LIQUID - METAL

CAVITATION - EROSION

RESEARCH INVESTIGATION

FOR

NATIONAL ADVISORY COMMITTEE FOR

AERONAUTICS

Progress Report No. 1

UMRI Project 2824

November 1, 1958

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1.0 Introduction

A facility for the investigation of cavitation and erosion with fluids other than water generally, but with primary emphasis on liquid metals, is to be designed, constructed, and operated. As specified in the contract proposal and as described in detail in reference 1, the facility is to be a continuous flow tunnel with cavitating venturi, powered by a centrifugal pump. The basic objectives of the project and the anticipated research program are discussed in the next sections. These lead directly to the specification of the research equipment. The results of initial studies to determine suitable basic components are described in the following sections. The instrumentation details will be examined in later reports.

The program is outlined over a period of several years and the anticipated progress during the present contract period of one year stated.

2.0 General Objectives

The basic project objectives are the following:

1.) Determine those combinations of velocity, theoretical underpressure*, change of pressure with respect to time and axial distance, temperature, and container material which are permissible from the viewpoint of avoiding prohibitive wear with different liquid metals of interest. Such data could be used as a guide in producing optimum pump designs.

2.) Study the nature of wear or pitting as affected by temperature, material, fluid properties, underpressure*, rate of pressure change, and other applicable parameters which may become apparent. Fluid properties of interest include at least surface tension, density, viscosity, latent heat of vaporization, and freedom from impurities, solid and gaseous.

3.) Develop methods for determining cavitation effects on pump impellers with liquid metals through water-testing of models.

4.) Study basic mechanism of cavitation process with water and liquid metals.

3.0 Research Program

As presently planned, the research program will follow roughly the phases outlined in the following sections.

3.1 Water Phase

* Throat pressure which would exist in the absense of cavitation.

3.1.1 Objectives

1.) Check out general performance of loop and instrumentation equipment. Find Δp vs Q characteristics of test section without cavitation.

2.) Determine general appearance of cavitation as a function of cavitation number. Correlate this with sonic pattern and other indications of cavitation which may be available. Examine effect of velocity magnitude for a given cavitation number.

3.) Obtain wear results on transparent test sections as a function of cavitation number and velocity.

4.) Investigate scale effect; ie: try different size test sections for given cavitation number and velocity.

5.) Investigate effect of de-aerating water as far as possible to see if cavitation is suppressed.

6.) Check sonic pattern and other indications with steel test section under known cavitation number and velocity and compare with transparent section.

3.1.2 Equipment to be Utilized

1.) Continuous flow tunnel with water-cooled cooler.

2.) Transparent and steel venturi test sections of various sizes.

3.) Sonic and/or radioactive absorption equipment.

4.) Throat pressure measurement.

3.2 Mercury Phase

3.2.1 Objectives

1.) Compare visual appearance of cavitation of a liquid metal and water under same cavitation number, velocity, and rate of pressure change.

2.) Compare sonic and radioactive absorption effects under above conditions.

3.) Compare wear effects with water and Hg under otherwise similar conditions.

4.) Investigate possible effect of dissolved gas.

5.) Compare wear and sonic effects with plexiglass or pyrex and steel.

6.) Investigate relation between wear and velocity and rate of pressure change with same cavitation number. Include zero cavitation (ie: pure erosion).

7.) Investigate scale and rate of pressure change effects upon degree of cavitation.

8.) Investigate feasibility of wear detection with radioactive tracers.

3.2.2 Equipment to be Utilized

The equipment to be utilized is the same as for the water tests with the possible addition of material to allow radioactive tracer wear detection.

3.3 Lead-Bismuth Eutectic or Bismuth Phase

3.3.1 Objectives

1.) Compare wear effects on various materials with a given liquid at fixed velocity, rate of pressure change, and cavitation number at different temperatures. Compare with effects obtained with water. Compare with pure erosion.

2.) Establish limiting conditions of rate of pressure change, cavitation number, velocity and temperature for pump design with lead-bismuth and different structural materials of interest.

3.) Compare apparent "degrees" of cavitation with water and mercury through sonic effects and radioactive absorption ability at given cavitation number, rate of pressure change and velocity.

3.3.2 Equipment Required

1.) Continuous flow tunnel with spray cooler and heating coils.

2.) Metallic test sections as required.

3.) Sonic and radioactive absorption equipment.

4.) Throat pressure measurement @ 1000 F. with Hg.

5.) Temperature measuring instrumentation.

6.) Radioactive tracer equipment for wear detection.

3.4 NaK Phase

3.4.1 Objectives and Equipment

Objectives and equipment requirements are as above.

3.5 Further Phases

Additional research of application to liquid propellant rocket engines might be contemplated with such fluids as WFNA, JP-4, etc. The equipment is planned with sufficient flexability so that only moderations would be required.

3.6 Projected Time Schedule

The total program outlined in sections 3.1 to 3.5 above would require perhaps three to four years to complete. It is estimated that a major portion of the work outlined under 3.1 Water Phase and some of that outlined under 3.2 Mercury Phase, can be completed during the present contract period of one year.

4.0 Component Specification

As described in Reference 1, the facility is a continuous flow loop powered by a sump-type centrifugal pump and incorporating a venturi test section to create cavitation. Pump suction is held at approximately atmospheric pressure to avoid sealing difficulties. Two throttling values, upstream and downstream of test section respectively, are included to vary test pressure and velocity maintaining the desired absolute pressure in the throat. A venturi flow meter is included to measure flow. A further controllable variable is pump speed.

To meet the project objectives of delineating flow conditions suitable for large-scale liquid metal pump operation with respect to cavitation-erosion wear it is necessary to attain velocities and temperatures with the applicable fluids and structural meterials comparable to those expected in the full scale pumps. As a result of the work reported in References 1 and 2, it is believed that a velocity of about 50 ft/sec with the heavy metals as lead-bismuth or 100 ft/sec with the lighter fluids as NaK will suffice. Also operating temperatures up to 1000°F. should be obtainable.

It is necessary that a test section diameter large enough for instrumentation, observation, accurate fabrication, and suitable Reynold's Number be provided. To investigate possible scale effects it is necessary that different diameter test sections be provided. As explained in Reference 1, it is felt that a nominal diameter of about $\frac{1}{2}$ inch be used with the possibility of $\frac{1}{4}$ inch and 1 inch sections for specialized tests. The equipment then would be designed on the basis of attaining the maximum operating conditions in the $\frac{1}{2}$ inch test section.

Figure 1 shows the proposed layout of the facility. The pump, manufactured by the Berkeley Pump Company, is capable of pumping molten bismuth, lead-bismuth, or mercury at 40 gpm and a 45 ft. head at a pump speed of 1800 rpm and temperatures of 1000°F. It appears feasible and desirable to pump lighter fluids (such as water and/or NaK) at 3600 rpm.

4.1 General Sizing

Preliminary calculations of the pressure drop to be expected for the system as a function of pipe diameter gave the following results:

TABLE I

Nominal Pipe Dia. (inches)	Flow Rate (gpm)	Pump Head (ft)	Pipe Velocity (fps)	ΔH loss (loop piping) (ft)	% of pump head
1	40	45	14.9	17.5	38.0
$1\frac{1}{4}$	40	45	8.6	4.4	9.8
$1\frac{1}{2}$	40	45	6.32	2.02	4.4

This was based on the design flow rate of mercury or lead-bismuth for the Berkeley pump. Schedule 40 pipe was considered in all cases since it appears adequate for the expected pressures. Based on these results, $1\frac{1}{2}$" schedule 40 pipe was chosen to prevent excessive piping friction loss.

