

PAPERS IN PHYSICAL OCEANOGRAPHY AND METEOROLOGY

PUBLISHED BY

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

AND

WOODS HOLE OCEANOGRAPHIC INSTITUTION

(In continuation of Massachusetts Institute of Technology Meteorological Papers)

VOL III, NO. 2

THE METEOROLOGICAL AIRPLANE
ASCENTS OF THE MASSACHUSETTS
INSTITUTE OF TECHNOLOGY

I

On the Technique of Meteorological Airplane Ascents

BY

K. O. LANGE

II

Aircraft Instruments in Meteorological Flying

BY

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CAMBRIDGE, MASSACHUSETTS

August, 1934

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I. ON THE TECHNIQUE OF METEOROLOGICAL AIRPLANE ASCENTS

BY K. O. LANGE

A. PURPOSE, REGULARITY AND COST OF ASCENTS

In November 1931 the Meteorological Division of the Massachusetts Institute of Technology established a meteorological airplane station at the East Boston airport. Since that time regular ascents to heights of from 17,000 to 27,000 feet have been made daily at about 8 A.M. during the academic year, or from October 1 to the end of May. Part of the temperature and humidity observations obtained through these flights have been published in tabular form in the Monthly Weather Review [1].* The final and detailed publication of all flights will be included in a subsequent report in the form of reproductions of adiabatic charts and Rossby diagrams. These charts show, for each significant point, pressure in millibars, altitude in dynamic meters, temperature in °C, relative humidity, vapor-pressure in millibars, mixing ratio ($0.622 \frac{e}{p-e}$) in grams per kilogram, potential and equivalent potential temperature, supplemented by observations on clouds, haze, bumpiness, ice formation, high winds and other meteorological phenomena.

The aerological flights at Boston are part of the general research program of the Meteorological Division of Massachusetts Institute of Technology, which program since 1929 has been directed especially toward the study of American air masses and fronts. Recently, some results of these studies were published by Willett [2], who based his investigations on a series continuous over three years of morning and evening weather maps, analyzed at the Institute, together with upper air soundings from the United States Weather Bureau stations at Dallas, Omaha, Chicago, Groesbeck, Atlanta and from the United States Navy at Seattle, Anacostia, Pensacola and San Diego. These upper air data facilitated the determination of the properties of the air masses and so proved of inestimable value for the study. But the use of the data also showed that improvement both in the number of stations and in the quality of observations was highly desirable. Ascents in the northeastern part of the United States were lacking. Knowledge of the vertical structure of air masses reaching this region, however, is of special interest in forecasting for this densely populated district. For these reasons and since the direct comparison of actual local weather developments with upper air conditions is also considered to be very valuable, the Institute started its own airplane station at Boston. In addition to "regular" ascents at the time of the morning surface observations, special flights were made when particularly interesting weather situations prevailed. On a number of days series of ascents were carried out to obtain cross sections through fronts passing over Boston. Other special flights were made to obtain information on atmospheric turbulence. For this same purpose and also in order to study the diurnal changes of temperature in the lowest 5,000 feet, several series are planned of a number of comparatively low altitude flights at short intervals throughout the day.

Particular attention was devoted to the study of aerological observational technique. Observation methods and instruments had to be improved and reliable calibration equipment developed. It is this part of the work that will be treated in the present paper.

* References are indicated by figures within brackets and are listed at the end of the paper.

The educational value of practical experience in good aerological technique is an important consideration in the program of the airplane station. Realizing that in the future much greater use will be made of upper air observations for weather forecasting, the Institute gives its students in meteorology a thorough training in the technique and the use of data of meteorological ascents. Every regular flight observation is at once made available to the U. S. Weather Bureau station at the East Boston airport and distributed over the teletype system for use in the synoptic service.

Besides meteorological investigations a number of other problems were attacked in cooperation with the United States Department of Agriculture and with other departments of Massachusetts Institute of Technology. During the time of the development of the gypsy moth larvae in the spring, insect catchers were mounted on the plane and taken up to determine the altitude which the gypsy moth larvae reach while spreading. A report on these investigations has recently been published by Collins and Baker [3]. Since January 1933 a device for collecting bacteria and pollen is regularly carried up and exposed at different altitudes. A preliminary report on this work has been published by Proctor [4]. Air samples were taken at the top of climb for the determination of the composition of the air at this height and attempts were made to collect sufficient dust at high altitudes to permit a study of the amount of meteoric dust in the atmosphere.

During the National Glider Contests of 1932, 1933, and 1934 at Elmira, New York, aerological ascents were carried out with the aid of grants from the Soaring Society of America. Since these ascents were not a definite part of the program of the Boston station, they are not included in the tables to follow.

The airplane station is under the direction of Professor C. G. Rossby, and under the direct supervision of the writer, who was invited to the Institute mainly to establish and maintain the aerological and instrumental work of the division. During 1931-32, the research pilot was D. C. Sayre, Assistant Professor of Aeronautical Engineering, and during 1932-33 the late Lt. H. B. Harris. Professor Sayre left Massachusetts Institute of Technology at the end of the year 1932 due to ill health. The writer wishes to express his appreciation for the splendid cooperation given by both these men. Their excellent advice on all technical questions, their ability to establish contacts with all sources of help for the establishment of the station, and above all their courageous flying, even in hazardous weather conditions, contributed in a great measure to the success of the work from the very beginning. While the chief pilots flew five days a week, spare pilots made the remaining ascents. In 1931-32 the spare pilots were Lt. Pierson and Lt. Harris, in 1933 Mr. Joseph Barber. To assist in the meteorological part of the work Messrs. C. Harmantas, S. Lichtblau, and J. Namias worked regularly at the airport.

Due to the former connection of the writer with the Deutsches Forschungsinstitut für Segelflug (Rhoen-Rossitten-Gesellschaft) and with the Technische Hochschule Darmstadt, our airplane station has profited to a large extent from the experiences of the German aerological stations. It is here in Boston however, that the first attempt was made to run aerological ascents to high altitudes regularly with a "small airplane." The German system is to carry, besides the pilot, a meteorologist who completes the meteorograph records by eye observations and by such interpretation as only a trained observer can furnish. This procedure is what really makes the airplane superior to other kinds of aerological carriers, such as kites, captive balloons and sounding balloons. However, also a small single seated airplane can be used advantageously if flown by the meteorologist himself. This means a saving not only in running expenses but also the saving of one

salary. The "small plane station" with a meteorologist as pilot thus represents the ideal method if the purpose is solely to collect accurate and complete upper air observations such as are used in weather forecasting especially in forecasting for air traffic. If additional research work is planned a larger crew and a double seated airplane are essential.

During the flying period 1931-32, the Institute worked with a Cessna plane with a 110 H.P. Warner engine. Fully equipped with meteorological and navigation instruments and flown without passengers this ship had an absolute ceiling of over 20,000 feet and a service ceiling of about 17,000 feet attainable in $1\frac{1}{2}$ hours. Prof. Sayre quickly acquired the familiarity with observational aspects of aerological meteorology necessary to furnish valuable eye observations. Only on exceptional cases did the writer take part in the flights, for instance when particularly interesting weather situations required interpretation or when cloud photographs had to be taken.

At the beginning of the period 1932-33 the Cessna airplane was replaced by a Curtiss-Robin with a 185 H.P. Challenger engine. This was a step towards the two place plane which permits the ascent of two persons, one of whom concentrates completely on all the problems bearing on the exploration of the atmosphere which have been taken up since the establishment of the station. A special glass-encased cabin and the installation of new equipment made this plane a real "flying laboratory" capable of reaching 15,000 feet within one hour with two persons and 17,000 to 18,000 feet with one person.

