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TITLE: USE OF THE LAMPF ACCELERATOR AS A FUSION MATERIALS-RADIATION FACILITY

MASTER

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USE OF THE LAMPF ACCELERATOR AS A FUSION MATERIALS-RADIATION EFFECTS FACILITY*

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Materials for fusion applications will be subjected to radiation that produces large amounts of transmutation product gases such H and He, as well as others. These gaseous products can have a marked influence on material mechanical properties as they affect the microstructural evolution of the material. Previous calculations by others have shown that the 800 MeV proton beam at the Clinton P. Anderson Los Alamos Meson Physics Facility (LAMPF) will produce gaseous transmutation products in amounts near those expected in the fusion environment. This report will survey the LAMPF facility from the standpoint of experiment design, temperature control, available experimental volume and available beam time. Calculations have been made that predict that attainable displacement rates at specific available target stations at LAMPF. Results for W, Mo, Al and stainless steel will be reported.

1. INTRODUCTION

Dedicated radiation sources for fusion materials irradiation studies, other than the possible exception of the Intense Pulsed Neutron Source (IPNS), have been planned but, for the most part, have not reached an operational state. Cost, complexity and financial priority have all, seemingly, played their part in slowing progress on facilities such as the Intense Neutron Source (INS). In view of the large capital required for Controlled Thermonuclear Reactor (CTR) systems, and even their demonstration prototypes, the need for a complete early understanding of materials response to the high energy neutron spectra of these machines is self-evident.

It has been shown [1] that medium energy proton sources such as the Clinton P. Anderson Los Alamos Meson Physics Facility (LAMPF) can be considered as a simulation source for fusion-materials-irradiation studies. Recognizing this and the present mature state of LAMPF we have pursued use of this facility and have performed calculational studies aimed at determining its feasibility and utility. Additionally, we have recently concluded an experiment [2] at LAMPF that determined that ultra-high-purity aluminum material subjected to concurrent cyclic stress and medium-energy proton bombardment showed lower void formation than in identical material that was simultaneously subjected to the same irradiation history, but was under no applied stress. The conditions of concurrent cyclic stress and radiation are inherent in advanced energy source designs such as magnetically- and inertially-confined CTR systems; this experiment marks the first use of LAMPF for fusion materials studies.

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2. APPLICATION OF MEDIUM ENERGY PROTONS TO FUSION MATERIALS-IRRADIATION STUDIES

LAMPF accelerates protons to 800 MeV. At this energy, in addition to large numbers of atomic displacements, copious amounts of transmutation products are formed. [1] This is also the case for the 14 MeV neutron spectrum in CTR systems. Gaseous products such as He, as well as others, have been the subject of numerous studies since they are believed to be responsible for stabilizing void embryos. To date, major work in this area has required complicated and expensive two-beam irradiations. Fission neutron irradiation studies, although useful for a basic understanding of radiation effects, do not simulate the internal gas generation inherent in CTR systems. LAMPF provides a more direct simulation using just a single ion.

The 800 MeV proton "over simulates" the 14 MeV neutron case in the amount of transmuted gaseous products; direct simulation is not possible but accelerated experiments are. For example, the work of Coulter, Parkin and Green [1] calculates that LAMPF produces 10x more He than the 14 MeV case, for an identical unit of damage.

Since the proton source is a charged-particle beam, the bombarding species can be controlled and directed by steering magnets such that only the subject material is highly irradiated. Thus, peripheral equipment used for experiment control and data acquisition, such as monitors for load and strain, are not affected by the radiation and can be made reliable and simple. Additionally, "hands on" servicing of the experimental hardware is possible because only the relatively small amount of sample material is irradiated. These facts invite consideration of more complicated in-situ experiments that have previously been difficult or impossible. For example, Weertman and Green [3] have recently identified one such experiment in which they propose to study fatigue-crack growth as a function of dose rate. This experiment will be possible because the proton beam can be directed to impinge on only the sample; enlongation measurements can be made reliably, in-situ, and close to the specimen.

