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ANALYSIS OF THE TRITIUM-WATER (T-H_2O) SYSTEM FOR A FUSION MATERIAL TEST FACILITY

by

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FUSION POWER PROGRAM

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Analysis of the Tritium-Water (T-H_2O) System for a Fusion Material Test Facility

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ABSTRACT

The need for a high flux, high energy neutron test facility to evaluate performance of fusion reactor materials is urgent. An accelerator based D-Li source is generally accepted as the most reasonable approach to a high flux neutron source in the near future. The idea is to bombard a high energy (35 MeV) deuteron beam into a lithium target to produce high energy neutrons to simulate the fusion environment. More recently it was proposed to use a 21 MeV triton beam incident on a water jet target to produce the required neutron source for testing and simulating fusion material environments. The advantages of such a system are discussed. Major concerns regarding the feasibility of this system are also highlighted.

1. INTRODUCTION

The current understanding of materials behavior in a fusion-reactor radiation environment is insufficient to assure the necessary performance of future fusion reactor components. The need for a high flux, high energy neutron test facility to evaluate performance of fusion reactor materials is urgent. An accelerator-based D-Li source similar to that proposed in the original Fusion Materials Irradiation Test (FMIT) facility[1] is generally accepted as the most reasonable approach to a high flux neutron source in the near future. In this concept, a high energy (35 MeV) deuteron beam is bombarded into a lithium target to produce the high energy neutrons needed to simulate the fusion environment via the Li(d,n) nuclear stripping reaction. This neutron spectrum, which peaks near a neutron energy of 14 MeV, produces atomic displacements and transmutation products in irradiated materials similar to those conditions in real fusion reactors. Lithium is ideally suited as a target material because of the high rate of neutrons produced during the reaction. The high heat capacity and low vapor pressure of lithium are also advantageous properties for the coolant[2].

More recently it was proposed (KfK, Germany)[3] to use instead a 21 MeV triton beam incident on a water jet target to produce the required neutron source for fusion material testing. The main advantage of this system over the d-lithium scheme is that the T-H_2O neutron spectrum is cut off more sharply above 14 MeV. In addition to issues related to a tritium accelerator, major concerns regarding the feasibility of such a system include: instability of the water jet exposed to the high energy beam, erosion of the structure by the high velocity water, excessive vaporization of water into the vacuum system, and cost of the tritium recovery from the water. Preliminary analyses to determine the relative importance of these latter effects are presented in the following sections.

2. BEAM-TARGET INTERACTION

The deposition and the response of the water jet due to the bombardment of high energy tritons is modeled and simulated using the A*THERMAL[4] computer code. The code is modified to handle the deposition of high energy ions into different target materials. The code calculates, using different analytical models, the energy loss of the incident ion beam through both the electronic and nuclear stopping powers of the target atoms along its path. The analytical models use stopping cross-sections which incorporate some experimental data to accurately model the deposition profile. This code is much faster and more reliable than using Monte Carlo codes which require extensive running time and careful statistical interpretations of the result. The code then calculates the detailed spatial thermal response of the target jet using both finite element and finite difference methods.

A preliminary analysis of the triton deposition and the jet response is shown below. The detailed analysis of the D-Li system is presented elsewhere[5]. The analysis of the T-H_2O system is done assuming a particle beam current of 100 mA incident on a 3 cm^2 target area. Figure 1 shows the deposition profile of the proposed 21 MeV triton beam in a water jet compared to the deposition profile of the original 35 MeV deuterons in a lithium jet concept. The T-H_2O deposition profile is much closer to the surface and approximately a factor of four higher for the water case than that for the lithium case. In addition, the energy density at the front surface for the water case is about a factor of five higher than the lithium case. The deposition profile is important when calculating the surface temperature and consequently the resulting surface vaporization rate. The highly peaked close-to-the-surface deposition profile will result in higher temperature and higher vaporization rates that may destroy the required vacuum boundary between the beam and the jet. This deposition profile is for a 100 mA beam current with a Gaussian distribution of $\sigma = 0.5$ MeV. The water jet thickness should only be a few millimeter (i.e., 3→4 mm) compared to about 2 cm thickness of the lithium jet. Minimizing the thickness of the jet may be important in order to preserve and keep the neutron energy spectrum at values similar to those in real fusion reactor conditions in the test region. However, thin jets may be very unstable when running at very high velocities and small surface perturbations will have a significant effect. Figure 2 shows the water thermal response due to triton energy deposited for two different water jet velocities. For a water jet velocity of 20 m/s, the calculated temperature rise is very high throughout most of the deposition range and the critical water temperature (~650 K) is exceeded at the peak. About 10-15% of the water jet (assuming 2 cm thick water jet) could be converted into steam instantly which would drastically affect the jet stability. For a 3 mm thick jet, almost 50% of the water will be converted into steam. On the

