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STAGNATION LIQUID LAYER ABLATION OF
SMALL SPHERES IN HYPERSONIC TRANSITION
FLOW - SUMMARY REPORT

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OF SMALL SPHERES IN HYPERSONIC TRANSITION FLOW**

Summary Report

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for

Sandia Laboratories
Albuquerque, New Mexico

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This report is a summary report of two reports, SC-CR-69-3080 and SC-CR-69-3081, previously issued in limited distribution only in the form of contractor drafts.

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ABSTRACT

Test materials were selected and equipment designed, fabricated, and assembled to study the melting ablation of small spheres in hypersonic transition flow over the Weber number range 1 to 10. The design concept called for the free suspension of test spheres in a vertical hypersonic stream through a balance between gravity and aerodynamic drag. However, due to lateral instability, all attempts to achieve stable suspension of the test spheres in the flow were unsuccessful. This lateral instability resulted from an undesirable radial distribution of test stream dynamic pressure. It was concluded that additional study and experimentation with nozzle design would be required in order to obtain the proper radial distribution of dynamic pressure in this low Reynolds number regime. Due to exhaustion of contract funds, work was terminated at this point.

SUMMARY

The reentry of some nuclear fuels used in aerospace applications of radioisotopic thermoelectric generators can, in certain instances present microspheres to severe environments.

This study was undertaken as a means for observing the behavior of these spheres during their melting ablation in hypersonic transition flow with melting initiated at the stagnation point. It was desired to observe, especially, the loss of liquid particles or globules from the main body of a sphere, and, if it occurs, to observe the general disintegration of the sphere. Observation of changes of shape and flow of molten material was desired.

Mathematical expressions relating physical properties of materials to test conditions were developed and used in designing equipment and selecting materials which would permit the study of melting ablation of spheres having Weber numbers in the range of 1 to 10. These spheres were freely suspended in a vertical supersonic stream which provided transition flow. Candidate materials were selected which would, among other considerations, permit melting ablation to occur at moderate temperatures (a few hundred degrees centigrade or below), and over a wide range of viscosity number. Spheres of several sizes of two materials, bismuth and stearic acid, were prepared. A test chamber, nozzle, and flow system were designed with a flow system to achieve high volumetric flow rates at low density by the use of two ejectors driven by a large capacity helium system already available.

The equipment designed for the Vertical Aerodynamic Suspension Tunnel was fabricated, assembled, and operated. Modifications and

redesign were found to be necessary. As an expedient, the test section was ducted to a large vacuum receiver. This permitted sufficient test time to permit observation of test-sphere positional stability. Insufficient lateral stability was achieved and spheres were quickly thrown out of the stream. It was concluded that the nozzle must be specially contoured in order to obtain proper flow in this low Reynolds number regime. Data were obtained which will permit nozzle design.

FOREWORD

This report is an integration of two unbound reports, a quarterly report (SC-CR-69-3081) and a final report, (SC-CR-69-3080). These reports were not formally published and distributed. The reports were prepared by Cornell Aeronautical Laboratory, Inc., (CAL), Buffalo, New York, on Sandia Corporation Purchase Order No. 6005, Suborder No. 9, "Stagnation Liquid Layer Ablation of Small Spheres in Hypersonic Transition Flow," dated April 26, 1967. The purpose of combining these two limited distribution contractor draft reports into a single bound Sandia report is to consolidate the information contained in the two draft reports, and to provide a formal and permanent record of this information for distribution and future reference. To accomplish this goal, the compiler has integrated the individual introductions, abstracts, and tables of contents of the two original CAL reports into a single appropriate introduction, abstract, and table of contents. Certain other very minor modifications of the original CAL reports, such as renumbering the equations and figures of the second CAL report to provide a continuation of the numbers of the first CAL report, etc., were necessary to provide a logical sequence and continuity to the integrated form. However, the main body of the present report consists of the original wording of the original authors. Thus the compiler assumes neither credit nor responsibility for any of the contents of this report other than the abstract and introduction.

SYMBOLS

A	aera
a	materials constant defined by Equation 4
b	stream constant defined by Equation 7
C_D	drag coefficient
c	materials constant defined by Equation 10
D	diameter
g	gravity
H	enthalpy
ΔH_f	latent heat of fusion
Kn	Knudsen number λ / D
M	Mach number; molecular weight
m	mass; material constant defined by Equation 13
N	nozzle constant defined by Equation 20
P	vapor pressure
p	pressure
q	dynamic pressure, $\frac{1}{2} \rho_{\infty} u_{\infty}^2$
T	temperature ; time of oscillation
$\Delta T_{\max}^*$	maximum temperature difference in a uniformly heated sphere
t	time
t_f^*	idealized fusion time
u	velocity
ν	viscosity number defined by Equation 11
We	Weber number
X	distance beyond nozzle exit
x	distance in flow direction
y	distance in radial direction on sphere
θ	semi-vortex angle of nozzle wall
λ	mean free path
μ	viscosity
ρ	density
σ	surface tension

SYMBOLS (CONT.)

Superscripts

o reservoir condition

Subscripts

m melting

o nozzle exit

s sphere material

v vaporization

xe equilibrium position

∞ free stream condition

I. INTRODUCTION

The work covered by this report was accomplished during the period May 1967 through November 1967 under the direction of Mr. B. W. Marshall of Sandia Corporation. Dr. John L. Beal, Staff Scientist at CAL, was the principal investigator. The work is closely related to previous work by CAL, under Sandia contracts, as described in "Review Report on CAL Studies of the Breakup of Drops During Reentry," Report No. SC-CR-68-3736, dated March 1967.

The program which precipitated the work described in this report was conceived as one which would provide equipment, methods, and techniques for observing such phenomena as distortion, ablation, and disintegration of small spheres in hypersonic transition flow. Specifically, the scope of the present work includes only the design, fabrication, assembly, and operation of a flow system in the performance of a few tests to determine system operating characteristics and establish procedures for making observations. If satisfactory operating characteristics can be achieved, a program to investigate the influence of flow conditions and material properties on melting ablation is planned.

Motivation for this work stems from the desire to be able to predict the behavior of radioisotopic fuel microspheres subjected to reentry aerodynamic heating. The program, however, did not aim at reproducing any specific reentry conditions or utilizing any specific values of material properties, except in a very general sense. Instead, its purpose was to establish equipment and techniques which would permit observation of the melting ablation of spheres in an interesting Weber Number region over a wide range of material properties and flow conditions.

The basic concept upon which the equipment design was based, so as to make possible the detailed observation of melting and ablation of small spheres in hypersonic transition flow, is that of providing

a balance between the gravitational and aerodynamic forces acting on a sphere, thereby suspending the sphere in the flow without a support sting. To accomplish this, a flow system was designed and fabricated to provide a test stream flowing vertically upward through a test chamber. The lower portion of the test chamber includes the exit end of the expansion cone of a supersonic nozzle. Thus the test stream continues to expand (which decreases its density) during much of its travel through the test chamber. The test conditions are designed to be such that at some vertical level within the expanding stream, the upward aerodynamic drag force on a test sphere just balances the downward gravitational force. The nozzle dimensions were selected to provide a large change in stream density over a small vertical distance. This was done to minimize the possibility of the test sphere being prematurely swept out of the test chamber as a result of drag force changes due to melting distortion. The test chamber has glass walls to permit both visual observation and photography.

Sphere materials having desirable properties consistent with test objectives were selected. In particular, the sphere materials provide a wide variation in viscosity number. Also the relatively low melting temperatures of the sphere materials permit the stream temperature to be in a range where temperature can be conveniently adjusted so as to vary the melting rate over a considerable range. Test conditions can be varied to cover a range of Weber numbers from well below 6 to well above 6 with some of the tests, depending on the Weber number, in transition flow.

