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OAK RIDGE NATIONAL LABORATORY

Operated by

UNION CARBIDE NUCLEAR COMPANY

Division of Union Carbide Corporation

Post Office Box X

Oak Ridge, Tennessee

ORNL
CENTRAL FILES NUMBER

58-6-71

DATE: June 16, 1958

SUBJECT: HRP-Evaluation of Heat Removal Methods for
Controlling Temperatures of an ORR Slurry Bomb

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COPY NO. 43

ABSTRACT

Two methods were evaluated for removal of 1-5 kilowatts from a 1 in. d. by 10 in. long bomb to be maintained at 250-300°C. "Conductance control", varying the composition of a helium-air mixture in a 8 mil annulus to give a controlled conduction heat transfer resistance, gave a simple, smooth, flexible control method. Use of water sprayed into air gave the required range of heat fluxes, but sometimes gave uncontrollable instabilities due to progressive vapor binding.

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1.0 SUMMARY

Based on calculations and on experimental studies of alternate methods of cooling an ORR slurry bomb, use of controlled compositions of air-helium mixtures in an annulus is recommended for obtaining the required temperature control. From 1 to 5 kw can be transferred from a 1 in. d by 10 in. long cylinder at 300°C to boiling water at 100°C across an 8 mil thick annulus. The heat flux is uniform, temperature control is smooth and rapid, and the bomb geometry is simple compared to alternative methods of obtaining the required temperature control. Heat transfer through gases in the annulus were 0.5 kw for freon-12, 0.6 kw for argon, 1.0 kw for air, 2.2 kw for 50% air-50% helium, and 4.9 kw for 100% helium. Use of water sprayed into air was initially tested and gave the required range of heat fluxes, but sometimes gave uncontrollable temperature instabilities (hot spots) believed due to progressive vapor binding.

2.0 INTRODUCTION

Design of an ORR slurry bomb required that the gamma heat (up to 7 watts/g) be removed for a range of reactor power levels in order to give controlled bomb temperatures. The simple air cooling previously used for lower radiation levels cannot give the heat flux required; therefore calculations and experimental studies were made to select and confirm the performance of a satisfactory system. The type of bomb geometry expected would require removal of 5 kw at full reactor power from a 1 in. d by 10 in. long cylinder. In order to maintain the bomb at operating temperatures of 250-300°C, controlled heat removal down to 1 kw would be very desirable. Cooling water could easily give any one heat removal rate up to 5 kw, but control over a range is not practical by flow rate control unless the coolant system is pressurized to permit the water to approach the bomb temperature. The coolant should have a satisfactory radiation stability and should not result in a disposal problem (< 100 scf/min. of a gas as a maximum, less is desirable). From the heat capacity standpoint, the minimum volume for a gas coolant would be ~30 scf/min.

Two methods of obtaining a controlled heat transfer coefficient were studied experimentally. An electrically heated bomb mock-up cooled by an air-water mixture was tested initially. The results demonstrated poor temperature control plus evidence of an uncontrollable vapor binding problem. The second method tested is termed "Conductance Control". An aluminum jacket was placed around the bomb with a very close clearance between the inside diameter of the jacket and the bomb wall. Helium, or a helium-air mixture, flowing between the jacket and the bomb wall conducted the heat to the jacket maintaining the required temperature differential between the bomb wall and jacket. Water, boiling outside the jacket, dissipated the entire heat load and maintained the jacket wall at 100°C. Bomb temperatures were controlled by varying the composition of the gas which in turn varied its conductivity.

The procedure of varying the conductance of the gases by varying the composition was suggested by P. A. Haas and J. T. Long. Other suggestions by J. C. Bresee were most helpful.

