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UNIVERSITY OF MICHIGAN
ANN ARBOR

FINAL REPORT

SUBJECT: THE MEASUREMENT OF AMBIENT PRESSURE AND TEMPERATURE OF THE UPPER ATMOSPHERE

By

W. G. DOW
Project Director

N. W. SPENCER
Project Engineer

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ABSTRACT

The general objective of the work under subject contract is to obtain measurements of the ambient pressure and temperature of the upper atmosphere using high-altitude rockets as research vehicles.

A new method which permits an essentially point-by-point determination of ambient temperature from measured pressure values has been developed and utilized experimentally. Resulting upper-atmosphere data are presented.

The equipment necessary to implement the theoretical method has been developed. The alphatron ionization gage constitutes the basic pressure-sensitive device, and provides the basis for a pressure measurement system that will measure gas pressures in the range 760 mm Hg to 10^{-3} mm Hg.

Associated equipment utilizing a gyroscope to allow determination of missile angle of attack, and many accessory pieces of equipment, less spectacular but necessary to the experiment, have been developed.

This report reviews that portion of the research which was conducted under subject contract.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

LIST OF FIGURES

LIST OF FIGURES (cont.)

LIST OF TABLES

THE MEASUREMENT OF AMBIENT PRESSURE AND TEMPERATURE OF THE UPPER ATMOSPHERE

1. INTRODUCTION

The Electrical Engineering Department of the University of Michigan has been engaged since early 1946 in the measurement of the ambient pressure and temperature of the upper atmosphere, and, in addition, certain characteristics of the lower ionosphere regions including ion and electron concentrations and electron mean energies.

These experiments have been facilitated through the use of V-2 and Aerobee rockets, the field test portion of the work having been conducted exclusively at military bases in New Mexico.

The research accomplished prior to 1 June 1949 was carried out under USAF AMC Contract No. W-33-038-ac-14050. For a summary of those activities, the reader is referred to the final report,[1] which gives an indication of the instruments used and status of the resulting data. The report also lists, with abstracts, all the reports issued during the period of that contract.

The research conducted from 1 June 1949 to 1 October 1952 was carried out under USAF Contract No. AF 19(122)-55, which terminates 30 September 1953. The period from 1 October 1952 to the termination date has been devoted exclusively to publication and report writing. This report is the final report on the work conducted under Contract AF 19(122)-55.

[1]"Pressure and Temperature Measurements in the Upper Atmosphere", by W. G. Dow and N. W Spencer, USAF AMC Contract No. W-33-038-ac-14050, May 11, 1950.

2. SUMMARY OF RESEARCH

The research performed under this contract has been devoted almost exclusively to the measurement of ambient atmospheric pressure and temperature. In general, a single temperature-measurement method developed by project personnel from fundamental aerodynamic considerations has been employed. The Appendix to this report presents details of the method, which may be summarized as follows:

The ratio of the pressure (impact pressure) existing at the apex of a slightly truncated cone, moving axially at a supersonic velocity, to the pressure existing at a point along an element of the same cone may be interpreted as a Mach number. A mathematical consideration of this Mach number and the velocity of the cone (rocket) will yield the ambient temperature. Certain accessory considerations are basic to this computation. The angle of attack, that is, the angle between the axis of the cone and the air stream velocity vector, must be known. Implicit in a determination of this angle and the resulting adjusted pressure values is the assumption that the ambient wind is negligibly small as compared with the stream velocity, that is, the missile (cone) velocity.

The instrumentation developed by project personnel to implement the theoretical considerations and to apply the method experimentally uses, as the basic sensing elements, alphatrons and a modified attitude gyroscope. The overall instrumentation system employing these devices has undergone almost continuous development in order to improve the accuracy of the resulting data, facilitate operation in the field and rocket, and improve the reliability of operation in flight.

Each field test conducted under the contract employed equipment of this nature and also accessory instruments, the following list of which is typical:

(a) camera for recording gyroscope data,

(b) telemeter calibration unit,

(c) timing devices,

(d) missile acceleration indicators,

(e) telemetering signal limiters,

(f) invertor power supply for gyroscope,

(g) Alphatron-chamber temperature indicator, and

(h) circuit switching devices.

3. DESCRIPTION OF PRIMARY INSTRUMENTATION

This section will present moderately detailed descriptions of the various basic pieces of equipment of which a typical instrumentation is composed. In general, the latest model will be described. In many cases, the discussion will be extracted from the many progress reports written during the course of the work.

3.1. Alphatron System

An alphatron gage is an ionization gage wherein the ionization results from collisions between alpha particles, emanating from a radium foil source, and gas molecules. The charged particles resulting from this process are collected by electrically polarized elements of the gage and thus constitute a small current when an external circuit is completed. Figure 1 illustrates the constructional features of a typical Alphatron chamber, and Fig. 2 presents an actual curve of output current plotted as a function of pressure (temperature assumed constant).

It is apparent that the gage characteristic is linear over a large range of pressure. At higher pressures the departure from linearity indicates recombination before particles are collected. At the lower pressures, the current due to direct collection of alpha particles and the resulting secondary emission becomes more significant, which ultimately serves to limit the usefulness of the device at very low pressures.

In application, the total range of pressure measured by project equipment is from a ground level pressure of approximately 760 mm Hg to about 10^{-3} mm Hg. In order to obtain the desired definition, this total range is divided arbitrarily in many so-called subranges, usually seven to eight in number. The various subranges in the equipment are manifested as different values of alphatron load resistance.

The voltage range developed by the alphatron current under conditions of changing pressure in the load resistance is equivalent in magnitude to the desired range of output information signal. However, due to the very small current and hence the very large value of resistance required, it is necessary to provide an impedance match between the high resistance (which may be as high as 5×10^{12} ohms) and the input resistance of the telemeter, usually of the order of 5×10^{4} ohms.

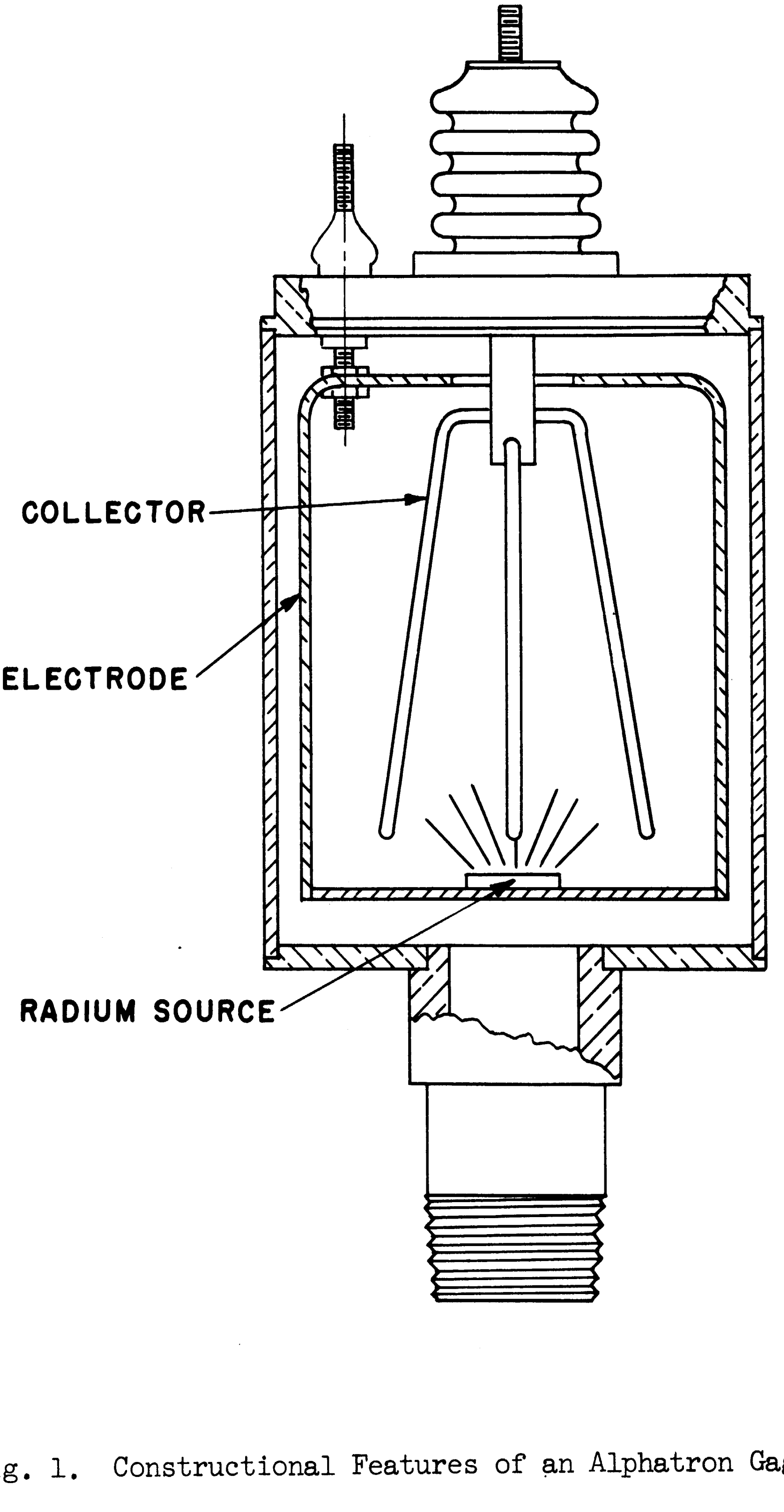

Fig. 1. Constructional Features of an Alphatron Gage.

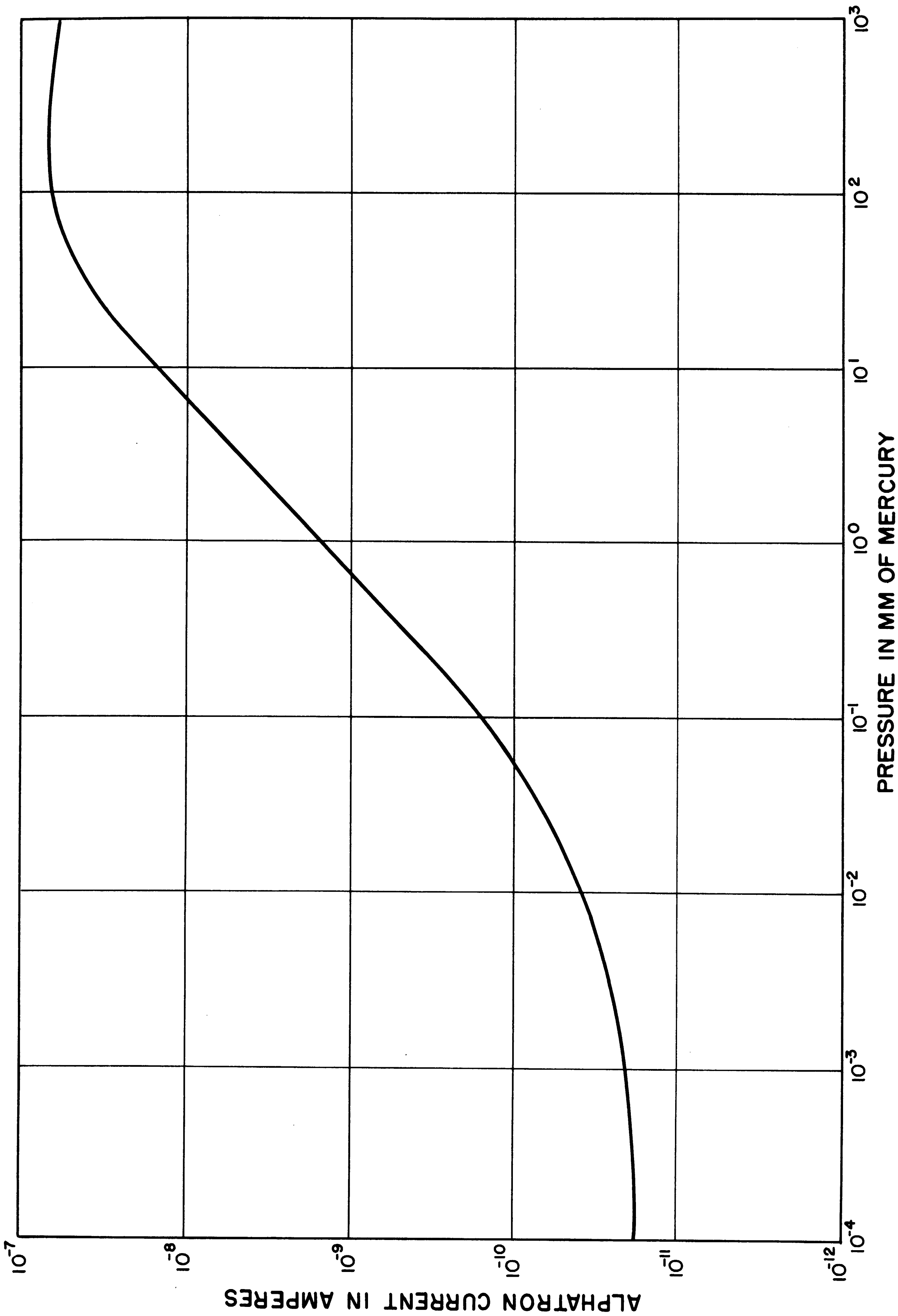

Fig. 2. Typical Curve of Alphatron Output Current Vs. Pressure.

A 100 per cent negative feedback amplifier provides the requisite impedance match. The first stage of the amplifier employs an electrometer tube (low leakage in shunt with high resistances) and the following stages employ conventional d-c amplifier techniques. A filament-voltage-variation compensating stage is included.

Independent of the amplifier but associated with the system is a switching circuit whose function is to insert the particular value of alphatron load resistance appropriate to a given chamber pressure range. The circuit in effect acts to keep the output signal voltage on scale as the chamber pressure progresses from atmospheric pressure to lower values, during flight use. A Ledex rotary solenoid serves to accomplish the actual resistance switching on activation by the switching circuit.

Several figures are included in this report to illustrate specific instrumentations. The external features of alphatron systems are shown. Figure 3 is a schematic diagram of a single alphatron unit.

3.2. Gyroscope and Camera Installation

A Sperry model F4A gyroscope has been modified for use in determining missile (cone) angular position during flight. The modifications deemed necessary are generally to adopt the unit to operation under the free-fall conditions of flight and to change the scale markings to facilitate data recording by the missile-borne camera.

The data obtained from the gyroscope may be utilized to determine the zenith (z) angle of the missile as shown by the following discussion:

The F4A gyro has two degrees of freedom. In the event that an Aerobee were to fly with no spin, it would be possible to mount the gyro so that pure pitch and yaw angles would be read. Such a mounting would require that the axis of the gyro rotor be along the figure axis of the missile (or axis of least moment) initially and, furthermore, that the gyro pitch axis be perpendicular to the plane of the trajectory.

For the purpose of this discussion, pitch angle is defined as the angle in the plane of the trajectory and yaw angle as the angle in a plane perpendicular to the plane of the trajectory and the earth. It is not to be inferred, however, that, in normal use of the F4A gyro in a missile, the two angles read are exactly pitch and yaw, for the measured angles vary with missile roll. From the indicated pitch and yaw angles, the zenith angle as referred to the gyro rotor axis, in this example, the tower axis, may readily be computed.

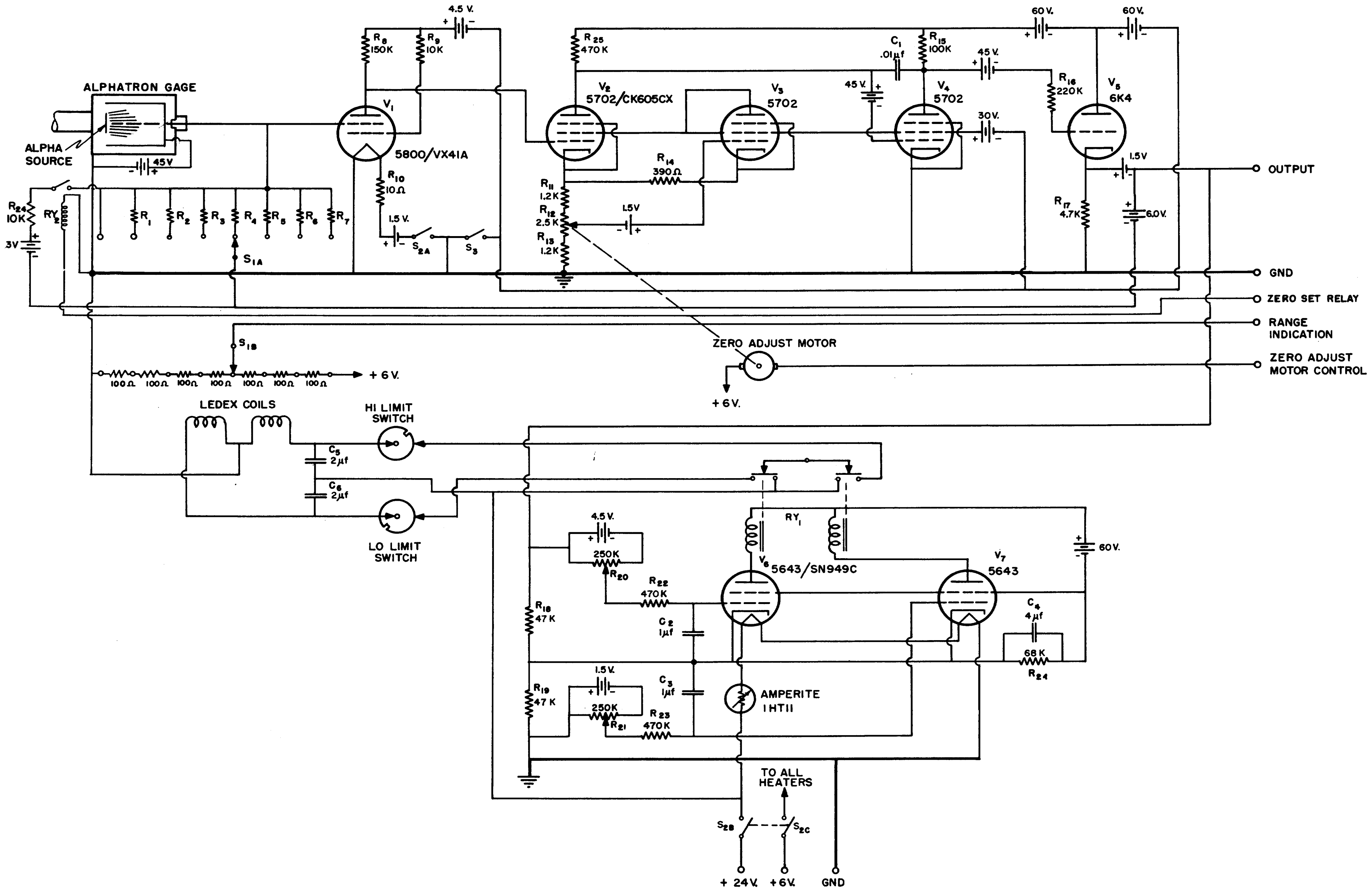

Fig. 3. Schematic Diagram of Single Alphatron System.

If the picture is now complicated by missile spin, it is still possible to determine the zenith (z) angle.

Consider the following: a missile spinning at a one-second rate, constant angle z, no precession. The gyro would indicate two sinusoids of one-second period, one as pitch angle and the other as yaw, appearing ninety degrees out of time phase. The maximum instantaneous value of either sine curve would be exactly the z angle. If precession about the gyro rotor axis is now allowed, there would be no change in the indications. Therefore, a so-called "cone of ambiguity" is defined whose half angle is the indicated maximum or z angle. It is not possible, therefore, to determine the missile's position on the precession cone. Note that in order to determine the z angle, missile spin is required.

In our normal installation, the gyro is mounted as stated above, except that the pitch axis, of course, does not necessarily remain perpendicular to the trajectory during flight. This does not alter the fact that the maximum values of the sine variations of the angles read as pitch and yaw are the z angle.

In actual, rather than hypothetical, flight, the axis of the precession cone does not remain parallel to the rotor (or tower) axis, but follows, more or less, the trajectory. This assists in the analysis, for it greatly reduces the ambiguity due to the precession cone by superimposing an envelope on the sine variation, suggestive of an amplitude-modulated radio-frequency wave, thereby altering the gyro indications. The period of the amplitude variations is the precessional period. The period of the sine variations is very nearly the spin period.

To determine the z angle, then, from the gyro data, the instantaneous indicated angle readings are used to determine an angle that would be the indicated maximum of a sine variation if the maximum had obtained at the time in question. The unknown in the equation is the spin position, which is readily obtained from the raw gyro data. The angle thus obtained is the zenith angle.

This angle information, combined with data concerning the trajectory of missile center of gravity, permits a determination of the angle of attack of the missile.

The gyroscope data is recorded in flight on film by a 16-mm motion-picture camera. Early flights utilized a standard GSAP gun camera, which was later discarded due to its unreliability. Later flights used a type B-2 navigation camera modified to the extent of providing take-up spool armor and a more reliable driving motor. A photograph of this modified camera is included here as Fig. 4.


TAKE-UP SPOOL ARMOR

[illegible]

Representative gyro data are likewise included in this report. The angles specified are those occurring between the missile's (Aerobee) longitudinal axis and the gyro rotor axis. The independent variable is the frame number, which may be converted approximately to seconds from launching instant by dividing by the frame rate of 7.2 frames per second. See Table 1.

TABLE 1

DATA FOR DECEMBER, 1950

Frame	Angle	Frame	Angle	Frame	Angle	Frame	Angle	Frame	Angle
0	0	50	4.72	109	9.1	158	9.4	207	11.4
1	0	51	4.22	110	9.1	159	9.9	208	11.5
2	0								
3	0	52	4	111	7.8	160	10.5	209	10.7
4	0	53	4.30	112	7.1	161	10	210	10.4
5	0	54	3.60	113	6.1	162	10.4	211	9.4
6	0	55	3.49	114	6.0	163	11.2	212	8.9
7	0	56	3.04	115	5.6	164	9.1	213	9.1
8	0	57	3.36	116	5.0	165	8.1	214	9.9
9	0	58	3.60	117	5.1	166	8.1	215	10.7
10	0	59	4.32	118	5.1	167	6.9	216	11.4
11	0	60	5.53	119	6.0	168	6.2	217	12.1
12	0	61	5.9	120	5.9	169	7.0	218	12.7
13	0	62	6.13	121	6.9	170	6.7	219	12.2
14	0	63	6.37	122	7.7	171	7.3	220	12.3
15	0.2	64	7.18	123	7.8	172	8.9	221	12.47
16	0.7	65	8.51	124	8.2	173	9.8	222	12.00
17	0.9	66	8.05	125	9.7	174	10.4	223	10.5
18	+1.0	67	8.59	126	9.6	175	10.7	224	8.54
19	2.05	68	8.07	127	9.6	176	10.9	225	9.00
20	2.05	69	6.84	128	9.0	177	11.0	226	8.97
21	4.12	70	5.83	129	8.5	178	10.4	227	8.84
22	4.15	71	5.9	130	7.3	179	10.9	228	9.48
23	4.0	72	5.14	131	7.4	180	10.4	229	10.18
24	5.0	73	4.46	132	6.3	181	10.0	230	11.5
25	5.36	74	3.67	133	5.8	182	8.6	231	12.1
26	4.17	75	3.0	134	5.7	183	8.7	232	12.0
27	3.16	76	3.60	135	6.0	184	7.6	233	11.29
28	2.6	77	4.72	136	5.8	185	9.1	234	11.05
29	2.235	78	5.93	137	6.0	186	8.7	235	8.54
30	2.32	79	6	138	7.1	187	9.1	236	8.04
31	1.49	80	6.7	139	8.0	188	10.5	237	8.4
32	1	81	7.78	140	8.0	189	10.7	238	9.33
33	1.14	82	8.53	141	8.8	190	12.1	239	9.49
34	1.80	83	8.00	142	9.8	191	12.0	240	7.61
35	9.87	84	7.99	143	10.3	192	11.1	241	9.8
36	3.165	85	7.2	144	10.0	193	11.7	242	10.2
37	3.83	86	7.03	145	9.5	194	11.0	243	11.94
38	4.0	87	6.09	146	9.1	195	10.7	244	10.79
39	4.12	88	6.0	147	8.7	196	10.0	245	10.68
40	4.29	89	4.5	148	7.8	197	9.8	246	9.02
41	4.85	100	3.2	149	7.3	198	9.7	247	10.24
42	5.52	101	2.92	150	6.3	199	9.1	248	9.55
43	5.8	102	3.9	151	5.0	200	9.8	249	9.19
44	6.41	103	5.1	152	5.2	201	9.95	250	8.52
45	7.09	104	6.1	153	5.4	202	11.2	251	9.45
46	7	105	6.7	154	6.1	203	11.2	252	8.96
47	6.19	106	6.7	155	7.6	204	12.5	253	10
48	5.64	107	8.1	156	8.3	205	12.7	254	11.3
49	5.7	108	8.7	157	9.1	206	12.2	255	12.6

TABLE 1 (cont.)

