PROGRESS REPORT ON THE VARYING TEMPERATURE EXPERIMENT

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OBJECTIVE

The purpose of this experiment is to determine the effects of temperature variation during irradiation on microstructure and mechanical properties of potential fusion reactor structural materials.

INTRODUCTION

A capsule has been designed that permits four specimen sets to be irradiated in an RB☆ location in the High Flux Isotope reactor (HFIR) with distinct temperature histories. During the reporting period critical component prototyping was completed. The results have lead to some design and operational changes from that previously reported. The primary design changes are 1) compression seals in the specimen holes of the beryllium holders, and 2) oxide-dispersion strengthened aluminum alloy (DISPAL) specimen sleeves in all holders.

Details of the capsule design are presented in the previous issue of this publication[1]. Four, axially displaced temperature zones are independently controlled. Holder temperatures are monitored by thermocouples and controlled by a combination of adjustable temperature control gas mixtures and auxiliary heaters. The high temperature holders are located in the center of the experimental region, which is centered on the reactor mid-plane, and the low temperature holders are located at the ends of the experimental region. The zones are to operate as follows:

A) low temperature, steady temperature zone (350°C),
B) high temperature, steady temperature zone (500°C),
C) high temperature, variable temperature zone (300-500°C),
D) low temperature, variable temperature zone (200-350°C).

Specimens will be irradiated to 5 to 10 dpa (depending on material and location). Specimen temperatures are controlled whenever the reactor is greater than a low power limit, tentatively set at 8.5 MW in order to reduce the exposure levels at improper temperature to below 10^{-4} dpa. The four zones are essentially identical. The primary differences in zones are 1) the amount of heat generated within them due to neutron and gamma heating, 2) the temperature at which they operate, and 3) the material of which they are made. The high temperature holders are made of a structural grade beryllium alloy (Brush Wellman S-200F), and the low temperature holders are made of 6061-T6 aluminum alloy.

Identical specimen sets are contained in corresponding steady and variable temperature zones (the high temperature and low temperature sets are different). The temperatures of the variable temperature zones are maintained at their respective low value for 10% of the total fluence, and then increased to match that of the corresponding steady temperature zones.

PROTOTYPE TESTING

A prototype capsule containing a single temperature zone was fabricated and operated. The gas flows, temperature control gas gaps, and heater arrangement within the prototype were similar to that of the Low-Temperature, Variable Temperature (LTVT) holder. The gas gap was set to produce a holder temperature of 165°C when the heat produced within the holder equals that expected in the LTVT holder during irradiation in an RB☆ position of HFIR.

The questions to be addressed by the prototype were:

1) what are the operational limits of the heaters, and are they adequate to properly control the experiment,

2) will the proposed mixing of the temperature control gas provide adequate time response to prevent specimen over-temperature as the reactor power is increased,

3) what are the end loss effects of the stainless steel separation pieces, and how does that affect the achievable temperature range of the holder, and

4) is the response time of the proposed heater controllers suitable for the application.

Issues 1 and 2 were addressed and reported on during the previous reporting period. The dual element heaters used for temperature control can operate safely with 9 amps of current passing through both elements or 15 amps passing through only one of the elements, before reaching a limiting sheath temperature of 1000°C in the section of the heater directly above the holder. Mixing the temperature control gases inside the capsule results in adequate temperature response to gas flow adjustments to prevent specimen over temperature during typical reactor power increases. The purpose of the final phase of testing was: 1) to test heater controllers, 2) verify the thermal models used in the design of the holders, and 3) verify that the heaters can meet the requirements of the experiment.

Heater Controllers

A software based, temperature control loop was developed to control the temperature of the prototype holder by issuing a demand for heater current based on holder temperature. Phase angle fired, silicon rectified controllers (SRC) were selected for heater control because phase angle firing results in a lower element temperature for a given heat output and reduces the temperature oscillations within an element compared to burst firing SRC controllers or ON-OFF controllers. The effect of which is longer heater lifetime.

Phase angle fired controllers regulate the point in each AC voltage sine wave at which the current is allowed to pass to the heaters. If 100% of the heater power is demanded, the full sine wave passes through the heaters. As less power is demanded, the controller delays the passing of the current until the phase angle corresponds to the demanded power percentage.

Estimate of holder heat loss

The thermal characteristics of the holder and separation piece assembly were tested to determine parasitic heat losses. A quick comparison of the potential heat loss paths from the holder suggests that no more than 25 watts out of 1450 watts should be lost across the separation pieces of the LTVT holder in the actual capsule. To test heat loss from the prototype, a known amount of heat was added to the holders and the temperature was monitored. The flow rate of argon through the temperature control gas gaps was scanned and the resulting temperature was recorded.

