ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN

ATMOSPHERIC PHENOMENA AT HIGH ALTITUDES

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Submitted for the project by:

L. M. Jones

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ATMOSPHERIC PHENOMENA AT HIGH ALTITUDES

Department of Aeronautical Engineering

1. INTRODUCTION

This is the second in a series of reports on Contract No. DA 36-039-sc-125 describing high altitude meteorological experiments being carried out by the University of Michigan for the Meteorological Branch of the Signal Corps. The program is a continuation of one which was carried out between July 1946 and August 1950 on Contract No. W-36-039-sc 32307. For background material the reader is referred to the Final Report on that contract and Progress Report No. 1 of the current series.

2. SUMMARY

2.1 Air Sampling

It was calculated that sufficient sample for an He/N_2+A analysis could be collected at 100 km with the present sampling instrumentation and the RTV-A-1a Aerobee. A new opener was designed. Construction of two instrumentations was started. Changes in the bottles, extractor and analyzer to accomodate the low pressure samples were begun.

2.2 Probe Aerobees

SC-19 was constructed and completely tested. It will be fired when a static fired missile is available.

2.3 Sphere Method for Ambient Density and Temperature

The investigation of the method continued. The error in temperature due to Doppler error in acceleration was calculated. A survey of sphere drag information was made.

3. AIR SAMPLING

The current air sampling instrumentation which has been described in previous reports and which is thought to have been successful in collecting at least one sample on SC-17 has the features required for sampling at altitudes higher than heretofore attempted. The intake system is aerodynamically simple, the intake orifice being the most forward part of the rocket and being connected to the bottle by a straight, large diameter tube. The sample is not heated after capture since the seals are made by cold welding so that little or no contamination by out-gassing is expected. One hundred km was chosen rather arbitrarily as a target altitude at which to attempt sampling. The RTV-A-la Aerobee(1) (4000 lb. thrust, gas pressurized) has a predicted velocity of Mach 2.3 at 100 km with a 150 pound payload which compares with Mach 2.5 at 70 km for the XASR-SC-2 Aerobees which have been used previously for sampling.

Since the mean free path at 100 km is the same order of magnitude as the diameter of the sampling orifice, sampling will take place in the aerodynamic "slip flow" region. No analytical approach to the determination of impact tube pressure specifically for this region has been made. Expressions for impact tube pressure in the continuum region by Rayleigh and in the free molecular flow region by Chambre and Schaaf(2) indicate that one might expect to realize pressure gains of a minimum of seven times ambient at Mach 2.3. Further, Chambre and Smith(3) have shown that in the upper continuum region where viscosity effects are significant, i.e., approaching slip flow conditions, corrections to the Rayleigh relation for viscosity give an increase in the impact tube over ambient pressure ratio. In short, theoretical work shows that as the density decreases the impact tube pressure over ambient pressure ratio increases so that at 100 km an increased ram effect over that at lower altitudes might be expected.

However, experience with sampling at lower altitudes has shown that the pressure gains predicted by the Rayleigh relation have not been realized in flight. The collecting pressures have been within a factor of two of ambient in four cases where the collecting tube operated as an inpact tube in the main stream.

Bottle No.	Aerobee No.	Altitude km MSL	Mach No.	Ambient(4) Pressure mm Hg	Rayleigh Impact Press. mm Hg	Collecting Press. mm Hg
74	SC-7	43.2	1.7	1.7	6.9	3.4
79	SC-7	49.3	1.3	.88	2.5	1.0
77	SC-3	51.8	1.3	.68	1.9	0.8
B-6	SC-17	67	1.5	.15	.51	0.1
		100	2.3	.0027	.02	?

From this, it appears that a realistic and conservative assumption to make is that, in any region, ambient pressure will be collected. Based on this assumption, the amounts of gas that could be collected in three bottles at 90 and 100 km using Grimminger's[(4)] and NRL's[(5)] values for ambient pressure were calculated*.

Altitude	Total amount collected in three 8200 c.c. bottles (c.c. NTP)	
	Grimminger	NRL
90 km	.28	.084
100 km	.090	.024

Charcoal adsorption analyses by Dr. Paneth require 0.1 c.c. NTP of gas for one run at best accuracy, and less at reduced accuracy. Chapman[(6)] shows that the optimum time for a bottle to be open at 100 km is 0.7 seconds. Bottles collecting samples below 70 km have been open 5 to 8 seconds, but the time interval can be adjusted easily to any value. Therefore, it appears that the combination of the present sampling instrumentation and the RTV-A-1a Aerobee will collect useful samples at nearly 100 km. Steps have been taken to procure the rockets, and construction has started on two sets of instrumentation.

Because of the failure in flight of three out of a total of six revolving knife type openers flown on SC-13 and SC-17, a new type pyrotechnic opener has been designed. See Fig. 1. The pyrotechnic cylinder is mounted below the air tight bulkhead of the rocket. It operates a rod through a packing joint or sylphon bellows joint. The hammer hits a collar which is attached to the top of the intake tube. A grooved section in the tube is expected to break during operation thus opening the tube and permitting the hammer to throw the collar and tube top out of the way. An experimental model is under construction. If successful, the device will also be used to release the $C^{14}O_2$ contaminant in the nose cone.

Sampling bottles have heretofore been equipped with Pirani gages for monitoring the vacuum prior to flight. However, bottles for collecting low pressure samples will have to be evacuated to lower pressures, and outgassing and leak rates will have to be small. In the case of the present Piranis, the ambient temperature effect masks the pressure effect so that the gages are not useful in the desired range which is from about 0.02 to 10.0 μHg. The use of a temperature compensating Pirani to eliminate the temperature effect is being investigated.

* In the sampling altitude range of the four bottles shown above, pressures based on refs. (4) and (5) agree, but are different at 90 and 100 km.