Frame	Angle	Frame	Angle	Frame	Angle	Frame	Angle	Frame	Angle
256	12.38	307	9.5	358	11.33	409	21.18	460	20.55
257	11.4	308	10.79	359	7.0	410	21.14	461	18.1
258	11.31	309	12.29	360	5	411	20.45	462	16
259	9.22	310	11.88	361	6.70	412	16.07	463	14.4
260	8.74	311	11.13	362	9.25	413	13	464	10.19
261	7.63	312	11.03	363	11.13	414	9.82	465	10.13
262	7.00	313	8.56	364	13.3	415	7.0	466	9.52
263	8.13	314	8.06	365	15.48	416	5.81	467	8.97
264	8.24	315	5.39	366	15.18	417	5.1	468	8.25
265	10	316	7.1	367	14.65	418	6	469	7.43
266	11.33	317	9.48	368	12.95	419	7.03	470	4.66
267	11.23	318	11.4	369	11.85	420	7.58	471	2.83
268	10.5	319	13.85	370	10.05	421	9.15	472	2.83
269	10.48	320	13.79	371	8.0	422	10.43	473	4.93
270	9.8	321	13.1	372	5.02	423	13.35	474	7.96
271	8.5	322	11.29	373	5.45	424	17.65	475	10.0
272	7.15	323	7.3	374	8.54	425	20.8	476	10.37
273	8.25	324	5.0	375	11.79	426	21.0	477	10.53
274	8.05	325	6.33	376	16.1	427	22.4	478	10.33
275	8.72	326	8.72	377	17.42	428	22.58	479	11.32
276	10	327	12.02	378	19.6	429	21.3	480	12.95
277	12.1	328	14.9	379	19.6	430	20.75	481	15.48
278	11.58	329	14.48	380	16.3	431	19.4	482	17.7
279	11.0	330	13.02	381	13.17	432	18.6	483	20.28
280	11.1	331	11.59	382	9.35	433	19.53	484	21.0
281	9.95	332	7.09	383	4.18	434	16.72	485	22.13
282	8.5	333	4.24	384	3.21	435	15.5	486	21.32
283	7.42	334	5.5	385	5.81	436	13.2	487	20.72
284	7.28	335	10.8	386	8.36	437	9.8	488	20.9
285	8.04	336	14.6	387	10.33	438	7.75	489	21.47
286	9.0	337	16.62	388	12.05	439	3.16	490	22.55
287	10.2	338	17	389	13.65	440	3.35	491	23.88
288	11.72	339	14.9	390	15.03	441	4.24	492	24.9
289	11.48	340	12	391	16.98	442	7.06	493	25
290	10.5	341	7.5	392	19.38	443	7.63	494	23.8
291	11.23	342	3.04	393	20.4	444	8.13	495	22.88
292	8.91	343	5.5	394	18.65	445	8.93	496	19.88
293	8.05	344	10.58	395	17	446	9.99	497	20.25
294	7.2	345	15.25	396	13.4	447	12.53	498	18.87
295	7.15	346	17.65	397	9.06	448	16	499	18.12
296	8.56	347	17.77	398	5.38	449	18.88	500	19.57
297	10.05	348	16.70	399	1.41	450	20.52	501	19.4
298	11.48	349	13.17	400	5.1	451	21.3	502	19
299	12.49	350	7.78	401	8.25	452	20.3	503	16.45
300	11.28	351	2.24	402	10.75	453	20.75	504	14.05
301	10.73	352	5.66	403	12.94	454	19.46	505	11.68
302	9.66	353	11.0	404	13.3	455	20	506	9.84
303	9.03	354	16.5	405	15.48	456	20.1	507	8.91
304	7.25	355	17.8	406	18	457	21.05	508	8.24
305	7.29	356	17.55	407	17.4	458	21.77	509	6.76
306	9.17	357	15.11	408	20.15	459	21.24	510	8.54

TABLE 1 (cont.)

Frame	Angle	Frame	Angle	Frame	Angle	Frame	Angle	Frame	Angle
511	7.28	562	24	612	21.68	663	34.35	714	25.6
512	5.00	563	22.5	613	21.15	664	35.85	715	25.0
513	3.16	564	19.8	614	20.81	665	37.55	716	24.73
514	1.5	565	18.6	615	21	666	37.6	717	27
515	3	566	16.25	616	20.2	667	35.3	718	27.28
516	4.61	567	14.96	617	21.5	668	35.1	719	28.35
517	7	568	16.07	618	24	669	32.2	720	26.5
518	8.04	569	16.69	619	26	670	35	721	24.3
519	7.3	570	15.62	620	28.55	671	29.1	722	23.6
520	7.62	571	16	621	26.95	672	34.3	723	22.0
521	8.25	572	13.89	622	25.35	673	35.85	724	21.2
522	9.38	573	11.87	623	25.39	674	37.15	725	22.25
523	11.18	574	9.47	624	24.3	675	36.63	726	23.05
524	13.52	575	7.6	625	25	676	35.3	727	24.0
525	15.18	576	5.8	626	24.68	677	34.1	728	24.6
526	17.28	577	7.75	627	28.08	678	33.05	729	21.68
527	16.7	578	7.16	628	29.35	679	35	730	21.17
528	17.03	579	7.6	629	31	680	33.3	731	18.58
529	16.48	580	7	630	31	681	34.3	732	18.6
530	18.24	581	5	631	28.7	682	35.05	733	18.4
531	18.62	582	3.16	632	28.37	683	36.65	734	17.5
532	20.5	583	1	633	27.42	684	35.55	735	20.05
533	22.9	584	1	634	29	685	33.25	736	21.4
534	24.1	585	1.8	635	27.32	686	33.1	737	20.73
535	25.13	586	3	636	30.1	687	31.65	738	19.52
536	24.75	587	3.61	637	32.8	688	33	739	18.11
537	24.08	588	3	638	32.3	689	30.6	740	16.26
538	22.85	589	2.06	639	31.85	690	32.3	741	14.83
539	23.75		3.17	640	31.35	691	34.3	742	15.12
540	23.3	590	5.38	641	30.65	692	34.3	743	14.07
541	25.58	591	7.1	642	29.8	693	32.85	744	17
542	27.42	592	9.65	643	30/30	694	32.07	745	16.05
543	29.1	593	10	644	31.9	695	31.1	746	16.48
544	30	594	11.33	645	32.3	696	27.55	747	16.08
545	28.15	595	10.28	646	34.3	697	30	748	14.7
546	27.5	596	10.2	647	34.6	698	29.8	749	13.03
547	26.2	597	10.25	648	33.8	699	31.1	750	11.93
548	25.0	598	10.42	649	33.07	700	31.6	751	11.0
549	24.5	599	11.12	650	33.1	701	30.95	752	10.93
550	26.6	600	14.15	651	31.7	702	30.9	753	12
551	27.1	601	15.45	652	32	703	29.1	754	13.65
552	29.12	602	17.1	653	26.7	704	28.32	755	12.6
553	30	603	17.07	654	33.3	705	27.4	756	12.6
554	26.35	604	16.85	655	35.1	706	29	757	11.32
555	26.8	605	16.7	656	33	707	27.24	758	10.5
556	23.3	606	16.18	657	34.75	708	30.1	759	8.98
557	22.23	607	17.35	658	33.35	709	30.1	760	9.07
558	21.3	608	17.8	659	34.55	710	31.15	761	8.16
559	23.8	609	21	660	33	711	29.05	762	9.06
560	24.5	610	22.75	661	34	712	27.49	763	10.23
561	24.32	611	22.0	662	33.25	713	26.4	764	11.12

TABLE 1 (cont.)

Frame	Angle	Frame	Angle	Frame	Angle	Frame	Angle	Frame	Angle
765	10	816	21.5	877	40.8	919	61.6	970	69.0
766	9.94	817	22.03	878	40.55	920	56.3	971	78
767	8.54	818	23.78	879	43.65	921	60.7	972	79
768	7.76	819	26.0	880	41.4	922	58.6	973	70.68
769	6.38	820	27.1	881	46.15	923	60	974	74.25
770	6.32	821	25.8	882	44.6	924	57.45	975	71.7
771	6.7	822	25.0	883	48	925	63.0	976	76
772	8.1	823	23.8	884	45.4	926	64.68	977	72.6
773	9.85	824	23.45	885	45.5	927	66.0	978	73.3
774	10.42	825	24.1	886	43.15	928	67.9	979	72.4
775	10.3	826	25.39	887	43.0	929	60.5	980	80
776	9.85	827	27.65	888	46.0	930	59.55	981	82
777	8.53	828	29.38	889	46.2	931	60.95	982	73.6
778	7.34	829	30	890	48.9	932	65.0	983	74.6
779	7.27	830	25.05	891	47.7	933	58.7	984	70.7
780	6.37	831	28.62	892	50	934	66.05	985	80
781	8.25	832	28.3	893	47	935	62.9	986	75.4
782	9.83	833	29.88	894	48.6	936	68	987	77.15
783	11.58	834	29.5	895	46.6	937	65.9	988	75.14
784	12	835	29.78	896	47.5	938	63.35	989	84
785	11.6	836	32.5	897	48.6	939	59.35	990	83
786	10.72	837	33.6	898	48.2	940	72.13	991	75.85
787	9.95	838	32.0	899	52.05	941	69.15	992	75.15
788	9.38	839	32.4	900	50.7	942	61.5	993	80.09
789	10.0	840	32.05	901	54	943	68.3	994	82
790	10.22	841	30.65	902	48.7	944	67.1	995	77.32
791	12.15	842	31.4	903	52.7	945	72	996	80.04
792	14.0	843	32.4	904	48	946	66.35	997	80.02
793	15.2	844	32.8	905	52	947	66.2	998	88
794	14.45	845	35.2	906	50.1	948	61.1	999	86
795	13.8	846	36.6	907	51.8	949	70	1000	79.35
796	13.31	847	36.55	908	53.2	950	67.4	1001	78.78
797	12.7	848	35.8	909	56.0	951	65.2	1002	82
798	12.65	849	36.1	901	57	952	68.3	1003	85
799	14.09	850	35.25	902	50.75	953	70.5	1004	82.1
800	17.05	851	38	903	56	954	74	1005	82.04
801	17.4	852	35.65	904	50.6	955	67.4	1006	85.12
802	18.4	853	38.2	905	57	956	70.55	1007	90°
803	19.55	854	38.9	906	53.2	957	65.4	1008	90°
804	18.1	855	42.15	907	55.95	958	72	1009	84.2
805	17.4	856	41.0	908	55.35	959	70.35	1010	82.33
806	16.42	857	37.8	909	59.0	960	67.1	1011	86
807	17.28	858	38.5	910	60.2	961	69.55	1012	89
808	17.78	859	42.6	911	53.8	962	73.2	1013	88
809	20.05	870	41	912	58.1	963	77	1014	83.02
810	22.05	871	39.25	913	59.8	964	69.4	1015	90°
811	22.35	872	41.5	914	58	965	73.05	1016	88
812	21.67	873	41.8	915	58.3	966	68.6	1017	89
813	21.23	874	45.35	916	59.25	967	75	1018	90
814	21.0	875	42.2	917	56.2	968	71.5	1019	85.03
815	20.08	876	41.6	918	62.2	969	69.8	1020	90

TABLE 1 (cont.)

Frame	Angle	Frame	Angle	Frame	Angle	Frame	Angle	Frame	Angle
1021	89	1072	73.58	1123	52.7	1174	46.0	1225	53.1
1022	89	1073	79.1	1124	58	1175	47.2	1226	55.6
1023	89	1074	81	1125	53.4	1176	48.0	1227	51.6
1024	85.17	1075	73.98	1126	60.2	1177	48.4	1228	57.0
1025	82.49	1076	73.02	1127	57.2	1178	48.6	1229	54.1
1026	89	1077	68.78	1128	54.6	1179	45.9	1230	60.4
1027	89	1078	75.00	1129	52.6	1180	48.0	1231	56.2
1028	90	1079	71.48	1130	53.2	1181	43.4	1232	56.7
1029	90	1080	82.05	1131	53.4	1182	46.5	1233	51.8
1030	89	1081	66.40	1132	49.4	1183	45.8	1234	58.4
1031	90	1082	75.09	1133	51.6	1184	49.0	1235	57.2
1032	90	1083	75.96	1134	51.8	1185	43.7	1236	56.3
1033	90	1084	67.3	1135	57.0	1186	57.6	1237	58.7
1034	90°	1085	70.4	1136	51.8	1187	55.7	1238	61.1
1035	85.53	1086	67.9	1137	52.7	1188	46.3	1239	61.9
1036	90	1087	71.0	1138	49.6	1189	46.8	1240	57.7
1037	90	1088	62.9	1139	52.6	1190	45.8	1241	61.0
1038	89	1089	70.03	1140	51.5	1191	48.4	1242	55.5
1039	87.03	1090	64.3	1141	48.9	1192	45.3	1243	60.1
1040	88.02	1091	73.95	1142	52.0	1193	50.2	1244	58.1
1041	87	1092	69.45	1143	51.8	1194	47.6	1245	61.5
1042	90°	1093	63.85	1144	54.3	1195	50.0	1246	59.8
1043	87	1094	62.05	1145	50.1	1196	47.8	1247	65.4
1044	83.7	1095	67.3	1146	51.0	1197	49.0	1248	66.3
1045	83.72	1096	67.15	1147	45.3	1198	46.3	1249	58.4
1046	89	1097	60.2	1148	50.2	1199	48.3	1250	62.6
1047	89	1098	67.3	1149	47.2	1200	48.6	1251	56.2
1048	86	1099	82.4	1150	50.4	1201	48.7	1252	65.3
1049	82.07	1100		1151	48.0	1202	50.4	1253	60.3
1050	81.32	1101	63.4	1152	49.8	1203	45.2	1254	66.0
1051	84.0	1102	69.2	1153	50.9	1204	53.2	1255	61.3
1052	85.0	1103	56.7	1154	48.3	1205	49.0	1256	69.4
1053	79.65	1104	62.9	1155	48.0	1206	51	1257	58.8
1054	82.53	1105	79.4	1156	45.7	1207	45.4	1258	62.1
1055	84	1106	58.2	1157	45.1	1208	50.2	1259	62.6
1056	85	1107	59.5	1158	44.7	1209	48.1	1260	67.0
1057	84	1108	61.4	1159	51.0	1210	52.4	1261	67.3
1058	78.3	1109	65.2	1160	47.4	1211	50.0	1262	62.1
1059	75.03	1110	57.7	1161	50.1	1212	54.8	1263	69.1
1060	83	1111	68.1	1162	45.0	1213	54.8	1264	66.5
1061	81	1112	55.9	1163	46.9	1214	49.7	1265	73.3
1062	73.25	1113	76.0	1164	46.0	1215	52.4	1266	69.8
1063	79.28	1114	55.0	1165	47.0	1216	50.2	1267	66.0
1064	80.1	1115	72.4	1166	48.0	1217	52.7	1268	62.6
1065	82	1116	55.6	1167	45.5	1218	47.0	1269	73.1
1066	77.32	1117	60.3	1168	48.8	1219	55.0	1270	71.3
1067	78.03	1118	60.6	1169	47.3	1220	50.4	1271	65.9
1068	69.47	1119	50.1	1170	49.7	1221	58.2	1272	70.9
1069	78	1120	56.6	1171	46.3	1222	54.7	1273	74.2
1070	77.1	1121	54.6	1172	43.2	1223	53.4	1274	77.0
1071	69.57	1122	61.2	1173	47.2	1224	52.4	1275	71.3

TABLE 1 (cont.)

Frame	Angle	Frame	Angle	Frame	Angle	Frame	Angle	Frame	Angle
1276	73	1289	74.7	1302	83.2	1315		1328	
1277	69.3	1290	73.3	1303	81.1	1316		1329	
1278	75.2	1291	84.0	1304	85.4	1317	85.1	1330	
1279	72.2	1292	84.0	1305	86.6	1318		1331	87.0
1280	68.9	1293	77.1	1306	85.0	1319		1332	82.7
1281	68.6	1294	79.2	1307	68.0	1320		1333	89.0
1282	79.0	1295	80.1	1308	89.4	1321		1334	
1283	80.0	1296	84.2	1309		1322	49.0	1335	88.1
1284	73.1	1297	84.0	1310		1323		1336	83.0
1285	76.1	1298	78.3	1311		1324		1337	70.5
1286	73.6	1299	80.5	1312		1325		1338	
1287	78.2	1300	79.2	1313		1326	51.9	1339	
1288	77.2	1301		1314		1327	70.7	1340	84.2

4. SUMMARY OF ACCESSORY EQUIPMENT

As noted previously, many accessory devices are necessary in the instrumentation in addition to the basic measuring instruments.

(1) Telemeter input-voltage limiters are used to prevent the application of any voltage that lies outside the limits of 0 to +5 volts d-c to the telemeter.

(2) Panel meters are provided to present certain data, some of which are also recorded by telemetering, to the gyro camera. Some cross checking of data-recording accuracies is thus possible.

(3) An acceleration switch is used to indicate missile take-off, end of boost phase, and end of sustaining-motor phase. The switch trips when the acceleration exceeds 2-3 g's, closing the circuit to a small light which is viewed by the gyro camera.

(4) Two clocks, one normal spring-wound and the other motor-driven, are included to establish a time base for the camera film.

(5) Thermistors are included in some instances for the determination of various temperatures, chiefly alphatron-chamber temperature.

(6) Mercury cell battery packs are utilized to provide constant, known voltages for in-flight telemeter calibration.

(7) A vibrator-type inventor serves to provide a source of 110v 400w voltage for gyroscope operation. Its input and output are filtered.

(8) Rotary solenois selector switches are utilized for all switching operations, including disconnection of pull-off control leads immediately preceding missile take-off.

(9) Binary coded neon light systems are used to present alphatron-system range information tothe camera.

5. AIR DENSITY MEASUREMENT BY UHF GAS-DISCHARGE BREAKDOWN

During the course of the contract, an investigation was initiated into the feasibility of determining ambient air density by means of a measurement of the RF field strength necessary to cause a gas-discharge breakdown of the air at a point several inches in front of the nose of an Aerobee missile.

Laboratory experiments were conducted which resulted in causing the desired breakdown in an evacuated chamber.

Although it appeared to project personnel that such an experiment was feasible and that useful results could be obtained, contract support for the work was withdrawn. The work was therefore not continued under this contract.

6. SUMMARY BY ROCKET FLIGHT

This section will summarize the work under the contract by reference to the rocket flights in which the research group participated.

6.1. V-2 No. 47, June 1949

A single thermionic ionization gage with newly developed circuitry was utilized in this experiment. The primary purpose of the instrumentation was to provide a field test of techniques that were to be used in later Aerobee flights. The experiment was considered successful and the equipment was recovered intact.

No pressure or temperature data were anticipated nor obtained from this test.

A photograph of the recovered equipment is included in this report as Fig. 5.

6.2. Aerobee USAF-3, December 1949

The following basic equipment was installed for this flight:

(1) Four thermionic ionization gages, each provided with independent automatic control of filament emission to permit reliable and stable operation (10^{-2} mm Hg to approximately 10^{-6} mm Hg).

(2) Two alphatron-type ionization gages each supplied with an automatic range-seeking circuit for presenting an appropriate voltage to the telemeter in accord with the particular pressure being measured at any given instant. These gages were intended to measure the pressure from the ground level to approximately 10^{-3} mm Hg, slightly overlapping the thermionic gages.

(3) A Sperry attitude gyro to provide information regarding the aspect of the rocket during the useful portion of its flight.

Certain difficulties in the missile fuel-control system caused a loss of power a few seconds subsequent to launching. This resulted in excessive missile yaw, causing ejection of the nosepiece and instrumentation, which fell to the ground and was demolished. The experiment was, of course, unsuccessful.

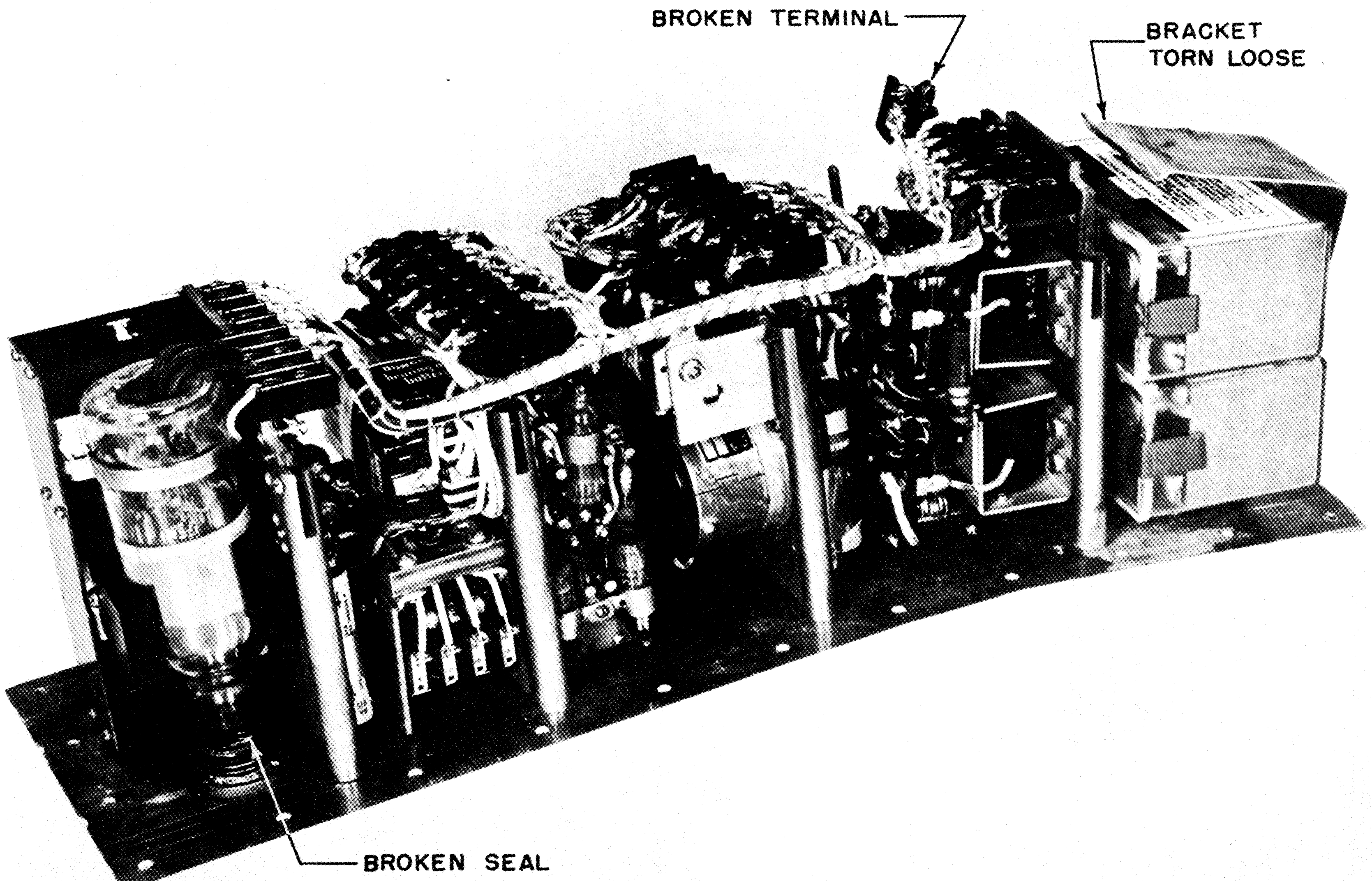

Fig. 5. Photograph of Equipment Recovered from V-2 No. 47.