The thermal conductivity of the temperature control gas mixture is calculated from the relative flow rates of helium and argon through the system, and the average temperature of the holder and housing tube. The calculated thermal conductivity is very sensitive to the percentage of helium in the gas mixture. The measured helium flow rate through capsule during the experiment was 10 standard cubic centimeters per minute (sccm). The experimentally measured temperatures are higher than the predicted temperatures if a flow rate of 10 sccm of helium is assumed through the temperature control gas gap. This implies that the actual helium flow through the gas gap was less than the measured helium flow rate through the experiment. The flow rate instrumentation was calibrated for air and a factor was used to correct for the use of helium, and the flow rate measurement was made at 10% of the full scale reading of the instrument, where the accuracy is reduced.

Also, the prototype capsule had some leakage out of a temporary top seal, the affect of which on the gas mixture is not exactly known. So it is reasonable to assume that the helium flow rate through the gas gap was lower than the measured flow rate through the experiment. It is also probable that the flow rate of helium through the gas gap was reduced as the argon flow was increased. There is, therefore, a degree of uncertainty associated the calculation of the thermal conductivity of the control gas mixture.

A correction must be made to the helium flow rate in order for the experimentally measured data to have a reasonable fit to the predicted data. The assumed flow rate of helium was reduced until acceptable agreement was achieved between the predicted and measured temperatures at the low temperatures, where parasitic heat loss should be small and the gas mixture was mostly helium. There is a degree of subjectiveness in determining the fit, however the best results are obtained for assumed helium flow rates of 4 to 5 sccm.

With the low temperature data corrected by assuming a reduced helium flow, the measured temperature deviates from the flow-corrected, predicted temperatures at higher temperatures. This deviation is assumed to be due to parasitic heat loss from the ends of the holder. The magnitude of the parasitic heat loss is estimated by assuming that it is proportional to the temperature of the holder. The value of the proportionality constant is determined by adjusting it until the experimental data has reasonable agreement with the predicted temperature over the entire temperature range.

Figure 1 shows the measured data, the predicted temperature assuming the measured helium flow (10 sccm), the predicted temperature assuming the reduced helium flow (4 sccm), and the predicted temperature assuming reduced helium flow and corrected for parasitic heat loss. The required parasitic heat loss factor increases as the assumed helium flow is reduced. For an assumed flow of 4 sccm to 5 sccm, the required values of the proportionality constant suggests that over 80% to 90% of the heat loss will occur across the temperature control gas gap in the prototype when the temperature difference between the holder and the housing tube is 270°C.

The parasitic losses in the capsule are expected to be lower than that of the prototype due primarily to the use of thinner-walled separation pieces and increased gap between the separation piece and the I.D. of the housing tube. For the LTVT holder the upper separation piece is a heat source instead a heat sink. The heaters and TCATs are also a heat source, but the heat conducted through them is expected to be negligible.

