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2200°C FUEL CENTERLINE THERMOCOUPLES

FOR THE LOFT PROGRAM

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SUMMARY

The technology as well as commercial suppliers have been developed for high temperature thermocouples for the Loss-of-Fluid-Test (LOFT)* program. Two types of thermocouples were developed and tested. Model B units contained a 1/16-inch O.D. 24-inch long Mo/Re sheath probe and were capable of temperature measurement to 1550°C. Model A units contained a 1/16-inch O.D. 41-inch long W/Re-augmented sheath probe and were capable of temperature measurement to 2200°C.

Both thermocouples were insulated with sintered hafnium dioxide insulators and contained W/5Re - W/26Re thermoelement wires. Both probe sheaths were terminated with an alumina ceramic-to-metal seal capable of maintaining hermeticity to 10^{-9} cc He/s during temperature transients to 360°C/min. at 2500 psi continuous and pressure transients of 350 psi/s at 450°C continuous. The alumina seal provides a barrier to fission gas escape from the fuel rod in the event the thermocouple probe sheath fails. The probe sheath is tested at 2500 psi for hermeticity to 10^{-9} cc He/s prior to assembly. The ceramic seal and thermoelement wires were connected by means of a transition assembly to a 25 foot length of stainless steel sheath MgO insulated cable for signal transmission to the ex-vessel reactor measurement instrumentation.

The thermocouples operated for 1,000 hours at their maximum operating temperatures of 2200°C (model A) and 1550°C (model B) with less than 2% drift in the emf output. The thermocouples also survived thermal transients of up to 145°C/s with no measureable degredation in measurement performance. The time response of the thermocouples was measured to be less than 2-1/2 seconds at 2000°C and less than 5 seconds at 1500°C.

INTRODUCTION

LOFT is an experimental program to support safety research investigations for the Nuclear Regulatory Commission (NRC). One objective is to study fuel behavior during simulated loss of coolant accident tests. Measurement data from the tests will be used to check analytical predictions of core response. Measurement of the fuel centerline temperature is considered an important parameter for full characterization of the fuel bundle during the reactor coolant loss tests.

The Hanford Engineering Development Laboratory (HEDL) has been engaged in a program for the NRC to develop a 0.062 inch O.D. fuel centerline temperature measuring system which can operate at 2200°C and 2500 psi for 400 hours minimum at full LOFT reactor power.

A reliable commercial instrument capable of measuring fuel centerline temperature did not exist at the start of the development program. However, previous development programs on high temperature thermocouples provided a technological base from which to develop thermocouples capable of satisfying the LOFT requirements. The majority of studies in this area consist of laboratory tests on thermocouple materials contained inside a furnace environment. The probe and insulators of the thermocouples developed are fabricated from materials similar to those used by Kulman and Baxter(1) in studies on 2200°C thermocouples. Studies by Burns, et. al.,(2) provided a basis for understanding the extent to which tungsten/rhenium thermoelements decalibrate in temperature environments to 2200°C. The LOFT program required complete thermocouple assemblies, commercially fabricated, capable of operating at 2200°C with less than 2% decalibration over a 400 hour test period.

THERMOCOUPLE REQUIREMENTS

The LOFT specifications require fuel centerline temperature measurement at distances of 2.2-ft. and 3.6-ft. from the bottom of the fuel pellet stack. Thermocouple entry is from the top of the fuel pin.

Mechanical requirements:

Sheath length (model A): 41 inches
Sheath length (model B): 23 inches
Sheath diameter: $\leq$ 0.063 inches
Transition junction diameter: $\leq$ 0.295 inches
Compensating lead cable diameter: $\leq$ 0.063 inches
Compensating lead cable length: $\sim$ 25 ft.

Measurement performance requirements:

Range: 260°C - 2200°C
Accuracy: $\pm$ 20°C or 2% of reading (whichever is larger)
Resolution: 3.3°C
Response Time: 1 second
Service Life Time: > 400 hours (1000 hours desired)

Operating environment requirements:

Temperature: 2200°C (model A); 1550°C (model B)
Temperature transient: 145°C/s (on sheath); 6°C/s (on ceramic seal)
Pressure: To 7.2 MPa (2500 psi)
Pressure transient: 2.4 MPa/s (350 psi)/s
Radiation: 1×10^9 R/hr
2×10^{13} n/cm^2
Media: UO_2, helium, water vapor, fission product gas, (10 ppm)

All of the above requirements were satisfied by the developed thermocouple except for 1 second rise time. Tests indicated a rise time at 2200°C of $\sim 2\frac{1}{2}$ s. However, accurate rise time tests at these high temperatures are difficult to perform and the result is considered an upper bound.

It is also important that the thermocouple materials not significantly alter the neutron flux inside the fuel rod. A theoretical analysis by EG&G personnel at Idaho Falls(3) indicates that the HfO_2 insulated thermocouple will reduce the flux intensity a maximum of 6½%.

