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TEST REPORT
MONOBALL ENERGY TRANSFER

June, 1986

Dr. Francis C. Wessling

Prepared In Response To:
Grant #NAG8-046

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The University of Alabama in Huntsville

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ABSTRACT

An aluminum platform serves as a storage shelf for experiments transported on the space shuttle. This platform is attached to the shuttle storage area through several supports, each consisting of an attachment fitting, a monoball bearing, a clevis pin and a support strut. The experiments must be temperature controlled during and after launch. Consequently, heat loss through the plate, attachment fitting, monoball bearing, and strut are important.

The overall conductance of the monoball bearing has been determined by an experimental method of heating the outer ring with a nichrome resistance wire and cooling the inner ball with propylene glycol. Temperature differences across the bearing have been measured for various heat fluxes. The overall conductance is 0.42 Watts/°C (0.80 BTU/Hr °F). This yields a 16 watt loss for a 38° C temperature difference across the bearing.

INTRODUCTION

An aluminum platform serves as a storage shelf for experiments transported on the space shuttle. This platform is attached to the shuttle storage area through several supports, each consisting of an attachment fitting, a monoball bearing, a clevis pin and a support strut. See Figure 1. The experiments must be temperature controlled during and after launch. Consequently, heat loss through the plate, attachment fitting, monoball bearing, and strut are important.

The monoball bearing with a liner presumably of teflon connects the strut to the storage platform. The liner is designed to serve as the thermal barrier between the ball and the outer ring. The geometry of the bearing makes difficult the determining of the actual contact between the various parts. The bearing is suspected of having a higher heat loss than previously estimated. Analysis and experimentation of the bearing is necessary to determine the heat loss.

EXPERIMENTAL APPARATUS

The monoball (see Figure 2) is tested in a specially designed experimental jig. It is cooled by a water-propylene glycol mixture flowing through the interior of the ball. The mixture is in contact with the ball inner surface. The outside ring of the monoball bearing is heated with resistance heating elements wrapped around the circumference of the outer ring. The monoball has thermisters placed around its circumference both on its inner surface and outer ring. Three thermisters are used to measure the absolute temperature of the outer ring of the monoball. These thermisters are installed between the wire resistance elements on the outer ring. Three thermisters are used to measure the temperature of the inner ring. The thermisters are attached to the bearing with a thermal conducting epoxy (Omegabond 101 supplied by Omega Engineering, P.O. Box 4047 Stamford, CT 06907-0047). The locations of the thermisters are given on Figure 3. A photograph of the monoballs with the thermisters attached is given in Figure 4.

The temperature of the water-propylene glycol mixture is controlled by a constant temperature bath (GCA Corporation Model #R-20). The liquid is circulated through the interior of the monoball and back to the constant temperature bath reservoir. The experiment is conducted until steady state temperatures are indicated by the thermisters on the monoball itself. The electric heating element is set at a constant power setting during the experiment and the temperatures allowed to equalibrate. In this way, the heat transfer into the monoball can be estimated by measuring the energy supplied to the resistance heating element on the outer ring of the monoball. Heat losses from the heating element to the surroundings and to teflon fittings that join the ball to the hoses of the constant temperature bath are estimated to be less than two percent of the total energy transfer.

The thermisters are used to determine the temperature difference between the outer ring and inner ball of the monoball. By measuring the energy supplied to the outer ring resistance element and measuring the temperature difference, one can infer the effective thermal conductance of the overall assembly of the monoball. This includes the thermal conductance of 1) the A286 outer ring, 2) the liner between the outer ring and inner ball, 3) the inner Inconel 718 ball. A radial heat transfer model is used to estimate this overall thermal conductance.

A special jig has been constructed in order to assure a leak proof fitting between the monoball inner ball and the hoses which go to and from the constant temperature bath. A photograph of this fixture is shown in Figure 5. The fixture has two teflon nipples which attach to the hoses of the constant temperature bath; the other ends of the nipples attach to the inner ball of the monoball. Pressure is applied to these two nipples by three micarta rods, which are attached to two plexiglass spiders that hold the nipples. Design of the spider and nipple arrangement is chosen in order to minimize the amount of heat transfer between the monoball and the environment.

The entire assembly of the nipple jig and monoball is encapsulated in polyurethane foam insulation ("Great Stuff"). The insulation is held in a cylindrical container, approximately 3 7/8" in diameter and 3" long. The insulation is foamed in place. First, however the monoball thermister assembly is sprayed with silicon lubricant. Then, enough foam is applied in order to fill the circular container.

The amount of energy lost through the polyurethane insulation to the surrounding air is less than 1% of the energy transfer from the outer to the inner ring of the monoball.

A special concern is the amount of energy transfer from the outer ring of the monoball to the inner ball of the monoball through the foam insulation as opposed to through the teflon liner of the monoball. A thermal model was used to demonstrate that the amount of heat transfer by this mechanism is negligable. See Appendix A for heat transfer calculations.

EXPERIMENT INSTRUMENTATION

The power to the resistance heating element is given as the product of the current times voltage. The current and the voltage are measured by two Hewlett Packard 3465 digital volt/ammeters.

The temperature of the waterbath is measured with a mercury in glass laboratory thermometer, and with a calibrated resistance thermometer. The thermisters after being attached to the monoball, have been calibrated with the constant temperature bath. Measurements of resistance versus temperature have been recorded using 5° C increments of temperature. The temperature ranged from -10° C to +60° C. A third order polynominal fit of the calibration data yielded accuracies better than 0.06° C root mean square error when the temperature is considered to be a function of the natural log of the resistance. The resistances have been measured with a Fluke Model 77 digital meter. The meter utilized less than 400 millivolts to measure resistance. This causes self heating of the thermisters to be negliable.

EXPERIMENTAL PROCEDURE:

The following steps are accomplished in order to calibrate the monoball experimental apparatus.

1) Calibrate the temperature thermisters by connecting them to their measuring circuits, then wrap them in a plastic bag which is closed at the top, submerge the bag several inches into a constant temperature

bath. Then record the temperatures indicated by the thermisters. The temperature thermisters are calibrated over a temperature range from -10 C to 60 C.

2) Selected the best thermisters from step 1 to use for mounting onto the monoball.

3) Mount the thermisters on the monoball using Omegabond 101. Then apply silicon rubber over the thermisters which are on the inner surface of the monoball. These are the thermisters that other wise would be exposed to the liquid from the constant temperature bath.