For the chief purpose of the ascents, the determination of the vertical temperature and humidity distribution, the additional altitude of nearly 3,000 feet attainable by leaving the meteorologist on the ground seemed more valuable than the contributions of a trained meteorological observer. Therefore, during the period 1932-33 most regular ascents were made by the pilot alone. In the second half of May 1933 observers were carried up regularly, the altitude sometimes being increased by extending the time of climb to 90 minutes. During this period studies with psychrometers and dew point indicators were made and dust samples were taken. Careful manometric measurements on Venturi tubes and Gyro pumps were made. Moving pictures of the behavior of the navigation instruments in extreme flying positions and at different elevations were taken. Results of these tests are discussed by C. S. Draper in another section of this report. Unfortunately, the financial situation did not allow the acquisition of a plane of higher performance, which would have facilitated studies of this kind throughout the year.

During the years 1931 and 1932 the station was maintained by a special fund from the Institute, a contribution from the Joseph Henry Fund of the National Research Council and a special appropriation from the Daniel Guggenheim Research Fund in meteorology, which had previously been placed at the disposal of the Meteorological Division. At the end of 1932 the Rockefeller Foundation made possible the continuation of the work through a special grant for the year 1933. On account of the restricted means available for the work, utmost economy had to be observed from the beginning. A short survey is given below of the financial side of the work. For comparison with similar ascents of other institutions the following tables present also the technical results since 1931. All the data in these tables are separated into the period of the "small plane station" and the later period.

Table I, column IV shows the regularity of the ascents as the ratio between the number of flights actually made to the number of scheduled flights. It should be noted here that there were no ascents made on Sundays and holidays during the first three months. Since February 1932 every day was scheduled for a flight with the exception of the sum-

TABLE I
REGULARITY OF THE METEOROLOGICAL FLIGHTS AT BOSTON
November 1931-May 1932; October 1932-May 1933

		I	II	III	IV
		No. of regular flights to be made	No. of flights missed due to weather	No. of flights missed due to technical reasons	regularity $\frac{I - (II + III)}{I} \cdot 100$
1931	Nov. 17-30	12	2		83
	Dec. 1-19	17	1		94
1932	Jan. 4-31	25	5	1	77
	Feb.	29	4		86
	Mar.	31	2	1	91
	Apr.	30	3		90
	May 1-16	16	1		94
Flying Period 1931/32		160	18	2	88
1932	Oct.	31	3		91
	Nov.	30	3		90
	Dec. 1-23	23	2		91
1933	Jan. 3-31	29	2		93
	Feb.	28	3		90
	Mar.	31	5		84
	Apr.	30	4		87
	May	31	2		94
Flying Period 1932/33		233	24		90
Total 1931-1933		393	42	2	89

mer vacation and a few days at Christmas for top overhaul of the engine. The regularity has a minimum of 77% in January 1932. From then on it increases to 90% and 94% due in part to more favorable flying weather, in part to our increased experience in cloud flying and to the gradual completion of our flying and safety equipment. The mean regularity during the two years was 89%, in other words, we missed three to four flights per month. At first glance this seems to be a fairly poor average. However, it must be taken into account that the work at the aerological station was only a part time job for both pilot and meteorologist. Consequently, when for any reason an ascent could not be made in the early morning hours, in general it had to be cancelled altogether. Only if there was a particular interest in the weather situation, flights were arranged later in the day. In these cases the ascent at the time nearest to 8 A.M. was designated a "regular flight" and included in the tables as such.

The regularity of aerological observations is of course of the same importance as the regularity of ground observations. Nevertheless, the fact that no attempt was made to force the regularity of the Massachusetts Institute of Technology station to 100%, is due to our belief that the value of an individual meteorograph ascent is not to be compared with the value of human life or even a serious risk of plane and instruments. During the first period there occurred two emergency landings outside the home airport due to very bad weather. In one case expensive repairs were caused. In both cases it became impossible to fly on the following day on schedule. The even more conservative attitude observed after these incidents probably helped considerably to avoid similar mischief later on. Decisions not to fly were made only after a careful study of the weather map and

TABLE II
DIURNAL DISTRIBUTION OF METEOROLOGICAL FLIGHTS AT BOSTON
The plain numbers refer to the "regular" flights. The numbers in parenthesis give the special flights.

		at 6 ^h	7 ^h	8 ^h	9 ^h	10 ^h	Number of Ascents						Total	
						11 ^h	12 ^h	13 ^h	14 ^h	15 ^h	16 ^h	17 ^h	18 ^h	
1931	Nov.	0	8	1	0	1	0	0	(1)	0	0	0	0	10(1)
	Dec.	0	6	8	1	1	(2)	(1)	(1)	(2)	(1)	0	0	16(7)
	Jan.	0	10	7	(2)	0	1	1	(1)	(1)	0	(1)	0	19(5)
	Feb.	0	9	10	2	1	2	0	(1)	1	0	(1)	0	25(2)
1932	Mar.	0	22	4	1	(3)	(1)	1	(2)	(3)	1(1)	0	0	28(10)
	Apr.	2	16	6	0	1	0	1(1)	(1)	0	0	0	0	27(2)
	May	8	7	0	0	0	0	0	(1)	0	0	0	0	15(1)
1931/32		10	78	36	4(2)	4(3)	3(3)	3(2)	0(8)	1(6)	1(2)	0(2)	0	140(28)
	Oct.		25	1	1	1		(1)		(1)		(1)		28(3)
1932	Nov.		24	3	(1)		(1)							27(3)
	Dec.		19	1					1					21(0)
	Jan.		24	3										27(0)
	Feb.		18	3		1	1	1	(2)	1	(1)	(1)		25(4)
1933	Mar.		23	1		2		1	(1)		(1)	(1)	(1)	26(4)
	Apr.		19	2	2		(1)	2	1		(1)			26(2)
	May		26	2			1							29(0)
1932/33			178	16	3(1)	4	2(2)	3(1)	2(3)	1(1)	(3)	(3)	(1)	209(16)
1931-33		10	256	52	7(3)	8(3)	5(5)	6(3)	2(11)	2(7)	1(5)	(5)	(1)	349(44)

the latest available airway observations. On account of the regulations of the insurance company flights had to be cancelled when there was a ceiling of less than 500 feet of a thick solid overcast nature. This includes dense fog over large areas. Furthermore, flights were not made when there was continuous precipitation out of thick solid clouds, causing a visibility of less than 1 kilometer together with considerable danger of ice formation. This situation is encountered rather frequently in New England with a low pressure center to the East and northeasterly winds. It frequently stops all flying for two or three successive days.

As already pointed out, the ascents lose considerable value for their main purpose if not made at the time of the morning ground observations and if not available for the students' synoptic laboratory course. Table II shows the diurnal distribution of the ascents. During the first period 124 out of 140 flights were started before 9:30 A.M., during the second period 194 out of 209, that is 91% of all regular flights.

Next to regularity the mean altitude of ascents is the most important characteristic of an aerological station. It is generally given as the sum of the individual tops of climb divided by the number of ascents carried out. This ratio is lowered when ascents are made in very bad weather to low heights, although the efficiency of the station really is higher than if no flights are made. A more significant number is the ratio between the sum of all heights over the number of flights which should have been made. These ratios are given for the individual months in Table III, column I. Column II shows the mean altitudes as the first mentioned ratio between sum of altitudes of the regular flights over the number of regular flights to be compared with the corresponding data of other stations. Finally, in column III there are shown the average altitudes of all the flights including the special ones. The mean cost of one ascent as computed below, is related to all the flights, in other words it corresponds to the average altitude of 4680 meters.