THERMOCOUPLE DESCRIPTION

The technology as well as commercial suppliers were developed for the thermocouples. A complete thermocouple assembly consists of the following components: 1) a measuring probe consisting of a refractory metal sheath which contains 2 thermoelement wires insulated with hafnium dioxide; 2) a transition junction assembly, which hermetically seals the probe, comprised of an alumina ceramic-to-metal seal and thermoelement wires spliced to the leads of compensating lead cable; and 3) 25 feet of stainless steel sheathed, MgO insulated twinaxial compensating lead cable. The measurement junction in the probe is formed by twisting and welding the thermoelement wires together.

Two types of thermocouple assemblies were developed: model A units, capable of operation to 2200°C, contain a 41-inch length, 0.062-inch O.D. Re/W-augmented sheath; model B units, capable of operation to 1550°C contain a 23-inch length, 0.062-inch Mo/48Re sheath. The difference in sheath material type and length constitutes the only difference between the two units. Mo/Re was used as a sheath material on the model B assemblies because of its lower cost and the lower temperature requirements. Material compatibility tests[4] and a literature review at the start of the program dictated the choice of W/Re and Mo/Re alloys as sheath and conductor materials and hafnia as the insulator material.

Sheath Tubing and Thermoelement Wires

The 4-foot, 0.062-inch O.D., 0.048-inch I.D., Re/W-augmented sheath tube for model A thermocouples was fabricated using a chemical vapor deposition process; the addition of <5% W stabilized grain growth. Other W/Re alloys were too brittle to support the 41-inch sheath length required and the large grain size of pure Re would not meet the 2500 psi requirement. The tube I.D. was chemically etched to provide the required cleanliness for 2200°C thermocouple operation. The Mo/48Re sheath tube used in the model B thermocouples was formed using standard cleaning and swaging procedures. The thermoelements used were standard 0.010-inch W/5Re - W/26 Re wires.

Insulators

A commercial supplier for HfO_2 insulators did not exist at the start of the program. Specially processed high purity HfO_2 powder was obtained suitable for sintering purposes (BET > 20). The powder was extruded and then sintered at 1700°C to provide a hard fired 0.044-inch O.D. insulator suitable for thermocouple fabrication. Tests have demonstrated that the electrical resistivity of the present HfO_2 insulators limits the maximum thermocouple operating temperature to 2200°C.

Sheath Termination

The 41-inch probe was required to be hermetically terminated to withstand thermal transients of 6°C/s while continuously pressurized at 2500 psi and pressure transients of 350 psi/s while at 450°C. The seal termination occurs near the top of the fuel rod. An Al_2O_3 ceramic-to-metal seal with Mo/Ni sleeving was developed which satisfied the service requirements.

Fabrication

The final thermocouple assembly was fabricated by assembline the insulators, conductor components, and ceramic seal in ambient air, vacuum baking at 450°C, and backfilling with high purity argon gas. Sheath materials were thoroughly cleaned (acid/solvent) prior to assembly. Cost considerations made a simple fabrication procedure like the one used highly desirable since the production order required 100 units. A transition region and 25 feet of compensating lead cable were then added to complete the assembly. It is noteworthy that 2200°C operation was achieved without prebaking components at similar temperatures. Figure 1 is a photograph of a 2200°C model A thermocouple assembly.

PERFORMANCE TEST APPARATUS AND PROCEDURES

Qualification tests evaluated the performance of the three test thermocouples under conditions similar to those existing in the severe test environment of the LOFT reactor. Two model A (2200°C) and one model B (1550°C) thermocouple were tested. Test conditions duplicated those anticipated for temperature and pressure in the LOFT reactor fuel centerline. Radiation tests were not performed because they were not considered feasible for the qualification thermocouples. A literature review(5) established that the performance of this type of thermocouple in an irradiation field is generally known; decalibration errors due to irradiation are estimated to be less than 1% over the expected lifetime neutron exposure of 1.4×10^{20} nvt. However, gamma heating tests are planned for 1980.

