10/20/80
1 cy DeSalvo, Kelber, staff, Silberberg, McPherson
File
5 cy Fuel Behavior Br
10 cy Van Houten

NUREG/CR-0961
HEDL-TME 79-50

QUALIFICATION TEST RESULTS ON 1550°C AND 2200°C 1/16-INCH O.D. FUEL CENTERLINE THERMOCOUPLES FOR THE LOFT PROGRAM

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ABSTRACT

The technology and commercial vendors have been developed for fabrication of thermocouples to measure fuel centerline temperatures to 2200°C in the Loss of Fluid Test (LOFT) reactor. Two model A and one model B qualification thermocouples satisfied all test requirements during life tests at 2200°C and 1550°C. The emf output drifted less than 2% during 400 hour tests at the maximum test temperatures of 2200°C and 1550°C. Measurement performance remained unimpaired after 145°C/s transient survival tests.

The thermocouples did not meet the time response requirement of one second. Time responses of 4-1/2 seconds at 1550°C and 2-1/2 seconds at 2200°C were measured. However, this result was not considered too negative to preclude useful temperature measurement of fuel centerline temperatures in the LOFT reactor. The first qualification thermocouples satisfied all other test requirements.

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FIGURES (Cont'd)

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1.0 SUMMARY

Qualification tests have been completed on fuel centerline thermocouples developed for the LOFT program. Two types of thermocouples were developed and tested. Model B units contained a 1/16" O.D. 24" long Mo/Re sheath probe and were capable of temperature measurement to 1600°C. Model A units contained a 1/16" O.D. 41" long W/Re-augmented sheath probe and were capable of temperature measurements 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.

Two model A and one model B thermocouples were tested in qualification tests. All three thermocouples operated for 400 hours at their maximum operating temperature 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 measurable degradation and measurement performance. The time response of the thermocouples was measured to be approximately 2-1/2 seconds at 2000°C and approximately five seconds at 1550°C.

The only performance requirement out of specification was the response time: one second was required at 2200°C as opposed to the five to two and one half second response times measured during the tests. Follow on development work is expected to improve the response time of the thermocouple. Significantly, each of the three units successfully operated for over 400 hours with less than 2% decalibration after being subjected to severe thermal transients, similar to those to be experienced in the service environment of the LOFT reactor.

2.0 INTRODUCTION

2.1 OBJECTIVES

This report summarizes test data on three qualification thermocouples designed to measure reactor fuel centerline temperatures for the LOFT program. The qualification thermocouples were procured by HEDL, and represent the culmination of a two year development effort. The objective of the development program was a fuel centerline measuring system that could operate at 2200°C and 2500 psi for a minimum of 400 hours at full LOFT reactor power.

Two model A thermocouples, rated to 2200°C, and one model B thermocouple, rated at 1600°C, were tested. The tests were designed to evaluate the performance of the thermocouples under near prototypic service temperature and pressure conditions. Tests included both life and transient temperture tests, pressure transient tests, response time, transition junction emf error tests, and post test destructive examinations.

2.2 BACKGROUND

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.

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 probe of the thermocouple discussed in this test report is fabricated from materials similar to those used by Kulman and Baxter(1) in studies of 2200°C thermocouples. Studies by Burnes, et. al.,(2) and Wilkins(3) provided a basis for understanding the expected performance of tungsten/rhenium thermoelements in temperature environments to 2200°C. However, the majority of studies in this area consist of laboratory tests on thermocouple materials contained inside a furnace environment. 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.

2.3 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 (350 psi)/s
Radiation: 1×10^9 R/hr for 1000 hours
$2xz10^{13}$ n/cm^2
Media: UO_2, helium, water vapor, fission product gas, (10 ppm)

2.4 THERMOCOUPLE DESCRIPTION

The technology as well as the commercial suppliers have been developed for thermocouples to satisfy the LOFT performance requirements (except response time which is approximately 2.5 seconds). A complete thermocouple assembly consists of the following components: 1) a measuring probe consisting of a refractory metal sheath that contains two 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 wire spliced to the leads of compensating lead cable; 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, containing a 41-inch length, 0.062-inch O.D. Re/W-augmented sheath; model B units, capable of operation to 1550°C, containing 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 lower cost and 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.

The 4-foot, 0.062-inch O.D., 0.048-inch I.D., Re/W-augmented sheath tube for the model A thermocouple 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 larger grain size of pure Re gave less margin of safety for the 2500 psi requirement. The tube I.D. was chemically etched to provide the required cleanliness for 2200°C thermocouple operation. The thermoelements used were standard 0.010-inch W/5Re - W/26Re wires. The Mo/48Re sheath tube used in the model B thermocouple was formed using standard cleaning and swaging prodedures.

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 HfO_2 insulators limits the maximum thermocouple operating temperature to 2200°C.

For safety reasons, 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 to satisfy service requirements.

The final thermocouple assembly was fabricated by assembling the insulators, conductor components, and ceramic seal in ambient air, vacuum baking at 450°C, and backfilling with high purity argon gas. Cost considerations made a simple fabrication procedure 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. Operation at 2200°C was achieved without prebaking components at similar temperatures.

3.0 TEST REQUIREMENTS AND PROCEDURES

3.1 TEST OBJECTIVES

The objective of the qualification tests was to evaluate performance of the three test thermocouples under conditions similar to those existing in the severe test environment of the LOFT reactor. 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 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 Fiscal Year 1980.

The qualification tests discussed in this report were conducted in accordance with LOFT-QTP-CT-1, Revision 2, LOFT Fuel Centerline Temperature Instrumentation Qualification Test Program, dated May 9, 1979. 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. A failure of this type is denoted as a Type 1 failure. The second major objective of the tests was to determine the reliability of the transition junction. The ceramic-to-metal seal inside of the transition junction acts as a barrier to fission gas escape up the compensating lead cable in the event the sheath of the thermocouple probe ruptures in service. 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. Failure of the transition region is denoted as a Type 2 failure.

3.2 TEST REQUIREMENTS AND PROCEDURES

Tests on the thermocouples are divided into eight separate categories. When not given in this test report, the complete procedure for performing a given test is found in the test logbook. A brief summary of required tests follows.

3.2.1 General

A complete record of all tests performed on the thermocouples was permanently recorded in bound logbooks. The test description was recorded in a logbook, and included the equipment arrangement, the identification number of each equipment component, and the wiring interconnection diagram. All data was recorded in a logbook. Where data sheets were used, they were permanently affixed in a logbook. Where appropriate, photographs were taken of test arrangements and setups; they too were permanently affixed in the test logbooks. Calibrated instruments were used, and copies of the equipment calibrations were permanently affixed in the logbooks.

3.2.2 Receiving Examination

Upon receipt, each thermocouple was examined for indications of shipping damage. All dimensions were verified and x-rays were taken of the loop, i.e., wire-to-wire, and the insulation resistance, wire-to-sheath, was measured using a Multimeter and a megohm bridge respectively. The minimum insulation resistance required is 1 x 10^8 ohm feet at 50 volts (Probe itself is greater than 10^{12} ohm). The measured loop resistance is required to agree within 10% of the calculated value for thermoelements of that length and diameter.

3.2.3 Life Tests

The model A assemblies were subjected to a temperature of 2200°C and the model B assembly was subjected to a temperature of 1500°C for a minimum of 400 hours. All thermocouple assemblies received a minimum of three 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.

The life temperature tests were conducted with 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 1 is a sketch of the furnace interior. Figure 2 is a photograph of the furnace interior looking down with the upper heat shields removed. Figures 3 and 4 are photographs of the furnace exterior.

The temperature of the Brew furnace was calibrated according to LOFT-FCP-1, Revision 0, High Temperature Vacuum Furnace Temperature Calibration Procedure. 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

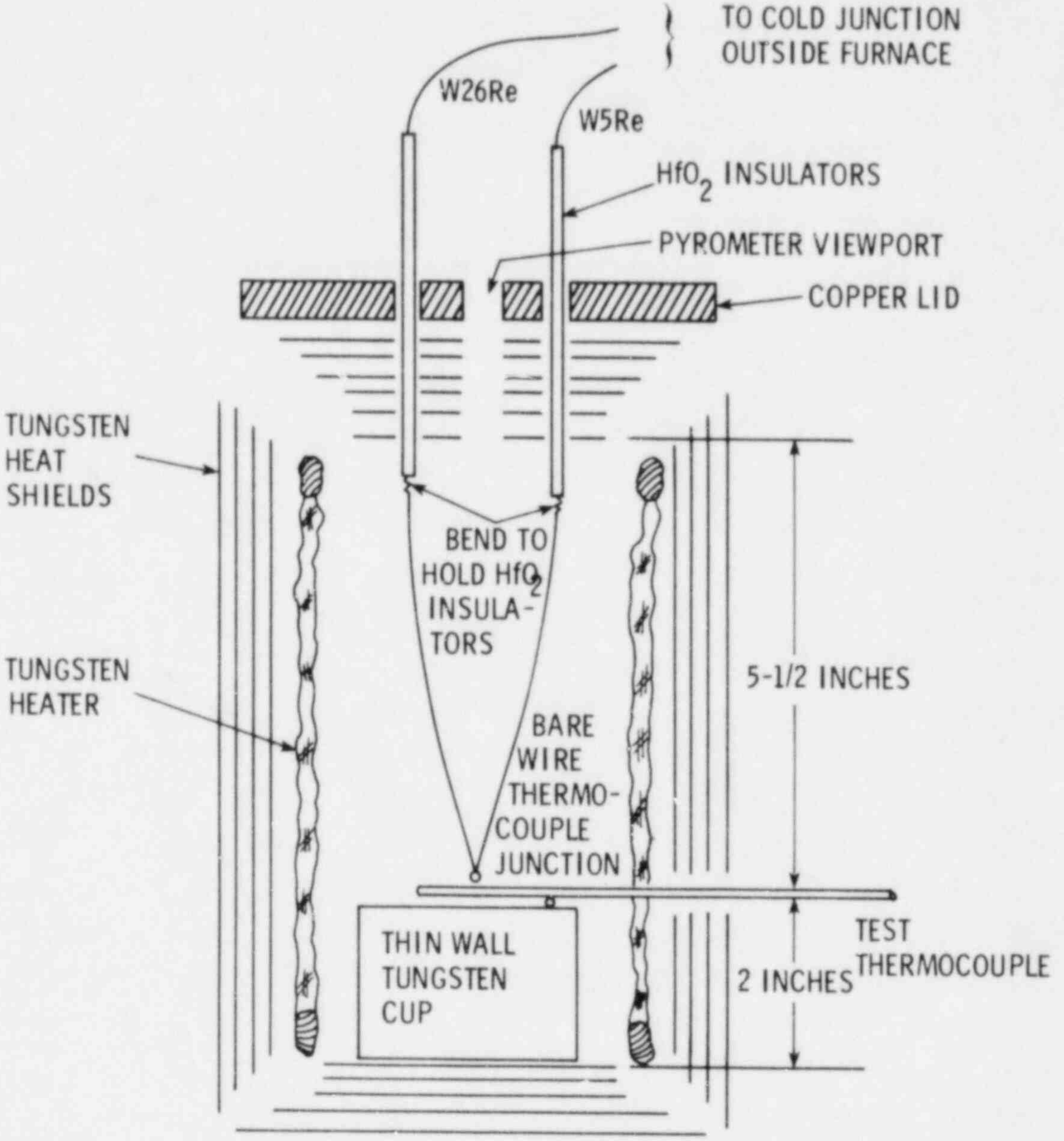

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FIGURE 1. Sketch Of the Brew High Temperature Furnace Interior Used To Test The LOFT Qualification Thermocouples.

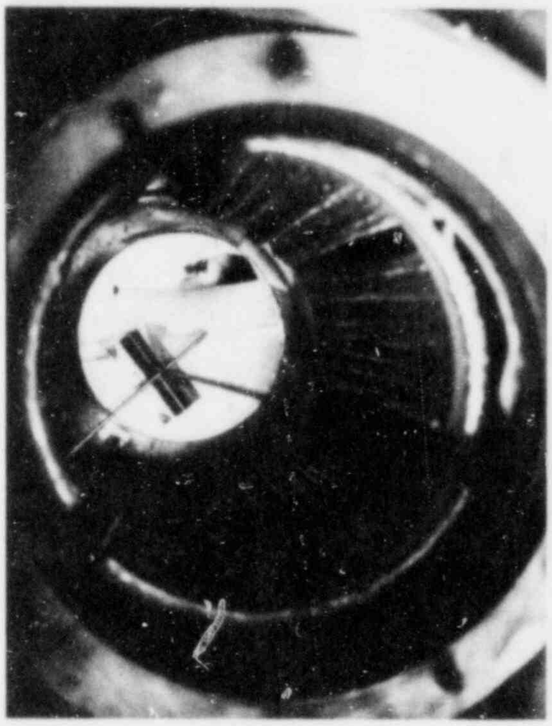

FIGURE 2. Photograph Of The Brew Furnace Interior Showing Two Test Thermocouples In Place.

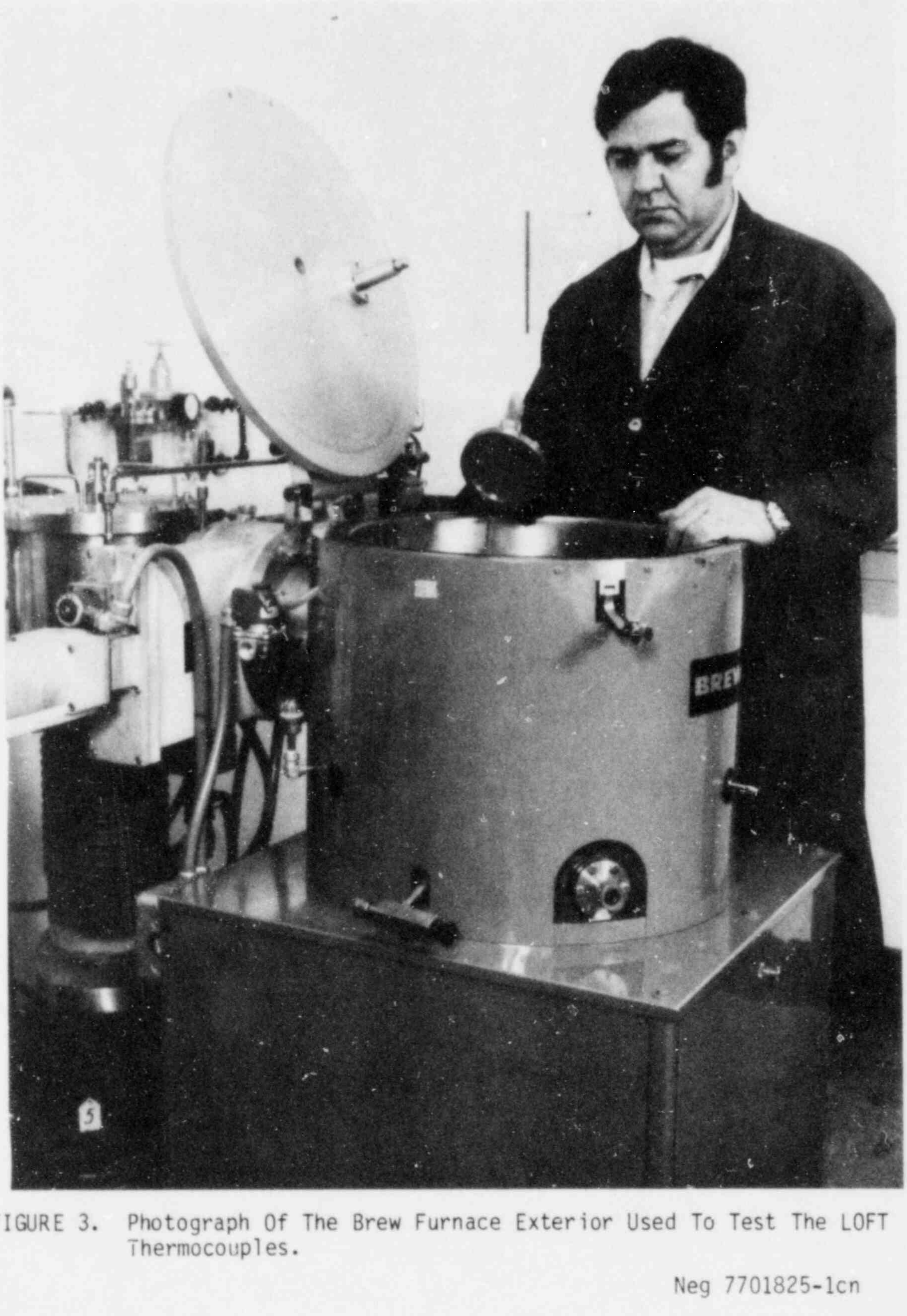

FIGURE 3. Photograph Of The Brew Furnace Exterior Used To Test The LOFT Thermocouples.