6.3. Aerobee USAF 6, June 1950

The purpose of this flight was to provide a test of missile control functions, and at the same time obtain upper-atmosphere data. Therefore, a portion of the instrumentation (not supplied by this project) was to be used to monitor the operation of the normal equipment carried by the Aerobee, including beacon, cut-off system, ejection system, and related equipment. The balance of the instrumentation, for which this project was responsible, was to be used for upper-atmosphere experiments. It was decided to include two alphatron ionization gages and the aspect determination system using the Sperry attitude gyro.

The alphatron gages were mounted so that one would measure ram pressure and the other cone wall pressure, an arrangement suitable for ambient-temperature calculation.

The forward portion of the warhead was to be used for the upper-air experiments, so it was decided that the special magnesium nose section this project had constructed for previous warheads would be employed.

Accordingly, two alphatrons and their associated circuits were installed in the magnesium cone section (see photographs in Figs. 6 and 7). The circuits used were very similar to those used in the past, with some modifications. For example, the range-switching circuit was slightly altered for more stable operation and also for the incorporation of a time delay. It was felt that due to the spinning of the missile, the instantaneous pressure in the cone-wall alphatron could vary sufficiently to cause the system to change range in the roll period, under conditions of high yaw. Such a variation and consequent rapid switching would render the data useless. A time delay of approximately two seconds was therefore introduced to delay switching.

The aspect determination equipment consisted of a Sperry attitude gyro, type F4A, and a project-modified gun camera used for photographing the gyro sphere.

In addition to the gyroscope, the camera photographed four panel meters and a clock. Two of these meters were Simpson 2-inch square 0-1-ma meters, and the other two were Marion "ruggedized" 0-1-ma meters. See Fig. 8.

One Marion and one Simpson were connected in parallel and indicated the range position of the ram alphatron. These data were transmitted by telemetering as well, the object of the parallel connection being to give some indication of the operation of each meter as compared to telemetering, and also some information relative to the general usefulness of the camera - panel-meter system of data recording.

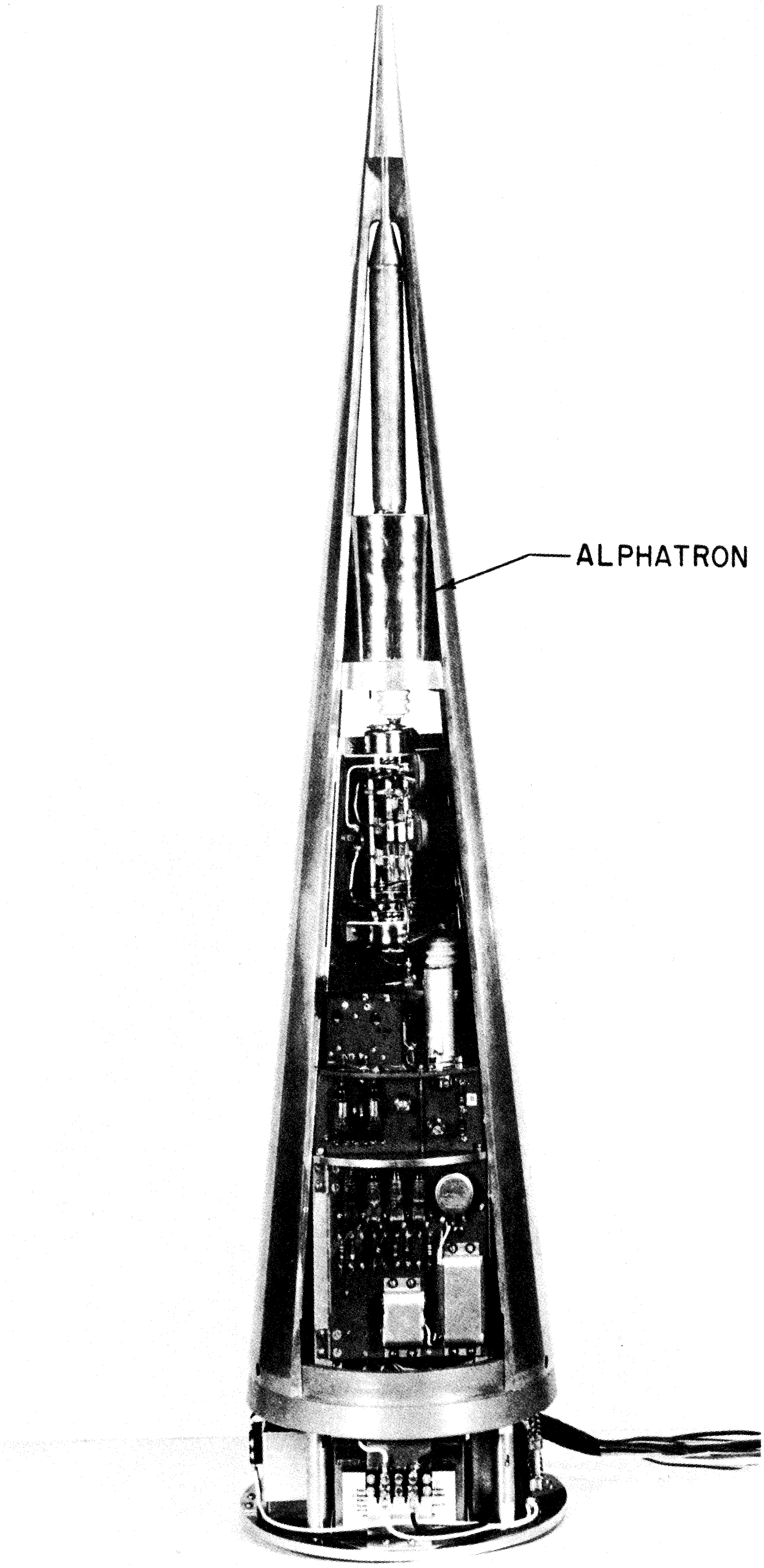

Fig. 6. View of Alphatron Instrumentation, June 1950.

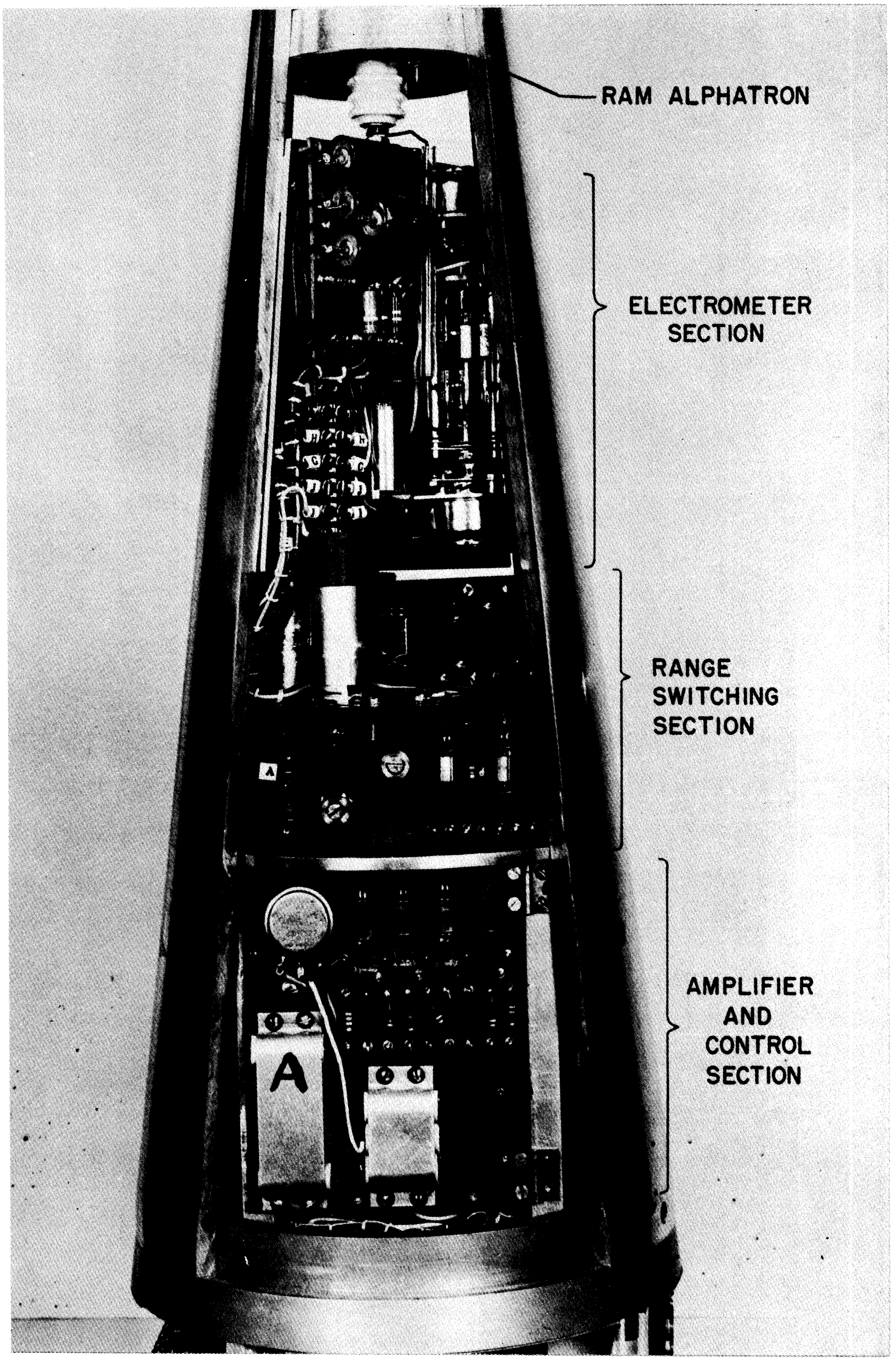

Fig. 7. View of Alphatron Instrumentation, June 1950.

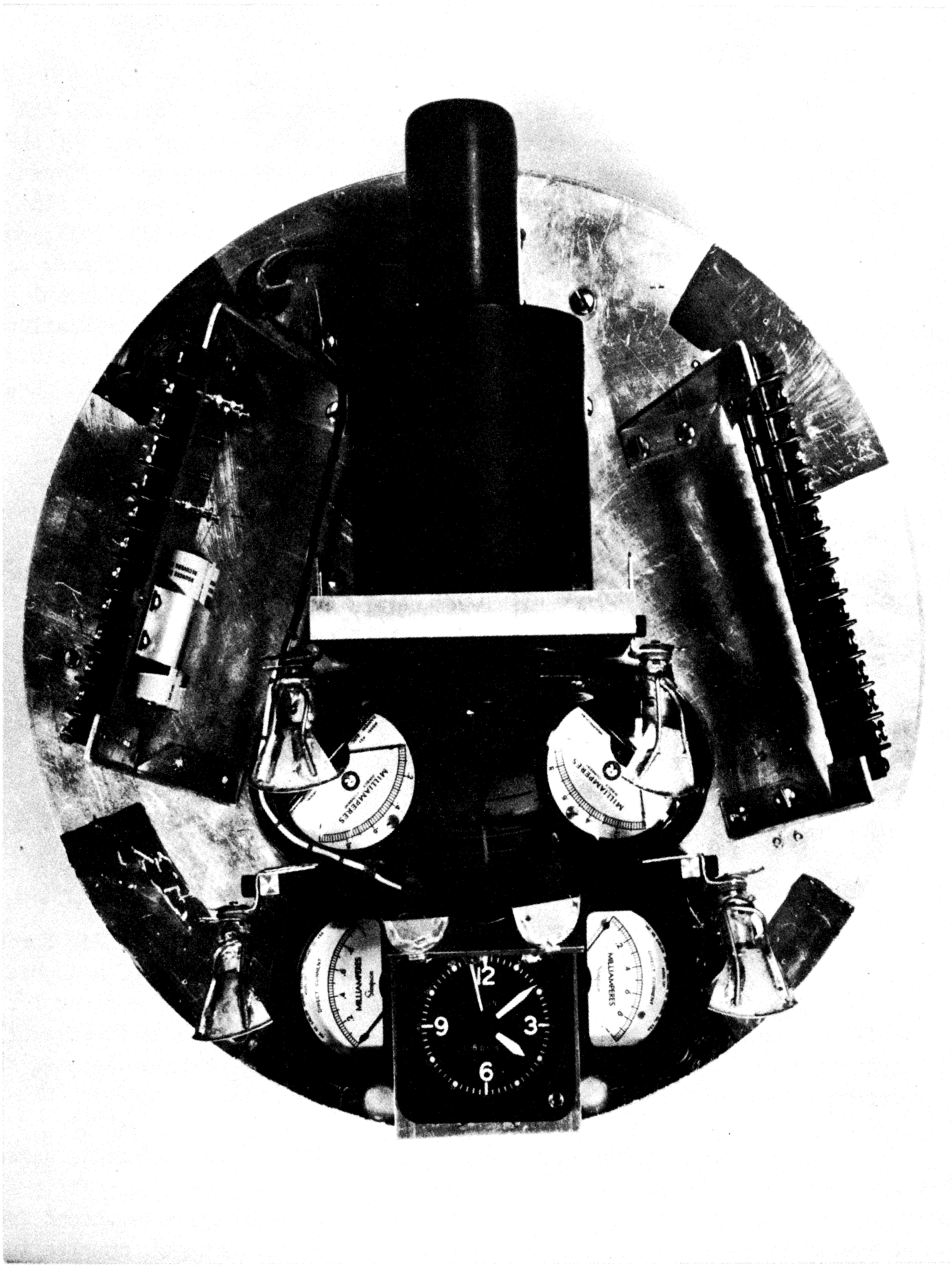

Fig. 8. Gyro and Meter Panel as Viewed by Camera, June 1950.

The third panel meter recorded the output of the ram pressure unit, which data were likewise displayed by telemeter.

The missile was fired at approximately 0840, Tuesday, June 20, and was very successful. Maximum altitude was fifty-seven miles, and most of the instrumentation was recovered intact. This project's equipment operated satisfactorily from take-off until warhead separation at about 160 seconds (the peak of the trajectory), at which time both alphatron units failed. This, however, is approximately the time (zenith) at which the pressure data ceases to be useful, and so it is not considered that there was any loss of information. The shock of warhead blowoff was apparently very severe and caused the failure, the nature of which was not apparent from the recovered equipment. Unfortunately, the telemeter commutator also stopped at warhead blowoff, so that certain operational information that was presented to the telemeter was not available for analysis.

The gyro, camera, clock, and panel meters were undamaged by the nose-cone blowoff and operated satisfactorily throughout the flight. All the film was used, resulting in a full ten minutes of gyro and meter information. The film supply was exhausted about one minute before impact.

Upper-atmosphere pressure and temperature data resulting from this flight are tabulated in Table 2 and plotted in Figs. 9 and 10. It should be noted that the computation of many additional points is possible from the recorded data. In general, however, due to the magnitude of the computation, intervals of 1-2 km, are chosen, as this defines the curve adequately.

6.4. Aerobee USAF 10, December 1950

In the early stages of this project's participation in the Air Force Aerobee program, two nearly identical warheads were instrumented for a double firing scheduled in December 1949, one for a daytime firing and the other for a nighttime firing. The first of the two firings was unsuccessful because of a flight failure (USAF 3 as noted previously). The second warhead was used for the December 1950 firing.

The instrumentation consisted of two alphatron-type ionization gages for cone-wall pressure measurement from ground level to approximately fifty miles; four thermionic ionization gages for cone-wall pressure measurement from about twenty miles to rocket ceiling; a single thermionic ion gage mounted in the forward portion of the tank section of the missile for measuring the surface pressure at this point; an attitude gyro, Sperry type F4A, with camera for zenith-angle determination throughout the flight; and a single phototube mounted in the rocket skin to assist in determining roll position of the missile.

TABLE 2

UPPER ATMOSPHERE DATA FOR JUNE 20, 1950

Measured Alt. km	Measured Pressure mb	$\log_{10} P_m$ dynes/cm^2	Derived* Temp. °K	$\log_{10} P_d$ dynes/cm^2	$\log_{10} P_m - \log_{10} P_d$
30	12.5	4.095	234	4.095	0.00
32	9.33	3.969	235	3.970	-0.001
34	7.01	3.846	238	3.847	-0.001
36	5.36	3.730	250	3.730	0.00
38	4.13	3.616	260	3.617	-0.001
40	3.21	3.507	265	3.507	0.00
42	2.49	3.397	265	3.397	0.00
44	1.94	3.288	268	3.288	0.00
46	1.51	3.178	268	3.179	-0.001
48	1.18	3.070	268	3.070	0.00
50	0.914	2.961	267	2.961	0.00
52	0.709	2.850	265	2.851	0.001
54	0.548	2.739	261	2.739	0.00
56	0.421	2.625	256	2.625	0.00
58	0.321	2.507	249	2.508	-0.001
60	0.242	2.386	241	2.387	-0.001
62	0.182	2.262	231	2.261	0.001
64	0.133	2.123	218	2.128	-0.005
66	0.0964	1.983	202	1.984	-0.001
68	0.0681	1.834	194	1.834	0.00
70	0.0479	1.681	189	1.681	0.00
72	0.0336	1.526	187	1.526	0.00

*The measured temperature values are utilized in an integrating computation employing the hydrostatic equation to obtain the "derived" pressure values. The derived pressure values may then be compared with the actual measured values. This procedure allows an overall check of the data analysis. The derived pressures compare very favorably with the measured values as shown by the last column of figures.

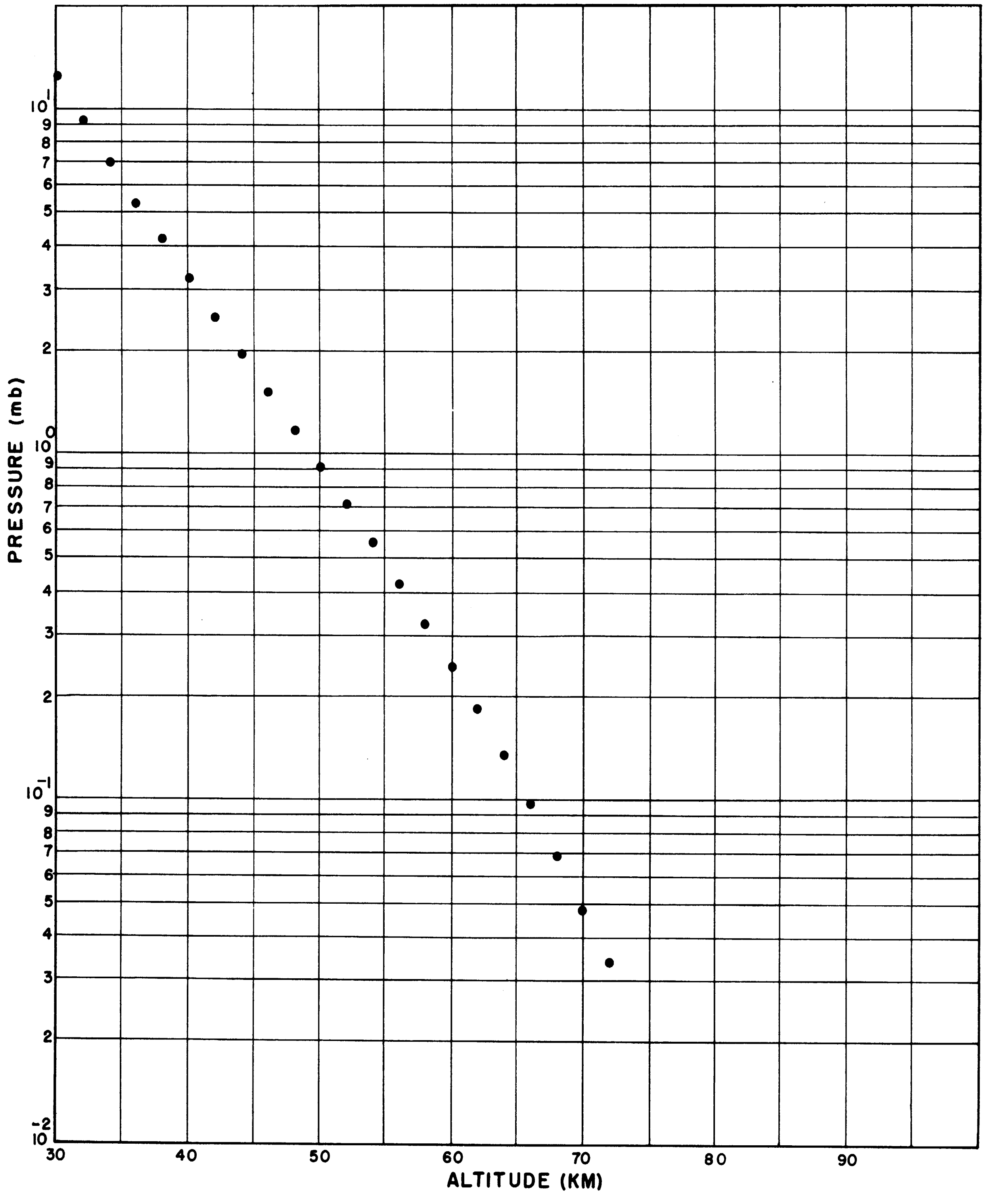

Fig. 9. Curve of Ambient Pressure Vs. Altitude, June 1950.