3.0 DESIGN CRITERIA

The following criteria were established for the design of the slurry bomb mockup tests:

1. Gamma heat load of up to 7 watts/gm at bomb wall temperature of 300°C.
2. Estimated maximum weight of bomb of 715 gms.
3. Estimated maximum gamma heat load of 5 KW. Estimated heat load range for bomb at 300°C of 1-5 KW.
4. Maximum length of bomb of 10 inches.
5. Maximum diameter of bomb - to fit inside square housing with 3 in. x 3 in outside dimension.
6. Estimated heat transfer coefficient required = $200 \frac{\text{BTU}}{\text{hr ft}^2 \text{ } ^\circ\text{F}}$
7. Type of coolant - radiation stable.
8. Maximum gas flow to off-gas system of 100 cfm; lower-off-gas rates preferred.
9. Maximum pressure of coolant to bomb (approximate) of 50 psi.
10. Bomb housing wall temperature of less than 100°F.

4.0 WATER SPRAYED INTO AIR AS A COOLANT

This method combined the advantages of the high latent heat and heat transfer coefficient associated with boiling water and the simple flow control of gas coolants to give control over a wide range of heat fluxes. The experimental studies were carried out with procedures and apparatus selected to meet the design criteria of Section 3.0. An axially distributed heat source of 0-5 kw was necessary to permit detection of irregular temperature distributions. Electrical heating was selected to duplicate gamma heating in that it is a volume heat source and will give hot spots at points of reduced heat transfer.

4.1 Description of Bomb Mockup

The bomb mockup was designed to use electrical resistance heating to give an axially distributed heat source equivalent to the radiation heating expected (see Figures 1 and 2). The bomb was fabricated of a stainless steel tube, 0.976 ± .001 inch outside diameter and .010 inch wall thickness. Two 1/2 inch diameter copper bus bars were silver soldered on the ends after the bomb was filled with concrete and the thermocouple tubes positioned. The housing consisted of a 12 inch long 4 inch OD aluminum cylinder with end caps which positioned the copper bus bars in the housing. Initially, a clearance between the bomb and housing of 17 mils was maintained. However, subsequent air tests demonstrated that a more uniform temperature profile could be attained by tapering the clearance from 67 mils at the inlet to 17 mils at the outlet. It was also found necessary to coat the housing wall with Dow Corning No. 996 Silicone varnish to prevent short circuits between the

Fig.1 Bomb Mockup and Bomb Housing Assembly

Fig. 2. Equipment Schematic-Bomb Cooling Test.

housing and the bomb wall. The actual taper of the housing measured after a series of tests, was used to determine the gas mass velocities. Air and water droplets were mixed at the spray nozzle and then fed to the housing through the 1/2 inch inlet at the bottom. The porous stainless steel distributor shown (No. 7 on Figure 1) was not used during this series of tests.

Power for the resistance heating was supplied by four General Electric "Spirakore" transformers (Figure 2). A No. 1256 "Powerstat" was used to vary the voltage to the transformers in order to cover the range of heat loads required for the experiments.

4.2 Test Results - Air-Water Cooling

The desired heat transfer rates were attained using the air water mixtures but the temperature uniformity was poor. The required heat transfer coefficient was achieved at a gas rate of 30 lb/hr ft² and a water/air ratio of 0.43 (Figure 3).

The heat transfer data shown on Figure 3 are compared with data obtained by other investigators on Figure 4. In the range of water to air ratios of 0.1 to 0.7, the data compare fairly well considering that they were taken on a wide assortment of equipment. A wide gap exists between water/air ratio of 1-10. Above 10, the data from other sources indicate that the upper and lower sets of curves might be roughly extrapolated to obtain data in the 1-10 water/air ratio region.

One problem encountered during these tests was the large temperature deviations experienced at high cooling loads. The maximum temperature deviation from the mean at a 5 KW load ranged between 90 - 140°C (Figure 5). Temperature deviations at lower loads were substantially reduced.

Another more serious problem encountered was that of vapor binding. During periods when this occurred, it was impossible to control the bomb wall temperature even though the air-water ratio were in the range known to give adequate cooling. Once vapor binding started, it was not possible to regain control by increasing the air or water rates. To regain control, it was necessary to turn off the current, cool the bomb to below its operating temperature and then resume heating at the same air-water rates.

After taking the above problems into consideration it was apparent that fool-proof control would be very difficult using air-water cooling. In addition, it was apparent that the problem of adequately mixing air and water before injection plus the length of time needed to establish temperature equilibrium would necessitate unreasonably long and careful startup periods.

