TESTING AND ANALYSES OF A HIGH TEMPERATURE THERMAL BARRIER FOR GAS-COOLED REACTORS

W. E. BLACK, W. S. BETTS

General Atomic Company,
P.O. Box 81608, San Diego, California 92138, U.S.A.

P. FELTEN

Commissariat à l'Energie Atomique, Direction des Relations Internationales,
33, rue de la Fédération, Cedex 15, F-75752 Paris, France

Summary

A full size, multi-panel section of a thermal barrier system was fabricated from a nickel-base superalloy and a combination of fibrous blanket insulation materials for specific application in a steam cycle gas-cooled nuclear reactor. The 2.4 m square array was representative of the sidewall of the lower core outlet plenum and included cover-plates, attachments, seals, and a simulated water-cooled liner.

Testing was conducted in a reactor grade, helium-filled chamber at 816°C for 100 hours, which established a normal (baseline) condition; 982°C for 10 hours, which satisfied an emergency condition; 1093°C for 1 hour, which simulated a faulted condition; and 1260°C, which was a non-design condition test to demonstrate the temperature overshoot capability of the system.

Post-test examination indicated: (1) an acceptable performance by the anti-friction chromium carbide (Cr_3C_2) coating; (2) no significant galling between non-coated surfaces; (3) no distortion of attachment fixtures; (4) predictable coverplate deflection during the design conditions testing (normal, emergency, and faulted); and (5) considerable plastic deformation resulting from the near-incipient melting temperature.

A finite element elastic analysis and creep analysis were conducted for the thermal barrier configuration model and for the tested conditions. The elastic analysis indicated a relatively small deflection of less than 2.5 mm and a relatively high maximum stress of 110 MPa. The peak stress decreased rapidly with distance from the attachment cutout to 24 MPa in the center of the plate. The creep analysis clearly showed the stresses redistributing with time. During the 100-hour test at 816°C, the predicted coverplate deflection increased to a maximum value that was in close agreement with the measured value of 9.2 mm. During the same time, the peak stress decreased from 110 MPa to 26 MPa, while the minimum stress decreased from 24 MPa to 15 MPa. During the 982°C test, the maximum deflection increased significantly to 16.9 mm; however, the stress distribution in the plate did not change significantly.

1. Introduction

Thermal barriers are used in conjunction with a cooling water system to protect the steel liner and concrete of a prestressed concrete reactor vessel (PCRV) from exceeding defined temperature limits. For the steam cycle high-temperature gas-cooled reactor (HTGR) in question, the approximate average temperatures are maintained below 65°C at the liner/concrete interface. The primary coolant (helium) temperatures range from about 316°C for the core inlet to about 816°C for the local core outlet.

It was recognized early in the design and development program that full size testing of typical thermal barrier components would be necessary to demonstrate their capability to withstand normal and abnormal operational conditions. Hence, a test program was established by the General Atomic Company and the French Commissariat a l'Energie Atomique to develop a reliable thermal protection system.

To qualify the system, two sets of operational conditions were defined:

(a) Short-term tests at temperatures simulating conditions that could occur during a postulated period if there was a delay in initiating emergency core cooling.

(b) Long-term tests simulating normal conditions.

It is the accident conditions as experienced by the high-temperature thermal barrier in the core outlet region toward which this paper is directed.

2. Thermal Barrier Design

General Atomic's basic thermal barrier design consists typically of multiple layers of fibrous ceramic insulation installed on the helium side of the PCRV liners. The insulation blankets are compressed uniformly against the liner by coverplates, seal sheets, and multiple attachments (Figure 1). The attachment fixtures consist of a center post (Figure 2), which locates an individual coverplate, and peripheral attachments (Figure 3), which are designed to accommodate relative thermal movements between the coverplates and the liner. All attachments are designed to minimize heat transfer to the liner. The seal sheets prevent the fibrous insulation from migrating by overlapping the individual coverplates and thereby positively retaining the blankets. This allows the coverplates to be designed with relatively liberal edge clearances to minimize installation irregularities. The insulation blankets are beveled on all sides, and mate with correspondingly shaped blankets to assure that there are no gaps within the assembly. This basic system, with modifications as dictated locally by geometric and environmental conditions within the primary circuit, is used throughout the steam cycle plant.