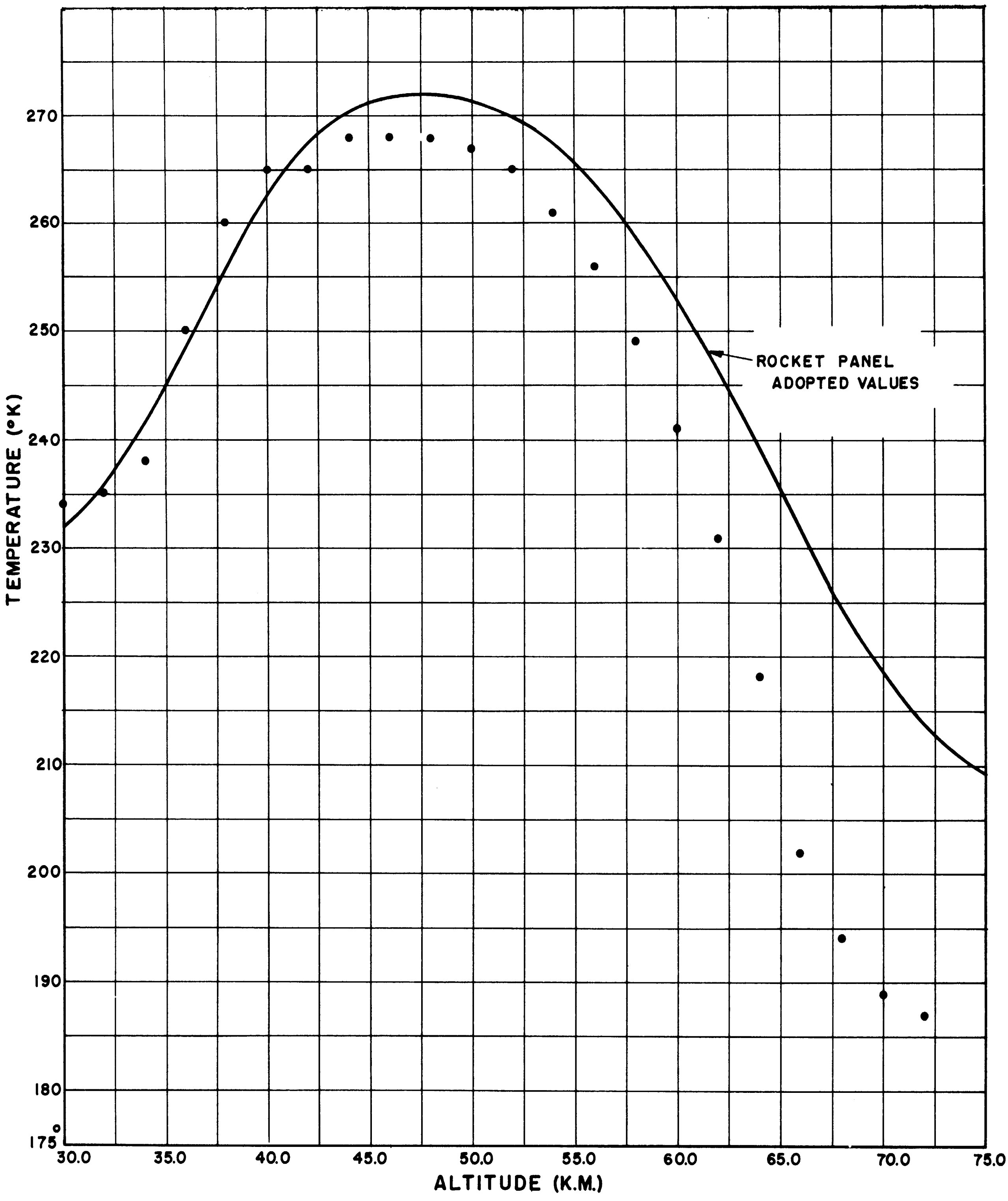

Fig. 10. Curve of Ambient Temperature Vs. Altitude, June 1950.

The alphatron system used was similar to previous installations except that the range-changing circuit was modified to include a switching time delay as noted previously. The purpose of this delay was to prevent a range change when the output momentarily goes off-scale, as might be the case with a large angle of attack. Under a condition of large angle of attack one can expect that the instantaneous pressure at the gage port may change by as much as a factor of ten or twenty as the missile rolls, with consequent amplifier output swing. Without the time delay, the system would be forced to switch to another range momentarily and then return to the original range. This switching sequence is unnecessary and undesirable, for the useful data exist in the normal range. Hence the time delay system was incorporated.

A portion of the ionization gage system employed four thermionic ion gages, mounted for cone-wall pressure measurement similar to the alphatrons. Each gage with its associated circuit was independent of the other gages, so that a possible failure in one would not result in failure of all. The emission current of each gage was controlled by a special servo unit detailed in early progress reports. A voltage indication of the grid and plate current of each gage was presented to the telemeter, as was the output and range indication of each alphatron unit.

In addition to photographing the gyro, the camera photographed six panel meters, a light actuated by an acceleration switch, two neon lights, and a clock.

The output and range of one alphatron unit and the grid and plate currents of two of the ionization gages were applied to the six panel meters as well as to the telemeter as an alternate means of recording the data.

This flight outwardly was very successful. The instrumentation apparently operated properly as intended. However, the gyro information indicated very large angles of attack and this was verified by the pressure data, which exhibited very large variations about the expected mean. These variations were great enough (factor of 10-20) to preclude a normal data-reduction procedure. Accordingly the reduction of data from this firing was postponed to a later date.

As of the time of writing of this report, the work has not been resumed, due to pressure of other data reduction from later firings.

Photographs of the instrumentation of this flight are included as Figs. 11 and 12 of this report.

The only item recovered from this flight was the missile camera film.

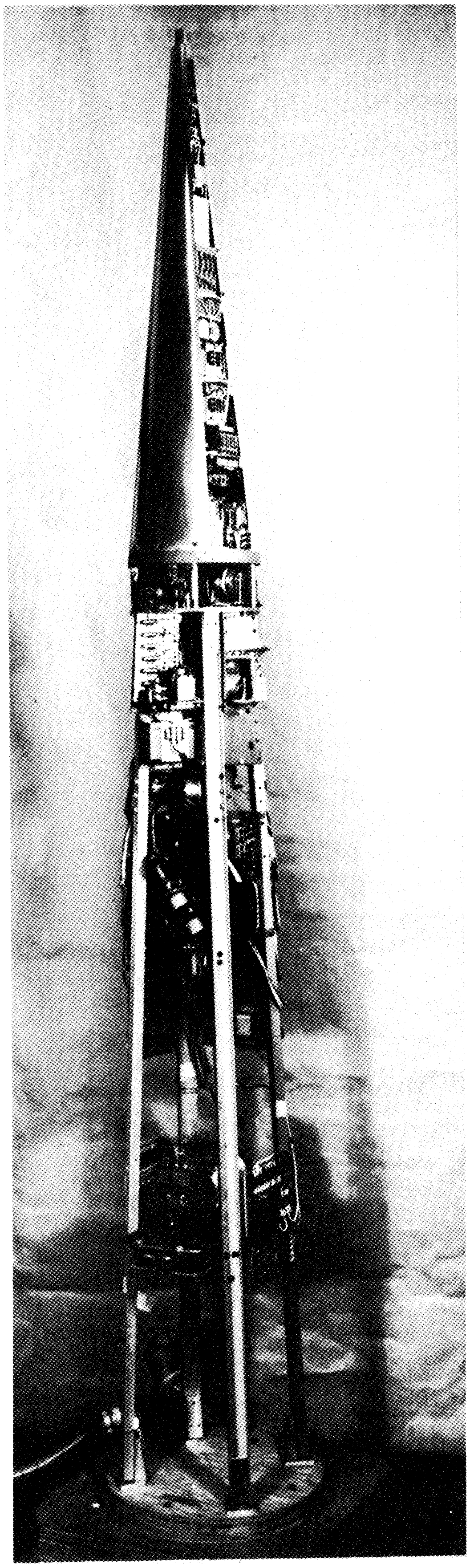

Fig. 11. Overall View of Instrumentation, December 1950.

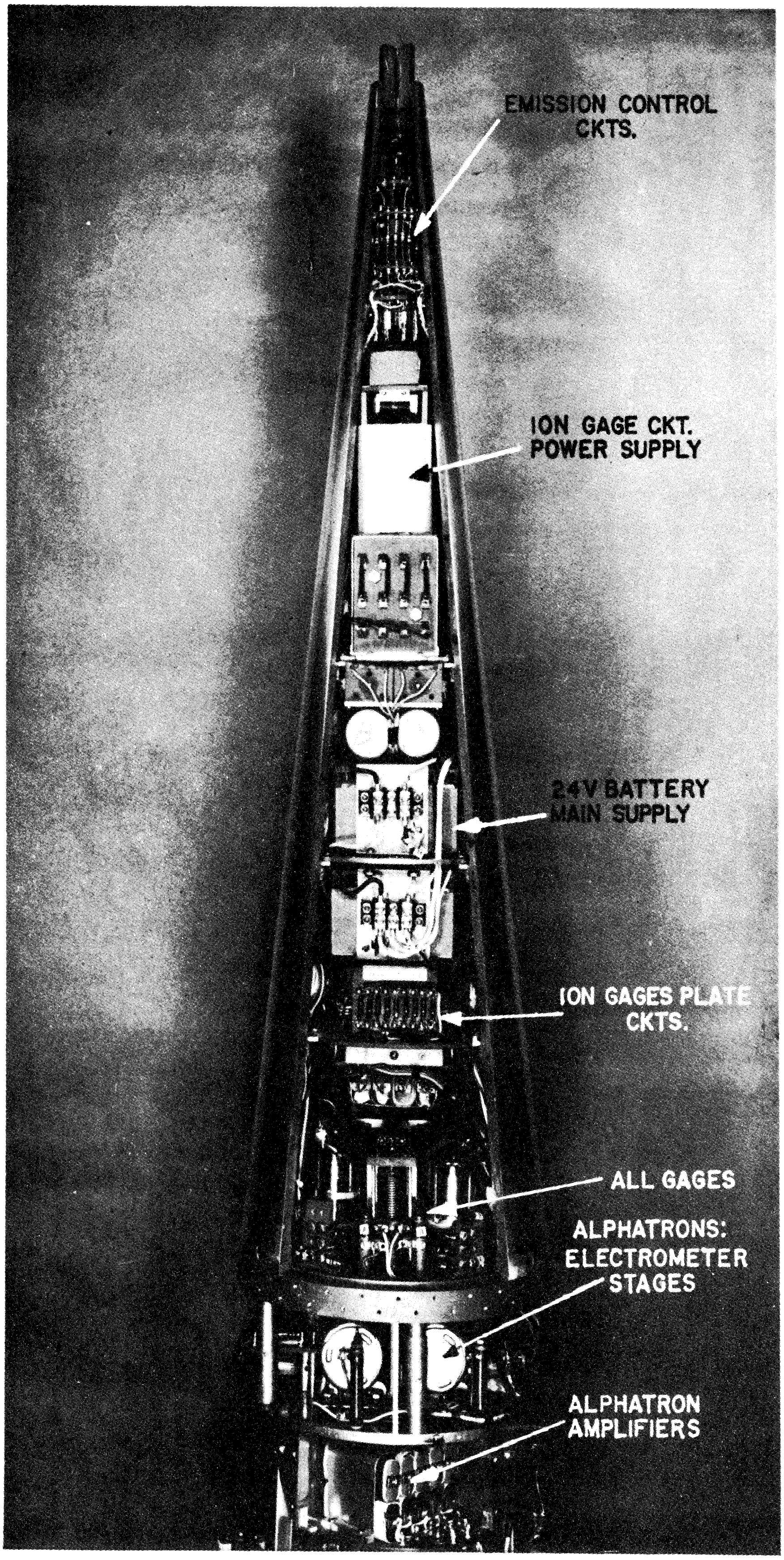

Fig. 12. Portion of Instrumentation, December 1950.

6.5. USAF 18, September 1951

Aerobee USAF 18 was instrumented as follows:

1. Three alphatron ionization gages for pressure measurement, two mounted for indication of cone-wall pressure, and the third mounted for impact (ram-pressure) measurement.

2. A special controlled air gap, as a portion of the nose cone, for measurement of breakdown potential. This measurement allows computation of air density.

3. A gyroscope for measurement of zenith angle of the missile, from which it is possible to compute the angle of attack of the missile with the air stream.

4. A type B-2 aircraft 16-mm motion-picture camera for recording gyro data.

5. Four panel meters photographed by the camera for additional data recording.

6. An acceleration switch used to indicate time of take-off, end of boost, and end of burning of the missile-sustaining motor.

7. Equipment comprised of two fine wires mounted in the air stream off the surface of the nose cone, to obtain data leading to information regarding stream velocity profile in the boundary layer.

6.5.1. Alphatron System. A newly designed alphatron gage was utilized in the equipment for this test, and other modifications to previous alphatron systems were effected. Since these changes represent advances in the technique of alphatron use, some discussion of them is included in this report.

The modifications effected included, in addition to the new gage unit, an increase in the number of subranges from five to seven, a redesign of the "zeroing" system to allow recording of the zero reading during flight, and slight changes in the switching circuit in regard to time delays.

In previous systems used by the project in Aerobee firings, the amplifier zero reading was obtained (and correction made) only immediately prior to flight by simulating a known value of pressure (in this case, zero pressure) and recording the corresponding value of output signal. To accomplish this, it was necessary to disconnect the range-switching circuit (which inserts an appropriate value of alphatron load resistance consistent with the pressure being measured) from the amplifier and connect it to the circuit ground reference. This operation caused the switching circuit to insert the lowest resistance, zero ohms, which simulated zero pressure.

The time involved merely to observe the zero reading was so long (of the order of ten seconds) that the possibility of recording the zero reading during flight was precluded. The system was altered, therefore, to allow observance during flight, the time required being reduced to approximately one second. A small auxiliary relay was installed so that when it was energized, a d-c voltage was impressed across the alphatron load resistance. The amplifier then sees a voltage as if some unique value of pressure were impressed upon the gage, and responds accordingly. The voltage used is of such magnitude that the amplifier output indicates approximately at midscale of the normal 0-5-volt range, this indication then being considered as the zero reading of the system. Note that the zero reading may be obtained regardless of the value of input resistance that may be in use (except zero ohms), for the battery voltage is of course unaffected by the high resistance that it may shunt. Therefore, it is possible to obtain a zero reading during flight without disturbing the amplifier substantially, for the switching circuit does not know that any change has occurred.

This system was utilized for the three alphatron circuits included in the instrumentation of the September Aerobee. A motor-driven cam switch actuated the zero relays for approximately one second every thirty seconds, allowing the recording of any zero shift and hence correction in the analysis of the data. (Any shift is merely added algebraically to a given reading.)

In regard to the new style of alphatron gage used for this instrumentation, as compared with the units used previously, the volume occupied is reduced by a factor of ten, the activity of the radium source is much greater, and the overall sensitivity of the unit is greater by a factor of approximately five. The advantage of the reduced volume is obvious; however, the increased activity of the source poses a moderate problem from the standpoint of the health hazard involved. The AEC standard dosage allows 10 milliroentgens (mr) per hour for 8 hours, with a limit of 3 consecutive days, or a total of 300 mr per week. The new type of alphatron contains 3 mg of radium in equilibrium with decay products. The measured radiation rate (gamma) at the surface of the gage is 400 mr/hr. At a distance of approximately 15 inches, the rate is 10 mr/hr., the 8-hr. tolerance value. It is obvious, therefore, that extreme care must be exercised in the handling of gages to avoid personnel injury.

The increased sensitivity, however, is a considerable advantage, for it allows a reduction in the magnitude of the load resistances required, from 500,000 megohms to 100,000 megohms (for the lowest pressure range desired), which assists greatly in solving construction problems in regard to leakage which may be complicated by humidity effects, for example.

The new type of gage will not respond to as low a pressure as the previous model, in spite of the increased sensitivity, for the increased activity of the source produces a greater "dark current", a relatively small current produced in the load resistance as a result of particles emitted by the radium colliding with, and producing secondary emission from, the electrodes of the gage.

The construction of the amplifier input stage (electrometer stage) was revised for this flight to allow pressurization. A question has arisen on previous flights regarding the possibility of condensation in this portion of the system, resulting in calibration errors. It was felt, therefore, that it would be desirable to pressurize this portion of the instrumentation for at least one flight to answer this question. A photograph of the completed unit without pressurizing can appears in Fig. 13.

The upper-atmosphere data resulting from use of this equipment appears in tabular form in Table 3, and in graphical form in Figs. 17 and 18.

6.5.2. Boundary-Layer Experiment. An exploratory experiment designed to indicate mass-flow conditions in the boundary layer of air surrounding the missile during flight was prepared for the Aerobee launched in September 1951.

Two fixed wires were mounted adjacent to the surface of the nose of the missile, approximately 2 feet from the tip. One wire was located approximately 1/16 inch from the surface and the other about 1 inch from the surface. The wires used were tungsten, very small in diameter (0.0005 inch) and approximately 1/4 inch long. The inner wire was heated by the passage of a constant current, and the voltage drop was measured, providing an indication of the temperature of the wire. An amplifier was included which allowed recording of the information by telemeter. The outer wire was not heated, but its continuity was recorded, likewise by telemetering.

Upon examination of the results, it was learned that the inner heated wire remained intact approximately 30 seconds after launching, while the outer wire lasted 40 seconds. This is longer than had been anticipated, for it was expected that the wires would probably not survive the boost phase of the flight.

The experiment was considered successful, as it indicated probable success for a future experiment developed from this fundamental device.

6.5.3. Paschen-Law Density Experiment. An independent experiment developed for cone-surface stream density determination was included in the instrumentation of this flight.

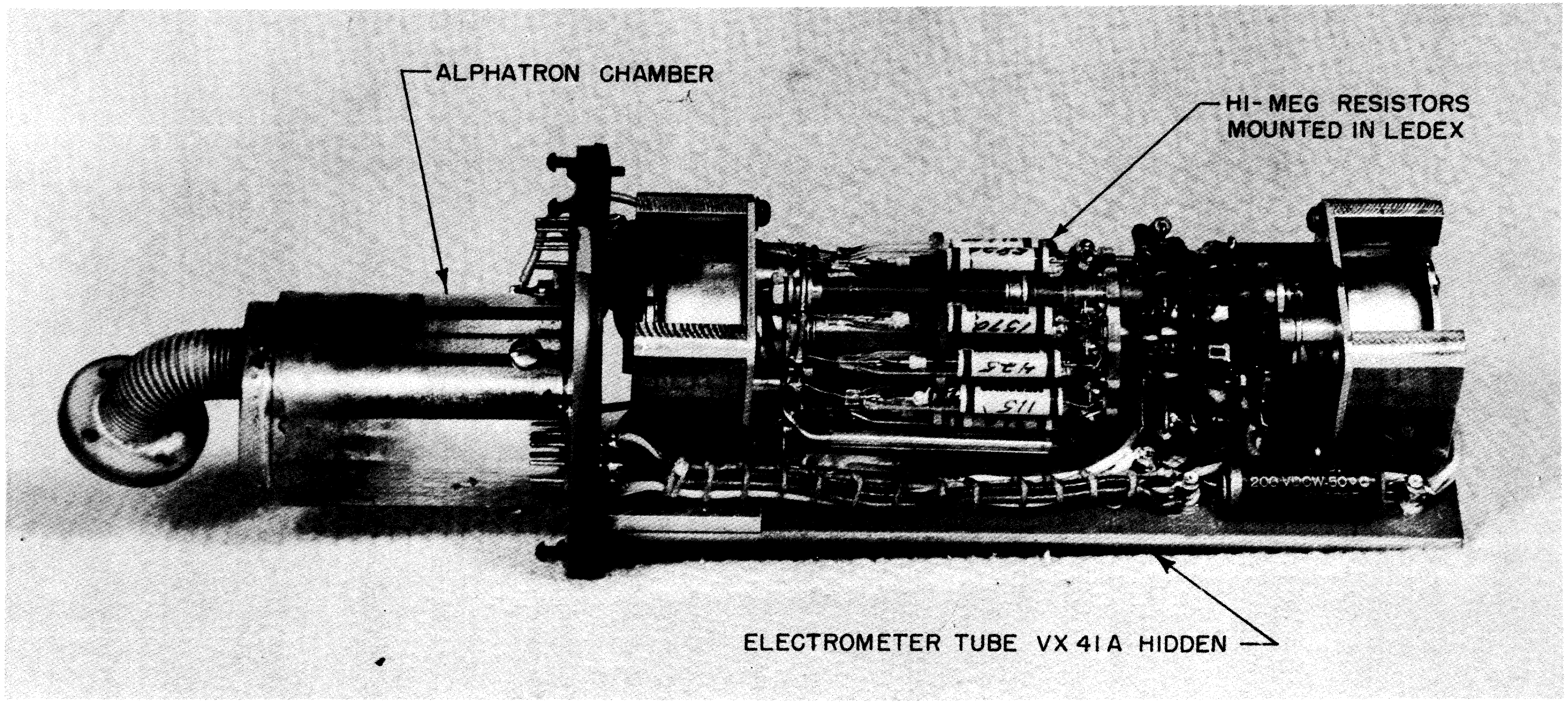

Fig. 13. Cone Wall Alphatron Electrometer Stage, September 1951.

TABLE 3

UPPER ATMOSPHERE DATA FOR SEPTEMBER 13, 1951

Measured Alt. km	Measured Pressure mb	$\log_{10}$ P dynes/cm^2	Derived Temp. °K	$\log_{10}$ P dynes/cm^2	$\log_{10} P_m$ $-\log_{10} P_d$
30	12.4	4.093	226	4.092	+0.001
32	9.24	3.966	226	3.965	0.001
34	6.83	3.834	228	3.834	0
36	5.21	3.717	251	3.718	-0.001
38	4.07	3.610	272	3.610	.000
40	3.20	3.505	277	3.504	+.001
42	2.49	3.397	277	3.398	0.001
44	1.95	3.291	276	3.293	-0.002
46	1.54	3.187	275	3.187	0.000
48	1.20	3.080	273	3.080	.000
50	0.935	2.971	269	2.971	.000
52	0.727	2.861	264	2.860	+0.001
54	0.561	2.749	259	2.748	+0.001
56	0.431	2.634	253	2.633	+0.001
58	0.329	2.517	246	2.515	+0.002
60	0.247	2.392	236	2.390	+0.002

A specially designed air gap was incorporated as part of the nose-cone design, Fig. 15, and provision was made for causing an electric arc across this gap. The voltage applied to cause the arc had a sawtooth-shaped variation with time, and a sensing device was utilized to ascertain the voltage at which the arc formed. A consideration of the voltage at breakdown through use of Paschen's Law allows determination of the density of the arc's path.

The experiment was successful, operating as anticipated throughout the flight. The resulting data have been analyzed, and are presented here in Fig. 16. A forthcoming technical report is in preparation which will describe this experiment in detail.

6.5.4. Gyroscope and Camera Installation. The gyroscope and camera installation in USAF 18 were similar to that in the December 1950 Aerobee USAF 10. Satisfactory missile-attitude data were obtained.

A photograph of the complete instrumentation of USAF 18 is presented in Fig. 14.

6.6. USAF 31, October 1952

The instrumentation for Aerobee 31 was prepared during the period of this contract. The field use of the equipment, however, was accomplished under a continuing contract.[2]

The instrumentation was similar to earlier units constructed at the University of Michigan, the objective being the measurement of atmospheric pressure and temperature. The equipment included:

(a) five alphatrons

(b) one gyroscope

(c) two cameras

(d) accessory equipment associated with a, b, and c.

6.6.1. Pressure Measurement. Of the five alphatrons, two were mounted to indicate impact pressure and the remaining three to indicate cone-wall pressure.

One impact and two cone-wall units constituted the basic pressure-measuring devices necessary to satisfy the requirements of the temperature-measurement method. Each of the actual alphatron chambers of these three units

[2]Contract No. AF 19(604)-545.