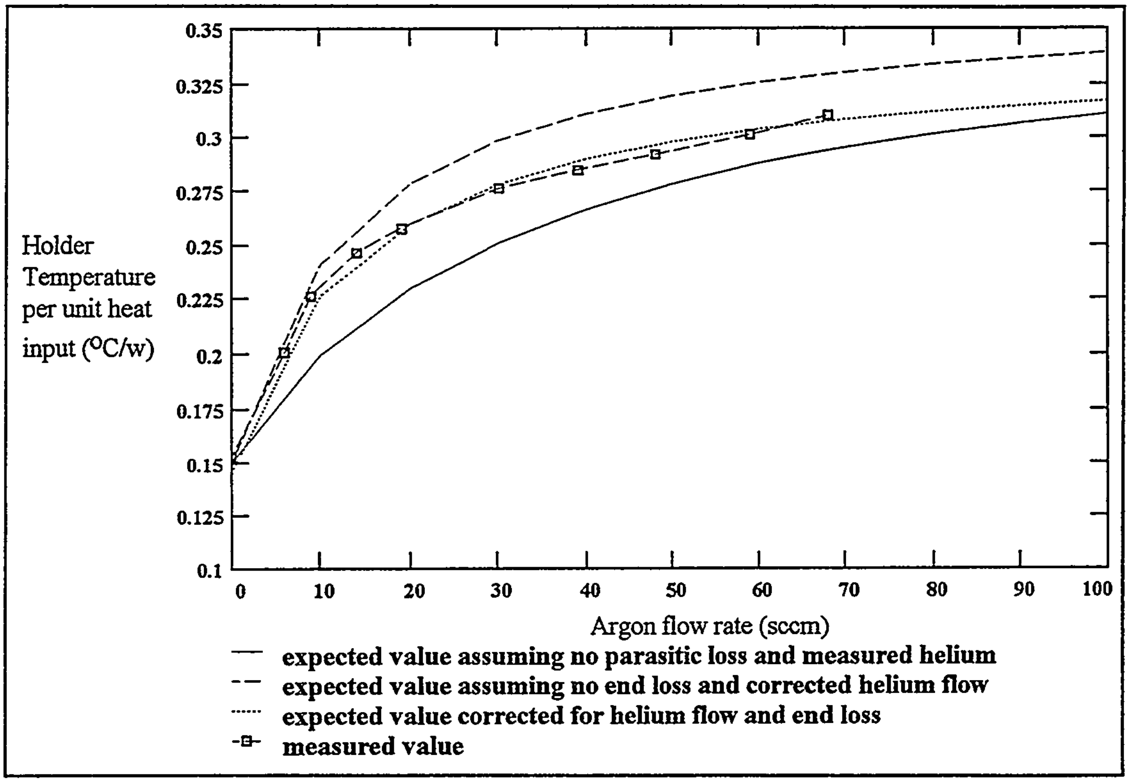

Fig. 1. Temperature of the holders as a function of argon flow compared to the expected value.

Holder Temperature Range

With the parasitic losses from the capsule conservatively estimated, the expected temperature range of holders can be calculated. The gas mixing scheme used in the capsule does not allow pure argon to flow through the gas gaps of the holders without turning off the helium purge flow. This limits the minimal thermal conductivity in the temperature control gas gap to below that which could be produced by flowing pure argon in the gaps. This, in addition to parasitic heat losses limits the achievable temperature range of a holder.

Figure 2 shows: 1) the expected temperature range for the LTVT holder (designed to operate at 165°C when the temperature control gas is pure helium and 1450 watts are generated within the holder) as a function of heat generated within the holder, if pure argon can be input into the gas gaps and there were no parasitic heat losses, and 2) the expected temperature range if parasitic heat losses are assumed equal to the largest value estimated in the prototype experiment (helium flow = 4 sccm) and the gas mixture is assumed to vary from pure helium to a 95% argon-5% helium mixture.

The achievable temperature range of the LTVT holder with parasitic losses and 5% helium content is very close to required temperature range of 165°C to 330°C. If the parasitic heat loss is higher than expected or the heat generated in the holder due to nuclear interactions is lower than expected, auxiliary heat from the heaters could be required to elevate specimen temperatures to the desired high temperatures.

The losses assumed for this calculation are larger than those expected in the capsule, and the helium purge can be terminated when high power is not being demanded from the heaters if needed. It is expected that the required high temperature in the LTVT holder can be achieved without the use of auxiliary heat. Because of the location of the LTVT, the heat generated within it will increase as the reactor cycle progresses, making it easier to maintain temperature.