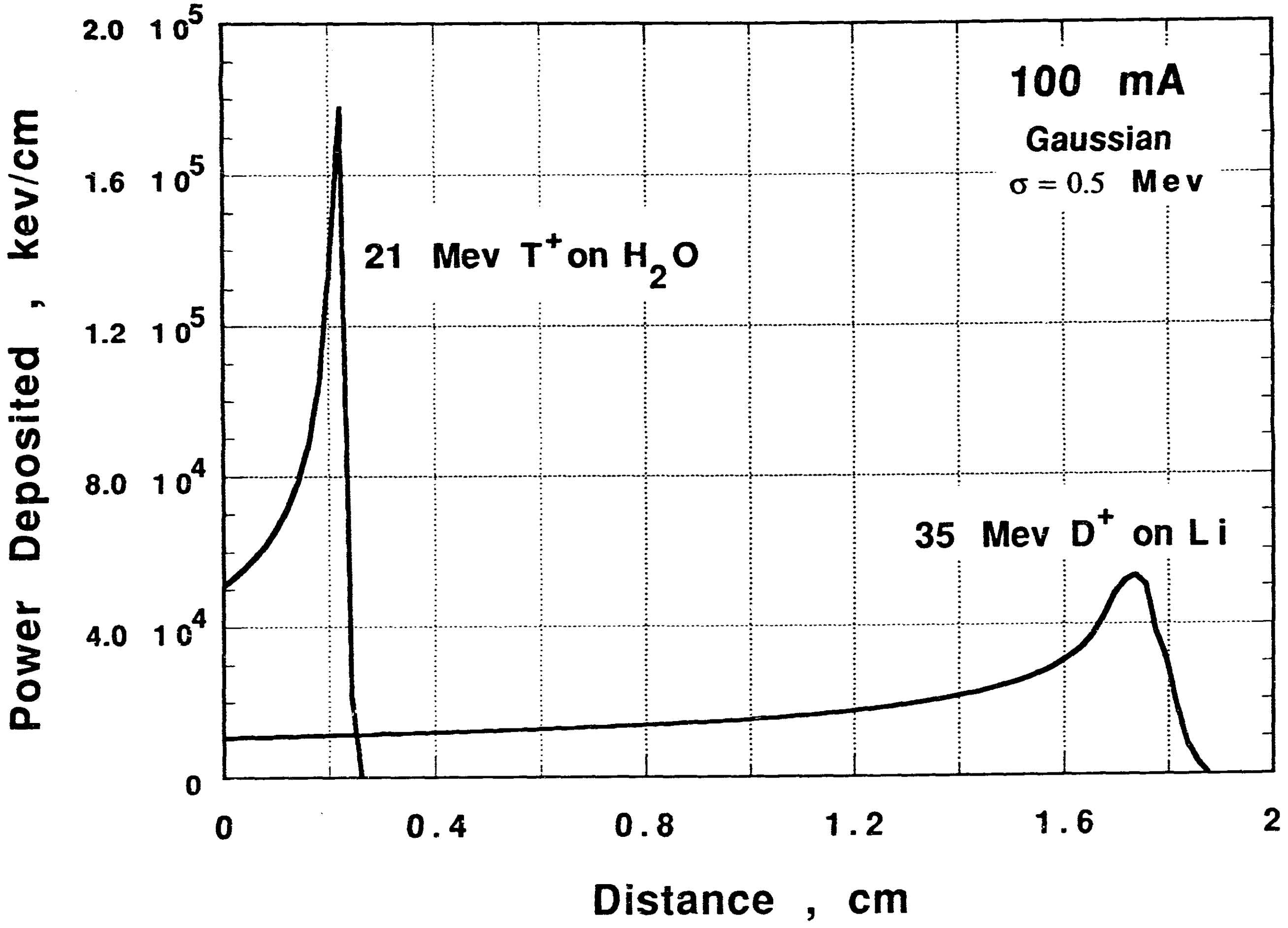

Fig. 1 Comparison of triton beam deposition in water and deuteron beam deposition in lithium.