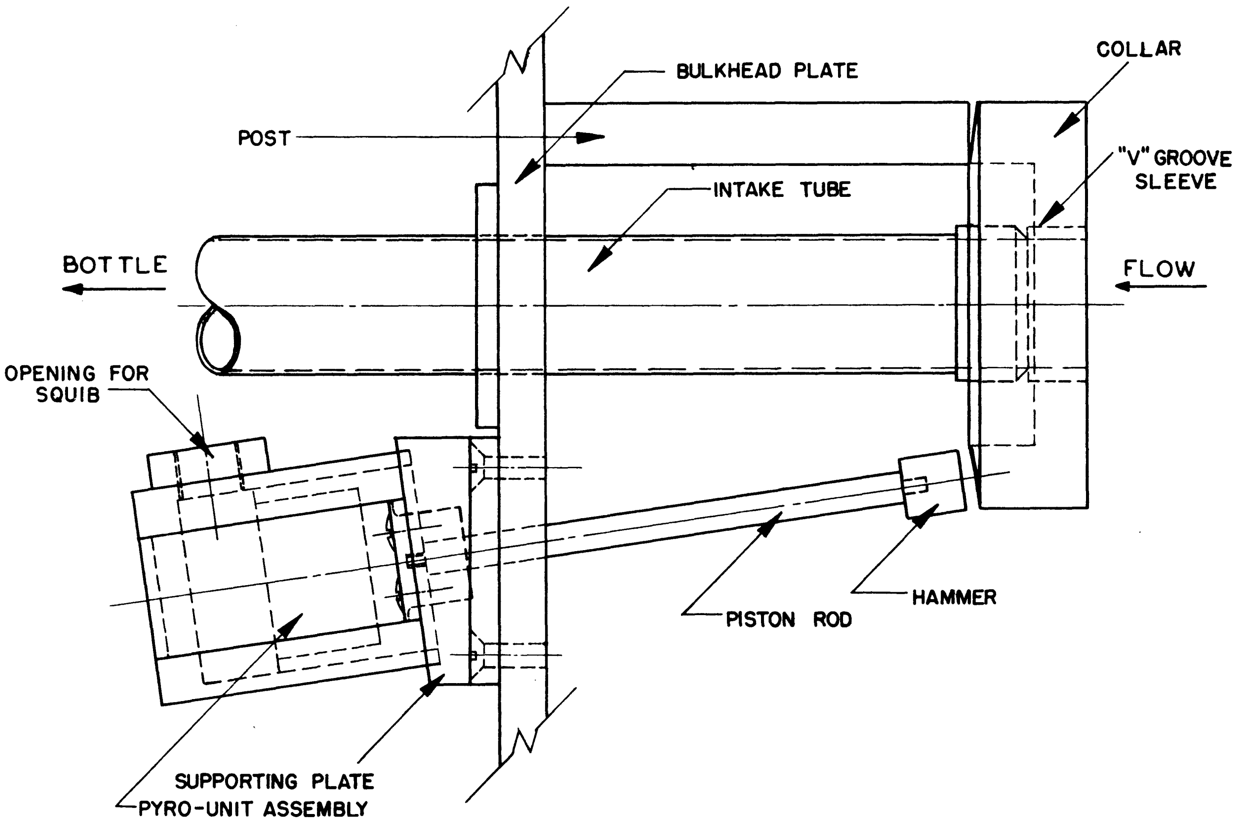

Fig. 1. New Pyrotechnic Bottle Opener

Another possibility for bottle monitoring is the Distillation Products, Inc. type PHG Phillips gage. The gage has sensitivity in the right range and is sufficiently rugged to be mounted in or on the bottle and to survive impact. Tests of the suitability of the Phillips gage are being made. Three of these gages with the associated electronics are shown in Fig. 2 and their sensitivity compared with the present bottle Pirani in Fig. 3. Other modifications in the sampling instrumentation which have been designed are:

a) Provision for removing the nose cone skin without removing the rest of the instrumentation from the rocket.

b) Increased protection for the forward part of the bottles.

c) Increased space for a parachute to accomodate a new high altitude parachute system when it becomes available.

d) Changes in the timer for shorter sampling interval.

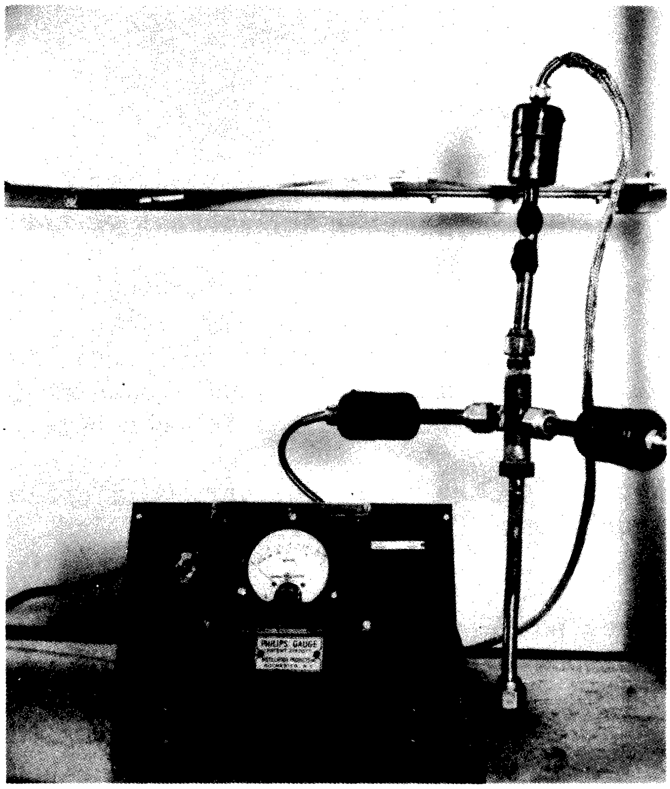

Fig. 2. Phillips Gages

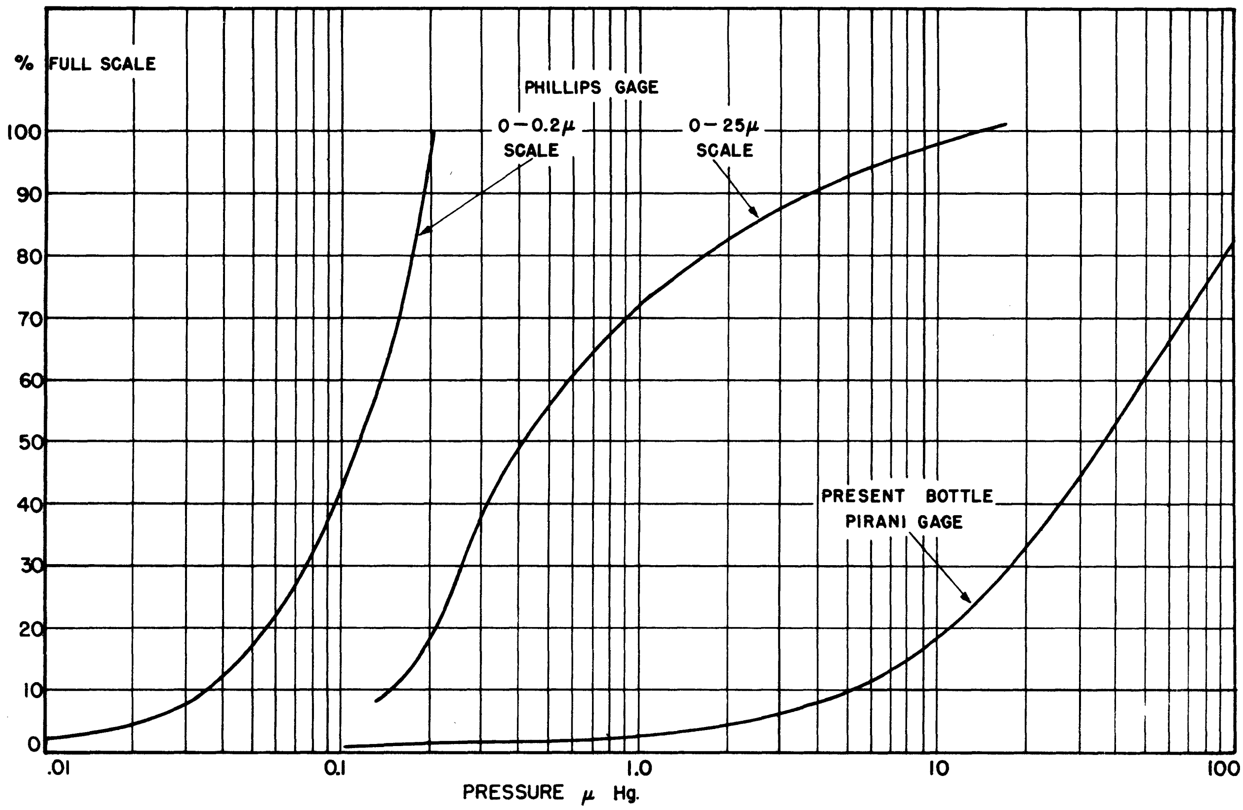

Fig. 3. Phillips Gage and Bottle Pirani Characteristics

References:

(1) Aerojet Engineering Corp., Specification ATS-L4.115, Feb. 1, 1950.
(2) Chambre, P. L. and Schaaf, S. A., Journal of the Aeronautical Sciences, Dec. 1948, pp. 735-737.
(3) Chambre, P. L. and Smith, H. R., University of California Report No. HE-150-63, Project NR061-003, Aug. 29, 1949.
(4) Grimminger, G., Project Rand Report R105, Nov. 1948.
(5) Havens, R., Koll, R., LaGow, H., Naval Research Laboratory Report, "Pressures and Temperatures in the Earth's Upper Atmosphere", March 1950.
(6) Progress Report for the Third Quarter, California Institute of Technology, Signal Corps Project No. 24-172 B, Jan. 1, 1951.