Additionally, the proton beam can be directed into sizable experimental volumes. This allows use of generous amounts of subsidiary equipment for experiment control and monitor. Relative to the core of a fission test reactor and most of the proposed experimental areas in intense neutron sources, this sizable volume is seen as a large advantage. A schematic layout of one of the experimental areas at LAMPF is shown in Figure 1. Here a usable experimental volume of greater than 0.5 m^3 is available.

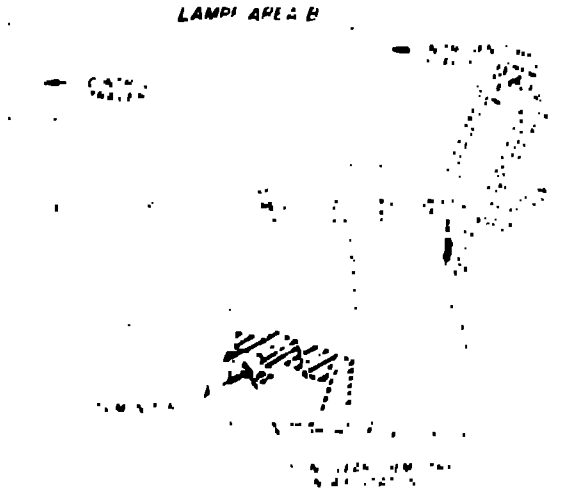

FIGURE 1: Schematic layout of LAMPF Area B. Scale is 1" =50'.

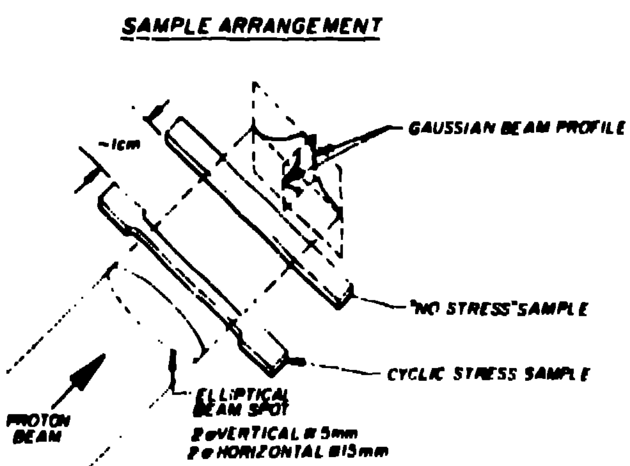

FIGURE 2: Sample arrangement in the LAMPF beam.

800 MeV protons can penetrate substantial thicknesses of material; energy loss is only 5.0 MeV/cm in aluminum. The requirement of extremely thin sections and the possibility of ambiguous surface effects inherent to many heavy-ion irradiation studies are eliminated. Additionally, multiple samples may be easily irradiated simultaneously by stacking the material along the beamline, making maximum use of accelerator beam time. Yet another advantage of the high penetrating power of 800 MeV protons can be seen by noting Figure 2. For this experiment, [2] it was necessary that the two foils have an identical irradiation history. The foils were mechanically aligned so that they would both be in an identical position in the Gaussian-intensity-profile LAMPF beam. Calculations [4] indicated that multiple scattering effects in the leading foil would not alter the flux at the second foil. Post-irradiation radiochemistry analysis [5] confirmed the calculation and assured that the differential comparison that we sought was meaningful, both samples received identical doses.

3. DETAILS OF LAMPF EXPERIMENT DESIGN

3.1 LAMPF Beam Profile and Time Structure

The LAMPF beam profile is essentially Gaussian in intensity. Its time structure is pulsed (0.5 ms pulses at 120 Hz, 8.33 ms between pulses). These parameters were applied to calculations on point-defect kinetics as affected by radiation induced temperature oscillations. The results of these calculations are summarized below.

