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

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ABSTRACT

A 0.6 scale model of a steam cycle gas-cooled reactor high temperature duct was tested in a closed loop helium facility. The object of the test series was to determine : 1) the thermal effects of gas permeation within the thermal barrier, 2) the plastic deformation of the metallic components, and 3) the thermal performance of the fibrous insulation.

A series of tests was performed with thermal cyclings from 100°C to 760°C at 50 atmospheres until the system thermal performance had stabilized hence enabling predictions for the reactor life. Additional tests were made to assess permeation by deliberately simulating sealing weld failures thereby allowing gas flow by-pass within the primary thermal barrier.

After 100 cycles the entire primary structure was found to have performed without structural failure. Due to high pressures exerted by the insulation on the cover plates and a design oversight, the thin seal sheets were unable to expand in an anticipated manner. Local buckling resulted.

Pre and post test metallurgical analyses were conducted on the Hastelloy-X structures and reference specimens. The results gave evidence of aging in the form of noticeable changes in room temperature tensile and reduction in area parameters. The Hastelloy-X welds exhibited greater changes in properties due to thermal aging. The antifriction coating ($Cr_3 C_2$) performed well without spallation or excessive wear.

The insulation retained an acceptable degree of resiliency. However, some fiber damage was observed within both the high and low temperature insulation blankets. Also a chemical reaction between the silica insulation and chromium from the metallic structures was noted. The result was a thin, hard, sintered layer immediately adjacent to the hot surfaces, but performance was not degraded.

A thermal analysis was conducted to correlate the hot duct heat transfer results with those obtained from the analytical techniques used for the HTGR design using a computer thermal model representative of the duct and test setup. The thermal performance of the insulation, the temperature gradient through the structural components, the heating load to the cooling system and the permeation flow effect on heat transfer were verified. Excellent correlation between the experimental data and the analytical techniques were obtained. The results of the thermal analysis can be summarized as follows :

(a) Temperature gradients along thermal sleeves can be accurately predicted.

(b) Temperature distribution along the retainers and attachment fixtures can be accurately

estimated.

(c) The heating load to the liner cooling system can be calculated with existing techniques.

(d) The permeation flow effect on the thermal barrier heat transfer performance can be predicted.

1. Introduction

The French Commissariat à l'Energie Atomique and General Atomic Company have been carrying out a research and development program in the field of high temperature gas cooled reactors /1/.

This program emphasizes particularly the thermal insulation aspect of the high temperature reactors.

In the frame of this program, a 0.6 scale model of a steam cycle gas cooled reactor high temperature duct was tested in a closed loop helium facility.

The aim of the test series was to determine the thermal performance of the fibrous insulation, the thermal effects of gas permeation within the thermal barrier and the possible plastic deformations of the metallic components.

The effect of thermal cycling on those parameters was checked.

2. Model Description

The model is an exact duplication of the insulation of the lower cross-duct of an HTGR reactor except for the scale which is 0.6.

The insulation itself is made of ceramic fibers pressed against the liner by cover plates. Those cover plates are themselves fastened to the liner by the means of fixtures (See figures 1, 2, 3).

To protect the insulation from the pressure gradient in the duct a thermal shield attached to the thermal sleeve is built in. All metallic parts on the hot side are made out of Hastelloy X alloy. The liner itself is made out of carbon steel. On its outer side, cooling tubes are welded. These tubes are also used to monitor the heat load of the duct. The insulating fibers are kaowool on the cold side and quartz and silice fibers on the hot side.