Price estimates were obtained for all pipe size possibilities in schedules 40 and 80. Of the sizes considered, all schedule 40's were in the same approximate range, however, schedule 80's were about double the price.

5.0 Overall Heat Balance

5.1 General

In designing a facility such as this, with the desired flexibility to handle several liquid metals and perhaps other corrosive fluids some design features required by a specific fluid are necessary while in other cases a compromise is the most practical solution. Since mercury, bismuth, and lead-bismuth are all heavy metals, the major difference is in the melting temperature and hence the required heat input. Sodium and NaK are both lighter fluids and so have different pumping characteristics than the heavier fluids. Tabulated below are melting points and heating requirements for these fluids:

TABLE II

Fluid	Melting Point	Heat Input Req'd to melt	Heat Input Req'd to heat to max. temp	Max. Temp
Mercury	-37.97 °F		1425 Btu	150°F
Bismuth	520	6450 Btu	6050	1000
Pb-Bi eutectic	257	3180	12,450	1000
Sodium	208	2200	9170	1000
NaK	66.2		8360	1000

It is apparent that no preheating is needed for mercury or NaK, but that it is required for the other fluids. The heat required to bring the liquid metal and structure up to temperature, assuming no losses is shown as a function of the temperature in Figure 2. Mercury, lead-bismuth, and NaK are discussed separately as being indicative of the fluids presently considered for test.

5.2 Mercury

Mercury does not require preheating and the heat input to attain operating temperature (150F) is reduced from the total requirement by the amount of the pump work (Figure 3). Under maximum conditions the pump would supply 50,000 Btu/hr while at a minimum (approximately 2 hp with mercury) it would supply 5000 Btu/hr. Under the worst conditions, minimum flow rate and maximum desired temperature increase (from 70°F to 150°F) 22 minutes would be required to heat the mercury using pump work only. Since this is not an intolerable warm up time, no additional heat input is needed for mercury beyond that of the pump.

In fact, the major problem becomes one of providing sufficient cooling capacity to maintain operation at 150°F and full pump power. Calculations shown in detail in the Appendix indicate that a counter-flow type water cooler, 7 feet long, consisting of stainless steel tubing containing the liquid metal and surrounded by a large pipe containing water, will suffice at the maximum conditions. Stainless steel tubing is used rather than a pipe to reduce the wall thickness, which accounts for a major portion of the temperature differential (1-7/8" BWG 21 tubing, wall thickness 0.032"). Figure 4 presents the total capacity of the cooler assuming 70 °F cooling water and the losses to the atmosphere of the remainder of the loop and pump, which need not be insulated due to the low maximum temperature (150°F), as a function of fluid temperature.

5.3 Lead-Bismuth Eutectic

The lead-bismuth eutectic will have to be heated from room temperature (70°F) to about 300° F in the dump tank to melt it and allow transfer to the pump. This will require 3180 Btu for the Pb-Bi plus 2400 Btu for the tank which is equivalent to 1.6 kw hr. With a wrapping of resistance wire (220 v, 3 circuits @ 2.6 kw/circuit) this can be accomplished in 13 minutes (see Appendix for detailed calculations). Also the loop must be preheated to 300°F. Using 2 resistance circuits, this requires 7 minutes.

The sump tank must also be brought up to temperature before operation is commenced. With 4 resistance circuits on the tank only 5 minutes is needed to heat it from room temperature to 300°F. Thus, in the 13 minutes that the dump tank and full load of Pb-Bi are preheating, both loop and sump tank will also reach the required temperature. Hence, there is no time delay beyond the 13 minutes.

Once the molten Pb-Bi is in the sump an additional 30 minutes is required to heat the sump and full load of fluid to 1000°F.

Approximately the same time is required to heat the loop. If the fluid is being pumped around the circuit during this period the elapsed time will be reduced depending upon the pump speed and the valve positions. However, with no assistance from the pump and a heating circuit as described, it will take about 45 minutes to bring the system from a shut down condition at room temperature to 1000°F. The required electrical input will be about 25 kw, allowing 1 kw for loss to ambient (Figure 5). The distribution of 220 v, 2.6 kw circuits is as follows: 3 on dump tank, 2 on loop, 4 on sump.

At temperatures above about 300°F it will be necessary to insulate the system as a safety precaution for the personnel. Hence, the heat loss to the atmosphere will be very little, and a cooler will be required to remove pump work at least at high head and flow. The loss through the insulated piping and pump to atmosphere is given in Figure 5. With the insulation described in Figure 5 the maximum temperature of the outer surface of the insulation is 170°F.

The maximum amount of heat to be removed will occur at full flow rate and pressure for low temperature tests. Considering only the input of the pump work and the losses to piping and pump, approximately 33,000 Btu/hr, must be taken out by the cooler at maximum flow and about 600°F. (see Figure 6). The heat load is not particularly sensitive to fluid temperature as shown in Figure 6 because heat loss to ambient is small.

Because of the high temperature of the fluid and pipe a spray type cooler appears most desirable. The cooling capacity obtainable in spray coolers 28 and 18 inches long is plotted in Figure 6 (calculations are in the Appendix). As presently designed, a maximum of 28 inches is available. Considering the maximum requirements of about 33,000 Btu/hr, it is apparent that 18" of spray cooler is probably sufficient for the job and that a 28" cooler would allow ample reserve cooling area. It appears that full power operation down to about 300°F should be possible. At a vaporization rate of 1000 Btu/lb of water, 30 lbs. of water per hour or 4 gal/hr will be needed.

5.4 NaK and Water

From the standpoint of heat input and cooling requirements, NaK and water fall well within the limits defined by Pb-Bi and Hg. Preheating is not required. For NaK, about 7000 Btu are required to attain 1000°F, and at 80 gpm the pump work input is about 14,000 Btu/hr. Thus, both the heater and spray cooler designed for the Pb-Bi case will be more than sufficient for NaK. The water-cooled cooler will be necessary for water tests.

5.5 Bismuth and Sodium

Bismuth and sodium involve no additional problems or considerations except that a larger amount of preheating will be needed for the bismuth. This can easily be provided by an additional wrapping of 2 resistance wire circuits on the dump tank.

6.0 Pressure Loss

The head loss in various sections of the loop and the operating characteristics of the complete system for mercury and NaK are shown in Figures 7 and 8 respectively.

The head-flow characteristics for the various fluids considered are virtually identical in many respects because the Reynold's Number is sufficiently high so that the friction factor is not particularly sensitive to Reynold's Number. Hence the curves are generally applicable also to water and mercury. The exception to this general applicability lies in the following two factors:

1.) The test section throat pressure for all fluids must be approximately 0 psia and the pump suction pressure about 14 psia. Therefore, the head rise required from test section throat to sump is inversely proportional to fluid density. This limits the minimum usable throat velocity, (about 5 ft/sec for Hg and 60 ft/sec for NaK).

2.) The pump horsepower, thrust loads, pressure stresses, etc, depend directly on fluid density for a given head rise. Hence a maximum head of about 45 feet obtainable at 1800 rpm seems limiting with mercury (about 20 hp and 260 psia). However, it is expected that 3600 rpm and 180 feet head should be feasible with NaK or water (only about 1.5 hp and 20 psia).

It is expected that water tests with minimum velocity similar to that obtainable with mercury can be made by applying a suitable vacuum to the sump to obtain the suction head available with mercury under atmospheric sump pressure. This does not appear feasible with NaK because the in-leakage of air could not be avoided.

The pipe friction loss was based on the layout as shown in Figure 1. The various components have a pressure drop equivalent to the following length of $1\frac{1}{2}$" pipe.

45° elbow	2.0 ft.
90° elbow	2.7 ft.
Straight-run Tee	2 ft.
Valve	max. 40 ft, min. 10 ft. depending upon type of valve finally selected.