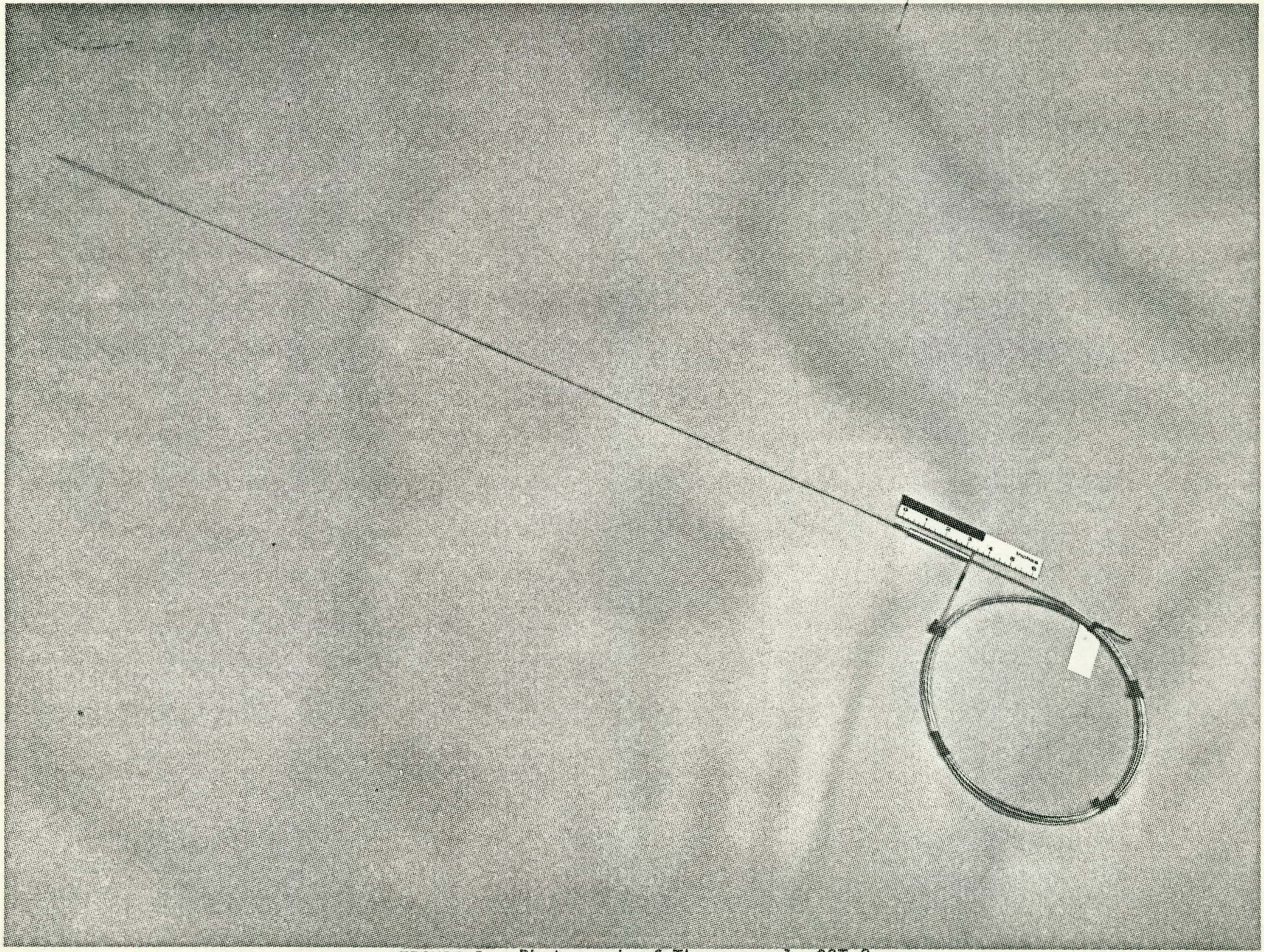

FIGURE 1. Photograph of Thermocouple CQT-2.

Test Objectives

The primary objective of the qualification tests was to determine whether the thermocouples would open circuit or decalibrate severely during 400 hour steady-state life tests at the maximum operating temperature (2200°C for model A, 1550°C for model B) or during thermal transient tests at rates up to 145°C/s. The second major objective of the tests was to determine the reliability of the transition junction. The tests subjected the transition junction to thermal transients of 6°C/s while at 2500 psi continuous and pressure transients of 350 psi while at 450°C continuous.

Furnace Testing

The life temperature tests were conducted in a Brew Model 424-B High Temperature Vacuum Furnace in a vacuum/high purity argon environment. The majority of life tests were conducted in vacuum. The argon environment was used primarily during furnace calibration and data taking because the gas more effectively provided a uniform temperature in the furnace interior. Figure 2 is a sketch of the furnace interior.

Certified bare wire W/5Re - W26Re thermoelement wires were inserted into the furnace cavity through the top heat shields. The junction of the thermocouple was placed within 1/4 inch of the tip of the thermocouple to be tested. The insulation resistance to ground of the bare wire thermocouple was continuously monitored during calibration; errors due to electrical shunting were less than 1%. A Raytek model SL-400-SC Infrared Pyrometer monitored the temperature of the bare wire and test thermocouple region. The bare wire thermocouple was used to calibrate the pyrometer to 2200°C and the pyrometer was used to control the furnace temperature during the life tests. Periodic recalibration against a bare wire thermocouple provided an overcheck against drift. The furnace temperature at 2200°C was estimated to be known within ±40°C. The ±40°C error results primarily because the bare wire thermocouple was stable to only 2000°C - 2100°C. Above those temperatures instability (due to lack of electrical shielding against the electrical heating units) required extrapolation to calibrate the pyrometer to 2200°C. It is noteworthy that the emf output of the bare wire thermocouple during calibration runs gave excellent agreement to 2100°C with the emf output from the test thermocouple assemblies.