3. Experimental and Analytical Techniques

A cross section of the model along with the instrumentation location is shown in Fig.1, while Fig. 2 shows the peripheral and central attachment fixtures along with typical dimensions. The heat transfer rate to the liner were obtained by measuring the increase in temperature and flow rate of the water in the cooling tubes system subdivided in twelve zones using the equation :

$$\dot{q}'' = \frac{\dot{m}c_p}{A} (T_{out} - T_{in}) \tag{1}$$

where :

$\dot{q}''$ = heating rate to liner

$\dot{m}$ = mass flow rate of water

c_p = specific heat of water

A = liner surface area of the zone

T_{out} = water outlet temperature to zone

T_{in} = water inlet temperature to zone

The thermal conductivity of the thermal barrier were then obtained from :

$$k = \frac{\dot{q}''L}{(T_{cp}-T_L)} \tag{2}$$

with :

k = thermal conductivity T_{cp} = cover plate temperature

L = thermal barrier thickness T_L = liner temperature

In general, three sets of data points were taken during each thermal cycle which consisted in heating up the model for about four hours to the test conditions temperature which was maintained for approximately four hours, during which data were taken and a cooldown of at least four hours.

Analytical methods based on the principles of conservation of mass, momentum and energy have been developed for application to the design of the HTGR thermal barrier. These are contained in the heat transfer and fluid flow computer codes of References /2/ and /3/. In most applications thermal analysis are performed using the TAC-2D code which detailed the temperature distributions on thermal models. Material properties that are a function of temperature are evaluated locally for each node point within the analytical model. Local bulk fluid temperatures are evaluated and used to compute temperature-dependent fluid properties, Reynolds numbers and film coefficients.

4. Test Conditions

The tests were carried out in dry helium at 50 atmospheres. Cycling from 100°C (212°F) to 760°C (1400°F) were performed until the change in performance with cycling was no longer experienced to permit predictions for the reactor life.

Overall cross duct differential pressure up to 7000 Pa ($\sim$ 1 psi) were simulated.

The effects of helium permeation due to a weld failure at the inlet of the thermal shield of the duct were simulated by drilling holes at the inlet lip which permitted hot helium to enter in the interspace between the thermal shield and cover plate.

The test model was subjected to 100 thermal cycles. The instrumentation consisted in measuring the helium gas flow, its pressure, velocity and temperature. In addition, temperature data were obtained on a peripheral and a central attachment fixture.

This study used three thermal computer models : an overall model of the cross duct, a central fixture model and a peripheral fixture model to verify their thermal response to the test conditions using the analytical techniques for HTGR design.

5. Results and Discussions

As far as general behaviour is concerned, after 100 cycles, the entire primary structure was found to have performed without structural failure. Due to high pressures exerted by the insulation on the cover plates the thin seal sheets were unable to expand in an anticipated manner. Local buckling resulted.

Pre and post test metallurgical analyses were conducted on the Hastelloy X structures and reference specimens. The results gave evidence of aging in the form of noticeable changes in room temperature tensile and reduction in area parameters. The Hastelloy X welds exhibited greater changes in properties due to thermal aging. The antifriction coating (Cr_3C_2) performed well without spallation or excessive wear.

The insulation retained an acceptable degree of resiliency. However, some fiber damage was observed within both the high and low temperature insulation blankets.

Also, a chemical reaction between the silica insulation and chromium from the metallic structure was noted. The result was a thin, hard sintered layer immediately adjacent to the hot surfaces, but performance was not degraded.

The thermal performance of the insulation system was verified using data from three test runs to cover a wide range of temperatures. Heating rates along with cover plate, insulation and liner temperatures were selected in a region of the cross duct model not influenced by structural components such as supports and attachment fixtures. The values of the thermal conductivity are shown on Fig. 4 along with the estimated high and low values of Kaowool. It is noted that the experimental data agree more closely with the low value for Kaowool for temperatures up to 370°C (700°F) and is about at mid-point between the low and high values at higher temperatures. Based on these results, the low value of the insulation thermal conductivity was used in the simulation.