Since a variety of configurations may be used for the test-section venturi and no precise data is available in any case, a maximum and minimum head loss were considered consistant with current practice. The maximum loss is 20% ΔP between inlet and throat and the minimum is 10%. These were used as the criteria for both the flow meter venturi and the test-section venturi. The flow meter venturi has been sized to provide a minimum of 2 inches ΔH under minimum flow conditions. This was deemed satisfactory to provide acceptable precision. The maximum ΔH is then about 30 inches. ΔP across the test section venturi varies according to the pressure at the venturi inlet since, in order to obtain cavitation with the low vapor pressure , a pressure of approximately zero is required at the throat of the venturi. The pressure reduction required of the downstream valve (sump tank must be maintained at about atmospheric pressure) can then be determined from the pressure at the test section exit and the friction losses in the remainder of the loop. Tables III and IV show the detailed data upon which Figures 7, 8 and 9 are based.

These results indicate that flows as low as 4 gpm, V_{throat} = 5 fps, can be obtained with mercury considering an equivalent 10' of $1\frac{1}{2}$" pipe head loss thru the upstream valve. With NaK the minimum possible flow rate is 47 gpm (V_{throat} = 61 fps) under the same conditions, if atmospheric pressure is to be maintained in the sump.

REFERENCE:

1. Hammitt, F. G. and Desai, B. C., Continuous Flow Fluid Tunnel Cavitation - Erosion Facility, Engineering Research Institute, University of Michigan 461:1117-3-P, May 1957.

2. Hammitt, F. G. "Considerations for Selection of Liquid Metal Pumps", Chemical Engineering Progress, May, 1957

3. Liquid Metals Handbook, Atomic Energy Commission and Department of the Navy, NAVEXOS P - 733 (Rev.), June, 1952

4. Liquid Metals Handbook Sodium - NaK Supplement, Atomic Energy Commission. Department of the Navy, July, 1955.

HEAD LOSS FOR MERCURY FLOW THROUGH LOOP

TABLE III

Flow Rate	V_{pipe}	H_s psia	H_d		H_{v_i}
gpm	fps	ft	ft globe	ft "Y"	ft
40	6.32	16 / 2.72	48.24	45.46	43.72
33.3	5.26	16 / 2.72	33.41	31.50	30.29
26.7	4.22	16 / 2.72	21.50	20.27	19.49
20	3.16	16 / 2.72	12.05	11.36	10.92

Flow Rate	H_{v_o}	ΔH_{loss}*		Head to be Dissipated by Downstream Valve		V_{throat}
gpm	ft	ft globe	ft "Y"	ft globe	ft "Y"	fps
40	39.35 / 34.98	6.62	3.84	32.73 / 28.36	35.51 / 31.14	52.08
33.3	27.26 / 24.23	4.75	2.83	22.51 / 19.48	24.43 / 21.40	43.36
26.7	17.54 / 15.59	3.26	2.02	14.28 / 12.33	15.52 / 13.57	34.76
20	9.83 / 8.74	2.07	1.38	7.76 / 6.67	8.45 / 7.36	26.04

*ΔH_{loss} = friction loss of 15 ft. of pipe, 3 long radius els, a straight run tee, static head, and minimum possible valve loss to return fluid to pump suction head.

HEAD LOSS FOR NaK FLOW THROUGH LOOP

TABLE IV

Flow Rate	V_{pipe}	H_s	H_d		H_{v_i}
		psia ft	ft		
gpm	fps		globe	"Y"	ft
80	12.7	16 46.2	194.48	183.61	176.56
66.7	10.5	16 46.2	133.17	125.52	120.69
53.4	8.4	16 46.2	85.22	80.32	77.24
40	6.32	16 46.2	49.32	46.54	44.80

Flow Rate	H_{v_o}	ΔH_{loss}*		Head to be Dissipated by Downstream Valve		V_{throat}
		ft		ft		
gpm	ft	globe	"Y"	globe	"Y"	fps
80	158.90 140.52	68.44	57.25	90.46 72.08	101.65 83.27	104.16
66.7	108.62 96.55	60.72	53.07	47.90 35.83	55.55 43.48	86.84
53.4	69.52 61.79	54.71	49.81	14.81 7.08	19.71 11.98	69.53
40	40.32 35.84	50.08	47.30	-----	-----	-----

* ΔH_{loss} = friction loss of 15 ft. of pipe, 3 long radius els, a straight run tee, static head, and minimum possible valve loss to return fluid to pump suction head.

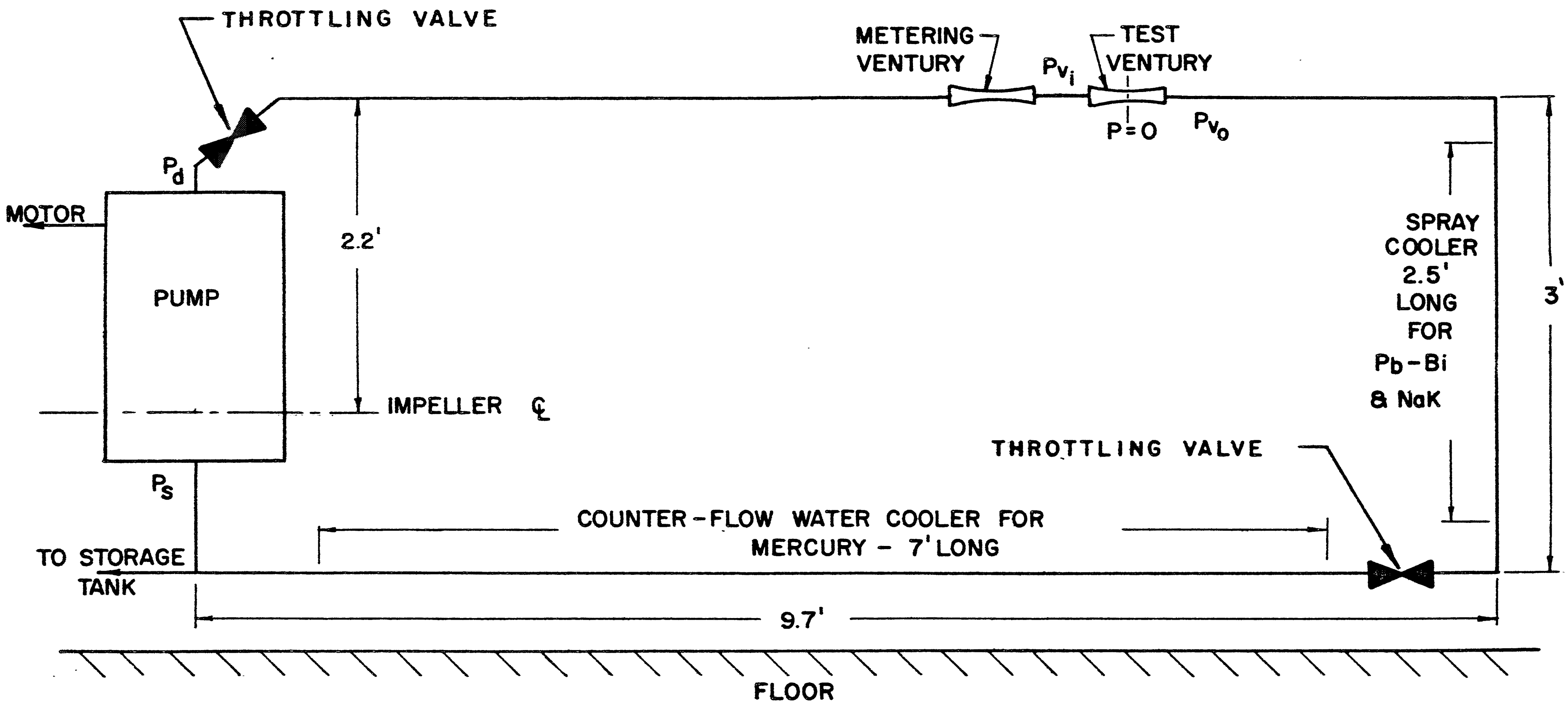

Figure 1. Sketch of Cavitation Loop Layout.