Unfortunately, unexpected problems encountered with the test equipment resulted in exhaustion of contract funds prior to development of the equipment to the point of successful operation. To some extent, these problems were associated with the fact that the flow Reynolds number is below the range in which diffuser and ejector flow characteristics are well known. In view of the need for basic knowledge in this area, CAL decided to provide sufficient additional effort, at their own expense, to at least obtain a definition of the problems.

The many trials in which the stable suspension of spheres through a balance of aerodynamic and gravitational forces was attempted, were unsuccessful. The spheres were thrown out of the test stream in a fraction of a second. Closer investigation indicated that a force was acting on the spheres in a radially outward direction which carried them to the edge of the stream where boundary shocks acted upon them. Descriptively, the q -force acting vertically on the spheres decreased radially; whereas a radial increase is needed for stability. This q -distribution is intimately associated with nozzle design. It is believed that additional study and experimentation with nozzle design in this little known low Reynolds number regime would produce the desired q -distribution. With this problem definition, work was terminated.

II. RELATIONS BETWEEN PHYSICAL PROPERTIES AND TEST CONDITIONS

The test-stream conditions which can be used to support--that is, balance--test spheres and simultaneously provide tests in a specified Weber number range are closely associated with the density and surface tension of the materials of which the spheres are composed. In the preliminary consideration which led to the undertaking of the program, the equations relating stream conditions to material properties were compiled and applied to several types of candidate materials. For the sake of completeness in reporting, these equations are incorporated in this report as Equations 1-13.

Dynamic Pressure

At a balance of gravity and upward drag

$$D = \frac{3}{2} \frac{C_D}{g\rho_s} \frac{\rho_\infty u_\infty^2}{2} \quad \dots(1)$$

Since, by definition of Weber number,

$$D = \left(\frac{\sigma We}{\rho_\infty u_\infty^2} \right) \quad \dots(2)$$

it follows that

$$\frac{\rho_\infty u_\infty^2}{2} = a \frac{We^{1/2}}{C_D^{1/2}} \quad \dots(3)$$

in which

$$a = \left(\frac{2}{3} g\rho_s \sigma \right)^{1/2} \quad \dots(4)$$

and a is a constant dependent on the properties of the material of the sphere.

Knudsen Number

The mean free path of the gas in the stream, at the stream condition, is given by

$$\lambda_{\infty} = \frac{\lambda^* \rho^*}{\rho_{\infty}} = \frac{\lambda^* \rho^* u_{\infty}^2}{2 \left(\frac{\rho_{\infty} u_{\infty}}{2} \right)} \quad \dots(5)$$

in which λ^* and ρ^* are values at a reference condition. A combination of equations 2 and 5 yield

$$Kn = \frac{\lambda_{\infty}}{D} = \frac{\lambda^* \rho^*}{2} \frac{u_{\infty}^2}{\sigma We} \quad \dots(6)$$

Equation 6 may be expressed as

$$Kn = b \frac{1}{\sigma We} \quad \dots(7)$$

in which

$$b = \frac{\lambda^* \rho^*}{2} u_{\infty}^2 \quad \dots(8)$$

and b is a constant dependent on the properties of the stream.

Drag Coefficient

C_D is a function of Kn as shown in "Analytical Methods Used in Predicting the Re-entry Ablation of Spherical and Analytical Bodies," by L. O. Cropp, Sandia Report SC-RR-65-187, September 1965.

Diameter

A combination of equations 1 and 2 yields

$$D = c C_D^{1/2} We^{1/2} \quad \dots(9)$$

in which

$$c = \left(\frac{3}{2} \frac{\sigma}{g \rho_s} \right)^{1/2} \quad \dots(10)$$

and c is a constant dependent on material properties.

Viscosity number

$$Vi = \frac{\mu}{(\rho_s \sigma D)^{1/2}} \quad \dots(11)$$

A combination of equations 9 and 11 yields

$$Vi = \frac{m}{(C_D We)^{1/4}} \quad \dots(12)$$

in which m is a material constant, and

$$m = \frac{\mu}{(\rho_s \sigma c)^{1/2}} \quad \dots(13)$$

III. CANDIDATE TEST MATERIALS

The materials used as test spheres need to have known values of surface tension and viscosity. Although these properties can be measured experimentally, it seems desirable that the time and expense for determination of properties be avoided in this program if possible. Other properties of interest include density, specific heat, latent heat of fusion and vapor pressure, and these should be known.

The test materials need to cover a range of viscosities such that the influence of significant variation in viscosity number will be observed. Judging by the influence of viscosity number on the breakup of fully liquid drops (Ref. 7), the variation in viscosity number should cover several orders of magnitude.

Materials with only moderate melting points, below about 400°C , are desired in order that they can be melted readily in the test stream. The test stream will have an adjustable temperature. Tests with stagnation temperatures near 1500°R are planned, and this will readily melt the materials with moderate melting temperature. The stream temperature can be raised to approximately 3000°R in order to accommodate higher melting materials if necessary. It is believed, however, that the use of moderate temperatures will facilitate the operation and accuracy of the tests.

For initial trials, two materials have been selected, bismuth and stearic acid. Their properties are known; sphere preparation with them has been tried successfully; and they give a viscosity number ratio of approximately 90 to 1. Their properties are given later.

For a still higher viscosity number, glycerol is a candidate material. A large uncertainty is ability to form it into spheres. The liquid is readily supercooled to temperatures much below the melting point. Presumably, spheres must be cast, and it is possible that volume changes may prevent success. The melting point of glycerol is 18°C . The fact that this is below normal room temperature makes storage and handling awkward, but this is not believed to be a severe problem. The viscosity number for test

spheres of glycerol will be approximately four orders of magnitude greater than that of bismuth.

Both as variation in viscosity number (but within the above range and only a few times greater than that of bismuth) and as a variation in type of material, lead bromide is a candidate material. The properties of lead bromide are known except for its surface tension. The latter can be estimated sufficiently well for the purpose (a few percent) unless, as discussed later, oddities in the melting phenomena are observed, and such oddities appear to be a real possibility. Its vapor pressure is on the high side for the tests, but it is believed that this will not interfere; an alternate possibility is that tests with some vaporization may be a desirable inclusion in the program. Its properties are given later.

It seems desirable--but perhaps not essential--to have an oxide-type material in the tests. The lowest melting appropriate binary oxide is chromium trioxide. Its trial, however, shows that it decomposes too readily when melted. The next binary oxide, in terms of melting point, is vanadium pentoxide, which melts at 650°C . It is believed that this melting point can be handled in the tests, but almost no other property data have been located. Presumably its use would require determination of both surface tension and viscosity. Potassium dichromate is an approach toward the binary oxide type. It might be classified either as a complex oxide or as a salt. Its experimental trial reveals the fact that there is a transition between room temperature and the melting point, and the accompanying volume change cracks the material to fine fragments. The use of this material will require hot storage and handling, and this is thought to be very awkward. It is believed that decomposition is insufficient to interfere, but this is not yet certain. Further consideration of oxide-type materials will be left to a later time.

The physical properties of bismuth, lead bromide, stearic acid, and glycerol have been collected from the literature. Where property data are missing, estimates have been made. For the sake of readability of this report, these property data are given in an appendix at the end of this report.

IV. ILLUSTRATIVE TEST CONDITIONS

A test gas of helium with a reservoir temperature of 1500°R is used to illustrate the general range of characteristics with the four above mentioned candidate materials. In the tests, other gases may be used; in fact, argon appears to be preferable for tests of stearic acid. The reservoir temperature will be varied in order to adjust the melting time, and this is mentioned later. The comparison of the four candidate materials in 1500°R helium, however, illustrates the influence of the material properties.

The test-stream characteristics are shown in Table I. Pertinent physical properties of the materials are shown in Table II. The values in these tables, together with the relations given in the earlier section, lead to the calculated test characteristics shown in Table III.