The high-temperature thermal barrier utilizes the aforementioned design and employs the nickel-base alloy Hastelloy-X (Ni, 22 Cr, 1.5 Co, 9 Mo, 0.6 W, 19.5 Fe) for all coverplates, seals, and attachment fixtures. The insulation blanket assemblies consist of composite high- and low-temperature fibrous materials. For the tested design, the cooler portion (less than 500°C) was composed of Triton Kaowool alumina silica blanket insulation, while the hotter portion was composed of Quartz et Silice, a high purity silica material.

This class of thermal barrier is suitable for service in areas on the core outlet side of the primary coolant loop where the hot face might be exposed to local temperatures up to about 816°C. This design is required also to accommodate temperature excursions for a maximum of 10 hours total accumulation at 982°C without any damage. It is also required to withstand a 1-hour excursion to a maximum temperature of 1093°C without failure. For this test, an added temperature condition was imposed: 1260°C, which is termed ultimate. This temperature is near the incipient melting temperature of the coverplate material, and it demonstrates a significant margin of temperature overshoot.

3. Test Model and Instrumentation

The central test panel and the attachment fixtures (Figure 4) were faithful models of the true design. The main panel was 878 by 926 by 9.5 mm thick. It was surrounded by partial panels to simulate edge effects, and all were incorporated into a configuration 2360 by 2360 mm. As a cost consideration, the corner panels and their attachments were fabricated from AISI 309 austenitic steel. In order to reduce friction forces, the contact surfaces of the washers and coverplates were flame-spray-coated with chromium carbide (Cr_3C_2).

Two specimens were fabricated and assembled in the manner shown in Figure 5. When assembled to the central heater fixture, the specimens constituted an autoclave. The symmetric autoclave configuration permitted the testing of a further criterion: a "failed" attachment fixture. This condition was simulated by simply removing the nut and washer (see Figure 3) from one of the mid-edge retainers.

Instrumentation of the model was provided by thermocouples, displacement sensors, and force sensors. In addition, measurements were made of chamber pressure, moisture, and gas composition.

4. Test Procedure

After measuring the initial force exerted by the insulation and establishing the reference coverplate deflections, dry reactor grade helium (<500 µatm $CO + CO_2 + H_2O$, <1500 µatm H, <50 µatm CH_4) was fed into the chamber and increased to a pressure of approximately 1.4 bars. The chamber was heated at a rate of 5°C per second until the maximum temperature for each test series was reached:

		Duration (h)	
Condition	Temperature (°C)	Test	Design
Normal	816	100	280,000
Emergency	982	10	10
Faulted	1093	1.25	1
Ultimate	1260	<1	0

The normal reactor lower core outlet temperature of 816°C was held for 100 hours in order to stabilize the system. Cooldown was at a rate of approximately 5°C per second. A slight time deviation occurred during the faulted test due to equipment problems; the test time was 1.25 hours instead of the planned 1 hour.

During each test, the main coverplate deflection and the insulation pressure were continually recorded. Visual inspections were made after each test, and complete disassembly and inspection were performed following the ultimate test.

5. Test Results

The entire structure completed the test series without any structural failure. The test specimens and the heating unit are shown, following exposure to 1260°C, in Figure 5. In general, the configuration performed in a predictable manner. That is, the insulation forces relaxed, and the coverplates and seal sheets deformed progressively with time at temperature.

It can be seen from Figure 6 that the maximum pressure exerted by the insulation, as recorded by sensor F4, decreased from 21 kPa at the beginning of testing to 12 kPa after 100 hours at 816°C. Further decrease to 2.5 kPa is shown at the end of 1.25 hours at 1093°C. The mean values recorded by the three insulation pressure sensors were: initial force, 18.5 kPa; after 100 hours at 816°C, 9.7 kPa; after 10 hours at 982°C, 6.1 kPa; after 1.25 hours at 1093°C, 1.7 kPa; and after 0.25 hour at 1260°C, 0.5 kPa.

The gradual decrease in pressure is to be expected due to fiber creep. Also, due to the high silica content of the insulation, additional loss of strength and ductility can be expected above 900°C since a phase change from quartz to cristobalite occurs in this temperature regime.

The behavior of coverplate deformation, as recorded by the five deflection sensors for the various temperature conditions, is shown in Figure 7. Considering the locations of the sensors, the deflection magnitudes were as might be expected. For example, sensor D8 at the corner of the coverplate consistently exhibited the greatest deflection. Conversely, the sensors located approximately midway between the central and mid-edge attachment (D6 and D10) exhibited the lowest and almost identical deflections.