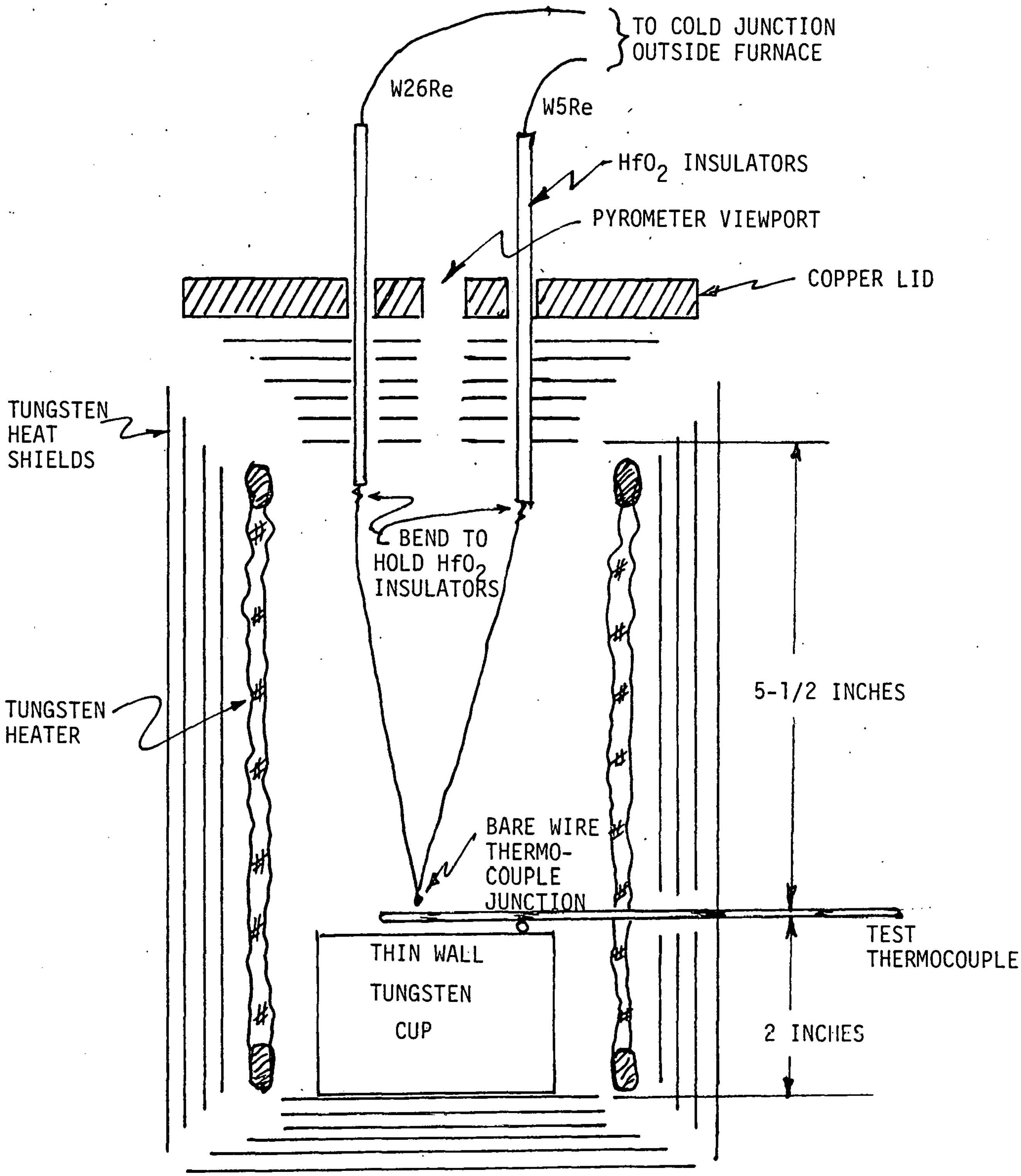

FIGURE 2. Sketch Of The Brew High Temperature Furnace Interior Used To Test The LOFT Qualification Thermocouples.

Thermal cycles to room temperature were performed during the life tests. Cool down cycles times of approximately 1/2 hour were achieved by shutting off the furnace power. Approximate heat up times of 1/2 hour were used to heat from room temperature to 2200°C.