The insulation system of the thermal barrier consisted of a 38 mm (1.5") blanket of Quartz and Silice (just below the cover plate) and two blankets of 1" each of Kaowool, compressed to about 75 % to a total thickness of 65.5 mm (2.58"). The temperature distribution through the insulation is shown in Fig.5 for the three test runs selected. As noted, very good correlation between the experimental data and the TAC-2D computer simulation is obtained. The computer data were taken from the overall cross duct thermal model at locations away from the thermal sleeve, the inlet and outlet regions to minimize their influence on the temperature distribution. The experimental thermocouples temperature data were also selected on that basis.

The temperature distributions along the thermal sleeve (Hastelloy-X material) is shown in Fig.5, where in general, excellent correlation is obtained between the prediction and the experimental data. The temperature gradient along the sleeve is consistent with the experimental data.

The temperature gradients along the length of the peripheral and central attachment fixtures as obtained from the computer simulation are shown on Fig. 7 and 9 respectively. Most of the experimental data and the computer results agree fairly well with the exception of the thermocouple data on the top of the central attachment fixture in Fig.8 which appear to be reading temperature much higher than expected on the top of the fixture. In fact, it gives temperature at about the value of the cover plate.

Since the heat load to the cooling water system is available both from experiments and the computer simulation, a comparison was made for the cross duct models. It was found that with the effect of the attachment fixtures taken into account in the computer thermal model, the total heat load to the liner could be predicted to within an accuracy of about 1 %.

The effect of permeation flow on heat transfer to the liner cooling system was also verified. Permeation flow into the thermal barrier was induced from drilled holes at the inlet of the model to simulate a weld failure and by a pressure drop from the inlet to outlet of the duct. This caused a flow of hot helium over the cover plate.Experimental data on heating load with and without the holes were used and they are shown in Fig.9.

6. Conclusions

The 0.6 scale hot duct test results were correlated with the analytical techniques used for the HTGR thermal barrier design. The experimental data of selected test runs gave good agreement with the methods presently used for thermal designs.

Due to its close agreement with the test data, the low value of the thermal conductivity of Kaowool was used in this analysis. However, for the actual design the high value for Kaowool is recommended to account for insulation degradation in long term use.

The predictions for the temperature gradients along the thermal sleeve was excellent while for the temperature distribution along the attachment fixtures were fairly accurate.

The theoretical estimate of the heating load to the liner cooling system to within 1 % of the experimental data on the cross duct overall model, which substantiate the technique used to calculate this heat load.

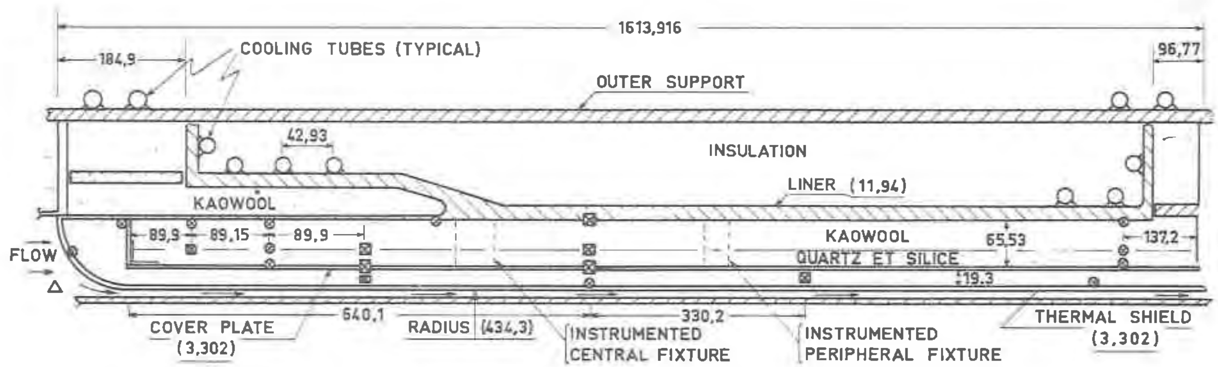
Experimental data indicate that the permeation flow problem from a simulated weld failure at the inlet on the existing thermal barrier design is small and represents an increase of 3 % for a pressure drop of 3500. Pa (o.5 psi).