TABLE III
MEAN ALTITUDES OF THE METEOROLOGICAL FLIGHTS AT BOSTON

Regular Flights					All Flights		
I			II		III		
		Number of days when flights should have been made	Ratio of sum of alt. over no. of scheduled flights	Number of regular flights carried out	Mean alt. of the flights carried out	Number of all flights carried out	Mean alt. of all flights made
1931	Nov.	12	3440	10	4120	23	3970
	Dec.	17	4650	16	4940		4690
1932	Jan.	25	3780	19	4980	24	4590
	Feb.	29	3200	25	3720	27	3780
	Mar.	31	3900	28	4320	38	4120
	Apr.	30	3880	27	4320	29	4330
	May	16	4160	15	4440	16	4460
1931-32		160	3820	140	4370	168	4260
1932	Oct.	31	4670	28	5170	31	5050
	Nov.	30	4450	27	4950	30	4450
	Dec.	23	4650	21	5090	21	5090
1933	Jan.	29	4460	27	4790	27	4790
	Feb.	28	4550	25	5100	29	4980
	Mar.	31	4290	26	5110	30	4650
	Apr.	30	4730	26	5460	28	5400
	May	31	4870	29	5220	29	5220
1932-33		233	4580	209	5100	225	5000
1931-33		393	4280	349	4810	393	4680

The survey of the cost of the ascents had to be restricted to the first period, since the inclusion of the later activities would have delayed publication of this report.

The expenses were separated into three groups:

1. Running expenses
 - a) regular
 - b) caused by forced landing
2. Expenses for instruments and parachute
3. Salaries

The running expenses should be the same within narrow limits for similar stations. The expenses for the instruments are primarily determined by the choice of a rate of depreciation. It is assumed that the average life of the instruments exceeds five years, which seems to be very reasonable, especially since a considerable amount for instrument repair and overhaul is included in the running expenses. The item for instrument depreciation is entered separately, so that it might be modified to agree with the policy of other institutions, if desired. The expenses for personal compensation form the third group. They are mentioned separately, since the very favorable arrangements at the Massachusetts Institute of Technology during the first period hardly can be expected to obtain at other stations. There is practically no salary paid, since the work at the station is considered as an addition to regular duty at the Institute. To give an idea of expenses

for personnel, it might be mentioned that the amount paid to relief pilots is now \$5 to \$7 per ascent.

The Running Expenses were:

Cessna airplane bought for \$1,200	
sold for 600	\$ 600
Liability Insurance for 7 months	135
Storage of plane and daily service of mechanic—6½ months per \$35	228
Seven 20-hour checks on engine (average price \$20)	154
Top overhaul	79
Repairs on plane and engine, caused by regular use	218
Installation and repairs on instruments (including supplies which became worthless after the plane was taken out of service, such as meteorograph brackets, etc.)	268
Gas and oil	441
Office material, furniture, telephone, hydrogen, oxygen, dry ice, photo material, etc.	147
	<hr/>
Expenses, mainly repairs, caused by an emergency landing	\$2,270
	354
	<hr/>
Total Running Expenses	\$2,624

Meteorological instruments:

Two Bosch airplane meteorographs	\$237
Pressure-temperature chamber built at Massachusetts Institute of Technology	150
Humidity calibration apparatus	10
Ventilation shelter built at Massachusetts Institute of Technology	40
	<hr/>
	\$437

Depreciation for one year \$87

Flying instruments:

Artificial Horizon	
Altimeter	
Bank and Turn indicator	
Cup-speedometer	
Wing thermometer	
Gyro compass	
Climb indicator	
Radio set and shielding	
Oxygen device	
Parachute	\$1,310
Depreciation for one year	\$ 262

Total depreciation of equipment \$ 349

Pay to spare pilots and assistants \$ 292

Total expenses \$3,265

With a total amount of \$3,265, which covered all expenses including the airplane and a five years' depreciation of all instruments the Massachusetts Institute of Technology "small plane station" carried out within six months 168 ascents to an average altitude of 4,670 m. This gives an average total expense of \$19.43 for one flight.

B. MEASUREMENTS OF TEMPERATURE

Surface air temperatures are usually measured with standard mercury thermometers which are protected from radiation and kept properly ventilated. Temperatures of the free atmosphere are normally recorded with the aid of bimetal elements. What really is determined in both cases is not the air temperature but the temperature of the mercury or the bimetal. We assume that air temperature and instrument temperature are sufficiently equal. They never are absolutely the same when the air temperature is changing, since a heat transfer from the air to the instrument has to take place in order to change the instrument temperature accordingly and since this heat flow is possible only when

there exists a temperature difference between the two media. The temperature difference between air and instrument will be larger, the larger the heat capacity of the instrument is and the quicker the air temperature changes. Temperature changes at the ground are generally rather slow. The heat capacity of all standard thermometers is roughly the same. Thus the error in taking air temperature in this way is small and of the same order of magnitude for all stations. This makes it permissible for many purposes, especially for temperature comparisons of different locations, to use the thermometer readings without corrections. The conditions for upper air soundings are different. No matter which one of the aerological methods is used, whether balloon, kite, airplane or parachute, the velocity with which the thermometer is carried vertically through the atmosphere is so high that the instrument always undergoes large and rapid temperature changes. Moreover, the different types of meteorographs are equipped with thermometers of quite different heat capacities. The ventilation conditions of different carriers and different meteorographs differ among themselves. The errors in these temperature indications are therefore likely to be larger than in the surface readings, and data gathered at different aerological stations are not readily comparable. It is therefore essential that a careful investigation of these effects be made at each individual station. In many cases temperature corrections should be applied in order to keep the errors within reasonable limits. Since the application of corrections is a tedious procedure and since even a very careful correction can not eliminate all the errors, efforts should be directed towards the designing of thermometer elements for aerological soundings which do not require corrections.

Thermometers are influenced by two different types of temperature changes, namely, those caused by the rapid change of elevation of the carrier and those caused by certain quick changes of temperature which seem to take place in the air all the time. Investigations with highly sensitive thermocouples prove that the temperatures indicated by the standard thermometers actually represent mean values of temperature fluctuations of short periods and variable amplitudes. A certain type of such fluctuations, having amplitudes of the order of magnitude of 1°C and periods of, roughly, one second, have been registered by Barkow [8]. Fluctuations of larger size can easily be measured anywhere with sensitive thermographs. Measurements of this kind made by J. Namias at East Boston Airport in June 1932 showed fluctuations up to 4°C near the ground. Doubtless similar temperature oscillations prevail throughout the turbulent layer of the atmosphere. Even at 5,000 meters, "horizontal gradients" of 1.5°C (Boston, April 6, 1933) were registered by the Standard Bosch meteorographs. It is reasonable to assume that they are even more frequent than our present observation methods indicate.