5.0 "CONDUCTANCE CONTROL" COOLING TESTS

Use of either the sensible or latent heat of cooling water at atmospheric pressure can easily remove the maximum heat loads; however, reducing the cooling capacity to maintain the bomb at 250-300°C for reduced heat loads is

Fig. 3. Heat Transfer Coefficient for Air-Water Cooling.

Fig. 4. Heat Transfer Coefficient for Air-Water Cooling.

Fig.5. Temperature Uniformity for Air-Water Cooling Tests.

difficult. A pressurized cooling system would reduce the temperature differential between the bomb and coolant but is not practical for the cramped in-pile geometry. The addition of electrical heat to maintain a constant bomb heat load was considered but space limitations and dependability considerations governed. Therefore, a gas filled annulus used as a variable heat transfer resistance appeared most promising from a simplicity and dependability viewpoint.

The heat transfer coefficient required for "Conductance Control" cannot be changed by varying gas flow rates. For any reasonable pressure drop and gas consumption, the gas flow in the annulus is streamlined and the heat transfer coefficient is equivalent to that across a stagnant film. The heat transfer coefficient is also independent of pressure until high vacuums are obtained. Therefore, a practical method for varying the heat transfer coefficient involves changing the thermal conductivity of the gas by varying its composition. Commercially available gases have conductivity ratios approaching 20 (19 for $H_2 \cdot SO_2$). The air helium mixture (thermal conductivity ratio of 5/1) was selected for experimental study because it is non-combustible, non-corrosive, stable to radiation and readily available. The ratio of 5/1 gives control down to 1/5 of the maximum gamma heat capacity.

5.1 Description of Bomb Mockup

"Conductive Control" required modification of the bomb to provide a narrow annulus surrounding the bomb wall. To accomplish this, an aluminum jacket was slipped over the bomb providing an 8.5 mil clearance between the inside diameter of the jacket and the bomb wall (Figure 6). Glass tape, about 8 mils thick, was used to prevent the jacket from touching the bomb wall. The area of the tape was approximately 0.016 ft^2 comprising about 7.5% of the surface area of the bomb. The ends of the jacket were sealed with teflon plugs plus cement and a $1/8$ " diameter aluminum tube was provided for gas fed to the annulus. The gas outlet was a $1/8$ " hole drilled into the upper end of the jacket.

The remainder of the equipment was identical to that used for the air-water tests except that the bomb housing was drilled out to a $1 \frac{1}{2}$ inch diameter to accommodate the bomb plus jacket. The makeup water to compensate for the steam generated in the housing was fed to the bottom inlet and the stream-water mixture flowed from the upper outlet. Temperatures were measured 2", 5" and 8" from the top of the bomb on the bomb center line.

5.2 Design Considerations for "Conductance Control"

The annulus surrounding the bomb for the "Conductance Control" tests was designed to maintain the bomb wall temperature at 300°C for a 5 KW heat load using pure helium gas for conduction. At room temperature this annulus was approximately 8.5 mils wide. Increasing the bomb wall temperature to 300°C , decreased the annulus width to approximately 7.0 mils (Figure 7) by thermal expansion.

In order to predict a heat transfer coefficient for the system, it was necessary to first estimate the thermal conductivity of oxygen-helium mixtures

Aluminum Housing used for
Air-Water Tests.
(see fig. 1)

Fig. 6. Slurry Bomb Mockup for "Conductive Control" Experiment.

Fig. 7. Clearance Between Jacket ID and Bomb Wall vs Temperature Bomb Wall.

since literature data were not available for the system. Davis⁽¹⁾ indicated that the thermal conductivity of hydrogen-nitrogen mixtures could be determined using the following formula:

$$\log \left(100 k + \frac{0.246}{100 k} \right) = bx + c$$

where k = conductivity, x = fraction H_2 in mixtures, b and c = constants.