References

/1/ RASTOIN, J. and BRISBOIS, J., "Gas Cooled Reactor Experience and Programs in France", Annals of Nuclear Energy Vol 5, pp 455-488 - 1978.

/2/ BOONSTRA, R.H., "TAC-2D - A General Purpose Two-dimensional Heat Transfer Computer Code-User's Manual", GA-A 14032, July 15, 1976.

/3/ BAXI, C.B., "Porous - A General Purpose Code to Calculate the Steady-State Velocity and Temperature Distribution in a Porous Medium", GA-D 12767, February 1974.



NOTE :
SKETCH NOT TO SCALE

⊗ FOUR THERMOCOUPLES EVERY 90° FROM TOP OF MODEL
⊠ TWO THERMOCOUPLES EVERY 180° FROM TOP OF MODEL
△ FOUR THERMOCOUPLES IN FLOW AT 45°, 135°, 225° & 315° FROM TOP OF MODEL

FIG 1 HOT DUCT 0.6 SCALE MODEL WITH INSTRUMENTATION

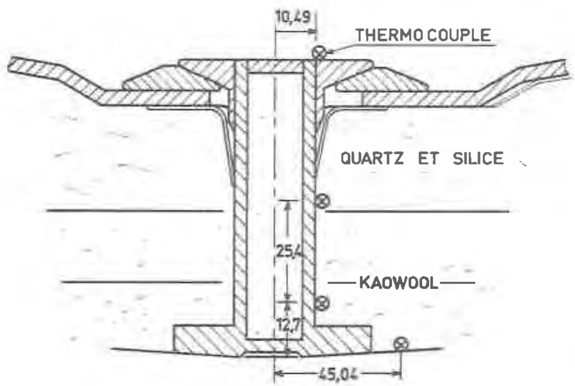


FIG 2 PERIPHERAL FIXTURE

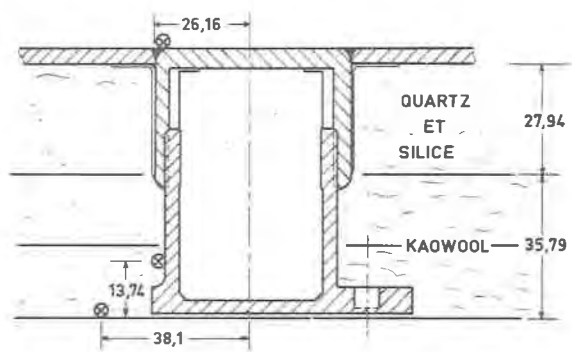


FIG 3 CENTRAL FIXTURE

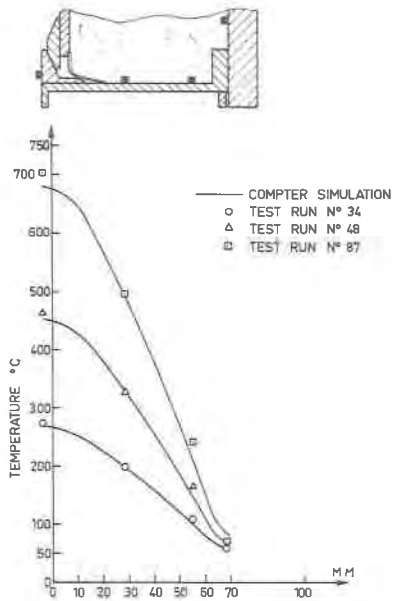


FIG 7 TEMPERATURE DISTRIBUTION ALONG A PERIPHERAL FIXTURE

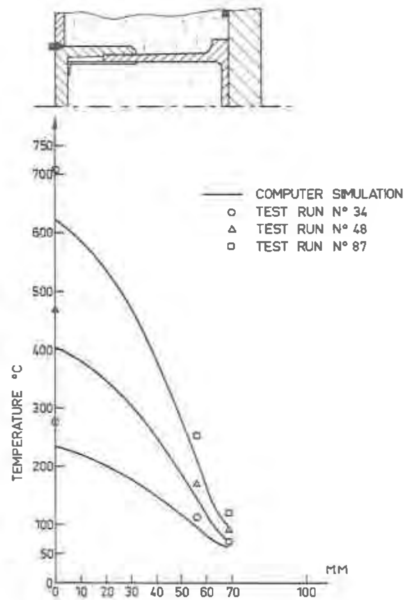


FIG 8 TEMPERATURE DISTRIBUTION ALONG A CENTRAL FIXTURE

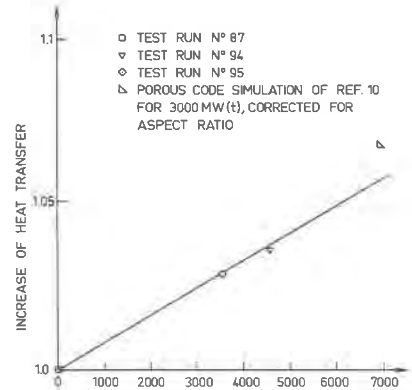


FIG 9 EFFECT OF PERMEATION FLOW ON HEAT TRANSFER

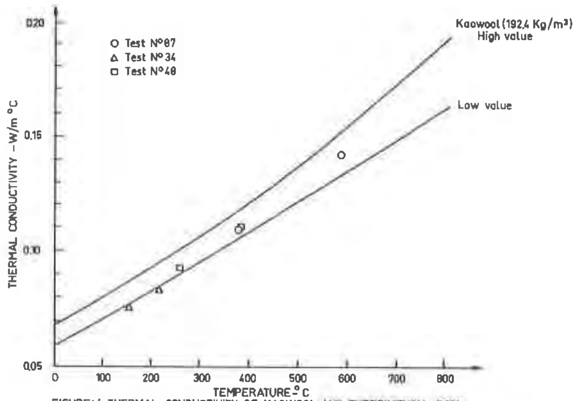


FIGURE: 4 THERMAL CONDUCTIVITY OF KAOWOOL AND EXPERIMENTAL DATA

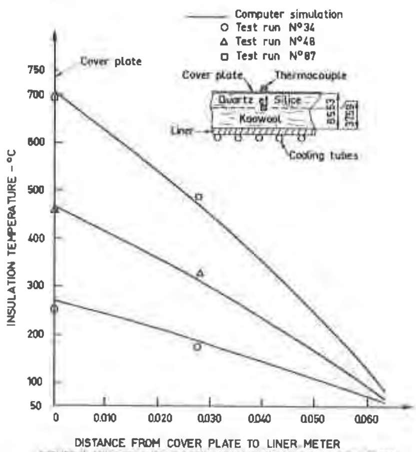


FIGURE 5 TEMPERATURE DISTRIBUTION THROUGH THE INSULATION

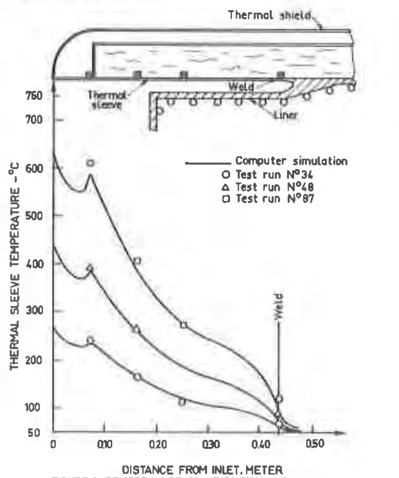


FIGURE 6 TEMPERATURE DISTRIBUTION ALONG THERMAL SLEEVE