It would be of the highest importance for the study of turbulence to measure the temperature structure of the atmosphere regularly at different altitudes. This would require thermometers of extremely high sensitivity. Such thermometers could be developed in the form of recording thermocouples, probably even for use in airplanes. Since the temperature changes due to turbulence are faster than the temperature changes due to the climb of the fastest climbing meteorograph carriers now in regular use, thermometers of this kind would naturally register the vertical temperature changes without noticeable lag. It is nevertheless questionable whether such a record of the actual air temperature structure as could be obtained by our ordinary aerological soundings would be of much use for research in turbulence. Our aerological soundings give us, not a simultaneous, but a successive, record of the temperatures at the different eleva-

tions. Balloons, kites and especially airplanes change their location during the ascent. Thus, the temperature records would present the air temperature in a rather complicated form, as a function of time, height and location. For the study of turbulence with the help of exact temperature measurements it seems to be necessary to abandon our usual aerological methods. Temperature—time records from highly sensitive thermographs placed at certain elevations must be taken. This has already been done by mounting resistance thermometers or thermocouples at different heights on towers. It should not be impossible to extend this method to kites. Thermographs could be carried on an airplane and on cables hanging down from an airplane, the plane flying at constant altitude. The difficulty will consist in keeping the altitude constant.

The use of such sensitive thermometers in regular aerological ascents implies considerable disadvantages. The temperature traces would represent a superposition of horizontal, vertical and time temperature structure. At our present state of knowledge, we would not be able to differentiate correctly between these effects. Most aerological soundings are carried out to gather information to be used immediately in forecasting. The vertical temperature and humidity distribution are the most important data gained from the ascents and to distribute them quickly is often more vital than to collect additional scientific information. For this reason too detailed temperature traces are not desirable. However, it would facilitate computations if the lag of the thermometers could be kept low enough to get records of the vertical temperature distribution without marked errors. In the following an attempt is made to show to what extent it is possible to reach this goal with the help of an ordinary mechanically recording bimetal thermometer.

It is well known that the indicated temperature T_i differs from the actual temperature T by an amount which is proportional to the time rate of change of the indicated temperature, thus

$$T - T_i = \alpha \frac{d T_i}{d t}.$$

α represents the lag coefficient of the thermometer expressed in minutes. α is known to be 0.38 minutes for a mercurial thermometer of the standard Assmann psychrometer at a ventilation velocity of 2 meters per second. This means that the indications of the thermometer lag 0.38°C behind the actual air temperature provided the actual temperature changes at the rate of 1°C per minute. Changes of 3°C per minute are encountered rather frequently when making aerological ascents, the plane climbing at the rate of 300 meters per minute through layers with dry adiabatic lapse rates. Even changes of more than 7°C per minute (Boston, May 28, 1933) are not rare when the ascents are carried out at early morning hours with radiation inversions. In these cases, readings of a standard mercury thermometer (if ventilated at the rate of 2 m.p.s.) would be 1.1°C or 2.6°C too high or too low respectively.

The lag coefficients of some of the types of meteorographs which are used in aerological observations in the United States were determined in the Massachusetts Institute of Technology wind tunnel at an air speed of 63 miles per hour. The standard Bosch Meteorograph as used in the Massachusetts Institute of Technology ascents has a lag coefficient of $\alpha=0.27$. The same type of meteorograph, but equipped with a bimetallic test strip of a thickness of $0.01''$, gives $\alpha=0.10$. The lag coefficient of a standard Friez aerograph was found to be $\alpha=0.75$. Another Friez aerograph, which was kindly put at

our disposal for these investigations by the U. S. Weather Bureau, has a lag coefficient of $\alpha = 1.04$. Kopp [19] gives the lag factor of a Marvin kite meteorograph, used as an airplane meteorograph by the Berlin aerological station, as $\alpha = 0.17$. Based on the above mentioned frequently encountered rate of a temperature change of 3°C per minute, these five instruments reach their state of equilibrium when the deviations from the true air temperature are the following:

Standard Friez I	3.1°C
Standard Friez II	2.3°C
Standard Bosch	$.8^{\circ}\text{C}$
Marvin Kite	$.5^{\circ}\text{C}$
Bosch with Test Strip	$.3^{\circ}\text{C}$

These examples show clearly that without the application of corrections the upper air data, especially those obtained with Friez aerographs, may frequently differ from real conditions and not be comparable among themselves. The Friez company is now developing a meteorograph with greatly reduced temperature lag.

Assuming that the meteorograph registers the correct temperature at the moment of take off ($t=0$) and assuming furthermore that the actual temperature encountered during the flight drops at a linear rate,

$$T = T_0 - \beta t,$$

then the lag formula shows that the indicated temperature will drop at the rate

$$T_i - T = \Delta = \alpha\beta[1 - e^{-t/\alpha}] = \Delta_{\infty}[1 - e^{-t/\alpha}].$$

Δ_{∞} represents the constant difference between indicated and actual temperature listed above for five different instruments. If the actual temperature changes at a rate of 3°C per minute (actual lapse rate, $1^{\circ}\text{C}/100\text{ m}$, rate of climb 300 m per minute) the indicated average lapse rates for the first 300 m and for the first 600 m will differ considerably from the true lapse rate, as may be seen from the following table.

TABLE IVa
INDICATED LAPSE RATES

Instrument	$0-300\text{ m}$	$0-600\text{ m}$	Adiabatic Atmosphere, Rate of Climb 300 m per minute
	$\frac{dT_i}{dz}$ in $\frac{^{\circ}\text{C}}{100\text{ m}}$	$\frac{dT_i}{dz}$	
Standard Friez I	0.36	0.56	
Standard Friez II	0.45	0.65	
Standard Bosch	0.74	0.87	
Marvin Kite	0.83	0.91	
Bosch with Test Strip	0.90	0.95	

By reducing the rate of climb during the first ten minutes to, say, 100 m . per minute the final constant differences between indicated and actual temperatures would be reduced to one third of their listed values. Under those conditions the indicated lapse rates would come closer to the actual, as seen in Table IVb.

Besides showing the disastrous effect of lag in masking the true lapse rate, these two tables indicate the necessity of maintaining a very slow rate of climb near the

ground. Since most aerological stations carrying out routine observations do not correct their records for lag, one is probably justified in assuming that adiabatic and superadiabatic lapse rates are much more common than is generally assumed.

The determination of the lag coefficient is a comparatively simple experiment. The in-

TABLE IVb
INDICATED LAPSE RATES

Instrument	0-300 m	0-600 m	Adiabatic Atmosphere, Rate of Climb 100 m per minute
	$\frac{dT_i}{dz}$	$\frac{dT_i}{dz}$	
Standard Friez I	0.67	0.83	
Standard Friez II	0.75	0.87	
Standard Bosch	0.91	0.95	
Marvin Kite	0.94	0.97	
Bosch with Test Strip	0.97	0.98	

strument has to be heated or cooled to not more than 6°C [5] off the actual constant temperature T and then exposed to an air current of the temperature T and a speed corresponding to that encountered during aerological ascents. A trace representing T_i as a function of

time is thus obtained. From this trace corresponding values of T_i and $\frac{dT_i}{dt}$ may be

taken and substituted into the above formula in order to get α .

