpy added to the flow, a quantity

$$\frac{q}{C_p T_1} = \frac{(270-50) \times 10^3\ I}{n_g\ v\ w\ h} \frac{\gamma-1}{\gamma} \frac{1}{kT_1}$$

$$= 2.5 \times 10^8 \frac{I}{h\ v_1\ T_1} .$$

In order to find M_2 from M_1 and q/C_pT_1 one solves the implicit relation[10]

$$\phi(M_2) = \phi(M_1) + \tilde{\phi}(M_1) \times (q/C_pT_1), \quad \text{where}$$

$$\tilde{\phi}(M) = M^2 (1 + \gamma M^2)^{-2} , \quad \text{and}$$

$$\phi(M) = \left(1 + \frac{\gamma - 1}{2} M^2\right) \tilde{\phi}(M) .$$

The auxiliary functions $\tilde{\phi}$ and ϕ are plotted in Fig. 9 for reference.

The upstream flow (condition 1) is, of course, derived through expansion from a plenum (with conditions denoted by subscript o) through the nozzle sketched in Fig. 8. Again quoting standard results in terms of M_1, we have

$$T_1/T_o = \left[1 + \frac{\gamma - 1}{2} M_1^2\right]^{-1} ,$$

$$p_1/p_o = \left[1 + \frac{\gamma - 1}{2} M_1^2\right]^{-\gamma/(\gamma-1)} ,$$

$$n_1/n_o = \left[1 + \frac{\gamma - 1}{2} M_1^2\right]^{-1/(\gamma-1)} , \quad \text{and}$$

$$v_1 = \left[\frac{2\gamma}{\gamma - 1} \frac{k\ T_o}{M_{D_2}}\right]^{1/2} \left[1 + \frac{2}{\gamma - 1} \frac{1}{M_1^2}\right]^{-1/2} .$$

These relationships are all graphed and tabulated in many standard texts. Rather than attempt a general solution here in terms of the many parameters involved, consider a specific example.

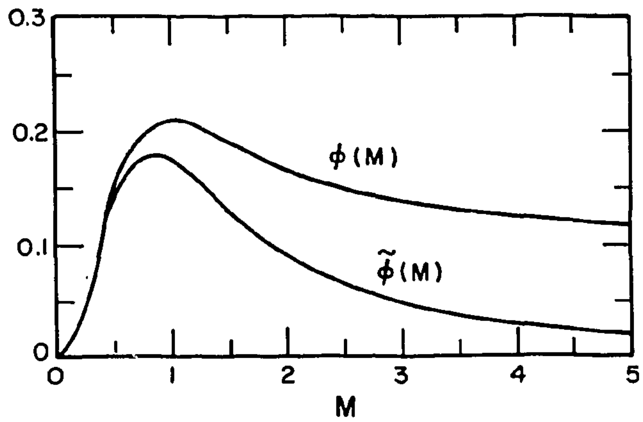

Fig. 9. Auxiliary functions used in text.

Assume $w = h = \ell = 1$ cm

$I = 1$ amp

$M_1 = 3.5$

$T_o = 2000$ K.

In this case the required plenum conditions are $n_o = 4.0 \times 10^{20}$ cm^{-3}, $T_o = 2000$ K, and $p_o = 1610$ psi. The upstream test conditions are $M = 3.5$, $n_1 = 1.82 \times 10^{19}$ cm^{-3}, $T_1 = 580$ K, $p_1 = 21.1$ psi, $v_1 = 4.52 \times 10^5$ cm/sec and $F = 8.23 \times 10^{24}$ molecules/sec. After the heat addition at 220 kW, the downstream test conditions are $M_2 = 2.04$, $n_o = 2.02 \times 10^{19}$ cm^{-3}, $T_2 = 1400$ K, $p_2 = 56.8$ psi, and $v_2 = 4.08 \times 10^5$ cm/sec.

It is important to note that flow of 8.23×10^{24} = 13 moles/sec from a plenum at 1610 psi to a static temperature of 1400 K are within the experience of the LASL Rover Program. Design of the flow system would borrow from that experience. Also certain test facilities, adequate to these conditions, could be used for gas target testing.