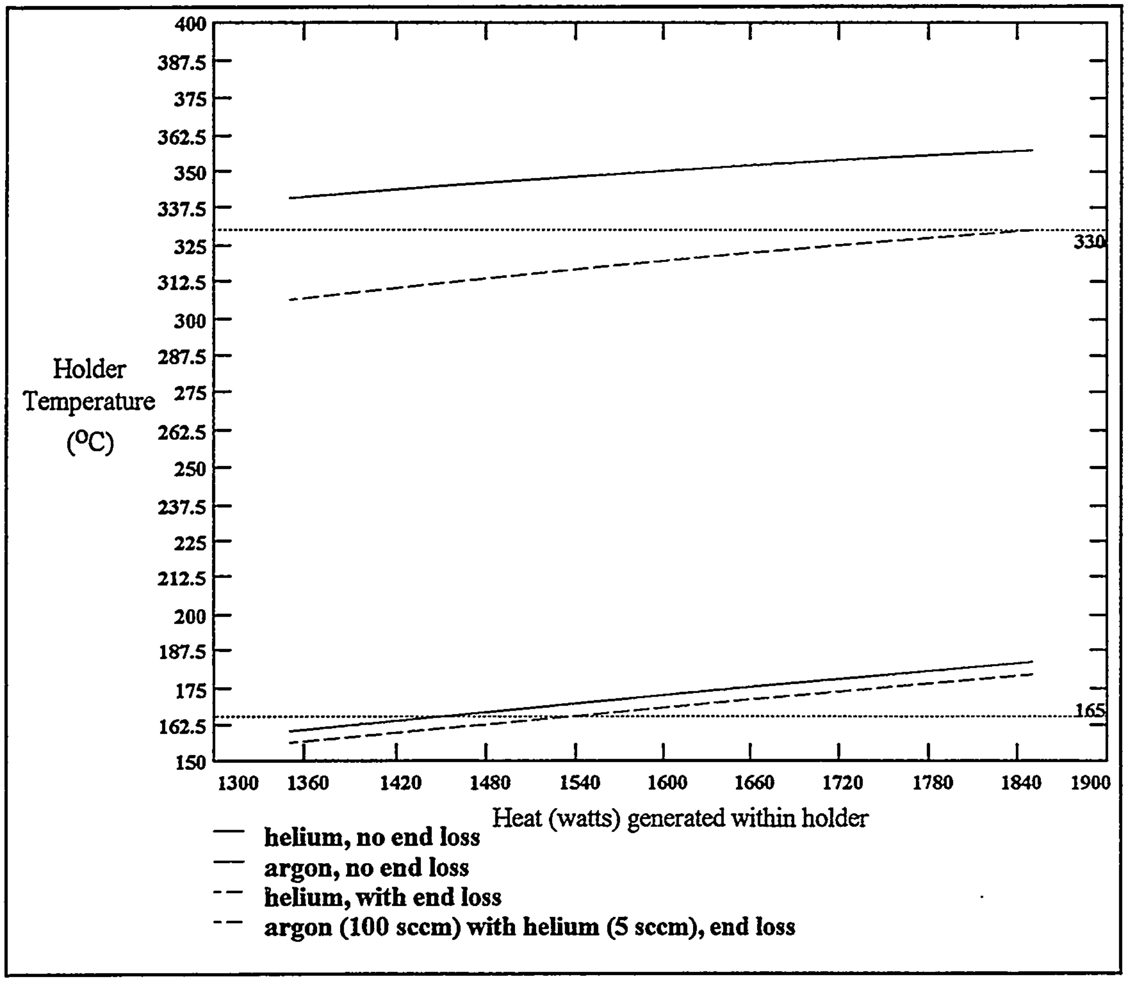

Fig. 2. Predicted temperature range of the LTVT holder.

Heater Performance

The maximum heat output from the heaters is dependent on the design temperature of the holder. In order to have a margin for error, holders are designed to operate below the required temperature. If more heat is generated within the holders than anticipated, the specimens can still be controlled at the desired temperature. Increasing the margin for error (lowering the design temperature) increases auxiliary heat requirements when the reactor is operating at reduced power. The maximum heat requirements will occur if a large margin for error is assumed, and 1) the actual heat generated is less than anticipated, and 2) parasitic heat losses are larger than expected.

The design temperature of each holder is set to limit the maximum credible auxiliary heat requirement to less than that produced when 9 amps pass through the nine elements in each holder. The estimated heat required to maintain specimen temperature in each of the four holders as a function of argon flow through the gas gaps (along with an assumed helium flow rate of 3 sccm) is shown in Fig. 3. This calculation assumes the parasitic heat loss implied by an assumed flow of 4 sccm of helium through the gas gap of the prototype holder.

The maximum required heat input is estimated to be 1200 watts, to maintain a temperature of 350°C in the LTST holder if it is designed to operate at 235°C at EOC with pure helium as the temperature control gas. At 10% power, approximately 220 watts will be generated in the LTST holder due to neutron and gamma interactions. To maintain the desired specimen temperature, 980 watts of auxiliary heat must be added to the holder when 70 sccm of argon and 3 sccm of helium is flowing through the gas gap. If the 980 watts are evenly distributed over the 9 heaters in the holder (average element resistance is 1.35 ohms), then 9 amps will be required through each heater element.

