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**INVESTIGATION OF STICK-SLIP
(CHATTER) PHENOMENON OF HTGR
THERMAL BARRIER ATTACHMENT
FIXTURE SLIDING INTERFACES**

**PHASE I TEST:
CLASS A THERMAL BARRIER
HARDWARE AND ENVIRONMENT**

**by
A. MIDDLETON**

**Prepared under
Contract DE-AT03-76ET35300
for the San Francisco Operations Office
Department of Energy**

DATE PUBLISHED: JULY 1979

GENERAL ATOMIC COMPANY

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ABSTRACT

This test program was performed to investigate if significant chatter (stick-slip) would occur at the thermal barrier sliding surfaces. Given such conditions, cyclic loads could be induced in the thermal barrier attachment fixture and studs. A representative section of thermal barrier was tested with realistic HTGR temperature cycles in a high purity helium environment. No significant chatter was detected and there was no visible deterioration of the hardware after testing.

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1. SUMMARY AND CONCLUSIONS

An investigation was carried out to determine whether chatter (stick-slip) occurring at the thermal barrier sliding surfaces would be sufficient to induce cyclic loads in the thermal barrier attachment fixtures and studs. A representative Class A thermal barrier was subjected to realistic High-Temperature Gas-cooled Reactor - Steam-Cycle (HTGR-SC) plant temperature cycles in a high-purity helium environment. Two tests were performed, one with nominal and one with worst-case design hardware configuration.

No significant chatter was evident during either test. Some extremely small chatter was identified in one test in the temperature range of 390° to 400°C (730° to 750°F). Chatter of this magnitude would have no consequence on the design of the Class A thermal barrier. Examination of the Class A hardware before and after testing revealed no detectable deterioration or change.

2. INTRODUCTION

2.1. THERMAL BARRIER DESCRIPTION

The functions of the thermal barrier are to control the temperature levels and gradients in the prestressed concrete reactor vessel (PCR) liner and adjacent concrete in conjunction with the PCR cooling water system and to minimize heat losses from the primary coolant system. In zones where the temperature does not exceed about 800°C (1500°F), these functions are typically provided by layers of fibrous insulation blankets, which are compressed against the PCR liner by cover plates and seal sheets (see Figs. 1 and 2). Insulation blankets of varying thickness and composition are used, depending on the hot-side temperature and other factors. In zones where the maximum operating temperature is below 400°C (750°F), the insulation has been designated Class A. Class B insulation is used in zones where this maximum temperature is exceeded.

The Class A and Class B insulation cover plates are held in place by attachment fixtures which pass through the insulation and are fastened by threaded studs welded to the liner (see Fig. 3). Seal sheets bridge the gaps between cover plates and retard permeation of the insulation blankets by the hot gas.

An attachment fixture, called the central attachment fixture (CAF), is located at the center of each cover plate. Four additional fixtures, one at the midpoint of each edge of each cover plate, are used to control deflection of the edges. These fixtures, called mid-edge retainers (MERs), are shared by adjacent cover plates. Each CAF is fastened to the liner by four 12.7-mm (1/2-in.) diameter welded studs. Each MER is fastened by four 9.5-mm (3/8-in.) diameter welded studs.

Fig. 1. Typical thermal barrier cover plate

Fig. 2. Typical thermal barrier section

Fig. 3. Typical thermal barrier attachment fixture (Class A and Class B)

The CAFs and MERs employed in support of the Class B insulation are longer than those used for Class A owing to the greater insulation thickness. Hastelloy X is a principal candidate material for the Class B metallic assembly to meet the temperature requirement. Carbon steel (AISI 1020) is used for the Class A assembly. Identical stud material and stud welding procedures are used for Class A and Class B attachments.

2.2. DISCUSSION OF CHATTER (OR STICK-SLIP) PHENOMENON

The two most significant influences on the welded studs with respect to their ability to meet fatigue life requirements in the HTGR environment are (1) the chatter, or stick-slip, phenomenon, which is postulated to produce a marked increase in stud stress cycles compared with reactor operational thermal cycles, and (2) the superposition of complex stud stresses resulting from elastic deformation of the beveled flange surface of the CAF and MER.

Chatter is a well-documented phenomenon (Refs. 1-3). Its occurrence is based on the fact that the coefficient of dynamic friction between two surfaces sliding with respect to each other is less than the coefficient of static friction between the same two surfaces when motion is impending.

In the HTGR thermal barrier design, the surfaces sliding with respect to each other are the cover plates and the MER washers (see Fig. 3). The driving force is provided by thermal expansion and contraction of the cover plates due to reactor thermal cycling.

A simplified explanation of the transverse mode of chatter is as follows. The cover plate is assumed to be fixed at its center by the CAF and to expand outward toward the MERs as reactor temperature increases. As the cover plate expands, relative motion tends to occur at the washer interface. This motion is resisted by the static friction force $\mu_s N$ (where μ_s is the static friction coefficient and N is the normal force).

As the cover plate expansion force builds up, it is stored as equilibrating strain energy in the plate and in the MER assemblies. When the expansive or driving force exceeds the resisting or static friction force, slipping occurs at the interface. Motion during the slip is controlled by the dynamic friction coefficient, inertia of the MER, and the stored strain energy. The combination of these factors causes the MER to spring back to a position beyond its initial position. As the cover plate continues to expand, the MER is returned to its initial position, then deflected beyond this position as the static friction force builds, and the cycle is repeated. Each deflection and spring-back cycle is translated into a stress cycle in the MER assembly. The theory also applies as the cover plate cools and contracts. Curved thermal barrier cover plates give rise to axial chattering loads by the same type of mechanism (Ref. 4).

Quantitative values for the number of stick-slip cycles per reactor thermal cycle (the chatter multiplier) depend on the values of the following parameters: the mass and stiffness of the parts, the normal force between the sliding surfaces, the purity level of the helium environment, the temperature and rate of temperature increase, the static and dynamic friction coefficients, and the damping present in the system.

A conservative analysis using the single-degree-of-freedom system described above (single cover plate fixed at center and single MER) indicates that the chatter multiplier may be as high as 3660. That is, 3660 chatter cycles may occur for each reactor thermal cycle, resulting in a total of nearly 10^8 chatter cycles over reactor design life. The predicted number will vary with reactor location and thermal cycle due to variation of one or more of the parameters used in the analysis.