The three bottles from SC-17, of which one probably contained a sample, were shipped to Dr. Paneth at Durham for extraction and analysis. A copy of the device used at Michigan for puncturing the diaphragm seal of the extractor tube and permitting the sample to enter the extraction pumping system was also included. It was thought that starting with the samples in their original steel bottles at Durham would make more complete the parallel independent analyses being made at Durham and Michigan.

The problem of completely extracting and combining without contamination the contents of two or three sample bottles containing low pressure samples was considered. The present Toepler pump has the disadvantage that on low pressures the compressed gas is compressed into a small bubble that will not pass through the pump valve mercury. Also, on the down flow of the mercury, the pressure on the vial side is not sufficient to close the valve. These faults will be remedied by operating the valve magnetically instead of by the floating action of the mercury. See Fig. 4.

The possibility of using a mercury diffusion pump to extract the samples was considered; however, the hot mercury would remove at least the oxygen from the sample. This would not have been of serious consequence in the case of samples collected with a hot sealer since most of the oxygen was removed in sealing. However, in the case of samples collected with the cold-weld sealer in which it is expected that the oxygen will not be lost in oxidation of hot copper, it is desirable to not lose it in the extraction process. Referring to Fig. 5, the extraction operation would procede as follows:

1) With A and B closed and a good vacuum between A and B, and A and the analyzer; E, C, D, S and T are opened and pump W is operated for pre-pumping.

2) Open A and B to complete pumping with analyzer diffusion pump.

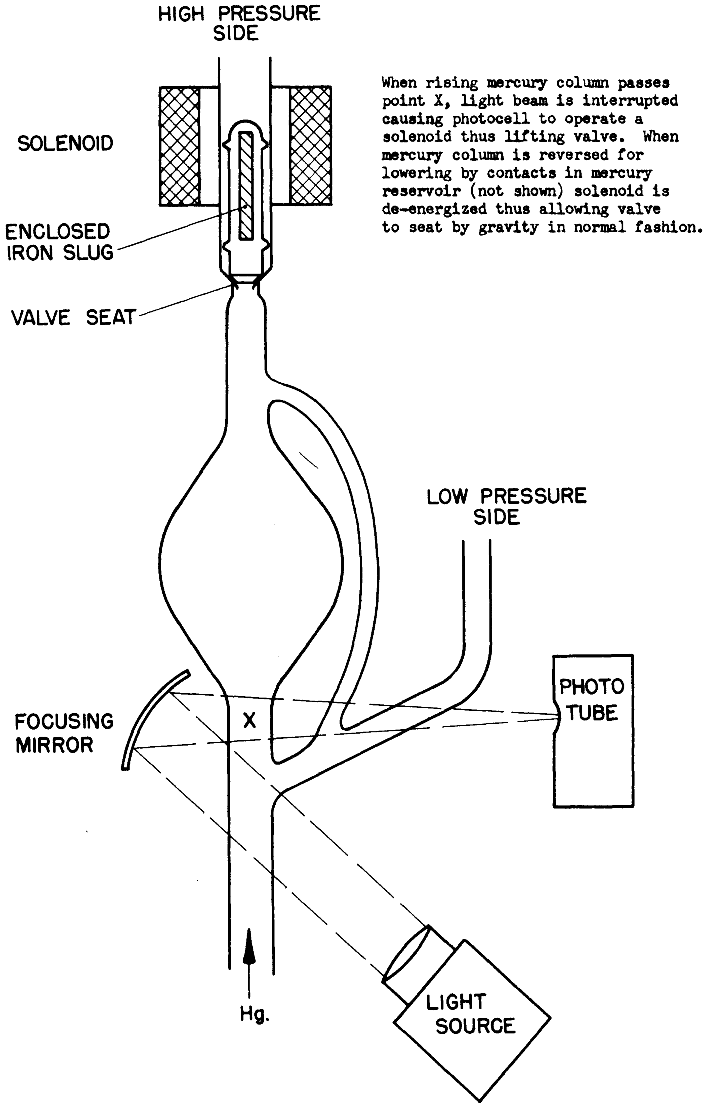

Fig. 4. Magnetically Operated Toepler Pump

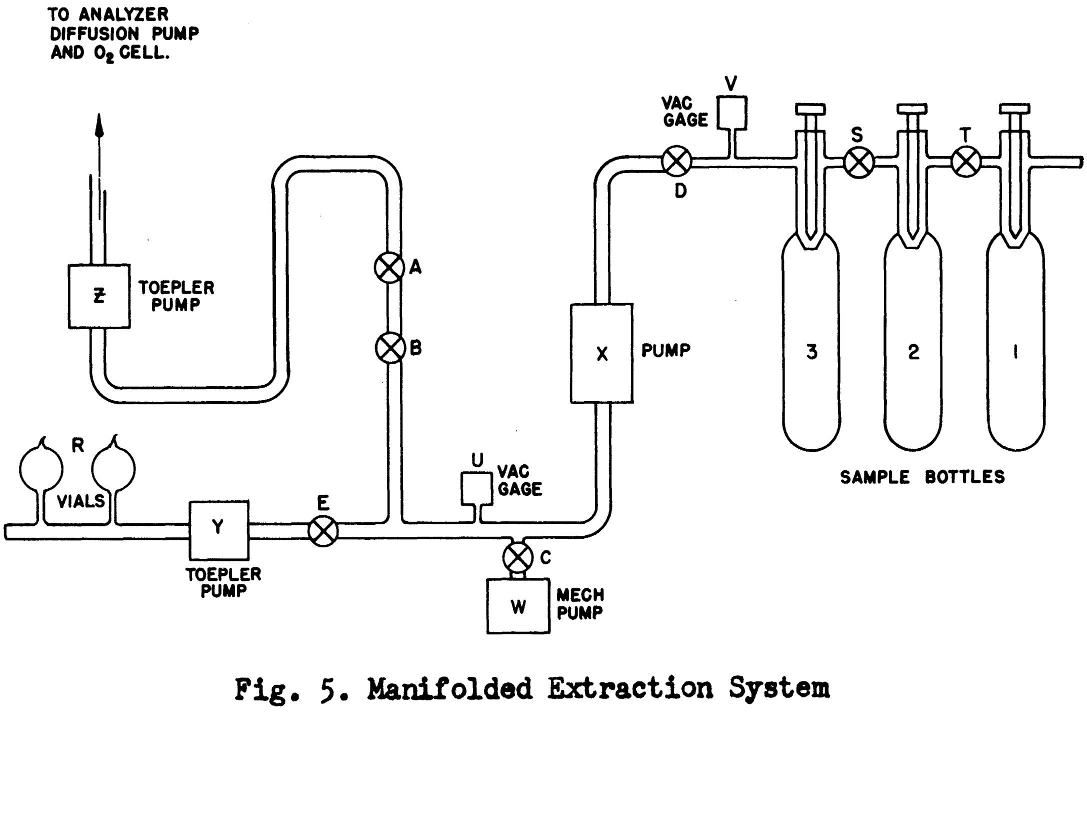

Fig. 5. Manifolded Extraction System

3) Close B and C and check for leaks with gage V.

