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CALIBRATION OF GAMMA MONITORS

R. M. Roidt and W. A. Stewart
Heat Transfer and Fluid Dynamics

Research Report WERL-TAGOV-2

May 11, 1972

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Heat Transfer and Fluid Dynamics

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May 11, 1972

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ABSTRACT

A molten tin bath has been utilized to calibrate four gamma monitors in the temperature range, 500°F to 700°F, for internal heating rates of from 2 watts/in to 15 watts/in. The experimental scatter on a $(q/L)/\Delta T$ versus $\bar{T}$ plot is less than ± 5 percent for heater element powers greater than 5 watts/in but lower power inputs do not correlate successfully on this plot.

A description of the molten tin bath and experimental technique is given.

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May 11, 1972

CALIBRATION OF GAMMA MONITORS

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Heat Transfer and Fluid Dynamics

I. INTRODUCTION

The temperature drop across an gas filled annulus is used to determine the internal gamma heating of a stainless steel cylinder within a reactor core and hence, yield a measure of the gamma activity level. A schematic of such a gamma monitor is shown in Figure 1(a). For calibration purposes an auxiliary calibration thermocouple, shown in Figure 1(b), is used to determine the internal monitor temperature while the centrally located thermocouple used during normal operation is replaced by a heater element to simulate gamma heating.

Under operating conditions the monitor surface heat transfer coefficient is so large that the temperature of this surface may be considered constant and uniform at the reactor coolant temperature. Previous calibration procedures, which involved monitor immersion in hot oil baths, suffered from an inability to obtain a uniform external heat transfer coefficient and therefore, a uniform monitor surface temperature. Also the average monitor temperatures were below the reactor operating range so that extrapolation of the experimental results was required. The purpose of the present effort was to provide a constant uniform monitor surface temperature in the reactor operating range of from 550°F to 650°F, while allowing the power input to the monitor heater to be varied from 2 watts/in (monitor length) to 15 watts/in. This was accomplished by using a forced convection cooled molten tin bath. Painting the stainless steel monitors with an MgO suspension prevented the tin from attacking or even adhering to them.

Fig. 1-Gamma monitor schematic

The experimental results appear to be satisfactory with a scatter contained within a ± 5 percent spread on a $(q/L)/\Delta T$ versus $\bar{T}$ curve for heater inputs, q/L , greater than 5 watts/in. Here ΔT is the temperature difference between the internal calibration thermocouple and the monitor surface temperature while $\bar{T}$ is their mean value. Use of a simple correlation at powers less than 5 watts/in would not appear possible but direct use of the temperature difference readings should give a good estimate of low level gamma heating.

II. THE CALIBRATION APPARATUS

The constant temperature bath constructed for this work is shown in Figure 2. The bath cylinder was made of 304 stainless with 5/8 inch I.D. and 7/8 inch O.D. This was wound with thin asbestos cloth over which the guard heaters (used to maintain the monitor temperature) were wound. These three guard heaters were wound from fiberglass covered nichrome resistance wire (1 ohm/ft) and were held in place by another layer of asbestos tape. This bath cylinder was then centered in a 3.5 inch diameter pipe through which flowed cooling air supplied by a Dayton No. 1C180 motor-blower with a 60 CFM free air delivery capability. This was to provide a reasonably uniform heat transfer coefficient over the outside of liquid metal bath cylinder so that it would not be subject to the variations of free convection cooling.

The power supplies for the guard heaters were autotransformers (Variac-General Radio Company) with ammeters incorporated into the power leads. The power supply for the monitor internal heater was also an autotransformer but with both a voltmeter and ammeter included in the circuitry. Two sets of these meters were used; one for monitor power inputs less than 5 watts/in and another for the higher power levels.

The material chosen for the bath was tin (melting point, 449.4°F) due to its high conductivity (17.1 Btu/hr-ft°F) which could help reduce

Fig. 2-Calibration device for gamma monitors

circumferential and axial temperature variations at the monitor surface. The thickness of the molten tin annulus is 0.0625 inches yielding a Grashof-Prandtl product of 0.74, considerably less than the value, 1000, below which free convection effects are negligible.*⁽¹⁾ This calculation and the relevant physical property values are included in Appendix A.