The experimental investigation documented in this report was conducted to examine the existence of chatter under conditions of a representative Class A thermal barrier assembly (Phase I). If significant chatter was encountered the intent was to establish the frequency and amplitude of cyclic excitation for design purposes.

3. TEST SETUP

During the initial attempt by the test laboratory to perform test No. 1, a large number of strain gages failed due to incorrect installation techniques, and the test was declared invalid. The faulty strain gages were repaired or replaced and test No. 2 was run. A valid test No. 1 was performed later with new strain gages and a new test MER washer.

Because the initial test No. 1 was invalid, data from that test have not been included in this report. By reason of actual sequence of performance and because of experience gained with the progress of testing, test No. 2 will be presented first, followed by the valid repeat of test No. 1.

3.1. TEST SETUP FOR PHASE I TEST NO. 2

3.1.1. Test Specimen

The test specimen represented a full-size section 1.65 m wide and 2.87 m long (65 in. wide x 113 in. long) of a typical Class A thermal barrier (Fig. 4). A specimen of this size allowed a reasonable simulation of thermal barrier panel boundary conditions. The hardware was the same Class A thermal barrier hardware as would be applied in an HTGR. This hardware included design and materials used in fabrication of CAFs, MERs, thermal insulation blanket assemblies, cover plates, and Nelson weld studs. The cover plate configuration necessary to achieve the desired boundary conditions consisted of two half cover plates and four quarter plates (see Fig. 4). Thin seal sheets 0.79 mm (0.031 in.) beneath the cover plates were also represented.

Fig. 4. Chatter test assembly

The thermal insulation comprised five blanket assemblies with 45-deg chamfers at the joints. The insulation blanket assemblies were built up using three layers of 25.4-mm (1.0-in.) nominal thickness and one 12.7-mm (1/2-in.) layer of Kaowool. The nominal 89.0-mm (3.5-in.) blanket assembly was compressed to a thickness of 66.0 mm (2.59 in.) during construction of the test specimen (i.e., compressed to about 75% of nominal thickness). (For further details, see Appendix A.) Test No. 2 simulated the worst combination of hardware tolerances that would be expected to maximize susceptibility to chatter. This was accomplished by skewing the test MER, i.e., by tilting and spot welding the test MER sliding washer (see Fig. 5).

3.1.2. Test Autoclave and Subsystems

3.1.2.1. Test Autoclave. The test autoclave assembly was designed and fabricated by the test laboratory. The base plate of the box assembly was made from carbon steel, ASTM A537, Class 2 material to simulate the PCRV liner. The 12.7-mm (1/2-in.) and 9.5-mm (3/8-in.) Nelson weld studs were supplied, installed on the base plate, and inspected per the General Atomic (GA) test specification (Ref. 5). The remainder of the test autoclave was fabricated from mild steel.

The autoclave heater was equipped with 100 quartz infrared lamps with water-cooled bus bars. The heater (which was fabricated per Ref. 6) consisted of three control zones. The central control zone contained two rows of lamps, and the two edge zones each contained a single row of lamps.

3.1.2.2. Helium Gas Supply System. The test autoclave was connected to a helium supply system that was supplied from two high-pressure helium bottles connected to a manifold (Fig. 6). Each gas bottle had a two-stage pressure regulator upstream of the manifold. The manifold supplied gas to the autoclave through a third regulator that was normally set at about 138 kN/m^2 (5 psig).

Fig. 5. Method of achieving skewed test MER washer during test No. 2

3.1.2.3. Helium Gas Sample System. Gas samples were obtained from both the gas supply side and gas relief side of the autoclave (Fig. 6). Gas samples bottles were connected to a tee on the supply line. Helium gas samples were obtained from the autoclave vent system in the same manner.

3.1.2.4. Lamp Array Cooling System. The lamp array bus bars were cooled with a demineralized deionized water system that supplied water to the bus bars through a system of filters and flow switches. A loss of pressure or flow to this cooling system was designed to shut off water to the bus bars. A pressure switch on the autoclave was designed to cut the flow of water to the cooling system in the event of a bus bar rupture that would otherwise dump water into the hot autoclave.

3.1.2.5. Autoclave Lower Cooling System. The lower half of the autoclave (containing the test specimen) was equipped with parallel flow coolant lines welded to the sides and base plate. Lexol brine for this cooling system was temperature controlled by a Bemco heat exchanger unit that buffered a liquid nitrogen cooling coil with a Cal-rod heater. The Bemco heat exchanger was controlled with a Barber Coleman proportionating controller that sensed the brine temperature with a thermocouple. The controller alternately heated or cooled the brine, as required to maintain the brine setpoint temperature.

3.1.2.6. Autoclave Upper Cooling System. The upper half of the autoclave was equipped with liquid flow lines welded to the sides and upper plate. The lines were connected to a parallel flow manifold, which received 15°C (60°F) water from the laboratory recirculating water system.

3.1.2.7. Temperature Control System (Fig. 7). The temperature control system consisted of a Nova 12 minicomputer that generated the time-temperature profile in accordance with the GA test specification (Ref. 7). The profile signal was fed to three special servoamplifiers, which also received signals from three Chromel-Alumel thermocouples that were attached

Fig. 6. Schematic of helium and autoclave pressure control system (test No. 2)

Fig. 7. Schematic of temperature control system for thermal barrier chiller tests

to the insulation cover plates of the test specimen under each zone of the autoclave heaters. The error signal generated by the three servo-amplifier inputs was fed to a 50-kVA Ignitron power controller, which, in turn, supplied power to the individual lamp zone. Each lamp zone was controlled with a system of this type.

3.1.3. Instrumentation

The instrumentation consisted of 22 thermocouples, 48 strain gages, one triaxial accelerometer, and one audio microphone.

3.1.3.1. Thermocouples (Figs. 8 and 9). Thermocouples 1 through 5 were located on the top side of the cover plates, 6 through 8 were located on the attachment fixtures (one on each of two CAFs and one MER). Thermocouples 9, 10, and 11 were located on the autoclave lower plate. The remainder of the thermocouples were installed on the top surface of the insulation cover plates. Thermocouples 17, 18, and 19 provided feedback for the temperature control system, and 17A, 17B, and 20 recorded on a strip chart recorder for operator information.