3.1a Kinetics Calculations

Considerable work has been done on point-defect kinetics calculations under pulsed irradiation. The initial work [6,7] developed computer codes with the capability of accounting for point-defect production under irradiation, diffusion, and annihilation at sinks, for both steady irradiation and for a single pulse of radiation followed by an annealing period. This work recognized the fact that under pulsed conditions, point-defect concentrations would rise during the radiation pulse and then decay at a rate dependent on the sinks in the material. The pulsed system can be vastly different from prior experience in fission studies in which the radiation is essentially steady state in that, for a given net fluence (total number of incident energetic particles per unit area), the pulsed system is subjected to periods of intense point-defect generation with an intermediate time for annealing between pulses. Void growth is governed not only by total fluence but also by point-defect concentrations as a function of time. To allow comparison to the large amount of fission data available, account must be made of the difference between steady-state and pulsed irradiation, the later being the condition inherent in advanced-energy system designs including magnetically- and inertially-confined CTR systems.

Our group [8,9] extended the calculational procedures to include the effect of multiple pulses of radiation and also included the effect of the inherent radiation-produced time-dependent temperature. This work was initiated first in an effort to understand the effects of pulsed irradiation since an eventual comparison of our LAMPF results to available data under steady irradiation was desired. Secondly, the calculation is an aid toward the understanding of the effects of pulsed radiation in CTR systems. The results of our calculations are summarized in Figure 3. For this work, 100% "on-time" is steady irradiation. For other "on-times", the flux is adjusted such that each pulse for each "on-time" contains an equal number of incident 800 MeV protons but the pulse length is shorter. It is seen that the rate for steady state and 6% on-time, which is the LAMPF case, are very nearly the same after 30,000 pulses of radiation.

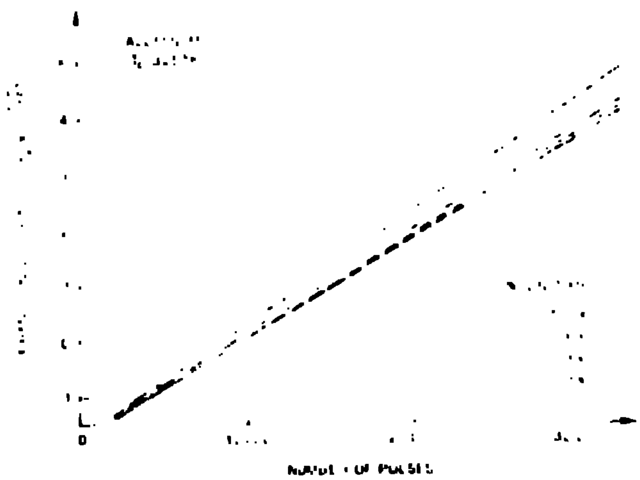

FIGURE 3: The calculated effect of pulse intensity on void growth in aluminum. The figure is from Ref. [9]. The flux for this calculation was 2×10^{18} protons/m²s.

Only when the pulse is very intense, 0.1% "on-time", does the rate become significantly different; this work concluded that this effect could be explained by the large radiation-produced temperature pulse caused by the intense 0.1% radiation pulse and its direct effect on point-defect diffusivity. In summary, our calculations concluded that the pulsed nature of LAMPF would not significantly alter the kinetics of void growth relative to steady irradiation and thus a comparison of our results to steady irradiation data would be possible.

3.1b Temperature Calculations

For this calculation, [10] it was assumed that the temperature would remain fixed at the surface of the foil and at a radius, a, 3σ (where σ is one standard deviation of a Gaussian beam) from the center. This "ambient" temperature in reality is the temperature of the coolant plus a small film gradient. This assumption is realistic because in practice coolant flow rate can be adjusted to a value where the heat-transfer film coefficient is large enough to keep the temperature gradient (foil surface to coolant) at less than 1 °C. The calculation required a solution to the two-dimensional time-dependent heat conduction equation in cylindrical coordinates:

$$\frac{1}{\kappa}\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial z^2} + \frac{1}{K}Q ,$$