4) Place nichrome resistance wire inside of teflon spaghetti. Wrap around the outer race of the monoball, the nichrome wire covered with the teflon spaghetti and in parallel with it, a second teflon spaghetti without any nichrome wire. This allows even spacing of the resistance wire around the monoball. Secure the teflon spaghetti with Omegabond 101.

5) Recalibrate the thermisters attached to the monoball by repeating the procedure in step 1.

6) Mount the monoball in the experimental apparatus for connecting the constant temperature bath hoses. Leak test the apparatus in the monoball assembly to assure no leaks. Then remove the hoses.

7) Spray the monoball with silicone lubricant suitable for electronic switches.

8) Place the monoball jig for foaming around the outside of the assembly and foam the urethane insulation around the monoball assembly. The urethane foam used is called "Great Stuff". After the polyurethane foam has cured, do not remove the outer mold.

Once the above steps are accomplished, Testing of the monoball itself begins. Attach the hoses for the constant temperature bath to the monoball assembly. The monoball assemblies are tested, at -10° C. The power level to the monoball is set at approximately 4,8,12 and 16 watts. Care is taken that the outer temperature of the monoball does not exceed the temperature required for safe operation of the urethane foam insulation. Maintain each power level for three hours[1], measure the temperatures on the inner and outer race. Record all temperatures and power settings. Record not just the power setting, but the voltage and amperage as well as the product of the voltage times the amperage.

Data have been recorded or calculated from the tests. See Table 1.

[1]The temperature oscillates with an amplitude of less than 0.05C during the last thirty minutes of the three hour period.

EXPERIMENTAL RESULTS

Run #	Monoball #	Temp. of Bath (C)	Supply Voltage (Volts)	Supply Current (Amps)	Calculated Power (Watts)	Outer Race Temp. (C)	Inner Race Temp. (C)	Calculated Temp. Difference (C)
1	2	-9.5	11.332	1.4103	15.98	46.9	8.1	38.8
2	2	-8.8	9.898	1.2354	12.23	33.8	5.1	28.7
3	2	-10.0	8.020	1.0055	8.06	19.7	-.1	19.8
4	2	-10.7	5.686	0.717	4.06	6.1	-5.0	11.1
5	1	-9.2	11.246	1.4083	15.84	47.4	7.9	39.5
6	1	-8.9	10.020	1.2578	12.60	36.7	5.1	31.6
7	1	-8.5	8.032	1.0116	8.13	19.8	0.1	19.7
8	1	-9.2	5.643	.7234	4.08	19.7	-0.1	19.8

Table 1. Experimental Results

An estimate of the value of the thermal conductivity of the liner divided by the liner thickness can be made based on the data. The heat transfer can be estimated using a radial heat transfer model. The spherical interface can be linearized by using a mean radius, rm, of a circular arc.

$$rm = \frac{r \sin c}{c}$$

r = arc radius (0.436 inches)

c = arc half angle (45.84° or 0.80 radians)

Thus,

rm = mean radius (0.391 inches)

$$q = \frac{\Delta T}{\dfrac{\ln (r_2/r_1)}{2\pi K_1 l} + \dfrac{\ln (r_3/r_2)}{2\pi K_2 l} + \dfrac{\ln (r_4/r_3)}{2\pi K_3 l}}$$

k_1 = thermal conductivity of inconel ball

k_2 = thermal conductivity of liner

k_3 = thermal conductivity A286 outer ring

l = typical length for conduction (0.50")

r_1 = inner radius of ball (0.250")

r_2 = outer radius of ball (0.391")

r_3 = inner radius of ring (r_2 + S)

r^4 = outer radius of ring (0.50")

S = liner thickness (inches)

The temperatures of the outer race and inner race are separately averaged; the difference of the averages gives the average temperature difference. A least squares linear fit is used to find the equation best matching the heat loss versus temperature difference data. See figures 6 and 7. The equations for the two monoballs are:

1) $q = 0.405\ \Delta T - 0.690$ monoball #1

2) $q = 0.432\ \Delta T - 0.556$ monoball #2

where q is given in watts and temperature difference ΔT is given in °C.

The overall unit conductance U is given by the slope of the curve of q versus ΔT. Thus;

3) $U_1 = 0.405$ Watts/°C monoball #1

$= 0.77$ BTU/Hr °F

4) $U_2 = 0.432$ Watts/°C monoball #2

$= 0.82$ BTU/Hr °F

The conductances differ from each other by 6%. The agreement is somewhat suprising because one monoball appeared to fit more tightly in its outer ring than the other. The average conductance $\bar{u}$ is 0.80 BTU/Hr of (0.42 W/°C).

Recognizing that the natural logarithm of r_3/r_2 can be approximated by S/r_2 for small values of S/r_2 and solving for k_2 yields:

$$\frac{k_2}{S} = \frac{(1/r_2)}{\dfrac{2\pi l}{\bar{u}} - \dfrac{\ln(r_2/r_1)}{k_1} - \dfrac{\ln(r_4/r_3)}{k_3}}$$

using:

$k_1 = 6.6$ BTU/(hr ft °F)

$k_3 = 7.3$ BTU/(hr ft °F)

$l = 0.50$ inches

$r_3 = 0.411$ inches

$\bar{u} = 0.80$ BTU/(hr °F)

$$\frac{k_2}{S} = \frac{4.3}{r_2}\ \frac{(\mathrm{BTU})}{(\mathrm{hr\ ft\ F})}$$

If S = 0.020" k_2 = 0.21 BTU/(hr ft °F)

The value of k_2 does not strongly depend on the quantity $\frac{\ln(r_4/r_3)}{k_3}$. Thus, estimating the value of r_3 in this term does not significantly affect the results.

CONCLUSION

The overall conductance $\bar{u}$ of the monoball is 0.42 W/°C (0.80 BTU/Hr °F). This is the average of measurements on two monoballs which differed by only 6%. This indicates that an energy loss of 16 Watts can be expected for a 38° C temperature difference across the monoball.

