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Performance of Insulating Materials for Future Fusion Blankets

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INTRODUCTION

In all fusion reactors using the deuterium-tritium fuel cycle, a large fraction (~ 80 percent) of the fusion energy will be released as ~ 14 MeV neutrons. These neutrons must be slowed down in a relatively thick blanket surrounding the plasma and their kinetic energy converted to high temperature heat. This heat will be continuously removed from the blanket by a coolant system and either converted to electricity or used in a process to produce synthetic fuels, for example, the electrolysis of steam at high temperatures for the production of hydrogen and oxygen.

In either case high temperature operation of the blanket will be of interest. A blanket cooled with helium subject to typical HTGR conditions may operate at maximum temperatures of $\sim 800^\circ\text{C}$ while electrolysis of steam may require passage of steam through the blanket at temperatures in excess of 1000°C .

While there have been a number of ideas for the design of high temperature blankets, BNL designs have focused on a two-temperature zone blanket concept. The cool zone ($\sim 300^\circ\text{C} - 400^\circ\text{C}$) is the outer metallic shell interfacing the plasma. The hot zone comprises the materials inside the structural shell which vary depending on the application. For the electricity/tritium breeding blankets, the hot zone may include graphite, beryllium, and solid lithium compounds cooled by helium while the process steam cooled blanket may include alumina or zirconia.

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In either case the two zones will be thermally isolated or insulated by a low conductivity insulator. A conceptual design of a fusion blanket is shown in Figure 1.

Critical to the successful operation of the two temperature zone blanket concept is the performance of the insulator. In addition to low thermal conductivity the insulating material should have high resistance to radiation damage, should maintain its structural integrity in the coolant/radiation environment, and should have low density to minimize total internal heat generation within

EXPERIMENTAL TEST APPARATUS

Thermal conductivities of five candidate insulating materials were determined in the temperature range of 300 to 1000°C in air, argon, and helium @ 1 atm so that a comparison would be made with existing data. These were done in a non-nuclear environment. The test apparatus was a cylindrical shell cooled with water flowing through tubes attached to the shell (Figure 2). The insulation to be tested lined the inner part of the shell which was heated along the axis of the cylinder with a single electric rod heater (Figure 3).

Axial temperature gradients were minimized to assure radial heat flow so that the thermal conductivity could be determined by the equation:

$$Q = \frac{2.73 \cdot L \cdot K \cdot \Delta t}{\log_{10} \frac{D_1}{D_2}} \quad (1)$$

where: Q = heat transferred
 K = thermal conductivity of test specimen
 L = length of insulation

Δt = temperature difference across insulation
 D_1 = outer diameter of insulation
 D_2 = inner diameter of insulation

The temperature difference was measured by thermocouples placed at the inner and outer surface of the insulation. The heat transferred to the shell was calculated from the flow rate of the cooling water and the difference between the inlet and outlet water temperatures. The thermal conductivity was then calculated by the equation, (1).

In practice four layers of half-inch thick insulation were used to line the cylinder with twenty-two type K thermocouples placed in four quadrants between the layers. The temperature differences for each quadrant were averaged for the final calculations. Heat leakage from the ends of the insulation was minimized by placing three layers of reflective aluminum foil at each end.

TEST RESULTS

The results of many runs with alumina-silica mat in air were found to agree well with the manufacturer's thermal conductivity data¹ (Figure 4) particularly at the higher temperatures of interest. Results of the alumina-silica mat in argon showed very little difference from the results formed in air (Figure 5). As a consequence of the higher thermal conductivity of helium compared with air and argon, at temperature, the thermal conductivity results for the aluminum silica mat in helium show a large increase compared with those in air. The results are about twice as high as those in air @ 800°C.

Carbon felt² was tested in both argon and helium (Figure 6). The results in argon were similar to the alumina-silica results, and the thermal conductivity in helium was about double that for argon. The thermal conductivity results

of the lower density graphite felt were very similar to those of the carbon felt (Figure 7).

Carbon felt was also tested in combination with the alumina-silica mat. That is using the known values of thermal conductivity for the alumina-silica mat and the respective temperature difference across each insulation layer, the thermal conductivity of the carbon felt was calculated by the following equation:

$$\frac{k_1}{k_2} = 1.456 \frac{\Delta t_2}{\Delta t_1} \quad (2)$$

where the constant accounts for the geometric difference between the two contacting layers of insulation. The thermal conductivity calculated by Eq. (2) gave identical results to the heat measurement method, Eq. (1).

