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DESIGN AND ANALYSIS OF THE LITHIUM TARGET SYSTEM FOR THE INTERNATIONAL FUSION MATERIALS IRRADIATION FACILITY (IFMIF)

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Design and Analysis of the Lithium Target System for the International Fusion Materials Irradiation Facility (IFMIF)*

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ABSTRACT

Three lithium target design options are being evaluated for the IFMIF. The impact of various requirements on material selection, lifetime, operation and maintenance are discussed. Analysis for the free jet option is presented. Key aspects include jet stability, thermal and nuclear responses.

1.0 INTRODUCTION

A conceptual design activity (CDA) for an International Fusion Materials Irradiation Facility (IFMIF) is being conducted under the auspices of the International Energy Agency by three international partners: the United States, Japan, and the European Union. The design concept utilizes a high energy deuteron beam, 30-40 MeV, impinging on a flowing lithium jet to produce high energy, nominally 14 MeV, neutrons for irradiation of candidate fusion structural materials (Fig. 1). Neutrons are produced via the d(Li)p nuclear stripping reactions. Previous activities of similar purposes were the development of Fusion Materials Irradiation Facility (FMIT) in the early 80s [1], and Energy Selective Neutron Irradiation Test Facility (ESNIT) in late 80s [2]. ESNIT is essentially a small but extended version of FMIT. Neither facility was constructed due primarily to budgetary constraints.

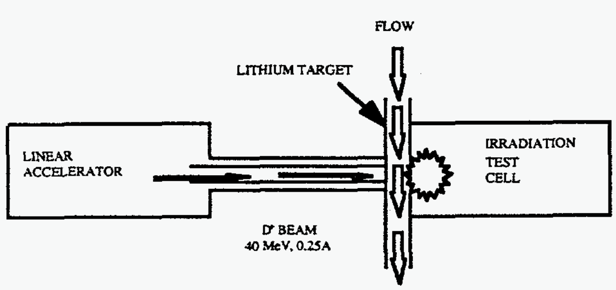

Fig. 1. Schematic of IFMIF design concept.

One of the major CDA activities is in the design, development and analysis of the lithium target system. One of the most significant differences in IFMIF is the larger deuteron beam size (5 cm tall by 20 cm wide) than in FMIT (1 cm x 3 cm), resulting in an order of magnitude reduction in beam energy deposition density in the lithium jet. Key aspects of the design are configuration, target assembly material selection, lifetime, maintenance, and interface with other systems including the accelerator, and test cell. Key aspects of analysis are jet stability, thermal-hydraulic, lithium vaporization, and nuclear response.

2.0 TARGET CONCEPTUAL DESIGNS

While some aspects of the target system will benefit from FMIT design and experiences, the large change in beam spot size and material database obtained since FMIT require new considerations for the target under IFMIF conditions. Currently, three Li-target design options are being evaluated for IFMIF.

2.1 Option A: FMIT-type

Figure 2 shows a schematic of the FMIT-type lithium target assembly. The flow straightener, nozzle, backwall, and sidewalls constitute an integrated component. The backwall will receive the highest neutron damage rate and will be the life-limiting component of the target assembly. Effects of neutron irradiation on the backwall material include swelling which would degrade jet stability, embrittlement, impracticality for rewelding, etc.. Potential failure/rupture of the back plate as a result of excessive embrittlement is a major concern. Rupture of backwall could result in severe lithium contamination and damage to the accelerator. Currently the choice of target material has not been defined for meeting the target lifetime goal of 9 full-power months [3]. Candidate materials include austenitic steel, ferritic steel, and vanadium alloy. The data base on materials indicate that the lifetime of the austenitic steel back plate may be very limited, thus requiring frequent replacement which will affect facility availability, and is a costly process. The data base for ferritic steel also indicates severe embrittlement after irradiation, particularly with simulated He transmutation effects. Although experiments are in progress, there is very little data on the embrittlement of vanadium alloys at the low operating temperatures.

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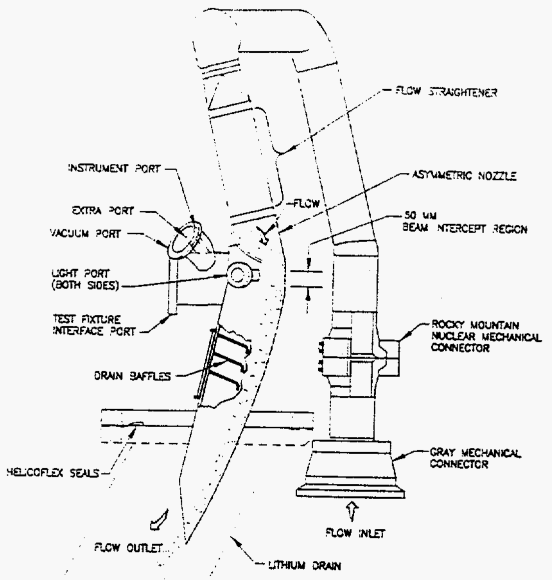

Fig. 2. FMIT-type target (Option A).