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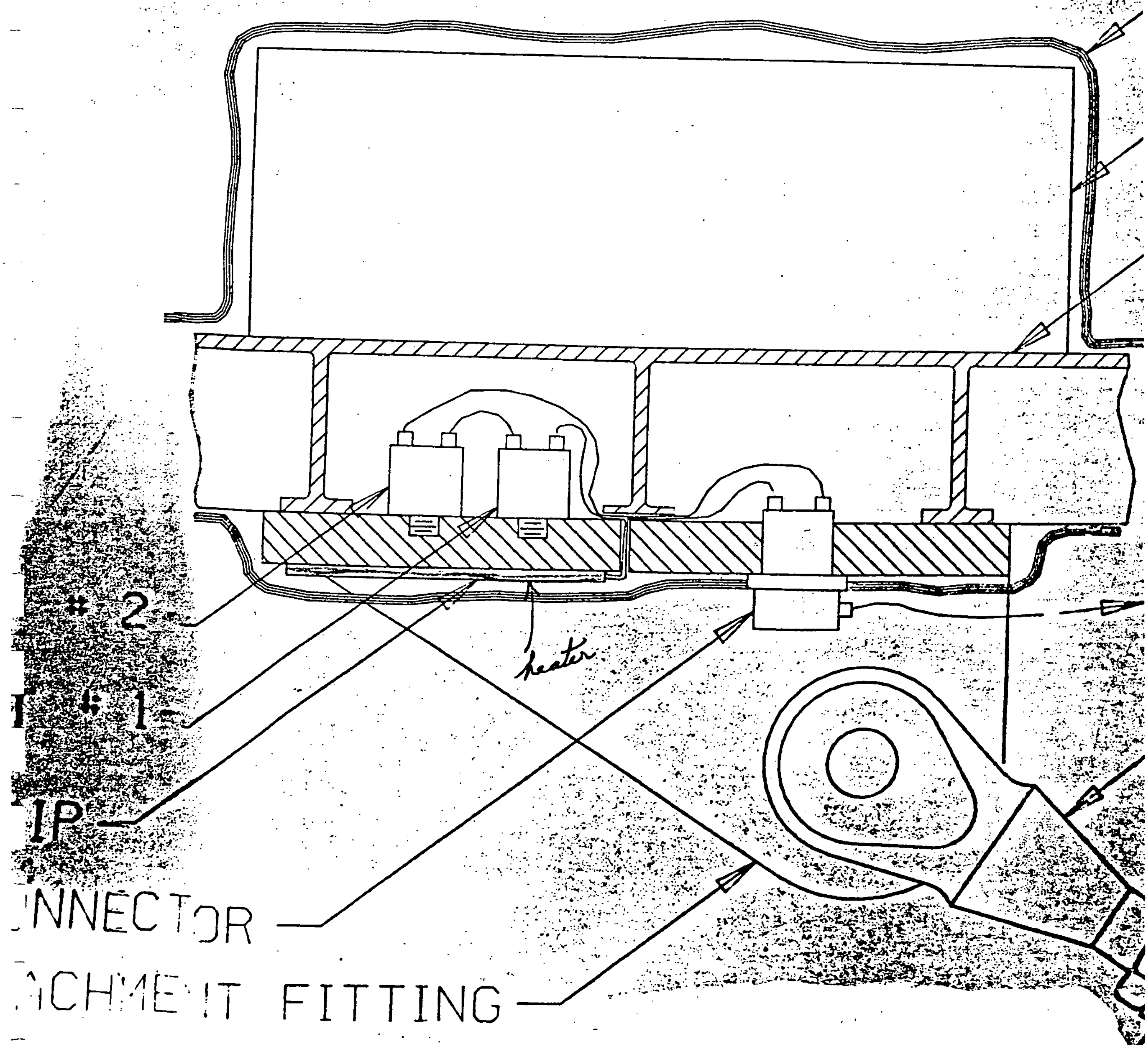
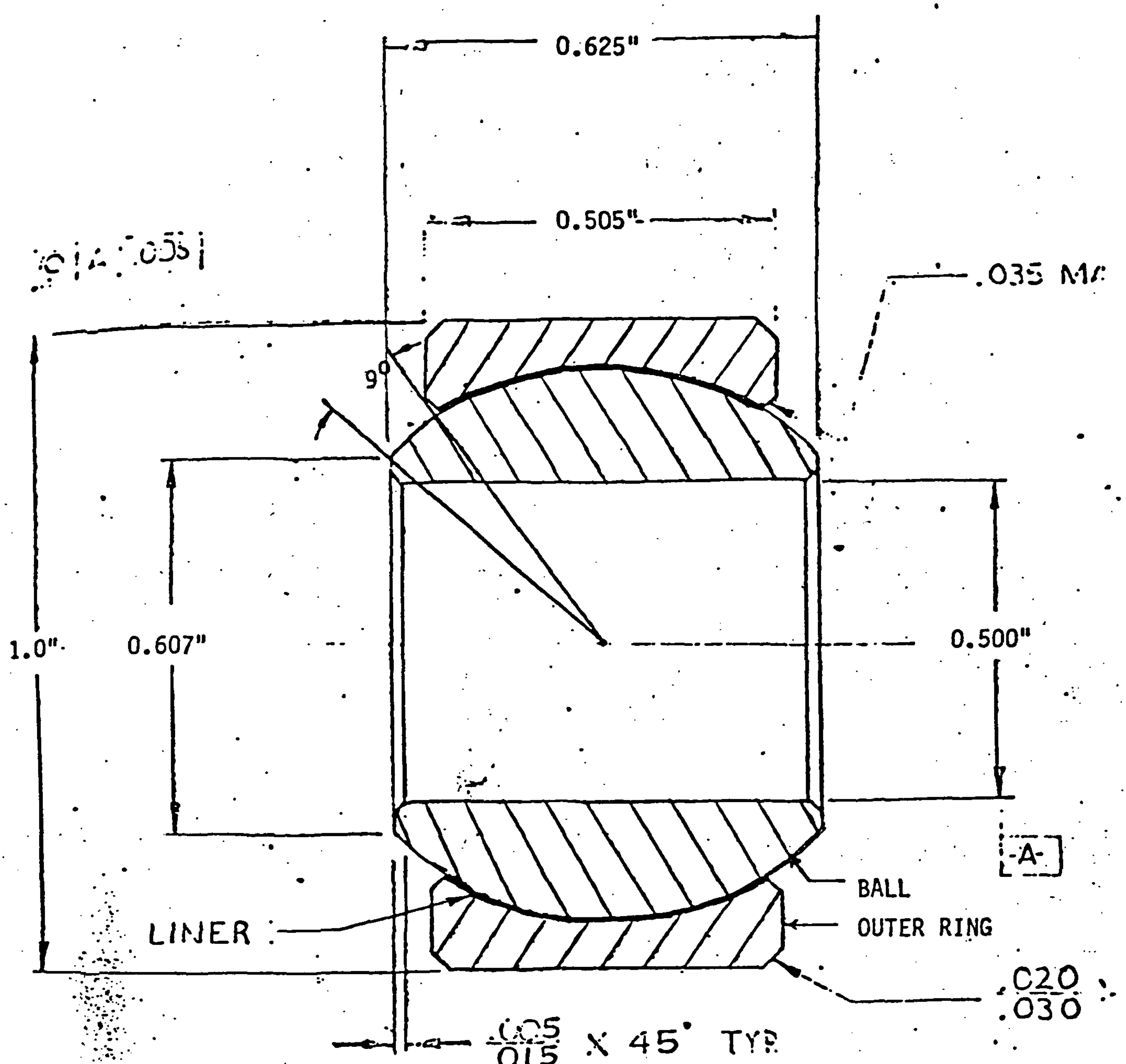


