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AUTHOR(S): Kirk E. Christensen
Gloria A. Bennett
Walter F. Sommer

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Los Alamos
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

AN *IN SITU* MECHANICAL-RADIATION EFFECTS TEST CAPSULE FOR SIMULATING FUSION MATERIAL ENVIRONMENTS*

K. E. Christensen, G. A. Bennett, and W. F. Sommer

Los Alamos National Laboratory, Los Alamos, New Mexico

Conditions of radiation and simultaneous cyclic stress on materials are inherent in advanced energy source designs such as inertially and magnetically confined controlled thermonuclear reactors. A test capsule capable of applying a cyclic stress to test specimens while they are being irradiated in the 800-MeV proton beam at the Clinton P. Anderson Los Alamos Meson Physics Facility has been developed. The design and performance of this device are discussed in this report.

This machine has facilities for seven pairs of differential samples; one sample of a pair receives an applied cyclic stress and its companion in an identical flux will be the unstressed control. Control of the sample temperature and *in situ* monitoring of sample elongation and load are provided in the design. Results of an earlier experiment will be discussed, along with those of preliminary bench tests of the redesigned capsule.

1. INTRODUCTION

Recently, we performed an *in situ* mechanical-radiation effects study at the Clinton P. Anderson Los Alamos Meson Physics Facility (LAMPF).[1] This study required development of an irradiation capsule that could apply a cyclic tension-tension stress to an aluminum sample while the sample is being irradiated by 800-MeV protons. These parameters were chosen because conditions of radiation and concurrent cyclic stress on first wall materials are inherent to advanced energy system designs such as magnetically and inertially confined controlled thermonuclear reactors. Our experiments are designed to simulate these conditions. *In situ* experiments such as these require that the device can be operated remotely and reliably for extended periods of time; these criteria dictated that the design be made as simple as possible.

Our initial machine was used successfully to complete an investigation [1] that showed void formation was less in material receiving a concurrent cyclic stress and 800-MeV proton radiation than in identical unstressed material that was simultaneously irradiated to the same dose level. The encouraging results from this experiment led us to a new design that allows seven pairs of samples to be tested. Each pair has one sample that is the irradiated control specimen and the other, also in the proton beam, receives an applied cyclic stress. This new design greatly increases the data that can be obtained from a single LAMPF run as multiple samples can be tested with the ability to vary the load applied to the stressed samples.

These tests were run at temperatures above ambient (50°C) where kinetics dictate that a constant temperature be maintained during the irradiation period. Accurate temperature control was also mandated because the heat deposited in the sample from the proton bombardment had to be removed.

Calculations [2] and bench experiments established that temperature control could best be achieved by flowing gas directly over the samples and taking advantage of large surface-to-volume ratio in the sample design (Figure 1). This design greatly enhances the ability to extract the energy deposited by beam heating and maintain near-uniform sample temperatures.

The initial temperature control system was quite simple. Nitrogen gas was used, supplied by a tank trailer, and was heated slightly above the experiment temperature of 50°C by being passed over resistance heaters that were controlled by a thermal switch (Figure 2).

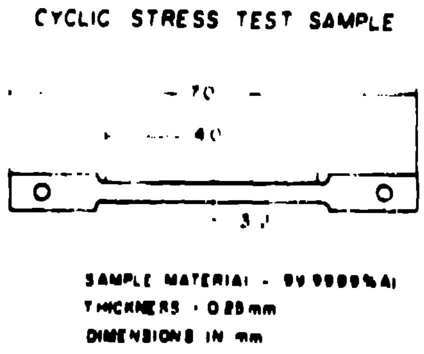

Figure 1: Schematic of the tensile sample used for the experiment.

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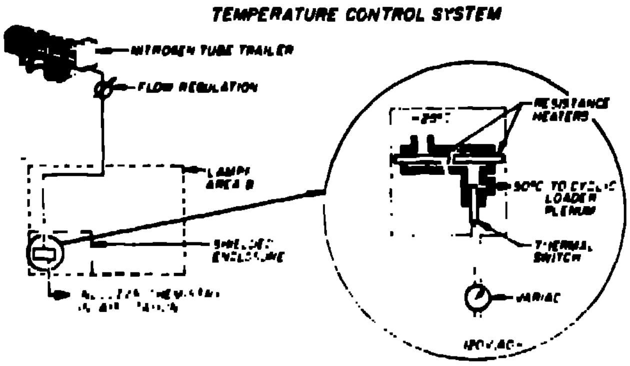

Figure 2: Schematic drawing of the heaters and flow system used to control sample temperature at 50°C.