2.2 Option B : Replaceable Backwall

To optimize target lifetime and replacement, this design concept utilizes a replaceable backwall with mechanical attachment to the target assembly as shown in Fig. 3. Under this scheme the rest of the target assembly will have a longer lifetime than the replaceable part. Replacement of the backwall only will be simpler and faster than replacing the entire target assembly. In addition, because there is no welding, the replaceable backwall can be made of a different material if desired. For example, a combination of ferritic steel assembly and vanadium alloy backwall could increase the lifetime of the target system. A key development task for this concept is to design and maintain a smooth surface transition between the permanent and replaceable parts and maintain acceptable seals at the joint.

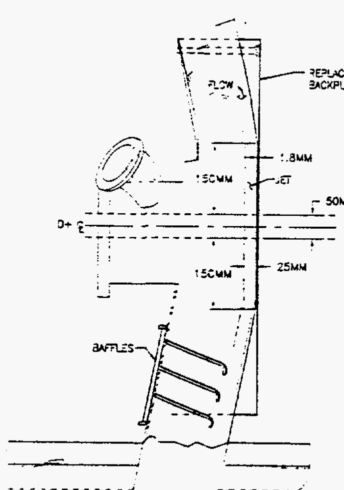

Fig. 3. Replaceable backwall target (Option B).

2.3 Option C: Free Jet

A free jet concept eliminates the need for backwall replacement and can essentially provide permanent lifetime for the target assembly. The test assembly will be located right up against the nozzle to receive maximum neutron fluxes (Fig. 4). A downstream diffuser collects the jet and recovers its dynamic pressure. A vacuum tight barrier between the test cell and target chamber is needed to protect the flowing jet, the accelerator, and accelerator vacuum condition. To provide relief to the seals requirement, a vacuum which is comparable to the vacuum in the target chamber is proposed for the test cell environment. In fact a vacuum in the test cell appears to have major advantages even with a backwall. If atmospheric pressure is maintained in test cell, the pressure difference could impose large stress on the thin backwall, presenting a potential risk of backwall rupture.

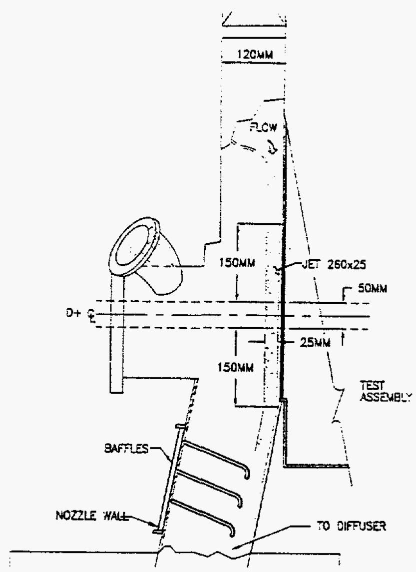

Fig. 4. Free jet target (Option C).

3.0 STABILITY AND THERMAL HYDRAULIC ANALYSES FOR THE FREE JET OPTION

3.1 Dynamic stability

The stability of a jet is influenced by ambient medium, turbulence in the nozzle, the extent of velocity profile relaxation, and fluid properties. In practice, care must be taken in design of the nozzle and its mechanical support components to assure smooth flow profile with minimum flow perturbations. In describing jet stability, one usually refers to the coherent portion of the jet, or breakup length, as a function of velocity. Our first analysis is based on an extension of Weber's theory on capillary instability of fully developed laminar pipe flow[4].