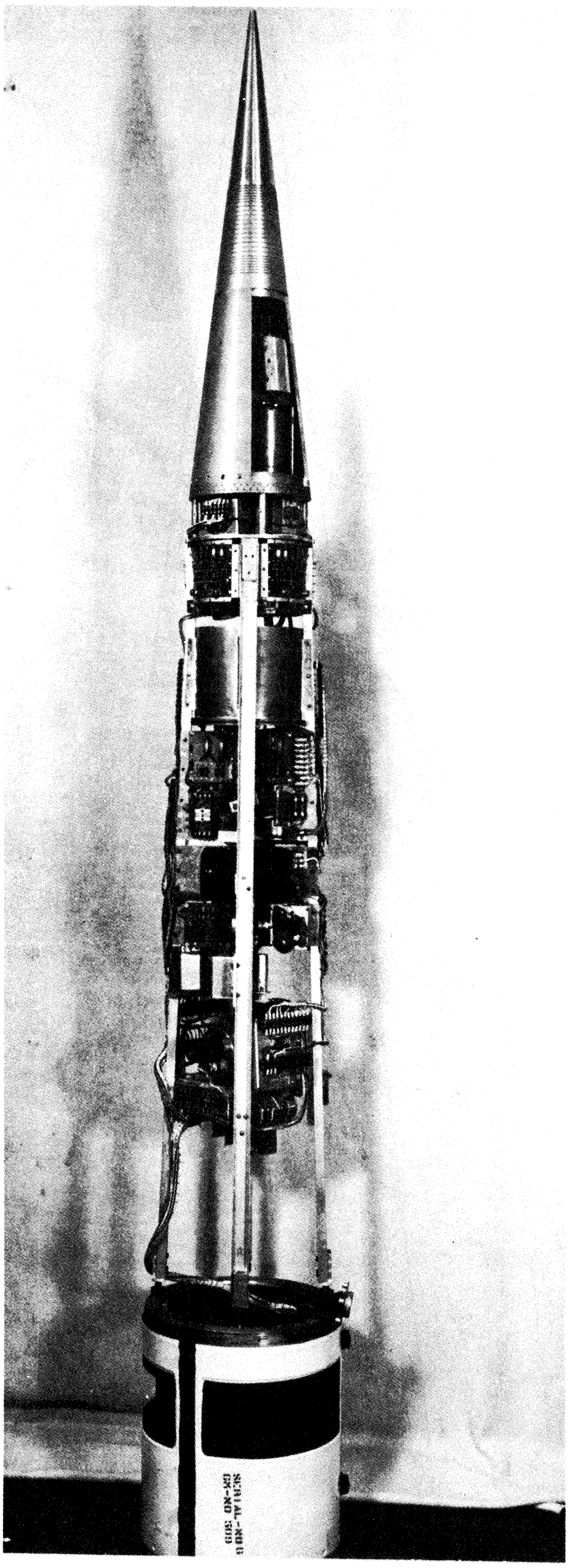

Fig. 14. Complete Instrumentation Rack, September 1951.

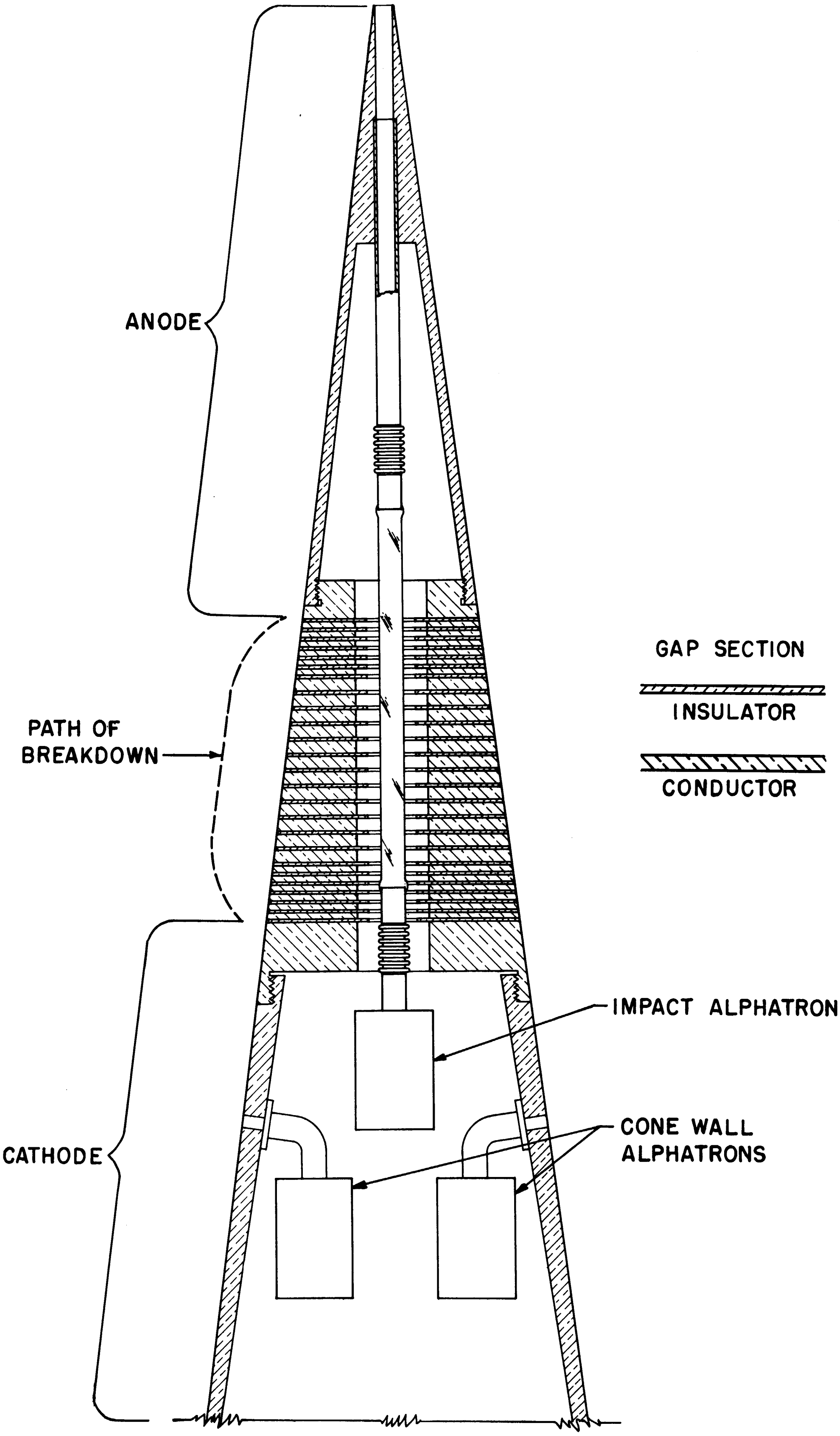

Fig. 15. Functional Sketch Illustrating Location of Alphatron Gages and Arc Discharge Gap on Aerobee Nose Cone, September 1951.

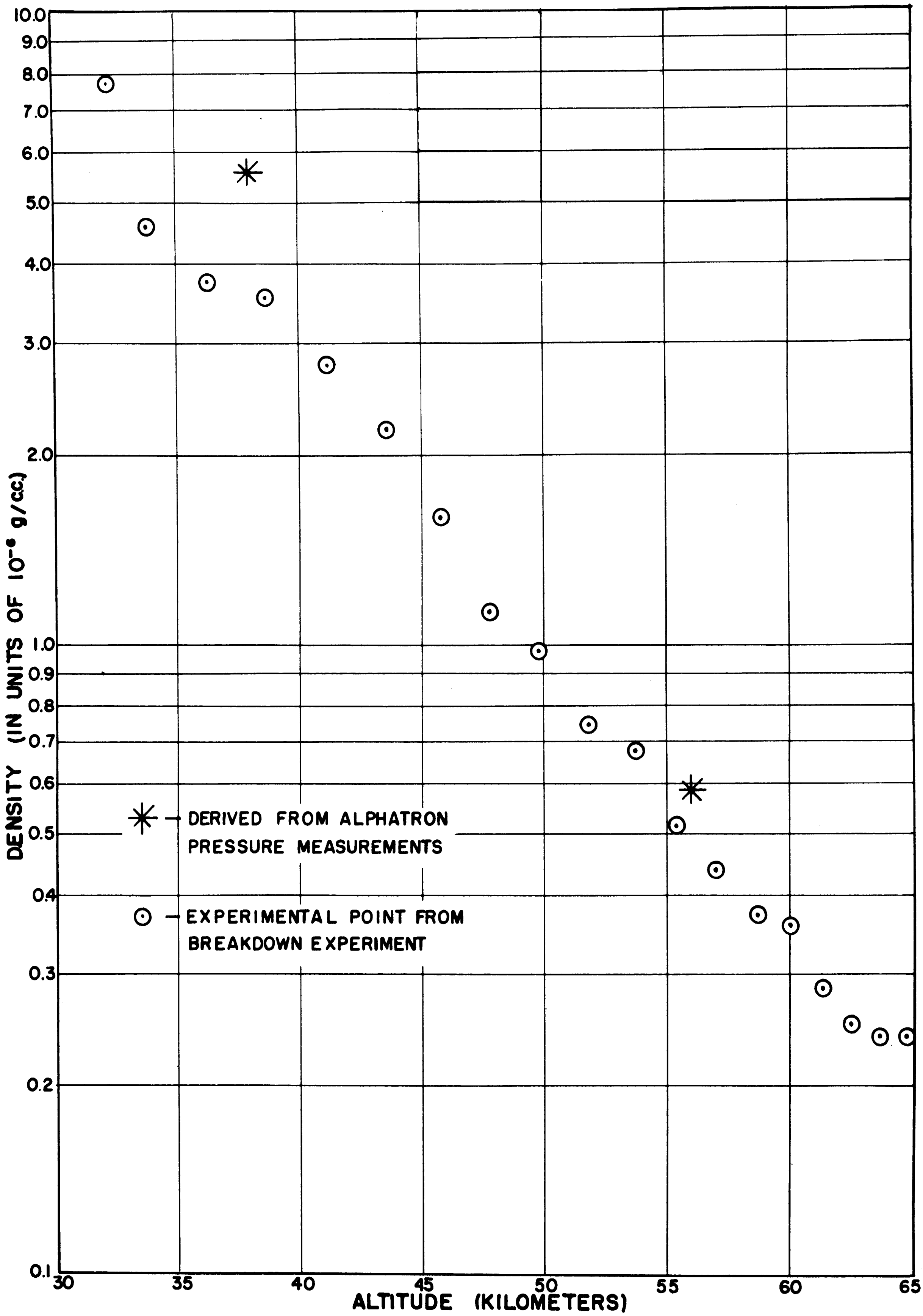

Fig. 16. Minimum Local Cone-Wall Density as Obtained from Gap Experiment, September 1951.

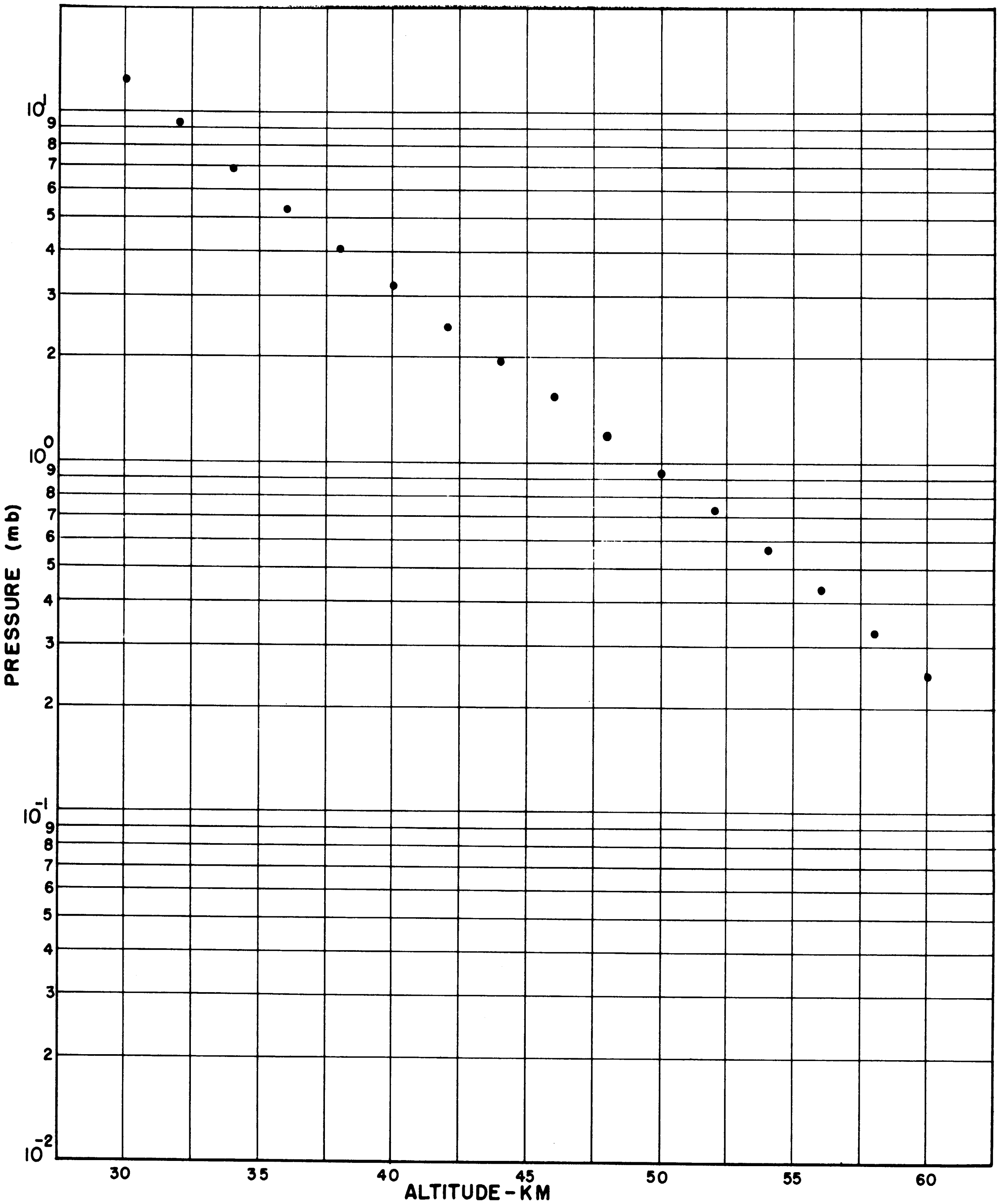

Fig. 17. Curve of Ambient Pressure Vs. Altitude, September 1951.

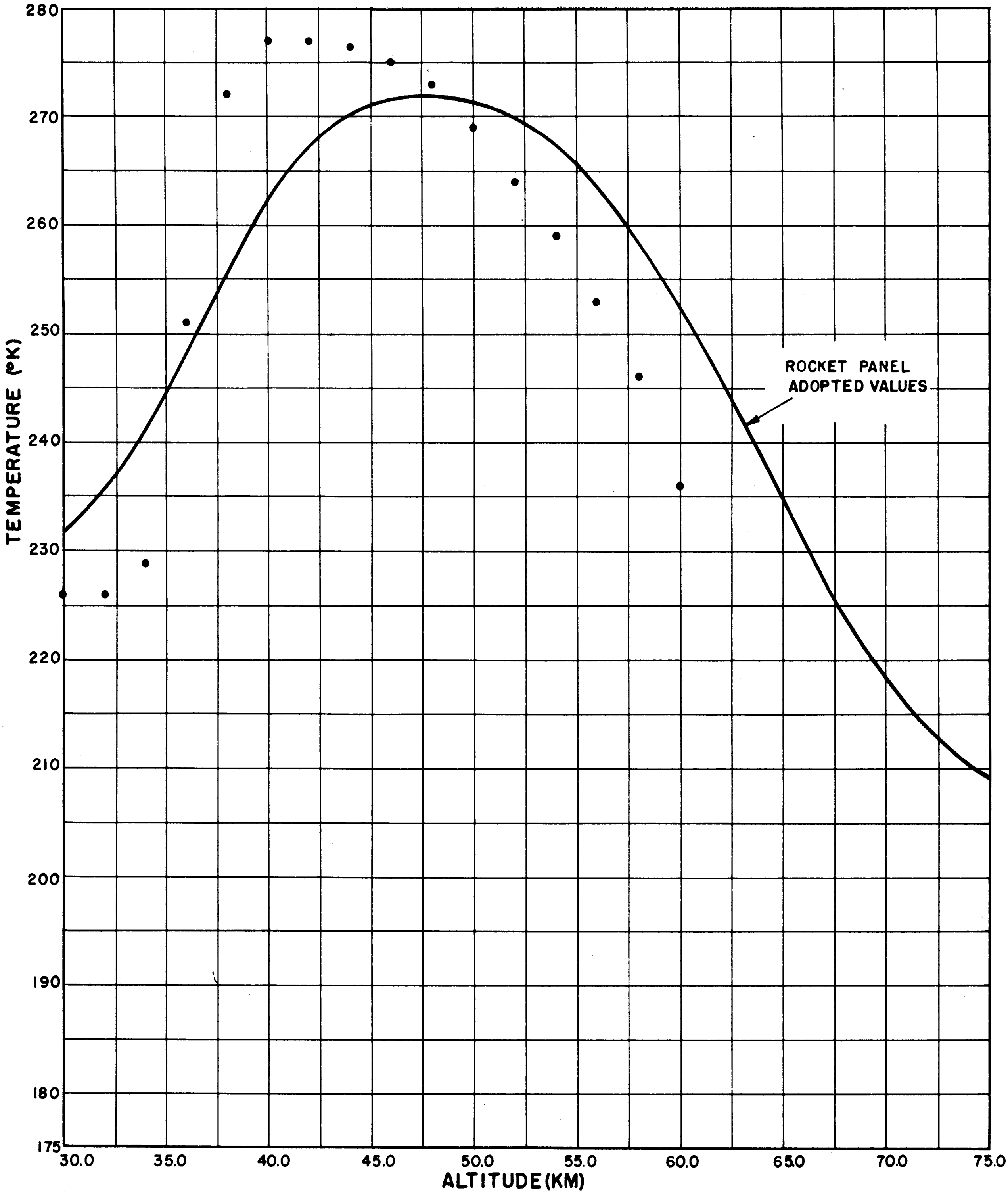

Fig. 18. Curve of Ambient Temperature Vs. Altitude, September 1951.

was provided with a valve, whose function was to seal the unit and hence maintain a pre-established vacuum in the chamber until some predetermined point in the flight. That is, each chamber was pumped to and maintained at some low pressure (10^{-2} mm Hg) many hours before flight use, following which the valve was closed, thus sealing the chamber. The valves, which were motor-driven, were then activated at the desired point of the flight, exposing the gages to the atmosphere.

This procedure, which establishes a "pressure history" for the gage, contributes to the accuracy and reliability of the device. The reasons justifing this operation are not too well understood at the time of this writing. They may be associated with the release of radon gas from the radium ionizing source that is employed in each alphatron, or they may be due to the presence of water vapor. Laboratory studies are underway to assist in our understanding of the phenomena.

The two additional alphatrons that were employed without valves were used as controls for comparison with valved units. The data from these units were considered as supplementary to the data from the valved units.

6.6.2. Gyro and Camera Installation. The gyroscope installation was identical with that of earlier equipment. An additional camera was included, however, to lend assurance that the gyro information would be recorded, although failure of the main camera was not expected nor did it occur.

6.6.3. Results of USAF 31 Firing. Inasmuch as the flight use of the USAF 31 equipment took place under a following contract, a discussion of the launching is not presented in this report. In the interest of completeness, however, it is appropriate to state that the flight was successful. The resulting data are being analyzed at the time of writing.

7. REPORTS AND PAPERS

During the course of the contract, several papers and reports were undertaken. Fifteen quarterly progress reports were written which presented in some detail the course of the research. A scientific report was issued detailing the theoretical work and early experimental aspects of ionospheric probe work. It is designated as follows:

"Dynamic Probe Measurements in the Ionosphere" by Hok, Spencer, Reifman, and Dow, August 1951.

A supplement to this report was also issued. A technical paper bearing the same title was published in the June, 1953, issue of the Journal of Geophysical Research.

A paper detailing the project temperature-measurement method was written and has been submitted for publication in the Journal of Applied Physics. It is designated as follows:

"Rocket Measurement of Upper-Atmosphere Ambient Temperature and Pressure in the 30-75-Km Region" by Sicinski, Spencer, and Dow.

Three papers were written and presented at technical society meetings:

(1) "Rocket Atmospheric Pressure Measurement System", by Spencer and Schulte, presented by Spencer at the I.R.E. National Conference on Airborne Electronics, May, 1951, Dayton, Ohio.

(2) "Rocket Measurement of Upper-Atmosphere Density by Paschen's Law," by Smith and Early, presented by Smith at the Conference on Gaseous Electronics; September, 1952, Princeton, New Jersey.

(3) "Rocket-Borne Electronic Devices in Upper-Atmosphere Research" by Spencer, presented before I.R.E. Detroit Branch Meeting, March, 1953, Ann Arbor, Michigan.

Numbers 1 and 2 above are currently in preparation for submission as technical papers to the Review of Scientific Instruments.

The writer has an invitation from the I.R.E. to prepare (3) above for submission for publication as a technical paper in the Proceedings of the

I.R.E.

An additional paper on the subject of the use of a single gyroscope in a rocket is likewise in preparation for submission to an appropriate technical journal.

8. PERSONNEL ENGAGED IN CONTRACT WORK

Professor W. G. Dow	Supervisor
Gunnar Hok	Research Engineer
W. G. Kartlick	Research Technician
H. F. Schulte	Research Engineer
H. S. Sicinski	Research Physicist
N. W. Spencer	Research Engineer

The above list constitutes the heart of the working group involved in contract activities. In addition, many other individuals, in most cases students hired on a part-time basis, contributed substantially to the project. Their efforts were applied to computing procedures, equipment construction, laboratory testing, etc.

Professor W. G. Dow has served as supervisor of the work under this contract. He has provided very necessary and desirable guidance and counsel in regard to the general objectives, as well as direct participation in many project activities.

Mr. Gunnar Hok has acted as technical consultant to the project and has, in particular, contributed directly by his theoretical studies of the bipolar probe.

Mr. H. F. Schulte has been intimately associated with instrumentation activities, and has, in particular been responsible for the detailed development of the alphatron system.

Mr. W. G. Kartlick has served as the only full-time technician on the project. His careful attention to instrumentation details has been a contributing factor to the success of the instrumentation.

Mr. H. S. Sicinski has served as a research physicist. His responsibilities have included the theoretical aspects of project work as well as data-analysis efforts. He has, during the course of the contract, developed the theoretical method used for temperature measurement, as well as being responsible for the initial development work on use of the gyro.

The writer has served as project engineer for the work, coordinating the overall effort.

9. GENERAL REMARKS AND SUMMARY

The reader, unfamiliar with the detailed procedure involved in rocket measurement of ambient pressure and temperature, summarized in this report, may conclude that such measurements are readily accomplished. It is not the intent of the writer to suggest that the procedure involved is excessively complicated or unduly lengthy. On the contrary, it is believed to be a straightforward, realistic approach to temperature measurement. In fact is is the only method known to project personnel that yields accurate, essentially point-by-point temperature values.

However, as with any scientific investigation where accurate, reliable data is desired, care is required in the design and preparation of the equipment used as well as in consideration of the theoretical aspects of the method employed. Data analysis, too, requires careful attention to details, to insure confidence in the results.

In particular, upon reviewing the work performed under this contract, it is the opinion of project personnel that the following may be considered as accomplishments:

a) Reliable temperature, pressure, and density information on the atmosphere has been obtained. This constitutes the major stated objective of the contract.

b) A theoretical study of certain aspects of the ionosphere has been completed and recorded. Data obtained under an earlier contract have been analyzed.

c) A new and experimentally proven method has been developed for the measurement of atmospheric temperature from a rocket.

d) A new and partially experimentally verified method involving a so-called bipolar probe has been developed for exploration of the ionospheric regions from a rocket.

e) A pressure-measurement system employing an alphatron ionization gage has been developed to the point that it is a reliable tool for use in a rocket. It is capable of providing accuracies of 1 part in 100 over a pressure range of several decades, in particular 760 mm Hg to 10^{-3} mm Hg. A redesign of the gage chamber would allow greater range.