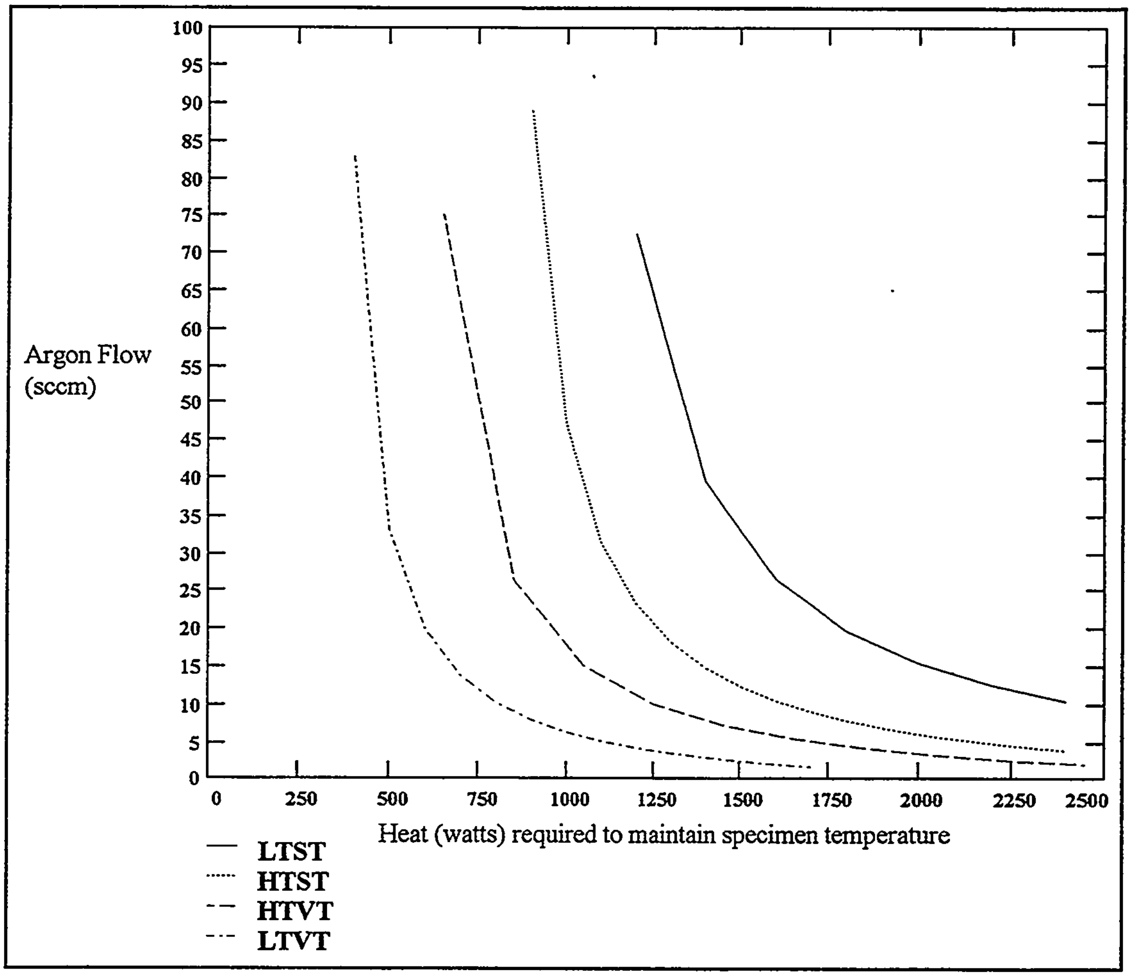

Fig. 3. The estimated heat required to maintain specimen temperature in each of the four holders as a function of argon flow through the gas gaps. A constant helium flow rate is assumed.

The maximum current requirement of 9 amps through the heater elements is the limit established during prototype testing as the operating limit. The 9 amp limit was set to limit sheath temperature to 1000°C in the region between holders, because melting of the sheath at this location was the predominant form of heater failure during testing. The melting temperature of the sheath material (304 stainless steel) however, is > 1450°C, and dual-element heaters have been operated at > 12 amps through both elements in steady state, and > 15 amps through only one of the elements without failure. If four of the original nine elements in a holder are operational, specimen temperatures can be elevated and controlled in the LTST whenever the reactor power is above 10% of full power, even if parasitic heat loss in the capsule holders are as high as the most conservative estimate of the heat losses from the prototype holder.

Heater element lifetime for mineral insulated heaters is limited by wire oxidation, which occurs at a rate proportional to temperature. To ensure a lifetime of at least one year, it is recommended that the element temperature be limited to 870°C. The temperature of a heater element when 9 amps are passing through it, while it is operating in a 500°C holder is estimated to be below 800°C, however, the temperature of the extension wire in the region directly above the holder is known to be >1000°C when 9 amps are passed through both elements. This is an important reason for limiting the current through the heaters. While it is possible to operate at higher power output, doing so will reduce heater lifetime.

During a typical startup, reactor power is increased to approximately 10% of full power and held for 15-20 minutes for instrumentation checks. Specimen temperatures will be elevated and controlled during this period. The heaters will be required to operate at the highest power for approximately 150 minutes over the course of the entire 10-cycle experiment, if all start-ups proceed smoothly. The prototype heaters were operated at 9 amps through both elements longer than the total time expected to be required during the experiment, and were cycled to >9 amps many times more than the 10 cycles required during the experiment. If the current to the heaters can be limited to 9 amps, heater failure due to wire oxidation or melting of the sheath is unlikely.