It may be noted from Table III that the size of spheres is of the order of a few millimeters for tests whose Weber numbers range from 1 to 10. It may also be noted that these materials give a desirable range of values of viscosity number.

The values of Knudsen number associated with stearic acid, in Table III, are quite high, indicating that these tests will be in or very near free-molecular flow. The substitution of argon for helium lowers the Knudsen number but leaves the Mach number unchanged. This substitution is planned for stearic acid tests in order that they may be in, or near, transition flow.

A more detailed estimation of test conditions is given for bismuth spheres and stearic acid spheres, as shown in Figures 1 and 2. For $3/16"$ diameter spheres (4.76 mm), the variation in Weber number and Knudsen number is shown as a function of reservoir temperature.

The reservoir temperature will be varied in order to vary melting time. Figures 1 and 2 show estimations of an "idealized" melting time. Once melting starts, distortion may occur and this will presumably introduce unknown changes in the heating rate. In part, the term "idealized" refers to the fact that the body is assumed to remain spherical and the heating rate is so estimated. Further, melting will start before the body is all raised to the melting point; this is ignored in the estimation.

TABLE I
STREAM CONDITION NO. 1

Test gas	helium		
Reservoir temperature T° , $^{\circ}\text{R}$	1500		
Free stream temp. T_{∞} , $^{\circ}\text{R}$	166		
Nozzle exit area A , ft^2	0.1365 (diam = 5")		
Free stream velocity u_{∞} , ft/sec	9120		
Mach number M_{∞}	4.91		
T_{∞}/T°	.1103		
p_{∞}/p°	4.07×10^{-3}		
$\rho_{\infty}/\rho^{\circ}$	3.69×10^{-2}		
p_s/p°	2.71×10^{-2}		
A/A^*	9.38		
A^* , ft^2	1.46×10^{-2}		
Stream constant b , lb/ft	8.4×10^{-3}		
$\rho_{\infty} u_{\infty}^{2/2}$	1	4	10
p° , lb/ft^2	13.1	52.4	131
ρ° , lb/ft^3	2.26×10^{-5}	9.01×10^{-5}	2.26×10^{-4}
μ_{∞} , lb/ft^2	5.33×10^{-2}	.213	.533
ρ_{∞} , lb/ft^3	8.31×10^{-7}	3.33×10^{-6}	8.31×10^{-6}
$\rho_{\infty} u_{\infty}$, $\text{lb/ft}^2 \text{ sec}$	7.59×10^{-3}	3.04×10^{-2}	7.59×10^{-2}
Flow rate, lb/sec	1.035×10^{-3}	4.15×10^{-3}	1.035×10^{-2}
Flow rate, ft^3/min	7.9×10^4	7.9×10^4	7.9×10^4

TABLE II
MATERIAL CONSTANTS

Type	Metal	Salt	Organic	
Material	Bismuth	Lead Bromide	Stearic Acid	Glycerol
Property values				
<u>cgs units</u>				
melting point, °C	271	370	69.3	18
σ , surface tension, dynes/cm	385	132	26.7	63.5
ρ_s , density, gm/cm ³	10	6.5	.847	1.25
μ , viscosity, centipoise	1.62	10.5	9.75	1800
<u>engineering units</u>				
melting point, °R	980	1155	617	524
σ , surface tension, lb/ft	2.62×10^{-2}	$.90 \times 10^{-2}$	1.81×10^{-3}	4.32×10^{-3}
ρ_s , density, slugs/ft ³	19.5	12.7	1.65	2.44
μ , viscosity, lb sec/ft ²	3.38×10^{-5}	2.19×10^{-4}	2.04×10^{-4}	3.76×10^{-2}
Material Constants:				
$a = \left(\frac{2}{3} g \rho_s \sigma \right)^{\frac{1}{2}}, \text{ lb/ft}^2$	3.30	1.57	.254	.475
$c = \left(\frac{3}{2} \frac{\sigma}{g \rho_s} \right)^{\frac{1}{2}}, \text{ ft}$	7.90×10^{-3}	5.74×10^{-3}	7.16×10^{-3}	9.08×10^{-3}
$m = \frac{\mu}{(\rho_s \sigma c)^{\frac{1}{2}}}$	5.33×10^{-4}	8.55×10^{-3}	4.41×10^{-2}	3.84

Material-stream constant for
stream No. 1:

$$\frac{b}{\sigma} = \frac{\lambda^* u^* u_{\infty}^2}{2\sigma} = \frac{8.4 \times 10^{-3}}{\sigma} \frac{\text{lb}}{\text{ft}} \quad .32 \quad .93 \quad 4.65 \quad 1.94$$

Note: $\lambda^* p^*$ for helium = 2.04×10^{-10} slugs/ft², based on $\lambda = 14.72$ cm at 25 °C and 10^{-3} mm Hg.,
Reference 8

TABLE III
CALCULATED TEST CHARACTERISTICS
FOR STREAM NO. 1 HELIUM AT $T^{\circ} = 1500^{\circ}R$

	Bismuth	Lead Bromide	Stearic Acid	Glycerol
$We = 1$				
$Kn = \frac{b/\sigma}{We}$	.32	.93	4.65	1.94
C_D from Fig. 5, Ref. 7	1.88	2.00	2.00	2.00
$\frac{1}{2} \rho_{\infty} u_{\infty}^2 = a (We/C_D)^{\frac{1}{2}}$	2.41	1.11	.179	.335
D in ft $= c (C_D We)^{\frac{1}{2}}$	.0108	.0081	.0101	.0128
D in mm	3.40	2.47	3.08	3.90
$Vi = m/(C_D We)^{\frac{1}{4}}$	.00062	.0102	.0525	4.56
$We = 2$				
Kn	.16	.46	2.32	.97
C_D	1.48	2.00	2.00	2.00
$\frac{1}{2} \rho_{\infty} u_{\infty}^2$	3.82	1.57	.254	.475
D in ft	.0136	.0115	.0143	.0182
D in mm	4.15	3.50	4.36	5.50
Vi	.00070	.0121	.0625	5.43
$We = 5$				
Kn	.064	.186	.93	.39
C_D	1.10	1.55	2.00	2.00
$\frac{1}{2} \rho_{\infty} u_{\infty}^2$	7.02	2.81	.401	.750
D in ft	.0185	.0159	.0226	.0287
D in mm	5.65	4.85	6.90	8.75
Vi	.00081	.0142	.0785	6.83
$We = 10$				
Kn	.032	.093		.194
C_D	.90	1.25		2.00
$\frac{1}{2} \rho_{\infty} u_{\infty}^2$	10.1	4.44		1.06
D in ft	.0237	.0203		.0406
D in mm	7.22	6.20		12.4
Vi	.00092	.0161		8.10

Figure 1 PREDICTED TEST CHARACTERISTICS FOR BISMUTH

Figure 2 PREDICTED TEST CHARACTERISTICS FOR STEARIC ACID

Actually, the idealized fusion time, t_f^* , is the time required to add an amount of heat equal to the heat of fusion of the spheres. Even this, however, can be estimated only approximately because the radiation loss from the body will depend upon an unknown emissivity, here taken as 0.7.

In the program, it was expected that successively lower reservoir temperatures would be used until no evidence of melting was observed. Figures 1 and 2 indicate the range in which such temperatures may be expected.

V. DISCUSSION OF CERTAIN PROBLEM AREAS ASSOCIATED WITH MATERIAL PROPERTIES

In addition to the properties of primary interest, namely, surface tension, density, and viscosity, other material properties may have an influence on the behavior during melting ablation. A high vapor pressure will permit vaporization during tests. Excessive vaporization could interfere with the flow of molten material. A low thermal conductivity will tend to permit the liquid layer to be raised above the melting point, thereby changing the surface tension, viscosity, and vapor pressure. Unfortunately, one cannot decide on the properties and then find materials which have them. For high viscosity numbers, it appears that the organic materials are required, but organics have low thermal conductivities and, in general, moderate vapor pressures. The following discussions suggest that difficulties along this line are present but not excessive.