where κ is the thermal diffusivity, T the temperature, t the time, r the radius, z the incremental thickness along z, K the conductivity and Q the heat input from the incident 800 MeV proton. Since the proton flux for the LAMPF beam is Gaussian in profile, the current can be described as

$$I(r,z,t) = I(t)\exp\left(-\frac{r^2}{r_0^2}\right) ,$$

where $I(r,z,t)$ is the current, r_0 is a characteristic dimension equal to $\sqrt{2}\,\sigma$, and $I(t)$ accounts for the pulsed structure of the LAMPF beam given by

$$I(t) = \begin{bmatrix} 0 & \text{for } t < 0 \\ I_0 & \text{for } m\tau \le t \le m\tau + \tau_1 \\ 0 & \text{for } m\tau + \tau_1 < t < (m+1)\tau \end{bmatrix} ,$$

where $m = 0, 1, 2, \ldots$ (the pulse number), τ_1 the beam pulse "on-time", τ the time between pulses, 1/120s for LAMPF. I_0 is the total current, given by

$$I_0 = \frac{n_p/\Delta t}{\int_0^a 2\pi r \exp(-r^2/r_0^2)\,dr} = \frac{n_p/\Delta t}{\pi r_0^2} ,$$

where n_p is the total number of protons in a pulse of duration Δt. Also, the heat input, Q, is given by

$$Q = \varepsilon^* \frac{n_p/\Delta t}{\pi r_0^2}\exp\left(-\frac{r^2}{r_0^2}\right)$$

where ε^* is the energy loss per proton per unit length.

The heat flow equation was solved [10] and used to calculate beam heating magnitudes for various beam current densities at LAMPF where, in principle, radiation effects studies could be performed. The results are summarized in Figure 4. Presented here are temperature rises after a 0.5 ms LAMPF pulse of 1 mA for the most heavily irradiated area at the foil center line.

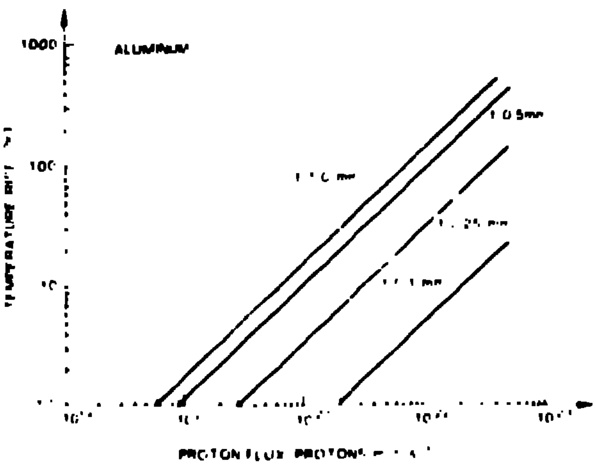

FIGURE 4: Maximum calculated temperature rise in an aluminum metal target as a function of proton flux and sample thickness (t). The figure is taken from Ref. [9] and shows the relation between temperature rise, sample thickness and flux, at the end of the pulse.

In addition to the requirement that the temperature rise during a LAMPF pulse be small, the material must return to "ambient" or coolant temperature prior to the arrival of the next pulse (7.8 ms later) or a gradual rise in temperature will occur with time and vary with beam current. This temperature rise is not acceptable if temperature control is required. Additional calculations were done, based on the equations described above, to determine the sample temperature both at the end of the pulse and just before the arrival of the next pulse; the coolant flow is maintained and thus heat is continually being transferred. These results are shown in Figure 5. The bottom line on this plot is the temperature rise at the end of a cooling period, just before the arrival of a pulse, for aluminum samples with a thickness less than 0.5 mm. At this thickness the sample will reach the coolant temperature before the arrival of the next radiation pulse. However, for a thickness of 1 mm and flux greater than 1×10^{21}, the sample does not return to coolant temperature prior to the arrival of the next pulse. Under these conditions, the sample temperature will gradually rise with each pulse. These conditions, however, are deemed unacceptable when temperature control is necessary.