TEST RESULTS AND DISCUSSION

The model A assemblies were subjected to a temperature of 2200°C and the model B assembly to 1500°C for 400 hours minimum. All thermocouple assemblies received a minimum of 3 thermal cycles to room ambient temperature during the 400 hour tests. An additional requirement was that one room temperature cycle be performed within the first 100 hours and another be performed within the last 100 hours of the 400 hour life test. The emf outputs of the test thermocouple assemblies were required to drift no more than 2% during the duration of the 400 hour life tests.

Life Tests

The three test thermocouple assemblies survived 400 hour life tests at the maximum operating temperature with less than 2% decalibration over the duration of the test. Figure 3 plots the output emf of a typical model a thermocouple at 2200°C during 400 hours of testing. Figure 4 plots the output emf of the model B thermocouple at 1550°C during 400 hours of testing. After thermal cycling to room temperature, the thermocouple output emf returned to within 1/2% of its value at the maximum operating temperature prior to the cycle. All thermocouples remained within 2% of their initial reading. Figure 5 plots the value of insulation resistance as a function of temperature for the three thermocouples. The good agreement on all three units suggests good consistency in bakeout and handing procedures since the three thermocouples were fabricated in different lots. Figure 6 plots the value of loop resistance, i.e., thermoelement wire resistance, as a function of temperature prior to and after 325 hours of testing at 2200°C. The slight increase in loop resistance after the 325 hours at temperature is attributed to wire embrittlement and other forms of wire deterioration.

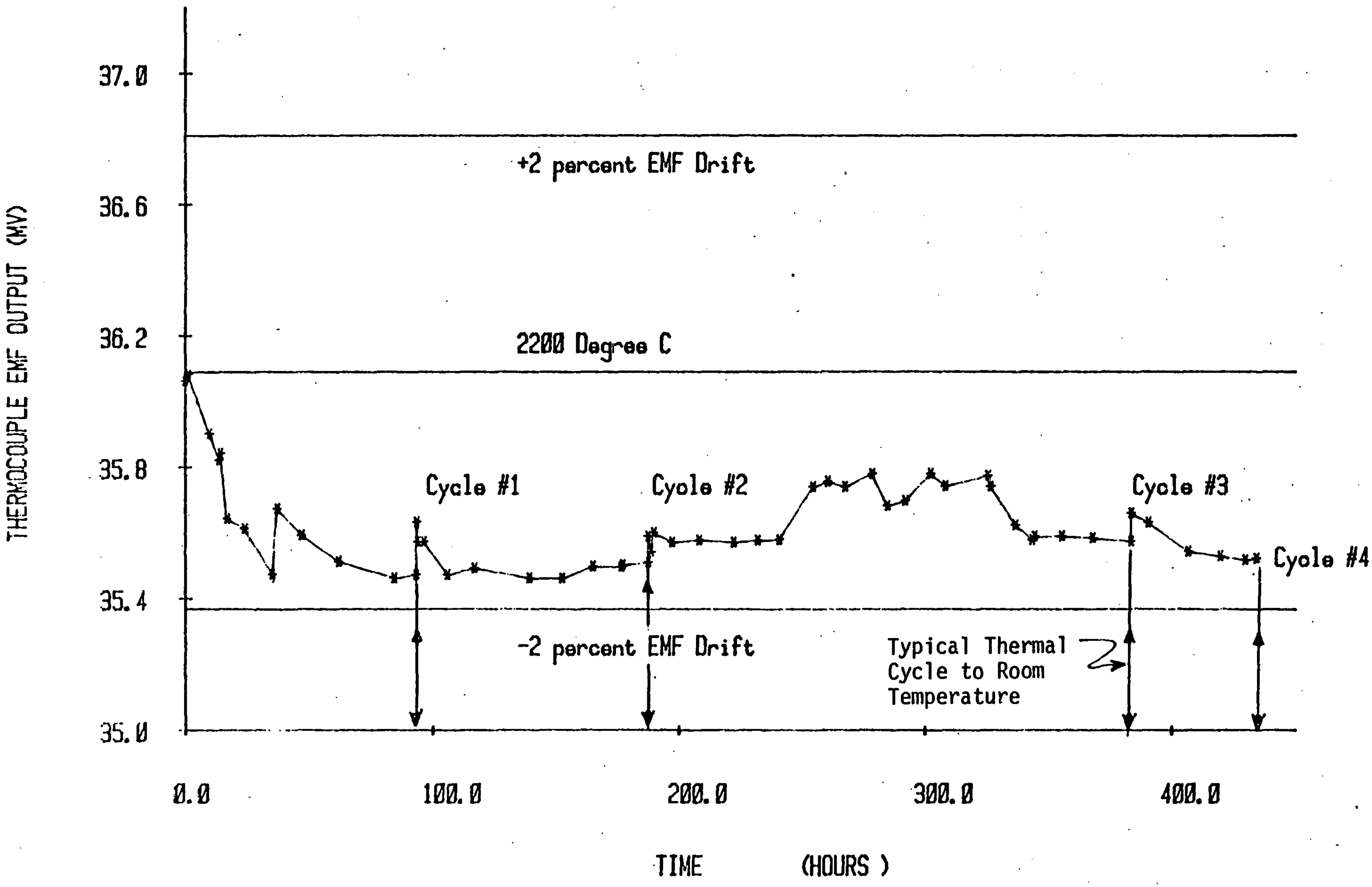

FIGURE 3. EMF Drift Test For Qualification Thermocouple No. 1 At Constant 2200°C.