3.1.3.2. Strain Gages (Figs. 10 and 11). Forty-eight strain gages were installed on the three test attachment fixtures (Ref. 6). Eight of the strain gages on each fixture were connected into bridges for determining bending in the 0-deg and 90-deg directions. The remainder of the gages were read as single gages for determining tension loading.

3.1.3.3. Accelerometer. One three-axis accelerometer was attached to the lower plate of the autoclave. The accelerometer was installed to detect building vibrations or extraneous vibrations that could affect the chattering effect.

3.1.3.4. Microphone. One microphone was installed in the test MER as an audio indication of chatter. During test No. 2 this item failed, and a second microphone was bonded to the autoclave bottom plate.

TO CONAX FITTING
ON TOP BOX (17A & 17B)

THERMOCOUPLE LOCATIONS - COVER PLATES

□ THERMOCOUPLE IDENTIFICATION

● THERMOCOUPLE LOCATION

THERMOCOUPLE WIRE: AWG 20, TYPE K, REFRASIL INSULATION

□ CONTROL AND MONITOR THERMOCOUPLES

Fig. 8. Attachment fixture identification, thermocouple location, and numbering system (cover plate)

THERMOCOUPLE LOCATIONS - AUTOCLAVE FLOOR

THERMOCOUPLE IDENTIFICATION

● THERMOCOUPLE LOCATION

THERMOCOUPLE WIRE: AWG 28, TYPE K, GLASS INSULATION

--- INDICATES THERMOCOUPLE ON BOTTOM SIDE

Fig. 9. Attachment fixture identification, thermocouple location, and numbering system (base of autoclave)

Fig. 10. Position of strain gages on MER

Fig. 11. Position of strain gages on CAF

3.1.3.5. Gas Analysis System. Helium supply to and outlet from the test autoclave were monitored for moisture and other impurities as detailed below.

1. Hydrogen, CO₂, N₂, and O₂. Samples were taken at intervals in evacuated stainless steel sample bottles and sent for analysis using a gas chromatograph.
2. Moisture. A Panametric Moisture Minder Model 1000 and probes were used at the test autoclave to measure moisture level directly. The probes were dried with nitrogen between samples.
3. CO and CH₄. A small portable detector measured CO and CH₄ levels at the test autoclave.

3.1.4. Data Acquisition

Measurements from the static strain gages, dynamic strain gages, accelerometer, and thermocouples were made throughout the temperature-time history profile. The instrumentation block diagram is shown schematically in Fig. 12. The following paragraphs describe these acquisition methods.

3.1.4.1. Static Strain Measurements. Measurement of the strain gages on MER 1, CAF 1, and CAF 2 was accomplished on an SDS 910 Digital Data System. Data recordings were made at 5-min intervals throughout the test. Recordings were made of all the single strain gages as well as the 0-deg and 90-deg bridges on the three instrumented attachment fixtures.

3.1.4.2. Dynamic Strain Measurements. Dynamic data recordings were made on each of six bending bridges. These bridges were designed to measure bending strain in the 0-deg and 90-deg directions of MER 1 and CAFs 1 and 2. During test No. 2, the six bridge channels were recorded intermittently on magnetic tape.

3.1.4.3. Accelerometer Measurements. Output from the triaxial accelerometer was recorded on magnetic tape. These recordings were intermittent during test No. 2.

3.1.4.4. Thermocouple Measurements. The output from the thermocouples was measured on the SDS 910 Digital Data System. Data recordings were made at 5-min intervals throughout the test. The digital data were printed out on the line printer in engineering units and recorded on magnetic tape in millivolts.

3.2. TEST SETUP FOR PHASE I, TEST NO. 1 REPEAT

3.2.1. Test Specimen

The test specimen was essentially as described in Section 3.1.1. Two differences are notable, however: the insulation compression was reduced to 80% of nominal uncompressed thickness, and the test MER washer was not skewed per the GA test specification (Ref. 8).

3.2.2. Test Autoclave and Subsystems

The test hardware and autoclave were essentially the same as used during test No. 2. The major design improvements are noted below.

3.2.2.1. Helium Gas Supply System (Figs. 13 and 14). The test autoclave was equipped with a helium gas purge and supply system. This system consisted of a gas supply line with three gas input ports. Two of the input ports were hookups for high-pressure bottled gas and the third was a hookup to the laboratory helium supply system. Gas could be supplied to the autoclave independently through the three ports. The hookups for the bottled gas were through special two-stage regulators designed for ultra-high-purity gas regulation. These regulators were equipped with special purge ports designed to purge the regulator input line while changing gas bottles.

Fig. 13. Schematic of helium and autoclave pressure control system
(test No. 1 repeat)

Fig. 14. Details of helium supply and sample system (test No. 1 repeat)

Unlike the previous test setup, inlet and outlet helium control valves in this setup were designed to fail in the normally open condition. This allowed for a continuous helium purging of the autoclave in the event of an electrical power failure.

3.2.2.2. Helium Gas Sample System (Figs. 13 and 14). The gas analysis system takes test samples from the vent side of the autoclave. A quadropole sensing head detected the quantities and mass number of the gases entering the chamber, and these were recorded by a quadropole mass spectrometer (residual gas analyzer). Another sample of the outlet gas was valved to flow through a Panametric dew point sensor that determined the moisture content of the sample in parts per million.

3.2.3. Instrumentation

The instrumentation was essentially the same as used in test No. 2. Significant changes are noted below.

3.2.3.1. Gas Analysis System (Fig. 15). Gas analysis of the autoclave outlet gases was made utilizing a Leybold-Heraeus Model Q2000 Quadravac Residual Gas Analyzer. This unit measures masses from 1 to 200 atomic mass units.

The only constituent not measured by the Quadravac was moisture. Moisture was measured with a Panametric Model 1000 hygrometer. The measurement was made by flowing gas through a crystal sensor at the autoclave working pressure.

3.2.4. Data Acquisition

The data acquisition system was essentially the same as used in test No. 2.