Figure 5 compares the computed breakup length of water jets, 2 cm in diameter, at ambient pressures of 1, 0.5 and 0.2 atm. The influence of aerodynamic forces decreases rapidly with decreasing ambient pressure. Results for a lithium jet in vacuum condition is also shown for comparison with the water jets. At high velocities, the breakup length of the lithium jet in vacuum is at least an order of magnitude greater than a water jet in air. Note that at very low pressures, aerodynamic forces are greatly reduced, and aerodynamic effects may no longer be the controlling factor. The relaxation effects, which are negligible at normal pressures, and unchanged at lower pressures, may become dominant as the aerodynamic forces are reduced. Since relaxation effects are not included in this analysis, the breakup length at very low ambient pressures may be shorter than those shown in Fig. 5

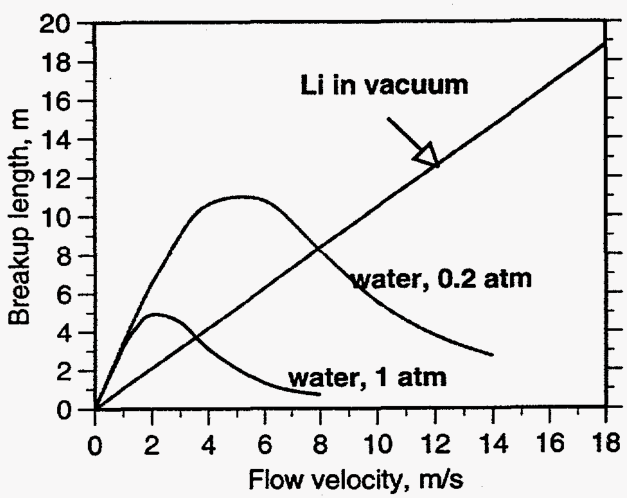

Fig. 5. Breakup length of water and Li jets 2-cm in diameter, in different ambient medium.

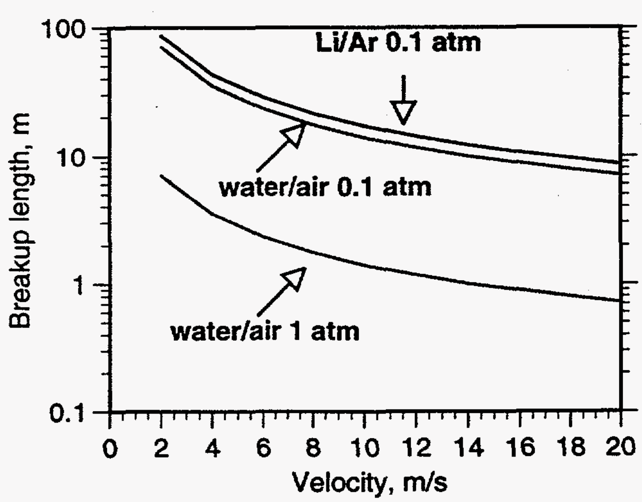

Fig. 6. Breakup length of infinitely wide rectangular water and lithium sheets in various surrounding medium

Analysis was also carried out for liquid sheets, i.e., of rectangular geometry with large aspect ratios. The sheet is assumed to be of infinite extent so that edge effects are neglected. The growth behavior of sinusoidal aerodynamic waves is analyzed taking into account pressure, surface tension, inertial, and viscous forces acting on the liquid sheet [5]. Fig. 6 shows the predicted jet breakup length of water sheets 2 cm thick at various pressures and of a hypothetical lithium sheet in Argon gas at 0.1 atm. The trend of improved jet stability at reduced ambient pressure in Figs. 5,6 is consistent with previous experiments for both circular jets [6], and rectangular jets [7].

3.2 Thermal hydraulic analysis

A three-dimensional thermal hydraulic analysis was performed, using the BKHEAT code [8], to compute the temperature distribution in the lithium jet assuming slug flow profile. The energy equation is solved in three dimensions

$$\rho c_p u \frac{\partial T}{\partial x} = \nabla \bullet (k \nabla T)$$

where ρ, c_p, and k are temperature dependent, and u is the lithium jet uniform velocity. The deuteron beam is 5 cm high by 20 cm wide with a total beam current of 250 mA. The nominal beam energy is 40 MeV, and it has a Gaussian distribution with a standard deviation of 0.5 MeV. The stopping power of the deuteron beam in lithium is calculated using different analytical models [9]. Fig. 7 shows the temperature profile in the jet at the end of the heated length for lithium velocity of 15 m/s. For comparison, the temperature profile for FMIT parameters (100 mA beam current, 35 MeV Gaussian beam with beam size of 1 cm x 3 cm) is also shown. In both cases, inlet temperature of 250°C is prescribed. Although beam current is lower, the higher lithium temperature in FMIT is due to the order of magnitude smaller in beam size (3cm^2 compared to 100 cm^2), resulting in much higher power deposition density. The temperature distributions reflect the beam energy deposition profiles which peak near end-of-range, and the range is proportional to initial beam energy. Of particular interest in the jet thermal response are the surface temperature which determines lithium vaporization rate from the free surface, and peak internal temperature for evaluating the amount of fluid superheat and possibility of nucleate boiling. These temperatures for flow velocities from 10 to 20m/s are shown in Fig. 8 for both IFMIF and FMIT parameters.