Integration between the time limits t_2 and t_1 gives

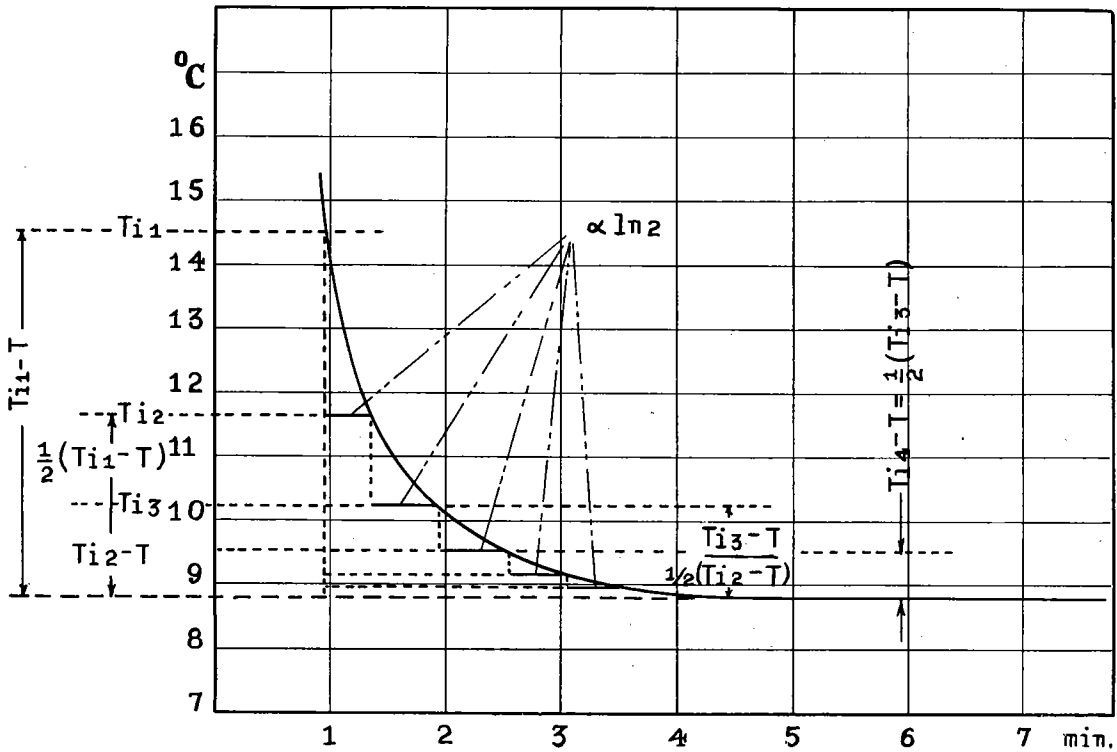
$$\alpha = \frac{t_2 - t_1}{\ln \frac{T_{i_1} - T}{T_{i_2} - T}}$$

If T_{i_1} and T_{i_2} are chosen so that $T_{i_2} - T$ equals $1/2 (T_{i_1} - T)$, a certain value $t_2 - t_1$ will

be obtained. α becomes equal to $\frac{t_2 - t_1}{\ln 2}$ or, $t_2 - t_1 = \alpha \cdot \ln 2$. This value $\alpha \cdot \ln 2$ often is noted

instead of α . Since, in most cases, the temperature deflection of bimetal thermographs is a linear function of temperature for the small range of 6°C, this latter method has the advantage of simplicity. The lag coefficient is obtained graphically by dividing a distance in half and multiplying the time interval thus determined with $\ln 2 = 0.695$. Compare Fig. 1.

As has been pointed out before, a transfer of heat from the air to the thermometer has to take place in order to equalize the temperatures of the two. The time required represents the lag of the thermometer. The heat transfer takes place at the surface of the thermometer. The larger this surface A is, the smaller the lag. The heat capacity of the thermometer is given by its mass times its specific heat, or volume V times density s times specific heat c . The smaller this heat capacity is, the less time will be required to change the temperature of the thermometer. Finally a factor H representing the heat exchange per cm² at the surface of the thermometer regulates the heat flow. The larger



$$\frac{1}{2}(T_{i1} - T) = T_{i2} - T$$

FIG. 1.—Graphical determination of thermometrical lag.

H , the smaller the lag. The lag coefficient is thus represented by the following equation:

$$\alpha = \frac{V \cdot s \cdot c}{A \cdot H}$$

This relation does not permit the determination of the numerical value of α . V , A , c and s are known, but the factor H depends not only on the surface condition of the thermometer, but also on the ventilation velocity and air density and includes in addition heat conductivity within the thermometer and radiational effects. H has been com-

TABLE V
HEAT CAPACITY $c \cdot s$ EXPANSION COEFFICIENT

Alcohol	0.46	$11 \cdot 10^{-6}$
Mercury	0.41	$60 \cdot 10^{-6}$
Glass	0.44	30 to $80 \cdot 10^{-6}$
Aluminum	0.58	$23 \cdot 10^{-6}$
Brass	0.75	$19 \cdot 10^{-6}$
Copper	0.80	$16 \cdot 10^{-6}$
Iron	0.86	$12 \cdot 10^{-6}$
Steel	0.86	1 to $19 \cdot 10^{-6}$

puted by theoretical considerations, but the great variation in exposure in different meteorographs seldom permits the use of the values of H found under greatly simplified assumptions. However, the formula does indicate how one has to proceed in order to reduce the lag. There are three possibilities:

1. Choose thermometer material of small heat capacity $s \cdot c$.
2. Make the ratio A/V large.
3. Increase H , the heat transfer, by increasing the ventilation speed.

The choice of materials is restricted since not only heat capacity but also expansion coefficient must be taken into account; in order to obtain reasonably large temperature deflections and actuating forces it is necessary to join one high expansion metal with one of low expansion coefficient. Table V shows the heat capacities and expansion coefficients for a number of materials used in thermometer construction. The heat capacities of glass covered liquid thermometers are about one half of the heat capacities of ordinary bimetal strips. Thus, liquid thermometers would have only half the lag of bimetal thermometers of the same shape. Bourdon tubes of the same shape would have intermediate values. Aluminum has a comparatively low heat capacity and a high expansion coefficient. A superior bimetal combination could be obtained if it were possible to join aluminum to a low expansion metal.

It is well known that mercury thermometers with spherical bulbs are less sensitive than the ones with cylindrical bulbs. The explanation is that the ratio V/A of the sphere is a maximum. The disadvantage of the large heat capacity of bimetal strips is made up for by the more favorable ratio V/A obtainable with bimetal strips. This ratio can be decreased still further by decreasing the thickness of the element. Since the thickness usually is negligibly small compared with length and width, the surface A remains practically constant, while V decreases as a linear function of the thickness. Using strips of smaller thickness however, produces effects, described later, part of which are not desirable. For this reason it was considered desirable to check the formula by a number of tests in order to find out if the decrease of lag actually is proportional to the thickness. For the experiments the following bimetals were put to our disposal by the General Plate Co., Attleboro, Massachusetts:

TABLE VI

NAME	CHARACTER	THICKNESS (h)	
		inches	cm.
#1 Precision Metal	Invar Steel—Chromium nickel steel	0.010	0.0254
#2 Precision Metal	Invar Steel—Chromium nickel steel	0.008	0.0206
#3 Precision Metal	Invar Steel—Chromium nickel steel	0.006	0.0152
#4 Lotemp Metal	Invar Steel—Brass	0.009	0.0229
#5 Lotemp Metal	Invar Steel—Brass	0.007	0.0178
#6 Lotemp Metal	Invar Steel—Brass	0.005	0.0127

The experiments were made with the help of a recorder having a recording drum of 30 cm. length and 15 cm. diameter, a displacement of 4.5 cm. representing 1 minute. On this device the 6 bimetal strips of 10 cm. length were mounted so that they furnished temperature traces on lamp-black paper, the deflections of the bimetal being enlarged by a 15 cm. recording lever. Several series of such traces were obtained by first bringing the temperature of the whole device to about 10°C. below room temperature and then exposing it to room temperature. Two ventilation conditions were used: (1) the ordinary

motion of air in a closed heated room, which may amount to an average of 1 or 2 meters per second, and (2) the ventilation by an electric desk fan, which stirred the air at about 5 meters per second. It proved to be necessary to direct the air current produced by the fan through a paper tunnel in order to get uniform ventilation for all the six elements. Without the tunnel the values of the lag coefficient α , determined from different parts of one and the same trace and from corresponding traces of different tests, had a dispersion as high as 33%. Using the tunnel the maximum dispersion of 10 determinations of α from each thermometer at the rate of 2 meters per second and 5 meters per second did not exceed 13%. The mean values of the lag coefficients found from these tests are given in table VII. Kleinschmidt [6] finds $\alpha = 0.15$ for bimetals of 0.5 mm. thickness at a ventilation of 5 mps, but already Raethjen and Huss [7] have stated that this value seems to be too small. Extrapolation of our tests also shows that this lag must be 0.4 to 0.5.