Fig. 15. Details of helium gas analysis system (test No. 1 repeat)

4. TESTING

4.1. TEST NO. 2

4.1.1. Test Specimen Buildup

The Kaowool blankets were stacked and cut into five blanket assemblies in accordance with the Boeing test procedure (Ref. 9). Samples 0.25 m x 0.25 m (10 in. x 10 in.) were cut from each face of the blanket assemblies. The weight, height, and compressive load characteristics of each sample were determined. From this information, the installed compressive load for each blanket could be estimated (see Appendix A). Any blanket with a particularly high or low load characteristic was rejected at this stage, and a new blanket was fabricated and tested.

The autoclave and test hardware were cleaned and degreased. The attachment fixture washers were photographed and weighed, and surface roughness measurements were made of the sliding surface of the test MER washer.

Thermocouples were mounted on the base plate. The strain-gaged attachment fixtures (one MER and two CAFs) were installed, each with a thermocouple and leadout wires. The rest of the attachment fixtures (six MERs and four CAFs) were subsequently installed. The studs were lubricated with Molykote 321. The 12.7-mm (0.5-in.) CAF studs were torqued to 21 ± 1 N-m (185 ± 10 in.-lb), and the 9.5-mm (0.375-in.) MER studs were torqued to 11 ± 1 N-m (100 ± 10 in.-lb).

The uncompressed blanket assemblies (with 45-deg chamfers) were installed in their specified positions. Next, seal sleeves and seal sheets were installed on top of the insulation blanket assemblies and correctly

aligned with the attachment fixtures. Cover plates were added on top of the seal sheets. After alignment with the attachment fixtures, the cover plates were made to compress the insulation with a system of beams and hydraulic jacks. The blanket assembly was compressed to 70% of its nominal thickness, and the CAF and MER hold-down nuts were installed. These were torqued in position to 3.4 N-m (30-in.-lb).

Prior to torquing the test MER, its washer was tilted 4.4 mm (0.174 in.) with a shim (see Fig. 5). The hold-down nut was then torqued to 3.4 N-m (30 in.-lb), and the washer was spot welded to the nut. The shim was subsequently removed, leaving a tilted washer. This simulated a skewed fixture under worst possible tolerance conditions. The other CAF and MER nuts were drilled, and roll-pins were installed to preclude any chance of unscrewing. Finally, the cover plate thermocouples were mounted, and lead-out wires were run to the instrument lead-out parts.

After a check was made to determine that the instrumentation and the power control system were functioning correctly, the top half of the autoclave (including the heaters) was installed. The system was checked for any water or helium leaks.

4.1.2. Preconditioning

An environmental preconditioning phase for the autoclave preceded the start of testing. The purpose of this preconditioning was to attain a helium atmosphere coupled with a hydrogen level which conservatively could be associated with an HTGR, and which would be adverse environmentally in regard to the phenomenon of stick-slip.

The test specimen (mounted inside the autoclave) was preconditioned in a large vacuum chamber for 72 hr. The autoclave was back-filled with high-purity helium prior to removal from the vacuum chamber. The sealed autoclave was moved to the test site and connected to the support equipment.

Preconditioning of the test specimen continued under sustained purging for about 18 days by cycling the upper surface of the test specimen about ten times between 120°C (250°F) and 400°C (750°F). This period included three hold periods of 48 hr each at 120°C (250°F).

It should be noted that during test No. 2 the only method of flowing helium through the autoclave was that due to expansion and contraction of the helium during temperature cycling. This was found to be ineffective, and the helium purge system was modified for test No. 1 repeat to allow higher helium flow rates through the autoclave.

4.1.3. Testing

Phase I of the thermal barrier chatter test required a realistic hot face temperature-time history from Ref. 10. It was possible to represent two different startup conditions (0 to 100% power), one transient from 100% to 50% power and back to 100% power (with 0.42%/min rate of power change), one transient from 100% to 25% power and back to 100% power (0.42%/min rate of power change), and two shutdowns from full power (Ref. 11). A composite curve (for use in the test) representing these power conditions was generated to simulate as closely as possible the above expected plant temperature-time transients. The temperature-time history is plotted in Fig. 16. The test specimen was subjected twice to these variations in temperature. A third cycle used a modified curve to reflect a rate of power change of 5%/min for the 100-25-100% reactor transient and a reactor trip from full power. The average steady-state (core inlet) temperature levels were taken from Ref. 12 for the 100%, 50%, and 25% power levels.

The test lasted about 5 days. During that period, eight helium samples were sent for analysis of impurities. The moisture level in the helium was measured ten times at the autoclave with a portable moisture monitor. Temperature and static strain gage data were measured and recorded every 5 min on the SDS 910 computer. The dynamic data (six

Fig. 16. Schematic of specified temperature-time profile (cover plate temperatures)

strain gage bridges, accelerometer and acoustic transducer) were measured at intervals on the FM magnetic tape and visicorder.

After two days of testing, a heater power outage resulted in ingress of impurities into the autoclave. The resulting high impurity level existed for the remainder of the test. Additionally, a failure of the computer resulted in a loss of about 7 hr of data.

4.1.4. Post-Testing

After completion of the established temperature-time history, the autoclave was cooled. All subsystems were disconnected, and the autoclave was opened. The spot weld on the test MER and the roll pins on the other MERs and CAFs were removed. The hold-down nuts were unscrewed and the cover plates removed. The seal sheets were then removed and examined for wear. According to the specification, samples were cut from each blanket assembly and sent for weight, height, and compressive load measurements.

The washers were weighed and photographed. The test MER washer was subjected to surface roughness measurements in the same position as pretest measurements.

4.2. TEST NO. 1 REPEAT

4.2.1. Test Specimen Buildup

The test specimen buildup was essentially the same as for test No. 2 (see Section 4.1.1). The two basic differences were that (1) the Kaowool blanket was compressed to 80% of nominal thickness, and (2) the test MER washer was installed flat (i.e., no skewed washer) per the Boeing test procedure (Ref. 13).

4.2.2. Preconditioning

Preconditioning started with helium purge of $1.6 \times 10^{-4} \text{ m}^3/\text{s}$ (20 scf/hr) of 99.999% purity but was subsequently downgraded to a laboratory helium supply of 99.995% purity. Following 2 days of steady purge, 2 complete thermal cycles per day over the temperature range of 115° to 400°C (240° to 750°F) were performed over the next 2 days.