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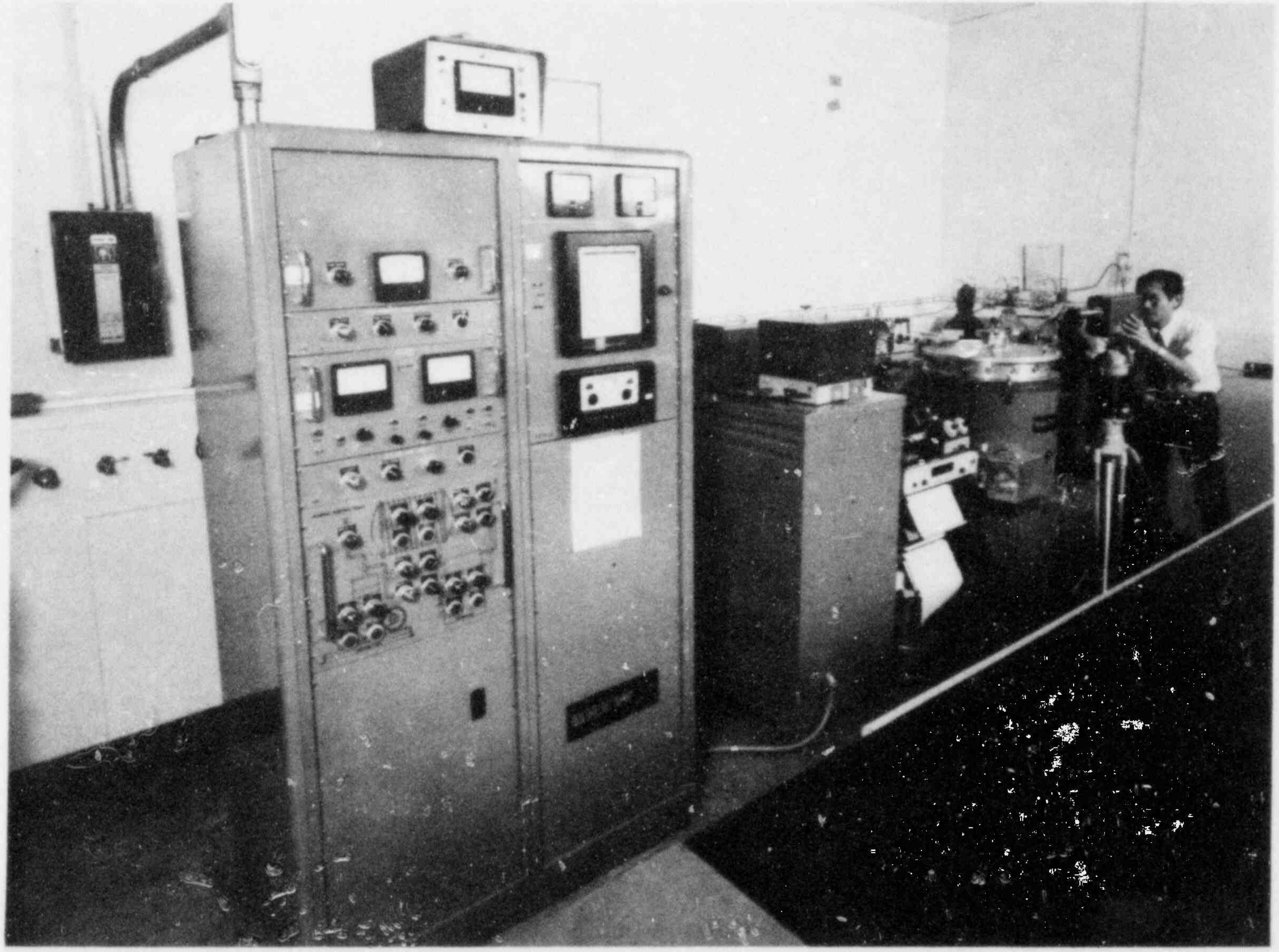

FIGURE 4. Photograph Of The Control Instrumentation For The High Temperature Brew Furnace.

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bare wire thermocouple during calibration runs gave excellent agreement to 2100°C with the emf output from the test thermocouple assemblies.

After installation in the Brew furnace, the test thermocouple temperature was gradually increased until the maximum test temperature was reached. The loop resistance, insulation resistance, and emf output was measured at 300°C intervals. The test thermocouple was then held at the maximum operating temperature for the 400 hour life test duration. As required by the test plan, data was recorded at 12 hour intervals at temperature; the test thermocouple output emf was recorded continuously by an automated data acquisition system.

Three thermal cycles to room temperature are required by the test plan during the 400 hour life test. Cool down cycle 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.

3.2.4 Transition Junction emf Error Tests

This test required the temperature at the transition junction to be varied while the measurement junction remained at a constant temperature. The test was conducted with the measurement junction at 1100°C and again at 1550°C. With the measurement junction at thermal equilibrium, the transition junction temperature was cycled between 100°C and 400°C at a maximum rate of 100°C an hour for three cycles. The maximum allowable deviation error on the output emf of the thermocouple cannot exceed 1.5% of the reading. For example, at 1100°C the maximum allowable error is the temperature equivalent of 6°C.

The test was conducted with the measurement junction of the test thermocouple inside the Brew furnace in the same test configuration used in the life test. The transition junction region was wrapped with copper foil to insure uniform temperature, and the copper foil was then wrapped with heater tape. The temperature of the transition junction was measured using sheathed Type K thermocouples placed inside of the copper foil. The measurement junction inside the Brew furnace was held at a constant 1550°C, and the transition junction was cycled between 100°C and 400°C as required. Concommitantly, the output emf of the test thermocouple was measured for changes that would represent errors due to transition junction heating effects. The test was then repeated with the measurement junction held at 1100°C.

3.2.5 Transient Temperature Tests

The thermocouple assemblies were subjected to three negative temperature transients each with a nominal rate of fall of 145°C/s. The thermocouple assembly must continue to perform to specification after the transient tests. The temperature transient included as a minimum the 400°C interval below the maximum operating temperature, i.e., 2200°C for model A assemblies and 1550°C for the model B assembly.

3.2.6 Thermocouple Time Response Tests

The time response of each thermocouple assembly must be measured. Time response was defined by the following formula:

$$t_t = \left[\frac{t_r^{\,2}}{1.1} - t_\beta^{\,2} \right]^{1/2}$$

where: t_r is the observed rise time on the test thermocouple.
t_β is the observed rise time (10% to 90%) of the bare wire thermocouple.
t_t is the calculated estimate of the test thermocouple rise time.

The temperature of the surrounding environment of the thermocouple junction must be measured by a low thermal inertia bare wire thermocouple. The measurement must be conducted over a minimum temperature interval of at least 40°C as near to the maximum operating temperature as possible. If it is not possible to conduct a time response measurement at the maximum operating temperature, measurement at three temperatures below this maximum temperature at 200°C intervals is an acceptable substitute. The time response of the thermocouple assembly is required to be less than or equal to one second.

Both the time response tests and the transient tests were performed inside of the Brew furnace. Figure 5 illustrates the test configuration: a bare wire thermocouple junction within approximately 1/8 inch of the test thermocouple measurement junction measures the temperature of the transient environment. Both the bare wire and test thermocouple outputs were continuously monitored and recorded on an automatic data acquisition system.

The temperature transient test is accomplished by flowing a cool argon gas stream around both the bare wire junction and the test thermocouple at a rate sufficient to cause the required transient rate of 145°C/s. Time response measurements were made at tempertures to 2000°C. After establishing temperature equilibrium, a stream of cool argon gas was allowed to flow around both the bare wire junction and the test thermocouple until both units came to a new equilibrium temperature approximately 40°C below the previous equilibrium. The stream of argon gas was stopped and both thermocouples experienced a steep increase of temperature back to the original equilibrium temperature. The recorded data established the response time according to the above formula.

3.2.7 Transition Junction Temperature and Pressure Transient Tests

At the conclusion of the above delineated temperature tests, the transition junction was removed from the test assembly by cutting the compensating lead cable and sheath. The transition junction was required to be thermal cycled between 100°C and 430° at a rate of 6°C/s (up and down) for a minimum

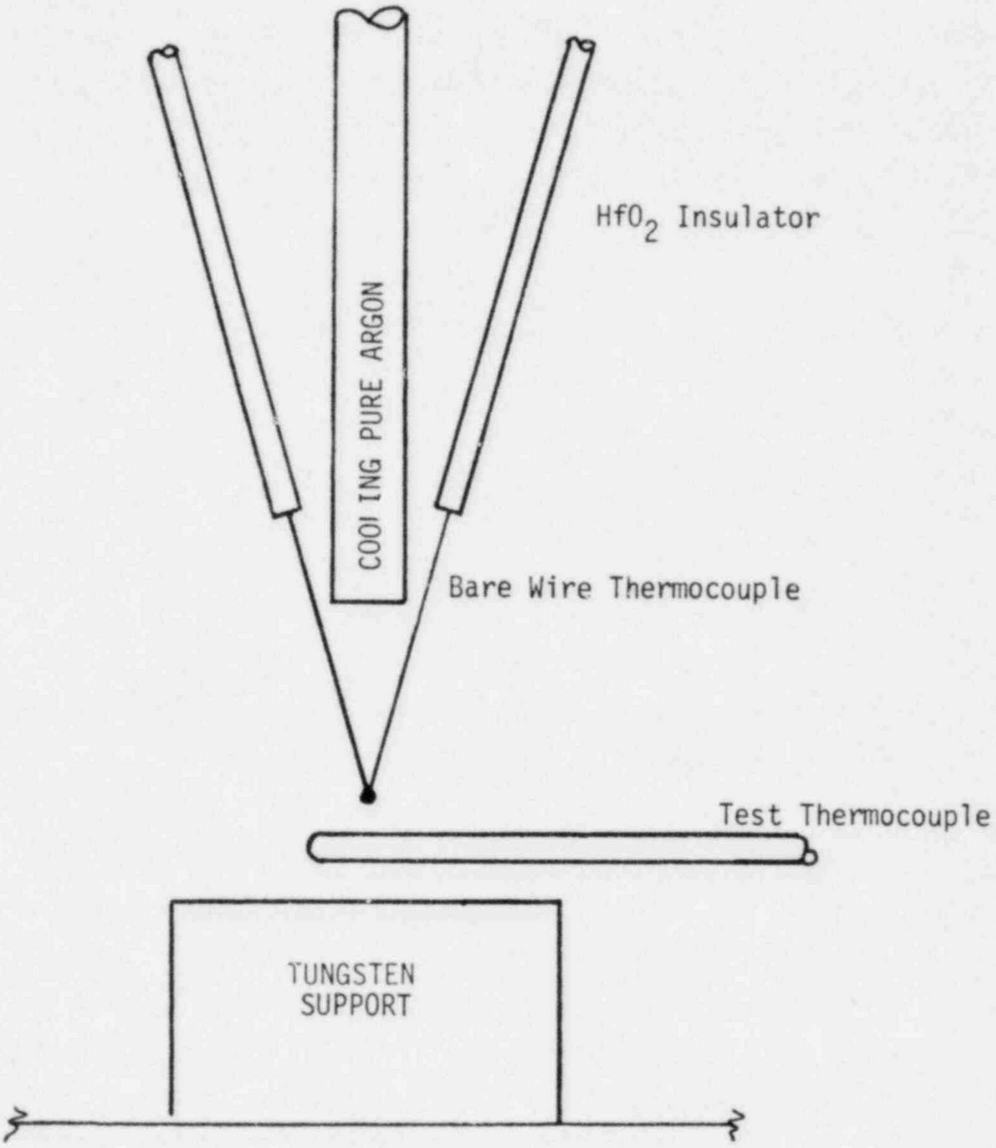

FIGURE 5. Sketch Of The Test Configuration Inside The Brew Furnace Used To Perform Time Response Measurements Tests.

of three cycles. The maximum allowable leak after this test must be less than 10^{-9} cc He/s. The transition junction must be internally pressurized on the probe sheath side of the junction at a continuous minimum pressure of 2500 psi during the above thermal cycles. The leak test is performed at ambient conditions. The transition junction is required to be subjected to three consecutive pressure transients $>$ 350 psi/s, while at 430°C continuous. No leak $>$ 10^{-9} cc He/s is allowable after the test.

The tests on the transition junction are performed inside the bell jar of a Balzar BA-510 Evaporator in a vacuum/argon environment. The transition junction, after being leak checked at ambient conditions, is mounted to a pressurizable gas line inside the vacuum chamber and internally pressurized to 2500 psi. An RF heater coil/furnace is placed around the transition junction region, and in a vacuum environment the transition junction is thermal cycled to 450°C at a rate of 6°C/s. The temperature during the test is monitored by two sheathed thermocouples wrapped in a copper foil around the outside of the transition junction. The cooling transient is accomplished by flowing cool argon gas over the transition junction. The output of the sheath thermocouples is continuously monitored and recorded on the strip chart recorder.

The pressure transient test is performed by holding the temperature at 450°C continuous and changing the internal pressure at a minimum rate of 350 psi/s. A pressure gauge on the gas line monitors the pressure change; a stop watch measures the time. More automated equipment was available, but was not considered necessary for the purpose of the test.

3.2.8 Transition Junction Vibration Tests

The transition junction must be vibrated to the LOFT requirement of 2G axial load at 40 to 50 Hz for 100 milliseconds minimum while at 450°C. This test is repeated for a total of five cycles. The transition junction must then be vibrated with a .5G axial load at 40-50 Hz for at least 40 seconds minimum, again for a total of five cycles. The transition assembly shall then be monitored for leaks when the exterior of the transition assembly is pressurized at 2500 psi. No leak greater than 10^{-9} cc He/s is acceptable.

3.2.9 Transition Junction and Thermocouple Junction Metallographic Examination

The transition junction from a minimum of one model B assembly and one model A assembly must be mounted in plastic compound polished in such a manner to allow examination of all pertinent details of construction. In particular, the closure welds and brazes shall be suitable for examination. Radiographs of the measurement junction region at 0^0 and 90^0 must be taken and compared with radiographs prior to testing. The radiographs shall be examined and the results recorded in the test logbook. The thermoelement wires and insulators must then be removed from the probe, and the insulators, thermoelement wire, thermoelement junctions carefully examined for signs of corrosion, embrittlement, contamination or other evidence of deterioration. Careful note shall be taken of dimensional changes in the insulators and thermoelement wires. The thermoelement junction must be subjected to metallographic examination by mounting the cross section of the weld and wire twist region. At the option of the cognizant engineer, purity analyses may be conducted on any or all of these materials.