This was a "once-through" system where the gas was expelled to the atmosphere after use. In anticipation of longer runs (six months) with higher operating temperatures, we have designed a closed-loop helium system that will be used for temperature control of these extended experiments.

In the text below, we describe the design and operation of our first and second generation machines, along with their attendant temperature control systems.

2. INITIAL EQUIPMENT

Our experiment required the design and development of a remotely operated machine capable of applying a cyclic tension-tension stress to a foil sample while the sample was being subjected to proton bombardment. In addition, the control sample required support so that it would experience a radiation history identical to that of the stressed sample. Figure 3 shows a schematic of the *in situ* cyclic stress capsule.

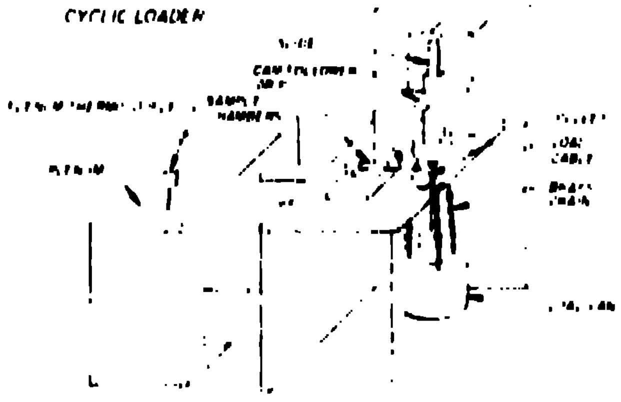

Figure 3: Schematic of cyclic stress-irradiation capsule.

A dead-weight loading system was used because of its inherent reliability and because it eliminated the possibility of overloading the sample. A constant-speed electric motor, operating through a cam and guide, raised and lowered the dead weight onto a load pan; the interface was damped by a spring to mitigate "overshoot" of the stress. The resulting load form was approximately sinusoidal at a frequency of 1/3 Hz. The profile of the LAMPF beam required that the samples be loaded in the horizontal plane. This required passing the load cable over a pulley before connecting it to the specimen grip (Figure 3). The elongation of the sample during the irradiation was measured by a linear variable differential transformer (LVDT) connected to this grip.

Figure 4 shows one of the stressed samples with its gripping system mounted in an installation fixture, which assures strain-free handling of the ultra-high-purity aluminum material.

Figure 5 shows the graphite support for the unstressed control sample. Graphite was chosen because of its resistance to radiation swelling and because its low Z would result in a minimum of beam heating. This support was necessary because the ultra-high-purity aluminum used in our initial experiment creeps under its own weight. The support structure was hollow, allowing cooling gas to flow over the sample. The sample was supported only on the edges to minimize the amount of graphite in the beam.

The support structure for both samples on the plenum side is also shown in Figure 5. The pin support anchored the stressed sample and kept the unstressed sample in position during the irradiation. Both specimens were inserted in 9.5-mm-o.d. by 0.25-mm-thick aluminum tubes that served to direct the nitrogen gas flow across the samples and thus maintain the controlled sample temperature.

Nitrogen gas heated to 52°C was introduced into the plenum area; the gas then passed

Figure 4: Tensile sample and grips in installation fixture.

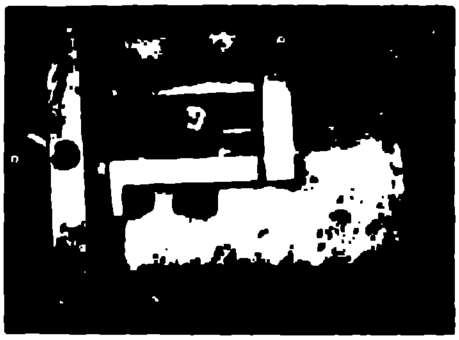

Figure 5: (a) Sample support structure.

Figure 5: (b) Static sample graphite holder.

through the sample chambers and over the samples. Calculations and bench experiments show that a stagnation temperature of 52°C in the static plenum resulted in a sample surface temperature of 50°C. The resulting temperature variation at the specimen center line was less than 1°C. The 52°C temperature was monitored by a thermocouple in the plenum throughout the irradiation.