The helium purge was maintained constant at $1.6 \times 10^{-4} \text{ m}^3/\text{s}$ (20 scf/hr) over the next 3 days without any associated thermal cycling. Cycling as above was resumed at the rate of 4 cycles per day over the next 2 days. Next, the purge at $1.6 \times 10^{-4} \text{ m}^3/\text{s}$ (20 scf/hr) was modified to a helium purity of 99.999% mixed with 0.5% of high-purity hydrogen; cycling continued at an average rate of 5-1/2 cycles per day for the next 2 days. The gas purge was adjusted to a rate $4 \times 10^{-5} \text{ m}^3/\text{s}$ (5 scf/hr) in preparation for the start of testing.

4.2.3. Testing

A helium purge rate of $1.6 \times 10^{-4} \text{ m}^3/\text{s}$ (20 scf/hr) was maintained throughout the test period. The same temperature-time history as for test No. 2 ran continuously for 4-1/2 days. During that period, 12 moisture and 12 helium purity samples were taken (i.e., 9 samples were taken at 400°C (750°F) and 3 samples at 115°C (240°F)). Static test data were taken every 10 min. Dynamic data were recorded continuously on magnetic tape and intermittently on visicorder.

4.2.4. Post-Testing

Post-test disassembly and examination of the test specimen were essentially as described for test No. 2 (Section 4.1.4).

5. TEST RESULTS

The test data were taken from Boeing test reports for Phase I tests Nos. 1 and 2 and Phase I test No. 1 repeat (Refs. 14 and 15, respectively).

5.1. TEMPERATURE DATA

Throughout the test program, data from thermocouples were collected every 5 to 10 min. Examples of these data from test No. 2 and test No. 1 repeat, presented in Fig. 17 through 22, show the variation of specimen temperature with time. Except for power outages, all temperatures were within specified levels.

5.2. STRAIN GAGE DATA

During the installation of the strain gages prior to test No. 1, low temperature lead-out wire tabs (epoxy glass laminate) were attached. These tabs failed during test No. 1 due to inadequate temperature resistance. Testing was continued although the strain data were rendered useless. New gages and leads were attached prior to test No. 2.

5.2.1. Test No. 2 Strain Gage Data

Typical low-speed strain gage data for the test MERs and CAFs are shown in Figs. 23 through 27. The lack of data during two periods of cycle 1 was due to a computer malfunction. The specified temperature profile was still being followed during those periods.

Although this test incorporated the skewed test MER washer, no significant chatter signal was seen on the dynamic or low-speed strain signals. Most of the spikes on the test MER signals were due to switching transients associated with the computer and the strain gage signal conditioning units.

Fig. 17. Test specimen temperatures during test No. 2, cycle 1

Fig. 18. Test specimen temperatures during test No. 2, cycle 2

Fig. 19. Test specimen temperatures during test No. 2, cycle 3

Fig. 20. Test specimen temperatures during repeat of test No. 1, cycle 1

Fig. 21. Test specimen temperatures during repeat of test No. 1, cycle 2

Fig. 22. Test specimen temperatures during repeat of test No. 1, cycle 3

Fig. 23. Strain data from test MER bridges during test No. 2, cycle 1

Fig. 24. Strain data from test CAF No. 1 bridges during test No. 2, cycle 1

Fig. 25. Strain data from test CAF No. 2 bridges during test No. 2, cycle 1

Fig. 26. Strain data from test MER bridges during test No. 2, cycle 2

Fig. 27. Strain data from test MER bridges during test No. 2, cycle 3

5.2.2. Test No. 1 Repeat Strain Gage Data

Typical low-speed strain gage data from the computer for the test MER and CAFs are shown in Figs. 28 through 32.

Examination of the dynamic data collected on visicorder traces (and magnetic tape) revealed no significant high-frequency chatter. However, over the temperature range of 390° to 400°C (730° to 750°F), small transients were evident on the visicorder trace which might be interpreted as chatter (i.e., they occurred in the transverse signal and not at 90 deg and were not caused by spurious signals such as opening and closing of solenoid valves). A typical trace is reproduced in Fig. 33 and enlarged in Fig. 34. Again, it is stressed that the signal was small (less than 10 microstrain) and only occurred about 20 to 30 times per temperature cycle to 400°C (750°F). From a fixture and stud fatigue point of view, such chatter loads are of no consequence in the design of the components.

5.3. HELIUM PURITY DATA

It has been widely recognized that low oxidation potentials (or high H_2/H_2O ratios) can cause an increase in the friction characteristics between two sliding surfaces. In the case of a cover plate sliding relative to the interfacing MER washer, a high friction coefficient could, in turn, cause increased chatter loads. Hence, the helium source and the gas outlet of the autoclave were carefully monitored. The results are detailed in Appendix B. In general, the helium impurities exceeded specification requirements, but no lack of chatter could be attributed to those excesses.

5.4. HARDWARE ANALYSIS

5.4.1. Weights of Washers

To determine the gain or loss of material due to attachment to an interfacing component, accurate weight measurements were made of all CAF and MER washers before and after each test. These data are presented

Fig. 28. Strain data from test MER bridges during repeat of test No. 1, cycle 1

Fig. 29. Strain data from test CAF No. 1 bridges during repeat of test No. 1, cycle 1

Fig. 30. Strain data from test CAF No. 2 bridges during repeat of test No. 1, cycle 1

Fig. 31. Strain data from test MER bridges during repeat of test No. 1, cycle 2

Fig. 32. Strain data from test MER bridges during repeat of test No. 1, cycle 3

Fig. 33. Dynamic data (strain gage and accelerometer) from test No. 1 repeat, cycle 1 (peak 3)

Fig. 34. Dynamic data (strain gage and accelerometer) from test No. 1 repeat, cycle 1 (peak 3)

in Tables 1 and 2. No significant weight changes were noted that could be attributed to material pickup or loss.

5.4.2. Surface Roughness

Since friction is a function of surface roughness, measurements were made on the sliding surface of test MER nitrided Nitralloy washers. Positions (identified as A, B, C, and D) were designated at 90-deg intervals at three radii. Measurements were made with a Talysurf.

The data for washer No. 4 (test No. 2) and washer No. 4A (test No. 1 repeat) are given in Tables 3 and 4. During test No. 2, the washer was located with position D pointed toward the autoclave 90 deg and position C toward the autoclave 270 deg. Prior to test No. 2, the skewing shim was placed under position C while the spherical nut was welded to the washer. After welding and prior to test No. 2, the shim was removed. During the repeat of test No. 1, the MER washer (No. 4A) was aligned with position A toward autoclave 90 deg and position B toward autoclave 270 deg.