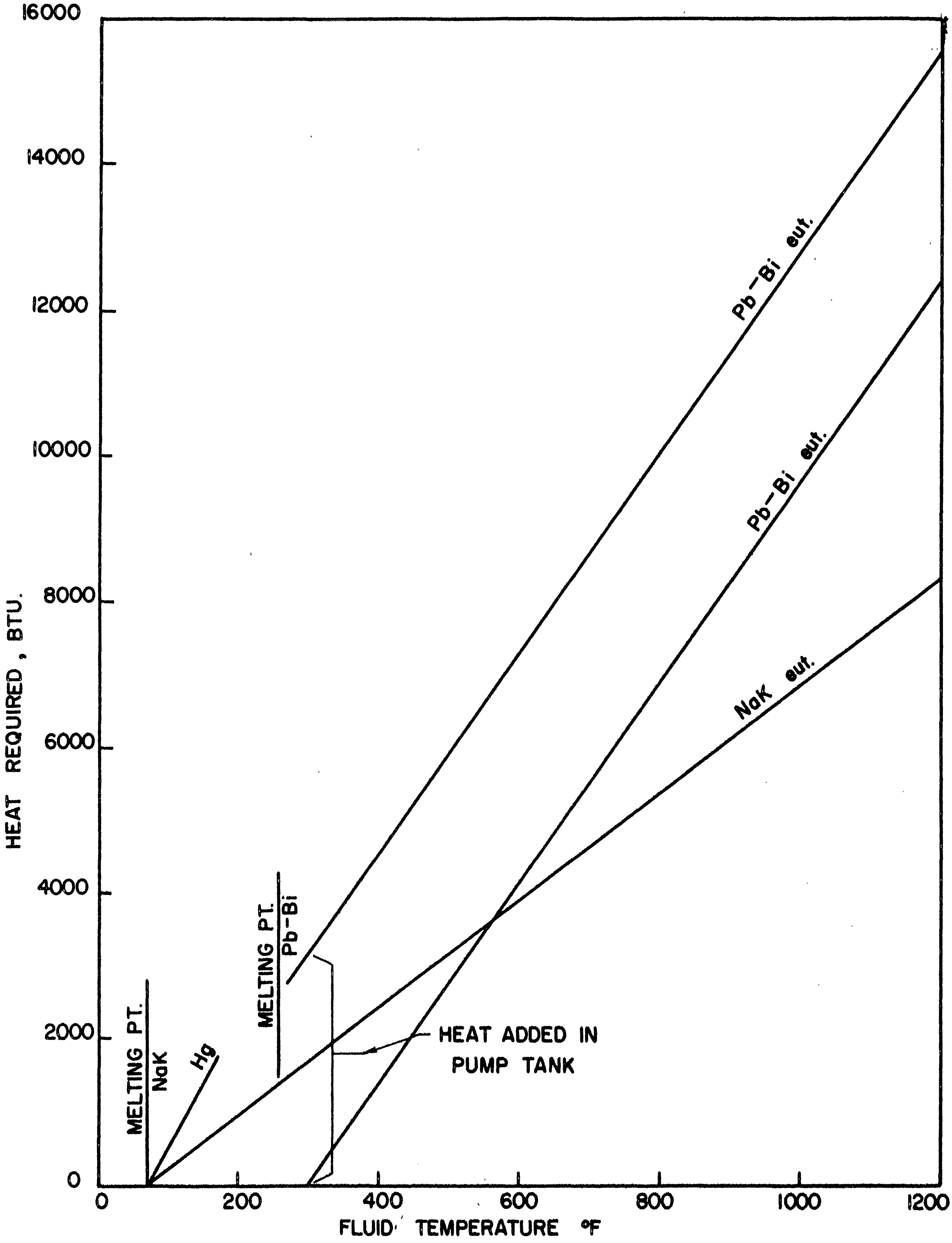

Figure 2. Heat Requirements of Various Liquid Metals.

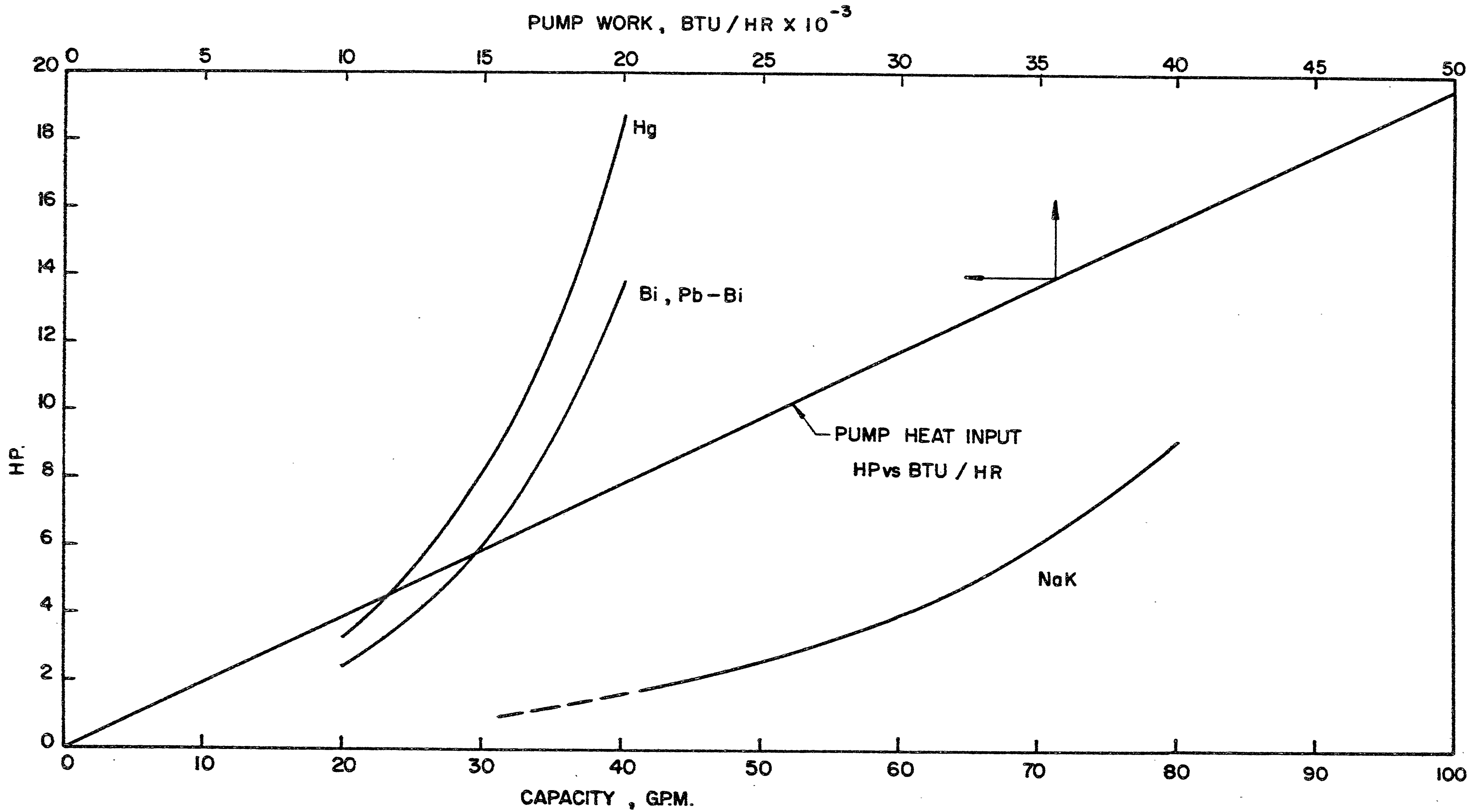

Figure 3. Pump Requirements for Various Liquid Metals as a Function of Capacity.