By evaluating the constants b and c from the conductivities of pure helium and air at $200^\circ C$, the formula was used to predict the conductivities of helium-air mixtures at $200^\circ C$. The following expression was obtained:

$$\log \left(100 k + \frac{0.246}{100 k} \right) = 0.679x + 0.371$$

where k = conductivity, $BTU/hr ft^2 ^\circ F/ft$, x = volume fraction of helium in mixture.

Curve A in Figure 8 shows the predicted heat transfer coefficients for air-helium mixtures using the formula and a calculated thickness from Figure 7. Curve B predicts the coefficient using a volumetric average conductivity. Curve C, drawn through the experimental data, has approximately the same slope as curve A for each helium concentration. This is an indication that the conductivity formula used was probably correct. Further proof of this is given by calculations of the glass tape conductivity (5.3).

The heat transfer coefficient for the boiling water film outside the bomb jacket was estimated to be $20,000 \frac{BTU}{HR ft^2 ^\circ F}$. Therefore, the temperature differential between the jacket and boiling water at the 5 KW load was probably less than $2^\circ C$.

5.3 Test Results for "Conductance Control"

The results of the "Conductance Control" tests demonstrated removal of from 1.3 to 5.0 KW by use of air-helium mixtures (Figure 9, Table 1). The $300^\circ C$ bomb wall temperature was maintained for these 1.3-5 KW heat loads by varying only the gas composition. No problems were encountered on the boiling water side of the jacket. The observed heat transfer coefficients (curve C, Figure 8) are higher than the predicted coefficients (curve A) due to the higher conductivity of the glass tape used to maintain the clearance between the bomb wall and jacket. In addition to the data shown for air-helium mixtures, two runs were made with argon and freon-12 to determine the lower heat load limits.

In order to determine the effect of heat transfer by the glass tape, the following equation was utilized:

$$\frac{q}{\Delta t} = \frac{k_1 A_1}{L} + \frac{k_2 A_2}{L}$$

(1) Davis, "Chemical Engineering Nomographs" p24, McGraw-Hill Book Company.

Fig. 8. Heat Transfer Coefficient for Air-Helium Mixtures. Annulus = 7.1 mils.

Fig. 9. Effect of Helium-Air Mixture on Cooling Load at 300°C Bomb Temperature.

Table 1

ESTIMATION OF HEAT REMOVED BY "CONDUCTIVITY
CONTROL" WITHOUT THE GLASS TAPE SPACER

Gas	Thermal Conductivity at 200°C		Heat Load (KW)
	BTU	ft hr ft ² °F	
100% helium	.112		4.9
75% he - 25% air	.076		3.3
50% he - 50% air	.051		2.2
25% he - 75% air	.035		1.5
100% air	.0224		0.97
argon	.0146		0.63
freon-12	.012*		0.51

* Estimated

where q = heat load, BTU/hr,

Δt = temperature differential, °F,

K_1 = thermal conductivity of the glass tape in $\frac{\text{BTU ft}}{\text{HR ft}^2 \text{ °F}}$

A_1 = area glass tape, ft²,

L = clearance between bomb wall and jacket, ft,

k_2 = gas conductivity, $\frac{\text{BTU ft}}{\text{Hr ft}^2 \text{ °F}}$,

A_2 = area for heat transfer through gas, ft².

A plot of $q/\Delta t$ vs gas conductivity should show a linear relationship with the slope equal to A_2/L and the intercept at $k_2=0$ equal to $k_1 A_1/L$. These values were obtained from the experimental data (figure 10). The glass tape thermal

conductivity was then determined as follows:

$$\frac{\text{slope}}{\text{intercept}} = \frac{A_2/L}{k_2 A_1/L}$$

$$k_1 = \frac{A_2}{A_1} \times \frac{\text{intercept}}{\text{slope}}$$

$$k_1 = \frac{0.198 \text{ ft}^2}{0.016 \text{ ft}^2} \times \frac{5.2 \frac{\text{BTU}}{\text{hr } ^\circ\text{F}}}{383 \frac{\text{ft}^2}{\text{ft}}} = 0.168 \frac{\text{BTU ft}}{\text{hr ft}^2 ^\circ\text{F}}$$

A knowledge of the glass tape conductivity permitted an estimation of the heat loads that could have been removed without the glass tape (table 1).