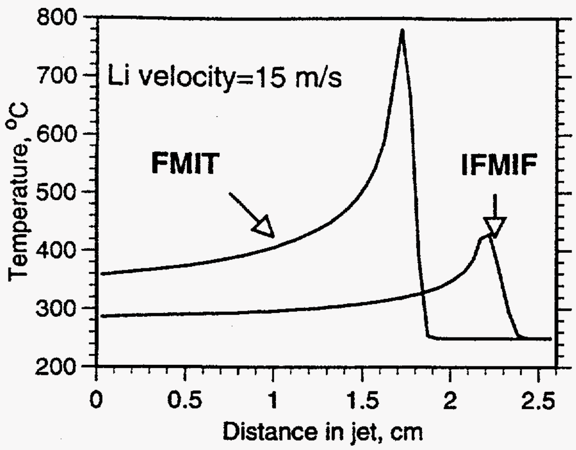

Fig. 7. Temperature profile at end of heated length

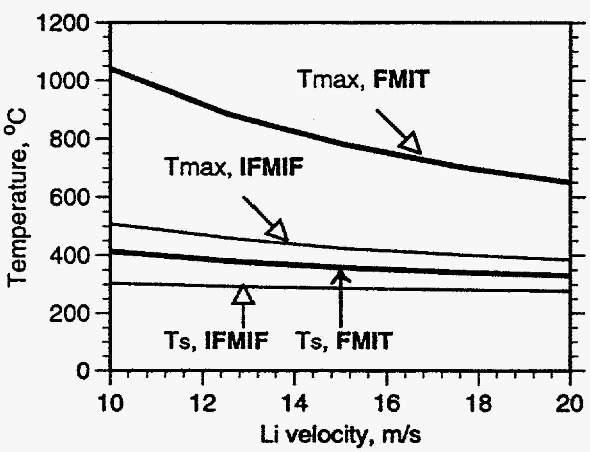

Fig. 8. Surface and peak temperatures for IFMIF and FMIT conditions.

3.3 Lithium vaporization

The vaporization rate depends strongly on jet surface temperature and the pressure in the target chamber. The surface evaporation flux is given approximately by the equation

$$\Phi = 2.6\text{x}10^{24}\frac{\alpha P}{(AT)^{0.5}} \qquad \text{(atoms/m}^2\text{.s)}$$

where $\alpha \approx 1$ is the sticking coefficient, P is vapor pressure (Pa), A is atomic weight (g/mole), and T is surface temperature (K). The lithium evaporation flux, expressed in g/full-power-year.m^2, for various lithium velocities are shown in Fig. 9. Lithium evaporation is more than an order of magnitude lower for IFMIF comparing to FMIT conditions as a result of lower surface temperatures.

Lithium atoms vaporized from the free surface will travel toward the beam tube. Detailed transport analysis will

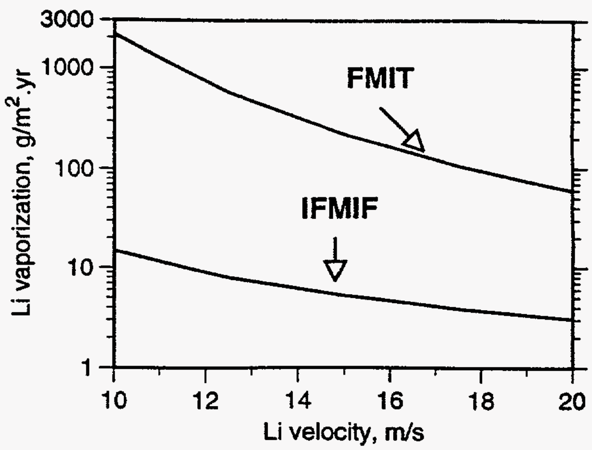

Fig. 9. Lithium vaporization rate from free surface

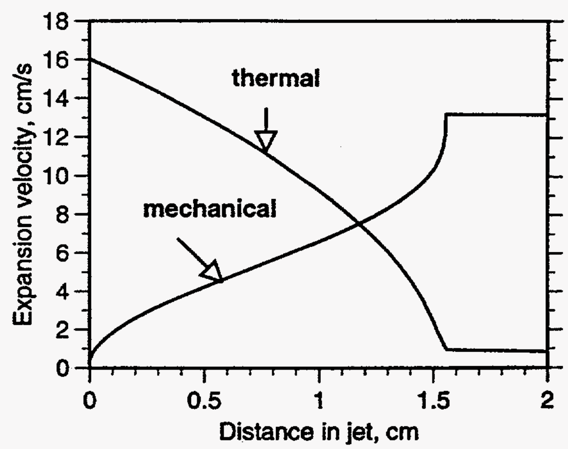

Fig. 10. Thermal and mechanical velocities in jet

be needed to assess the effect of lithium on the high energy beam tube and its interaction with the incident deuteron beam. Lithium deposition, condensation, and removal from the beam tube and target surrounding components require further investigation. Allowable limit of lithium vaporization rate must be established as it may influence the choice of lithium jet velocity.