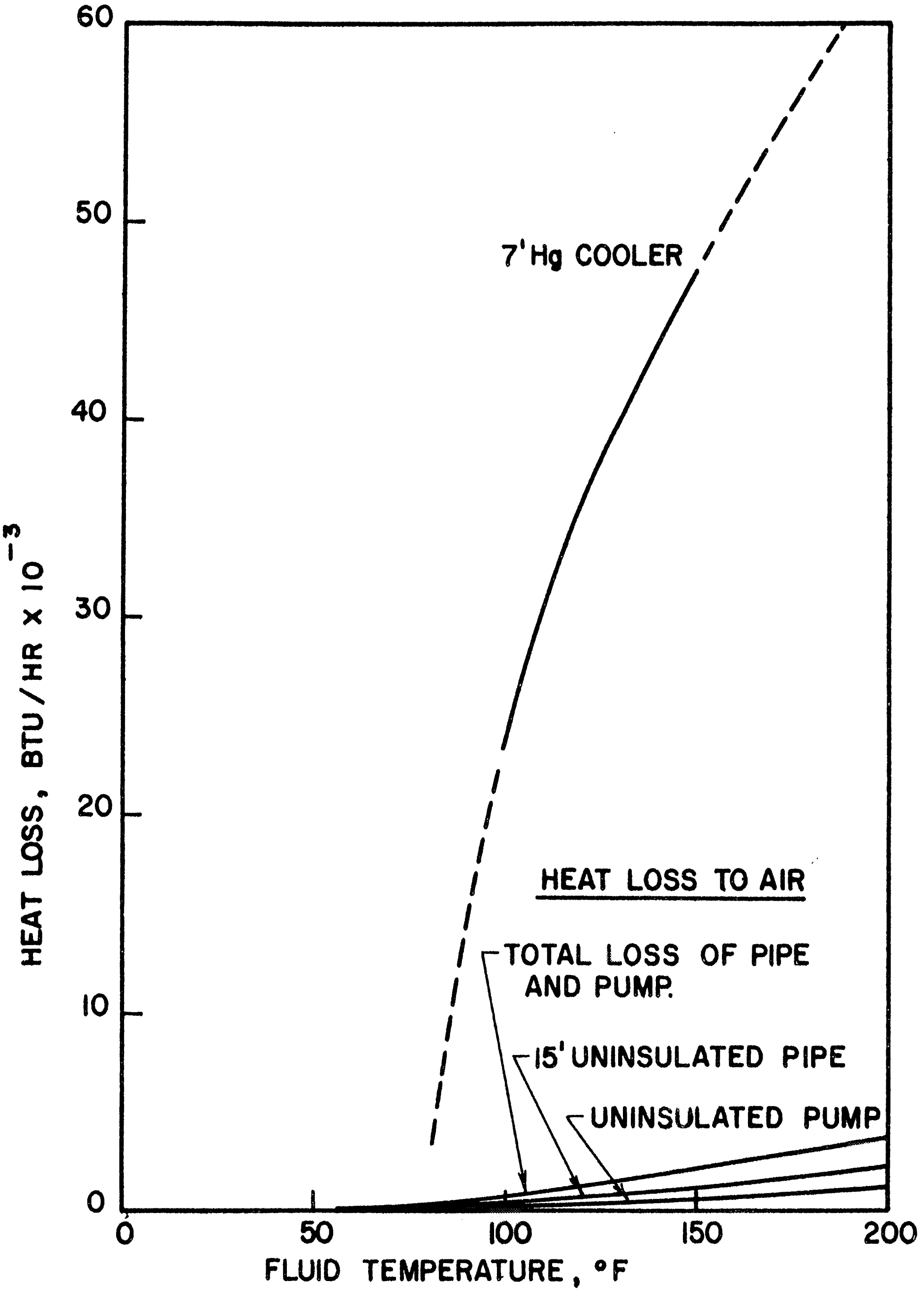

Figure 4. Heat Losses in Mercury Loop.

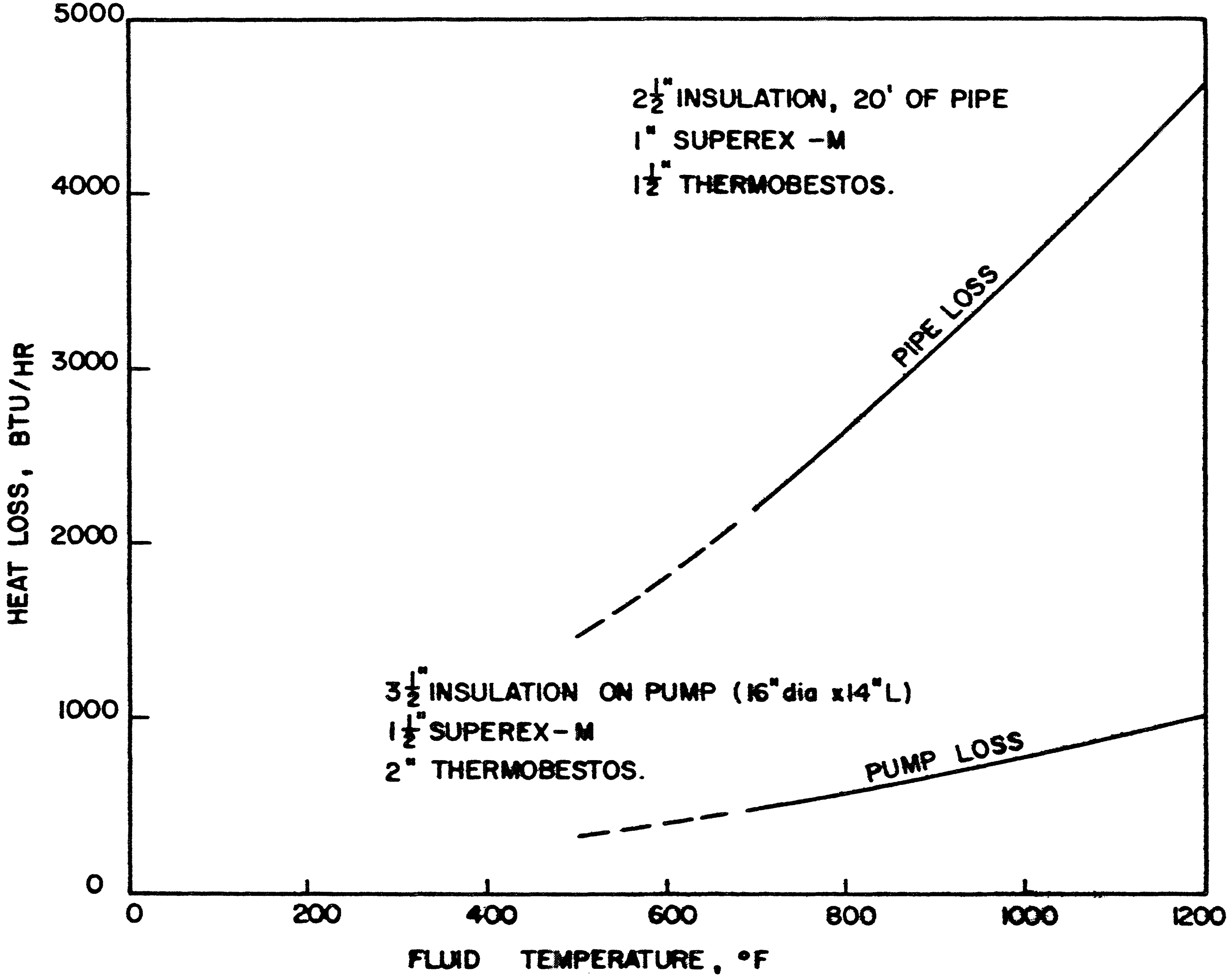

Figure 5. Heat Loss of Insulated Pipe and Pump.