The higher density zirconia fiberboard was fabricated into a cylinder and tested in combination with alumina-silica mat (Figure 8). The zirconia was phase stabilized with 8 percent yttria and the 5 micron fibers bonded with 5 percent zirconium silicate. The thermal conductivity results in air again closely followed the manufacturer's data⁴. The test results in argon were similar to those in air; however, the thermal conductivity in helium was the lowest of the materials tested. At 300°C it was 40 percent lower than the alumina-silica mat and carbon felt. At 800°C the thermal conductivity of the zirconia board was still nearly 20 percent lower than that of the alumina-silica mat and the carbon or graphite felt.

The less dense zirconia felt was also tested in air and argon and the results generally followed the manufacturer's data⁵ (Figure 9). The results in helium at low temperatures indicated a 30 percent higher thermal conductivity than the zirconia fiberboard, but at higher temperatures ($\sim 800^{\circ}\text{C}$) the felt and board thermal conductivities were about the same.

The thermal conductivity tests in helium were limited to temperatures on the order of 800°C due to the power requirements of the heater. The data were extrapolated to obtain the 1000°C values shown in Table I. At this temperature there appears to be not much difference between the five insulations tested. The zirconia felt is the lowest at 0.40 W/m-K and the alumina-silica mat the highest at 0.54 W/m-K .

DISCUSSION OF RESULTS AND MAIN CONCLUSIONS

- The thermal conductivity of any of the insulating materials was markedly increased when tested in helium due to the greater conductivity of the interstitial gas. An exception to this would be a totally closed cell material with totally impermeable cell walls, but such a material is not known at present.
- The helium pressure in a fusion blanket will be on the order of 50 atmospheres, a value much greater than the one atmosphere in which the tests were conducted. On the other hand, the high pressure environment will have little additional effect on those insulating materials whose pore size is already greater than the mean free path of the gas at one atmosphere which was the case for the materials tested.
- Of the materials tested, all have approximately the same thermal conductivity values in the temperature range of interest, which would be acceptable for the blanket applications.

In conclusion, a material to be used for insulation in a fusion blanket module should show high resistance to radiation damage, maintain its structural integrity, and more importantly, have a low thermal conductivity combined with a low density to prevent internal heat generation. The zirconia felt has the lowest thermal conductivity at 1000°C but its density is three times that of the carbon felt and two times the alumina-silica mat density. The graphite felt would give equal insulating properties in helium to the zirconia felt with 25 percent more thickness, and the increase in weight would still make it one of the lightest of the insulations; therefore, at this point, graphite felt would be the preferred insulation.

REFERENCES

1. Babcox & Wilcox data on Kaowool, 8 lbs/ft³, Refractories Division, Augusta, Georgia.
2. Carborundum Company, Graphite Products Division, Sanborn, New York.
3. Union Carbide Corporation, Carbon Products Division, Chicago, Illinois.
4. Zircar Products, Inc., Technical Bulletins ZPI-203 and 205, Florida, New York.
5. Zircar Products, Inc., Technical Bulletin ZPI-207.

THERMAL CONDUCTIVITY
OF
ALUMINA - SILICA MAT*
IN AIR

DENSITY - 8 lbs./ft.³
* 47% Al₂O₃ - 53% SiO₂

THERMAL CONDUCTIVITY
OF

ALUMINA-SILICA* MAT
IN HELIUM, ARGON & AIR

DENSITY - 8 lbs./ft.³
* 47% Al₂O₃ - 53% SiO₂

THERMAL CONDUCTIVITY
OF

CARBON FELT
IN HELIUM & ARGON

DENSITY — 5.0 lbs./ft.³

THERMAL CONDUCTIVITY
OF
GRAPHITE FELT
IN HELIUM & ARGON

DENSITY - 4.0 lbs./ft.³

THERMAL CONDUCTIVITY
OF
ZIRCONIA* FIBROUS
INSULATION BOARD
IN HELIUM, ARGON & AIR

DENSITY - 24 lbs./ft.³

* WITH 8% Y_2O_3
& 5% SiO_2

- - IN HELIUM
- - IN ARGON
- △ - IN AIR

THERMAL CONDUCTIVITY
OF
ZIRCONIA* FELT
IN HELIUM, ARGON & AIR

DENSITY - 14.3 lbs./ft.³

* 8% YTTRIA

THERMAL CONDUCTIVITY OF
INSULATORS IN THE TEMPERATURE
RANGE OF 300 TO 1000°C

Watts/m - °K						
	AIR		ARGON		HELIUM	
	300	1000	300	1000	300	1000
ALUMINA - SILICA MAT 8 lbs./ft. ³	.06	.22	.07	.28	.24	.54
CARBON FELT 5 lbs./ft. ³	—	NA	.11	.29	.24	.51
GRAPHITE FELT 4 lbs./ft. ³	—	NA	.11	.27	.26	.51
ZIRCONIA FIBROUS BOARD 24 lbs./ft. ³	.07	.14	.07	.14	.15	.49
ZIRCONIA FELT 14 lbs./ft. ³	.08	.17	.08	.17	.18	.40