4.0 TEST RESULTS AND DISCUSSIONS

Test data on qualification thermocouple assemblies is summarized in the following sections. Initial units satisfied all test requirements except for hermeticity requirements on the initial transition junctions and response time. A response time of two to five seconds was estimated at 2200°C compared to one second required. New transition junction units were fabricated that passed all qualification test requirements.

4.1 RECEIVING EXAMINATION

Figures 6 through 11 are photographs of the qualification thermocouple assembies: two model A, and one model B. They are designated respectively CQT-1 (model A), CQT-2 (model A), and CQT-3 (model B). Unit CQT-1 contains a prototypic probe terminated with a ceramic-to-metal seal; however, the remainder of the transition junction and compensating lead cable were omitted from this unit in order to expedite qualification testing. The transition assembly and the compensating lead cable were considered within the state of the art and their deletion from this unit was not considered within the state of the art and their deletion from this unit was not considered significant to qualification tests since units CQT-2 and CQT-3 are prototypic in all aspects, including the compensating lead cable and complete transition junctions. Tests on these two units were considered adequate to qualify the transition junction and compensating lead cable.

The required x-rays were taken on all three qualification units. Table I gives the summary of the measurements taken from the x-rays. All measurements are within specification requirements, except for the allowable spacing of loops in the thermoelement wires inside the sheath; measurements E, F, and G. The effect of reduced loop spacing has been evaluated and is of no consequence to the performance of the thermocouple. The cause of the increased looping results in production when the thermoelement wire/ insulator string is loaded into the sheath. There appears to be no cost effective

FIGURE 6. Photograph of Thermocouple CQT-1.

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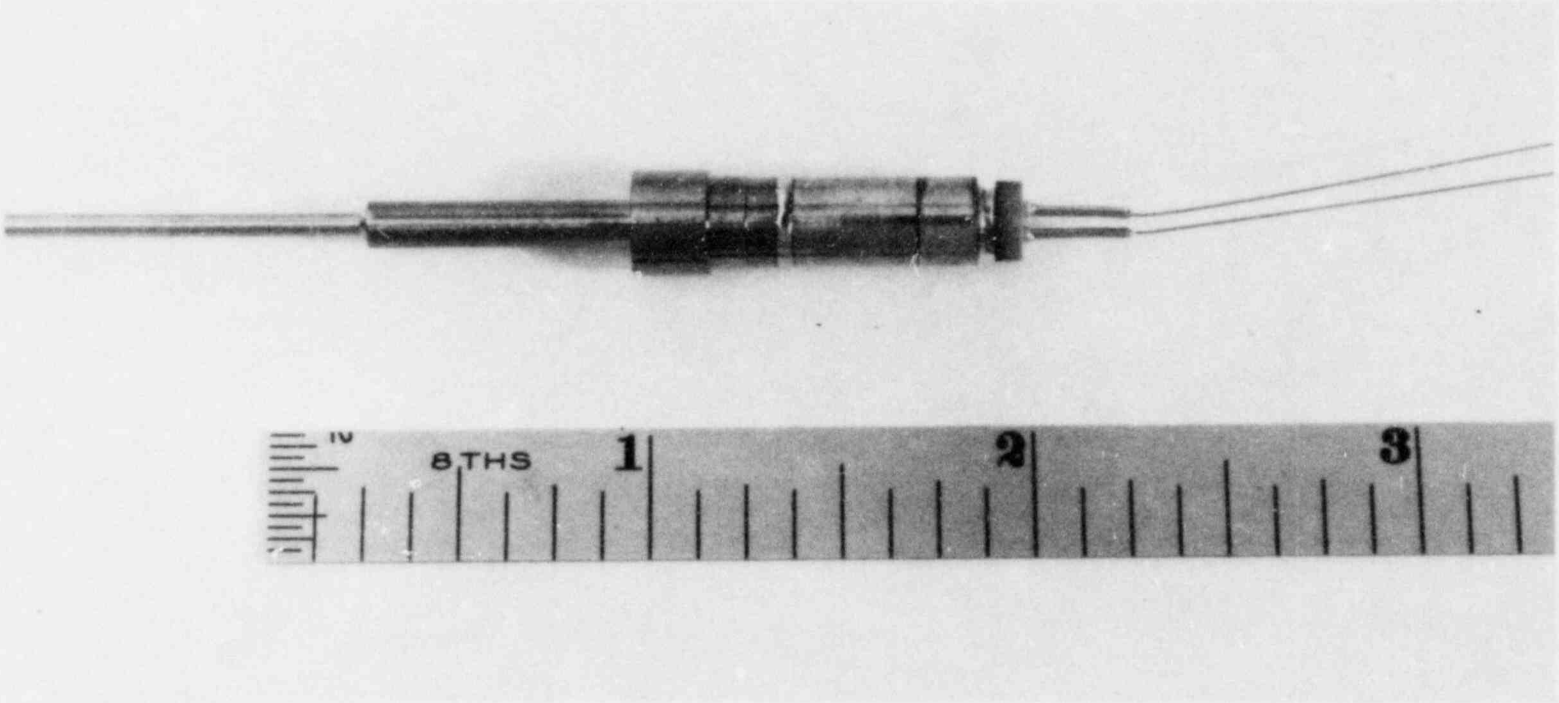

FIGURE 7. Photograph of Thermocouple CQT-1.

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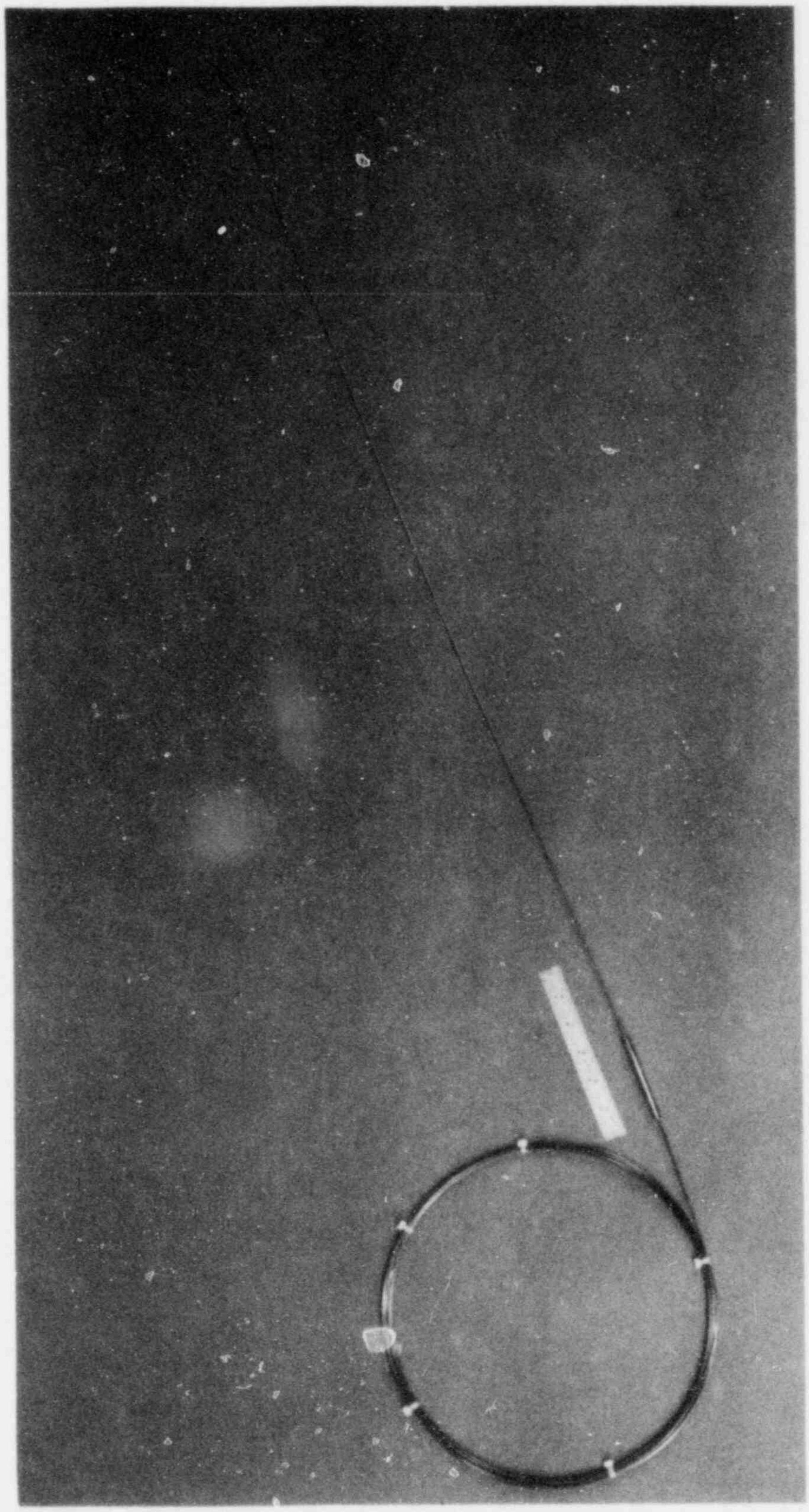

FIGURE 8. Photograph of Tnermocouple CQT-2.

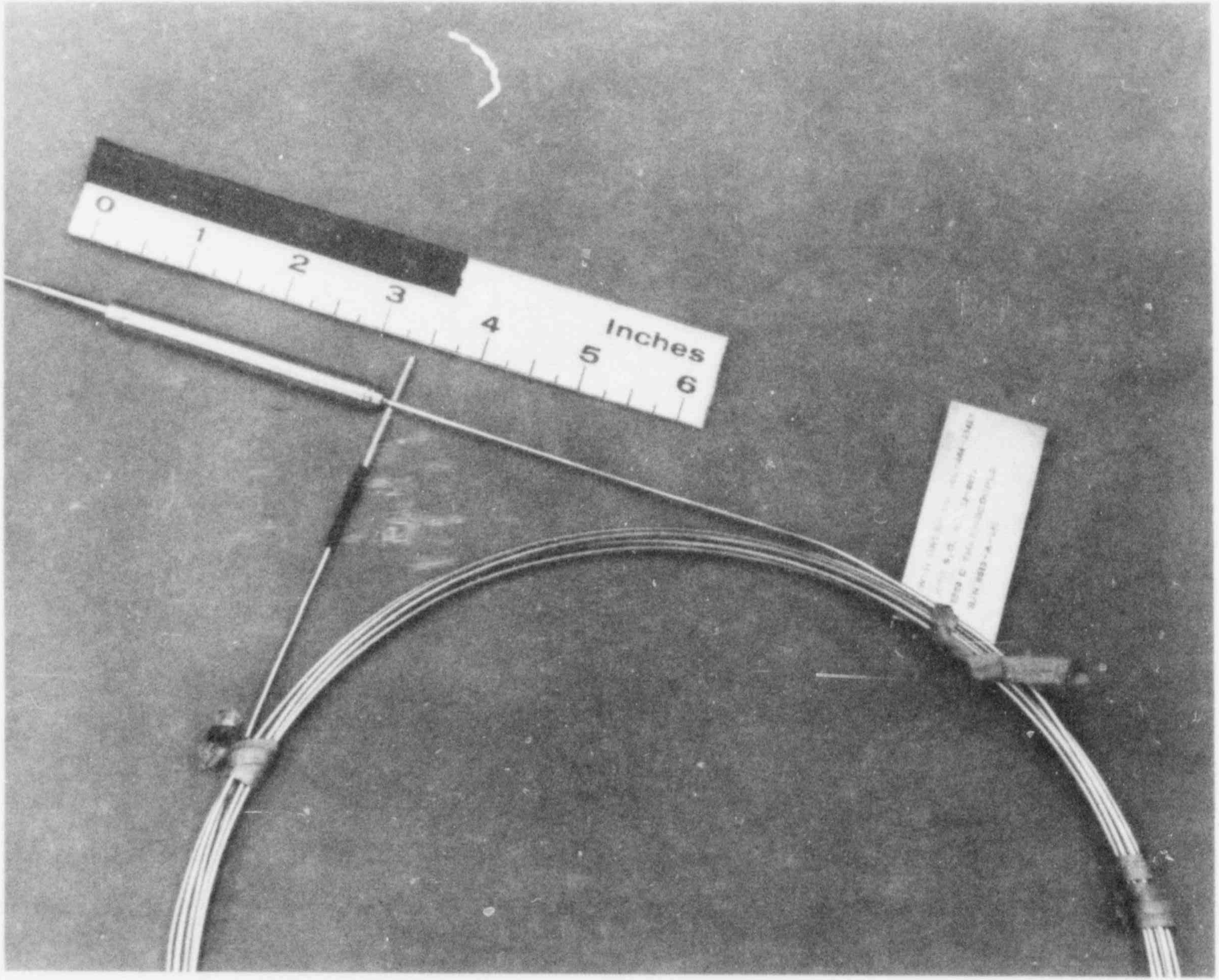

FIGURE 9. Photograph of Thermocouple CQT-2.

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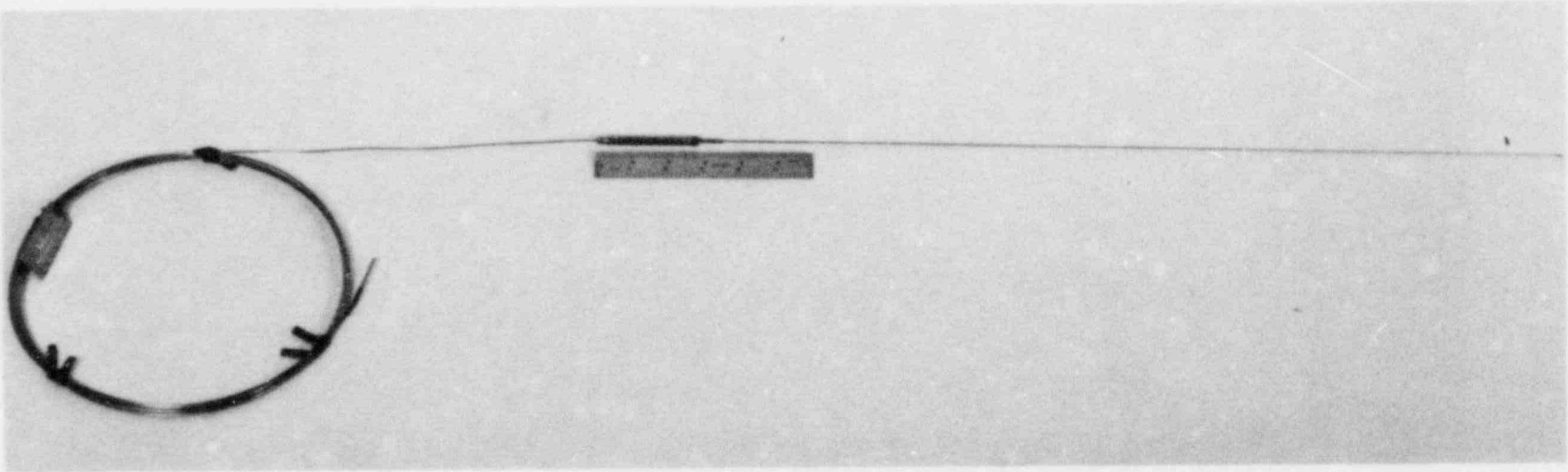

FIGURE 10. Photograph of Thermocouple CQT-3.