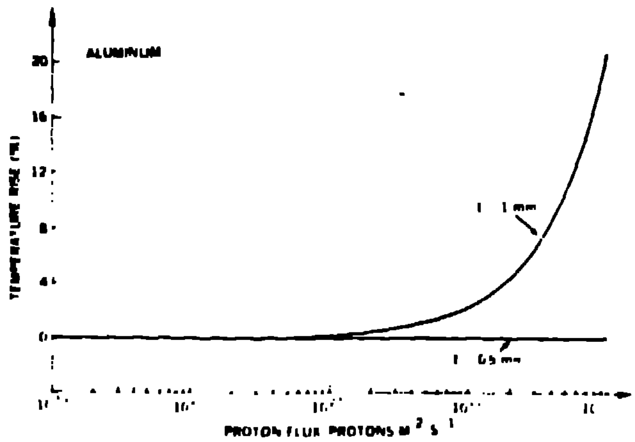

FIGURE 5: Calculated temperature rise in aluminum metal foils under 800 MeV proton irradiation as a function of flux and thickness, this plot gives the temperature of the foil 7.8 ms after the radiation pulse, just before the arrival of the next pulse. The figure is from Ref. [9].

3.2 Attainable Displacement Rates

Beam spot sizes vary throughout the LAMPF facility along the primary beamline (Line A), where proton current is typically 500-800 μA. Our initial study considered locations at the various target area in Line A where, in principle, access to the beam might be achieved. Beam spot sizes vary from 0.14 to 5.0 cm in diameter (FWHM) of the Gaussian beam. In practice, physical access is available in Line A only at Target Station at A-6, near the final beam stop. Here the proton beam is large; FWHM is about 5.0 cm. Although higher displacement rates can be achieved at other stations, our study indicates that temperature control becomes difficult at the current densities at these stations. At A-6, the instantaneous proton flux during a 0.5 ms LAMPF pulse is about 2×10^{20} protons-$m^{-2}s^{-1}$. Study of Figure 2 indicates that for aluminum, even at a thickness of 1 mm, the resultant peak temperature is <1°C. This proton current, however, leads to an appreciable atomic displacement rate, as shown below.

Using the threshold displacement energy, E_d, determined by Mitchell et al., [11] the displacement-energy cross section σ_d calculated for 800 MeV protons by Coulter et al., [1] now extended to include aluminum, 304 stainless steel, molybdenum, and tungsten and the modified Kinchin-Pease formula, we have calculated the dpa rates for the various LAMPF beam spot sizes at a current of 1000 μA. The results are shown in Figure 6.

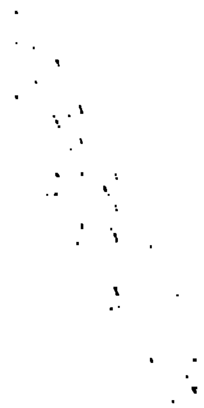

FIGURE 6: Displacement rates in the LAMPF proton beam at a current of 1000 µA.

For 301 stainless steel, this displacement rate translates to a damage level of 2 dpa in a nine-week LAMPF run cycle at target station A-6 for a 500 µA beam.

A low-current target station (10 µA maximum) is available in Area B. This station has been found to be excellent for short, highly-controlled experiments that do not require high dose or fluence. Additionally, access is now available to a neutron flux of ~10^{11}-10^{12} neutrons cm^{-2}-s through a "stringer" system that places specimens under the beam stop at target station A-6.

3.3 Proposals to LAMPF

All proposals for research at LAMPF are submitted to the Director of LAMPF, Los Alamos National Laboratory, PO Box 1663, Los Alamos, NM, 87545. Copies of the standard format and submittal instructions can be obtained from the LAMPF Users Office, Mail Stop 830, PO Box 1663, Los Alamos, NM, 87545.

4. CONCLUSIONS

a. LAMPF is a useful tool for fusion-materials radiation-effects studies.
b. Available dpa rates are high enough to perform accelerated experiments and beam heating is at a level where temperature control can be achieved.

5. ACKNOWLEDGEMENTS

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