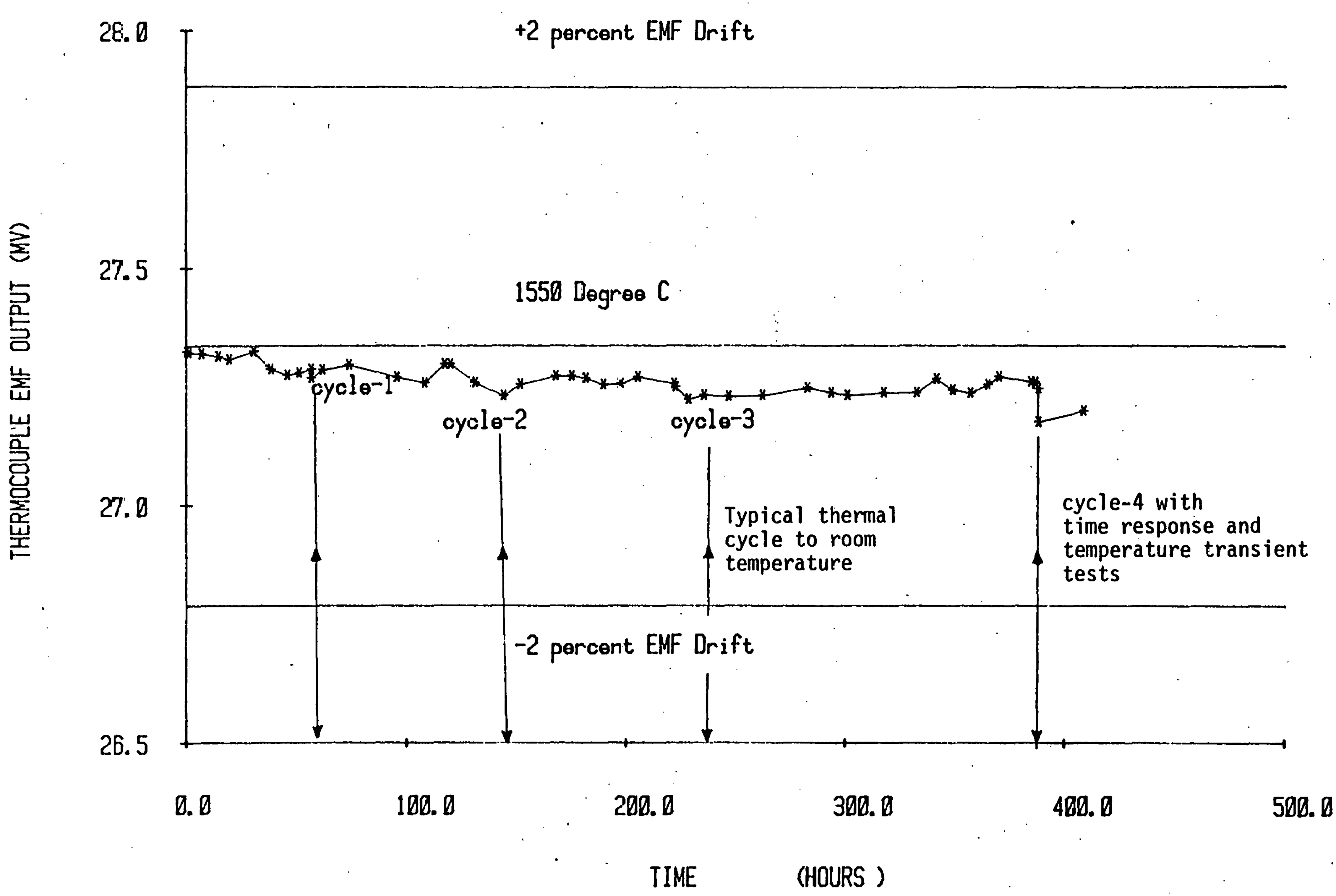

FIGURE 4. EMF Drift Test For Qualification Thermocouple No. 3 At Constant 1550° C