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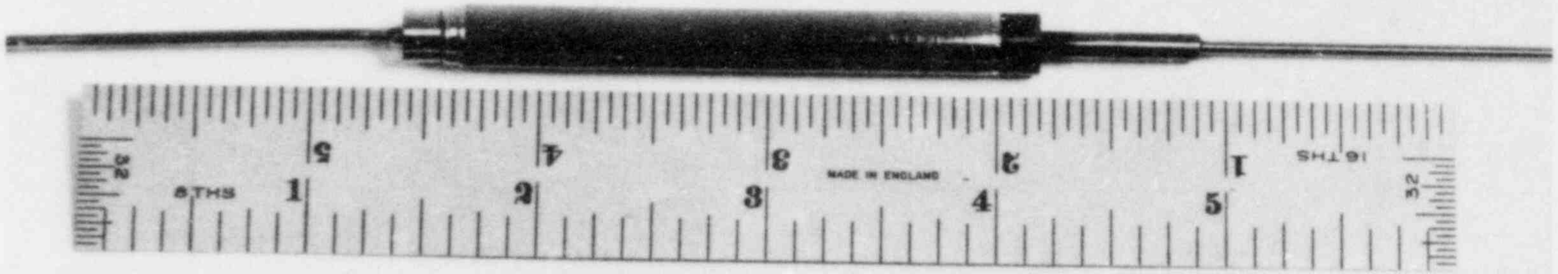


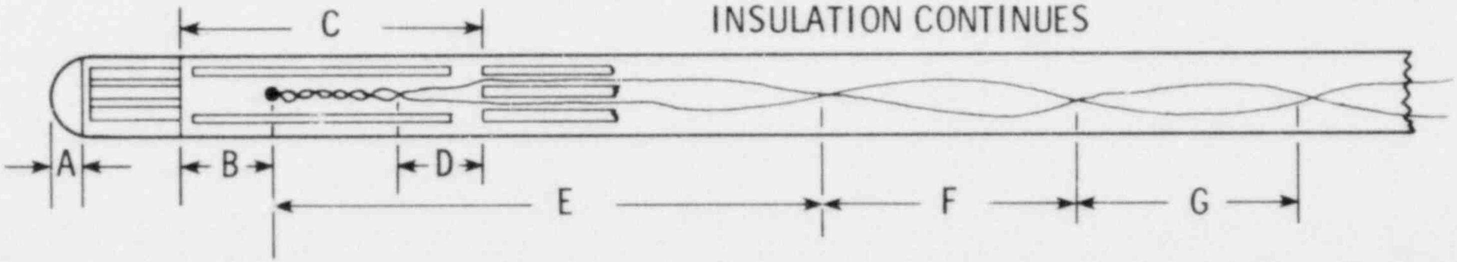
FIGURE 11. Photograph of Thermocouple CQT-3.

Neg 7905263-2cn

TABLE I

RADIOGRAPHIC MEASUREMENTS OF THERMOCOUPLE MEASUREMENT JUNCTION

THERMOCOUPLE	A (IN.)	B (IN.)	C (IN.)	D (IN.)	E (IN.)	F (IN.)	G (IN.)
MODEL A CQT-1	.05	.215	.605	.255	2.5	4.5	4.0
MODEL A CQT-2	.06	.22	.66	.175	.99	4.0	6.35
MODEL B CQT-3	.0375	.09	.61	.27	2.813	6-3/8	76



Sketch illustrating measurements taken from radiographs

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way of reducing the amount of rotation incurred while the unit is being assembled. Dimensions B and D, space provided for thermal expansion of the transition junction, are considered critical. It is noteworthy that these dimensions were within the requirement specifications. Good quality in the transition junction weld and wire twist areas appears to have been achieved by the production vendor.

Table II gives the external dimensions and ambient electrical measurements of each test article. The sheath and compensating cable lengths are not within the specification on some units. The changes were approved prior to fabrication by the vendor in the interest of cost effectiveness (this allowed the use of components too short for production) and do not impact the validity of the qualification tests.

4.2 LIFE TEST RESULTS

All three thermocouple assemblies survived 400 hour life tests at the maximum operating temperature with less than 2% decalibration over the duration of the test. Figures 12 and 13 plot the output emf of the two model A thermocouples at 2200°C during 400 hours of testing. Figure 14 plots the output emf of the model B thermocouple at 1550°C during 400 hours of testing. Note that after thermal cycling to room temperature, the thermocouple output emf returns to within 1/2% of its value at the maximum operating temperature prior to the cvcle.

Figure 15 plots the value of insulation resistance as a function of temperature for the three thermocouples. The good agreement on all three units suggests that the vendor achieved good consistency in bakeout and handling procedures. The three thermocouples were fabricated in three different lots. Figure 16 compares the value of insulation resistance versus temperature for a model A thermocouple before and after 325 hours of testing at 2200°C. Except for a small decrease at 2200°C, there is little noticeable change in the curves. Figures 17 and 18 plot insulation resistance for the two model A thermocouples as a function of time at 2200°C over the first 100

TABLE II

ELECTRICAL AND DIMENSIONAL MEASUREMENTS ON QUALIFICATION THERMOCOUPLES

THERMOCOUPLE	SHEATH PROBE LENGTH (in.)	COMPENSATING LEAD CABLE LENGTH (ft.)	PROBE O.D. (in.)	LOOP RESISTANCE (OHM)	LOOP/SHEATH RESISTANCE (OHM)
CQT-1 (Model A)	38.16	N/A	.063	10.6	$>10^{12}$
CQT-2 (Model A)	41.06	19	.063	93.9	1.96×10^{9}
CQT-3 (Model B)	22.16	17.5	.062	90.0	4.5×10^{10}

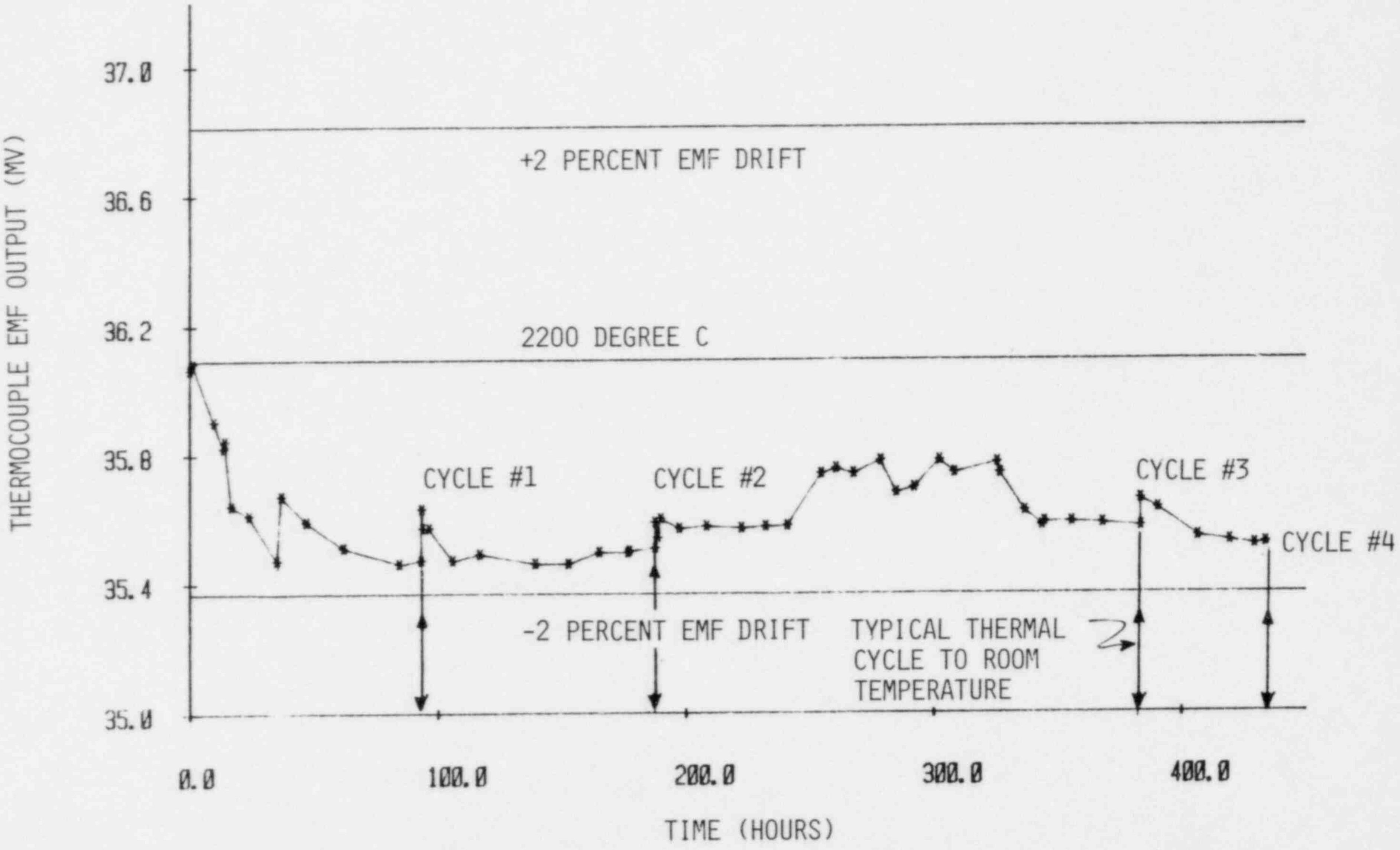

FIGURE 12. EMF Drift Test For Qualification Thermocouple No. 1 At Constant 2200°C.

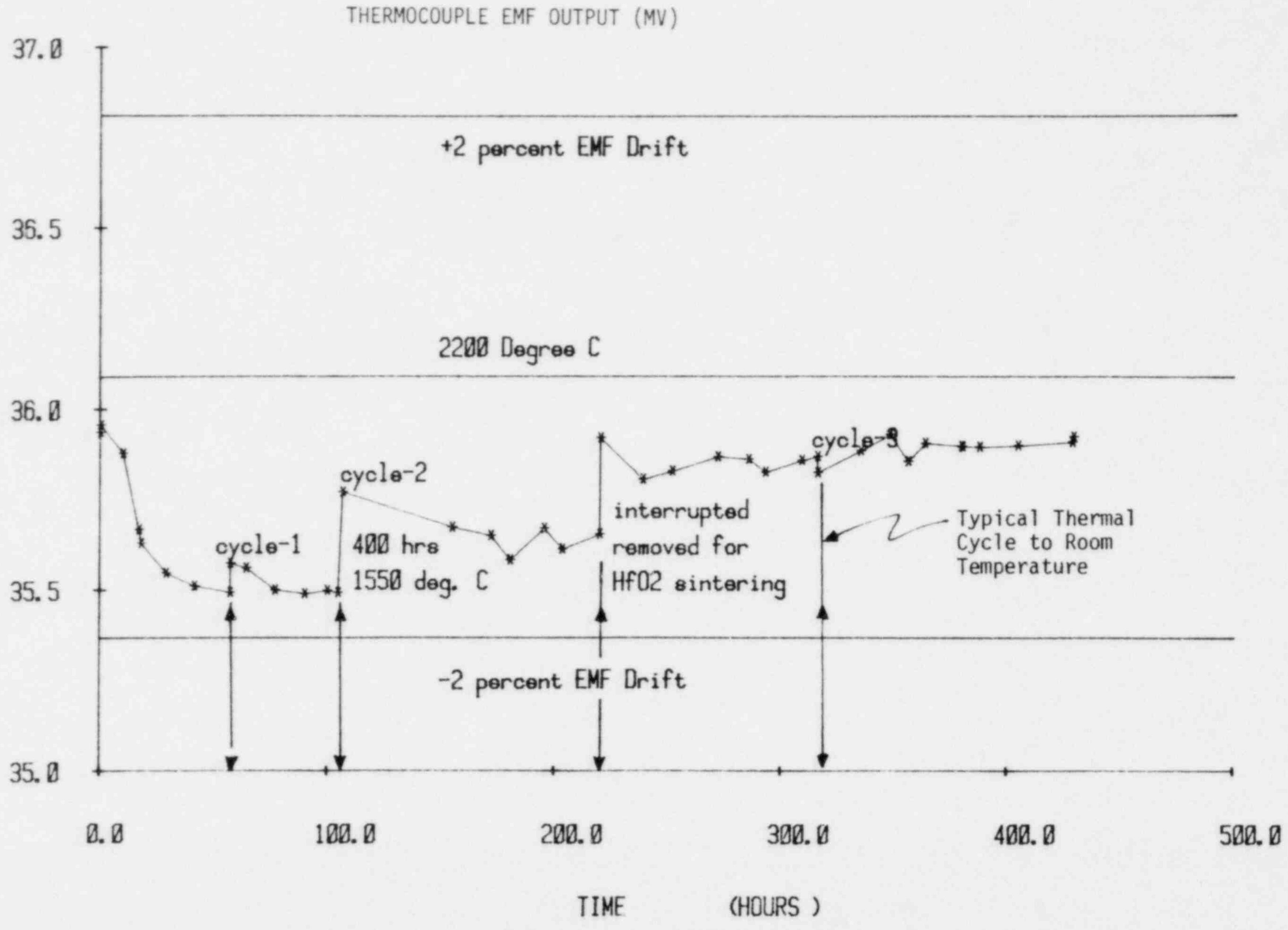

FIGURE 13. EMF Drift Test For Qualification Thermocouple No. 2 At Constant 2200 C.

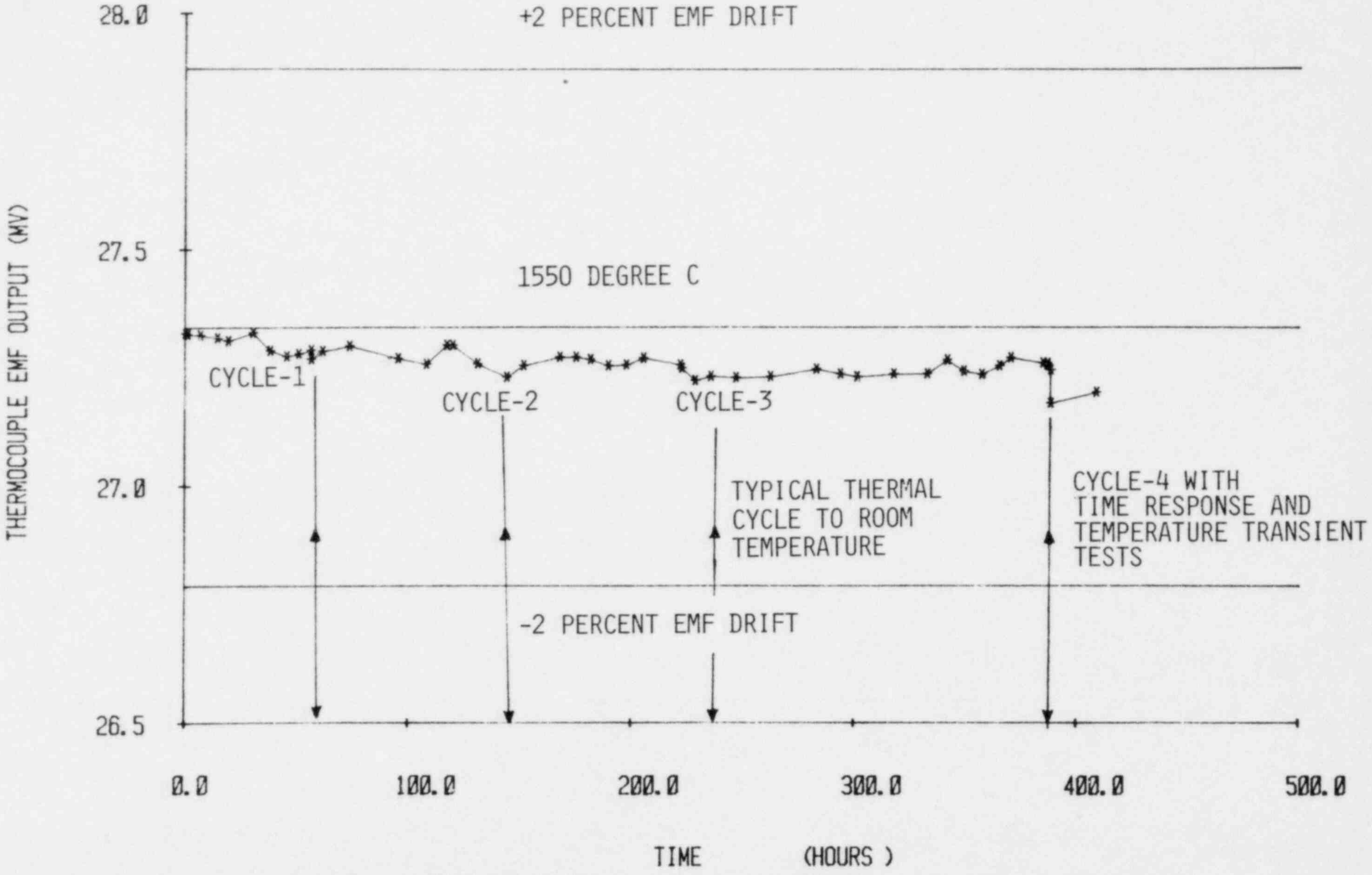

FIGURE 14. EMF Drift Test For Qualification Thermocouple No. 3 At Constant 1550°C.