With respect to the general behavior of the system, a slight buckling of the seal sheets between the coverplates was observed after the test at 1260°C. However, no evidence of self welding was found, and only very slight wear due to rubbing was noticed. In those regions where chromium carbide was used to preclude galling of the Hastelloy-X sliding surfaces, no spallation was found. An overall view of the specimen after the 1260°C test is shown in Figure 8 together with closeups of an intersection and a low profile view.

6. Analytical Evaluation

The coverplate configuration shown in Figure 4 was analyzed using the MARC computer code. The computer model simulated one-quarter of the plate as indicated. It had 20 rectangular elements and 30 node points, and each element was divided into 9 integration points with 11 layers through the thickness for a total of 1980 stress points.

The material properties of Hastelloy-X were input as indicated below.

Poisson's ratio $\nu = 0.32$

Creep constituitive relationship $\epsilon = A\sigma^B t^C$

where ϵ = creep strain, %

σ = stress, ksi

t = time, h

T = temperature, °F

$A = 10^{-(U_4/T + U_5)/D}$

$B = -U_1/(TD)$

$C = 1/D$

$D = U_2/T + U_3$

Young's modulus E = f(T):

T (°C)	E (10^3 MPa)
24.4	196.5
100	193.5
200	185.5
300	179.0
400	172.1
500	164.1
600	157.8
700	150.1
800	142.6
900	134.3
1000	126.4

For Hastelloy-X between 732°C and 982°C, $U_1 = -1.085 \times 10^4$, $U_2 = 4.694 \times 10^3$, $U_3 = -0.8981$, $U_4 = 4.95 \times 10^4$, and $U_5 = -17.86$.

The analyses simulated the 100-hour test at 816°C, and the 10-hour test at 982°C. The coverplate temperature and the insulation pressure load on the plate were input as measured, while the coverplate deflections and stresses were calculated by the MARC code. Figure 9 compares the calculated coverplate deflection at location D8 (in Figure 7) with that recorded during the test. The first 60 hours at 677°C did not significantly affect the plate deflection. However, after the temperature increased to 860°C (at 70 hours) the deflection increased significantly. The computed deflection using strain hardening correlated well with the test data. However, once the temperature decreased to 816°C (at 85 hours) the deflection using strain hardening underpredicted the measured deflection. When time hardening was used after the temperature decreased to 816°C, the calculated deflections again correlated well with the test data.

Based on this, it appears that in a given situation the most conservative of the two hardening laws (i.e., the one that yields the larger deflection) is the one that should be used. In the case presented here, this means that when the temperature is increased above a value previously specified, strain hardening should be used; however, when the temperature is decreased below a temperature previously specified, time hardening should be used. This approach was used to calculate the plate deflection during the 10-hour test at 982°C. As indicated in Figure 9, the deflection recorded after the 10-hour test correlated well with the calculated deflection.

Figure 10 shows how the calculated stresses in the plate changed with time. A stress initially (i.e., the elastic stress) at 105 MPa decreased to 26 MPa after the 100-hour test at 816°C. During the 100-hour test at 816°C, most of the reduction in the high stresses near the attachment fixtures was due to stress redistribution. The general decrease in stress that occurred during the 10-hour test at 982°C was due to a reduction of the pressure load on the plate, which was caused by a reduction of the insulation pressure loading, as indicated in Figure 6.

The results show that while the stress distribution in the plate did not change significantly during the 10-hour at 982°F accident condition tests, the deflection of the coverplate increased appreciably.

7. Conclusions

The tested thermal barrier model performed in a predictable manner, both thermally and structurally. Clearly, the design sustained the postulated 10-hour emergency and 1-hour faulted conditions without jeopardizing the integrity of the structure or insulation. Exposing the structure to 1260°C, which is well beyond any condition anticipated during reactor operation, further demonstrated the capability of the system to exceed design temperatures.

When performing creep analysis of a Hastelloy-X coverplate, the best correlation with the test data occurred when a combination of time hardening and strain hardening was used. The analysis also showed that the elastic stresses rapidly redistributed so that the stresses throughout the coverplate became fairly uniform.

8. Acknowledgements

The authors express their appreciation to J. J. Quillico and E. G. Tomachevsky of CEA DEMT for conducting and managing the tests, and S. A. Lightner of General Atomic for data analysis.