The LAMPF beam in Area B is quite stable in spatial alignment, allowing for some long-term drift. Alignment of the beam relative to the samples was accomplished by placing one leg of a Chromel-Alumel thermocouple at the vertical center line of the specimen. The second leg was spot welded at a position on the center line in the horizontal dimension. Heating of the couple is a direct function of proton current, and because the beam is Gaussian in intensity, alignment of the beam to the samples was easily deduced and maintained with bending magnets by maximizing the thermocouple output.

The LAMPF beam is Gaussian in intensity profile and elliptical in its spatial profile (Figure 6). This was used to advantage by placing the foils edge-wise relative to the beam, keeping the proton density high and uniform through the thickness of the sample; furthermore, this allowed using the wider horizontal part of the beam to achieve uniform dose over a reasonable gage length.

In addition, because this experiment is a differential one between the stressed and unstressed specimens, it is essential that the two samples receive an identical radiation history. To achieve this, advantage was taken of the high penetrating power of 800-MeV protons (energy loss is only 5.0 MeV/cm in aluminum) [3] by placing both samples in line along the proton beam. Calculations [4] indicated that multiple scattering effects in the leading foil would not significantly alter the flux at the back foil. Postirradiation radiochemistry results [5] support the calculation and prove that both samples received an identical dose.

The system operated for 21 days in a 10-μA LAMPF proton beam. The only major problem encountered was the electric motor failure. This was probably caused by overheating in the 50°C atmosphere. To alleviate this problem, the motor was replaced and kept cool with a cold gas flow. With this problem in mind, and with the desire to make the improvements mentioned earlier, a new test capsule was designed and is described below.

3. REDESIGNED EQUIPMENT

The desire was to provide a design that enhanced the capability, increased the reliability, and provided for greater instrumentation in the new test capsule. The new design is shown in Figure 7.

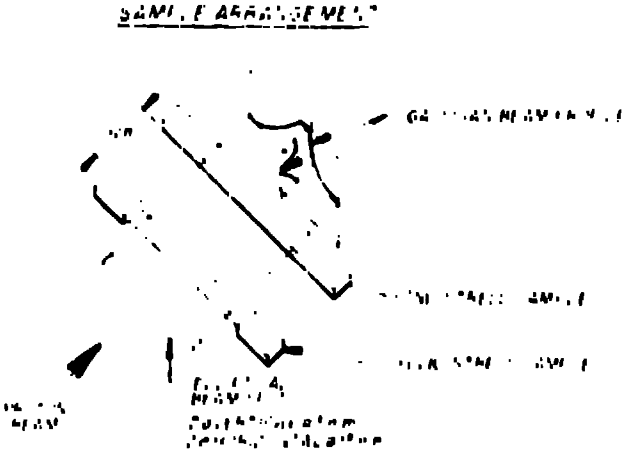

Figure 6: Sample arrangement in the LAMPF Gaussian beam.

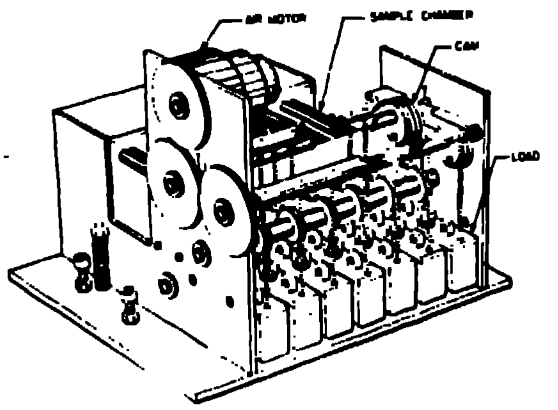

Figure 7: Cyclic stress irradiation capsule.

To enhance the capability of the device, seven pairs of samples were incorporated into the design, with the ability to load each one independently at a frequency of up to 3 Hz. The specimen pairs are staggered vertically to take advantage of the entire beam of protons; each subsequent pair following the leading pair was staggered up or down by one sample thickness.

To improve reliability, many changes were incorporated in the new design. An air motor was chosen over an electric motor because the carbon vanes were not subject to the degradation caused by the irradiation and elevated temperature as was the organic insulation in the electric unit. Bead chain was used to support the load, thus avoiding kinking of the chain or compression loading of the sample. The design called for other changes, including potting of the LVDT lead wires with an inorganic insulation and cleaning and lubricating all bearings with a light coat of a molybdenum disulfide lubricant. Also, the eccentric cams were fitted with thin radial bearings to minimize wear between each cam.