With the values chosen, the neutron production would be 7.9×10^{14} neutrons/sec with the flux at the top and bottom being $f = 2.5 \times 10^{14}$ neutrons/cm^2sec. While this is within our design goal of 10^{14} to 10^{15}, better figures may be possible through the choice of a bigger current, smaller dimensions, or both. The iteration of this calculation, subject to the requirement of reasonable plenum and flow conditions, needs to be undertaken in a systematic way.

Continuing with the closed deuterium flow circuit, the supersonic flux must be brought to rest as adiabatically as possible, cooled, compressed, and reheated to the plenum stagnation conditions. Such calculations are standard in the design of closed circuit hypersonic wind tunnels. The recovery of supersonic flow usually uses a second throat in order to partially choke the recompression shock to a lower Mach number,[11] but in this numerical example the flow is already thermally choked to $M = 2.04$ and the pump power saved does not appear to be worth the complexity. Accepting a normal shock at $M = 2.04$, the stagnation pressure is further reduced to 330 psi. The supersonic deuterium is then brought to rest and cooled, probably in a large quench tank so that the heat exchange surfaces do not have to work at the 2550 K stagnation temperature. After cooling, the gas is recompressed and returned to the plenum where it is reheated to T_o before expansion into the reaction volume. Some regeneration of heat between the quench tank and plenum is possible, but not a great deal unless the quench tank is to operate very hot. The deuterium circuit is summarized in Fig. 10. Again, the details of this calculation are not meant to indicate any kind of optimum or final design, but only to show that a practical design is possible.

The point of using a supersonic target is, after all, to minimize the gas lost out the beam holes. This loss may be separated into two parts: the boundary layer which is all lost, and the potential flow which turns outward. In order to minimize the boundary layer, which grows from near zero at the throat, the expansion nozzle will be made shorter than standard in wind-tunnel design. This would make a somewhat two dimensional flow at the test volume which is bad for aerodynamics but not very important here. According to wind-tunnel designers,[12] the boundary layer loss will be less than the potential flow loss, which is easier to calculate. We have estimated this loss from a Prandtl-Meyer turning calculation and conclude that it would be practical to deflect the downstream walls to catch all but about 2% of the deuterium flow. This missing fraction of the flow can be pumped out to regain the necessary base pressure of about one

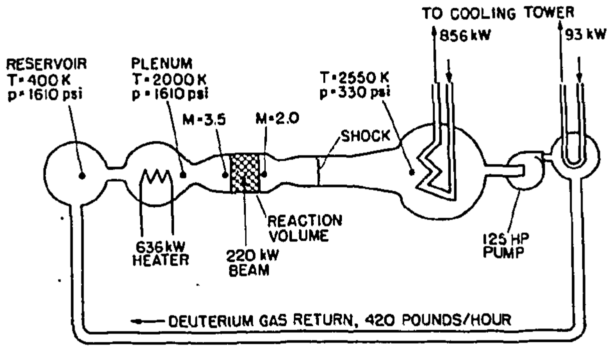

Fig. 10. Schematic of gas circuit.

microtorr in the accelerator column. Using published specifications on commercial blowers this can be accomplished with about five stages of differential pumping. Again the calculation was not carried through to any optimum, but only to show that a reasonable solution is possible.

The experimental samples which are to be subjected to the neutron flux would be located at the top and bottom of the reaction volume sketched in Fig. 8. They could, in fact, be the top and bottom members of the wind tunnel if desired. The pressure outside the tunnel could be adjusted to the inside static pressure so that these would not have to be sealed against a load; that is, the material could be selected and the mechanical stress could be selected and the mechanical stress could be applied as required for the effects experiment. By circulating cool deuterium against the outside of these surfaces the temperature could be maintained anywhere up to the gas stagnation temperature of 2000 K, the commonly discussed 1000 C being fairly easy to maintain.

Otherwise the samples could be mounted in apparatus located in the half-spaces above and below the top and bottom of the reaction volume. This apparatus would need to control the mechanical stress, any mechanical stress cycling, the temperature, any temperature cycling, and the chemical atmosphere as desired. It would also have to contain any neutron reflectors, multipliers, or moderators as desired for the experiment. Doing all of this while keeping the sample close to the reaction volume will not be easy, but the approximate half-infinity available should make it possible.