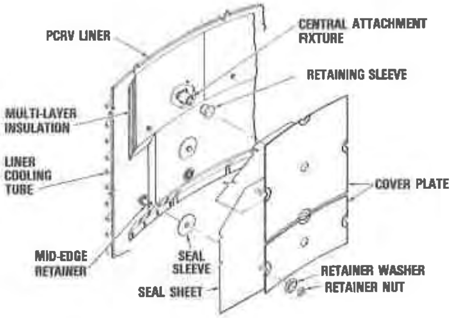

Figure 1. Thermal barrier on PCRV side walls

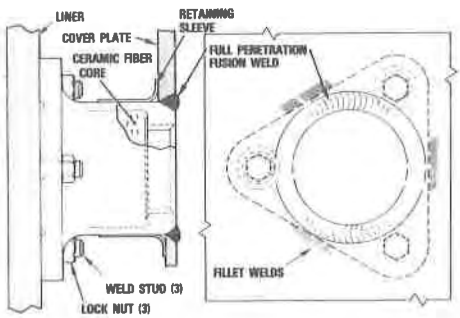

Figure 2. Central attachment fixture for thermal barrier

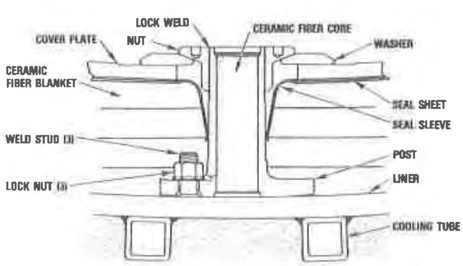

Figure 3. Mid-edge retainer for thermal barrier

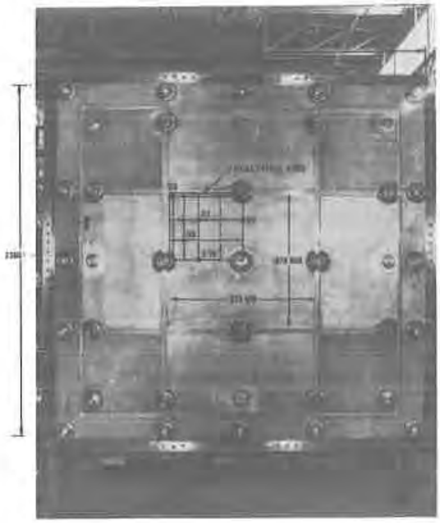

Figure 4. Test specimen before exposure

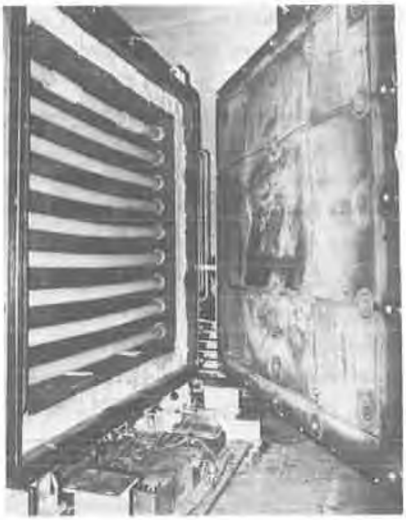

Figure 5. Test autoclave and specimens after thermal exposure

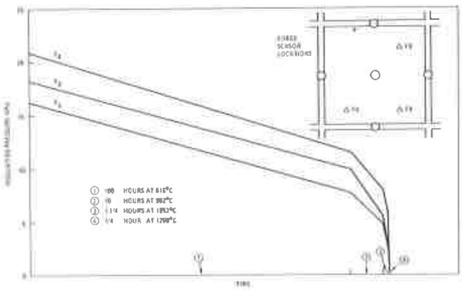