TABLE VII
COEFFICIENTS OF THERMOMETRICAL LAG

Bimetal		Lag coefficient α in minutes			
		Nat. Vent. = ab. 2 mps		Fan Vent. = ab. 5 mps	
Type	Thickness in inches	Measured	Computed from formula	Measured	Computed from formula
#1 Steel-steel	$10 \cdot 10^{-3}$	0.98	(0.98)	0.22	(0.22)
#2 Steel-steel	8	0.75	0.78	0.17	0.18
#3 Steel-steel	6	0.66	0.58	0.14	0.13
#4 Steel-brass	9	0.76	(0.76)	0.17	(0.17)
#5 Steel-brass	7	0.66	0.59	0.14	0.13
#6 Steel-brass	5	0.59	0.46	0.07	0.09

If the formula $\alpha = \frac{V \cdot s \cdot c}{A \cdot H}$ is correct, the lag coefficients of the two groups of bimetals

must have the ratios of the thicknesses, i.e., 10:8:6 and 9:7:5 respectively. The coefficients computed this way as related to #1 and #4, are shown for comparison in table VII.

Figure 2 is the graphical representation of the tests. It indicates that the lag of the steel-steel thermometers is approximately 15% higher than the one of the steel-brass thermometers which is in accordance with the heat capacities of the materials (compare table V). With merely room ventilation, the lag does not decrease as rapidly as expected. These curves for low ventilation are hard to explain. Lack of precision in the thicknesses of the thermometers used may play a rôle but should show the same effects in both tests. Heat conduction or radiation from the frame of the device can not be made responsible for these differences either, since only thermometer #6 was mounted near the solid frame. The most probable explanation is that the arrangement of the bimetal elements on the frame caused a systematic protection of the elements #3, #5, and #6 from the irregular little air currents in the room. How strong the influence of the ventilation is, can easily be seen from the big difference in the lag coefficients due to the two different ventilation conditions of the experiments. A check on the results obtained could have been made by repeating the tests with a different arrangement of the thermometers on the frame. At the time when the results were computed, however, the whole apparatus had already been changed for other experiments. The lag coefficients obtained using the

ventilation current of the fan, conform reasonably with the theory. The tests show that the lag decreases with decreasing thickness of the bimetal strips at a linear rate, when sufficient ventilation is used. That means that improvements as to the lag may be obtained by constructing the bimetal elements as thin as possible.

A limit to this procedure is set since for mechanically recording thermometers there must be a certain force available to overcome the friction of the recording pen and neces-

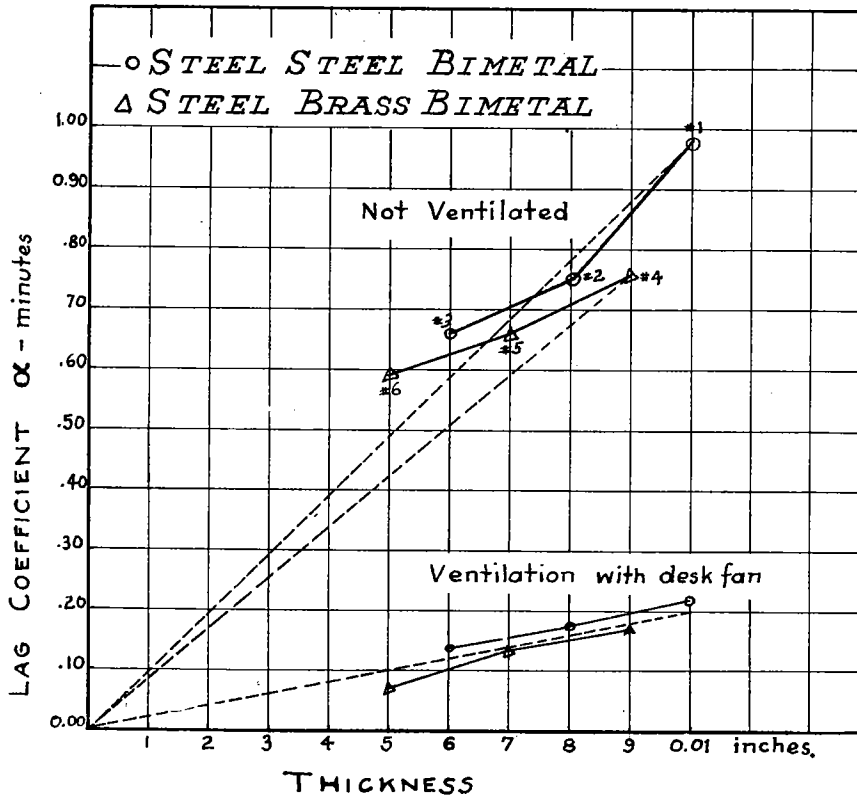


FIG. 2.—Lag coefficient vs. thickness of bimetal strips.

sary enlarging gears. The bimetal strip must be stiff enough to withstand a steady or oscillating deformation by the ventilation current. If the meteorograph changes its position, the bimetal must be stiff enough not to bend under its own weight and the weight of the enlarging mechanism.

A measure of the stiffness of the strip is the deflection of the free end under the influence of these forces. Friction of the pen and of the enlarging mechanism may be represented by a small force P acting at the free end of the strip in a direction opposite to the temperature change. If the length of the element is L , its width l and its thickness h , the deflection may be represented by the equation

$$\Delta S = \frac{4PL^3}{E \cdot l \cdot h^3},$$

where E is Young's modulus of the metal used.

The ventilation current produces forces upon the bimetal strip which vary con-

siderably with its shape and position relative to the current. In general a ring shaped strip facing the wind with its sharp edge will be less affected than a straight or shoe horn shaped strip in the approximate direction of the wind. The forces depend on the character of the flow around the thermometer body. As a first approximation it is permissible to assume, for a given ventilation velocity, a constant wind pressure p per unit of area. In this case both the weight of the element and the wind pressure will cause deflections of the form

$$\Delta S = \frac{3 \cdot p \cdot L^4}{2E \cdot h^3}$$

The first formula was checked in order to determine whether or not secondary effects reach noticeable importance for these unusually thin beams. If, with a certain bimetal combination, P , L and l are constant and only h is changed, the deflection ΔS should be inversely proportional to the third power of the thickness. In the experiments the six thermometers listed in table VI were used. They are of two different types so that the deflections of the two groups ought to be inversely proportional to their Young's moduli.

The tests were carried out by putting successive one gram weights to the free end of the strips while recording the deflections. Table VIII indicates the deflections per gram, measured according to this procedure. For comparison there are given the deflections as computed from the formula and based on #1 and #4.