New instrumentation included the addition of a mechanical counter to count the number of cycles. Miniature load cells were mounted at the back of each sample's load string so that an accurate load history could be kept.

3.1 Temperature Control System

As mentioned earlier, we wanted to develop a closed-loop, helium cooling system for use in long-term experiments and in future elevated temperature experiments. Helium is necessary for elevated temperature experiments because of its low reactivity with the test samples. It was necessary to design this system to operate very cleanly because the samples were used in post-test transmission electron microscopy, and surface contamination from the cooling gas would complicate postirradiation analysis. A schematic of the system is shown in Figure 8. The helium is circulated by three Metal Bellows pumps operating in parallel through a heater to the samples and then returned. Because future tests may be run at temperatures near 800°C, it is necessary to cool the gas to ambient before the pumping cycle begins. Considering that approximately 10 kW must be removed from the gas in a very small experimental area, this was a challenging design problem. After examining many possibilities, a single-pass counterflow heat exchanger was chosen, consisting of 20 ft of welded fin tube made up of 2.5-ft sections. A cross section of the flow path is shown in Figure 9. Air was chosen as the most practical cooling medium after eliminating several alternative fluids (water, chilled water, and Freon) because of technical and economic considerations.

To optimize the many factors involved, a computer program was written to perform parametric calculations to find an operating point that would give the lowest pressure drop for the two gases, lowest cooling air flow, and the most compact heat exchanger size. A safety factor of 2 was used on the calculated heat exchanger length because the helium was in the transitional flow range, giving rise to uncertainties in the heat transfer coefficient.

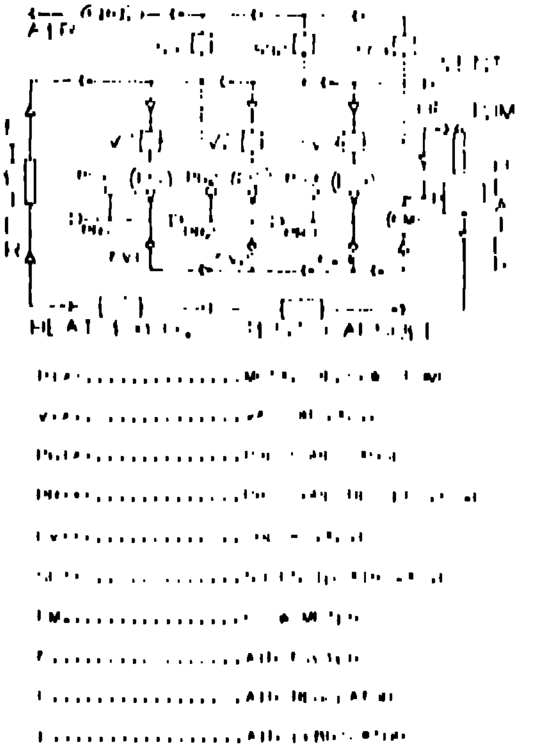

Figure 8: Temperature control system.

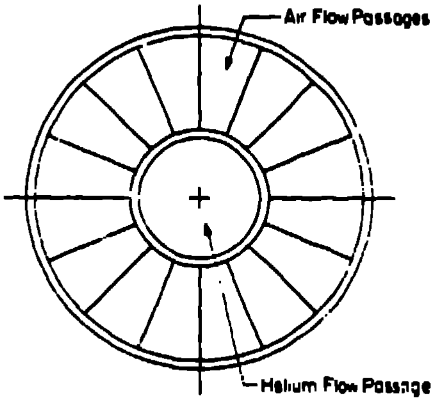

Figure 9: Heat exchanger cross section.

The system used stainless steel tubing, and connections were made with Cajon VCR vacuum couplings because their metal-to-metal seals eliminate contamination problems from the use of elastomeric seals.

4. CONCLUSIONS

In this paper, we have described the design and performance of an *in situ* mechanical-radiation effects test capsule. Early experiments performed well in this difficult environment and yielded the surprising results of lesser void growth with a combination of radiation and cyclic stress relative to an unstressed, irradiated sample.

The redesigned test capsule was described, along with its closed-loop helium temperature control system. Initial bench tests have shown very good reliability, in addition to the ability to run at higher frequencies and with better instrumentation.

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