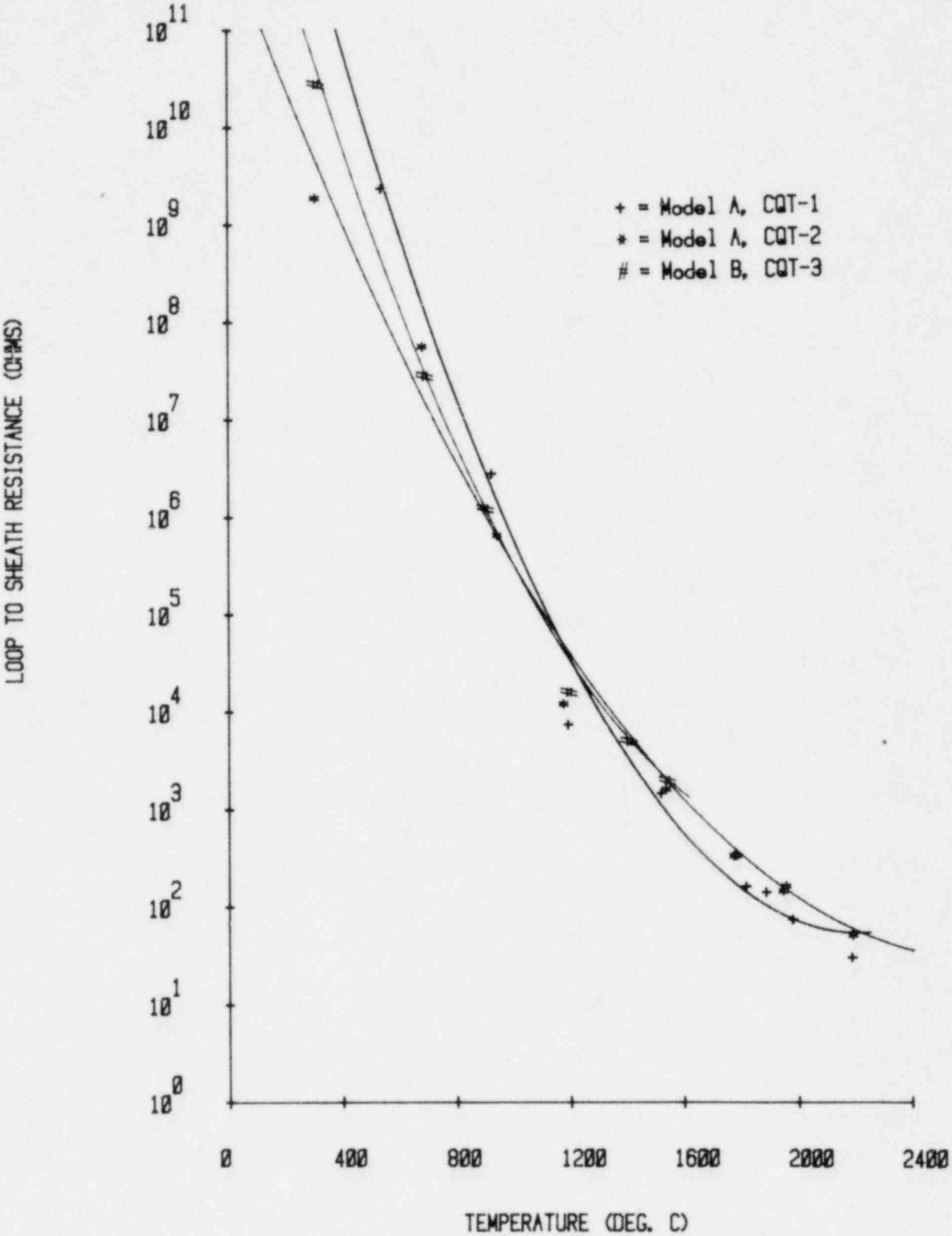

FIGURE 15. Plot Of Insulation Resistance Versus Temperature For The LOFT Qualification Thermocouples.

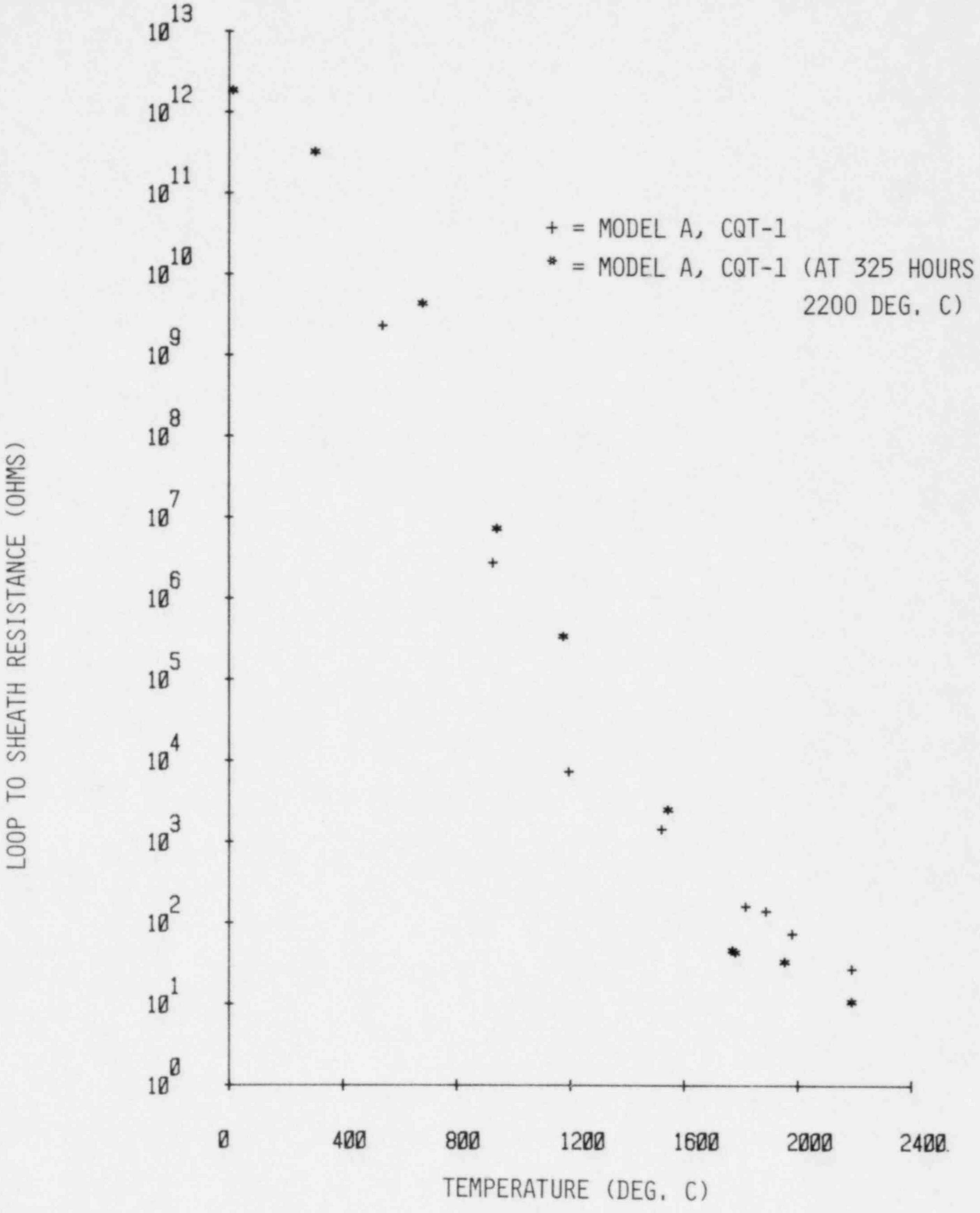

FIGURE 16. Plot Of Insulation Resistance Versus Temperature Prior To And After 325 Hours Of Testing At 2200°C.

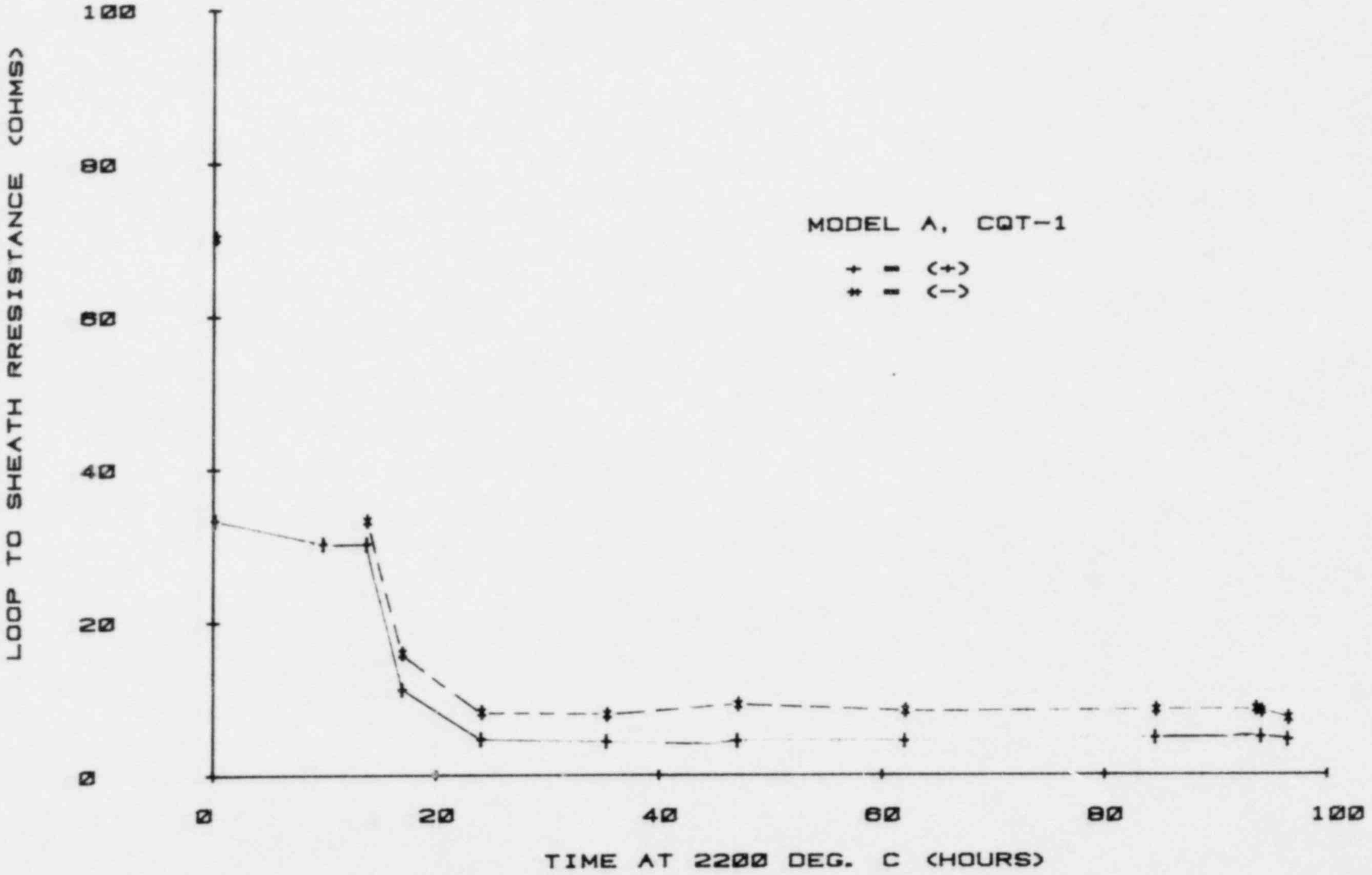

FIGURE 17. Plot of Insulation Resistance vs Time at 2200°C for Qualification Thermocouple No. 1.

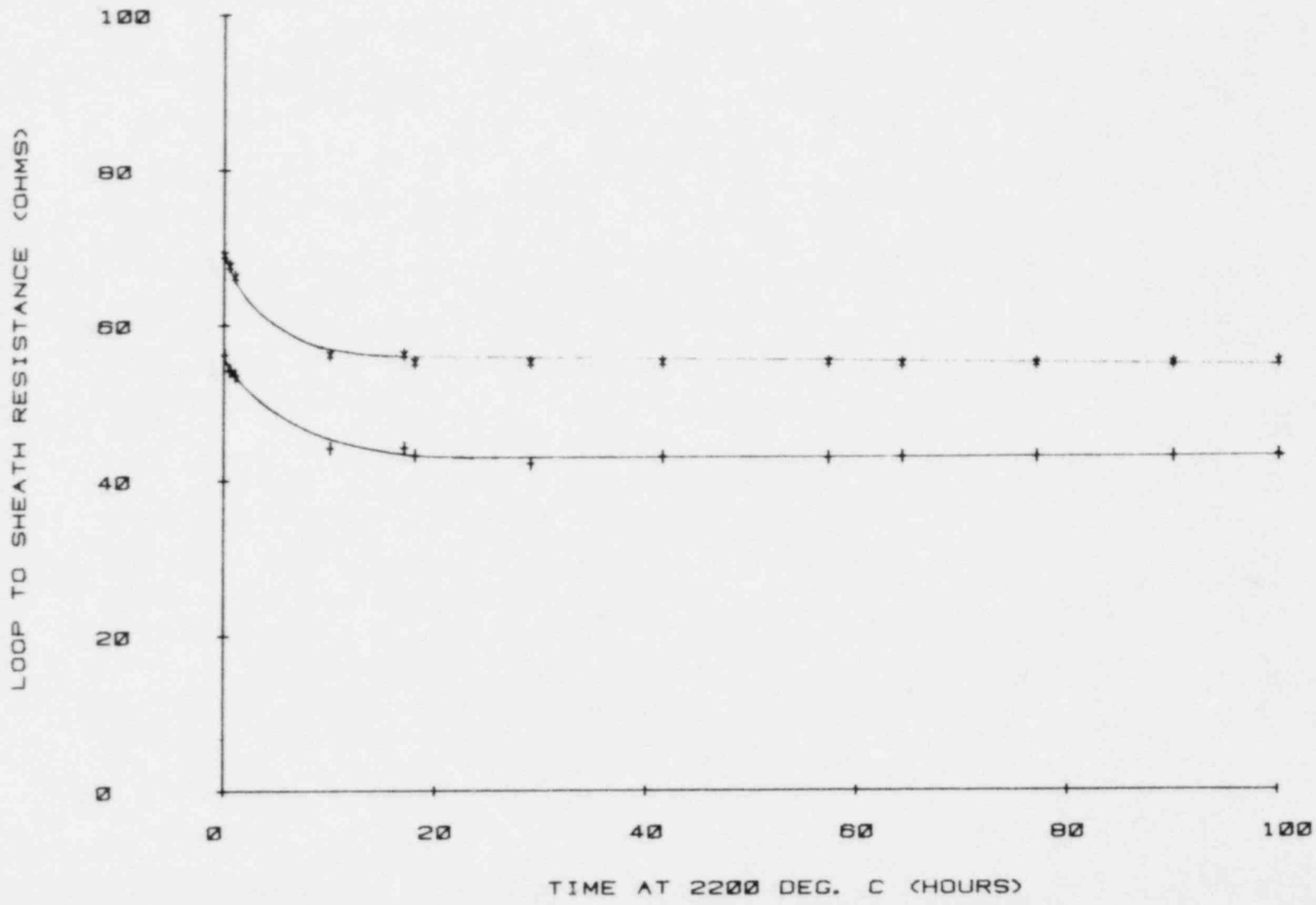

FIGURE 18. Plot of Insulation Resistance vs Time at 2200°C for Qualification Thermocouple No 2. (Plotted for Each Lead Wire)

hours of testing. The decrease in insulation resistance occurs at the start of the 2200°C test period as evidenced by the graphs, and then remains constant throughout the duration of the test period. Note that the value of insulation resistance is plotted as measured from each thermal element lead wire and that some asymetry exists. The apparently high values for insulation resistance given for model CQT-2 are due to the resistance of the lead wire and compensating lead cable. As previously discussed, model CQT-1 did not have compensating lead cable attached to the sheath probe.