4) Close E and D; open bottle No. 1 and measure the bottle pressure.

5) Open D and operate pump X to transfer sample from bottle 1 to analyzer side of pump X.

6) Close D and leak check bottle No. 1.

7) Open E, and using pump Y, transfer the sample to vials R.

8) Close valve E, open B, and repump with analyzer pump.

9) Close B, T and D, and open bottle No. 2 and measure pressure.

10) Open D and operate pump X to transfer 2nd sample from bottle to analyzer side of pump X.

11) Close D and leak check bottle 2.

12) Operate pump Y to add sample 2 to sample 1 in vials R.

13) Repeat for bottle 3.

Samples may be sealed off in vials R at this time or analyzed by opening E and B (D closed) and proceeding with the normal analysis technique.

In anticipation of analyzing low pressure samples in the charcoal adsorption analyzer a new, one filament, low volume oxygen cell was designed and built. See Fig. 6. The cell was provided with a glass spur for more accurate setting of the mercury column while measuring the O_2. The cell was then calibrated and mounted on the analyzer. The O_2 water jacket and fittings were replaced, various parts of the system were torched and cleaned and the mercury in the large mercury pots replaced with clean mercury.

4. PROBE AEROBEES

The construction and testing of Aerobee SC-19 was completed. SC-19 is a probe Aerobee designed to measure upper air ambient temperature by measuring the angle of the shock wave formed by the forward cone. It is essentially the same as SC-15 which was described previously and which was unsuccessful because of a rocket failure at take-off on December 11. The following changes were made in SC-19:

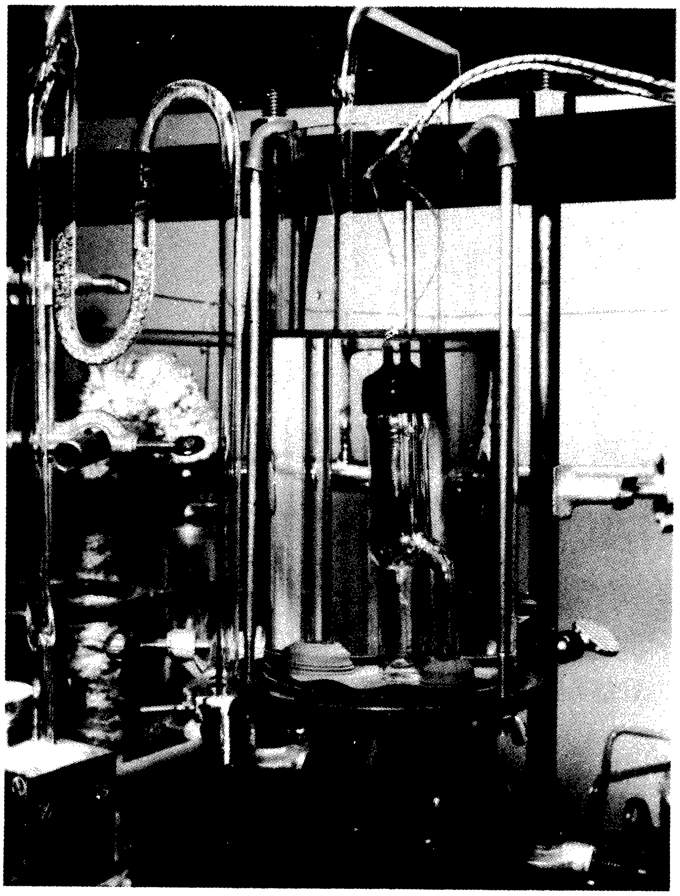

Fig. 6. Oxygen Cell for Adsorption Analyzer

a) The tape recorder was provided with a steel armoring casette as an integral part of the unit.

b) The recorder and timer were arranged for plug-in installation.

c) Provisions were made for measuring rocket chamber pressure.

d) The instrumentation will be 8" shorter than on SC-15 and lighter. The estimated payload is 175 lbs.

Figs. 7 and 8 show the plug-in installation of the recorder and the protective casette. Fig. 9 shows the gage which will be used to monitor rocket chamber pressure. The gage is a stainless steel Bourdon tube type in which the Bourdon tube operates a resistance potentiometer. The potentiometer will control a 0 to +5 volt D.C. signal which will modulate the single Doppler telemeter channel. The gage will be supplied by the G.M. Giannini Company according to their specification 46131SS-G-20/40-20. The potentiometer resistance is 2000 ohms. The gage operates between the limits 200 psig to 400 psig. It weighs about 12 ounces.