Figure 10 also demonstrates that the correct conductivity for the air-helium mixture was predicted by the formula previously discussed (§ 5.2). Conductivities predicted by this formula gave an excellent fit along the curve drawn through the points for pure gases. The conductivities determined from the volumetric average conductivity gave a poorer fit.

"Conductance control" demonstrated good temperature uniformity along the length of the bomb wall. The maximum temperature deviation from the mean of the three temperature readings ranged between 14 and 30°C depending upon the heat load (figure 11). Lower heat loads gave higher deviations because the glass tape was carrying a greater proportion of the total load and its conductivity was not as uniform as that of the gas.

The effect of gas velocity on the cooling rate was shown to be negligible for helium rates varied between 6.1 and 126.5 cfh. The flow in the annulus at the highest rate was still in the streamline region and the heat capacity of the gas was very small compared to the total heat transfer rate. Therefore, the only change that increased flow could have made in the heat transfer coefficient was due to entrance effects. Apparently, this was very minor since no significant changes in temperature profile or heat transfer rate were observed. This absence of a flow rate dependence is advantageous because it tends to increase the stability of control and minimizes the cost of the helium required.

6.0 RECOMMENDATIONS

"Conductance control" is recommended for temperature control of ORR slurry bomb experiments for the following reasons:

1. Safety - If the flow of gas to the experiment should stop, the system would "fail safe" because the gas already in the bomb would continue to transfer the same heat load as long as its composition was not altered.

Fig. II. Temperature Uniformity for "Conductance Control" Tests.

2. Simplicity - The only flow to the bomb would be the conductant gas and its flow would be very low (less than 10 cfh). Steam generated outside the jacket wall would be condensed on the wall of the bomb housing which will be cooled by high velocity reactor cooling water.

3. Response - Response times for the system would be a function of the gas flow rates and the time required to mix the two gas systems. This should be very low if small tubing is installed and the gases are mixed just before entering the bomb.

4. Cost - The cost of helium for a 10.5 cfh maximum flow rate would be roughly \$7.00 per day.

Table 2. Data for "Conductive Control" Tests

Bomb Dimensions: Length = 10"
 OD = 0.976"
 Width
 of Annulus = .007-.008/in.
 Avg. Electrical
 Resistance = 0.0092 ohms

Run	Gas I	Gas II	Heat Load-	Heat Load-	Flow Gas I	Flow Gas II	% Helium	Gas Thermal Conductivity	Average Bomb Wall Temp.	Overall Heat Transfer Coefficient
			KW	BTU/hr	scfh	scfh		BTU ft hr ft ² °F	°C	BTU hr ft ² °F
A	Helium	Air	1.77	6030	2.10	6.90	23.4	0.034	281	87
B	Helium	Air	3.85	13,150	12.25	2.75	81.7	0.085	293	177
C	Helium	-	5.04	17,200	12.25	-	100	0.112	302	222
D	Helium	-	5.04	17,200	39.5	-	100	0.112	299	224
E	Helium	-	5.04	17,200	126.5	-	100	0.112	299	224
F	Helium	-	5.04	17,200	6.1	-	100	0.112	301	223
G	Air	-	1.34	4,570	3.75	-	0	.0224	275	68
H	Freon-12	-	0.84	2,880	0.41	-	0	.012	288	40
I	Helium	Air	2.16	7,370	3.25	6.90	32.0	.039	293	99
J	Helium	Air	2.64	9,000	6.10	5.30	53.5	.054	291	122
K	Helium	Air	3.17	10,800	6.10	2.75	69.0	.069	290	148
S	Argon	-	1.01	3,440	2.1	-	0	.015	280	50
U	Helium	Air	4.29	14,650	12.25	2.15	85.1	.090	303	187
R	Argon	-	0.75	2,580	2.1	-	0	.014	236	49
T	Argon	-	1.50	5,130	2.1	-	0	.015	333	-
P	Argon	-	0.34	1,150	2.1	-	0	.013	147	-
Q	Argon	-	0.53	1,800	2.1	-	0	.013	199	-

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