IV. SYSTEM

There are clearly a large number of parameters in the present model which interact with one another in complicated ways. Only one path through the field of parameters is traced out in this report; only a few have been done. A complete system using details from another path is shown in Fig. 11. A good deal of work will be required to establish an optimum set of parameters in terms of output flux, feasibility, safety, and cost.

The ion source is marked "Oak Ridge" in the figure because high current ion beams, such as needed here, were first developed in support of the ORNL DCX program. This development continues as part of the ORNL ORMAK program and the LLL magnetic mirror program.

From the many published results of these and other groups,[13] it is clear that the fusion device heating objectives they pursue are more ambitious than that required here in both current and power. Also, we need H^+ beams while these groups seek H_2^+, H_3^+, or even H_2^- which are successively more difficult to obtain. Four ampere beams made up of 50% H^+ (and 50% H_2^+) have been reported[14] at 25 to 40 keV with 50% gas efficiency from a 5 kW arc. How well such a beam can be focused through a small aperture at one point is less clear because this is not the same as the long path divergence requirement of the fusion devices. The overall beam picture is, however, quite encouraging.

The accelerator column is marked "commercial" in the figure to indicate that such designs are quite standard. The computer codes developed for the design of the Los Alamos Meson Physics Facility (LAMPF) injector could be used to design the column, which could be engineered and built by a commercial vendor of such equipment.

The deuterium flow circuit has been discussed in the preceding section. The word "standard" does not mean that such a dense high-power gas target

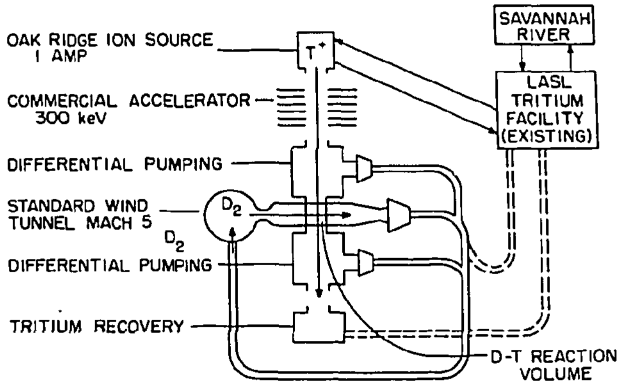

Fig. 11. Schematic of Pump System.

exists, but rather that hypersonic wind tunnels and high power hydrogen flow systems exist. The special techniques available from these fields appear to be adequate to the job.

Tritium recovery and tritium recovery from accelerators is a LASL specialty,[15] one which is essential to the project. If we assume 50% gas efficiency and that the triton beam trap, the ion source pumping trap, and the ion source gas supply are all replaced three times a day, then each trap will contain 8.6×10^3 curies and the supply bottle 1.7×10^4 curies. These traps will be emptied and the bottles refilled at a special LASL tritium facility. The current of tritium from the traps and to the bottles will each total 1.9×10^7 curies per year (or 1.4×10^7 dollar's worth per year), which illustrates the importance of the special techniques and resources.

V. FEASIBILITY STUDY

As a logical step toward construction of such an intense 14 MeV neutron source, further detailed feasibility study is suggested. This study should be directed toward exploration of questions in the following general areas:

1. Is a 14 MeV source at 10^{14} to 10^{15} neutrons/cm^2 sec in operation really practical? Although we believe it is, a closer look at the physical and engineering requirements is needed to be sure.

2. What is the best design from among the several variations possible? After a deeper look at the matter, we would not necessarily stay with the LASL suggestion,[3] the MIT suggestion,[2] or any existing concept. We would develop the best idea as judged by the several competing criteria.

3. How should the source be built? What will the costs and scheduling be like? What existing (surplus) equipment is available? A thorough engineering study should be undertaken to assess these questions.

This feasibility study would need to cover all components of the complete system, sketched out in the last section. In so doing, it would draw upon the many LASL specialties already cited and many which were not mentioned. It would require extensive use of the LASL computing facility, the large hydrodynamics codes written for it, and the people who know how to use them. The study would also seek cooperation from the existing high intensity beam groups at ORNL, LBL, and LLL and would draw on LASL's own ion source experience, especially in producing triton beams.

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