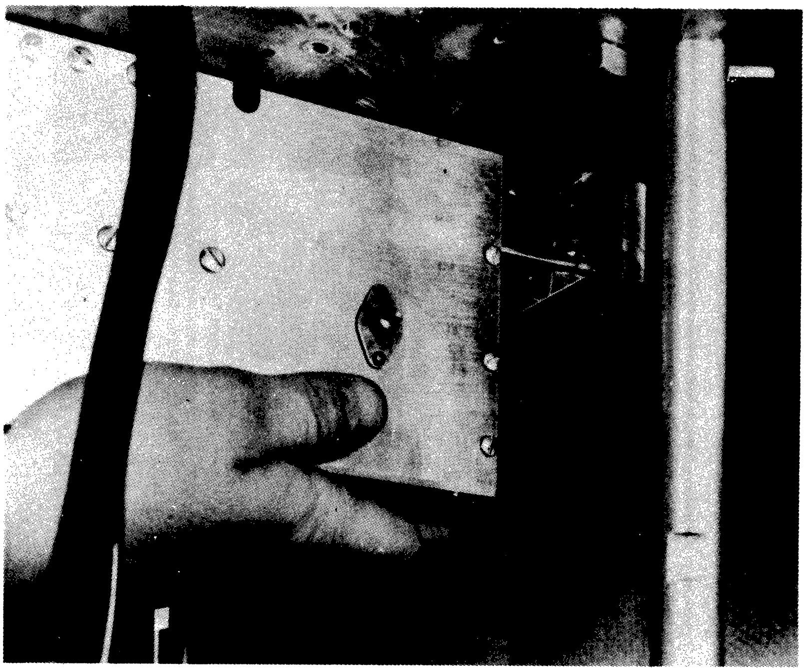

Fig. 7. Plug-in Installation of Recorder

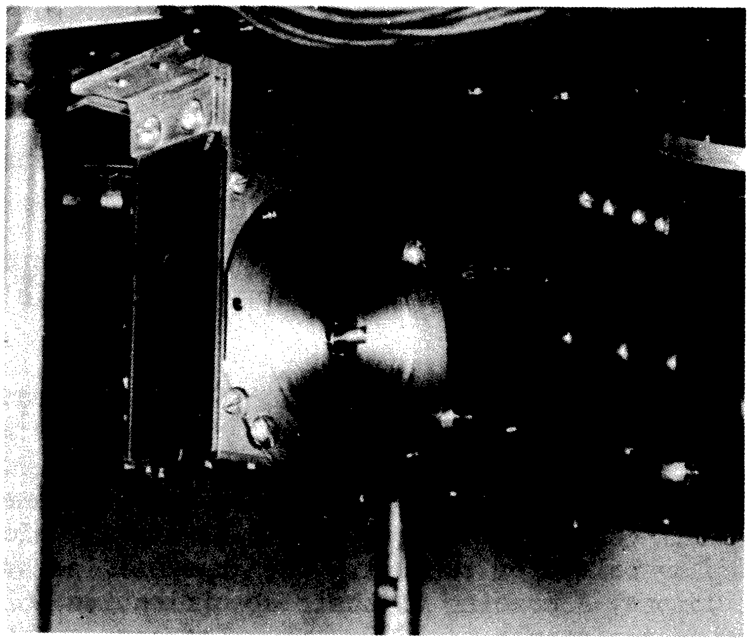

Fig. 8. Recorder Tape Casette

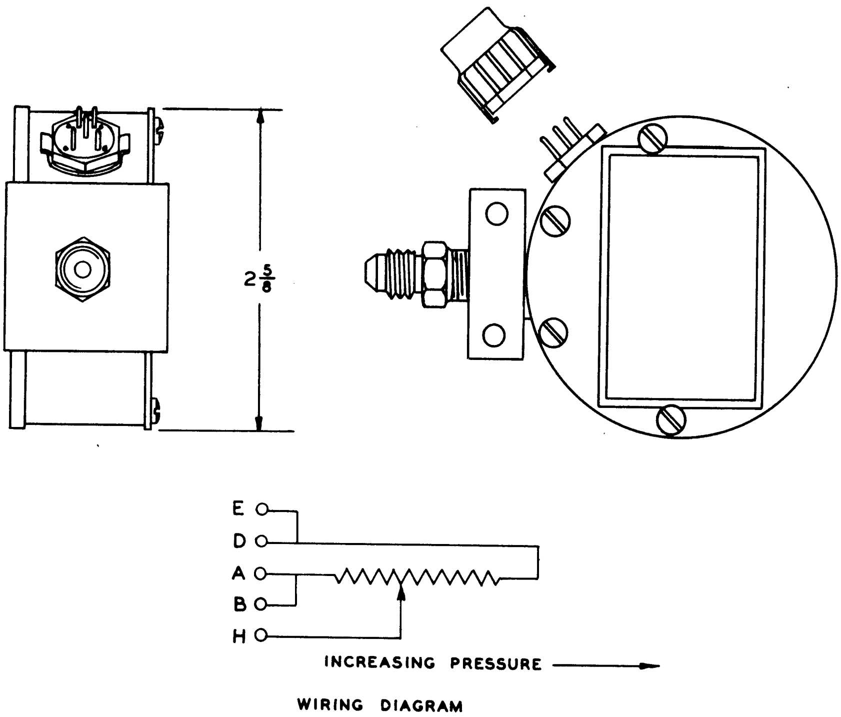

Fig. 9. Chamber Pressure Gage

In testing SC-19, signals recorded using one 13 channel set of recording heads were successfully played back on a second set of heads. This simplifies the recovery problem in that only the tape and not the flight head assembly need be recovered. Construction of a third probe Aerobee scheduled for firing in connection with the second "T-Day" program was started. The amplifiers and oscillators were wired, the moveable cone machined and the ejectable cone assembled.

Although the rated output current of Yardney Al-HR-1 Silvercels was found on SC-15 to be insufficient to start the probe motor, a worthwhile saving in weight could still be realized if they were used to power the electronics of the instrumentation. The cells weigh 0.86 ounces each, have a volume of 0.95 cubic inches and are nominally rated at 1 ampere-hour for a 5 ampere discharge rate.

Fig. 10 is a plot vs time of the terminal voltage of an average battery of sixteen cells in series under a constant 2 ampere drain. The voltage remains within 5% of maximum from 90 to 2020 seconds which is satisfactory for flight use. Constant voltage charging was found to be most convenient. The cells are placed in parallel with a lead-acid cell having a nominal terminal voltage of 2.1. Except for the initial precaution that the charging current to any cell does not exceed 0.2 amperes, no attention is necessary. Other tests performed showed:

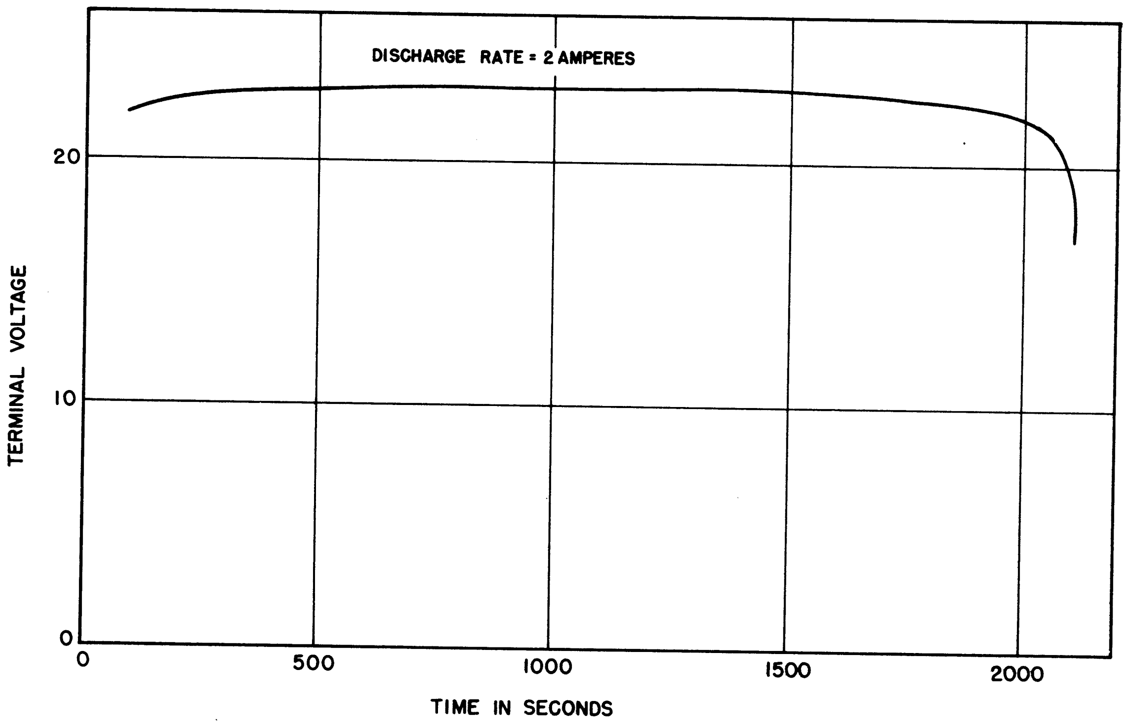

Fig. 10. Yardney Silvercel Characteristic

a) Internal resistance - 0.030 ± .006 ohms per cell under various conditions of discharge.

b) Vibration - no effect on one cell shaken at 2500 cpm, .064" peak to peak amplitude.

c) Reduced pressure - Peak voltage dropped 5% and useful time reduced 20% at a pressure where the electrolyte boiled vigorously (order of 10 mm Hg).

d) Cycling - the initial cycle seems to have the lowest capacity. Tests on one cell showed a slight drop in capacity at the sixth cycle.

e) Shelf life - a three day period between charge and discharge had no effect on capacity.