Figure 1 Monoball Assembly



MATERIALS: Ball Inconel 718
Outer Ring A286
Liner (assumed teflon)

Figure 2 Monoball Bearing

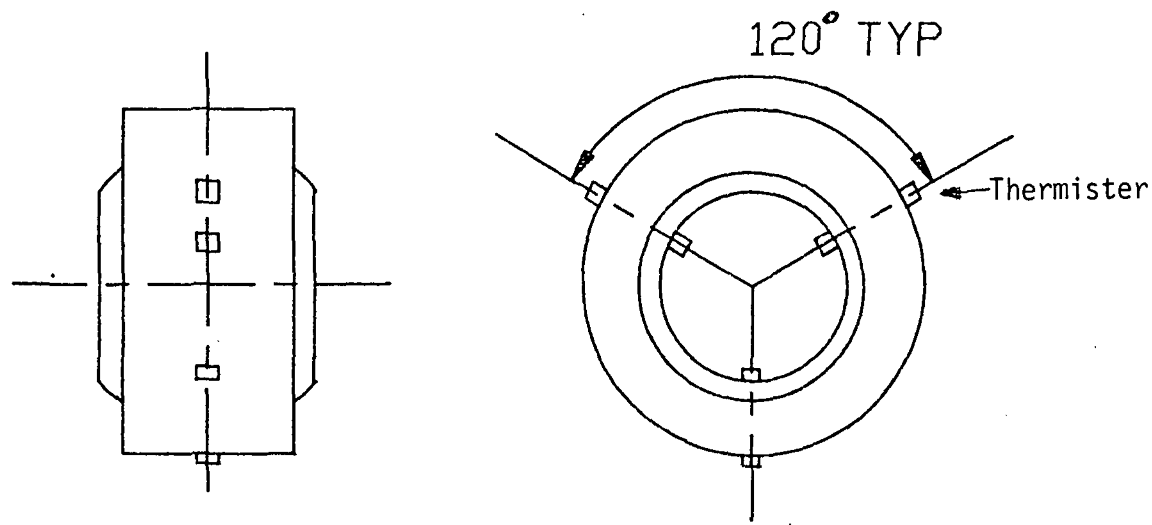


FIGURE 3 MONOBALL THERMISTER LOCATIONS

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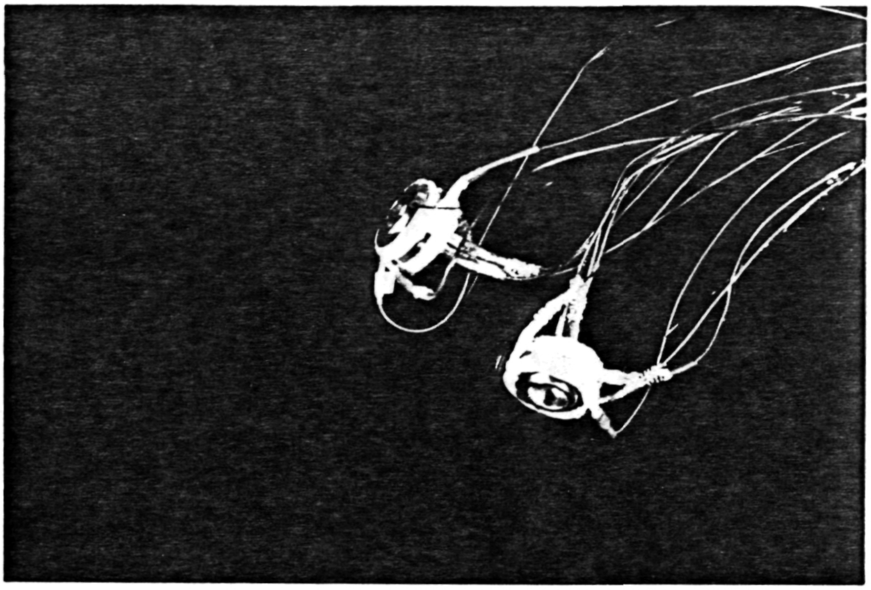