During the course of the contract about fifteen complete alphatron units were constructed and used. No significant failure was encountered, each flight use, however, indicating desirable improvements such as increasing the number of subranges and providing switching delay as discussed earlier in this report., some filament supply regulation, and means for zero indication during flight.

f) A missile-aspect system employing a single gyroscope and associated camera has been developed and used successfully. The method provides continuous missile-attitude information.

g) An alternative pressure-measurement system employing thermionic ionization gages has been developed. The troublesome problem of emission change with pressure has been solved with the development of a servo mechanism which maintains constant cathode emission over several decades of pressure change.

h) A method based on Paschen's Law regarding electric breakdown of air on a missile surface has been developed. On the basis of a single rocket experiment and moderate laboratory testing, it is believed to be a promising means of determining air density on the surface of a rocket. It is not considered that development of this method is completed; it was abandoned under the pressure of other work.

i) A method was conceived and the development initiated for a means of direct air-density measurement through use of an RF breakdown of air at a point ahead of a missile. This work was discontinued because support was withdrawn. A device of this nature could produce density measurements in undisturbed air, ahead of a missile, and hence would not be subject to aerodynamic sources of error.

j) Numerous accessory devices have been developed to augment fundamental instrumentation. Such devices, including telemetering limiters, motor-driven clocks, calibrating devices, pressure-gage valve systems, etc., are essential to an instrumentation and consequently require as much care in development as the more spectacular equipment items.

k) A quantity of technical writing was initiated during the contract term, and some papers were presented at technical society meetings. Publication of several papers is scheduled under a continuing contract.

APPENDIX

This appendix is a reprint of a technical paper submitted to the Journal of Applied Physics. The subject matter of the paper includes primarily a discussion of the theoretical temperature-measurement method used under this contract. Included also is a brief description of appropriate instrumentation.

Some repetition of material presented in the body of this report is unavoidable.

ROCKET MEASUREMENTS OF UPPER-ATMOSPHERE AMBIENT TEMPERATURE AND PRESSURE IN THE 30 TO 75- KILOMETER REGION

H. S. Sincinski, N. W. Spencer, and W. G. Dow*

ABSTRACT

A method for determining ambient temperature and ambient pressure in the upper atmosphere is described, using the properties of a supersonic flow field surrounding a right circular cone. The underlying fundamentals stem from basic aerodynamic principles as combined with the developments of the aerodynamics of supersonic cones by G. I. Taylor, J. W. Maccoll, and A. H. Stone. The experiment provides the necessary cone pressures, velocities and Eulerian angles, so that a Mach number characterizing the ambient space conditions may be computed. A description is given of the requisite experimental equipment and related techniques. Experimental data from two rocket-borne equipments are presented with the resulting calculated pressures and temperatures as experienced over New Mexico to approximately 70 kilometers.

*Department of Electrical Engineering, University of Michigan, Ann Arbor, Michigan.

I. INTRODUCTION

The research reported in this paper has been sponsored by the Geophysical Research Directorate of Air Force Cambridge Research Center, Air Research and Development Command, under Contract Nos. AF 19(122)-55 and W33-038 ac-14050.

The University of Michigan Department of Electrical Engineering has been engaged for the past several years in the measurement of the ambient temperature and pressure of the upper atmosphere. These measurements have been carried out in high-altitude rockets, in particular the "V-2" and the "Aerobee."

During the period in which V-2 rockets were employed, temperature measurements were implemented by application of the "barometric equation" to a measured curve of ambient pressure versus altitude. Although curves of ambient temperature versus altitude were obtained,[3] the computational procedure for obtaining the temperature is primarily one of differentiation, and hence yields only very approximate values of temperature.

In an effort to improve the quality of the measurements, a more exact method has been developed which overcomes certain disadvantages of the earlier procedure. Essentially point-by-point values are obtained in a manner that does not require an averaging process. That is, each temperature point on the curve is determined directly from the experimental pressure data independently of other points and gives the temperature at a particular location in space, as contrasted with values obtained from the barometric equation, which represent an average over a rather considerable altitude interval.

The experimental data required for a temperature computation by the new method include in general: a ratio of the nose-cone tip (impact) pressure to the pressure at some point on the cone wall, the instantaneous angle between the rocket's longitudinal axis and a space-fixed reference system, and the magnitude of the missile velocity vector in the same reference system.[4]

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[3]Rpt. No. 2, Upper Air Research Program, Engineering Research Institute, University of Michigan, July 1948.

[4]Another temperature-measurement method, similar in that correspondingly fundamental pressure measurements are employed has been utilized by the Naval Research Laboratory. See Haven, Koll, and La Gow, J. of Geophysical Research V. 57, 59-72 (March 1952).

The required pressure measurements are accomplished in the missile through the use of "alphatron" ionization gages, which are utilized in equipment that has been developed by this research group. The data obtained are telemetered from the rocket to ground stations, where they are recorded.

The fundamental information required for angle computation is similarly determined in the missile through the use of a single gyroscope. In this case, the data are recorded in the rocket on film, which is later recovered when the missile reaches the ground.

Velocity information is obtained by triangulation, employing ground-based instrumentation which tracks the rocket during flight.

Temperature measurements have been made on several rocket flights utilizing the new method. The following sections of this paper present the data resulting from two such flights of Aerobee rockets, a discussion of the theoretical basis for the measurements, and a description of the particular equipment developed to obtain the basic data.

II. THEORETICAL CONSIDERATIONS

A. General

Temperature is a typical "intensive" magnitude[5] quantity, which, for its determination, must be correlated with phenomena measured "extensively." Although the usual laboratory thermometric systems can measure temperature in extensive terms, these techniques cannot be directly extrapolated to supersonic missiles for upper-atmosphere ambient-temperature measurements without producing questionable results. The chief difficulty arises with the formation of a boundary layer about the instrument, which perturbs the temperature experienced. A more promising datum is pressure, which, unlike the temperature, is very nearly constant throughout any boundary-layer section, being nearly equal to the value just outside the boundary layer. The pressure datum thus "neglects" the boundary layer, approximating an inviscid flow.

For the practical case of a cone with a semi-vertex angle of 7.5°, very good argeement exists[6] between the inviscid theory and experimental data from viscid tests in the range of Mach numbers and yaw angles experienced.

[5]For definition of extensive and intensive properties, see Fowle, F. E., Smithsonian Physical Tables.

[6]Cronvich and Bird, "Pressure Distribution Tests for Basic Conical Flow Research", Ordnance Aerophysics Laboratory, Daingerfield, Texas.

The principal limitation to applying inviscid theory occurs for large yaw angles ($\epsilon \sim 0.8\ \theta_s$) where boundary-layer separation occurs.[7]

B. Nonyawing Cone

The problem of supersonic flow around a cone has been successfully analysed by G. I. Taylor and J. W. Maccoll,[8] with the subsequent embodiment of their results in tabular form by Z. Kopal.[9] These results are applicable to cone pressure measurements in order to compute ambient upper-air conditions for given conical geometry and the characteristic Mach numbers. Although surface pressure measurements alone do not constitute sufficient information to deduce the characteristic Mach number, knowledge of the total head pressure will, when taken concurrently with the surface pressures, define the characteristic Mach number. A schematic representation of the experiment and the physical quantities appearing is shown in Fig. 19. Quantities with subscript "1"

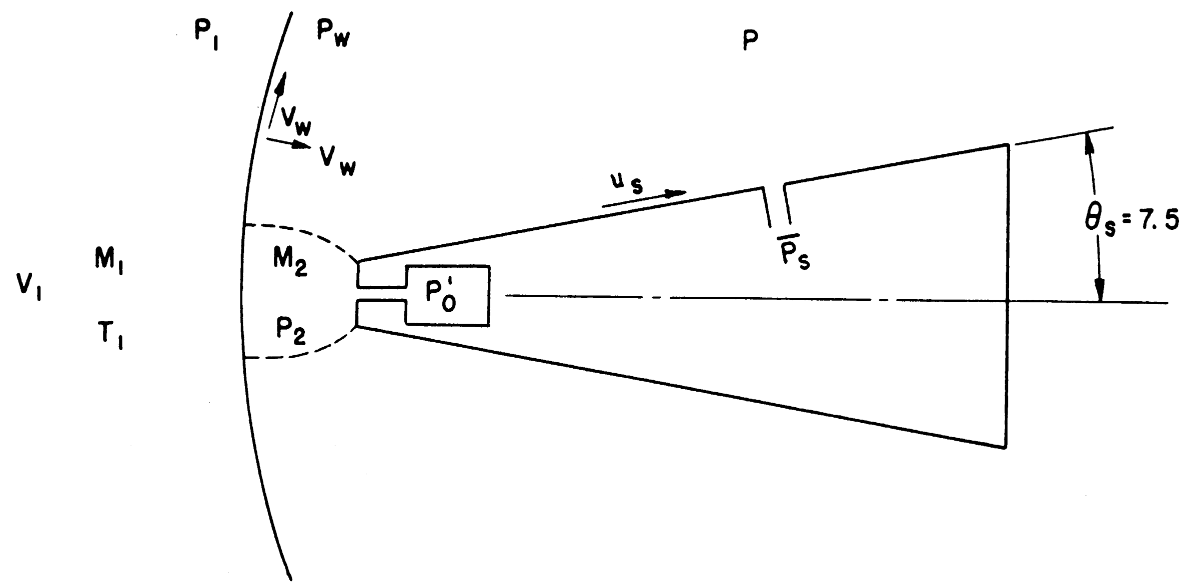

Fig. 19. Physical quantities appearing in nonyaw conical flow. Pressures measured by the experiments described appear inside of the outline of the cone. (For physical significance of symbols, see list in paper.)

[7]Moore, Franklin K., "Laminar Boundary Layer on a Cone in Supersonic Flow at Large Angles of Attack," NACA-TN-2844.
[8]Taylor, G. I., and Maccoll, J. W., Proc. Royal Soc. London Ser. A, 139, 279-311 (1933); Maccoll, J. W., Proc. Royal Soc. London Ser. A, 159, 459-472 (1937).
[9]Kopal, Z., M. I. T. Tech. Report No. 1, 1947, Dept. of Elec. Eng'g., Center of Analysis.

are the upstream conditions or so-called "ambient values". The dotted area about the cone vertex defines a subsonic flow region existing because the cone is truncated to permit total head measurement. This deviation from purely conical geometry affects the flow locally; however, a wind-tunnel analysis demonstrates that the conical flow regime is established ahead of the cone surface pressure measuring port.

The computation of the ambient conditions proceeds through a combination of the Taylor-Maccoll relations and the Rayleigh total-head expression. P'_o and P_s (cone-tip and cone-wall pressures) and cone velocity V relative to the ambient air are measured experimentally. The theory presented leads to a relationship (Fig. 20) between P'_o/P_s and the Mach number M_1, thus permitting a determination of the Mach number from the experimental data. The dependence of Mach number and cone-wall pressure P_s on the ambient pressure P_1 appears in the course of this determination. The ambient temperature is determinable from the familiar equation (6) relationship between Mach number and velocity relative to ambient air.

It is convenient to initiate the theoretical analysis by stating the ratio P'_o/P_s of the measured pressures in the following identity:*

$$\frac{P'_o}{P_s} = \frac{P'_o}{P_1}\frac{P_1}{P_w}\frac{P_w}{P_o}\frac{P_o}{P_s} \qquad (1)$$

The theoretical treatment consists of expressing each of the right hand factors in terms of the Mach number and the known ratio of specific heats, thus leading to the Fig. 20 relationship.

To accomplish this for the first factor, energy considerations permit expressing the ratio of pressures across the normal shock wave in terms of the Mach number and the ratio of specific heats as follows:*

$$\frac{P_1}{P'_o} = \left[\frac{2\gamma M_1^2 - (\gamma - 1)}{(\gamma - 1)}\right]^{1/(r-1)} \left[\frac{(\gamma + 1)\, M_1^2}{2}\right]^{\gamma/(1-\gamma)} \qquad (2)$$

Similar evaluation of the remaining three factors on the right of equation (1) requires use of the theory of the conical regime. Taylor and Maccoll[10] determined the pressure ratio across the shock wave using a lengthy graphical procedure. Z. Kopal[11] derived an explicit expression for this ratio using purely algebraic procedures; he also prepared tables providing values of the local velocities (radial velocity U_w, tangential velocity V_w, and sonic

*See list of symbols at end of paper.

[10]Taylor, G. I., and Maccoll, J. W., op. cit., pp. 288-292.

[11]Kopal, Z. op. cit., p. xii.

velocity, a) for any given cone angle as a function of the Mach number. By using values from these tables in his expression

$$\frac{P_w}{P_1} = \frac{(\gamma^2 - 1)(c^2 - u_w^2 - v_w^2)}{4\gamma\, v_w^2 - (\gamma - 1)^2\,(c^2 - u_w^2 - v_w^2)} , \tag{3}$$

the second factor on the right of equation (1) can be evaluated in terms of Mach number and γ.

The quantity c, appearing here, is a useful reference velocity, sometimes defined as the maximum velocity attainable by converting all the heat energy of the fluid into uniform motion. In terms of the local sonic velocity a and the velocity V relative to ambient air, the reference velocity c is defined as

$$c^2 = V^2 \left[1 + \frac{2a^2}{V^2\,(\gamma - 1)}\right] . \tag{4}$$

The third factor on the right-hand side of equation (1), the ratio of static pressure behind the shock wave to the stagnation pressure, is found directly from the Bernoulli integral and the assumption of adiabatic flow behind the shock surface.[11] This ratio, in terms of the local velocities provided by Kopal's tables, is

$$\frac{P_w}{P_o} = \left[1 - \left(\frac{u_w}{c}\right)^2 - \left(\frac{v_w}{c}\right)^2\right]^{\gamma/(\gamma-1)} . \tag{5}$$

Lastly, the ratio $\overline{P}_s/P_o$ of cone surface pressure to stagnation pressure behind the shock wave follows from equation (5) on setting the tangential velocity (v_w) equal to zero.

The results from using these four evaluation procedures in equation (1), expressed in terms of the Mach number for the nonyaw case of a 7.5° half-angle cone, are shown in Fig. 20.

With the requisite Mach number known from Fig. 20, the ambient pressure is available from equation (1) after dividing both sides by P_o'/P_1. The result of this procedure is shown in Fig. 21.

Computation of the ambient temperature depends on the definition of the Mach number and the adiabatic sonic velocity relationship. These express the ambient temperature explicitly as

$$T_1 = \left(\frac{V}{M_1}\right)^2 (R\gamma)^{-1} \tag{6}$$

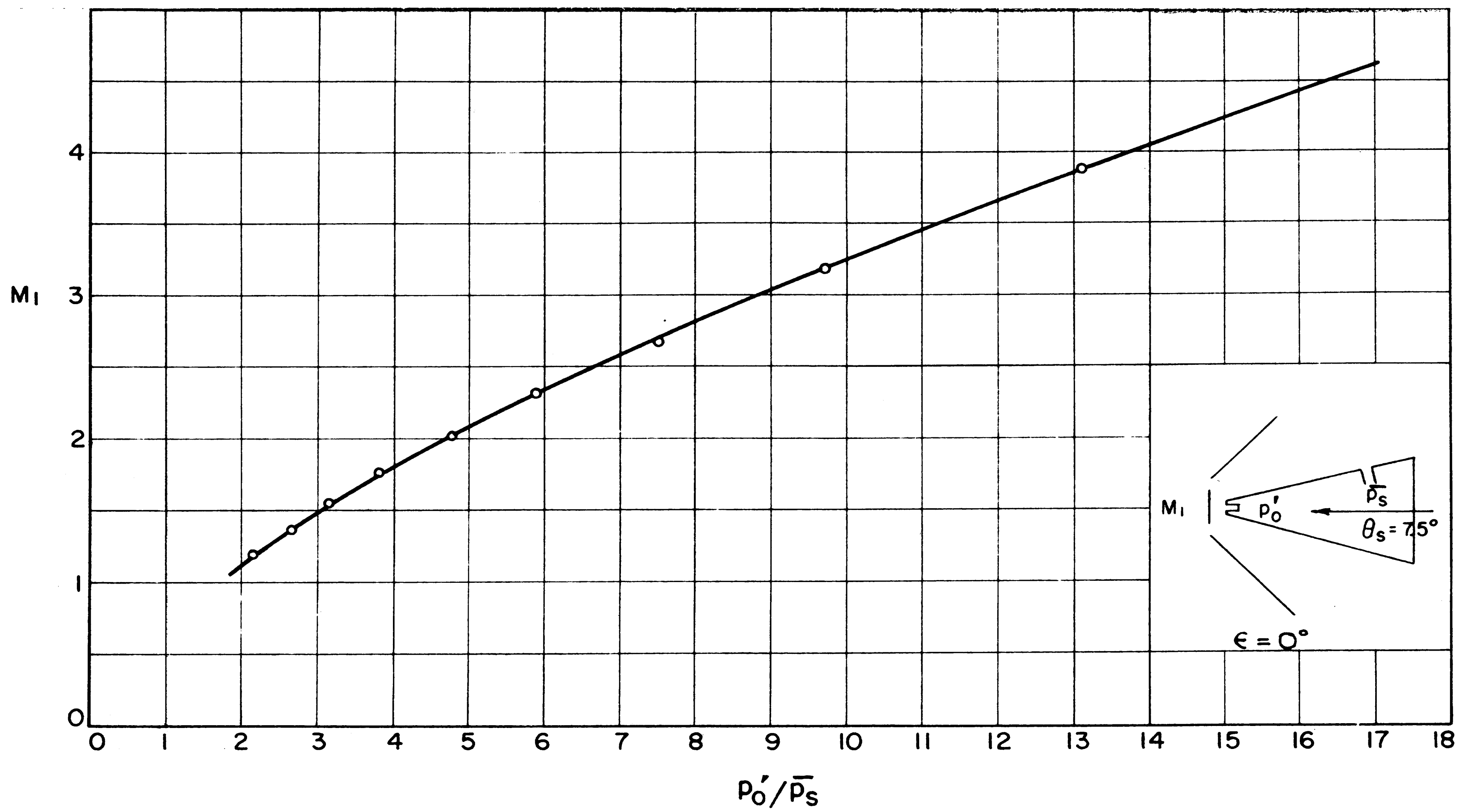

Fig. 20. Mach Number Vs. Quotient of Cone Pressures for Nonyaw Case of a 7.5° Half Angle, Supersonic Cone.

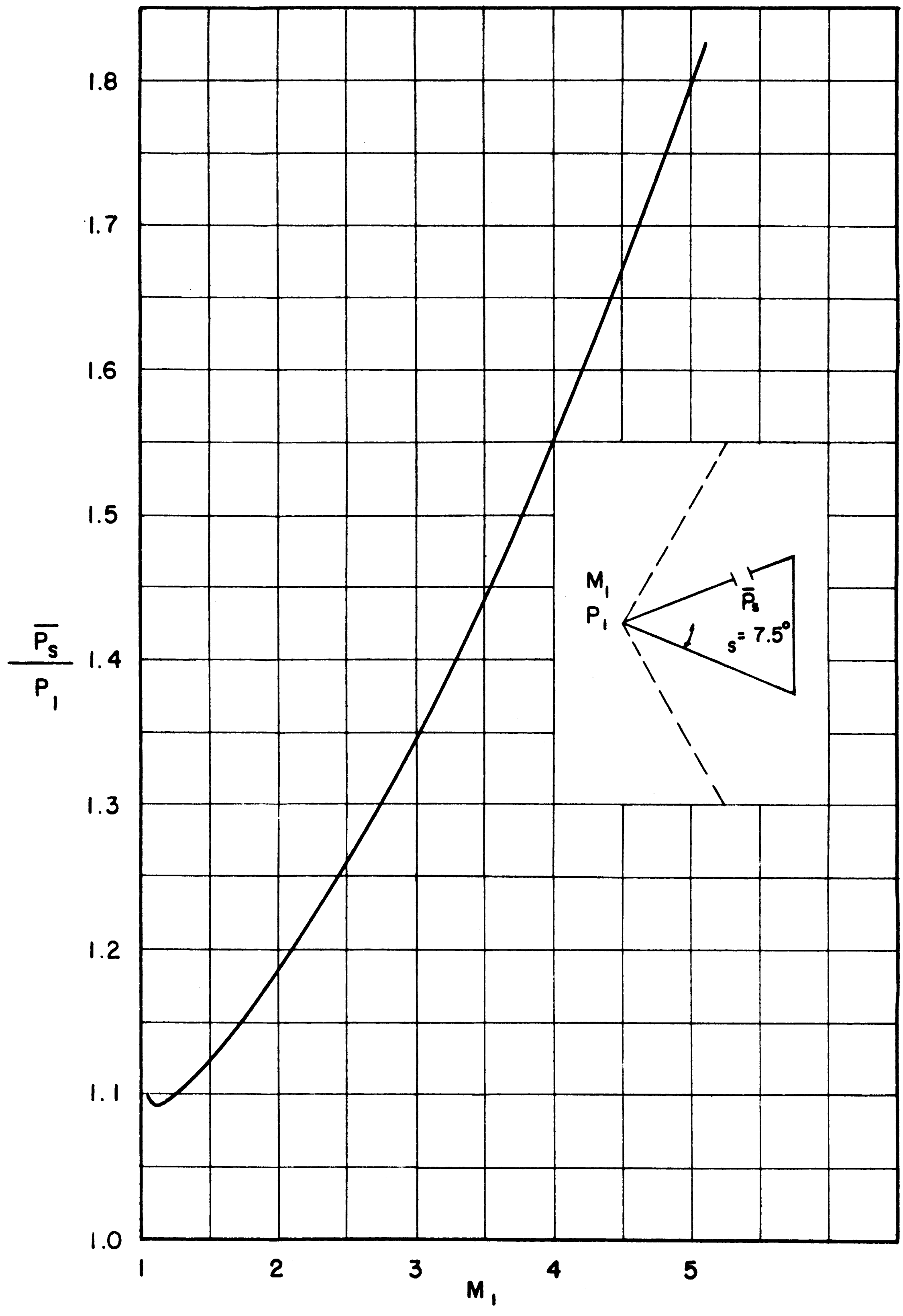

Fig. 21. The Relationship between the Unyawed Surface Pressure and the Ambient Pressure as a Function of the Free Stream Mach Number for a Nonyawing, 7.5° Half Angle Supersonic Cone.

The velocity V appearing here is the relative flight speed. In the experiments presented, no provision was made for estimating local wind conditions; consequently the missile velocity relative to the earth was taken as the defining velocity. Tacitly, this statement assumes that the winds present are negligible compared to the relative flight speed.

These data have given the Fig. 29 temperatures, through which a reasonably smooth curve could be drawn. The departure of the measured temperature from the smooth curve is of the nature that would result from the presence of a wind field varying in speed and direction. Uniform wind fields, on the other hand, would yield temperatures continuously higher or lower than the actual ambient temperature.

C. Yawing Cone

Under the conditions experienced by high velocities, missiles are fundamentally yawing bodies; that is, the missile's longitudinal axis does not usually maintain coincidence with the free-stream relative velocity vector. Consequently, the experiment must employ a yawing-cone theory for its analysis.

A theory for yawing supersonic cones was developed by A. H. Stone[12] which included second-order yaw effects. Stone's analysis led to Z. Kopal's[13] tabulation of the perturbation coefficients for use in the solution of supersonic flow fields about large-yaw cones. Of particular interest is Stone's expression for the cone's surface pressure, since it provides the basis for a pressure experiment on a yawing cone. In terms of the coordinates of Fig. 22, the surface pressure P_σ is

$$P_\sigma = \bar{P}_s + \epsilon \sum_{n=0}^{\infty} \eta_n \cos n\phi + \epsilon^2 \sum_{n=0}^{\infty} P_n \cos n\phi \; . \; . \; . \; . \qquad (7)$$

$\bar{P}_s$ is the surface pressure for a zero-yaw angle ($\epsilon = 0$), while the perturbation coefficients η_n and P_n are available from reference 9. Stone's analysis demonstrated that all the second-order yaw terms except $n = 0$ and $n = 2$ vanish under the boundary conditions on the cone, while the Rankine-Hugoniot conditions reduce all the first-order terms to zero except $n = 1$.

In application of equation (7) the perturbation coefficients as given by Kopal need to undergo a transformation by means of a Taylor expansion for

[12]Stone, A. H., Jour. of Math. and Phys., 30 XXX 200 (Jan. 1952).
[13]Kopal, Z., Report No. 3, M.I.T. Department of Elec. Eng'g. Center of Analysis and Kopal, Z., Report No. 5, 1949, M.I.T. Dept. of Elec. Eng'g. Center of Analysis.