Vaporization During Tests

Materials with high vapor pressure in the region of their melting points will tend to vaporize during the tests. In the extreme, vaporization might be so rapid that any liquid layer would vaporize before it had opportunity to flow as a liquid. Such a high vapor pressure material would not be a suitable one for studying melting ablation in which the flow and removal of a liquid layer are the phenomena of interest.

The maximum possible rate of vaporization of a pure material is readily estimated from its vapor pressure. The estimation assumes the rate to be that into a perfect vacuum. The actual rate when the environment is not a perfect vacuum and when the material contains impurities to an extent which has influence on the surface composition--perhaps only traces of impurities--is virtually unknown. It seems safe to assume, however, that in some cases the actual rate might be orders of magnitude smaller than the readily estimated maximum rate.

Clearly, a method which avoids having vaporization interfere with observations of melting ablation is the use of a material whose vapor pressure is sufficiently low so that even the maximum rate of vaporization is negligible.

The rate of vaporization into a perfect vacuum is given by the Langmuir equation as

$$\frac{dm_v}{A dt} = .05833 P \sqrt{\frac{M}{T}}, \text{ in grams/cm}^2 \text{ sec}$$

in which P is vapor pressure in mm. of mercury, M. is molecular weight, and T is temperature in degrees Kelvin. Division of the above rate by density, in gm/cm³, yields a depth rate, $\frac{dy_v}{dt}$, in cm/sec.

For bismuth, a material whose use is planned for the program, the rates of vaporization loss computed by the equation are listed below.

T	P	$\frac{dm_v}{A dt}$	$\frac{dy_v}{dt}$
<u>°K</u>	<u>mm Hg</u>	<u>gm/cm² sec</u>	<u>mm/sec</u>
544 (m. p.)	7.99×10^{-9}	2.89×10^{-10}	2.95×10^{-11}
600	3.02×10^{-7}	1.04×10^{-8}	1.06×10^{-9}
700	4.18×10^{-5}	1.33×10^{-6}	1.36×10^{-7}

It is seen that the depth rates of vaporization are small compared with the radius of the spheres to be tested. The smallest size sphere will have a radius of about 1.5 mm. Even if superheating of the liquid layer should occur, many hours of vaporization at its theoretical maximum rate would be required to vaporize a layer whose thickness is 1% of the radius. For the test time expected, vaporization would not be significant.

Similar calculations for stearic acid are given in the following tabulation:

T	P	$\frac{dm_v}{A dt}$	$\frac{dy_v}{dt}$
<u>°K</u>	<u>mm Hg</u>	<u>gm/cm² sec</u>	<u>mm sec</u>
342.3 (m. p.)	1.2×10^{-3}	$.64 \times 10^{-4}$	$.75 \times 10^{-4}$
350	2.4×10^{-3}	1.26×10^{-4}	1.5×10^{-4}
400	1.2×10^{-2}	5.9×10^{-4}	7.0×10^{-4}

For this, higher vapor pressure data were extrapolated. At 400°K, which is well above the melting point, approximately 20 seconds would be required to evaporate a layer whose thickness is 1% of the radius of a 3-mm diameter sphere. This estimation is based on evaporation to a perfect vacuum. Presumably the vaporization rate to the actual environment would be smaller. Although vaporization phenomena would be present, it appears that their extent would be too small to have significant influence on the flow of liquid in tests of the duration expected.

Of the four materials considered, lead bromide has the highest vapor pressure. For it, dy_v/dt at the melting point is computed to be 6.77×10^{-4} mm/sec., which is an order of magnitude greater than that for stearic acid. It is believed that even this value will introduce no serious vaporization problem. Vaporization competes with liquid run-off as a process for moving material away from the melting region. Lead bromide has low viscosity. Because of this, it seems unlikely that vaporization will be sufficient to influence the liquid flow.

Superheating of Liquid Layer

During melting, the liquid layer will be raised above the melting temperature while the remaining solid is being melted. This elevation of temperature of the outer surface of the liquid will have influence on the liquid properties. In general, this rise in temperature of the liquid surface will reduce the surface tension by a small amount and will raise the vapor pressure.

Exact estimations of the surface temperature during the melting period are believed to be impossible. Reference 9 discusses analytical solutions for problems in this general area and indicates that analytic solutions do not exist for spherical bodies. Numerical solutions would be complicated--presumably made impossible--by the need for information about non-uniform heating in the presence of distortion and liquid movement of the body as it melts.

The maximum temperature difference, designated as $\Delta T_{\max}^*$, within a spherical body whose outer surface is uniformly heated (uniform

with respect to both time and position) and which has no phase change can readily be computed. In the actual case, the presence of melting would reduce the temperature difference across the liquid layer to a smaller value; and the presence of non-uniform heating would raise the actual value. Nevertheless, it is here considered that $\Delta T_{\max}^*$ is a general indication of the approximate amount by which the liquid surface may exceed its melting point at a time when the model is nearly all melted.

From Reference 9 , one may write

$$\Delta T_{\max}^* = \frac{1}{6} \frac{r^2 \rho_s}{k} \frac{\Delta H_f}{t_f^*} \quad \dots (14)$$

in which ΔH_f is the latent heat of fusion of the material and t_f^* is the time in which an amount of heat equal to the latent heat of fusion of the sphere is added to the sphere. Calculated values of $\Delta T_{\max}^*$ for various values of t_f^* are shown in Table IV. These values indicate that slow heating rates yielding fusion times of the order of 100 seconds are required in order to avoid excessive superheating of the liquid layer with all materials other than those having metallic conductivity.

TABLE IV
VALUES OF $\Delta T_{\max}^*$ FOR $We = 5$

	Bismuth	Pb Br ₂	Stearic Acid	Glycerol
r, cm	.565/2	.485/2	.690/2	.875/2
ρ_s , gm/cm ³	10	6.5	.847	1.25
k, cal/cm °C sec	.0194	.00062	.00022	.000355
ΔH_f , cal/gm	12.6	11.7	47.5	47.5
$\frac{1}{6} \frac{r^2 \rho_s}{k} \Delta H_f$, °C sec	87	1850	3600	5300

Values of $\Delta T_{\max}^*$:

$t_f^* = 1 \text{ sec}$	87°	1850°C	3600°C	5325°C
$t_f^* = 10 \text{ sec}$	8.7	185	360	523
$t_f^* = 100 \text{ sec}$	4.9	18.5	36	52
$t_f^* = 200 \text{ sec}$	2.45	9.3	18	26

VI. PREDICTED VERTICAL MOTION OF AN AERODYNAMICALLY SUPPORTED MODEL

Oscillation

The expanding stream will have a variation of dynamic pressure, q , given by

$$d \ln q = N dx \quad \dots(14)$$

in which x is vertical distance in the flow direction and N is a constant determined by the nozzle angle. Taking q at the exit plane of the nozzle as q_0 and taking x as zero at that plane, then

$$q_x = q_0 e^{-Nx} \quad \dots(15)$$

Values of N from 1 to 4 per ft have been used in the preliminary design.