5. SPHERE METHOD FOR AMBIENT DENSITY AND TEMPERATURE

The possibility of measuring ambient density and hence ambient temperature by measuring the drag of a falling sphere was mentioned in Progress Report No. 19. It was noted that the drag force on a sphere 6 feet in diameter and weighing 20 pounds dropped from 400,000 feet would, in the region 300,000 feet to 100,000 feet, be sufficient to result in an acceleration differing enough from that due to gravity to be measured by Doppler. The equation of motion, solved for density, is

$$\rho = \frac{2}{AV^2C_D}\,\frac{W}{g}\left(g - \frac{dV}{dt}\right) \tag{1}$$

where

ρ = density

W = weight of sphere

g = acc. of gravity

$\frac{dV}{dt}$ = acc. of sphere

C_D = coef. of drag

A = area of sphere

V = velocity of sphere

From the hydrostatic equation and the equation of state of a perfect gas we have:

$$\frac{dT}{dh} + \frac{d}{dh}(\ln\rho)T = \frac{g}{R} \tag{2}$$

where

T = abs. temperature

h = altitude

R = gas constant

The general solution of (2) is:

$$T(h) = \frac{\rho_o}{\rho}\left[\frac{g}{R}\int_{h_o}^{h}\frac{\rho}{\rho_o}\,dh + T_o\right] \qquad (3)$$

It can be shown from (2) that

$$\frac{\delta T}{T} \approx \frac{\delta \rho}{\rho} \qquad (4)$$

and from (1) that

$$\frac{\delta \rho}{\rho} = \frac{\delta W}{W} - \frac{\delta A}{A} - \frac{2\delta V}{V} - \frac{\delta\left(\frac{dV}{dt}\right)}{g - \frac{dV}{dt}} - \frac{\delta C_D}{C_D} \qquad (5)$$

where $\frac{\delta T}{T}$ is the fractional error in temperature, etc.

Assuming that W, A, and V can be measured to a high order of accuracy, it is concluded that the principal errors in temperature will be contributed by errors in the Doppler measurement of acceleration and errors in coefficient of drag. Consequently an investigation of the accuracy of acceleration measurements and the availability and accuracy of C_D data was undertaken. Preliminary consideration was also given to some of the engineering problems of instrumenting the method, and they do not appear to be too difficult. The effect of sphere spin on the method was considered. Excessive spin would have two adverse effects. The Doppler accuracy might be decreased by introducing extraneous doppler cycles and possible cyclic loss of signal, and the coefficient of drag values which are expected to be obtained for nonspinning spheres would not be applicable. An analytical prediction of spin would be based on so many broad assumptions that it would be of little value. It appears, however, that it would be feasible to measure spin by monitoring the strength of the Doppler signal received on the ground from the sphere. For this purpose, the sphere transmitting antenna should have a mildly directional characteristic. Spin might be eliminated by locating the center of gravity of the sphere off center, but under this condition oscillations would probably be present which would also have an unknown effect on C_D.

In order to calculate errors due to Doppler errors and to ascertain the applicability of existing C_D data and what additional C_D data would have to be obtained, trajectories of spheres with different size-weight ratios were calculated.

From (1)

$$\frac{dV}{dt} = g\left(1 - \frac{C_D \rho A}{2Mg} V^2\right) \tag{6}$$

$$\frac{dV}{ds} = \frac{g}{V}\left(1 - \frac{C_D \rho A}{2Mg} V^2\right) \tag{7}$$

Assuming g, C_D and ρ constant over a small altitude interval (7) yields the solution

$$V_s^{\,2} = \frac{2Mg}{C_D \rho A}\left[1 - e^{\frac{-C_D \rho A(S-S_o)}{M}}\right] + V_o^{\,2} e^{\frac{-C_D \rho A(S-S_o)}{M}} \tag{8}$$

where

$S-S_o$ = the altitude interval
V_o = velocity at altitude S_o
V_s = velocity at altitude S

In this solution, which permits calculation of an approximate trajectory, distance is measured positive downward, being zero at the starting point. Calculations were made for spheres falling from 400,000 feet; 10,000 foot intervals were used. The curves of velocity and $g - \frac{dV}{dt}$ as functions of altitude are shown in Figs. 11 and 12. The spheres were assumed to fall vertically; density data were taken from Grimminger(1).

5.1 Error Due to Doppler Errors

Under conditions of no spin, velocity can be measured by Doppler with negligible error and acceleration at half second intervals with a