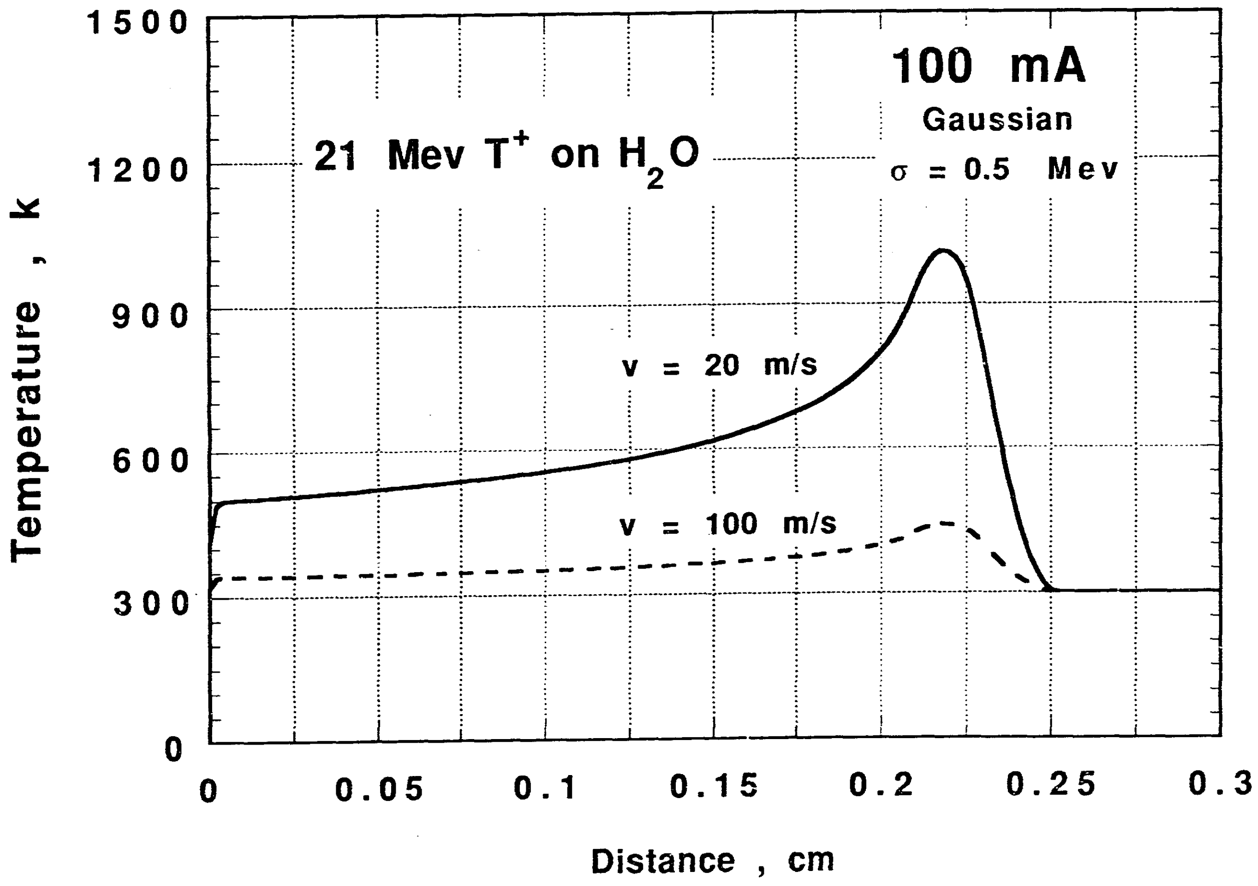

Fig. 2 Spatial distribution of water temperature for different water jet velocities.

other hand, velocities in excess of 100 m/s can substantially reduce the temperature increase of the water and the predicted temperature will remain below the critical temperature, with the possibility of a stable jet. However, the vapor pressure will still be quite high which could lead to instabilities in the jet and excessive vapor contamination of the vacuum system. A broader Gaussian distribution of the triton beam (i.e., $\sigma > 0.5$ MeV) will further reduce the temperature rise in the jet. However, the effect of the triton beam energy distribution on the resulting neutron spectrum needs to be studied further.

Figure 3 shows that lower jet velocities can be used at lower beam currents without exceeding the obvious critical temperature limit. Lowering beam currents will lower the amount of energy deposited in the system which will result in lower thermal response of the water jet and lower neutron yields. Lower jet velocities are desirable because of concerns that arise at high jet velocities such as the stability of the jet, high erosion rates at the jet nozzle, large momentum transfer downstream, excessive splashing as the jet stops and other factors. However, low beam currents will result in lower neutron fluxes. For testing material properties that primarily depend on neutron fluence such as swelling and embrittlement, accelerated dose rate tests are required, and the use of such systems may be impractical.