When a model is at the height where drag balances gravity

$$C_D q_{xe} A - mg = 0 \quad \dots(16)$$

At any other position the acceleration, a , toward the equilibrium position can be expressed as

$$a = C_D (q_x - q_{xe}) \frac{A}{m} \quad \dots(17)$$

For the case of small amplitude, the q gradient may be taken as essentially linear, leading to, as a small amplitude approximation,

$$a = - C_D N q_{xe} (x - x_e) \frac{A}{m} \quad \dots(18)$$

Comparison of Equation 18 with those for simple harmonic oscillation makes it clear that the period, T , for a complete oscillation is given by

$$T = \frac{2\pi}{\sqrt{C_D q_{xe} N \frac{A}{m}}} = \frac{2\pi}{\sqrt{N g}} \quad \dots(19)$$

For previously mentioned values of N of 1, 2, and 4 per foot, the periods and frequencies are:

<u>N per ft</u>	<u>T, seconds</u>	<u>frequency, sec⁻¹</u>
1	.1105	9.05
2	.0783	12.8
4	.0552	18.1

It can readily be computed that the maximum velocity attained by a model in this oscillatory motion is very small when the amplitude is limited to a small fraction of a foot. Because of this, there appears to be no damping of the oscillations. For example, at $N = 4 \text{ ft}^{-1}$ with an amplitude of 0.1 ft, the spread between the sum and difference of the squares of the stream velocity and the maximum model velocity is $9130^2 (1 \pm 3.86 \times 10^{-9})$. This difference between the times when the model motion is in the direction of the stream and when it is opposed to it is the only source of damping apparent. The damping is so small that one concludes that any oscillatory motion will continue.

The oscillatory motion makes it very important that models be released at their point of equilibrium and not at some appreciable distance removed from it. This motion also indicates that photographs of the models will require fast photography, that is, fast with respect to 20 oscillations per second. For an amplitude of 0.1 ft, the maximum velocity is approximately 0.57 ft/sec (174 mm/sec). For a typical small sized model, this is near 35 diameters per second. In order to see detail on such a model, photographs will need to be taken at rates of several hundred frames per second.

Change of Equilibrium Position

In a test it is expected that the ratio A/m will increase, due either to distortion of the melting model or to ablation. This change will cause the equilibrium position of the models to rise. The extent of such change which can be accommodated within a given distance depends on the nozzle design parameter N . Equations 15 and 18 may be used to express the change in equilibrium position with change in the ratio, and

$$\frac{(m/A)_2}{(m/A)_1} = e^{-x_{e2}N + x_{e1}N}$$

It seems reasonable to take x_{e1} at 0.25 ft above the nozzle exit and x_{e2} at 0.75 ft. The changes in the ratio are as tabulated below.

<u>N per ft</u>	$\frac{(m/A)_2}{(m/A)_1}$
1	.605
2	.367
4	.135
5	.0826

It is concluded that a value of N near, or slightly greater than, 4 per ft is sufficient to permit observation of major change in the ratio.

In case there is a sudden change in the mass/area ratio, there will be a sudden change in the equilibrium position. This will induce oscillation. As an example, if the equilibrium position had started at 0.25 ft above the nozzle exit and had slowly progressed to 0.35 ft and then some material were lost making a sudden change in the mass/area ratio of 10% of the initial value, the new equilibrium position would be at 0.375 ft. This sudden change would induce an oscillation whose half amplitude would be near 0.025 ft. While oscillations of appreciable amplitude appear to introduce a certain difficulty in observing and interpreting results, perhaps, on the other hand, changes in amplitude can be made useful in interpretation by indicating the extent of sudden change.

Because of possible oscillations, it will be desirable to perform tests both of freely suspended spheres and of spheres mounted on a fine sting. Observation of differences between their ablation phenomena should aid understanding. Presumably a fine sting will not have major effect on the ablation, other than eliminating oscillation, until such time when the molten material collects on the sting. As a further modification, the rigid sting might be replaced in some tests by a fine thread which would support the model slightly above its initial equilibrium position.

VII. SPHERE PREPARATION

To date, sphere preparation has been limited to two materials, bismuth metal and stearic acid. Four different sizes in each of the two materials have been made as required for Weber Number variation in the planned tests. Casting was found to be effective in forming the bismuth, but an injection molding technique was required to produce dense spheres of stearic acid.

Bismuth expands approximately 3.3 percent on freezing, according to some investigators, and has a thermal dilation coefficient ($7.4 \times 10^{-6}/^{\circ}\text{F}$ at room temperature) comparable to or lower than convenient mold-making metals. Difficulty might be expected, therefore, in releasing bismuth castings from metal molds, due to the relative size changes on freezing and cooling. Moreover, the ready oxidation of molten bismuth argues in favor of vacuum casting, but a vacuum would favor metal to metal sticking in the absence of a release agent, and surface contamination by such agents would be intolerable in the present case.

In contrast to a metal, boron nitride ceramic has a relatively low dilation coefficient, and is not generally wetted by molten metal. It is also very readily machinable, such that it was a simple matter to precision machine hemispherical cavities in two matching halves of a mold, using conventional ball end mills. A completed mold is shown in Figure 3 along with four of the 16 spheres cast in each filling of the mold. "Risers" and "gates" must of course be trimmed from each sphere; it is expected that the very slight surface imperfections remaining on the cast spheres can be smoothed by electro- or chemical polishing.

The casting process consists of (1) clamping the mold halves between two aluminum platens fitted with cartridge heaters for melting and with copper coils to carry cooling water once the mold is filled; (2) placing a slug of bismuth cut from an ingot* into a three-inch-high standpipe fitted to the top of the mold; (3) placing the assembly in a vacuum system and

* Cerro Sales Co., New York, 99.999 percent pure bismuth.

Figure 3 BORON NITRIDE MOLD WITH FOUR FINISHED BISMUTH SPHERES - SCALE IN INCHES

pumping to a pressure of 100 microns of Hg or less; (4) heating until the slug melts and molten metal overflows the riser; and (5) cooling completely under vacuum to minimize oxidation. In casting small objects such as these spheres, it is found to be essential to heat the mold to the melting point of the material being cast; otherwise freezing in the mold passages occurs prematurely.

Upon opening the mold it is found that some spheres release without effort, while others require cooling with ice to effect a shrinkage. It might be mentioned in passing that granular bismuth of the chemical reagent variety was found to cast very poorly due to the blocking of the mold passage by the preexisting oxide "skins" on each granule. The absence of air in the mold during casting, and the use of a small gravity head of molten metal resulted in dense castings; density calculated by measuring and weighing was greater than 97 percent of theoretical maximum. When melted rapidly by heating of the surface, melting is observed to proceed smoothly with no bubbling or other irregularity.

Attempts to cast stearic acid in Teflon molds were unsuccessful, due apparently to a peculiar freezing behavior exhibited by the wax-like material. A large shrinkage on freezing and a tendency to form very large crystals appeared to result in weak, porous castings. The waxy nature of the material suggested, however, that it might be amenable to pressure injection molding in the manner of many plastics.

Figure 4 shows the type of steel mold found to work very well. The passage labeled "air vent" might appear to be misplaced, but the mold functions well in the configuration shown. The forming procedure consists of (1) filling the reservoir with U.S.P. stearic acid powder; (2) cold pressing at perhaps 2000 p.s.i. to fill the mold; (3) warming the mold slightly while maintaining pressure, such that a substantial amount of the acid extrudes from the "air vent"; and (4) cooling and dismantling the mold (which is held together by screws) to release the spheres. After trimming, the spheres appear as in Figure 5.

Figure 4 STEARIC ACID INJECTION MOLD

Figure 5 INJECTION MOLDED STEARIC ACID SPHERES

Approximately 20 of the stearic acid spheres have been weighed, and their densities are found to be the same within about three percent generally, and within five percent at the most. Their average density is very close to 1.00 grams/cm³. This value is much higher than the value 0.874 grams/cm³ reported for the material at its melting point; no room temperature density data were found. The constancy of the sphere density data suggest that the theoretical maximum must be very near 1.00 grams/cm³.

A simple test of the melting behavior of the spheres was done by heating with a flame. Melting proceeded with no trace of bubbling or sputtering of any kind, indicating that the spheres will "behave" very well in the planned tests.