3.4 Thermal expansion and beam momentum

The thermal expansion of the jet due to deuteron energy deposition is calculated by solving the mass conservation equation of the Li jet. The jet expansion will result in a three-dimensional velocity distribution inside the flowing jet. To estimate the maximum effect, jet expansion is assumed to occur only in the normal direction to the jet flow . In addition, the deuteron beam momentum may also result in jet movement. This movement is estimated by solving the momentum conservation equation . Fig. 10 shows both expansion velocities, thermal and mechanical in the jet for 35 MeV D^+ energy. Results for 40 MeV energy are similar The magnitude of these velocities is much less than the Li velocity and would not affect jet stability.

3.5 Bulk nucleation

In practice, nucleation occurs almost exclusively on the surface of a heated surface. The temperature of that surface must be higher than the saturation temperature of the liquid. For the free jet concept, there is no heated surface in the beam-on-target area, boiling inception within the short beam exposure time in the jet will be unlikely. Nevertheless, assuming a heated wall surface existed at the peak lithium temperature, a stable vapor bubble in thermodynamic and mechanical equilibrium with the liquid satisfies a simple force balance equation

$$p_v - p_l = \frac{2\sigma}{r}$$

where p_v, p_l are pressure of bubble vapor and liquid respectively, σ is surface tension, and r is the bubble radius. Fig. 11 shows the minimum equilibrium bubble radius prior to boiling inception. For lithium temperature below 700°C, bulk nucleation is predicted not to occur because the bubble radius would be far larger than the jet thickness

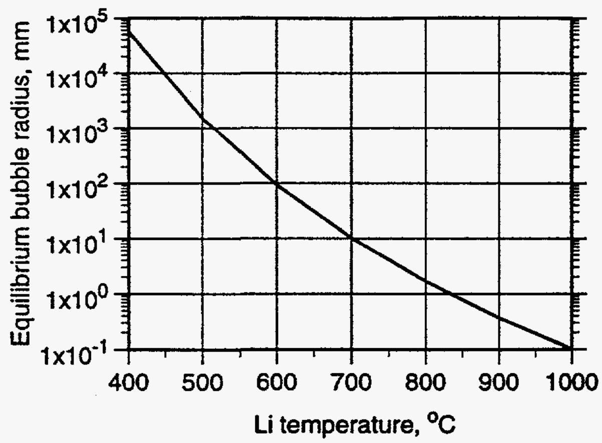

Fig. 11. Equilibrium bubble radius prior to nucleate boiling.

4.0 NUCLEAR ANALYSIS OF LITHIUM JET: IMPURITIES PRODUCTION

The main impurity in the lithium jet is deuterons since the majority of incident deuterons are dissolved in lithium, only about 6% react with Li. Other Impurities include: tritons, from (d,np) reaction and subsequent breakup of the excited Li^7 nucleus; protons, from (d,xp) reactions; Be^7, from $Li^7(d,2n)Be^7$ and $Li^6(d,n)Be^7$ reactions; He^4, from breakup of excited Li^7 and Be^7 nuclei. For each incident deuteron, the estimated production rates are 0.06 triton, 0.06 proton, 0.003 Be^7 atom, and 0.09 He atom. The amount of tritium produces is about 15 g/yr assuming 100% duty factor.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Three design concepts for the lithium target are being evaluated. While Option A will benefit from the FMIT design experiences, the potential short target backplate lifetime and requirement for frequent replacement is a major concern. Options B and C appear to offer major advantages in longer lifetime of target assembly, higher facility availability, lower maintenance/replacement cost, and less radioactive waste generated from target replacement. However, further evaluation, development, and proof-of-principle tests will be needed.

Results of analysis indicated that a free lithium jet will be stable in vacuum environment. The effects of beam momentum, and thermal expansion are found to have insignificant impact on the jet, and there will be no boiling in the free jet under IFMIF conditions. Jet velocity of as low as 10 m/s may be sufficient provided that the amount of lithium vaporization is acceptable.

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