Figure 19 plots insulation resistance for the model B thermocouples as a function of time at 1550°C for the first 100 hours of testing. The increase in insulation resistance as a function of time on the model A unit is not unusual for mineral insulated components of this type in high temperature environments. A possible cause is that contaminents are migrating from the high temperature end of the thermocouple into cooler regions, where their effect on insulation resistance is not as pronounced.

Figure 20 plots the value of loop resistance, that is, 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 necking down. However, the increase is slight and is within acceptable limits. Figure 21 plots the loop resistance of the second model A thermocouple and the model B thermocouple as a function of temperature. Again, their increased values are due to the longer lengths of thermoelement wire in the compensating lead cable. It is important to note in the above figures that the increases in loop wire resistance and insulation resistance are due only to changes in temperature on the last four inches of the sheath probe. Table 3 compares the value of loop resistance and insulation resistance on the three thermocouples before and after temperature testing.

The lift test data on all three thermocouple units satisfies all test requirements. However, the low insulation resistance at 2200°C is considered less than optimum and will be discussed later in this report.

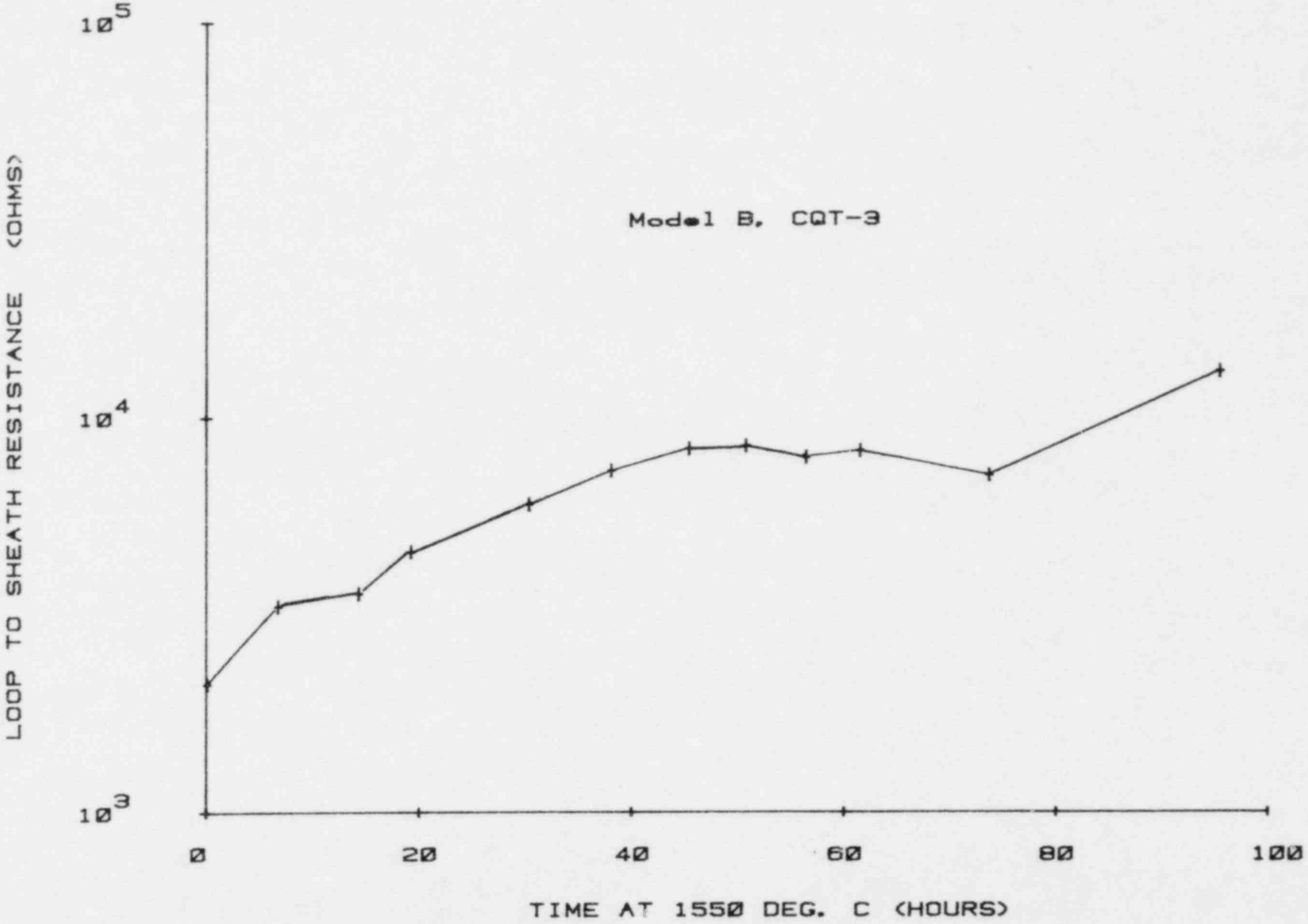

FIGURE 19. Plot of Insulation Resistance vs Time at 1550°C for Qualification Thermocouple No. 3.

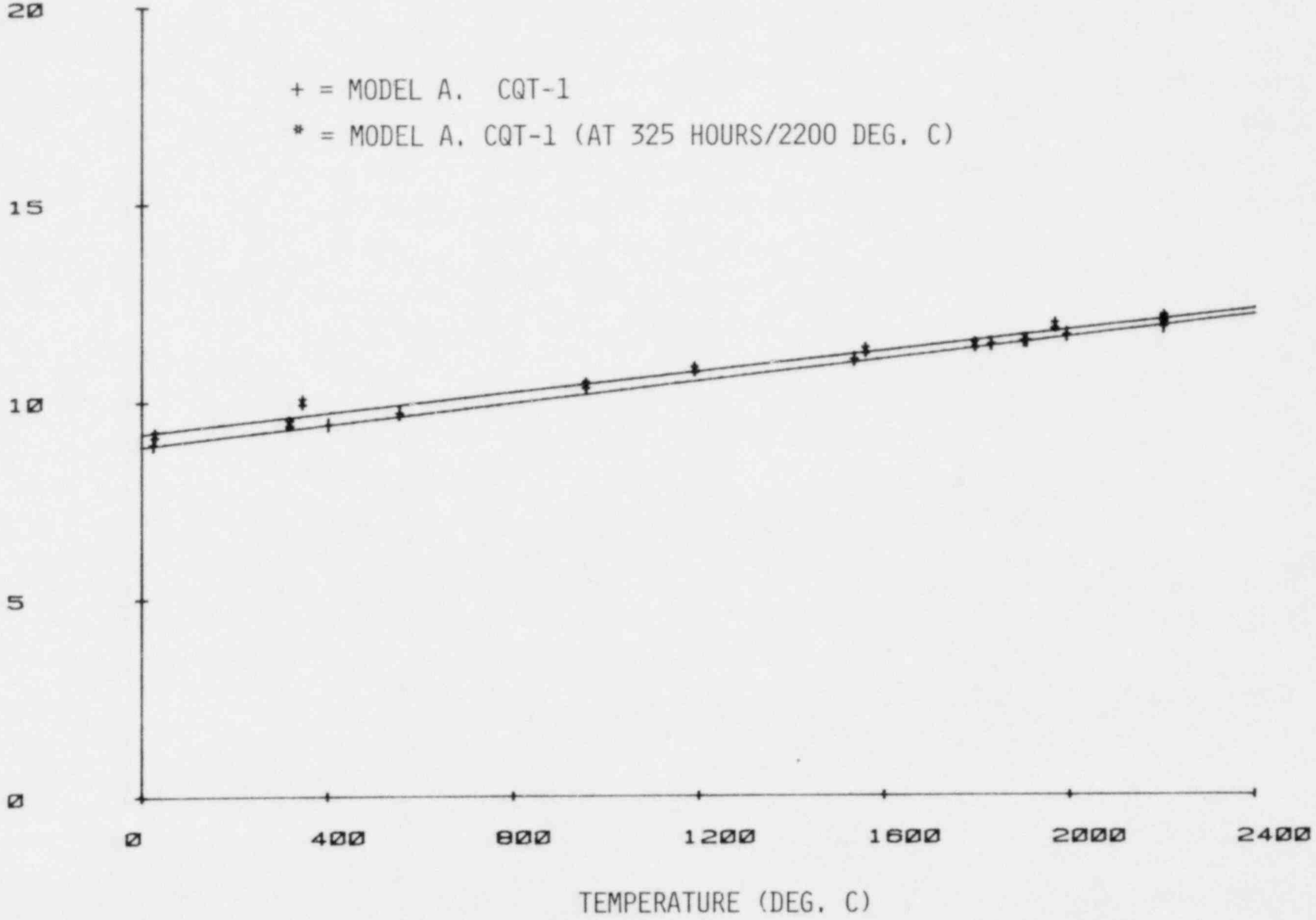

FIGURE 20. Plot Of Thermocouple Lead Resistance Versus Temperature Prior To And After 325 Hours At 2200°C.

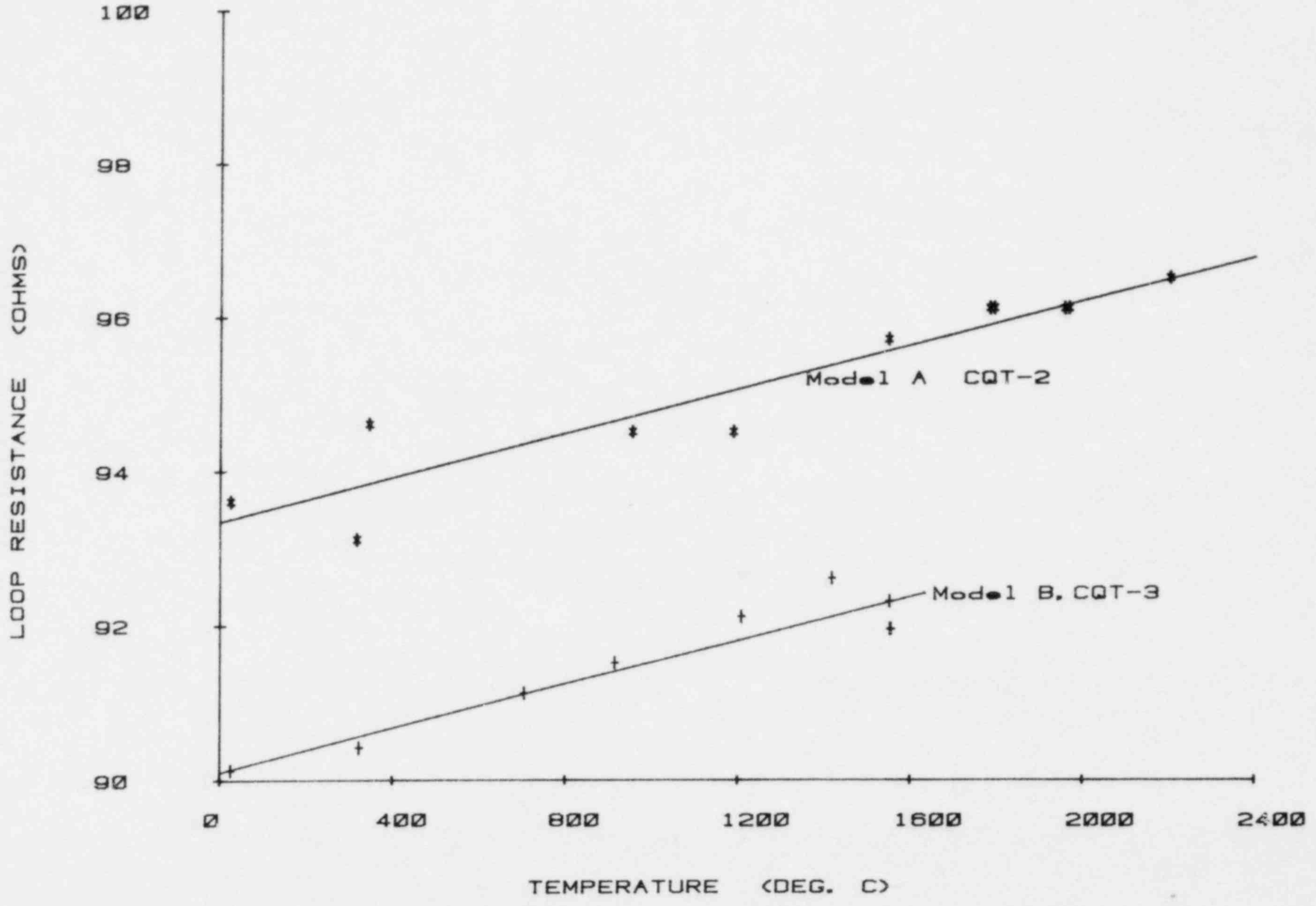

FIGURE 21. Plot of Thermocouple Lead Resistance vs Temperature for a Model A and a Model B Assembly.

TABLE III

LOOP TO SHEATH AND LOOP RESISTANCES AT AMBIENT TEMPERATURE AFTER 400 HOURS LIFE TEST AT MAXIMUM TEMPERATURE

THERMOCOUPLE	LOOP RESISTANCE (Ω)		LOOP TO SHEATH RESISTANCE (Ω)	
	BEFORE TEST	AFTER TEST	BEFORE TEST	AFTER TEST
Model A CQT-1	8.87	9.12	>20 MΩ at Room Temperature $2.5 \times 10^{9}\Omega$ @ 552°C	$2 \times 10^{12}\Omega$ at room Temperature $4.75 \times 10^{9}\Omega$ @ 693°C
Model A CQT-2	93.59	93.90	$2 \times 10^{9}\ \Omega$	$4.5 \times 10^{10}\ \Omega$
Model B CQT-3	90.02	89.65	$3 \times 10^{10}\ \Omega$	$6.5 \times 10^{10}\ \Omega$

4.3 TRANSITION JUNCTION EMF ERROR TEST RESULTS

Figures 22 and 23 plot the output emf of the test thermocouples as a function of transition junction temperature with the measurement junction held at the constant temperature indicated on the graph. As evidenced by the figures, this error remained within the specification requirement, ±1%. This error could be limited to ±1% only when precautions were taken to insure that the temperature of the transition junction was kept uniform, i.e., sizeable temperature gradients were not allowed to exist across the transition junction during the test. Non-uniform heating of the transition junction resulted in a larger error, as would be expected.