VIII. TEST SECTION AND NOZZLE

In preliminary design, stream conditions were used at which small spherical models of near critical Weber number would be supported against gravity by the upward dynamic pressure of the stream. As design points, the total temperature of the stream was taken as 1500°R and dynamic pressures of 1, 4, and 10 lb/ft² were used. The calculated parameters with helium as the test gas are shown in Table I which is given in an earlier section of this report.

It was concluded, as discussed in the previous section, that it would be best to have a large change in dynamic pressure occur over a short vertical distance of the test stream. This variation in q , the dynamic pressure, is related to nozzle dimensions by the expressions

$$\frac{2 \tan \theta}{r_n} = N = - \frac{d \ln q}{dx} \quad \dots(20)$$

and $q = q_n e^{-NX} \quad \dots(21)$

in which θ is the semi-vertex wall angle, r_n is the nozzle radius at the nozzle exit, q_n the value at the nozzle exit, and X is distance above the exit. The nozzle has been designed with N equal to 4 per foot. Nozzles of other dimensions can readily be substituted should that prove to be desirable.

The test sphere will be in the expanding test stream above the nozzle exit, where it can be viewed from all sides through the glass windows of the test chamber. Figure 6 shows the test section. The exit of the nozzle, not shown, is in the floor of the test chamber.

It has not been detailed, but the sphere inserting mechanism is a device which is mounted through an opening in the floor of the test chamber. Its vertical mast contains an arm which can be raised and lowered and rotated in and out of the stream. A test sphere will be supported on a fine-wire open mesh which will be rotated into the stream and lowered until the sphere is supported by the stream. The support will

then be removed. The fine wires of the mesh will be in free molecular flow and should cause little or no disturbance. As an alternate, the same mechanism can be used to hold a sting-mounted sphere in some tests.

Figure 6. Test Section

IX. VACUUM EJECTOR SYSTEM

The previously described test section and nozzle operating at the desired range of test conditions require a large volumetric flow rate at low pressure. This flow rate will be obtained by a two-stage ejector system. For the driver gas, the ejector system will utilize the large helium pumping, purifying, and storage capacity available at CAL.

The system is shown as an assembly drawing in Figure 7. The nozzle to the test section is fed by helium from a high pressure supply (bottle). The discharge from the test section is picked up, first, by an isolation ejector and, second, by the main ejector which raise the pressure to approximately one atmosphere at which the helium is returned to the existing helium storage sphere (capacity 125,000 cu.ft.).

The amount of helium used in the test section will be negligible compared with that used as driver gas in the main ejector. The latter, together with the capacity of the existing helium storage sphere, will determine the duration of flow. With the existing pumps operating to remove helium from the storage sphere and recompress it in the tank farm, the duration of flow will be approximately 40 minutes; without such pumping, the duration will be half that.

A very conservative estimate of efficiency indicates that it will readily attain a value of $\rho u^2/2$ of 1 psf, and it is expected that significantly lower values will be found available in practice.

The ejector nozzles are simple turnings made in the CAL shop. The connecting ducts will need to withstand only low pressure and are of sheet metal rolled and welded or simple pipe sections.

X. MODIFICATIONS OF THE FLOW SYSTEM

The discharge of the test stream from the test section was, according to the initial design, to be facilitated by two ejectors operating in series. These would raise the pressure to a high level at which the gases, chiefly helium, could be discharged into an available reservoir and recovery system. This plan would permit test times in excess of twenty minutes.

When the system was assembled, calibrated and tried, it was found that (a) the smaller of the two ejectors functioned perfectly as an individual unit, but (b) unexpected effects, associated with the low Reynolds number regime, required that it be relocated to a new position in the system, and (c) that the larger ejector required major rework.

As an expedient, the ejectors were removed from the system and the test section was ducted directly to a large vacuum receiver--140,000 cu ft--which was exhausted to low pressure prior to a test. This reduced the typical test time to one minute, varying with the conditions. This modification permitted tests in which the positional stability of spheres could be observed.

After the above modifications were incorporated, tests of the nozzle flow were made. It became apparent that the nozzle was not being completely "filled" and that the low Reynolds number stream was breaking away from the nozzle wall before expanding to the full stream diameter as desired. In studying this, the nozzle angle was reduced. This modification changed the vertical q -gradient from a four-fold decrease per foot to a two-fold decrease per foot.

These modifications permitted tests of the positional stability of spheres introduced into the stream at points above the discharge plane of the nozzle. The test section is shown in Figure 7. The discharge plane of the nozzle may be seen near the middle of the left window.

Figure 7. Test Section Showing Nozzle-Exit Plane
Through 6 3/8-inch-Diameter Window

XI. TESTS OF POSITIONAL STABILITY

The first attempts to introduce spheres into the stream indicated that the boundary shocks at the edge of the stream were sufficient to bounce a sphere-- a steel ball bearing usually 0.25-inch in diameter--from a supporting mesh. After trying several holding mechanisms, it was found that best results were obtained by supporting the sphere in a fine wire cage which held it firmly until the sphere was in the center of the test stream. A sphere in a cage is shown in Figure 8. The cage was supported by fine wires attached to posts outside the stream. The cage was initially introduced at a vertical level below the balance point and the bottom support wire of the cage was then removed. At this position, the upward drag was sufficient to keep the sphere in the cage. The cage was then slowly raised. Eventually, the cage raised above the sphere and was rotated out of the stream, leaving the sphere in the stream. Smoothness in this operation was difficult to achieve and many attempts appeared to be spoiled by interactions of the sphere with the wires of the cage as separation occurred.

In preliminary calibration tests of nozzle flow, the q -distribution in Figure 9 appears to be uniform across the central portion of the stream. This may have been misleading, however, inasmuch as the rake mechanism used in determining pressure distribution altered cabin pressure surrounding the nozzle exhaust in this low Reynolds number regime. None of the trials with spheres resulted in spheres remaining in the stream for longer than a fraction of a second.

Figure 10 shows the radial (horizontal) velocity of a sphere. These data were obtained by scaling distances and times recorded on motion pictures of Test Nos. 28 and 29. The characteristics of the pressure data (Fig. 9) and those of the lateral velocity data (Fig. 10) are remarkably similar, suggesting that the pressure data are indeed descriptive of the stream q . At the outset of the program, it was logically presumed that a sphere suspended aerodynamically would respond to the lateral q gradient as if it were a solid surface. The data of Figures 9 and 10 confirm this expectation and so provide firm grounds for predicting the lateral stability for such spheres.

Figure 8. View of Sphere in Cage Pending Release

Figure 9. RAKE STAGNATION PRESSURE

Figure 10. LATERAL STABILITY OF SPHERE

Furthermore, this same confirmation provides a firm basis on which to design the nozzle contours.

Figure 11 shows the axial (vertical) velocity of a sphere. It was noticed during previous experiments that sphere drag was higher while the sphere was in the cage than when it was out. This is demonstrated very clearly, qualitatively, in motion picture films for the three tests portrayed in these figures (Test Nos. 28, 29, and 31). In Test No. 31 (Fig. 11), the caged sphere was located nearly three inches above the nozzle exit and on the stream centerline. The cage door (bottom) was opened and the stream q slowly reduced. After approximately a 15 percent decrease in q , the sphere exited the cage and proceeded downward well aligned with the stream center. Figure 11 shows the ensuing motion.

The data shown on Figure 11 may be used as an experimental determination of the dynamic pressure, q , of the stream along its centerline. The equation associated with the relation between forces, mass, and acceleration may be expressed in the form

$$q C_D A - Mg = Ma$$

in which C_D is the drag coefficient, A is the appropriate area of the sphere, M is its mass, g is the acceleration due to gravity, and a is the acceleration of the sphere. Values of acceleration, a , are readily obtained from Figure 11. Their use in the above equation results in the values of dynamic pressure, q , depicted by the solid line of Figure 12. This vertical q distribution departs from the desired distribution, where the latter--shown by the dashed line of Figure 12--corresponds to the design values for a nozzle which is completely filled by the flow.