Figure 4 THERMISTERS ON MONOBALL

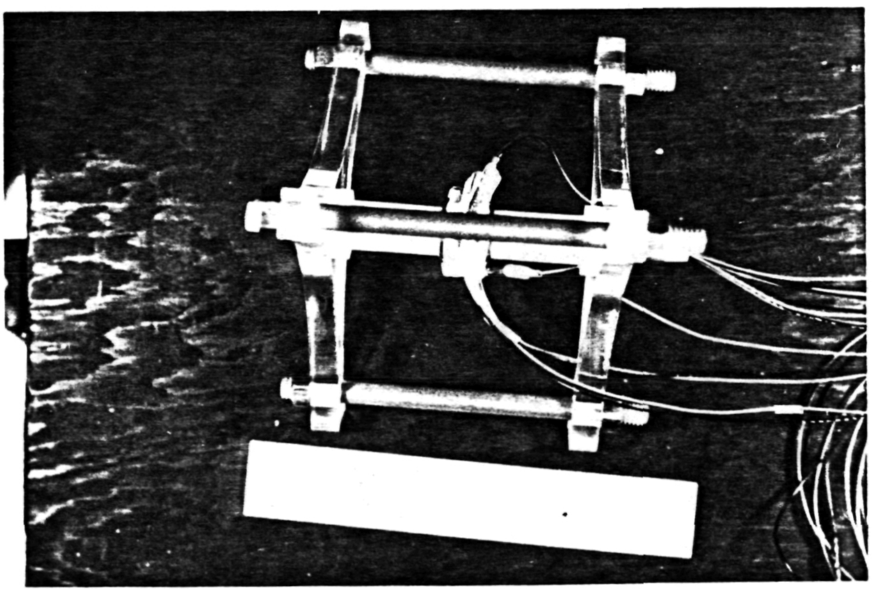

Figure 5 MONOBALL HOLDING JIG

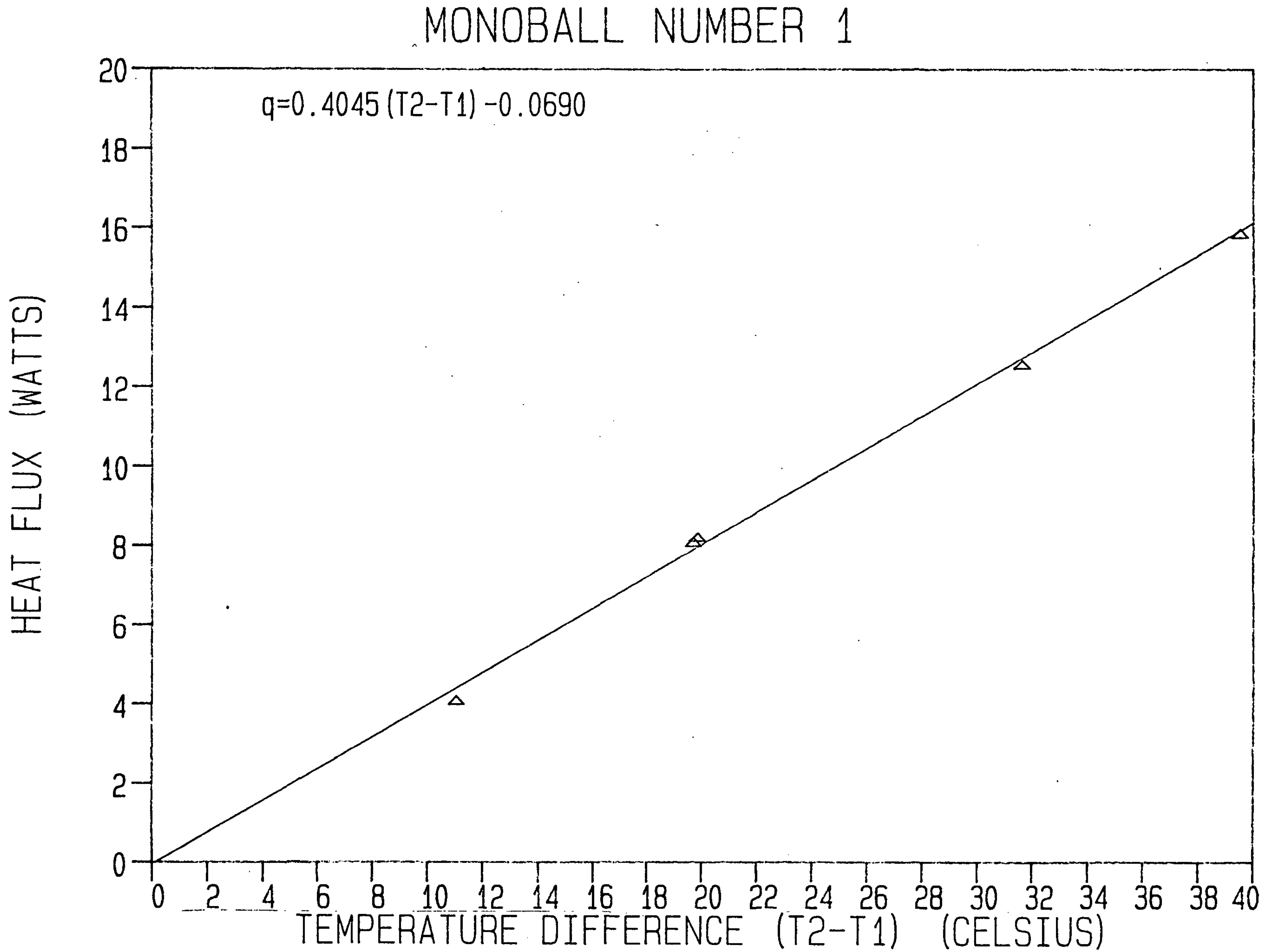

Figure 6 Heat Loss from Monoball #1

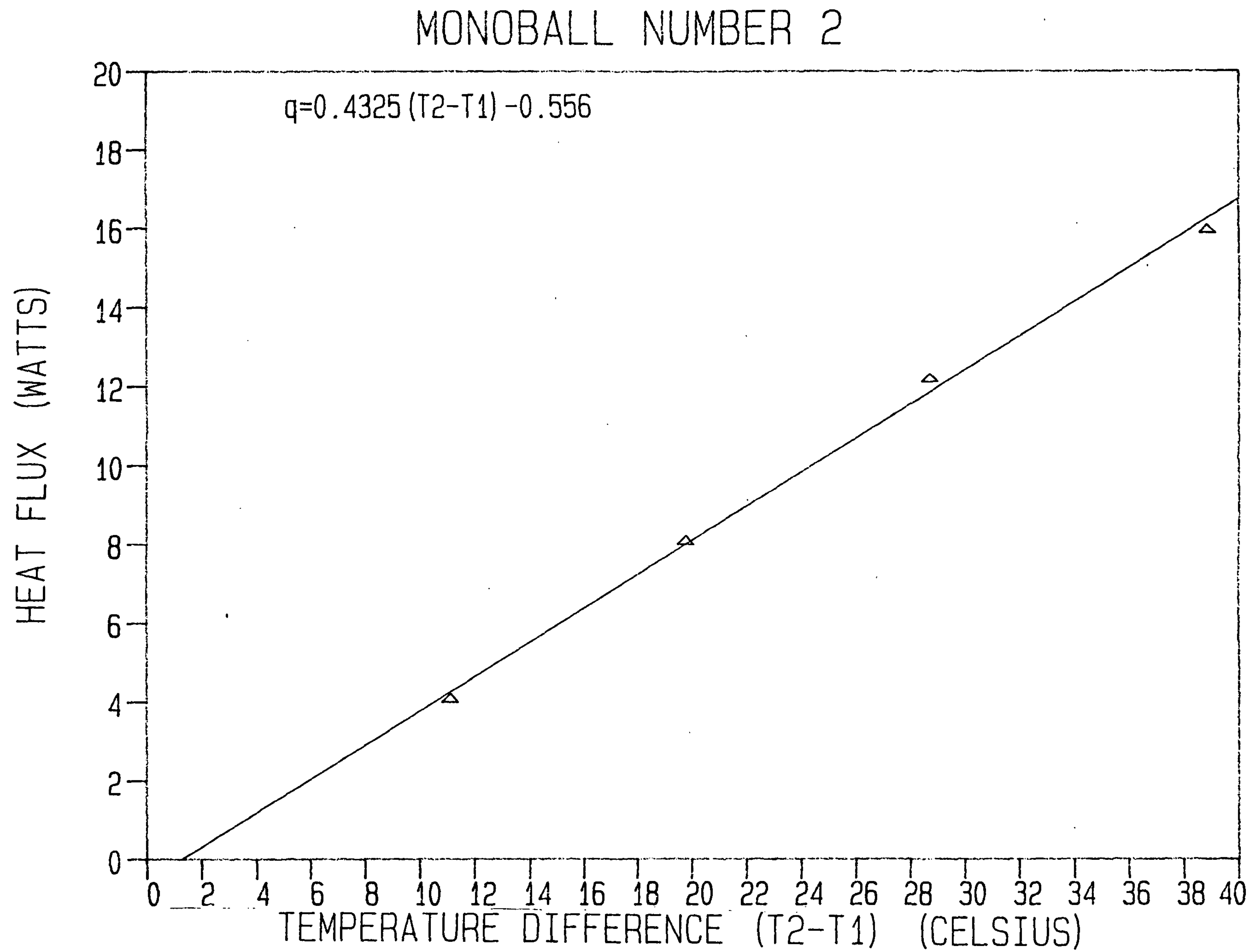

Figure 7 Heat Loss from Monoball #2

APPENDIX A

HEAT TRANSFER CALCULATIONS

A steady state calculation of the heat transfer from the outer ring of the monoball to the inner ring and to the cold tube connecting the inner ring to the constant temperature bath was made. The calculation was based on a steady state finite difference model. The node spacing in the insulation was shown on Figure A-1.

The boundary conditions for the finite difference model were specified. The nodes on the left side and top were considered to be well insulated. The bottom nodes (tube surface) were maintained at -17.7 C (0 F). The node (50) on the curve was maintained at -6.7 C (20 F). The insulation was assumed to have a thermal conductivity of 1.73 W/M/C (0.02 BTU/HR/FT/F).