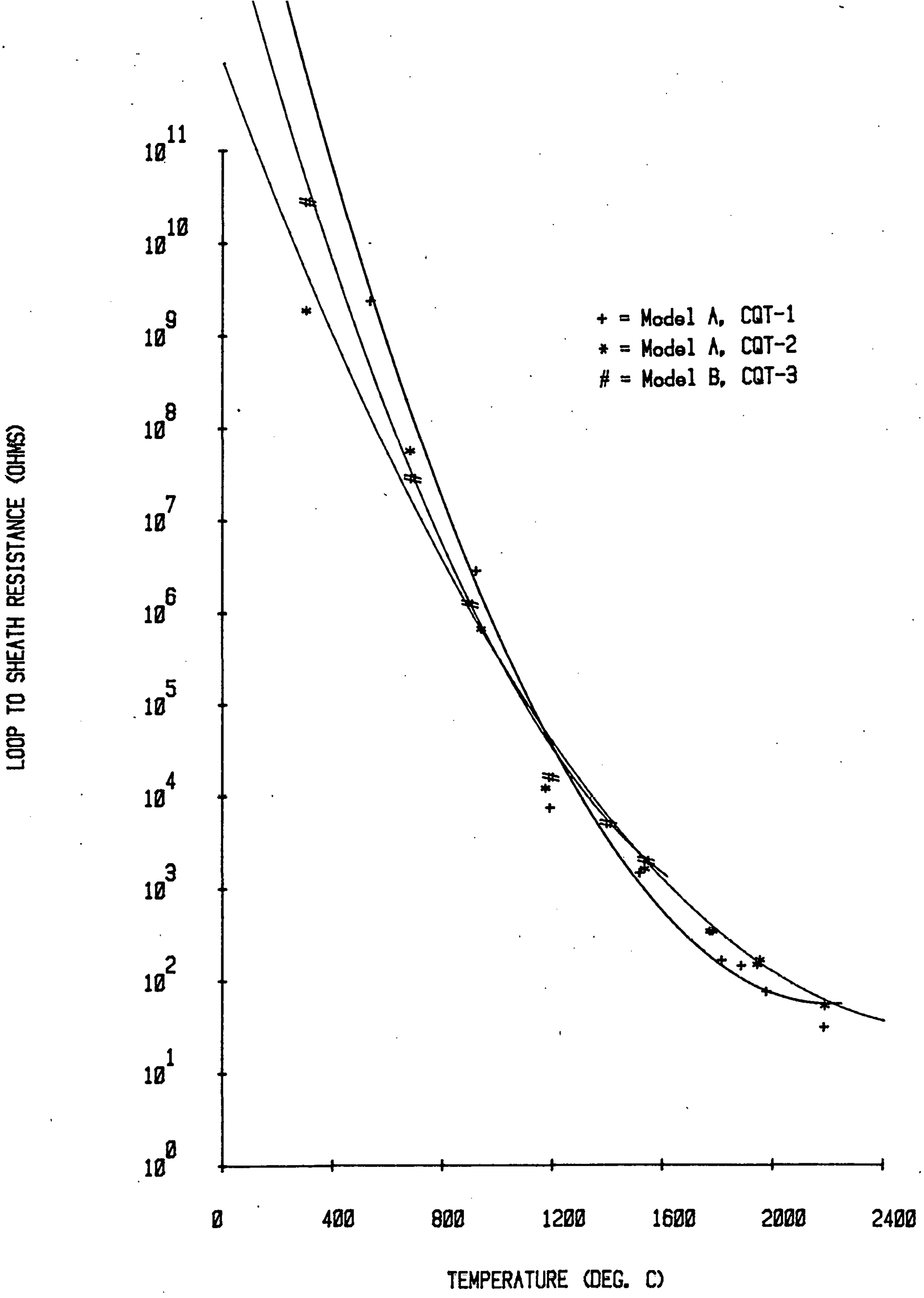

FIGURE 5. Plot Of Insulation Resistance Versus Temperature For The LOFT Qualification Thermocouples.