4.4 TRANSIENT TEMPERATURE TEST RESULTS

Figures 24 and 25 are typical plots of temperature versus time during transient tests of the model A and model B thermocouple assemblies. The emf output of the test article was used to monitor the temperature during the test. All thermocouples continued to perform to test requirements after the transients.

4.5 TIME RESPONSE TEST RESULTS

Figures 26 and 27 plot temperature versus time for thermocouple CQT-1 (model A) and CQT-3 (model B) during time response measurement tests. Table IV gives the time response of the two thermocouples as a function of temperature. Data was not obtained on CQT-2 (model A). This unit developed an open circuit during reloading into the furnace to perform the test. This type of failure is not uncommon when handling thermocouple assemblies that have been tested for long times at 2200°C; both the thermoelement wires and the sheath become somewhat embrittled after prolonged high temperature testing.

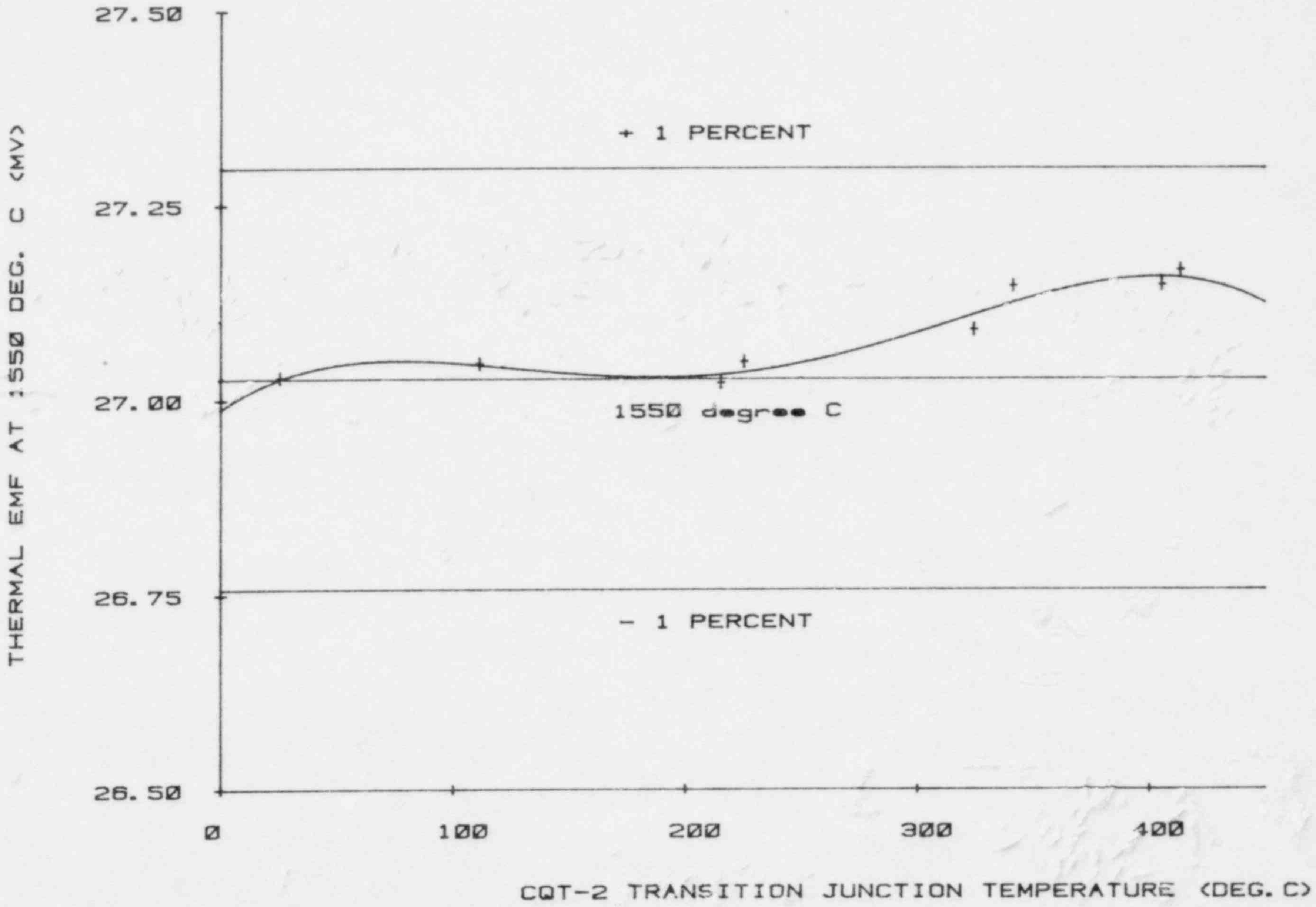

FIGURE 22. Output emf of Test Thermocouple No. 2 vs Temperature of the Transition Junction.

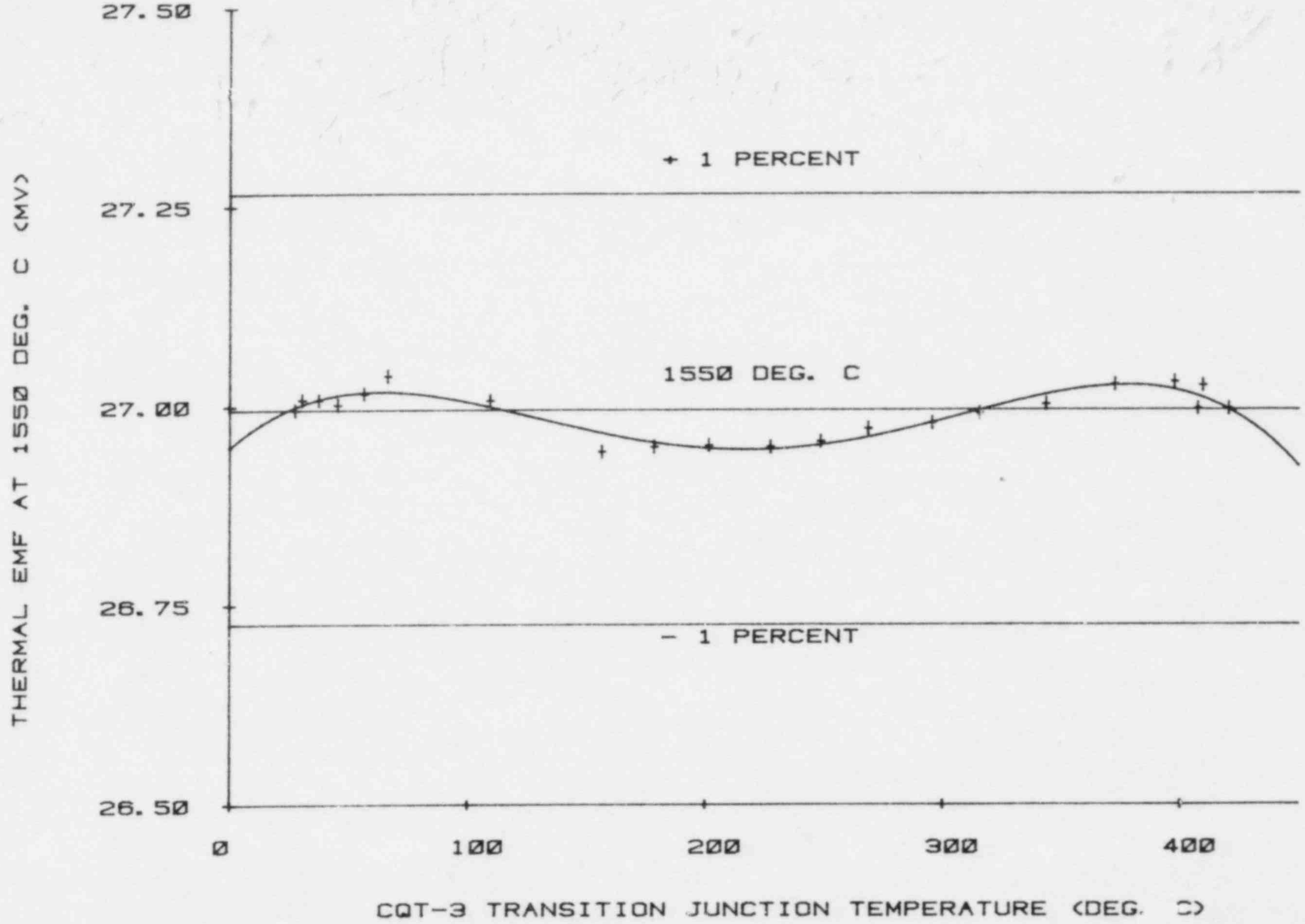

FIGURE 23. Output emf of Test Thermocouple No.3 vs. Temperature of the Transition Junction.

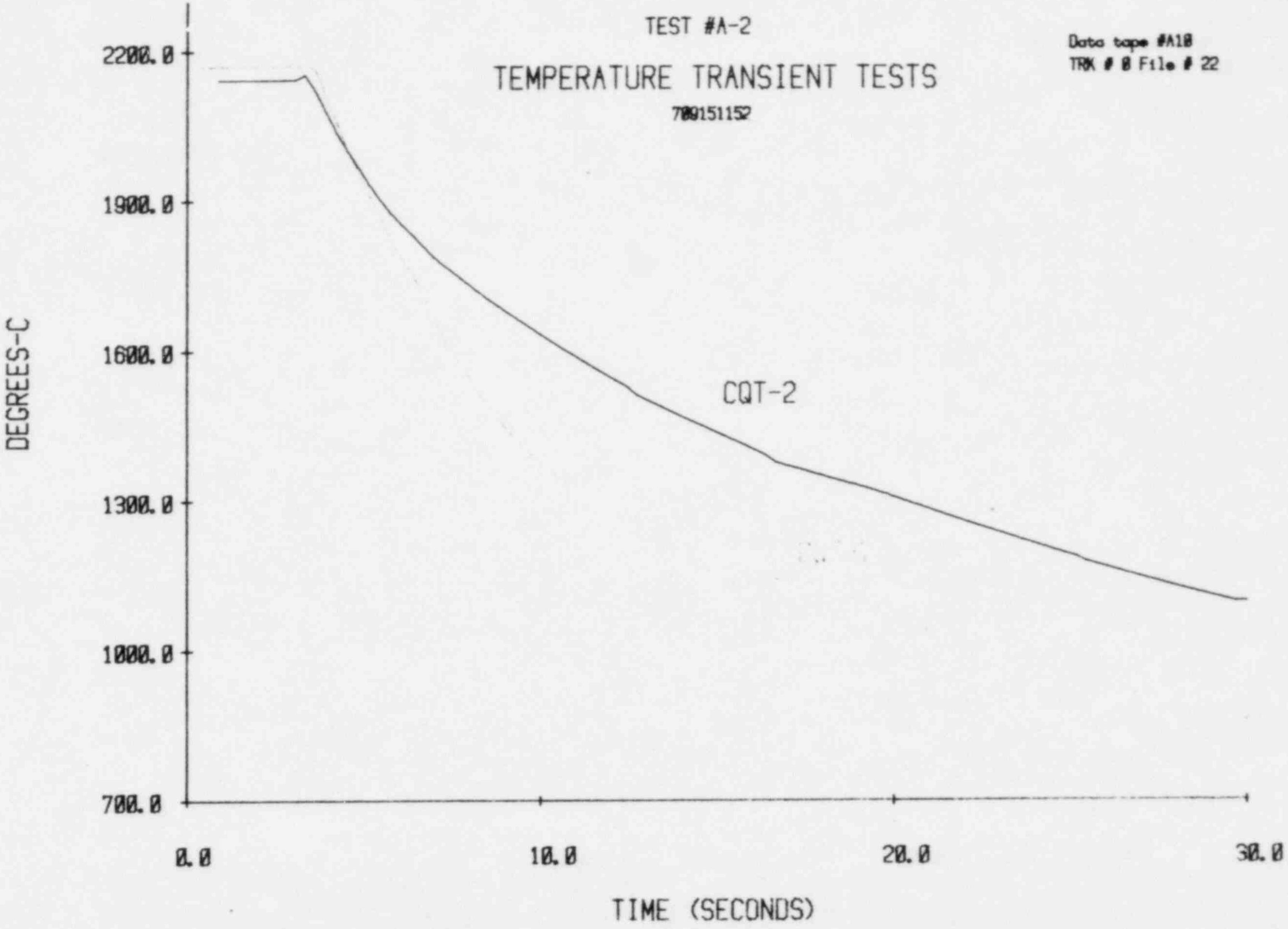

FIGURE 24. Plot of Temperature vs Time During Temperature Transient Tests on Test Thermocouples 1 and 2.

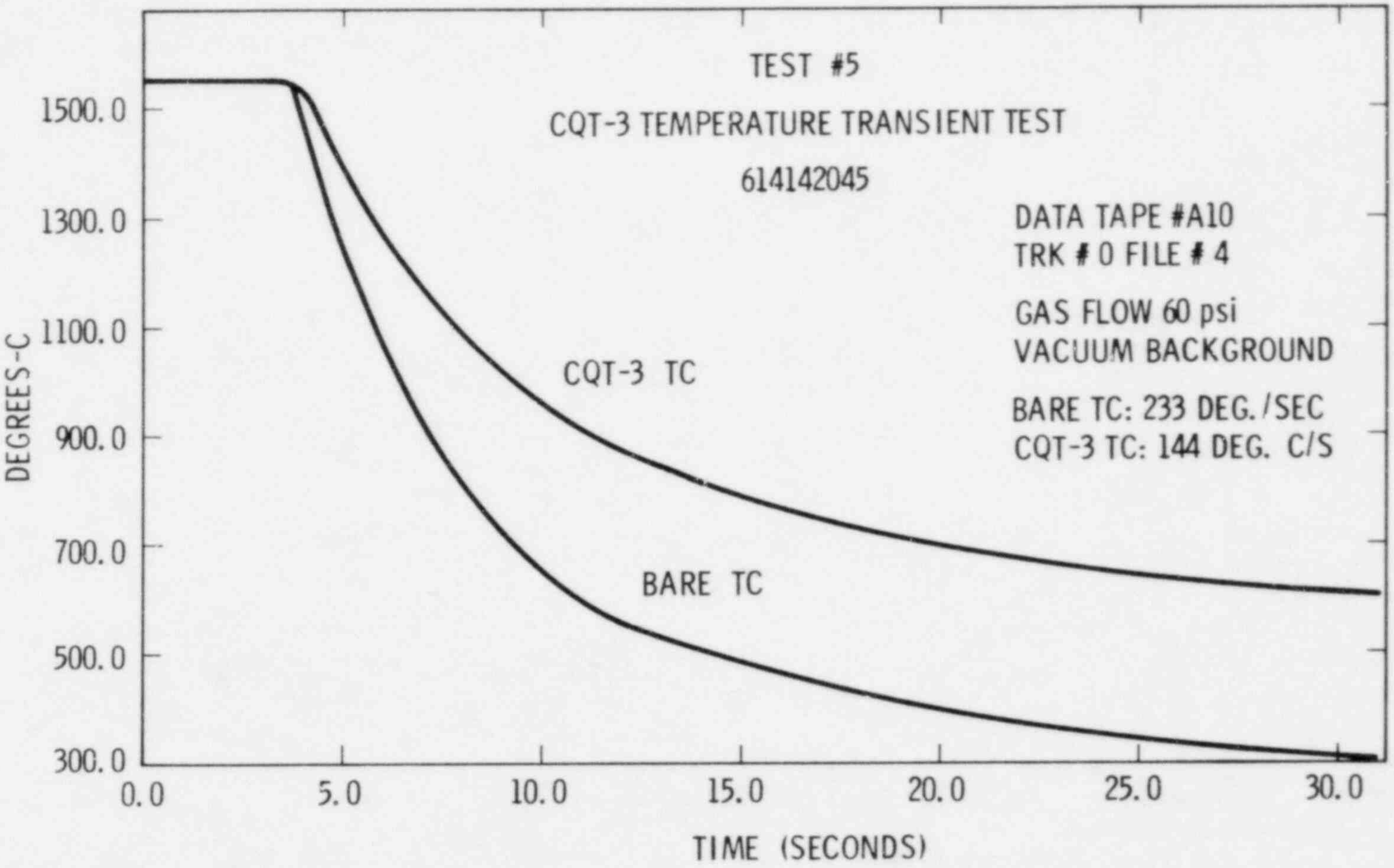

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FIGURE 25. Plot of Temperature vrs. Time During Temperature Transient Tests on Test Thermocouple No. 3.