The effects of transmutations in heater elements and extension wire are not precisely known. While heaters have been irradiated at higher temperatures, the linear power output from those heaters was not as high as the heaters used in this experiment, and heaters have never been operated at ORNL to the fluence that will be encountered in this experiment. These unknown factors provide added incentive for minimizing the heat demanded from the heaters.

Based on the measured resistances across sections of the (shortened) prototype heaters, the total resistance of a full length capsule heater is estimated to be 4.5 ohms. Three elements in series will produce a total loop resistance of approximately 13.5 ohms. A 110 VAC controller could only pass approximately 8 amps through a series of three heaters. Therefore, while a 110 VAC controller was used to test the prototypes, a 208 VAC controller, capable of outputting over 15 amps through three heaters, will be used for capsule operation.

CAPSULE CONTROL

Controller Response

To test the response of the control loop, the system was allowed to equilibrate and then was perturbed by changing operating conditions. The response of the controller for the control heaters and the temperature deviation from the set point temperature to a series of perturbations is shown in Fig. 4. The temperature set point is 175°C, and the helium flow rate and heat output from a secondary set of heaters were held constant during the experiment. Initially, the controller output is limited by the control computer even though holder temperature is below the set point temperature of 175°C. The argon flow is increased and the temperature increases. Upon the detection of increasing temperatures, the demanded current to the heaters is reduced. This is followed by a series of small argon flow increases, which result in small oscillations in holder temperature. At approximately 12:23, the coolant flow past the capsule is terminated and the holder temperature increases. The control heater output is reduced to zero, which reduces the holder temperature. (For operation in the actual capsule, a temperature deviation of this magnitude would result in an automatic reduction in the argon flow rate and termination of current to all heaters in the holder.) Coolant flow is resumed, and the controller returns the holder to the proper temperature after slightly overshooting the set point temperature. The final perturbations are large changes in the argon flow rate, which are designed to simulate changes in reactor power. The largest increase is estimated to simulate a reactor power increase of 10%. The resulting increase in holder temperature is approximately 5°C.

The controllers must respond quickly enough to compensate for expected reactor power increases of 20% of full reactor power (18 MW), and gas mixture adjustments will be made to keep heater outputs within acceptable limits. Reactor power will be increasing as gas mixture adjustments are made. Some temperature deviation is unavoidable during these transitions. Because reactor power increases are usually limited to 20% of full power (< 18 MW) and settling time is allowed between steps, the temperature deviations are expected to be < 10°C.

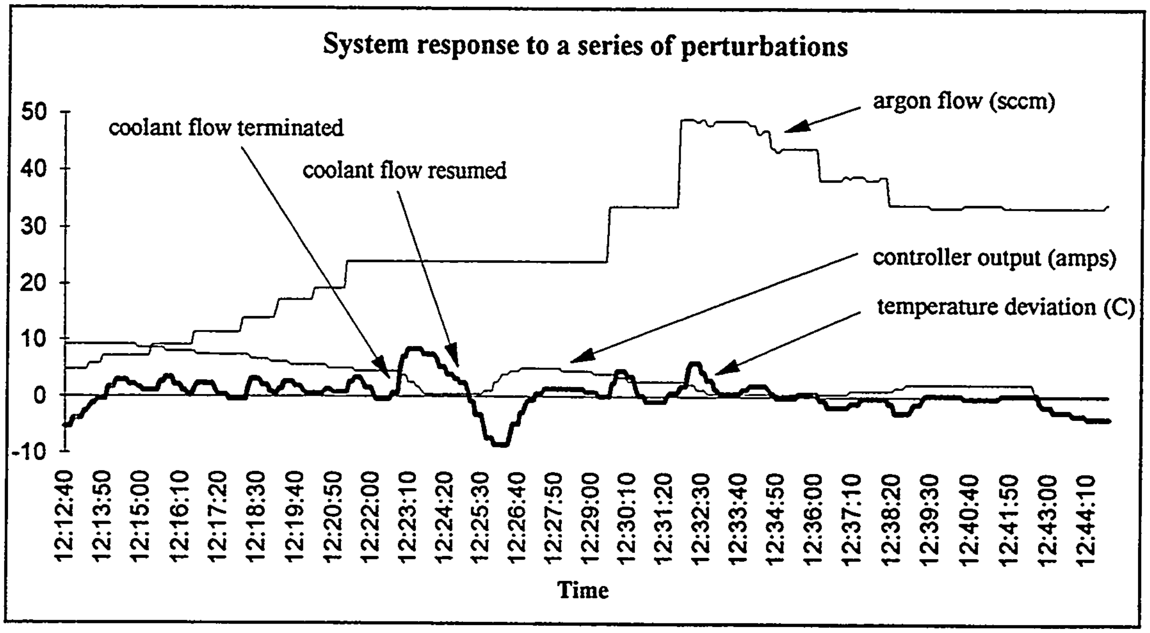

Fig. 4. System response to a series of perturbations.