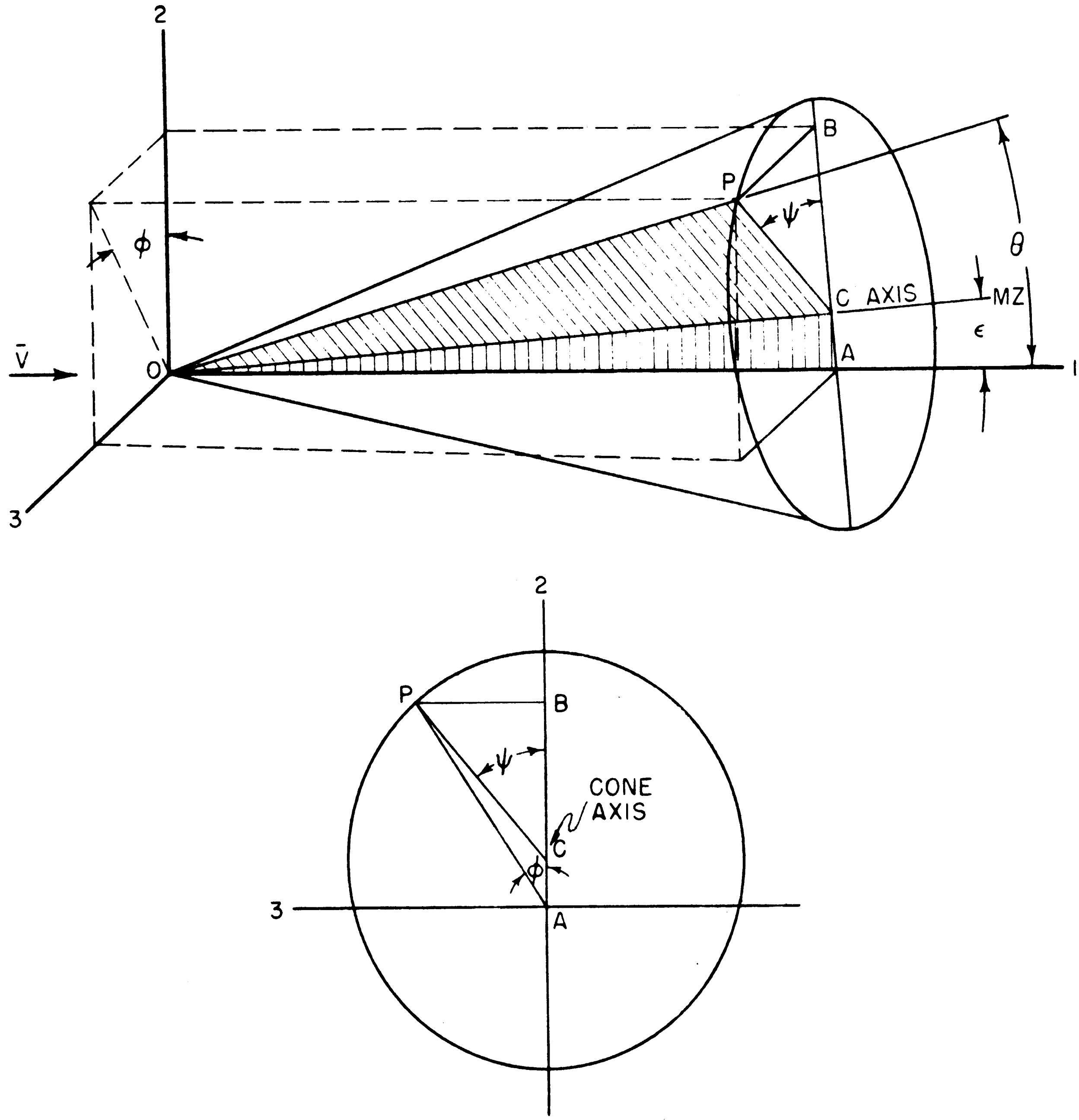

Fig. 22. Coordinates Describing the Yawing Cone.

utilization in the desired reference frame.[14] Kopal's tabulation presents these coefficients relative to arguments of the unyawed reference system, where the desired coefficients are perturbed by angle $\overline{\Delta\theta}$. Thus the pressure at any perturbed position θ is given by the relation

$$P(\theta) = P(\bar{\theta} + \overline{\Delta\theta}) = P(\bar{\theta}) + P'(\theta)\,\overline{\Delta\theta} + 1/2\,P''(\bar{\theta})\overline{\Delta\theta}^2 \ldots, \qquad (8)$$

where the barred quantities are with respect to the unyawed reference frame and the primes refer to differentiation with respect to θ. With equation (8) we still need an expression for the yawed conical surface with respect to the unyawed reference frame. In the region between the shock wave surface and the yawing cone the variables will be constant over surfaces of a generally conical nature. If it is assumed that these surfaces remain the equation[15] for any of these surfaces is

$$\bar{\theta}_s + \Delta\bar{\theta}_s = \bar{\theta}_s + \epsilon \cos \phi - (1/2)\,\epsilon^2 \cot \bar{\theta}_s \sin^2 \phi \ldots, \qquad (9)$$

where the particular surface is defined when $\bar{\theta}_s$ and $\Delta\bar{\theta}_s$ are stated. Using equations (8) and (9) in equation (7), then collecting terms to the order ϵ^2, and evaluating the derivatives gives the pressure at the yawed solid cone surface as

$$P_\sigma = \bar{P}_s \left[1 + \epsilon \cos \phi \left(\frac{\eta}{\bar{P}_s}\right) + \epsilon^2 \cos 2\phi \left(\frac{P_2}{\bar{P}_s} + \frac{\gamma}{2}\left(\frac{u_s}{a}\right)^2\right) + \epsilon^2 \left(\frac{P_0}{\bar{P}_s} + \frac{\gamma}{2}\left(\frac{u_s}{a}\right)^2\right) \ldots\right]$$

The experimental data provide values for P_σ, ε, and ϕ. These quantities along with equation (10) permit computation of $\bar{P}_s$, the unyawed pressure. With P_s determined, the experiment reduces to the nonyaw case for which expressions involving the ambient pressure and temperature have already been given. P_σ are surface pressures measured by suitable gages located in the cone, and ε and ϕ are computed from a combination of the trajectory locus and data from a missile-borne gyroscope. From the definitions, the yaw-angle computation makes prerequisite an assumption regarding environmental winds. In both experiments presented the wind velocities are assumed to be small compared to the missile velocity. The yaw angle is then determined with the wind vector tangent to the missile trajectory, while the missile aspect is taken from a gyroscope.

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[14] Van Dyke, M. D.; Young, G.; Siska, C., Jour. Aero. Sci., Vol. 18, p. 355, May 1951.

[15] Stone, A. H., "On Supersonic Flow Past a Slightly Yawing Cone," Jour. of Math. and Phys., 27, 73 (1948), Eq. 34.

III. INSTRUMENTATION

The instrumentation that has been developed and used in Aerobee rockets by this research group to obtain the fundamental data required utilizes an alphatron gage as the basic pressure-sensitive element, and a gyroscope for missile angular-position determination.

This section of the paper will describe briefly the manner in which each of these devices is employed.

A. Pressure Measurement

An alphatron is an ionization gage wherein the ionizing energy is obtained from alpha particles emanating from a small quantity of radium, generally of the order of milligrams.

The essential external characteristics of the particular gage chosen for use in this investigation are illustrated in Fig. 23, which presents a typical curve of output current versus chamber pressure. The lowest measurable pressure is determined fundamentally by the "dark current", the value on the curve to which the lower portion of the curve is asymptotic. The upper limit is determined by recombination of ionized particles before the ionization products are collected and measured, as evidenced by the bending of the curve at the higher currents.

Two features important from the standpoint of circuit requirements are immediately apparent from the curve: the very small current that constitutes the basic information signal, and the rather large ranges of current and pressure which must be accommodated in an instrument which utilizes the device over its useful range. The small current implies either the use of a relatively small (few megohms) load resistance and very large voltage amplifications, or the use of very high values of resistance, with the consequent problem of impedance matching. The extensive useful range, on the other hand, demands the use of several subranges in order to obtain a reasonable definition in the ultimate pressure data.

Figure 24 is an elementary block diagram illustrating the circuit developed[16] to meet these requirements. The alphatron current is passed through

[16] Developed from an original design by J. R. Downing and G. Mellen, Rev. Sci. Instr. 17, 218 (1946).

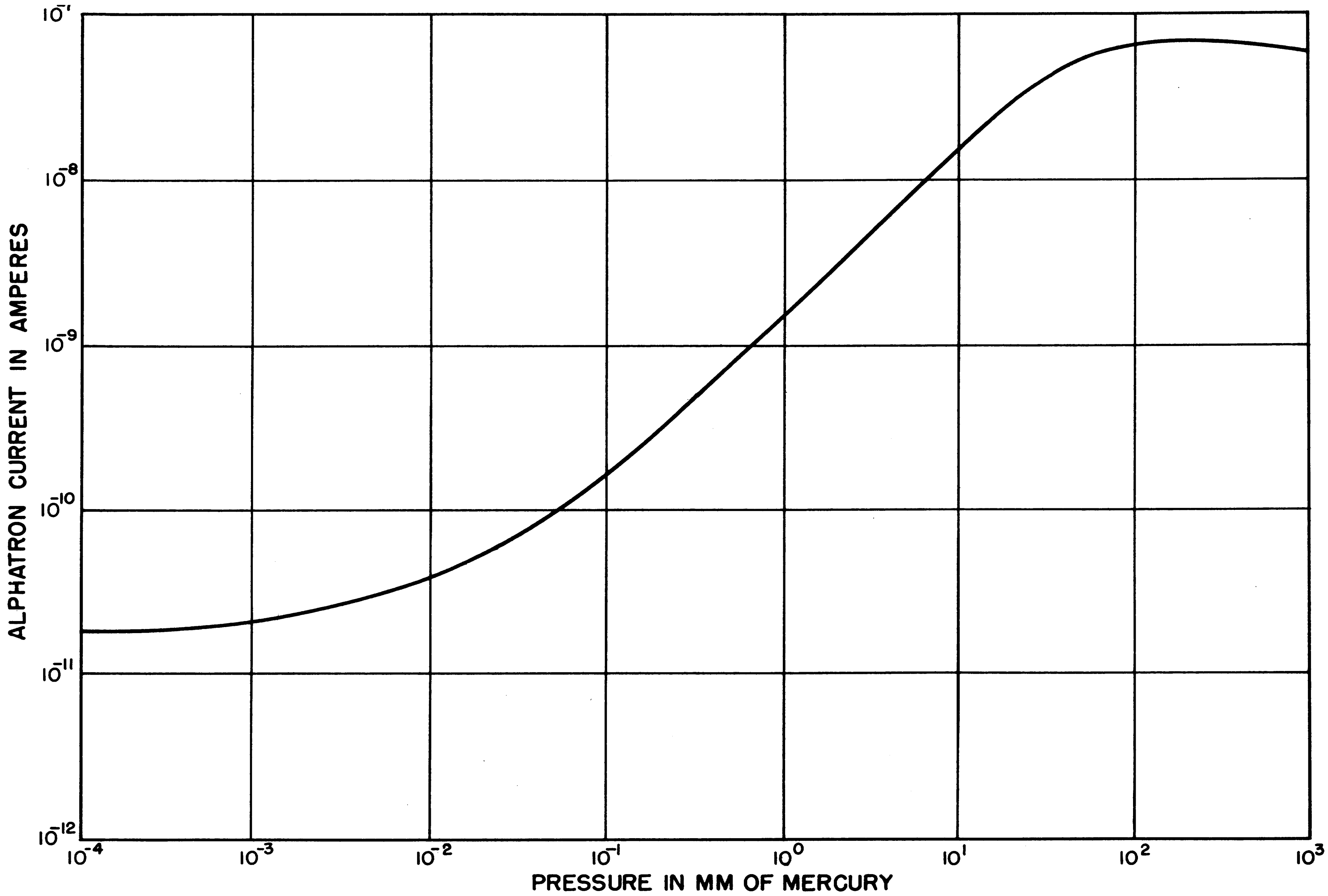


Fig. 23. Variation of Output Current with Chamber Pressure for a Particular Alphatron Pressure Gage.

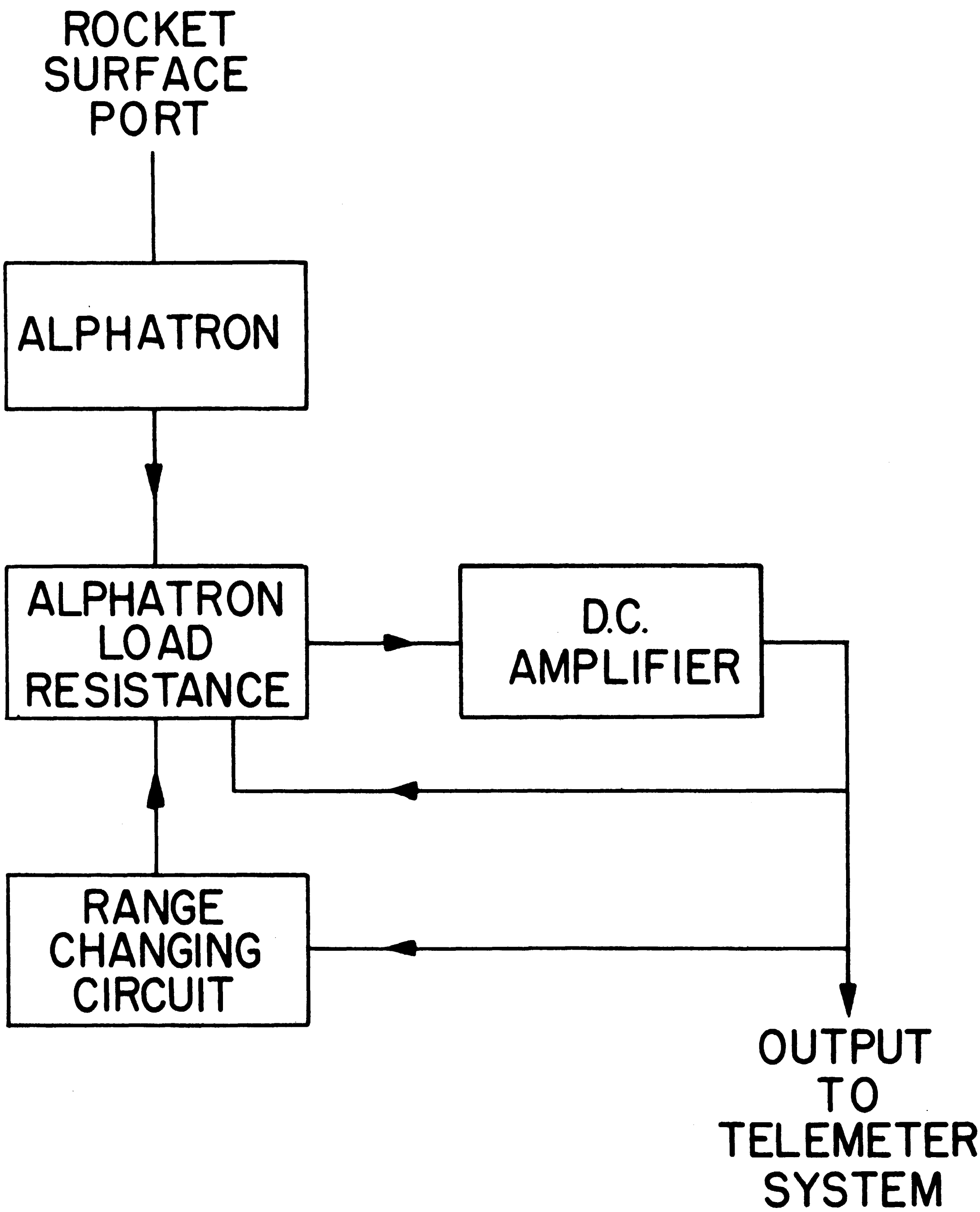


Fig. 24. Elementary Block Diagram of Alphatron Pressure Measurement System.

a resistance of sufficient magnitude to produce a voltage equivalent to the desired information signal. Because of the very small current, this resistance may be as high as 250,000 megohms.

The voltage obtained across this resistance is applied to a 100% negative-feedback d-c amplifier which acts essentially as an impedance-changing device. The first stage of the amplifier employs an electrometer tube in order to provide an input resistance that is large compared with any probable alphatron load resistance. The following sections of the amplifier are, in sequence; a voltage amplifier, a heater voltage regulator, another voltage amplifier, and finally a cathode follower stage. Inside the feedback loop the voltage gain is high, of the order of 4500. However, with feedback, the voltage gain of the system is unity, whereas the current gain is significantly high. Since the output voltage is equivalent to the input voltage (100% feedback) the current gain is numerically equivalent to the ratio of the input load resistor (alphatron load) to the cathode resistor of the cathode follower.

The voltage obtained from the cathode follower constitutes the desired data and is accordingly applied to the recording system, in this case the telemetering system.

In order to provide for the several subranges, different possible values of alphatron load resistance are provided, one for each subrange. It is the function of the range-changing circuit to select and insert the particular load resistance appropriate to a particular range of chamber pressure. To accomplish this, the amplifier output signal is applied to the range-changing circuit, which uses two thyratrons to control a bidirectional rotary solenoid. If the information signal voltage exceeds a predetermined value (in either direction) the next lower or higher value of resistance is inserted, thus returning the information signal to an "on-scale" value. An automatic range-selection device is, of course, necessary because the equipment operates unattended through the total pressure range encountered during a rocket flight.

Figure 25 illustrates the variation of output signal with pressure for a particular subrange. In this case the alphatron load resistance is 5000 megohms.

The complete alphatron equipment in a particular rocket includes several nearly identical, independent units similar to that described above, differing perhaps only in regard to choice of pressure subranges required by particular gage locations, for example, cone wall or cone vertex mounting.

B. Angle Measurement

The gyroscope used for missile angular position measurement is a modified Sperry type F4A unit. The modification was accomplished primarily in

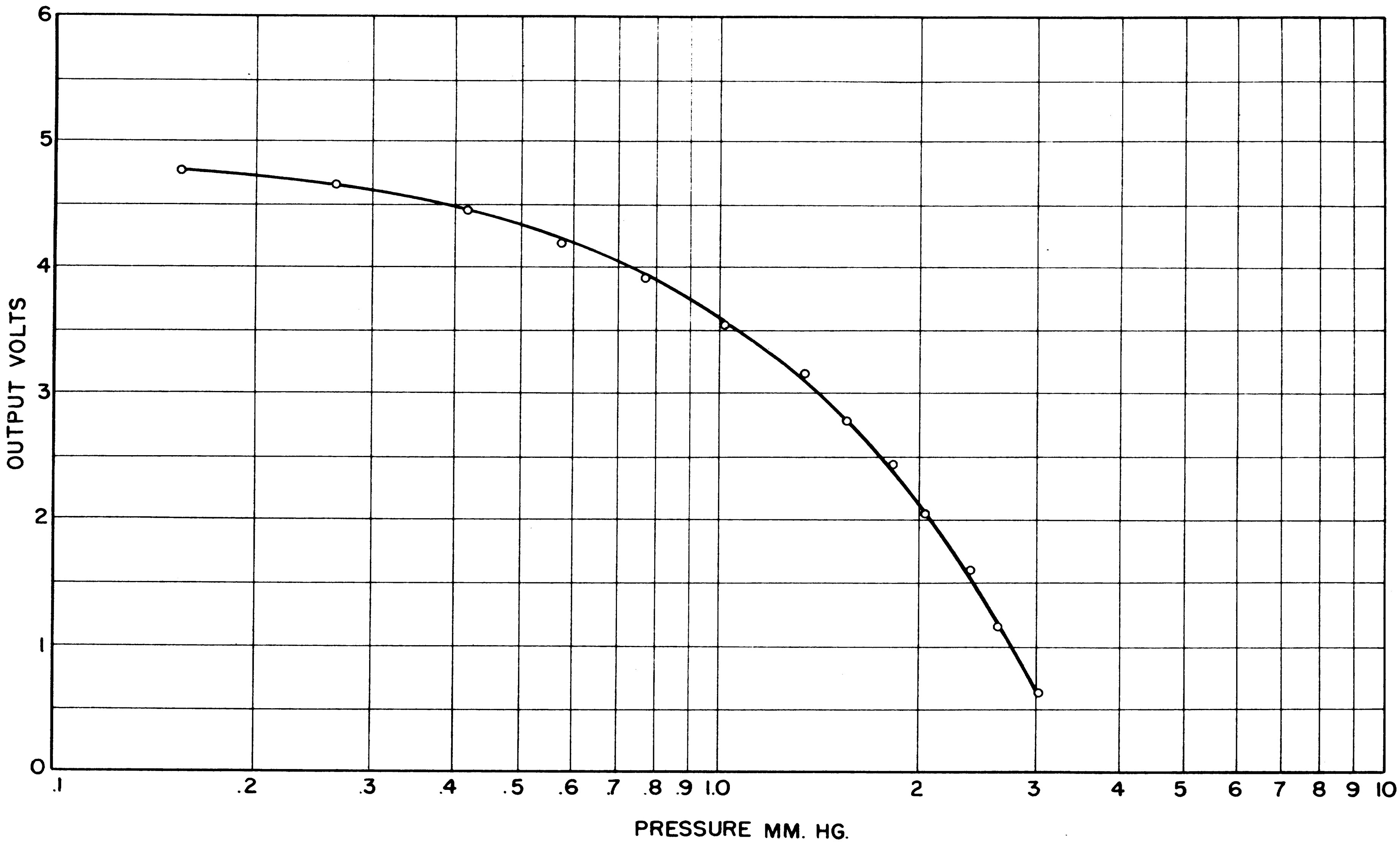


Fig. 25. Variation of Alphatron Pressure Measurement System Output with Pressure for a Particular Sub-Range.

order to allow operation under free-fall conditions. However, in addition, an attachment was developed that enables the establishment of zero position prior to rocket flight.

Recording of gyroscope data is accomplished by photography of the gyroscope sphere (gyrostat) position in reference to a missile-fixed coordinate system. The film on which the position is recorded is recovered at the end of the rocket flight.

IV. EXPERIMENTAL RESULTS

Two experiments based on the above theoretics have been successfully completed. Pressure equipment was instrumented in the Aerobee Sounding Rocket type of missiles for launching by the U. S. Air Force at the Holloman Air Force Base at Alamogordo, New Mexico. The first experiment, on 20 June 1950, carried one impact pressure gage and one cone surface pressure gage. For comparison purposes the two experimental pressures and the resulting computed ambient pressure are shown in Fig. 26. From this first experiment, the ambient pressure data are reliable to 1 part in 35.

The seemingly relatively large scatter in the cone surface pressure is a result of the missile's rotation as it assumes increasing yaw angles with altitude. The impact pressure is generally without such cyclic variations, since it remains independent of the yaw angle for values up to about 30°. Although not shown in entirety, maxima in the ratios of both cone surface and impact pressure to ambient pressure occur in the neighborhood of 35 kilometers in altitude. These maxima are presumably the result of the combination of maxima in the Mach number and the missile velocity; as such they must be constructed as having been caused by missile behavior, and not as representing properties of the atmosphere.

The temperatures computed from these data are shown in Fig. 27. No comment is offered on this curve other than that the maximum probable error is believed to be ± 8°K to about 60 kilometers and ± 13°K above about 60 kilometers.

The second experiment was completed on 13 September 1951. The instrumentation represented considerable improvement over that of 20 June 1950, with two cone surface gages and a greatly increased information-reporting capacity. The increase in sampling information rate resulted in a reduction of the overall probable error of the final temperature data. For Fig. 28 the temperatures up to 50 kilometers have a maximum probable error of ± 5°K while the probable error above 50 kilometers is ± 7°K. The ambient pressure resulting from this flight has an improved accuracy such that it is reliable to 1 part in 65. These data are shown in Fig. 29 as the "experimental-points".