These conditions were chosen as modeling a worse case temperature distribution. This led to a total energy transfer to the curved surface (node 50) of 0.04 watts (0.15 BTU/HR) and to the tube on the bottom of 0.09 watts (0.3 BTU/HR). These energies are considerably less than the energy applied to the outer ring heater during a test. The calculation showed that energy shunting through the insulation to the cold tube and to the inner ball was negligable.

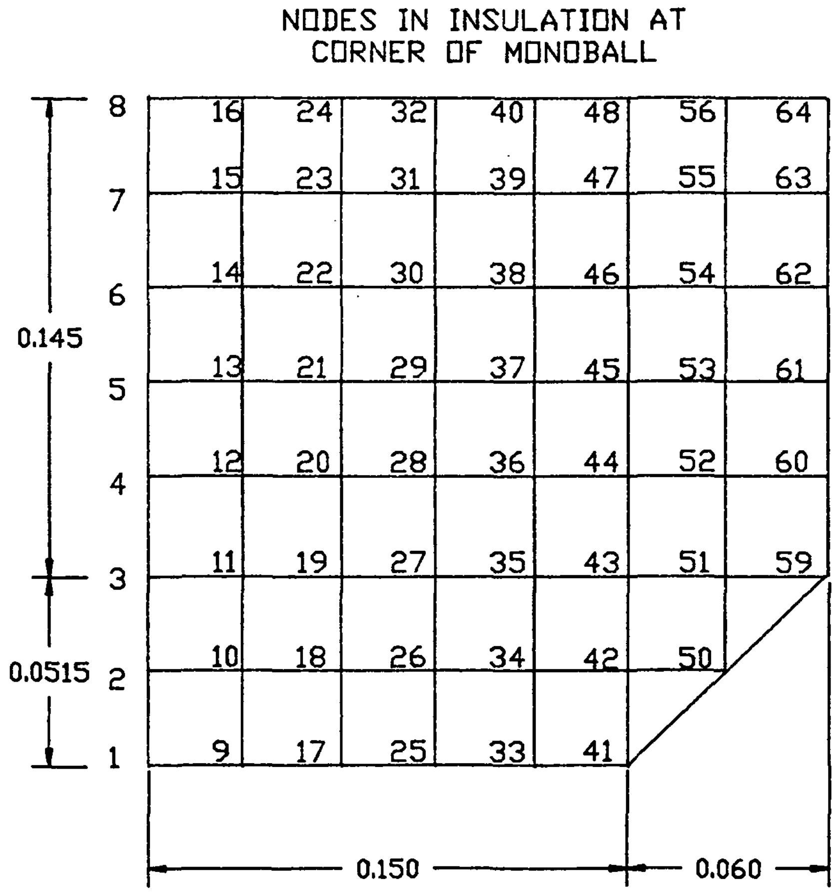

Figure A-1 FINITE DIFFERENCE NODES

APPENDIX B

MULTIMETER SPECIFICATIONS

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SPECIFICATIONS	
Operating Temperature	0°C to 50°C
Storage Temperature	-40°C to +60°C
Relative Humidity	
All ranges except 32 MΩ	0% to 90% (0°C o 35°C) 0% to 70% (35°C to 50°C)
32 MΩ range only	0% to 80% (0°C o 35°C) 0% to 70% (35°C to 50°C)
Temperature Coefficient	0.1 x (specified accuracy)/°C (applies from 0°C to 18°C and from 28°C to 50°C)
Battery Type	NEDA 1604 9V o 6F 22 9V
Battery Life (typical)	1600 hrs Zn-C 2000+ hrs alkaline
Size (HxWxL)	2.84 cm x 7.49 cm x 16.64 cm (1.12 in x 2.95 in x 6.55 in)
Weight	0.34 kg (12 ounces)
Safety Rating	Protection Class II per IEC 348