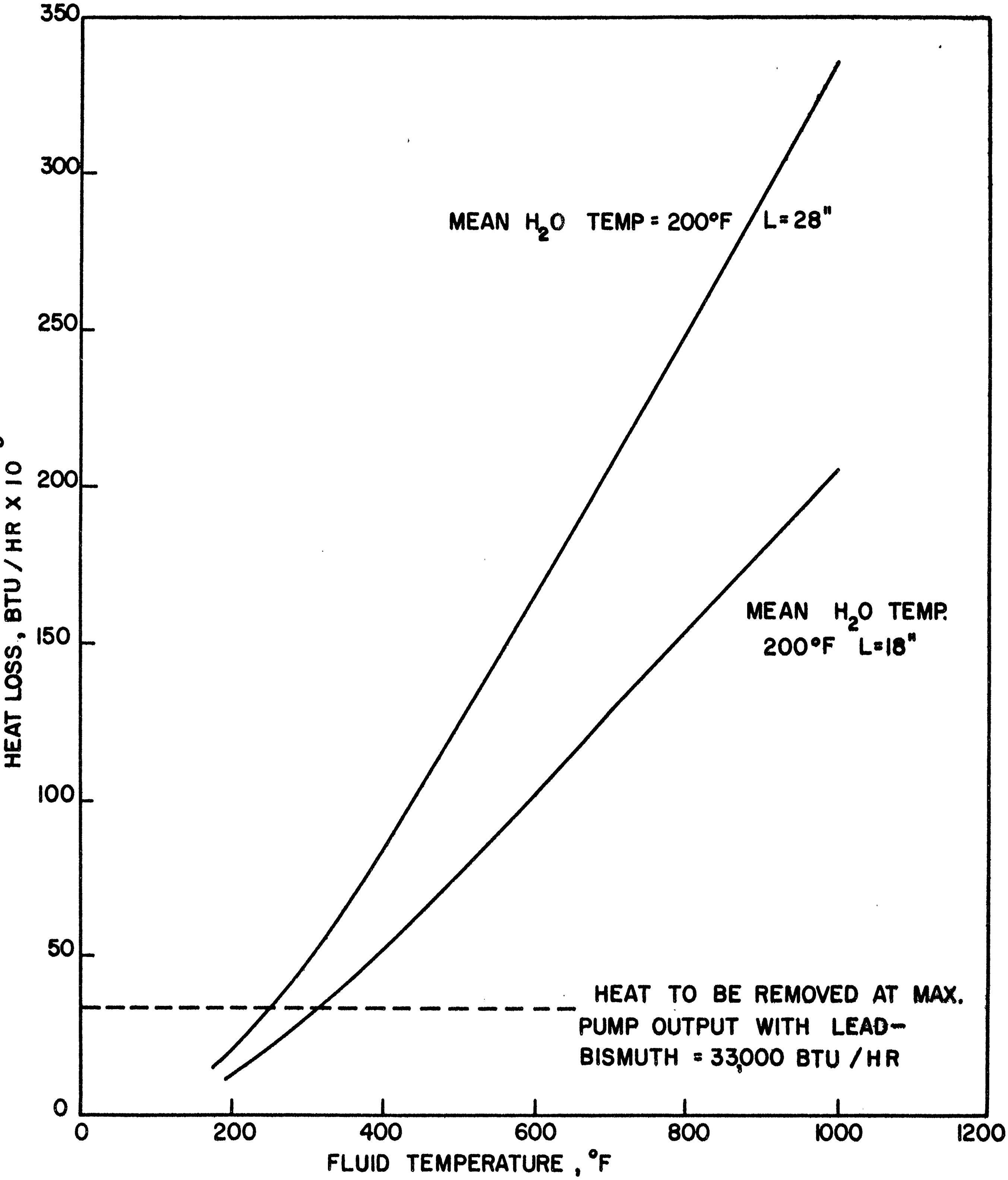

Figure 6. Heat Loss in Spray Cooler.

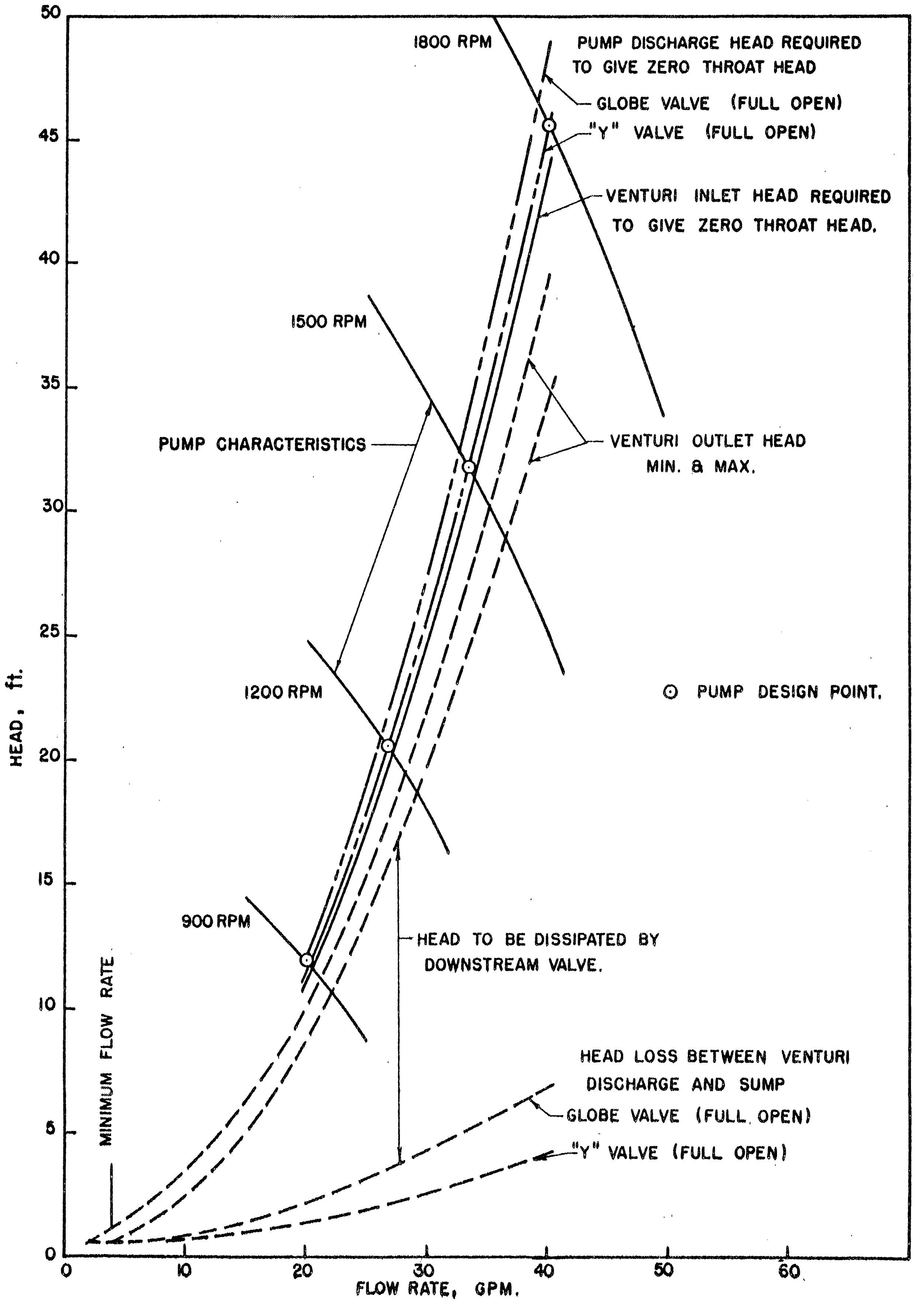

Figure 7. Loop and Pump Characteristics for Mercury.