3. THERMAL HYDRAULICS AND VACUUM SYSTEM REQUIREMENTS

Water Jet Velocities: The German proposal suggested that required water jet velocities of 140 m/s were common practice in hydro-turbines today. This, strictly speaking, is correct. There are so-called "impulse turbines" in operation which use a 1400 meter water head to drive the turbine wheel; and in these systems, the jet velocity issuing from the nozzle is comparable to the proposed jet velocities. The water jet velocity itself, is theoretically attainable. However, the pressure required to drive the water to these speeds is roughly 15 MPa. These numbers translate into a pumping power requirement of 1.2 MW. Therefore, the resulting circulating system to deliver such a jet will be more complex, expensive, and less reliable.

At such high water jet velocities, erosion would be a significant concern, certainly a much greater concern than in a lithium system with velocities one order of magnitude lower. The Reynolds number of the water jet

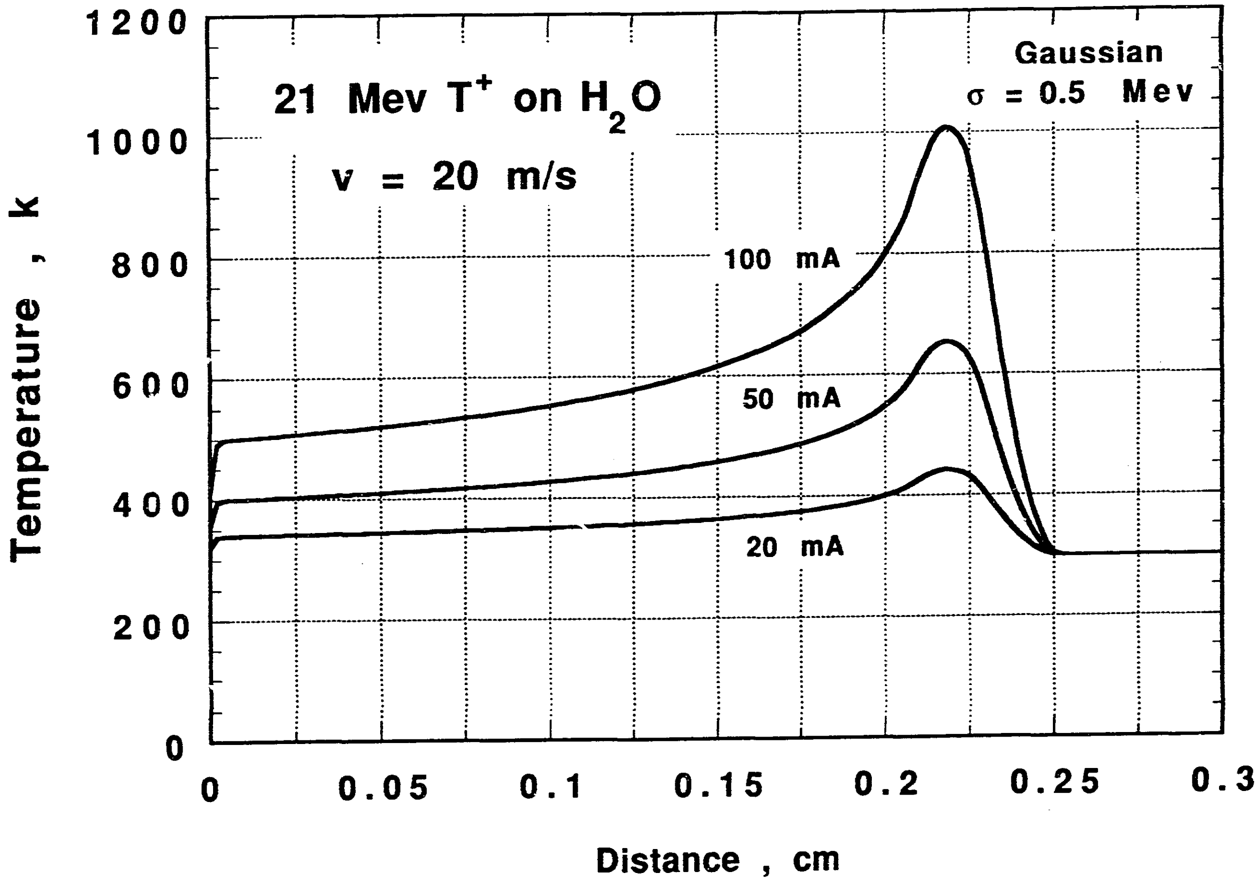

Fig. 3 Spatial distribution of water jet temperature for different beam currents.