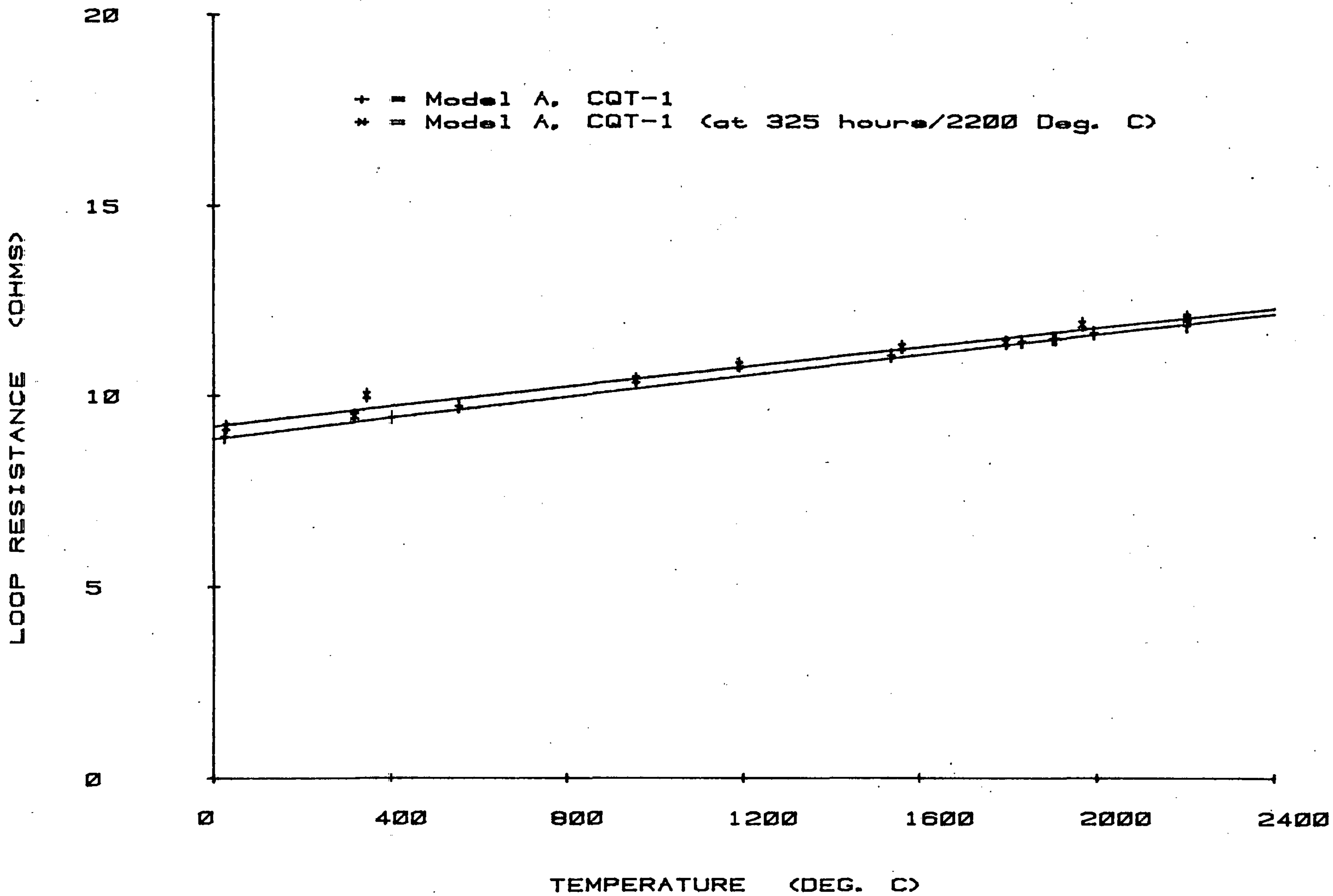

FIGURE 6. Plot Of Thermocouple Lead Resistance Versus Temperature Prior To And After 325 Hours At 2200°C.

Transient Tests

Each test thermocouple survived three temperature transient cycles of 145°C/s over a 400°C temperature interval. Each thermocouple also survived 5 thermal cycles from 2200°C (or 1550°C for model B) to room temperature at nominal rates of 75°C/s.

Transition Junction Tests

Transition junction errors were less than 100 μV due to changes of ambient temperature from room to 400°C. This error is less than 1/2% (<6°C) for an 1100°C measurement junction temperature.

The transition junction ceramic-to-metal seal performed to the requirements: 6°C/s transients to 450°C at 2500 psig and 350 psi/s transients to 2500 psig at 450°C. Hermeticity $>10^{-9}$ cc He/s was maintained throughout testing.

Post Test Examination

X-rays of measurement junction regions after testing gave no indication of any significant changes in thermoelement wire dimensions or position. Insulators upon removal from the measurement junction region appeared discolored especially in the region which was positioned in the temperature gradient zone of the test furnace. Auger electron microprobe analyses of these regions indicate some contamination on the insulators. These contaminants have been traced to materials used in production and do not appear to have had a detrimental effect on the operation of the thermocouple. The good performance at 2200°C is significant because the thermocouple components have not previously been baked out at 2200°C. Some changes in wire diameter in the hot region were observed; some areas between the insulators are reduced in diameter. There also appears to be some evidence of embrittlement. However, mechanical integrity of the insulator and thermoelement wire assemblies appears adequate and supports the test data taken on the units. Metallography on the weld closure at the end of the sheath tube indicates no abnormalities in the weld region.

CONCLUSIONS

Complete 1/16-inch O.D. thermocouple assemblies capable of satisfying the LOFT in fuel temperature measurement requirements have been developed and fabricated using commercial suppliers. The qualification units satisfied 400 hour (operated 1000 hours) life requirements at the maximum operating temperatures of 1550°C and 2200°C with less than ±1% emf drift as well as thermal transient survival tests of up to 145°C/s.

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