Automated Control During Start-ups

Gas mixture adjustments will be controlled automatically during a reactor startup. Before startup, the experiment operator will input values into a "setout" table that specifies the argon flow and set point temperature for each zone as a function of reactor power. The flow rates are set to allow the control heaters to operate within a defined power range while maintaining the specified specimen temperatures.

The inputs to this table will be determined during the start-up of the first cycle of operation, which will be strictly specified and monitored. Reactor power levels are either input to the system by the experiment operator or read by the control computer from an on-line database containing real-time reactor conditions. When the reactor power exceeds the power limit for which a temperature set point above ambient coolant temperature (50°C) is specified, temperature control begins automatically. As the reactor power exceeds the values in the setout table, the argon is reduced to the value listed in the table.

By the time the reactor reaches 90% of full power, essentially all of the argon will be removed from the system. At full reactor power, the experiment operator will manually adjust the flow of neon or argon to each temperature zone until the power output of the control heaters falls between the upper and lower alarm limits if required. Once this is done, the capsule can be operated automatically without operator supervision.

The capsule will remain in this configuration until it is time to increase the temperatures in the variable temperature zones (about 2 days). Before the transition, the operator will gradually eliminate the neon or argon from the steady temperature zones, increasing the current demand to the heaters in those zones. The purpose of this is to provide additional adjustment capability in those zones in the event that some of the argon added to the variable temperature zones leaks into the steady temperature zones.

At the time of the transition, the operator will increase the temperature control set points and the argon flow rates of the varying temperature zones. If the change of gas mixtures or temperatures in the variable temperature zones causes an increase in the temperature of the steady temperature zones, the control heater output for those zones will automatically compensate. After the transition, the operator will again manually adjust the neon or argon flow rates to all zones in order to force the control heater outputs between the alarm limits.

Heater Failure

If all three heater zones in a holder were to fail (power failure to control cabinet, for example), the temperature of the specimens would be temporarily reduced to the value dictated by the gas mixture, which is approximately 5°C below set point temperature. The capsule could then be controlled with automated gas mixture adjustments as is routinely done in instrumented RB☆ capsules.

Reactor Power Reduction or Unscheduled Shutdown

If the reactor must be operated at a reduced power level, the control heaters will attempt to compensate with increased heater output. However, once the control heater output from more than one zone exceeds a specified upper value (that is, once the reactor power falls below a certain level), the computer will turn off all heaters and allow the temperature of the specimens to fall below the setpoint value, activating the low temperature alarms. The control system is assuming that the reactor has shutdown and is attempting to prevent holding the specimens at elevated temperatures when they are not being irradiated. Reactor operators will be instructed to shutdown the reactor. If the reactor must be operated at reduced power levels, the experiment operator can manually reset the setout table to accommodate.

WELDING MOCK-UP

The specimens will be sealed in a static helium environment. The required seal was to be accomplished by laser welding a cap into the tops of the specimen holders after the specimens have been loaded. Testing of this sealing method was done for both aluminum and beryllium. An acceptable welding procedure was developed for the aluminum holder, but leak tight seals could not consistently be produced in the beryllium mock-ups with the available equipment, time and resources.

A mechanical seal was designed to facilitate seals in the beryllium holders. The specimen holes are threaded, and threaded, copper-beryllium alloy caps compress a titanium sealing disk between the polished base of the cap and a polished surface inside the specimen hole, as shown in Fig. 5. Titanium was selected as the gasket material because it will act as an oxygen getter in the event that a small amount of leakage does occur. Mock-ups of the mechanical seal are being fabricated and will be tested before the design is finalized.