Figure 6. Behavior of the insulation pressure as a function of time

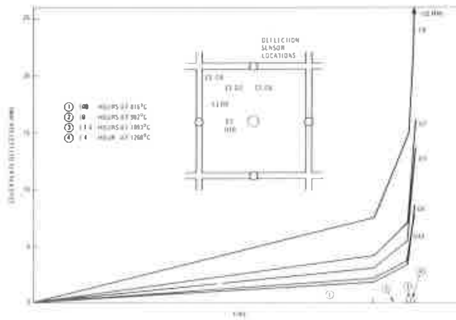

Figure 7. Behavior of the coverplate deformation as a function of time

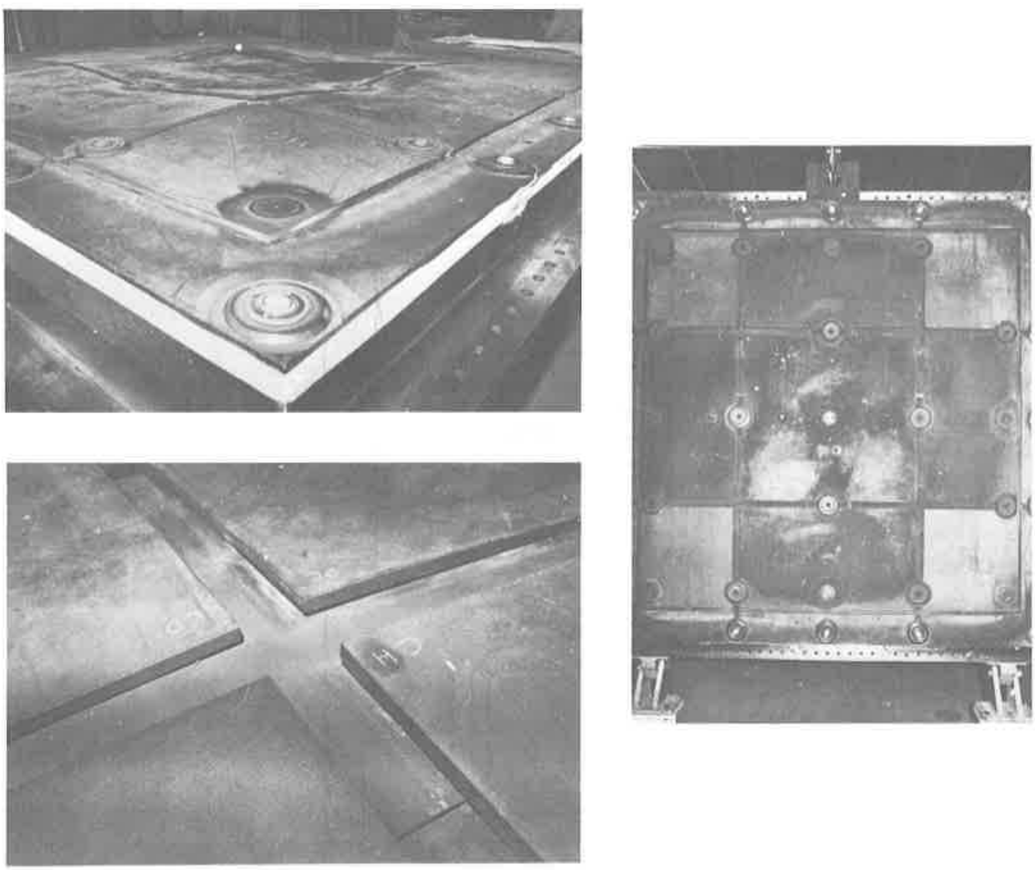

Figure 8. Specimen views after 1260°C test

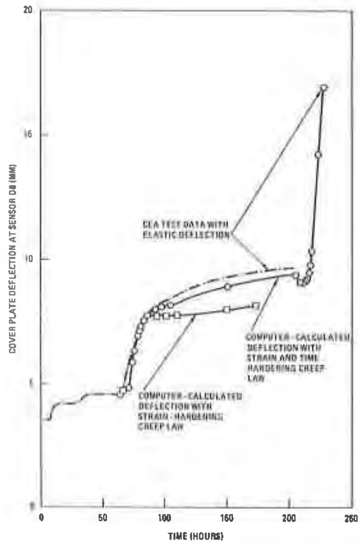

Figure 9. Coverplate deflection (D8) as a function of time as measured and as calculated

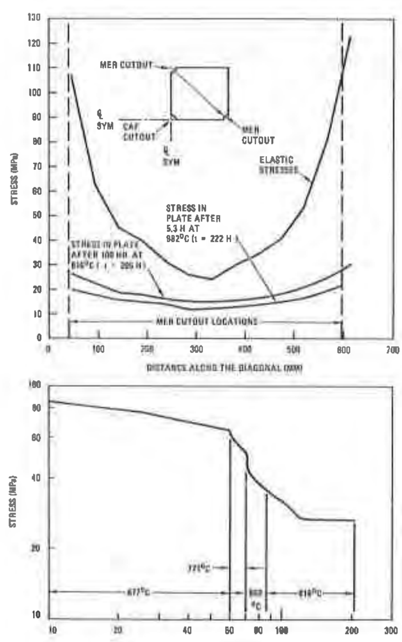

Figure 10. Predicted stress for main coverplate