Since molten tin may sometimes react with solid metal surfaces to attack and erode grain boundaries a suggestion of Mr. R. Gegick, Heat Transfer and Fluid Dynamics Department, Westinghouse Research Laboratories, to coat the surfaces exposed to the tin with Milk of Magnesia (MgO) was adopted. With the advice of C. H. Neergaard, Materials Applications Department, Westinghouse Research Laboratories, a test was run with four 304 stainless steel specimens, three of which were held in 700°F tin for six hours. Each specimen was treated a different way prior to the test:

1. Cleaned with carbon-tetrachloride and set aside as a control.
2. Cleaned with carbon-tetrachloride and immersed in the molten tin bath.
3. Cleaned with carbon-tetrachloride, dipped in concentrated HCl, and immersed in the molten tin bath.
4. Cleaned with carbon-tetrachloride, painted with MgO suspension, dried, and immersed in the molten tin bath.

These specimens were cross-sectioned, polished and etched by the Metallurgical Department, Westinghouse Research Laboratories and were then microscopically examined by W. J. Reicheneker, Welding Engineering and Materials Joining, Westinghouse Research Laboratories. Mr. Reicheneker

* Indicates References

found no signs of grain boundary penetration on any of the specimens and wetting of the stainless steel surface by the molten tin only in the acid treated specimen.

It was decided to retain the MgO treatment for working with the monitors; first, to guard against accidental spot wetting and secondly, although the molten tin did not penetrate any sample there was some adhesion of the tin to the untreated specimen. It was only with some difficulty that this tin could be removed while with the MgO treated specimen the tin simply fell off.

Some measure of the effectiveness of molten tin in attacking metals was found when the first constant temperature bath container was made of a 5/8 inch I.D., 1-1/4 inch O.D. copper cylinder. Although this container was very effective in reducing end to end monitor temperature variations, holding them to within several degrees F, apparently a low melting point Sn-Cu eutectic was formed which eroded the cylinder walls and gave rise to a considerable number of problems. After this and in view of the experience gained from the 304 stainless steel specimen tests, a new bath container was made of a 304 stainless steel cylinder 5/8 inch I.D. and 7/8 inch O.D. However, should it ever be found necessary to obtain an extremely uniform surface temperature it might well be worthwhile to study various schemes of rendering the copper impervious to the molten tin.

The usual experimental procedure involved first painting the monitor with an MgO suspension while it was outside the calibrating device and with the heater and thermocouples installed. About 10 watts was supplied to the unit during this process. Then the monitor was placed in the bath well which was filled with the MgO suspension. This was boiled away by applying power to both the external and monitor heaters. After the well and monitor were brought up to about 600°F the liquid tin was added to just below the top of the well.

After setting the desired monitor power the guard heater powers were manipulated to obtain a uniform axial temperature. Once this condition was obtained various monitor surface temperatures could be easily obtained by opening or closing a shut-off gate provided on the convection blower inlet. By varying only the external convection coefficient a minimum of adjustment was required on the guard heater power supplies.

The temperatures were read from six, 10-mil, cromel-alumel thermocouples twisted and spot welded to the monitor at the positions shown in Figure 3. The thermocouple numbers in that figure refer to the temperature readings given in Tables I-IV. These thermocouples and the auxiliary calibration thermocouple were read from a potentiometer with an ice bath base temperature provided. Reproducibility of the data and consistency of the experimental setup was satisfactory and may best be illustrated by noting that, in Table II, experiments 22 through 35 were run four days after experiments 12 through 21. The data from the two days is consistent.

An error analysis in Appendix B, based upon the manufacturers specified guarantee on thermocouple performance yields a calculated maximum uncertainty in the measured ΔT of $\pm 9.6^\circ\text{F}$. However, measurements made at the freezing point of tin (and discussed in the same appendix) yield, for the worst thermocouple, an uncertainty of $\pm 5.7^\circ\text{F}$ at 650°F .

A calculation based on smallest scale readings on the ammeter and voltmeter yields a maximum uncertainty of ± 6.1 percent for the monitor power input.