FUNCTION	RANGE	RESOLUTION	ACCURACY (Fluke 75)	ACCURACY (Fluke 77)	MAX. FULL SCALE BURDEN VOLTAGE
V~ 45 Hz-1 kHz (*45-500Hz)	3.2V 32V 320V 750V	0.001V 0.01V 0.1V 1V	±(2 + 2)* ±(2 + 2) ±(2 + 2) ±(2 + 2)	±(2 + 2)* ±(2 + 2) ±(2 + 2) ±(2 + 2)	
V⎓	3.2V 32V 320V 1000V	0.001V 0.01V 0.1V 1V	±(0.5 + 1) ±(0.5 + 1) ±(0.5 + 1) ±(0.6 + 1)	±(0.3 + 1) ±(0.3 + 1) ±(0.3 + 1) ±(0.4 + 1)	
300mV⎓	320 mV	0.1 mV	±(0.5 + 1)	±(0.3 + 1)	
Ω	320Ω 3200Ω 32 kΩ 320 kΩ 3.2 MΩ 32 MΩ	0.1Ω 1.0Ω 0.01 kΩ 0.1 kΩ 0.001 MΩ 0.01 MΩ	±(0.7 + 2) ±(0.7 + 1) ±(0.7 + 1) ±(0.7 + 1) ±(0.7 + 1) ±(2.5 + 1)	±(0.5 + 2) ±(0.5 + 1) ±(0.5 + 1) ±(0.5 + 1) ±(0.5 + 1) ±(2.0 + 1)	
→⊢ ·)))	2.0V	0.001V	±(1 + 1) typical		
A~ 45 Hz-1 kHz	32 mA 320 mA 10A	0.01 mA 0.1 mA 0.01A	±(3 + 2) ±(3 + 2) ±(3 + 2)	±(3 + 2) ±(3 + 2) ±(3 + 2)	0.2V 2.0V 0.5V
A⎓	32 mA 320 mA 10A	0.01 mA 0.1 mA 0.01A	±(1.5 + 2) ±(2 + 2) ±(1.5 + 2)	±(1.5 + 2) ±(2 + 2) ±(1.5 + 2)	0.2V 2.0V 0.5V

FUNCTION	MAXIMUM INPUT VOLTAGE (across input terminals)	RESPONSE TIME (of digital display to rated accuracy)	INPUT IMPEDANCE	COMMON MODE REJECTION RATIO (1 kΩ unbalance)	NORMAL MODE REJECTION RATIO (digital display only)
V~	1000V dc 750V ac rms (sine)	<2s	>10 MΩ in parallel with <50 pF (ac coupled)	>60 dB (dc to 60 Hz)	
V⎓	1000V dc 750V ac rms (sine)	<1s	>10 MΩ (input capacitance: <50 pF)	>120 dB (dc, 50 Hz, or 60 Hz)	>60 dB (50 or 60 Hz)
300mV⎓	500V dc 500V ac rms (sine)	<1s	10 MΩ (input capacitance: <50 pF)	>120 dB (dc, 50 Hz, or 60 Hz)	>60 dB (50 or 60 Hz)

MAXIMUM VOLTAGE BETWEEN ANY TERMINAL AND EARTH GROUND (all functions):
1000V dc 750V ac rms (sine)

FUSE PROTECTION (300 mA terminal only):
630 mA 250V FAST 3A 600V FAST

	MAXIMUM OVERLOAD (across input terminals)	RESPONSE TIME (of digital display to rated accuracy)	OPEN CIRCUIT TEST VOLTAGE (0°C to 50°C)	FULL SCALE VOLTAGE (0°C to 50°C)	
				Up to 3.2 MΩ	Up to 32 MΩ
Ω	500V dc 500V ac rms (sine)	<1s (up to 320 kΩ) <2s (up to 3.2 MΩ) <10s (up to 32 MΩ)	<3.1V dc (<2.8V dc typical)	<440 mV dc (<420 mV dc typical)	<1.4V dc (<1.3V dc typical)

	MAXIMUM OVERLOAD (across input terminals)	TEST CURRENT	
		Test Current (typical)	V_F
→⊢ ·)))	500V dc 500V ac rms (sine)	0.7 mA 0.5 mA 0.3 mA 0.1 mA	0.0V 0.6V 1.2V 2.0V

*Basic electrical specifications are defined over the temperature range from 18°C to 28°C for a period of one year after calibration.

Accuracy is specified as ±([% of reading] + [number of units in least significant digit]). In Touch Hold, accuracy is not specified for 300mV⎓ and Ω functions when test circuit impedance exceeds 1 MΩ.

V~ and A~ are average responding, calibrated for the rms value of sine waves.

Useful frequency response (typical): for 32V and 320V ranges, -0.5 dB at 10 kHz; for 3.2V and 750V ranges, ±3 dB at 5 kHz.

FLUKE 77 DIGITAL MULTIMETER SPECIFICATIONS

Table 1-1. Specifications.

DC VOLTMETER

Ranges: 20 mV, 200 mV, 2 V, 20 V, 200 V, 1,000 V

Maximum Input: 1,000 V (DC + Peak AC)

Accuracy (1 year + 23°C ± 5°C):

Range	Specification
20 mV	± (0.03% of reading + 2 counts)
200 mV through 200 V	± (0.02% of reading + 1 count)
1000 V	± (0.025% of reading + 1 count)

Temperature Coefficient (0°C to 50°C): ± 0.003% of Reading/°C

Effective Common-Mode Rejection (with 1 kΩ imbalance in either lead):

AC: > 120 dB at 50/60 Hz ± 0.1%

AC Normal-Mode Rejection:

> 60 dB at 50/60 Hz ± 0.1%

Input Resistance:

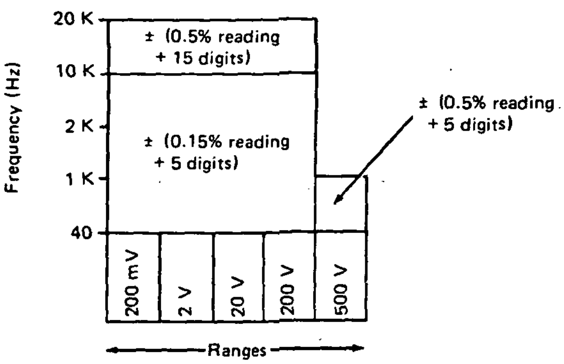
20 mV through 2 V ranges: (80% R.H.) ≥ 10^{10} Ω
20 V through 1,000 V ranges: 10 MΩ ± 1%

AC VOLTMETER

Ranges: 200 mV, 2 V, 20 V, 200 V, 500 V (500 V Max)

Overrange: The maximum reading decreases linearly from 19,999 at 10 kHz to 10,000 at 20 kHz.