5.4.3. Washer Evaluation

At the completion of test No. 2, three of the MER washers were sent to the Boeing Metallurgical Laboratory for analysis. The hardness was determined to be Rockwell Rc. 69. Microscopic evaluation at 40X magnification of a scuffed area 19 mm long x 0.51 mm wide (3/4 in. long x 0.020 in. wide) on one washer showed no evidence of base metal galling or scoring. Photographs were taken of CAF and MER washers before, between, and after testing. Typical photographs of the sliding surface of test MER washer (No. 4) before and after tests No. 1 and No. 2 are shown in Figs. 35 through 37. The sliding surface of test MER washer (No. 4A) before and after test No. 1 repeat is shown in Figs. 38 and 39.

TABLE 1
VARIATION OF WEIGHTS OF MER WASHERS DURING TESTING

Identification No.	Pretest 3/28/77	Post-Test No. 1 7/5/77	Weight Change	Post-Test No. 2 9/27/77	Weight Change	Pre-Rerun Test No. 1 4/25/78	Weight Change	Post-Test No. 1 Report 7/5/78	Weight Change
1	410.2770	410.2803	0.0033	410.3003	0.0233	410.3004	0.0234	410.2985	0.0215
2	412.5410	412.5409	-0.0001	412.5609	0.0199	--	--	412.5603	0.0193
3	407.6625	407.6619	-0.0006	407.6682	0.0057	--	--	407.6679	0.0054
4	413.2464	413.2522	0.0058	--	--	412.9908	0.2556	--	--
4A	--	--	--	--	--	413.5125	--	413.5101	-0.0024
5	412.0688	412.0687	-0.0001	412.0743	0.0055	--	--	412.0737	0.0049
6	417.6687	417.6717	0.0030	417.6920	0.0233	--	--	417.6913	0.0226
7	417.9352	417.9383	0.0031	417.9610	0.0258	--	--	417.9591	0.0239
Measurement uncertainty	0.05	0.05	--	0.05	--	0.10	--	0.05	--

- Note: 1. All weight change values are compared to pretest weights (3/28/77).
 2. Washer 4A used in rerun of test No. 1.
 3. All washer weight measurements are in grams.
 4. Washer 4 measurement (4/25/78) change due to welding it to nut during test No. 2 to achieve washer tilt.

TABLE 2
VARIATION OF WEIGHTS OF CAF WASHERS DURING TESTING

Identification No.	Pretest 3/28/77	Post-Test No. 1 7/5/77	Weight Change	Post-Test No. 2 9/27/77	Weight Change	Post-Test No. 1 Report 7/5/78	Weight Change
1	290.9229	290.9244	0.0015	290.9246	0.0017	290.9268	0.0039
2	287.7118	287.7143	0.0025	287.7209	0.0091	287.7228	0.0110
3	291.5429	291.5437	0.0008	291.5453	0.0024	291.5457	0.0028
4	288.3614	288.3603	-0.0011	288.3620	0.0006	288.3626	0.0012
5	292.0631	292.0657	0.0026	292.0749	0.0118	292.0750	0.0119
6	291.5606	291.5611	0.0005	291.5624	0.0018	291.5628	0.0022
7	290.5269	--	--	--	--	--	--
Measurement uncertainty	0.05	0.05	--	0.05	--	0.05	--

Note: 1. All weight change values are compared to pretest weights (3/28/77).
 2. All washer weight measurements are in grams.
 3. Washer 7 not used during testing.

TABLE 3
SURFACE ROUGHNESS MEASUREMENTS ON MER (NO. 4) WASHER DURING TEST NO. 2

Radial Position	Surface Roughness [μm ($\mu\text{in.}$)]											
	Position A			Position B			Position C			Position D		
	Pretest 4/15/77	Post-Test No. 1 6/30/77	Post-Test No. 2 9/27/77	Pretest 4/15/77	Post-Test No. 1 6/30/77	Post-Test No. 2 9/27/77	Pretest 4/15/77	Post-Test No. 1 6/30/77	Post-Test No. 2 9/27/77	Pretest 4/15/77	Post-Test No. 1 6/30/77	Post-Test No. 2 9/27/77
Outer	1.32 (52)	1.24 (49)	1.22 (48)	1.07 (42)	1.09 (43)	1.03 (40.5)	1.19 (47)	0.99 (39)	1.02 (40)	1.04 (41)	1.02 (40)	1.10 (43.5)
Center	2.18 (86)	1.63 (64)	2.22 (87.5)	1.22 (48)	1.09 (43)	1.42 (56)	1.65 (65)	1.30 (51)	1.46 (57.5)	1.47 (58)	1.42 (56)	2.01 (79)
Inner	2.51 (99)	2.33 (92)	2.41 (95)	2.06 (81)	2.33 (92)	2.21 (87)	2.39 (94)	2.26 (89)	2.24 (88)	2.13 (84)	2.44 (96)	2.48 (97.5)

- Note: 1. Uncertainty of surface finish readings $\pm 0.1 \mu\text{m}$ ($\pm 3.5 \mu\text{in.}$).
 2. During test 1 position A oriented to 90-deg autoclave position and position B to 270-deg position.
 3. During test 2, position D oriented to 90-deg autoclave position and position C to 270-deg position. Skewing shim was placed under point C while spherical nut was welded to washer.

TABLE 4
SURFACE ROUGHNESS MEASUREMENTS ON MER (NO. 4A) WASHER DURING TEST NO. 1 REPEAT

Radial Position	Surface Roughness [μm ($\mu\text{in.}$)]							
	Position A		Position B		Position C		Position D	
	Pretest 4/26/78	Post-Test 7/5/78	Pretest 4/26/78	Post-Test 7/5/78	Pretest 4/26/78	Post-Test 7/5/78	Pretest 4/26/78	Post-Test 7/5/78
Outer	0.61 (24)	0.79 (31)	0.64 (25)	0.74 (29)	0.74 (29)	0.74 (29)	0.74 (29)	0.76 (30)
Center	0.71 (28)	0.51 (20)	0.71 (28)	0.66 (26)	0.74 (29)	0.68 (27)	0.58 (23)	0.66 (26)
Inner	0.89 (35)	0.84 (33)	0.81 (32)	0.97 (38)	0.99 (39)	0.99 (39)	0.84 (33)	0.91 (36)

Note: 1. Uncertainty of surface roughness measurements $\pm 0.1 \mu\text{m}$ ($\pm 3.5 \mu\text{in.}$).