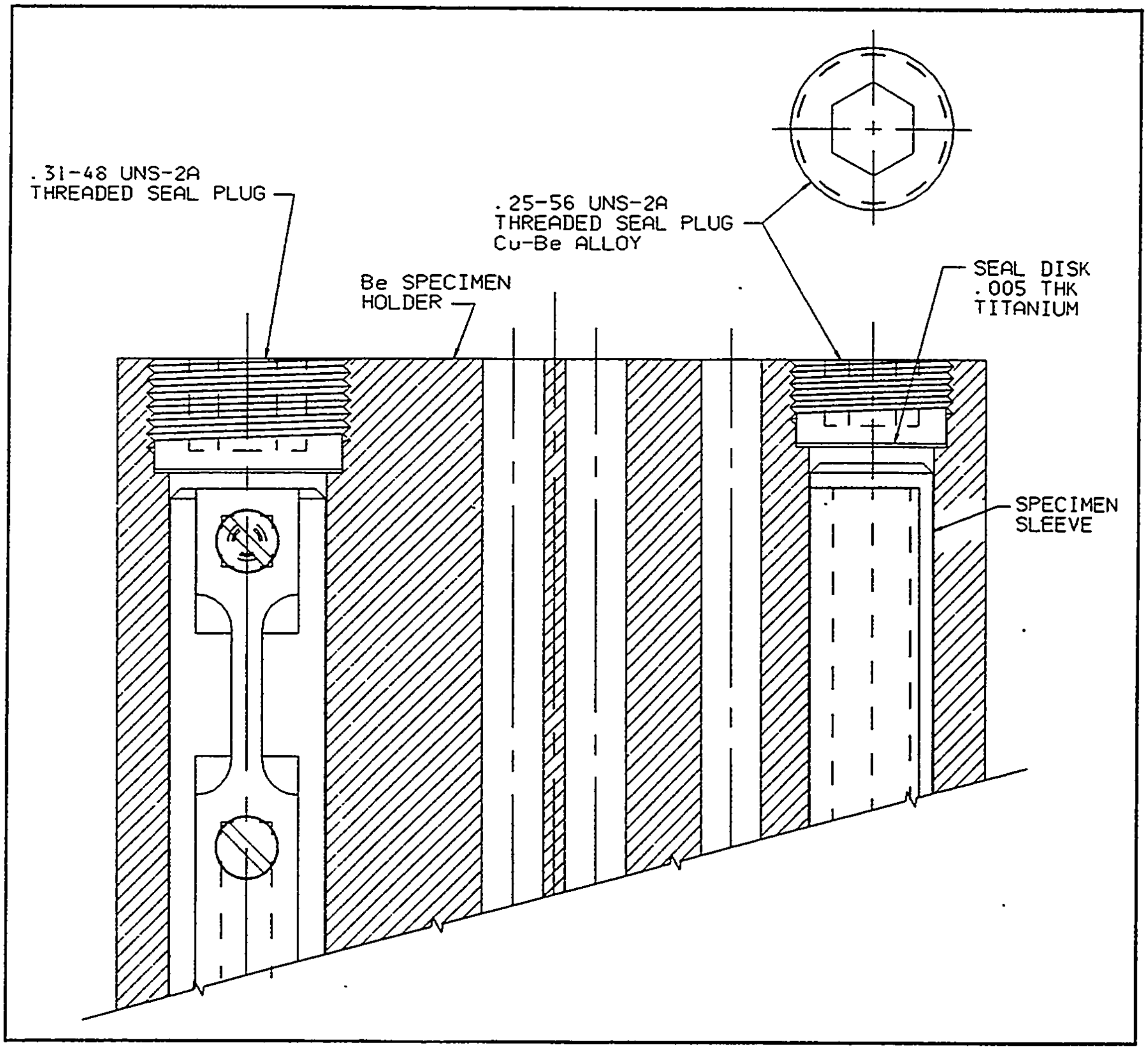

Fig. 5. Detail of the sealing caps to be used in the beryllium (high temperature holders).

MATERIAL CHANGE

The specimen sleeves were changed to DISPAL in both holders to reduce the expense associated with making identical sets out of different materials, and making and handling a large number of beryllium components. The DISPAL can be used at temperatures up to 500°C, and is therefore acceptable for use in all four holders. It will also prevent the specimens from being in direct contact with beryllium.

SCHEDULE

Fabrication of the capsule housing components and the heaters and thermometry has begun. The holders will be fabricated as soon as the mechanical sealing technique has been verified. Specimens are scheduled for delivery to ORNL in August 1997. Capsule assembly is scheduled for July - October. The control hardware is scheduled for completion by October 1997, and the assembled capsule will be connected to the control system in December 1997. Irradiation is scheduled to begin after the irradiation of RB-11J and RB-12J is complete, in February or March 1998.

REFERENCES

1) A. L. Qualls, T. Muroga, "Progress Report on the Design of a Varying Temperature Irradiation Experiment for Operation in HFIR," Fusion Materials, Semiannual Progress Report for Period Ending December 31, 1996, pp 255-262.