would be roughly 1.5 x 10^6 compared to 0.6 x10^6 for lithium; at 1.5 x 10^6 the flow is fully turbulent, and the combination of surface instabilities and jet thickness variations are significantly greater than those at the lithium conditions. The circulating pump would not be an ordinary high pressure pump similar to those found in PWR systems which operate at system pressures approaching 15 MPa. Those pumps operate at high system pressure, but do not have to create a large pressure rise. In the water jet system under discussion, however, the pump must raise the water from essentially a zero pressure all the way to 15 MPa. Such pumps would probably have to be developed, and reliability would definitely be a concern.

Ice Buildup Rate On Cryogenic Pumping Surfaces: The vacuum requirements from the FMIT system for the accelerator beam tubes and the target chamber were ~10^{-4} Pa. The vapor pressure of water limits the pressure at the water target surface and in the chamber immediately surrounding the jet to a minimum of a few hundred pascals (the vapor pressure of water at freezing is ~500 Pa). The water vapor cloud around the jet will have serious deleterious consequences on beam quality and beam losses. The length of this high pressure region around the water jet could be minimized if cryopumping could be used to continuously remove the water vapor. However, the rate at which "ice" will build up on cryopumped surfaces, under these conditions, is approximately 4 cm/min. This is unacceptably high. Hence, it appears that it would be very difficult to maintain the vacuum system requirement, due to the presence of water vapor. Under these circumstances, the beam would be neutralized, scattered, and unable to deliver its energy to the water jet.

4. COST OF TRITIUM RECOVERY FROM THE WATER SYSTEM

The reference case used here assumes two 250-mA targets. The important parameters are[3]:

Tritium beam current	2 x 250 mA
Tritium throughput	2 x 0.68 g/d
Beam power	10.5 MW
Tritium beam energy	21 MeV
Water inventory	2.0 m^3
Tritium concentration	~ 1 Ci/liter
Tritium recovery system cost	$20 Million

The basis for the cost estimate is as follows:

1. Water inventory: The power of the two beams is 10.5 MW. Assuming a bulk coolant ΔT of 20°C, the coolant flow rate 1.25×10^5 cm^3/sec. Therefore, the average coolant turn around time is 16 seconds. This appears reasonable.

The coolant inventory for a typical 3000 MW PWR is 2×10^5 liter. Therefore, the coolant inventory would be 700 liter for 10 MW. For a small system, the coolant volume percent/power ratio is higher. However, 2000 liter is reasonable.

2. Tritium Recovery System Cost: A water distillation system will be used to enrich the tritium concentration from 1 to 1000 Ci/liter. A vapor phase catalytic exchange process (VPCE) will be used to transfer tritium from water to hydrogen gas. A cryogenic distillation (CD) system will be used to increase the T/H ratio to about 100. The following parameters are predicted:

	Water Distillation	VPCE	CD
T/H]in	3×10^{-7}	3×10^{-4}	1×10^{-4}
T/H]out	3×10^{-4}	1×10^{-4}	100
Throughput	566 kg/hr*	0.57 kg/hr*	0.23 kg/hr**
System cost*** (M $)	4	1	6

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* Water flow rate.

** Hydrogen flow rate.

*** ITER cost scaling.

The total tritium recovery system has to include the piping, instrumentation, etc. Therefore, $20 M is a reasonable estimate for the complete system. In conclusion, the water inventory and the tritium recovery system cost all appear to be reasonable.

5. CONCLUSIONS

More accurate analysis is needed to study the effect of several important factors on the design of this system. The impact of thicker water jets (i.e., > 3 mm), because of the stability issues, on the neutron spectrum at the testing area is one factor. The impact of very high jet velocities on the feasibility of the system as a whole is another factor. Again, high velocity jets can cause severe erosion rates of some parts of the system components. The high vapor pressure of a water system compared to a liquid metal system can severely limit and interfere with the accelerator performance which generates the particle beam. This factor by itself needs to be assessed carefully because of its seriousness, which may completely inhibit or shut down the operation of such a system. In addition, additional analyses are needed to take into consideration the change of water properties at higher temperatures as the beam deposits its energy in the jet.

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