Fig. 35. Test MER washer (No. 4) prior to testing

Fig. 36. Test MER washer (No. 4) after test No. 1

Fig. 37. Test MER washer (No. 4) after test No. 2

Fig. 38. Test MER washer (No. 4A) before test No. 1 repeat

Fig. 39. Test MER washer (No. 4A) after test No. 1 repeat

5.4.4. Evaluation of Washer Performance

The nitrided Nitralloy washers were machined to a surface roughness of $3.0\text{ }\mu\text{m}$ (125 $\mu\text{in.}$) or less. Nitriding the washers to GA specifications (Ref. 16) resulted in a case depth of 0.15 to 0.23 mm (0.006 to 0.009 in.) and a minimum hardness of Rockwell Rc. 52.

It is evident from pretest measurements in Tables 3 and 4 that the sliding surfaces on both test MER washers (Nos. 4 and 4A) were within specification. Washer No. 4 indicated a significant increase in surface roughness from the outside to the inside of the washer. Washer No. 4A had a smoother, more uniform surface. Neither washer showed any significant change in surface roughness after testing.

Similarly, Tables 1 and 2 showed no significant weight changes during testing of MER or CAF washers (except washer No. 4 in test No. 2, which was welded to the nut to simulate skewed MER conditions). Visual and photographic evaluation of the washers showed some discoloration and surface polishing. However, there was no indication of wear or deterioration of surface roughness.

The average surface hardness of washers after test No. 2 was Rockwell Rc. 69, showing that the surface hardness had not changed significantly.

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APPENDIX A
KAOWOOL COMPRESSIVE LOAD DATA

During fabrication of the test autoclave, the floor and closure flanges became warped due to weld distortion. Attempts were made to straighten the assembly. Machining corrected part of the problem on the flanges but was not practical for the autoclave floor. Detailed mensuration of the base of the autoclave revealed that it was domed upward almost 12.7 mm (1/2 in.) at the center. To achieve flat and uniform cover plates during assembly of the test specimens, it was necessary to overcompress the central test MER by 4.76 mm (3/16 in.). Shims 6.35 and 3.18 mm (1/4 and 1/8 in.) were added to the other peripheral MERs and CAFs to achieve the flat cover plate profile. Subsequent measurements of assembled test specimens with shims installed showed that the cover plates were level within 2.5 mm (1/10 in.).

Pretest estimates of compressive loads were possible because samples of the blanket stack were taken on each side of the blanket assembly during the blanket-cutting operation. The load necessary to compress the blanket samples (to 70% or 80% of nominal thickness) was measured. Any faulty blankets were replaced at this stage.

Because the center test MER was overcompressed by 4.76 mm (3/16 in.), the central blanket samples were also overcompressed by the same amount during assembly. Compressive loads in the regions where the blankets were undercompressed by about 6.35 mm (1/4 in.) were estimated from interpolation of the blanket sample compressive load curve.

Based on the above, the following estimates were made of peak compressive load at the test MER and the average load over the test assembly.

	<u>Peak</u>	<u>Average</u>
Test No. 2	38.6 kN/m ² (5.6 psi)	17.3 kN/m ² (2.5 psi)
Test No. 1 repeat	22.8 kN/m ² (3.3 psi)	4.0 kN/m ² (1.6 psi)

More detailed pretest compressive loads are shown in Figs. A-1 and A-2.

After completion of testing, samples were cut from each blanket assembly and subjected to compressive testing as described above. Based on the data collected, the following estimates were made of peak compressive load at the test MER and average load over the test assembly.

	<u>Peak</u>	<u>Average</u>
Test No. 2	33.1 kN/m ² (4.8 psi)	13.8 kN/m ² (2.0 psi)
Test No. 1 repeat	19.3 kN/m ² (2.8 psi)	8.3 kN/m ² (1.2 psi)

More detailed post-test compressive loads are shown in Figs. A-3 and A-4.

Comparison of pre- and post-test data revealed a loss of load in the amount of about 15% to 25%. This reduction was probably due to temperature and thermal cycling effects.

Fig. A-1. Estimate of the variation of insulation compressive load prior to test No. 2

Fig. A-2. Estimate of the variation of insulation compressive load prior to test No. 1 (repeat)

Fig. A-3. Estimate of the variation of insulation compressive load after test No. 2

Fig. A-4. Estimate of the variation of insulation compressive load after test No. 1 (repeat)

APPENDIX B
DISCUSSION OF HELIUM IMPURITY LEVELS SPECIFIED
AND THOSE ACHIEVED DURING TESTING

B.1. BACKGROUND TO SPECIFIED IMPURITY LEVELS

Helium impurity levels for the HTGR-SC plant are defined in Ref. 17. Specifically, the allowable impurity levels at 5.07 MN/m^2 (50 atm) helium pressure are stated as follows:

"The total oxidants ($\text{CO} + \text{CO}_2 + \text{H}_2\text{O}$) in the primary coolant helium shall be maintained at a normal operating level of not more than 10 ppm by volume. The total oxidant level may be up to ten times greater for up to seven days or up to 100 times greater for up to one day. The total time between annual refueling periods at levels about 10 ppm shall be such that the product of concentration and time does not exceed 100,000 ppm-hr.

Other impurities which may be present in the primary coolant, but which must be removed to maintain concentrations below maxima, are hydrogen and hydrocarbons (mostly CH_4) which may be as high as 100 and 1 ppm, respectively."

In terms of impurity partial pressures this is

Total oxidants ($\text{CO} + \text{CO}_2 + \text{H}_2\text{O}$) $< 500 \text{ } \mu\text{atm}^*$,
Hydrocarbons (CH_4) $< 50 \text{ } \mu\text{atm}$,
Hydrogen $< 5000 \text{ } \mu\text{atm}$.

* At atmospheric pressure, $1 \text{ } \mu\text{atm} \approx 1 \text{ ppm}$ by volume.