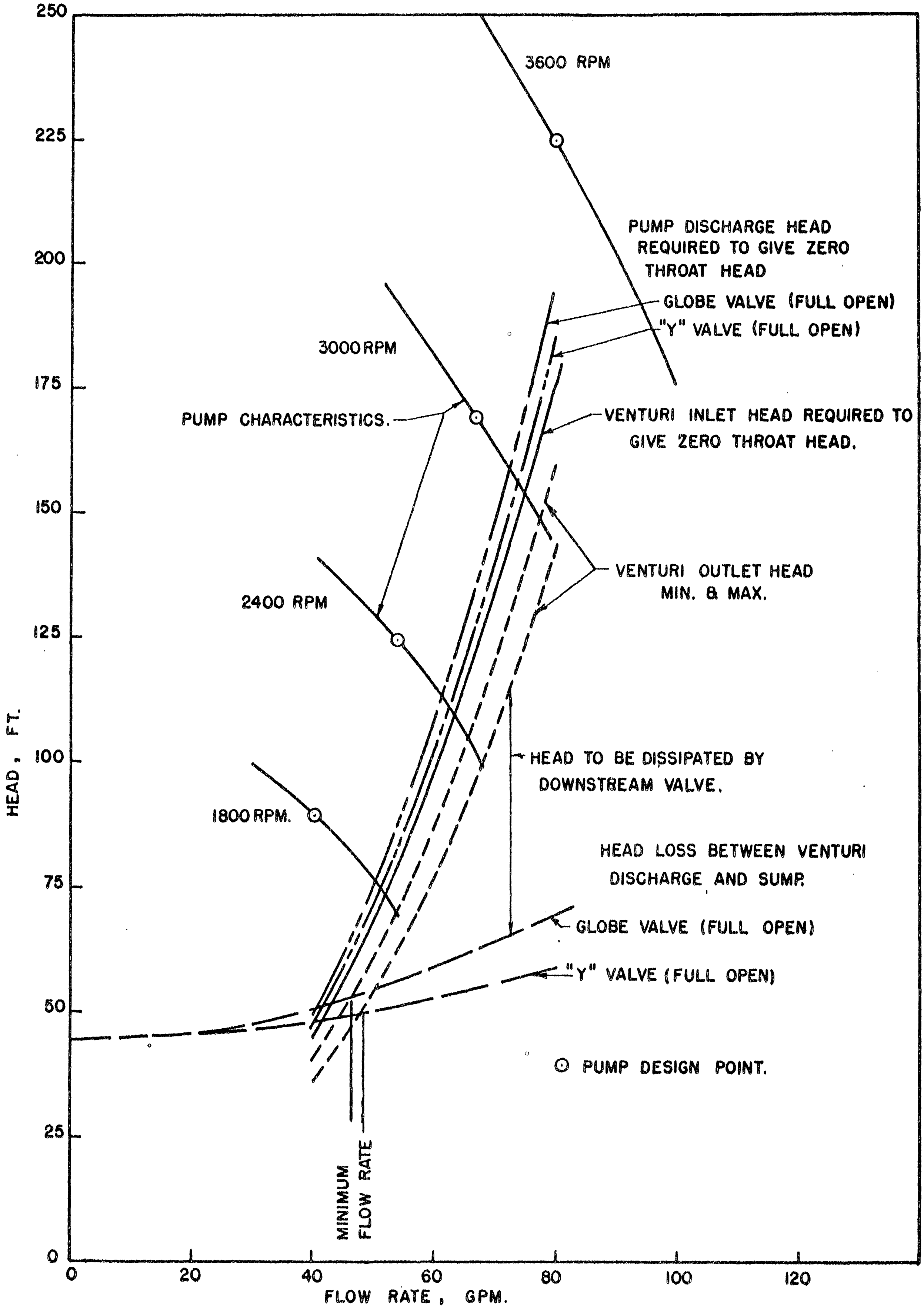

Figure 8. Loop and Pump Characteristics for NAK.