TABLE VIII
DEFLECTIONS OF THE FREE ENDS PER GRAM LOAD

Bimetal L = 10 cm, l = 3 cm		Deflections, cm		
Type	Thickness in cm	Measured	Computed from formula	error
#1 steel-steel	0.0254	0.044	(0.044)	—
#2 steel-steel	206	0.073	0.085	16%
#3 steel-steel	152	0.182	0.202	11%
#4 steel-brass	229	0.063	(0.063)	—
#5 steel-brass	178	0.118	0.134	13%
#6 steel-brass	129	0.345	0.400	14%

The results of the tests conform with the formula within less than 16%, the measurements showing somewhat less deformation for thinner thermometers than the theory would indicate. Figure 3 gives the graphical representation of the table. It should be noted here that the deflections of the steel-steel combinations are about 15% to 20% smaller than the deflections of the steel-brass combinations. Young's modulus for common brass being about half of the modulus for common chromium-nickel-steel indicates that the influence of E is noticeable in the correct sense. According to the relation, so proved, *the stiffness or the actuating force of the bimetal is directly proportional to approximately the third power of the thickness*. This would very soon put an end to the procedure of improving the lag by decreasing the thickness since the element would become too weak. However, a thinner bimetal also furnishes larger deflections per degree of temperature change. Or, if a thinner thermometer shall give the same deflection per degrees Centigrade, it must be made shorter. According to the formula the actuating force

varies inversely with the third power of the length L , so that part of the loss is made up for. In order to determine the extent to which this takes place it is necessary to know the relation between the temperature deflection of the bimetal and its dimensions.

From the many theories on the bimetal thermometer which are found in meteoro-

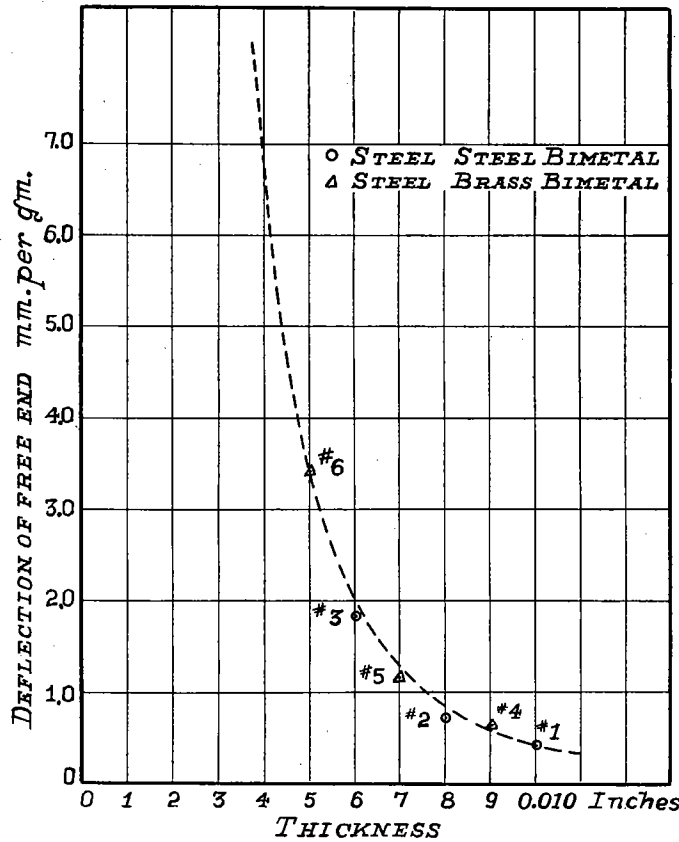


FIG. 3.—Bending vs. thickness of bimetal strips.

logical and technical literature, a recent study by Kleinschmidt [9] seems to furnish the most reliable data. Kleinschmidt established the following formula:

$$dS_i = \frac{12 \cdot R \cdot L^2}{13 \cdot \psi \cdot \delta} \cdot k \cdot dT^*$$

dS_i is the deflection in cm of the free end of the bimetal strip (not of the extension rod which is usually fastened to it) due to a temperature change of $dT^\circ\text{C}$. L is the length in cm of the bimetal body. The width l does not appear as long as it is small compared with L , which is usually the case with aerological thermometers. δ is half the thickness in cm of the bimetal under the assumption that the ratio δ_1/δ_2 of the thicknesses of the individual metals is equal to the inverse ratio $\sqrt{E_2/E_1}$ of the square roots of their Young's moduli. Kleinschmidt came to the conclusion that this ratio furnishes a maxi-

* The factor $12/13$ has later been corrected by Kleinschmidt to $\frac{1}{3}$. This affects our considerations only to the extent that the k -value computed below should be multiplied by $15/13$.

imum deflection, considering the resistance that the metal offers to its deformation by the thermal forces. Robitzsch [10], basing his considerations on the heat transfer in the

interior of the thermometer, concludes that a maximum deflection is obtained if $\frac{\delta_1}{\delta_2} = \frac{\lambda_1^2}{\lambda_2^2}$,

where λ^2 is the coefficient of temperature conductivity, or, the ratio of the coefficient of heat conductivity over the specific heat capacity. For the brass-steel combination, Kleinschmidt's ratio is $\delta_{St} = 0.7 \delta_B$, that of Robitzsch $\delta_{St} = 0.6 \delta_B$. According to the specifications given by the General Plate Co., Attleboro, manufacturer of our test pieces, δ_{St} is made equal to $0.75 \delta_B$. Since small changes in the individual thicknesses and a change in the Young's moduli of the metals probably take place when the material is being rolled out into thin strips, the present bimetal may be supposed to have within attainable limits, its best shape. For thick bimetals, such as may be used in oceanographic research, an experimental investigation of this particular phase may be useful.

k represents the difference between the expansion coefficients of the two metals of the bimetal. According to the specifications of the manufacturer, the invar used on the low expansion side of the bimetal has an expansion coefficient of 1×10^{-6} to 2×10^{-6} . The high expansion sides have coefficients of 18×10^{-6} to 19×10^{-6} . k is, therefore, between 16×10^{-6} and 18×10^{-6} . The expression R is a ratio introduced by Robitzsch [10] to show the influence of the form of the bimetal, whether straight or curved, on the deflection. Robitzsch assumed that the bimetal body always forms part of a circle. He gives the value for R/ψ , which has the character of a ratio of geometrical distances, as a function of the central angle ψ occupied by the bimetal. As seen from table IX, straight or nearly straight strips furnish the largest deflections:

TABLE IX

$\phi =$	0°	60°	120°	180°	240°	300°	360°
$R/\psi =$	0.50	0.48	0.44	0.38	0.30	0.22	0.16

Kleinschmidt's formula for the deflection of bimetal thermometers differs from others not only in the numerical factors but also in the exponent of the dimensions of the strip. For this reason the justification of the formula was tested by a number of experiments. The above mentioned six bimetal strips of different metals and varying thickness, equipped with six inch pens were exposed to room temperature. After a period long enough to guarantee equality of air temperature and thermometer temperatures, they were exposed to an outside temperature oscillating around 9°C . A further exposure to room temperature showed that hysteresis was negligible. The deflections were measured and reduced to the motions of the free end of the strip. The values thus obtained are represented in column I of table X. Since it was not possible to determine accurately the outside temperature and since the reduction could not be performed very accurately, these values are somewhat uncertain. Column II represents a check, made by measuring directly the deflections of the same bimetal strips without enlarging and recording pens. A third test was made with strips of precision metal and lotemp metal of different lengths and different shapes. These strips recorded with pens connected at their very ends on a smoked glass plate in an alcohol bath, the temperature of which was lowered by