III. CALIBRATION RESULTS

Experimentally determined differences between monitor outside surface temperatures and the internal calibration thermocouple temperatures for gamma monitors 87-305-I, 87-308-I, 87-310-I and 87-312-I are shown

Fig. 3—Thermocouple placement on gamma monitors

in Figures 4, 5, 6 and 7 for various internal heating levels. The data is shown in Tables I - IV where the thermocouple numbers correspond to the placement shown in Figure 3. The temperature difference is taken between T.C. No. 7 (the calibration thermocouple) and T.C. No. 2, the thermocouple located directly over T.C. No. 7.

The uniformity of the monitor surface temperature was reasonably good, the largest gradient being 20°F between T.C. No. 1 and T.C. No. 4 in Exp. No. 115. Otherwise the surface temperature differences were usually held to less than about 6°F.

The "average power" designation on the tables is included since the monitor power level would change slightly from run to run so that, for the purposes of drawing calibration curves, the average of the run power levels was used to describe the internal heating. The power setting for each run is included in the tables however. The low monitor power level runs for Gamma Monitor 87-310-I were not made since it was determined, after the experiments were underway, that these low power inputs were not within the range of expected operation.

To obtain calibration curves for the various monitors it is assumed that

$$\frac{q/L}{\Delta T} = \phi(\bar{T})$$

where ϕ is some function of $\bar{T}$. $\bar{T}$ represents the arithmetic average of the external monitor temperature and the internal calibration thermocouple temperature. This assumption is made since the thermal conductivity of the annulus gas may be taken as that corresponding to this mean temperature and also, the radiation across the annulus may be linearized and, to a first approximation, represented as proportional to $\bar{T}^3 \Delta T$. The plots of $(q/L)/\Delta T$ versus $\bar{T}$ are shown in Figures 8, 9, 10 and 11.

FIGURE 4 - Data Points for Gamma Monitor 87-305-I

Table I Calibration Data for Gamma Monitor 87-305-I

Average Power Exp. No.		Guard Heater Power (watts)			Monitor Power		Thermocouple Temperatures (°F)								ΔT
		Upper	Main	Lower	Total	watts inch	No. 1	No. 3	No. 4	No. 5	No. 6	No. 7	No. 2		
5.34	36	72.5	52	82.5	27.12	5.42	541.7	543.5	540.0	544.1	544.1	640.9	545.2	95.7	
	37	72.5	52	82.5	26.87	5.37	584.5	586.9	589.0	588.6	588.7	680.7	588.0	92.7	
	38	72.5	52	82.5	26.25	5.25	700.0	701.0	706.5	704.0	704.0	786.0	703.2	82.8	
11.50	39	72.5	52	82.5	26.71	5.34	672.0	668.7	668.6	670.1	670.1	754.0	671.0	83.0	
	40	86.4	9.0	115.5	55.36	11.07	563.0	564.1	566.8	565.5	565.5	756.3	567.0	189.3	
	41	102.0	8.5	115.5	57.97	11.60	678.5	683.0	687.5	684.5	684.5	862.5	684.0	178.5	
	42	102.0	8.5	115.8	58.28	11.66	654.5	645.0	641.5	646.0	644.0	829.0	648.0	181.0	
	43	80.6	8.5	116.4	58.28	11.66	579.7	582.3	576.3	582.3	582.0	771.0	585.5	185.5	
	44	67.2	67.5	63.8	8.82	1.76	525.8	518.0	521.7	517.9	517.9	549.9	520.2	29.7	
1.75	45	67.2	69.75	52.0	8.95	1.79	547.7	551.5	553.5	550.7	551.7	580.0	552.0	28.0	
	46	89.6	85.0	69.0	8.73	1.75	723.5	732.5	739.0	735.0	735.0	756.0	735.0	21.0	
	47	89.6	86.0	69.0	8.80	1.76	668.3	669.6	671.3	669.8	669.5	693.8	671.3	22.5	
3.65	48	91.0	85.0	87.1	18.36	3.67	612.6	616.4	617.0	618.0	618.0	674.8	618.1	56.7	
	49	105.0	85.0	86.1	18.05	3.61	692.3	690.5	692.3	692.3	692.3	740.0	692.3	47.7	
	50	62.1	50.7	72.0	18.46	3.69	499.7	491.5	491.5	491.5	491.0	557.0	493.3	63.7	
7.55	51	78.0	66.0	74.4	18.18	3.64	559.1	563.1	569.4	565.5	565.5	624.7	563.1	61.6	
	52	72.5	27.0	94.5	38.25	7.65	530.6	530.8	527.0	531.0	530.0	665.0	532.7	132.3	
	53	92.4	27.0	81.2	37.50	7.50	588.1	578.5	579.0	579.8	579.4	707.8	581.1	126.7	
14.92	54	72.5	30.0	88.4	37.50	7.50	625.0	630.5	626.5	630.5	630.5	758.0	633.5	124.5	
	55	—	0.0	137.6	74.62	14.92	619.0	630.5	628.0	630.0	631.3	876.0	634.0	242.0	
	56	108.5	0.0	124.0	74.62	14.92	685.5	689.7	691.0	689.3	689.3	908.0	689.7	218.3	
9.23	57	64.8	9.0	103.6	45.47	9.09	514.3	514.7	516.0	513.8	513.0	681.1	516.2	164.9	
	58	78.0	8.5	97.2	46.20	9.24	534.5	531.6	523.0	530.0	530.2	694.5	532.8	161.7	
	59	78.0	8.5	97.2	44.94	9.00	570.8	573.0	579.0	572.3	572.3	730.0	573.0	157.0	
	60	91.0	20.8	104.2	47.94	9.59	689.7	689.3	688.5	689.7	688.5	835.5	692.0	143.5	