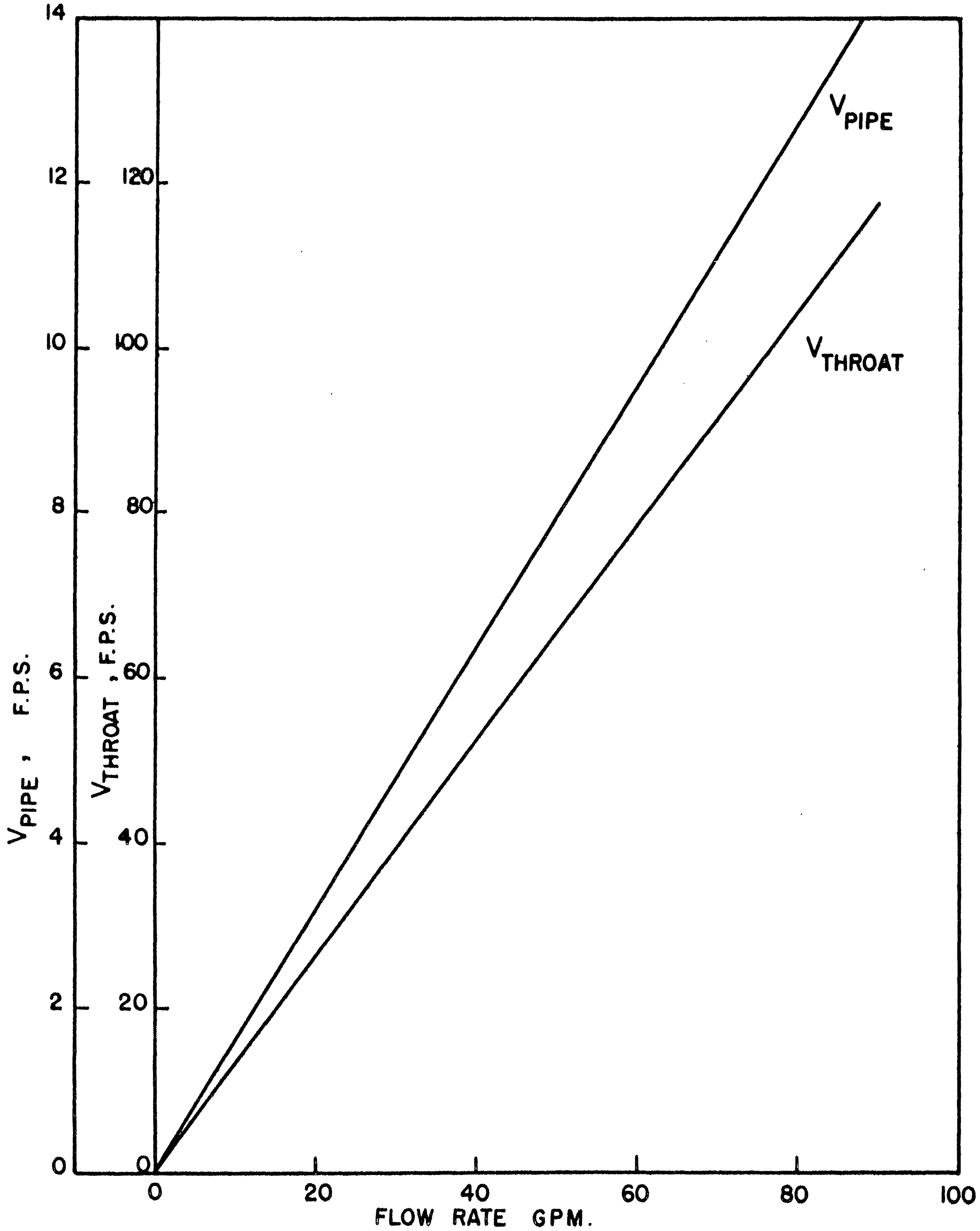

Figure 9. Pipe and Test Section Velocity.
(Based on: 1-1/2 sch 40 pipe and test section venturi diameter = 0.56 inch)

7.0 Appendix

7.1 Calculations of Cooler for Mercury Loop Mercury Side:

$$Nu = 7 + 0.025\, Pe^{0.8} = \frac{hD}{k} \quad \text{(Ref. 3)}$$

$$Pe = Pr \times Re$$

$$Pr = \frac{cp\mu}{k} = \frac{1.37 \times 2.42 \times 0.033}{4.83} = 0.0227$$

$$Re = \frac{DV\mu}{\rho} = \frac{845 \times 6.3 \times 1.61 \times 3600}{2.925 \times 12} = 5.8 \times 10^5$$

$$Pe^{0.8} = (0.0227 \times 5.8 \times 10^5)^{0.8} = 2050$$

$$Nu = 7 + 0.025 \times 2050 = 58.3$$

$$h = \frac{4.83 \times 12 \times 58.3}{1.61} = 2100$$

On the water side of the cooler:

$q = 50,000$ Btu/hr
$Q = 20$ gpm
$V = 3.2$ fps
$k = 0.363$
$R \sim 1.5 \times 10^4$ (turbulent)
$Pr \sim 5.0$

$$\frac{hD}{k} = 0.023\, Pr^{0.4}\, R^{0.8}$$

$$h = \frac{0.023 \times 5^{.4} \times (1.5 \times 10^4)^{.8} \times 0.363 \times 12}{0.6} = 705$$

Hence

$$\frac{1}{u} = \frac{1}{hi} + \frac{x}{k(\frac{d}{di})} + \frac{1}{ho(\frac{do}{di})} + \frac{1}{ho_s(\frac{do}{di})}$$

$$\frac{1}{u} = \frac{1}{2100} + \frac{.030/12}{9.4(\frac{1.75}{1.61})} + \frac{1}{705(\frac{1.90}{1.61})} + \frac{1}{1000(\frac{1.90}{1.61})}$$

$$u \cong 340$$

$$A = \frac{\pi \times 1.9}{12} \times 7 = 3.48 \text{ ft}^2$$

Hg Temp	$\Delta T_{\text{log mean}}$	$q^{\text{Btu/hr}}$
100°F	20	23,700
120	30	35,500
150	40	47,400

7.2 Heating Circuits for Pb - Bi Eutetic

$$q = \frac{KA(t_{max} - t_{max\,ins})}{L} = \frac{.06 \times .0208(2100-1200)}{.00533}$$

$$= 328 \text{ Btu/hr/ft or } 328/3.415 = 96 \text{ watts/ft}$$

K = thermal conductivity of insulating material Btu/hr -ft -°F.

A = mean surface area to be transversed per foot of length.

t_{max} = 2100F for wire

$t_{max_{ins}} \cong$ 1200F if fluid temp is 1000F.

$I = \sqrt{\frac{96}{0.685}}$ = 11.8 amps (resistance of wire = 0.685 Ω/ft)

On a 220 volt line:

$L = \frac{220}{0.685 \times 11.8}$ = 27.2 ft/circuit where resistance per ft in ohms. Above calculations are based on #20 AWG Nichrom -v from Lewis Engr. Co.

Power = 220 x 11.8 = 2.6 kw/circuit

On dump tank

Heat req'd to melt total vol. of Pb-Bi	3200 Btu
Heat req'd to heat tank to 300°F	2400
total heat input req'd	5600 Btu

5600/3413 = 1.64 kw hr.

3 circuits of resistance were 3 x 2.6 = 7.8 kw therefore, time = $\frac{1.64}{7.8}$ = 0.21 hr or 12.6 min. is required to heat the tank and total volume of Pb-Bi to 300°F.

To preheat loop to 300°F.

q = 2100 Btu
2100/3413 = 0.615 kw hr.
2 circuits of resistance wire 2 x 2.6 = 5.2 kw

$\frac{0.615}{5.2}$ = 0.118 hr = 7.1 min.

To preheat sump tank to 300°F.

q = 3000 Btu
3.000/3413 = 0.88 kw hr
4 circuits of resistance wire 4 x 2.6 = 10.4 kw
0.88/10.4 = 0.0845 hr = 5.06 min

To heat sump tank and Pb-Bi from 300°F to 1000°F

input to tank = 7700 Btu
input to Pb-Bi = 9700
17400 Btu

$17400/3413 = 5.1$ kw hr

$\frac{5.1}{10.4} = 0.49$ hr or 29.4 min

Total electrical power required

Dump tank	3 circuits
Sump tank	4
Loop	2
	9 circuits @ 2.6 kw each.

Required power approximately 24 kw

7.3 Heat Loss in Spray Cooler

$$Nu = \frac{hD}{k} = 7 + 0.025\ Pe^{0.8}$$

$Pr_{Pb-Bi} = 0.0282$ Reference 3

$Pr_{NaK} = 0.012$(at 500F) Reference 4

$R_{Pb-Bi} = 7 \times 10^5$

$R_{NaK} = 4 \times 10^5$

$$Nu_{Pb-Bi} = 7 + .025\ (.0282 \times 7 \times 10^5)^{0.8} = 75.5$$

$$Nu_{NaK} = 7 + .025\ (.012 \times 4 \times 10^5)^{0.8} = 29.0$$

$$h_{Pb-Bi} = \frac{Nu\ k}{D} = \frac{5.4 \times 12 \times 75.5}{1.61} = 3060$$

$$h_{NaK} = \frac{15.3 \times 12 \times 29.0}{1.61} = 3300$$

$h_{water} \backsim 2000$ for boiling water. Reference 3

$$\frac{1}{u_{Pb-Bi}} = \frac{1}{3060} + \frac{1}{2000\left(\frac{1.90}{1.61}\right)} + \frac{.15/12}{9.4\left(\frac{1.75}{1.61}\right)} + \frac{1}{1000\left(\frac{1.90}{1.61}\right)}$$

$u_{Pb-Bi} = 345$

$u_{NaK} = 350$

$$A = \frac{\pi \times 1.9 \times 28}{144} = 1.21\ ft^2 \qquad (28''\ \text{length})$$

$$= 0.746\ ft^2 \qquad (18''\ \text{length})$$

$q = uA\,\Delta T$

where $\Delta T = T_{fluid} - T_{boiling\ water} = T_{fluid} - 200$ except for cases where $T_{fluid} \leq 212^{\circ}F$. Then simple sensible heat cooling is assumed

Fluid Temp	ΔT	q (28" Length)
200°F	50°F	20,800 Btu/hr
400	200	83,500
600	400	167,000
800	600	250,000
1000	800	334,000