The zero gradient characteristic of q , in the region near the nozzle, suggests a family of compression waves superimposed on the conical expansion wave system. The sudden reduction of q suggests a shock with its attendant rapid low supersonic expansion and related recompression wave system. The sudden reduction of q may also suggest the limit of a

Figure 11. AXIAL STABILITY OF SPHERE

Figure 12. AXIAL q DISTRIBUTION

sphere thrusting interference between the sphere and the cage. Such an interference involves continuum and free-molecular flow regimes for the wires of the cage and a high pressure gas supply to the wake of the sphere. This mechanism is difficult to examine but simple to avoid in future work.

XII. CONCLUSION

The effort to achieve a supersonic aerodynamically suspended test sphere has been described. Certain problems arose during the conduct of the program which made necessary the redirection of the program objectives. While all the problems were not described in detail, the corrective measures for each can be listed and represent those things which must be done to bring the Vertical Aerodynamic Suspension Tunnel to an operational status.

The low pressure ejector, having been calibrated early in the program, is known to function properly and according to design requirements. However, it must be installed in the facility in such a manner as to reasonably well represent its calibration environment, free from secondary flow sources.

The high pressure ejector requires redesign, refabrication, and re-installation.

The modified tunnel diffuser, in its present position, functions well in this low Reynolds number flow. It requires no change.

A new nozzle is required. The data acquired to date is sufficient to permit the design of a contoured nozzle in which the radial q gradient will be satisfactory for lateral stability. These data apply to a nozzle in which the vertical q gradient is a two-fold decrease per foot. These data should be descriptive when applied to a nozzle with a four-fold decrease in q per foot, but additional data for this condition would make design more certain. The resulting nozzle must discourage flow separation from the wall and provide a negative radial Mach number gradient. Nozzle design capability has recently been increased at this Laboratory by the recent creation of a nozzle flow computer program. This program, based on the J. C. Williams' "slender-nozzle" equations, is designed for low Reynolds number, i.e., viscous, flow. Pressure is considered a function of station while velocities (u and v) are functions of x and r . Flow at the wall can be within the slip flow regime and the geometry can be specified. Even though flow

separation can not be embraced, the program will prove to be an invaluable aid in determination of radial dynamic head distribution. Flow separation from the wall can be empirically introduced as boundary conditions. This program effectively elevates the nozzle design effort above the plane of empirical methods.

The tunnel flow heater must be relocated to minimize the transfer pipe length.

Finally, repair of the flow regulators is required to correct damage caused by dynamic instabilities in their operation.

All other components and supply systems function properly and satisfactorily and require no further attention.

REFERENCES

1. Mellor, J.W.: "A Comprehensive Treatise on Inorganic and Theoretical Chemistry," Longmans Green and Co., Vol. VIII 1941, Vol. IX 1939.
2. Gray, Dwight E.: (Editor), American Institute of Physics Handbook, McGraw-Hill Book Co., 1957.
3. Washburn, Edward W.: (Editor), International Critical Tables, McGraw-Hill Book Co., 1926.
4. Nesmeyanor, An.N.: Vapor Pressure of the Elements, Academic Press, 1963.
5. Perry, John H. and Robert H. (Editor): Chemical Engineers' Handbook, McGraw-Hill Book Co., 4th Edition, 1963.
6. Hogdman, Charles D.: (Editor), Handbook of Chemistry and Physics, 44th Edition, Chemical Rubber Publishing Co., 1962.
7. Hinze, J.O.: A.I.Ch.E. Journal, 1, No. 3, p.289, 1955.
8. Duschman, Saul, Fundamentals of Atomic Physics, McGraw-Hill Book Co., 1951.
9. Carslaw, J.S. and Jaeger, J.C.: Conduction of Heat in Solids, Oxford University Press, 1959.

APPENDIX
PHYSICAL PROPERTIES

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PHYSICAL PROPERTIES
Bismuth

Melting Point

Melting point = 271°C, Reference 2.

Surface Tension

Surface tension values are given in Reference 1. Based on the values it attributes to Bircumshaw and to Hogness, the following equation is here deduced for liquid bismuth in the region of its melting point.

$$\sigma = (385 \pm 1.6\%) - 0.080 (T-271)$$

in which σ is in dynes/cm and T is in centigrade. This is in agreement with the value of 376 (with uncertainty in the last digit) at 300°C given in Reference 3.

Viscosity

Viscosity values are given in Reference 1. Based on the values it attributes to Arpi, to Plüss, and to Sauerwald and Topler, the following equation is here deduced:

$$\mu = (1.62 \pm 10\%) - 0.0021 (T-271)$$

in which μ is in centipoise and T is in centigrade.

Specific Heat

Values of specific heat taken from Reference 2 are listed below.

T°K	298.16	400	500	600 to 1200
Sp.ht, cal/gm mol x °C	6.10(c)	6.65(c)	7.19(c)	7.50(l)
Sp.ht, cal/gm °C	.0292	.0318	.0344	.0359

Latent Heat of Fusion (from Reference 2)

$$\Delta H_f = 2.63 \frac{\text{k cal}}{\text{mol}} = 12.60 \text{ cal/gm}$$

Bismuth - contd.

Density

Temp. °C	Density or Sp. Gr.	Reference
20	9.78 gm/cm ³ (vacuum distilled)	2
20	9.84 gm/cm ³ (cast) - by Dorsey	1
300	10.03 sp.gr. by Bircushaw	1
400	9.91 sp.gr. by Bircushaw	1
600	9.66 sp.gr. by Bircushaw	1

Volume change on solidification is reported from a few percent positive to a few percent negative by various investigators, Reference 1.

Vapor Pressure

Temp. °K	Vapor Pressure mm. Hg	Reference
500	3.30×10^{-10}	4
Melting point	7.99×10^{-10}	4
600	3.02×10^{-7}	4
700	4.18×10^{-5}	4

Thermal Conductivity

k at 18°C = 0.0194 cal/cm sec °CReference 2

PHYSICAL PROPERTIES

Stearic Acid

Melting Point

Melting point = 69.3°C , Reference 3.

Surface Tension

In the absence of direct data, surface tension was predicted by the methods of Reference 5. From the index of refraction, given in Reference 3 as 1.4229 at 80.2°C , Equation 3-51 of Reference 5 yields surface tension "with an average error of 2 to 3 percent," as

$$\sigma = 25.7 \text{ dynes/cm at } 80.2^{\circ}\text{C}$$

The variation with temperature was predicted by Equation 3-54 of Reference 5, stated to be "accurate within a few percent." This equation required knowledge of the critical temperatures, and this was predicted by Equation 3-5 of Reference 5 "within an average error of 1.0 percent." The calculations yield the following values:

<u>Temp. $^{\circ}\text{C}$</u>	<u>Surface Tension dynes/cm</u>
69.3 (m.p.)	26.7
80.2	25.7
100	23.9
150	19.7

An alternate method, Equation 3-52 of Reference 5, uses the density, given in Reference 3 as a sp.gr. of 0.847 at the melting point, yields 27.0 dynes/cm at the melting point "with an average error of 4 to 5 percent."

Viscosity

From the two sets of experimental data given in Reference 3, the following equation is deduced for the liquid in the region of the melting point.

$$\mu = (9.75 \pm 2.6\%) - 0.215 (T - 69.4)$$

in which μ is in centipoise and T is centigrade.

Stearic Acid-contd.