Temperature Difference Between T.C. No. 2 and T.C. No. 7 ($^{\circ}\text{F}$)

FIGURE 5 - Data Points for Gamma Monitor 87-308-I

Table II Calibration Data for Gamma Monitor 87-308-I

Average Power		Exp. No.	Guard Heater Power (watts)			Monitor Power		Thermocouple Temperatures (°F)								ΔT
			Upper	Main	Lower	Total	watts inch	No. 1	No. 3	No. 4	No. 5	No. 6	No. 7	No. 2		
4.18	{	12	105	40.0	—	20.9	4.18	688.4	682.5	689.6	683.1	683.0	730.0	684.5	45.5	
		13	62.1	48.1	63.8	20.82	4.16	575.5	572.3	572.3	573.2	573.0	643.0	573.2	69.8	
		14	52.5	50.7	52.0	21.04	4.21	510.7	510.2	512.5	508.0	508.0	592.3	509.5	82.8	
1.93	{	15	47.0	48.1	30.0	9.69	1.94	532.0	531.0	532.2	532.1	532.3	568.1	531.5	36.6	
		16	86.4	112.0	58.8	9.62	1.92	629.5	632.0	622.3	633.2	633.0	662.3	634.3	28.0	
		17	89.6	104.5	50.0	9.62	1.92	584.2	584.0	586.3	584.5	583.8	615.5	585.4	30.1	
5.51	{	18	80.6	80.8	82.5	27.56	5.51	628.0	632.0	632.0	631.7	631.5	726.0	632.8	93.2	
		19	102.0	85.0	80.0	27.30	5.46	668.7	668.2	666.5	669.0	668.8	751.3	669.5	81.8	
		20	62.1	44.4	69.0	27.81	5.56	536.0	542.3	544.2	541.0	540.1	651.0	542.3	108.7	
7.55	{	21	75.0	48.1	80.0	38.70	7.74	554.0	558.8	554.0	557.6	556.6	701.0	559.0	142.0	
		22	52.5	31.0	83.2	37.80	7.56	545.7	552.2	556.5	509.9	509.5	691.0	552.7	138.3	
		23	72.5	31.0	70.0	37.5	7.50	587.1	585.6	587.5	586.3	587.2	721.5	587.0	134.5	
14.57	{	24	78.0	32.0	80.0	37.05	7.41	660.5	663.7	661.1	665.5	666.0	784.0	665.7	118.3	
		25	94.5	0.0	129.6	72.87	14.57	681.7	678.0	671.7	678.5	678.5	913.0	680.7	232.3	
		26	94.5	0.0	129.6	72.87	14.57	707.3	708.0	702.0	708.5	709.5	940.0	709.5	230.5	
11.66	{	27	94.5	0.0	114.0	58.28	11.66	643.3	627.0	626.0	628.0	628.0	825.3	631.3	194.0	
		28	94.5	0.0	114.0	58.28	11.66	685.5	679.0	680.3	682.5	683.7	870.0	679.5	190.5	
		29	94.5	0.0	114.0	58.28	11.66	619.0	611.5	610.5	610.5	610.5	811.7	614.0	197.7	
9.57	{	30	70.0	0.0	98.0	48.11	9.62	544.5	539.7	543.5	538.5	538.0	719.7	541.0	178.7	
		31	70.0	0.0	98.0	48.11	9.62	582.3	580.0	587.0	581.5	582.3	755.0	580.5	174.5	
		32	95.7	32.0	114.0	47.6	9.52	743.5	747.0	750.0	747.0	748.0	897.0	748.7	148.3	
1.79	{	33	95.7	32.0	114.0	47.6	9.52	724.5	722.3	724.5	722.0	722.3	877.0	724.5	152.5	
		34	70.0	45.0	55.6	8.95	1.79	603.6	592.5	586.0	595.5	595.5	622.9	595.5	27.4	
		35	70.0	45.0	55.6	8.95	1.79	531.9	530.5	526.6	529.7	529.2	561.7	531.4	30.3	