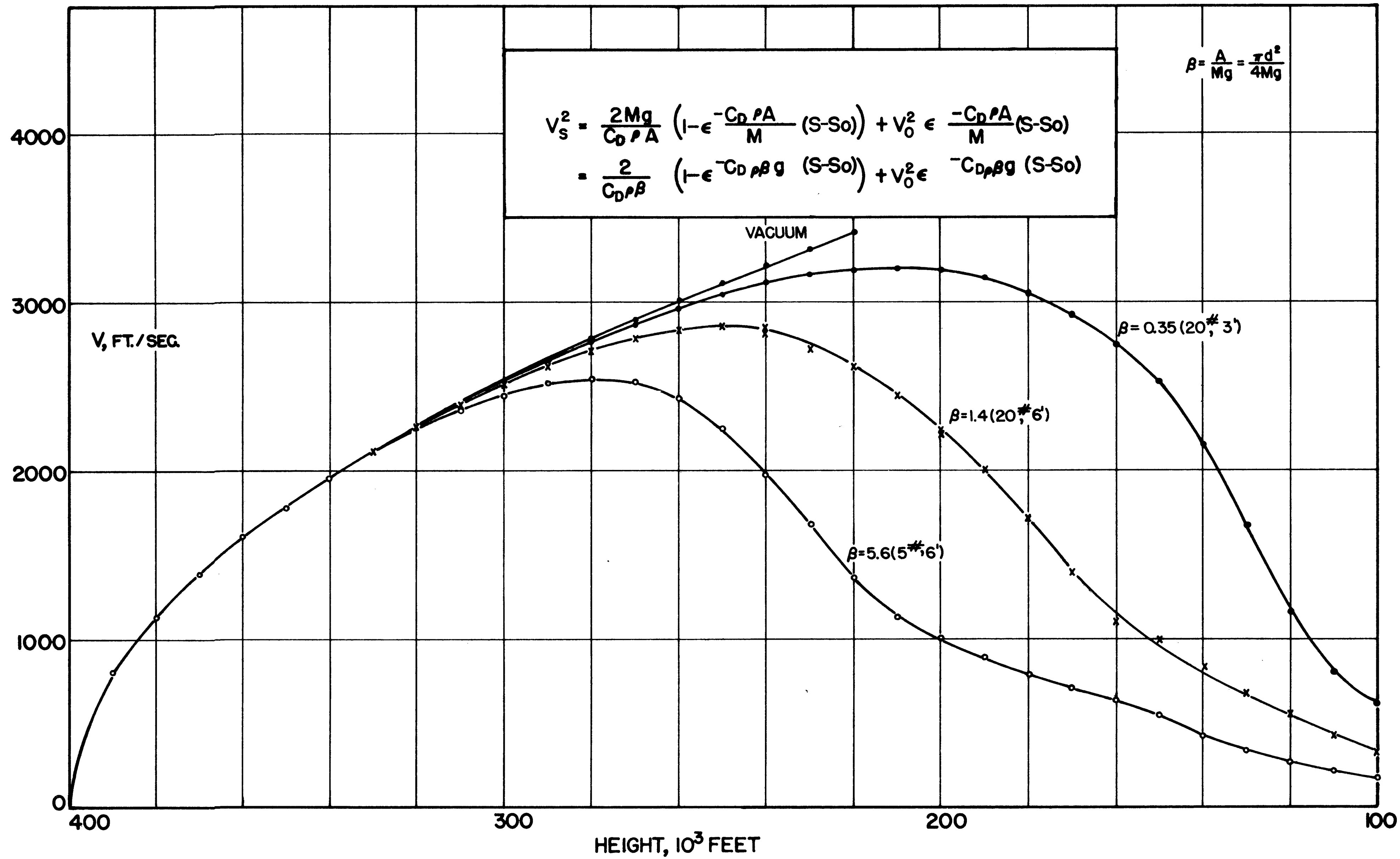

Fig. 11. Velocity vs Altitude for Falling Spheres

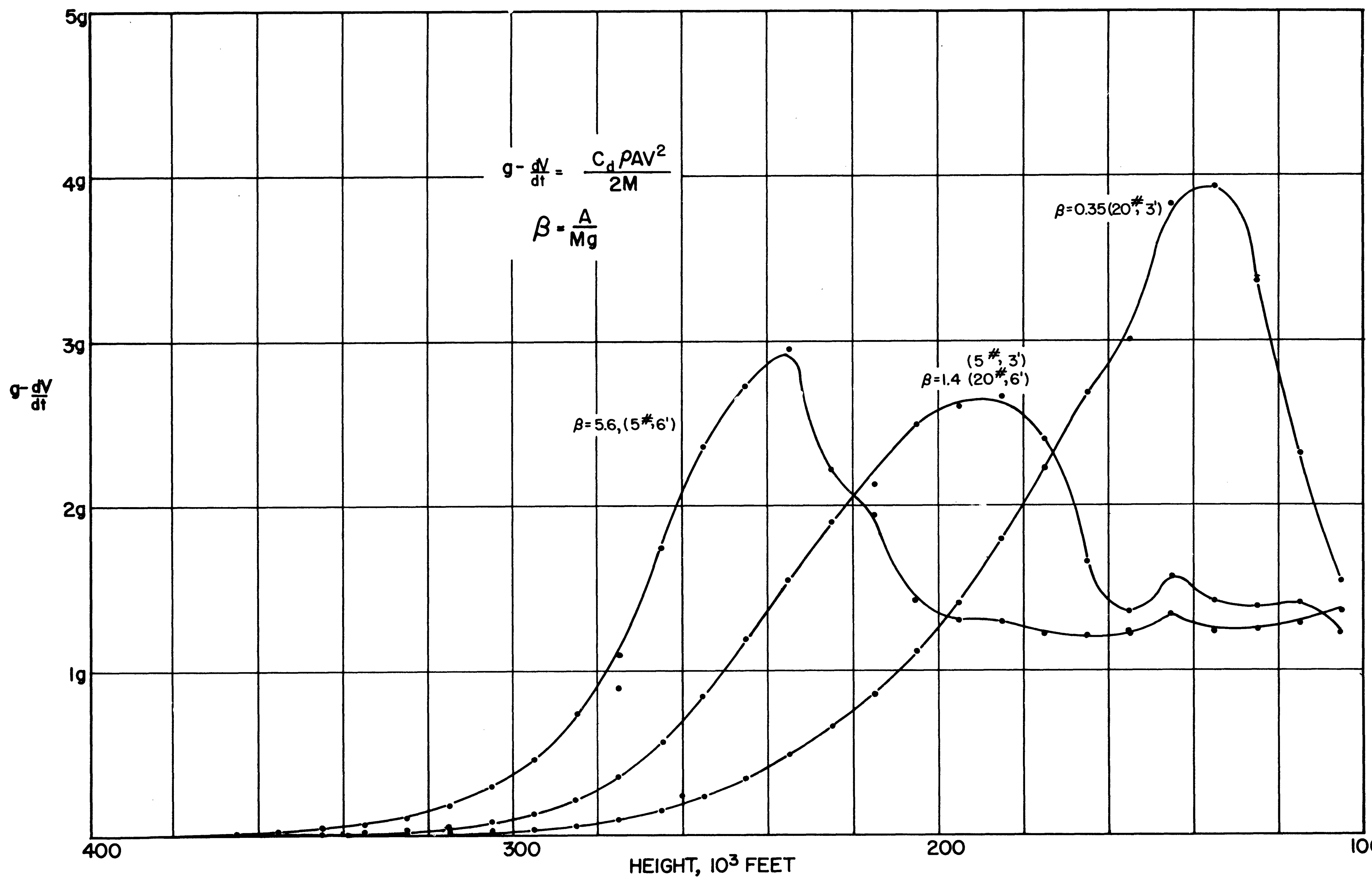

Fig. 12. $g - \frac{dV}{dt}$ vs Altitude for Falling Spheres

maximum error of about 3 ft/sec^2. The average acceleration over a 10,000 foot altitude layer will have an error less than this. The % error

$$\frac{\sigma\left(\frac{dV}{dt}\right)}{g - \frac{dV}{dt}} \times 100$$

in the average acceleration over 10,000 foot intervals for the trajectory of a 6 foot diameter, 20 pound sphere falling from 400,000 feet is shown in Fig. 13.

5.2 Availability of C_D Data

As pointed out above, the error in temperature due to an error in C_D is directly proportional to the error in C_D. A survey of available C_D data was made in the literature and by discussion with people who have made sphere drag measurements. The following data exist:

a) Sphere drag coefficients in low subsonic flow over a wide range of Reynolds numbers has been compiled in Ref. 2. Measurements were made in wind tunnels, in free flight and in dropping tests.

b) Sphere drag coefficients in subsonic and supersonic flow ($.29 < M < 3.96$) in the Reynolds number range 9.3×10^4 to 2.1×10^6 are given in Refs. 3 and 4. These measurements were made in a ballistic range.

c) Sphere drag coefficients in supersonic flow ($2.2 <$ M2.8) for Reynolds numbers from 15 to 1100 are given in Refs. 5 and 6. These measurements were made in a low density wind tunnel.

The data obtained at subsonic speeds ("a" above) in wind tunnels or in free flight are significantly different from those obtained in dropping tests. The reason for the differences is not established but may be due to the fact that dropped spheres are free to spin whereas the others are not. Since no drop test data are available at supersonic speeds a similar comparison for this range cannot be made.

Refs. 3 and 4 both indicate that, as Mach number increases in the supersonic range, the Reynolds number effect on C_D becomes less. This trend may be used to advantage in the falling sphere method. Good internal consistency is also shown in the data of these two references.