Specific Heat

<u>T</u> <u>°C</u>	<u>Specific Heat</u>		<u>Reference</u>
	<u>joules/gm</u>	<u>cal/gm</u>	
15	1.67 ± 4%	.399 ± 4%	3
75-137	2.302 ± .5%	.550 ± .5%	3

Latent Heat of Fusion

From Reference 3:

$$\Delta H_f = 199 \text{ joules/gm} = 47.5 \text{ cal/gm}$$

Density

Reference 3 gives the specific gravity, referenced to water at 4°C, at the melting point as 0.847.

Vapor Pressure

Vapor pressures from 1 mm to 760 mm are given as a function of temperature in Reference 5. These were extrapolated, using a plot of the logarithm of pressure and the reciprocal absolute temperature, to yield the following values:

<u>Temp.</u> <u>°K</u>	<u>Vapor Pressure</u> <u>mm Hg</u>
342.5	1.2×10^{-3}
350	2.4×10^{-3}
400	1.2×10^{-2}

Thermal Conductivity

Direct data were not found. A prediction method (Equation 3-65 of Reference 5) yields a value for the liquid as 0.00022 cal/cm °C sec. The average and maximum deviations associated with the method are stated to be 8.7 and 31.6%.

PHYSICAL PROPERTIES

Lead Bromide

Melting Point

Melting point = 370°C , Reference 2.

Literally, Reference 2 gives the melting point as 643.2°K . Other sources, however, give melting points which differ from this both by small and by large amounts. Reference 3 gives it as 373°C , with uncertainty in the last digit; Reference 6 gives it as 373; Reference 1 gives values by various investigators ranging from 363°C to 499°C ; Reference 5, Tables 3-1 and 3-7 give it as 373°C , but Table 3-169 gives it as 488°C . The spread in the reported values suggests that there may be some oddity in the melting phenomena.

Estimated Surface Tension

In the series of metals bismuth, silver, cesium, rubidium, potassium, and sodium, the surface tensions at the melting points are slightly smaller for the bromides than for the chlorides, and the difference between them increases as the melting point of the chloride increases, see tabulation below. All have about the same variation in surface tension with temperature. On this basis, the surface tension of lead bromide is taken as 5 dynes/cm smaller than that of lead chloride. It seems unlikely that the estimated values would be in error by more than 2 - 3 dynes/cm unless the possible oddity in melting phenomena mentioned above has influence here. The disturbing note in this is the fact that the high melting point of 488°C gives a melting point difference between the chloride and bromide of lead similar to that for the other metals, while the low melting point, 370°C , seems out of line in this respect.

Lead Bromide - contd.

	<u>Melting Point of Chloride °C</u>	<u>Experimental</u>			<u>Estimated</u>	
		<u>Surface Tension at Melting Point, dynes/cm</u>			<u>Surface Tension at Melting Point, dynes/cm</u>	
		<u>of chloride</u>	<u>of bromide</u>	<u>difference</u>	<u>difference</u>	<u>of bromide</u>
Bismuth	231	71.5	69.0	2.5		
Silver	455	125	121	4		
Lead	498	137			5	132
Cesium	646	91	84	7		
Rubidium	715	98	91	7		
Potassium	776	114	106	8		
Sodium	801	113	103	10		

Lead Bromide - contd.

<u>Surface Tension of Pb Cl₂</u>		<u>Estimated Surface Tension of Pb Br₂</u>	
<u>Temp. °C</u>	<u>σ dynes/cm</u>	<u>Temp. °C</u>	<u>σ dynes/cm</u>
490	138		
(498 m. p.)	(137)	370 m. p.	132
500	137	372	132
518	135	390	131
526	134	398	129
539	131	411	126
541	130	413	125
552	129	424	124
571	128	443	123
590	127	462	122
614	126	486	121

Lead Bromide - contd.

Viscosity (from Reference 3)

<u>Temp., °C</u>	<u>Viscosity, centipoise</u>
370 mp	(10.5 ext)
372	10.2
382	8.80
392	8.06
402	7.47
412	6.97
422	6.53
432	6.13
442	5.74
452	5.38
462	5.03
472	4.70
482	4.38
492	4.07

Specific Heat

<u>Temp., °C</u>	<u>sp. ht., cal/gm °C</u>	
0	.0502	Reference 3
50	.0531	Reference 3
100	.0543	Reference 3
200	.0550	Reference 3
400	.0562	Reference 3
550	.078 ± 1%	Reference 3
480-587	.078	Reference 1

Latent Heat of Fusion

$$\Delta H_f = 5 \text{ k cal/mol} = 14 \text{ cal/gm} \dots \text{Reference 2}$$

$$\Delta H_f = 4290 \text{ cal/mol} = 11.7 \text{ cal/gm} \dots \text{Reference 5, Table 3-169}$$

Lead Bromide - contd.

Density (from Reference 3)

<u>Temperature, °C</u>	<u>Sp.Gr. referenced to 4°C</u>
20	6.66
600-800	6.175 - 0.00145t
370 (mp)	5.73 by extrapolation of above equation

Vapor Pressure

Vapor pressure data from 1 to 760 mm of mercury are given as a function of temperature in Reference 5. These were extrapolated, using a plot of the log of pressure and reciprocal absolute temperature, to yield the following values:

<u>Temperature</u>		<u>Vapor Pressure</u>
<u>°C</u>	<u>°K</u>	<u>mm Hg</u>
370	643	10^{-2}
377	650	1.4×10^{-2}
422	700	8.0×10^{-2}

Thermal Conductivity

$$k = 26 \times 10^{-4} \text{ watts/cm } ^\circ\text{C} \dots \text{Reference 3}$$
$$\text{or } k = 6.2 \times 10^{-4} \text{ cal/cm } ^\circ\text{C sec.}$$

PHYSICAL PROPERTIES

Glycerol

Melting Point

Melting point = 18°C , Reference 3.

This material is subject to extensive supercooling as a liquid. (The melting point below normal room temperature will introduce awkwardness in storage and handling of test spheres; the supercooling as a liquid raises question about ability to form spheres.)

Surface Tension (from Reference 3)

<u>Temperature $^{\circ}\text{C}$</u>	<u>σ dynes/cm</u>
20	63.4
90	58.6
150	51.9

Uncertainty of 3 dynes/cm are associated with above values.

Viscosity (from Reference 2)

<u>Temperature $^{\circ}\text{C}$</u>	<u>Viscosity Centipoise</u>
0 (supercooled)	12,100
10 (supercooled)	3,950
18 (interpolated)	(1,800)
20	1,499
30	624

Glycerol - contd.

Specific Heat (from Reference 3)

<u>Temperature</u> <u>°C</u>	<u>Specific Heat</u> <u>cal/gm °C</u>
<u>as liquid</u>	
0	.054
50	.060
100	.067 ± 5%
<u>as crystalline solid</u>	
-200	.0115
-100	.0217 ± 2%
0	.0330

Latent Heat of Fusion

$$\Delta H_f = 47.5 \text{ cal/gm (from Reference 3)}$$

Density (from Reference 3)

At 15°C, Sp. Gr. = 1.2641, referenced to 4°C.

Density of liquid in range from 0 to 280°C

$$d = 1.2727 - .5506 \times 10^{-3} t - 1.016 \times 10^{-6} t^2 + 1.270 \times 10^{-9} t^3$$

Vapor Pressure (extrapolated from data in Reference 5)

<u>Temperature</u> <u>°C</u>	<u>Vapor Pressure</u> <u>mm Hg</u>
18	1.5×10^{-4}
25	3×10^{-4}
50	3.7×10^{-3}

Thermal Conductivity

As a solid at 0°C:

$$k = 30 \times 10^{-4} \text{ watts/cm } ^\circ\text{C} \dots \text{Reference 3}$$
$$\text{or } k = 7.2 \times 10^{-4} \text{ cal/cm } ^\circ\text{C sec.}$$

As a liquid at 25°C:

$$k = 3.55 \times 10^{-4} \text{ cal/cm } ^\circ\text{C sec.} \dots \text{Reference 2}$$

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