Temperature Difference Between T.C. No. 2 and T.C. No. 7 ($^{\circ}\text{F}$)

FIGURE 6 - Data Points for Gamma Monitor 87-310-I

Table III Calibration Data for Gamma Monitor 87-310-I

Average Power		Guard Heater Power (watts)			Monitor Power		Thermocouple Temperatures (°F)								ΔT
		Upper	Main	Lower	Total	watts inch	No. 1	No. 3	No. 4	No. 5	No. 6	No. 7	No. 2		
7.745	107	45.0	37.4	85.8	39.01	7.80	526.5	526.7	529.0	527.6	527.6	720.0	528.3	191.7	
	108	49.3	37.4	74.4	38.77	7.75	581.0	581.3	584.5	582.6	582.6	767.0	582.6	184.4	
	109	56.1	37.4	76.2	38.44	7.68	654.0	658.5	654.7	660.6	661.0	839.0	660.8	178.2	
5.268	110	50.4	44.4	74.4	26.32	5.26	517.4	506.5	511.8	507.3	507.9	650.2	508.0	142.2	
	111	50.4	32.4	74.4	26.32	5.26	531.5	528.6	535.0	529.6	531.0	668.1	528.9	139.2	
	112	64.8	57.4	75.6	26.32	5.26	606.5	606.0	611.5	607.3	608.1	739.0	606.1	132.9	
15.345	113	93.5	57.4	69.0	26.38	5.28	693.5	693.7	692.0	695.4	696.1	820.0	696.2	123.8	
	114	55.0	0.0	144.8	76.46	15.29	619.0	613.5	623.5	613.0	614.5	971.0	615.6	355.4	
	115	57.2	0.0	107.3	77.02	15.40	699.0	703.0	719.0	702.0	704.0	1047.0	705.0	342.0	
11.66	116	37.8	0.0	86.32	57.49	11.50	642.7	634.4	641.4	633.7	633.4	911.5	636.5	275.0	
	117	37.8	0.0	86.3	57.49	11.50	556.8	555.2	555.1	553.8	554.3	839.3	557.5	281.8	
	118	40.3	8.0	91.0	58.87	11.77	588.3	582.7	584.2	584.0	585.5	869.0	584.5	284.5	
9.60	119	57.2	8.5	82.5	59.45	11.89	675.0	669.1	666.5	669.5	669.5	943.5	671.9	271.6	
	120	42.7	8.5	82.5	47.84	9.57	663.5	659.2	663.5	659.9	660.5	888.0	661.5	226.5	
	121	45.0	8.5	82.5	48.10	9.62	570.5	566.3	571.2	565.2	566.2	806.5	565.5	241.0	
	122	39.6	8.5	69.0	48.10	9.62	610.0	612.7	614.9	613.8	614.9	847.0	614.2	232.8