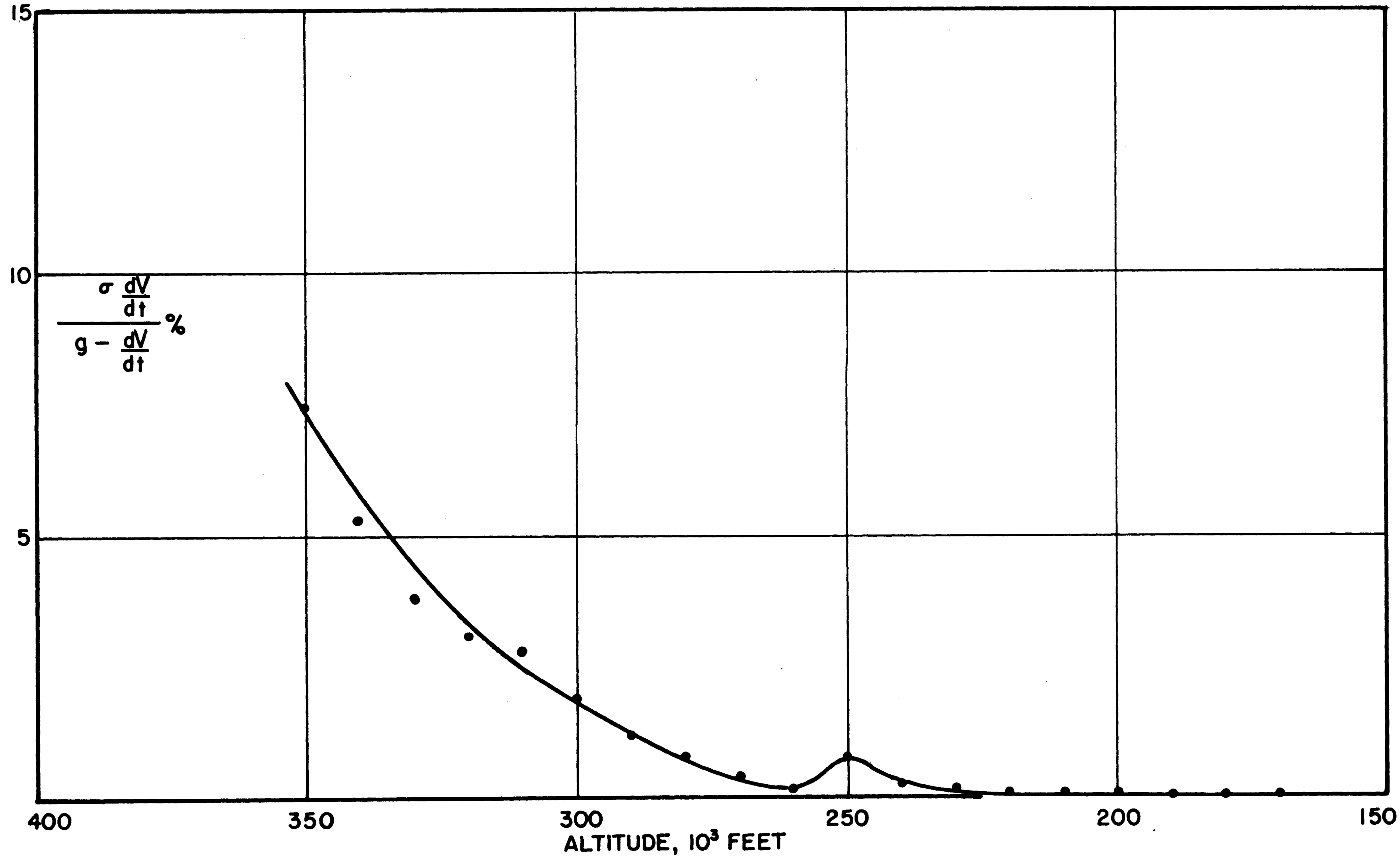

Fig. 13. Doppler Error in Acceleration vs Altitude for Falling Sphere

Fig. 14 is a plot of Mach number vs Reynolds number for existing C_D data and for estimated trajectories of three nonspinning spheres of different weight-diameter ratios. It can be seen that existing C_D data do not cover the range of the experiment. However, a discussion of the problem with personnel of the NOL Ballistic Range at White Oak, Maryland, revealed that it would be relatively easy to obtain data in the desired ranges of M and Re.

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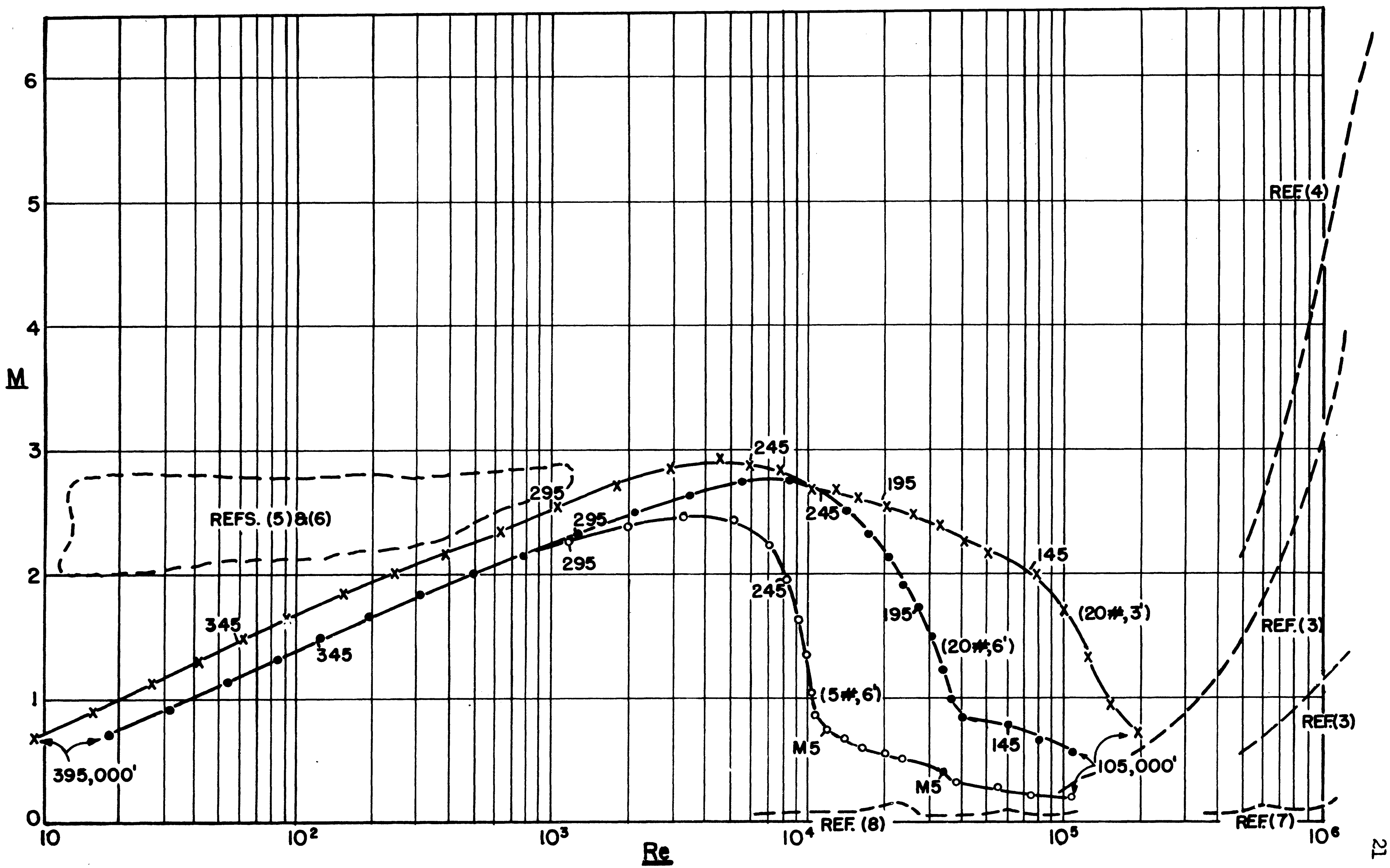

Fig. 14. Mach Number vs Reynolds Number for Spheres

6. REPORTS ISSUED AND LABORATORIES VISITED

No reports were issued during the period. The following places were visited during the course of the work:

Ballistic Research Laboratory
Evans Signal Laboratory
Low Density Supersonic Wind Tunnel
  University of California
Aerojet Engineering Corporation
Naval Research Laboratory
California Institute of Technology

7. FUTURE PROGRAM

Construction of sampling Aerobees will continue. Preparation of the sample handling and analysis equipment for low pressure samples will continue. Probe Aerobee SC-19 will be fired. Construction of probe Aerobee SC-21 will continue.

8. ACKNOWLEDGMENT

Thanks are due the Meteorological Branch of the Signal Corps for their cooperation and support. We are indebted to the Ballistic Research Laboratory and the Low Density Wind Tunnel Project at the University of California for their cooperation in investigating the sphere experiment.