The GA Structural Materials Department (SMD) evaluated the makeup of the total oxidants as

$$\text{H}_2\text{O} < 50 \text{ } \mu\text{atm},$$

$$\text{CO} < 450 \text{ } \mu\text{atm},$$

$$\text{CO}_2 < 2 \text{ } \mu\text{atm}.$$

The likely hydrogen level was estimated at less than 1500 μatm . Thus, the following recommendation for helium purity levels for test purposes was

$$\text{H}_2\text{O} < 50 \text{ } \mu\text{atm},$$

$$\text{CO} < 450 \text{ } \mu\text{atm},$$

$$\text{CO}_2 < 2 \text{ } \mu\text{atm},$$

$$\text{CH}_4 < 50 \text{ } \mu\text{atm},$$

$$\text{H}_2 < 1500 \text{ } \mu\text{atm}.$$

This will give a $\text{H}_2/\text{H}_2\text{O}$ ratio of 30/1. It should be noted that this was a design impurity level based on a small but continuous water leak from the steam generators into the primary helium coolant.

The SMD studies point out that it is unlikely that a large commercial HTGR would operate for long periods of time with such a water leak. Peach Bottom and Dragon operating experience indicate that it is probable that the reactor will operate for substantial periods with very dry helium atmospheres. The SMD estimate of these dry helium impurity levels is

$$\text{H}_2\text{O} < 1 \text{ } \mu\text{atm},$$

$$\text{CO} < 10 \text{ } \mu\text{atm},$$

$$\text{CH}_4 < 20 \text{ } \mu\text{atm},$$

$$\text{CO}_2 < 1 \text{ } \mu\text{atm},$$

$$\text{H}_2/\text{H}_2\text{O} \text{ ratio} > 1000/1.$$

In the general friction and wear literature, it is widely recognized that low oxidation potentials (or high H_2/H_2O ratio) cause an increase in the friction coefficient between two surfaces. For the HTGR thermal barrier design, high friction coefficients at the mid-edge retainer (MER) sliding interface could, in turn, cause higher chatter loads. In the chatter program test specification (Ref. 7) an attempt was made to balance the lack of helium mixing (and purification) facilities of test laboratories and the requirement to maximize friction coefficients. The compromise chosen initially was the following uniform low impurity level for all gas constituents:

$$H_2O < 5 \text{ } \mu\text{atm}$$

$$CO < 5 \text{ } \mu\text{atm}$$

$$CO_2 < 5 \text{ } \mu\text{atm}$$

$$H_2 < 5 \text{ } \mu\text{atm}$$

$$CH_4 < 5 \text{ } \mu\text{atm}$$

$$N_2 < 5 \text{ } \mu\text{atm}$$

However, subsequent evaluation of the Boeing test procedure (Ref. 9) and further evaluation of other fibrous insulation tests indicated that it was improbable that the helium atmosphere would attain the low impurity level in the specification. It was felt that it would be more realistic if the allowable moisture level were made the same as in the steam-cycle plant design basis allowable, i.e., 50 μatm moisture. To maintain a high friction-inducing atmosphere, it was necessary to increase the hydrogen level in the helium supply to 5000 μatm . Thus, the impurity levels finally recommended for Phase I of the chatter test program were as follows:

1. Helium Supply Impurity Levels

$$H_2O < 2 \text{ } \mu\text{atm}$$

$$CO_2 < 5 \text{ } \mu\text{atm}$$

$$\text{CH}_4 < 5 \text{ } \mu\text{atm}$$

$$\text{CO} < 5 \text{ } \mu\text{atm}$$

$$\text{N}_2 < 5 \text{ } \mu\text{atm}$$

$$\text{H}_2 \approx 5000 \text{ } \mu\text{atm}$$

2. Autoclave Outlet Helium Purity

$$\text{H}_2\text{O} < 50 \text{ } \mu\text{atm} \text{ average throughout test (100 } \mu\text{atm maximum allowable),}$$

$$\text{CH}_4 < 50 \text{ } \mu\text{atm}$$

$$\text{CO}_2 < 5 \text{ } \mu\text{atm}$$

$$\text{CO} < 450 \text{ } \mu\text{atm}$$

$$\text{N}_2 < 5 \text{ } \mu\text{atm}$$

$$\text{O}_2 < 1 \text{ } \mu\text{atm}$$

$$\text{H}_2 \approx 5000 \text{ } \mu\text{atm}$$

During the tests, helium impurity levels were high and variable (particularly H_2O , H_2 , and O_2). For the repeat of test 1, therefore, the specified impurity levels were modified as follows:

1. Helium Supply Impurity Levels

$$\left. \begin{array}{l} \text{O}_2 \\ \text{H}_2\text{O} \\ \text{CO}_2 \\ \text{CH}_4 \\ \text{CO} \\ \text{N}_2 \end{array} \right\} \text{ total less than } 10 \text{ } \mu\text{atm}$$

$$\text{H}_2 \approx 5000 \text{ } \mu\text{atm}$$

2. Autoclave Outlet Helium Purity

$\text{H}_2\text{O} < 150 \text{ } \mu\text{atm}$ average (or 300 μatm maximum)

$\text{CH}_4 < 50 \text{ } \mu\text{atm}$

$\text{CO}_2 < 5 \text{ } \mu\text{atm}$

$\text{CO} < 450 \text{ } \mu\text{atm}$

$\text{O}_2 < 1000 \text{ } \mu\text{atm}$

$\text{N}_2 < 4000 \text{ } \mu\text{atm}$

$\text{H}_2 \approx 5000 \text{ } \mu\text{atm}$

This was expected to give a minimum H_2/O_2 ratio at the test MER of about 10/1.

B.2. IMPURITY LEVELS ACHIEVED DURING TEST NO. 2

The helium impurity data measured during test No. 2 are summarized in Figs. B-1 and B-2.

B.3. IMPURITY LEVELS ACHIEVED DURING REPEAT OF TEST NO. 1

The helium impurity data during the repeat of test 1 are summarized in Figs. B-3 and B-4.

During the review of test No. 1, all impurities were within the modified test specification (Ref. 8) for the entire test period.

Fig. B-1. Moisture levels during test No. 2

Fig. B-2. Impurity levels during test No. 2

Fig. B-3. Moisture levels during test No. 1 (repeat)

Fig. R-4. Impurity levels during test No. 1(repeat)

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