FIGURE 7 - Data Points for Gamma Monitor 87-312-I

Table IV Calibration Data for Gamma Monitor 87-312-I

Average Power Exp. No.		Guard Heater Power (watts)			Monitor Power		Thermocouple Temperatures (°F)								ΔT
		Upper	Main	Lower	Total	watts inch	No. 1	No. 3	No. 4	No. 5	No. 6	No. 7	No. 2		
5.63	66	80.6	52.0	80.0	28.34	5.67	612.5	603.5	603.5	605.7	605.0	741.5	606.5	135.0	
	67	62.1	31.0	82.5	28.16	5.63	524.9	524.0	531.0	524.6	523.5	678.9	524.2	154.7	
	68	72.5	31.0	72.0	28.16	5.63	552.8	552.5	558.2	554.4	553.5	704.9	553.6	151.3	
12.15	69	72.5	31.0	72.0	28.16	5.63	602.7	596.7	600.0	599.4	599.3	742.0	598.5	143.5	
	70	72.5	31.0	75.0	27.95	5.59	671.3	666.7	669.5	671.3	670.5	797.0	668.7	128.3	
	71	86.4	7.5	117.0	60.8	12.16	614.5	618.0	620.5	619.0	618.0	882.0	619.0	263.0	
9.25	72	102.0	7.5	114.0	60.61	12.12	687.0	686.0	688.5	689.0	688.0	936.5	686.0	250.5	
	73	89.6	0.0	117.0	60.8	12.16	603.0	593.0	596.3	595.5	594.3	869.0	596.0	273.0	
	74	52.5	9.0	94.5	46.36	9.27	513.0	517.5	519.0	519.0	517.3	756.3	519.0	237.3	
7.14	75	72.5	8.5	81.25	46.2	9.24	559.5	559.7	557.0	561.5	560.5	792.0	561.0	231.0	
	76	72.5	9.0	80.7	46.15	9.23	638.5	643.3	646.7	647.5	647.0	855.0	645.0	210.0	
	77	78.0	24.3	81.25	35.52	7.10	530.5	528.7	527.5	530.0	529.0	714.0	530.0	184.0	
14.9	78	75.0	23.4	81.25	35.96	7.19	564.0	572.0	579.0	573.5	573.5	754.5	572.0	182.5	
	79	75.0	23.4	81.25	35.96	7.19	580.5	579.7	586.0	582.3	582.0	759.7	580.0	179.7	
	80	75.0	23.4	80.5	35.33	7.07	642.5	643.0	645.0	645.0	645.0	807.5	645.0	162.5	
4.03	81	95.7	0.0	134.4	74.55	14.9	561.5	562.7	561.5	566.3	565.0	906.5	565.5	341.0	
	82	95.7	0.0	134.4	74.55	14.9	699.5	698.7	609.3	702.5	701.0	991.7	700.0	291.7	
	83	105.0	85.0	88.4	19.82	3.96	656.0	650.6	653.0	653.0	652.9	738.4	653.5	84.9	
2.01	84	105.0	87.5	91.8	19.9	3.98	698.1	700.1	701.7	702.0	701.5	765.7	701.3	64.4	
	85	105.0	87.5	91.8	19.9	3.98	665.9	661.5	663.0	664.0	663.1	729.0	665.2	63.8	
	86	62.1	38.5	73.2	20.44	4.09	502.2	496.6	504.0	498.0	496.7	598.7	496.7	102.0	
	87	62.1	38.5	67.8	20.71	4.14	562.4	564.1	551.5	565.6	565.0	662.1	565.6	96.5	
	88	47.0	49.4	32.0	9.99	2.0	451.7	448.4	448.0	449.2	449.2	507.2	448.4	58.8	
	89	69.6	79.2	38.25	10.05	2.01	533.5	536.5	535.1	537.5	536.5	585.0	537.5	47.5	
	90	69.6	79.2	38.25	10.05	2.01	615.2	618.4	612.0	622.4	622.4	660.0	621.5	38.5

FIGURE 8 - Calibration Curve for Gamma Monitor 87-305-I

FIGURE 9 - Calibration Curve for Gamma Monitor 87-308-I

FIGURE 10 - Calibration Curve for Gamma Monitor 87-310-I

FIGURE 11 - Calibration Curve for Gamma Monitor 87-312-I

The symbols in each of these figures correspond to their counterparts on the data curves, Figures 4-7, except that those representing power levels greater than 5 watts/in have been filled in. These power levels correlate quite well and usually fall within a ± 5 percent band. With respect to the power levels below 5 watts/in it would seem that, should this operating level ever occur, a good estimate of the power level-temperature difference relationship could be obtained from the raw data curves of Figures 4, 5 and 7, which do not appear unreasonable. It is difficult to explain the non-correlating behavior of these points on curves 8, 9 and 11 except to note that any errors are amplified considerably as the denominator of $(q/L)/\Delta T$ becomes small.