Accuracy: 1 year + 23°C ± 5°C)



Temperature Coefficient (0°C to 50°C): ± (0.005% of Reading + .2 counts)/°C

Input Impedance: 1 M ± 1% shunted by < 100 pF

DC AMMETER

Ranges: 200 μA, 2 mA, 20 mA, 200 mA, 2,000 mA

Maximum Input: 2 A from < 250 V source

Protection: 2 A/250 V fuse (normal blow)

Voltage Burden:

Range	Max Burden at Full Scale
200 μA – 200 mA	< 250 mV
2,000 mA	< 700 mV

Accuracy: 1 year + 23°C ± 5°C)

Range	Specification
200 μA, 2 mA	± (0.07% of reading + 1 count)
20 mA	± (0.11% of reading + 1 count)
200 mA, 2000 mA	± (0.6% of reading + 1 count)

Temperature Coefficient (0°C to 50°C):

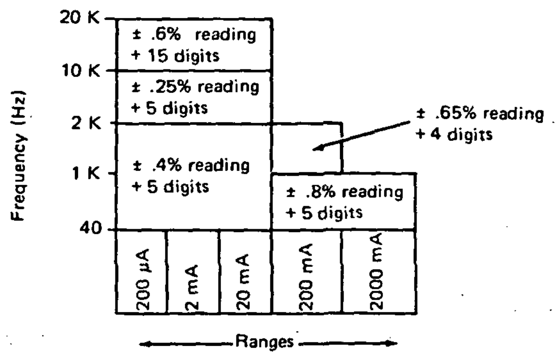
Range	Specification ± (% of Reading)/°C
200 μA	± 0.006%
2 mA, 20 mA	± 0.004%
200 mA, 2,000 mA	± 0.01%

AC AMMETER

Ranges: 200 μA, 2 mA, 20 mA, 200 mA, 2,000 mA

Overrange: The maximum reading decreases linearly from 19,999 at 10 kHz to 10,000 at 20 kHz.

Accuracy: (1 year, + 23°C ± 5°C)



Temperature Coefficient (0°C to 50°C): ± 0.01% of Reading/°C.

Protection: 2A/250 V fuse (normal blow)

Voltage Burden:

Range	Max Burden at Full Scale
200 μA – 200 mA	< 250 mV
2,000 mA	< 700 mV

OHMMETER

Ranges: 200 Ω, 2 kΩ, 20 kΩ, 200 kΩ, 2,000 kΩ, 20 MΩ

Accuracy: (1 year + 23°C ± 5°C)

Range	Specification
200 Ω	± (0.02% of reading + 2 counts)
2 kΩ through 2 MΩ	± (0.02% of reading + 1 count)
20 MΩ	± (.1% of reading + 1 count)

Temperature Coefficient (0°C to 50°C):

Range	Specification ± (% of Reading)/°C
200 Ω through 2 MΩ	± 0.0015%
20 MΩ	± 0.004%

HEWLETT PACKARD 3465

Digital Multimeter Specifications

APPENDIX C

DISPLACEMENT TORQUE MEASUREMENT

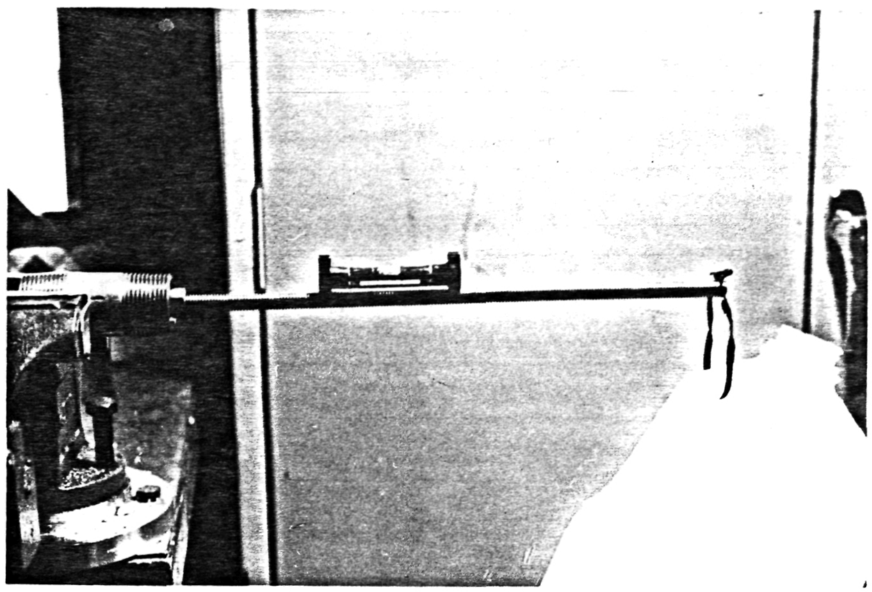


Figure C.1 Torque Measurement Apparatus

DESCRIPTION:

A 1/4" threaded rod was inserted through the monoball and held by a nut on each side of the bearing. The distance from the center of the bearing to the end of the rod was 12 inches. This assembly was placed inside a 1 inch Id galvanized pipe that was held level in a vise. No compressive forces were applied to the monoball outer race. See Figure C.1.

PROCEDURE:

A level was placed on the mid point of the threaded rod. Water was added to a milk bottle fastened at the end of the rod until the rod dropped off level. The bottle and water were weighed using a load cell and digital readout accurate to +/- 1/8 ounce.

RESULTS:

Two bearings were tested three times using this method. The bearings required a different amount of torque to move the inner race. The first bearing moved freely. The weight was recorded each time the rod dropped suddenly. The second bearing was stiff. Its first try had a sudden drop like the first bearing. The second and third tries showed a gradual drop of the rod. The weight was recorded when the bubble of the level was completely out of the lines marking the level position.

Torques for the first bearing were: 0.34 ft-lb, 0.32 ft-lb, 0.34 ft-lb.

Torques for the second bearing were: 1.54 ft-lb, 1.50 ft-lb, 1.34 ft-lb.