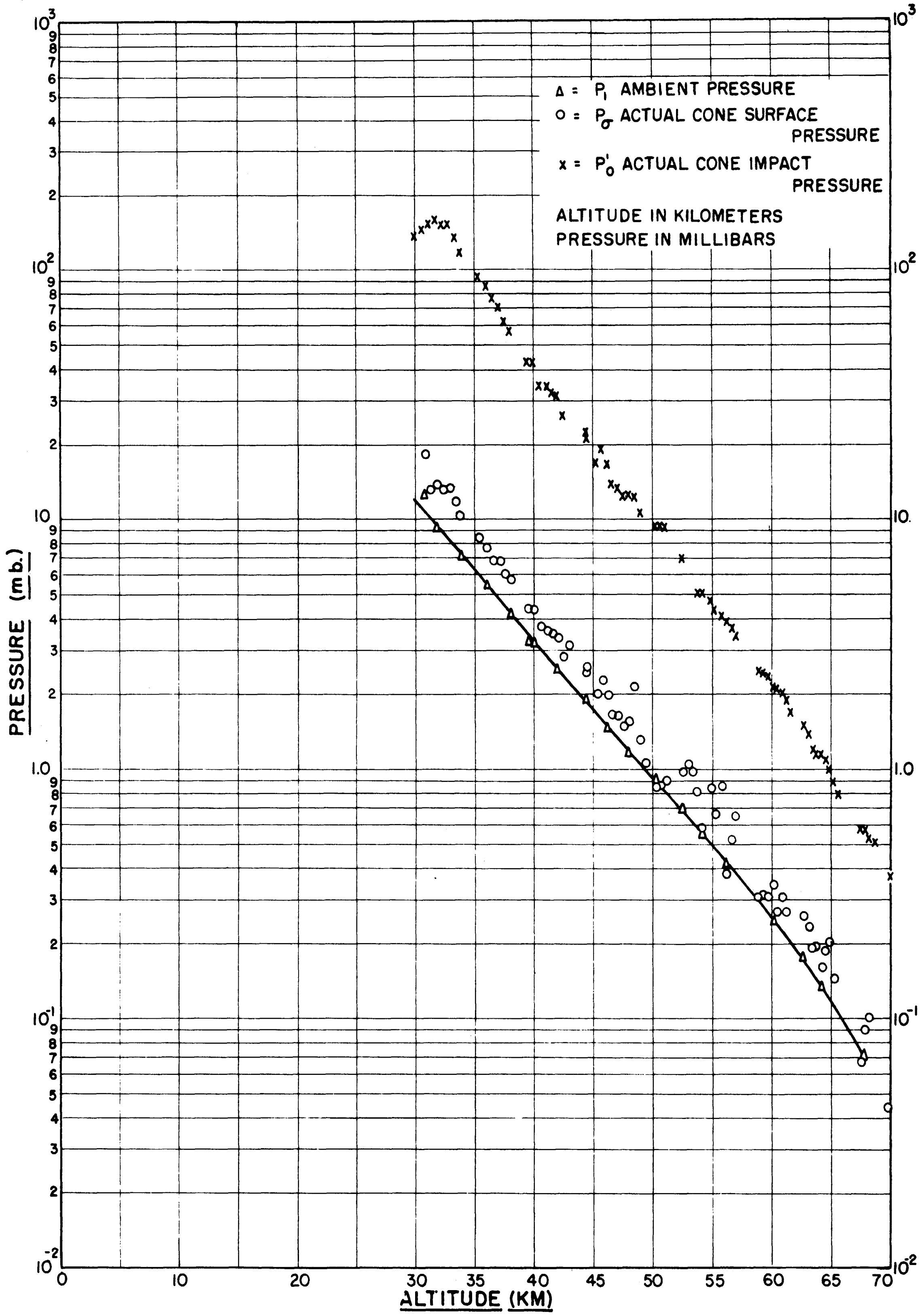


Fig. 26. Actual Cone Pressures, Total Head (Cone Tip) and Surface, Compared with the Ambient Pressure for Aerobee Rocket of June 20, 1950 at 0838 Hours, at Holloman Air Force Base, Alamogordo, New Mexico.

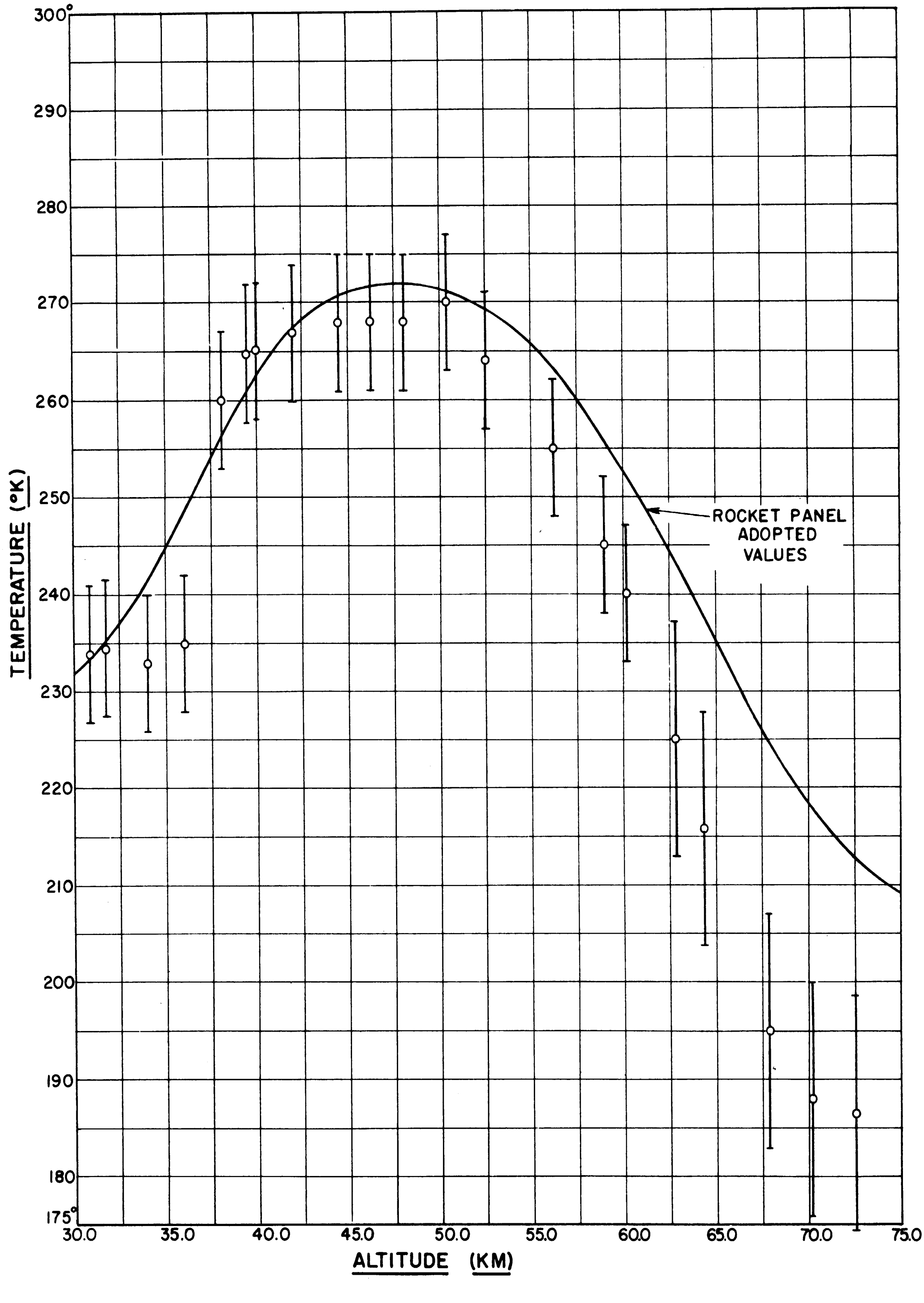
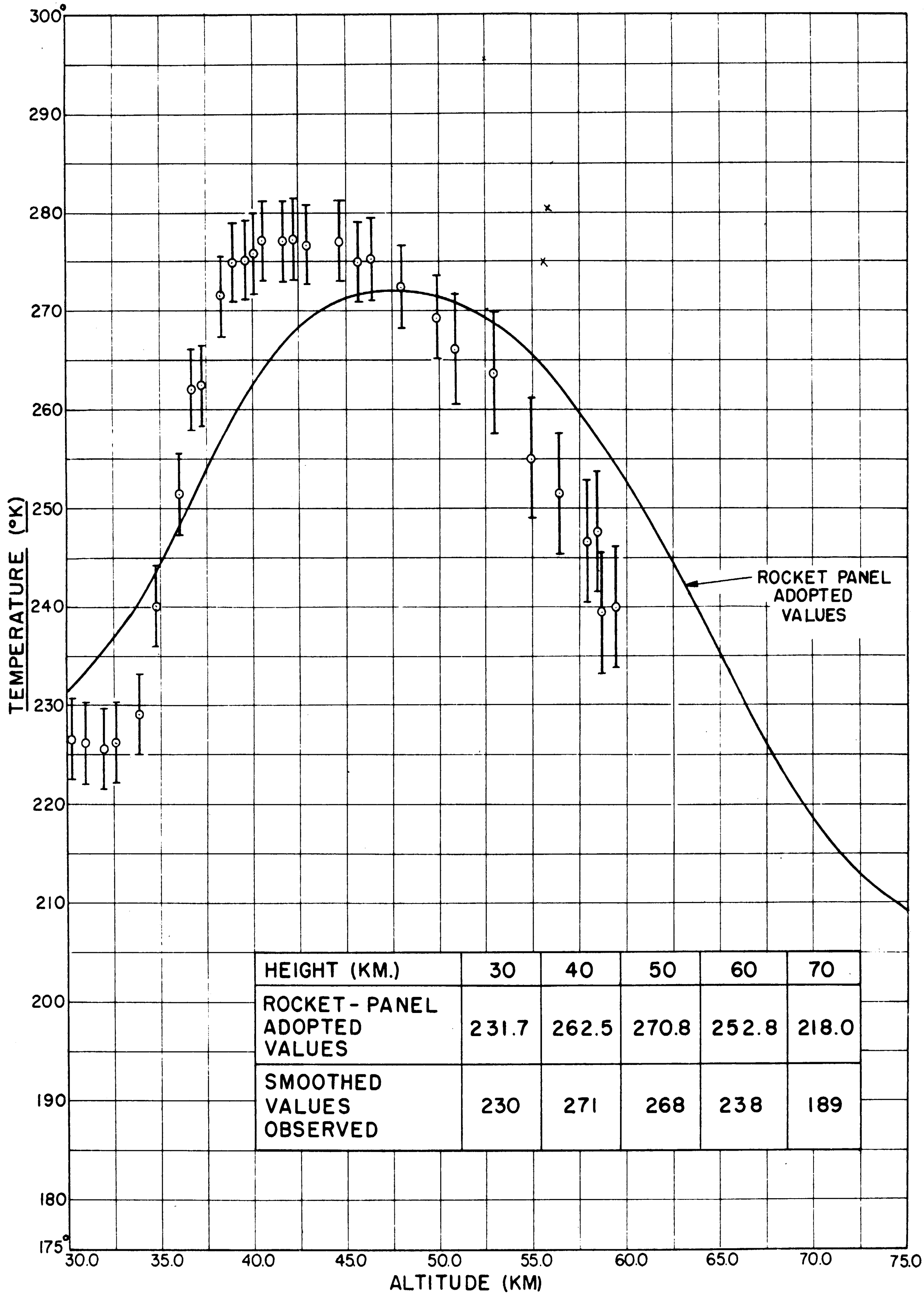


Fig. 27. Ambient Temperature at Various Altitudes above Alamogordo, New Mexico. These temperatures are computed from Aerobee Rocket data of June 20, 1950 at 0838 hours using the assumption of a limited wind field.



HEIGHT (KM.)	30	40	50	60	70
ROCKET - PANEL ADOPTED VALUES	231.7	262.5	270.8	252.8	218.0
SMOOTHED VALUES OBSERVED	230	271	268	238	189

Fig. 28. Ambient Temperature at Various Altitudes above Alamogordo, New Mexico. These temperatures are computed from Aerobee rocket data of September 13, 1951 at 0437 hours using the assumption of a limited wind field.

V. SELF-CONSISTENCY IN THE RESULTS

It has been pointed out above that each experimental point, for the temperature curves of Figs. 27 and 28, is evaluated from the experimental data independently of other points. Furthermore, in the nonyaw case, the temperature calculations leading to Figs. 29 and 30 employ only the ratio of the measured total head pressure and cone surface pressure, not their absolute values. Thus, the absolute values of the pressure measurements are not employed in determining temperatures.

It is obviously possible to employ the experimentally determined temperatures in the familiar hydrostatic equation[17] thereby determining the absolute values of the ambient pressures by a method that does not directly use the pressure measurements obtained by the rocket instrumentation. In such use of the hydrostatic equation an inverse-square variation of gravity is assumed, and a mean molecular weight of 28.966 for air is employed. Balloon observation results are employed to provide the absolute value of pressure at 30 kilometers, which serves as a constant of integration.

Figures 29 and 30 present, for the two data sets, Figs. 27 and 28 respectively, the absolute values of ambient pressure determined as follows:

(a) The values indicated by the circles were obtained by direct point-by-point determination from the data, using Fig. 21 in this case the ambient pressures are obtained, practically speaking, by applying an appropriate correction to the cone-wall pressures.

(b) The values indicated by the crosses were obtained by employing in the hydrostatic equation the Figs. 27 and 28 temperatures obtained point-by-point from the data.

The very good agreement between the two sets of points in each case provides a rather satisfying self-consistency check of the system of instrumentation and data reduction employed. The deviations between the two sets of points are less than the experimental errors of the method. Of course, self-consistency between these two different rocket flights and observations by other methods[18] is also of interest. However, seasonal and diurnal variations of

[17]Mitra, S. K., "The Upper Atmosphere," The Royal Soc. of Bengal Monograph Series, Vol. V, 1947, See equation 3, p. 5 ($dP/P = -mgdh/kT_1$).
[18]The Rocket Panel, Phy. Rev., 88, 1027 (1952).

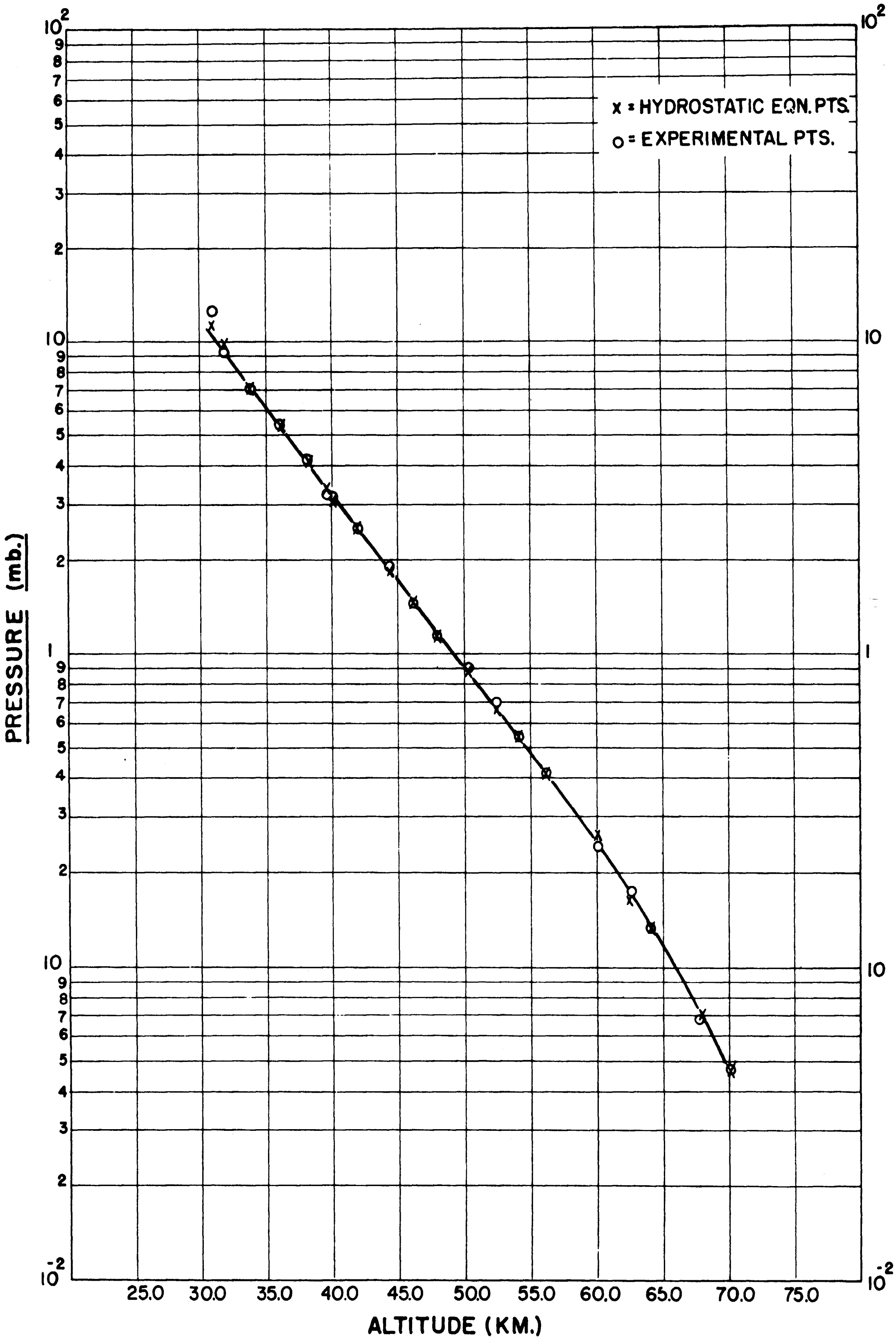


Fig. 29. Pressures Calculated from Hydrostatic Equation (dP/dh = - Pgm/RT) using Experimental Temperature of Fig. 9, Compared with Ambient Pressures for the Same Flight.

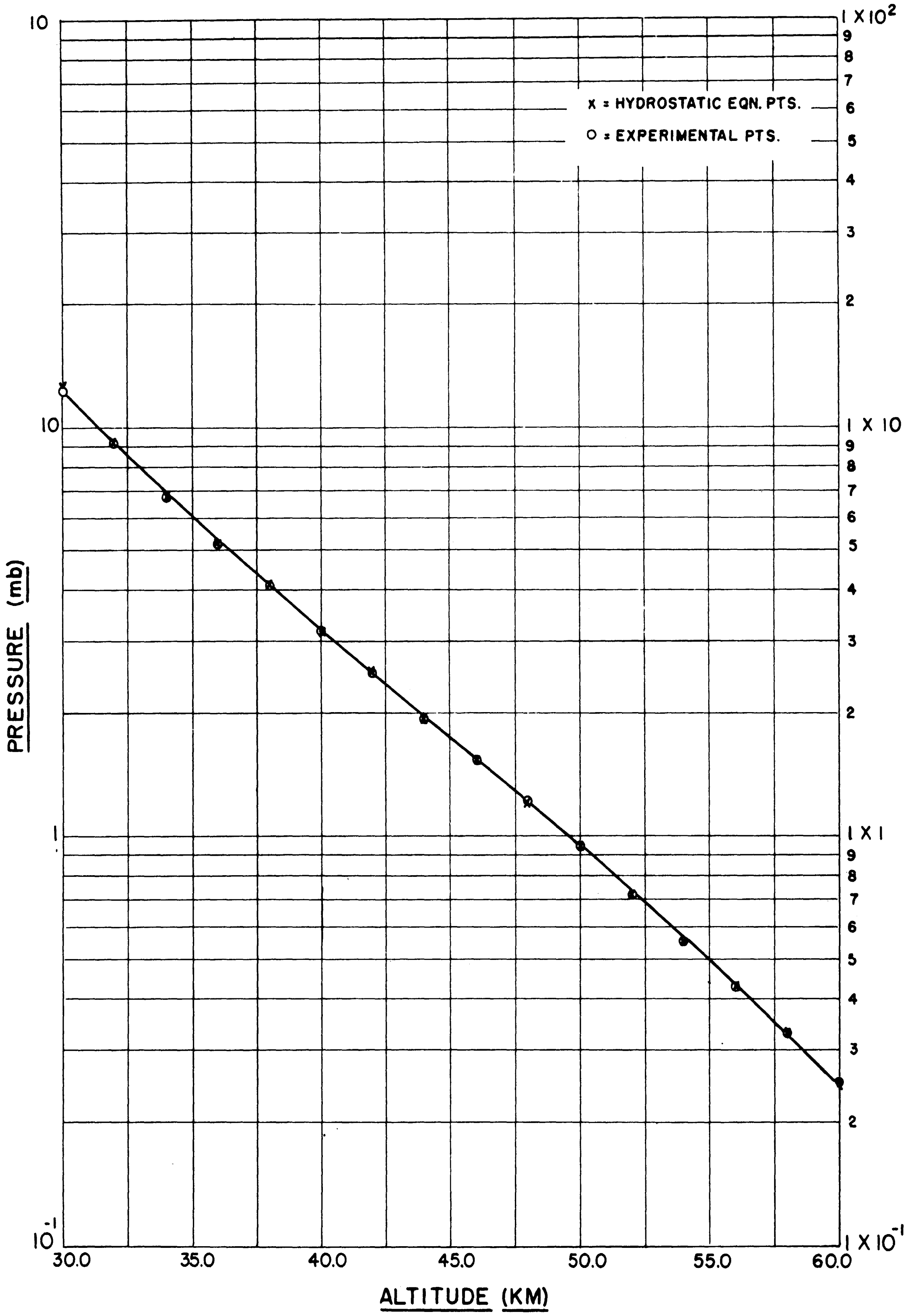


Fig. 30. Pressures Calculated from Hydrostatic Equation using Experimental Temperatures of Fig. 10, Compared with Ambient Pressures for the Same Flight.

the temperature curve certainly exist and must be taken into account in comparing the two sets of results here reported with one another and with results obtained by other methods.

We wish to take this opportunity to thank Mr. Ralph E. Phinney for his interest and valuable discussions involving the basic aerodynamics of this problem.

LIST OF SYMBOLS

P_σ Cone surface pressure of yawed cone, along ray at angle ϕ from plane of yaw.

P_1 Ambient pressure

P_o Stagnation pressure behind conical shock wave

P'_o Stagnation pressure behind normal shock wave

P_2 Static pressure behind normal shock wave

P_w Static pressure at shock wave surface on downstream side of a conical shock wave

$\bar{P}_s$ Cone surface pressure when yaw angle is zero ($\epsilon = 0$)

T_1 Ambient temperature

M_1 Free-stream Mach number

M_2 Mach number behind normal shock wave

V Free-stream velocity

v_w Tangential particle velocity

u_w Radial particle velocity

u_s Cone surface particle velocity

θ_s Cone half angle

c See equation (4)

ϵ Yaw angle

$\eta/\bar{P}_s$ Stone's first-order perturbation coefficient

$P_1/\bar{P}_s$ Stone's second-order perturbation coefficient

$P_o/\bar{P}_s$ Stone's second-order perturbation coefficient

ϕ Spherical coordinate

θ Spherical coordinate

ψ Angle of rotation about cone's longitudinal axis measured from plane defined by cone's longitudinal axis and the wind velocity vector $\overline{V}$

a Local sonic velocity

h Altitude

g Acceleration of gravity

m Mean molecular weight

R Universal gas constant

γ Ratio of specific heats