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APPENDIX A

PROPERTIES OF MOLTEN TIN FOR CALCULATION PURPOSES

Properties are taken at 600°F except where noted.

Specific heat, ⁽²⁾	$c_p = .0586 \text{ Btu/lb } ^\circ\text{F}$
Thermal Conductivity, ⁽²⁾	$k = 17.1 \text{ Btu/hr ft } ^\circ\text{F}$
Coefficient of Expansion, ⁽³⁾	$\beta = .467 \times 10^{-4} (^\circ\text{F})^{-1}$
Density, ⁽³⁾	$\rho = 434 \text{ lb/ft}^3$
Viscosity, ⁽³⁾	$\nu = 0.260 \times 10^{-5} \text{ ft}^2/\text{sec}$

The Grashof number is defined by

(at 572°F)

$$\text{Gr} = \frac{\beta g \ell^3 \Delta T}{\nu^2}$$

where g , ℓ , and ΔT are the gravitational constant, the gap spacing, and the temperature difference across the gap respectively. The Prandtl number is given by

$$\text{Pr} = \frac{\rho c_p \nu}{k}$$

and the product becomes;

$$\text{GrPr} = \frac{\rho c_p \beta g \ell^3 \Delta T}{k \nu}$$

The temperature drop across the liquid annulus may be estimated from

$$\Delta T = \left(\frac{1}{k} \ln \frac{d_o}{d_i} \right) \frac{q''}{2\pi}$$

where d_o and d_i are the diameters of the outer and inner surfaces of the gap and q'' is the heat flux per unit length. Taking $q'' = 20$ watts/in., $d_o = 5/8$ inch and $d_i = 1/2$ inch we find $\Delta T = 1.7^\circ\text{F}$. Substituting this number and the appropriate physical and geometric constants into the Grashof-Prandtl product we find;

$$\text{GrPr} = 0.73.$$

APPENDIX B

ERROR ANALYSIS

If the temperature of the external monitor thermocouple is taken as, say, 650°F and the internal calibration thermocouple temperature as about 800°F we have, as the ISA and ASA published limits of error, $\pm 3/4$ percent. The thermocouples used in this experiment are said by the manufacturer, Thermo-Electric Co. Inc., to conform to these standards. Thus we have maximum errors of 4.87°F and 6.0°F for the external and internal thermocouples respectively. Taking $\pm 4^\circ\text{F}$ as the error for each ice bath thermocouple we have a maximum uncertainty⁽⁴⁾ in the temperature difference of

$$\sqrt{(4.87)^2 + (6)^2 + 2(4)^2} = 9.6^\circ\text{F}$$

This calculated uncertainty of $\pm 9.6^\circ\text{F}$ appears quite conservative so an experiment was run to determine an estimate of the actual temperature error. For this the six externally mounted thermocouples were read in a solidifying bath of molten tin at 449.4°F. The measured temperatures were:

T.C. #1	-	448.5°F
T.C. #2	-	449.55°F
T.C. #3	-	451.57°F
T.C. #4	-	451.93°F
T.C. #5	-	449.4°F
T.C. #6	-	448.5°F

The 2.5°F error in thermocouple No. 4 was the largest and indicated a

maximum error of 0.55 percent. Assuming the internal calibration thermocouple is similar to the external ones we would calculate the maximum uncertainty at the previously mentioned temperature levels to be $\pm 5.7^{\circ}\text{F}$ for the measured temperature difference.

Calculations based on the smallest scale readings on the ammeter and voltmeter in the monitor power supply yield a maximum uncertainty of ± 6.1 percent for the monitor input power.

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