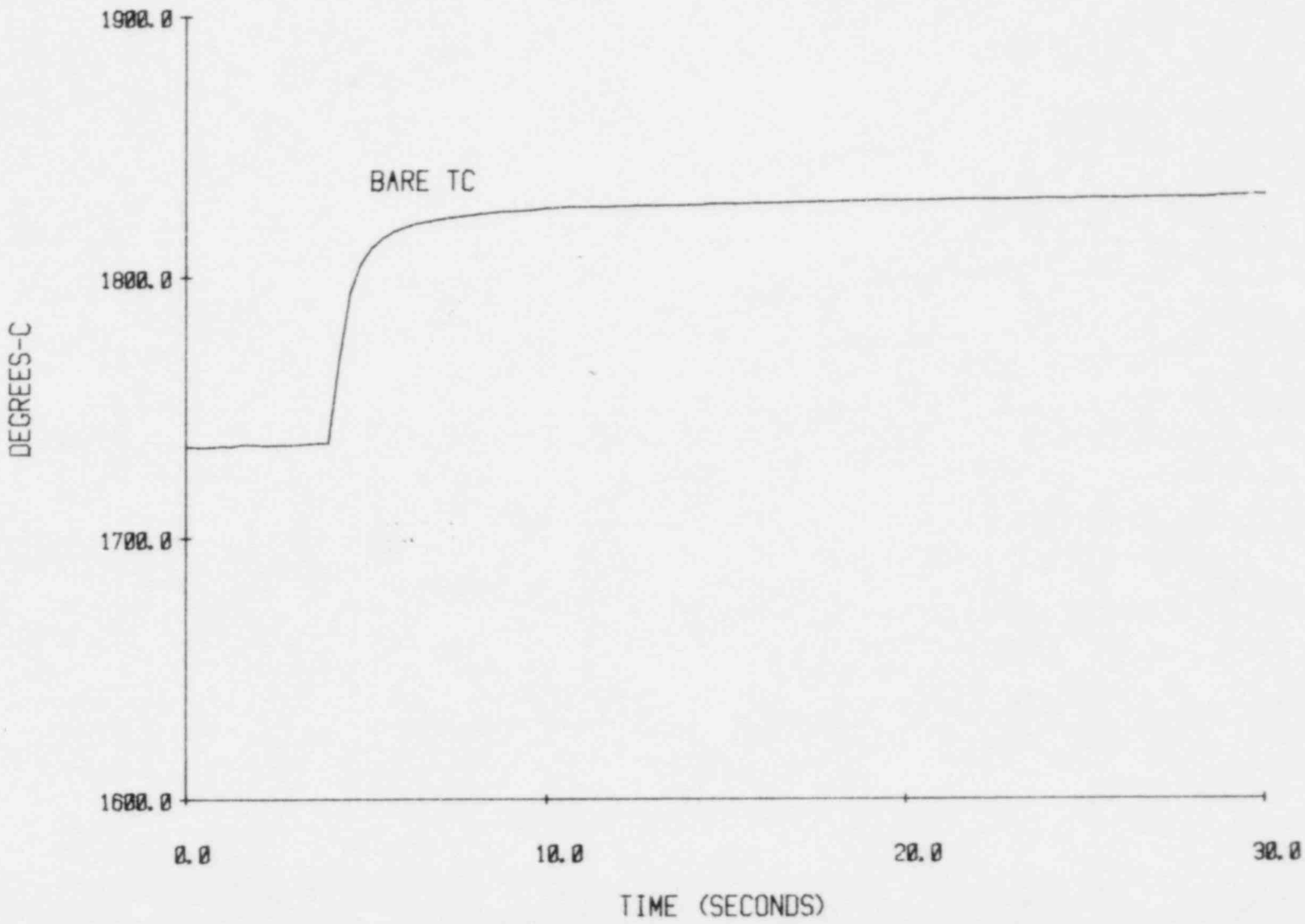

FIGURE 26. Plot of Temperature vs. Time for Thermocouple No. 1 During Time Response Tests.

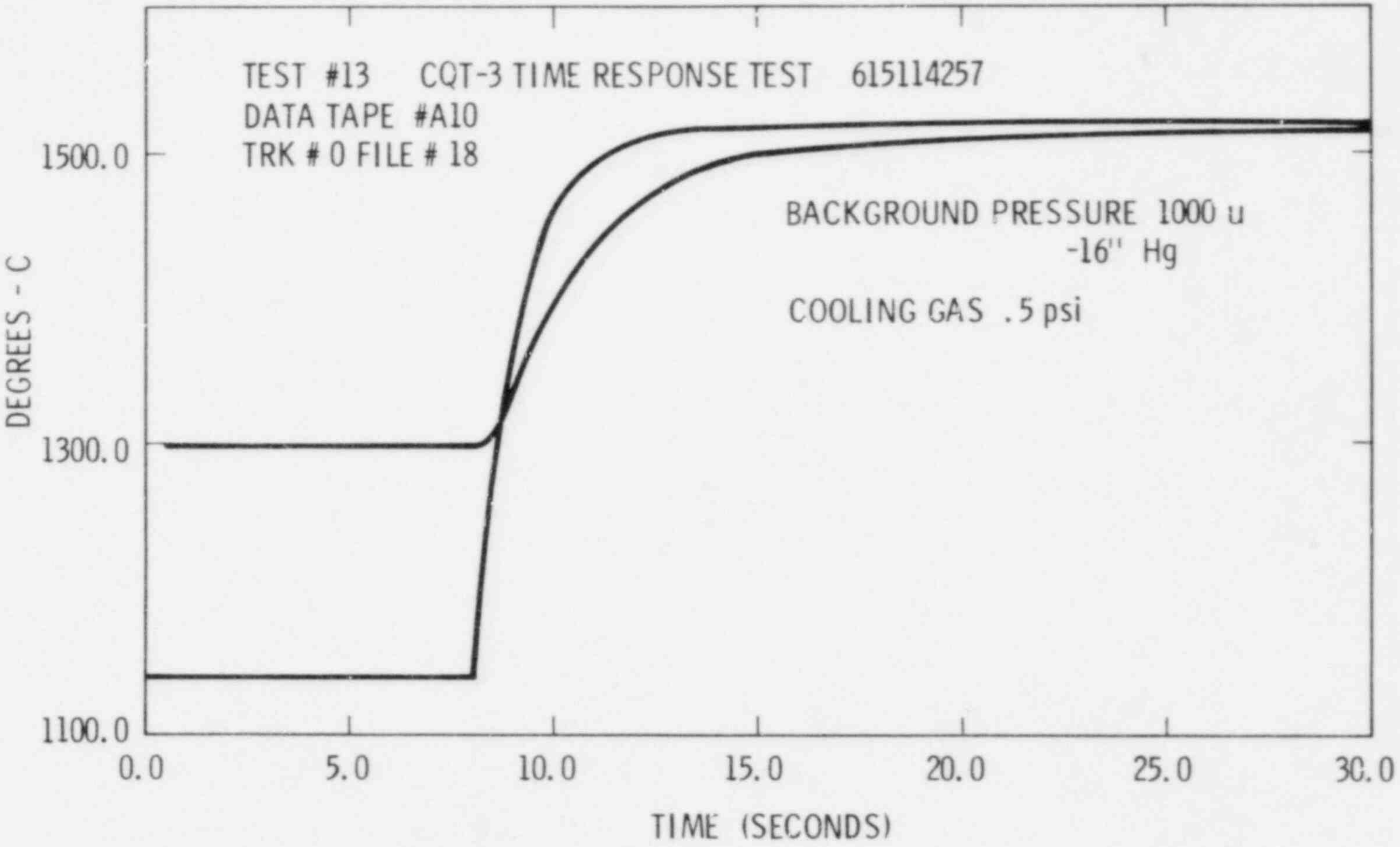

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FIGURE 27. Plot of Temperature vrs. Time for Thermocouple No. 3 During Time Response Tests.

TABLE IV

TIME RESPONSE MEASUREMENTS ON TEST THERMOCOUPLES 2 and 3

TEMPERATURE	TIME RESPONSE	
	CQT-2 (Model A) (seconds)	CQT-3 (Model B) (seconds)
1550°C		4.57
1550°C		4.49
1550°C		4.42
1550°C		4.30
1550°C		4.47
1620°C	4.9	
1620°C	4.47	
1800°C	2.43	
1800°C	3.95	
2020°C	2.52	

4.6 TRANSITION JUNCTION TEST RESULTS

The transition junction assemblies from the three initial qualification thermocouples showed leaks greater than 10^{-9}cc He/s. The source of the problem was identified and the vendor modified the fabrication procedure.

Two prototypic Model A junction regions and one prototypic Model B transition junction region were received for test and evaluation. All units included a section of sheath, ceramic-to-metal seal, transition assembly region, and at least two feet of compensating lead cable.

The tests required by section 3.7 of LOFT-QTP-CT-1 were performed. All tests were successfully passed by all three transition junction regions. While continuously internally pressurized at 2500 psi helium, the transition junctions were thermal cycled to 430^{0}C at rates of 6^{0}C/s for three cycles. Also, while continuously held at 450^{0}C, the internal helium pressure was cycled at a rate of 350 psi/s to a pressure of 2500 psi. There was no indications of helium leaks to a sensitivity of 10^{-9} cc He/s during subsequent leak testing. All welds and brazes in the transition junction assembly region were verified to be hermetic to 10^{-9} cc He/s with a pressure differential of 2500 psig of helium.

Each of the three transition junction regions were then subjected to the vibration tests required in section 3.8 of LOFT QTP-CT-1. The test consisted of mounting a transition junction to a vibration table and heating it to a temperature of 450^{0}C by means of heater tape. The transition junction was then vibrated at an axial load of 2G at 40 to 50 Hz and an axial load of .5G at 40 to 50 Hz as required in section 3.8. With a pressure differential at 2500 psig helium no leaks greater than 10^{-9} cc He/s were observed on any of the welds after the vibration test.

4.7 TRANSITION JUNCTION AND THERMOCOUPLE JUNCTION METALLOGRAPHIC EXAMINATION

The metallographic examinations required by section 3.7 in LOFT-QTP-CT-1 were conducted. All welds and braze junctions were examined for cracks and porosity. No indication of embrittlement, porosity, or cracking was observed in the weld and braze regions.

As required by section 3.7, the insulator and thermoelement wires were removed from the sheath regions subjected to the 400 hour temperature test. Discoloration occurred in the temperature transition region between the test temperature and ambient. An Auger electron microprobe analysis of this region did not indicate the presence of unusual quantities of contamination that would be considered harmful to thermocouple operation. The color of the hafnia insulation in the region of the thermocouples subjected to 2200°C maintained a light gray color uniformly over the region. An Auger electron microprobe analysis of this region indicated no contamination within the detectable limits of the testing apparatus.

Microscopic examination of the thermoelement wires in the test region that had been at 2200°C indicated slight necking down of the wire on those regions that existed between the hafnia insulators. An Auger analysis of these regions indicated tungsten depletion. However, the extent of necking down was limited to a reduction of the diameter to approximately 0.0075 in the worst case. Considering that thermocouples had been at temperature over 400 hours, the necking down was considered to have been an equilibrium situation and a condition that would not jeopardize the operation of thermocouples within the 400 hour life requirement. The author also hypothesizes that once the residual oxygen is tied up, the corrosion process ceases. This conclusion is reached because the amount of necking down on assemblies tested 400 hours is similar to the necking down observed on development units tested for over 1000 hours. Necking down was approximately the same on each thermoelement wire type. Some evidence of embrittlement was observed in 90° bend tests, but the thermoelement wires remained surprisingly ductile.

The sheath tubing was also examined as required by section 3.7 under 50X optical magnification. No evidence of material deterioration appeared evident other than the slight roughness of the surface. Sections of sheath tubing that had been at 2200^{o}C were able to withstand a 90^{o} bend test without breaking, indicating that the tubes retained ductile properties.

5.0. DISCUSSION

The qualification thermocouple assemblies satisfied all test requirements except for time response. It is significant that all three thermocouple assemblies satisfied the 400 hour life requirements at the maximum operating temperatures of 1550°C and 2200°C with less than 2% emf drift, as well as thermal transient tests of up to 145°C/s with no impairment in performance.

Development efforts to date have focused primarily on fabricating thermocouple assemblies capable of operating at 2200°C; little attention has been given to time response parameters. Substitution of helium for argon as the fill gas would improve the response time by a factor of six. The differences in thermal expansion between the thermoelement wires and the sheath over the extreme temperature range to 2200°C makes successful construction of a grounded junction in this type of unit highly unlikely. However, further development efforts focusing on mechanical parameters at the junction region and substitution of helium for argon as a fill gas should significantly improve the time response of the units.

Measurement of the insulation resistance as a function of temperature demonstrates that the resistance of the hafnia insulators approaches a marginal value of 1-10 ohms above 2200°C. However, this does not necessarily preclude successful thermocouple operation within ±2% at 2200°C. The effect is primarily one of electrically grounding the thermocouple junction to the end of the sheath; in this respect, at 2200°C the thermocouple operates no differently than a grounded junction thermocouple. As the temperature decreases down the sheath probe in the temperature gradient, the insulation resistance of the hafnia increases exponentially, thus providing adequate separation of the emf being generated along the thermoelement wires. Above 2200°C serious shunting errors are encountered. Error bars on the absolute accuracy of the thermocouple at 2200°C are ± 40°C. Most of this error is attributed to the shunting effect of the hafnia insulators.

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The technology and commercial vendors have been developed for fabrication of thermocouples to measure fuel centerline temperatures to 2200°C in the LOFT reactor. Two model A and one model B qualification thermocouples satisfied all test requirements during life tests at 2200°C and 1550°C. The emf output drifted less than 2% during 400 hour tests at the maximum test temperatures o f 2200°C and 1550°C. Measurement performance remained unimpaired after 145°C/s transient survival tests.

The thermocouples did nit meet the time response requirement of one second. Time responses of 4-1/2 seconds at 1550°C and 2-1/2 seconds at 2200°C were measured. However, this result was not considered too negative to preclude useful temperature measurement of fuel centerline temperatures in the LOFT reactor. The first qualification thermocouples satisfied all other test requirements.

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SEPTEMBER 1980