TABLE X
DEFLECTIONS OF BIMETAL STRIPS

Type	<i>h</i>		<i>l</i>	<i>L</i>	ψ	Deflections <i>dS</i> per 10°C in cm						
	inches	mm				Computed from formula		Measured				
						<i>k</i> =16·10 ⁻⁶	<i>k</i> =18·10 ⁻⁶	I 22° -9°	II 23° -12°	III 17° -0°	IV 0° -16°	V -16° -31°
PT #1	10·10 ⁻³	0.254	3	9.2	55-75	0.473	0.531	0.45	0.47			
PT #2	8	.206	3	9.2	55-75	.582	.655	0.59	0.59			
PT #3	6	.152	3	9.05	55-75	.764	.860	0.74	0.79			
LT #4	9	0.229	3	9.2	55-75	.521	.587	0.53				
LT #5	7	.178	3	9.15	55-75	.653	.735	0.67	0.67			
LT #6	5	.127	3	9.2	55-75	.951	1.071	0.99	0.93			
PT #1	10	0.254	3	10	55-75	0.559	0.627			0.50	0.52	
LT #4	9	0.229	3	10	55-75	0.615	0.691			0.63	0.65	0.65
PT #1	10	0.254	3	14.15	30	1.112	1.258					
PT #1	10	0.254	3	14.2	230	0.72				1.03	1.01	0.95
PT #1	10	0.254	3	14.2	200	0.85				0.67		
PT #1	10	0.254	3	14.2	160	0.95					0.89	0.96

dissolving carbon dioxide snow in it. The deflections are represented in columns III, IV, and V. Note that the curved 14 cm strip changed its form so much that three different *R/ψ* values for the temperature range from +17°C to -31°C had to be used.

For comparison deflections are computed from Kleinschmidt's formula, using differences of expansion coefficients of *k* = 16·10⁻⁶ and *k* = 18·10⁻⁶. At low temperatures, the deflections of both metals become slightly larger than indicated by the theory. However, the testing method can hardly be considered exact enough to justify a definite statement in this respect.

The tests show remarkable agreement with the formula although the latter, including its constants, was derived from purely theoretical considerations. The actual difference of expansion coefficients is for the precision metal a little less, for the lotemp a little higher than 16·10⁻⁶.*

The initial problem was to decrease the lag α by decreasing the thickness *h* of the thermometal strip. It was found that

$$\alpha = \text{const. } h. \tag{I}$$

The formulae on pages 17 and 18 show that the deformations of the strip by a certain friction and a certain wind pressure are represented by

$$\Delta S = \text{const. } \frac{L^3}{l \cdot h^3} \text{ and } \Delta S = \text{const. } \frac{L^4}{h^3}. \tag{II}$$

Thus, if the length *L* and the width *l* remain the same, the stiffness decreases directly as the third power of the thickness *h* decreases. At the same time the deflections per degree of temperature become larger. If the deflection per degree temperature is to be constant, Kleinschmidt's formula furnishes us with a relation between *L* and *h*:

$$h = \text{const. } L^2. \tag{III}$$

* Compare note on page 19.

This relation, substituted in II, gives

$$\Delta S = \text{const.} \frac{l}{h^{3/2}} \text{ and } \Delta S = \text{const.} \frac{l}{h}. \quad \text{IV}$$

Therefore, if the temperature deflection and the width remain the same, the resistance against forces at the free end decreases with 3/2th power of the thickness h ; the resistance against deformation by wind pressure decreases directly with the thickness h .

In order to keep ΔS constant in formula IV, it seems logical to increase the width l so that

$$l = \frac{\text{const.}}{h^{3/2}}. \quad \text{V}$$

In most cases this leads to complications which can not be overlooked. In the first

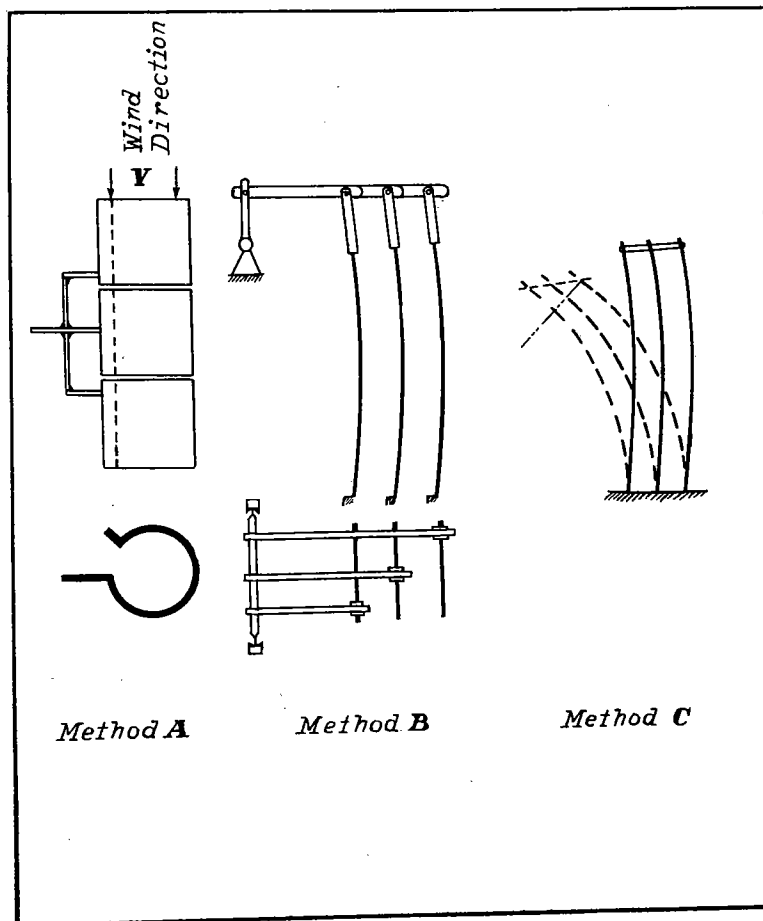


FIG. 4.—Combinations of bimetal strips.

place nothing is gained by stiffening the strip against wind force and its own weight as long as the wind force is assumed to increase with the exposed area. There is the prob-

ability that this assumption is incorrect. Only practical tests with thermometers of different shape and different position to the ventilation current can show this.

By increasing the width while at the same time decreasing the length, the ratio L/l will come down to an unsuitable measure. Kleinschmidt's formula is correct only if L is large compared with l . If the width l is made excessively large the thermal action will take place crosswise to the desired direction and the desired deflection for temperature change will be too small.

Following suggestions by Dr. V. Bush of M.I.T., attempts were made to overcome this action by subdividing the strip into several individual strips. They can be arranged either side by side (Fig. 4B) or one behind the other one (Fig. 4A). It is in this way the force necessary to overcome friction must be gained. As yet no experiments concerning the effect of wind pressure on elements of this type have been made. A first very promising idea of building several individual strips into one unit (Fig. 4C) by connecting them firmly at their ends proved to be unsuccessful. A number of tests were made with such units of two and three thin strips. They showed that the temperature deflections were very small, due to the resistance of the system against thermal deformation. Moreover, the individual thin strips were apt to break out, thus causing irregular deflections.

TABLE XI
CHARACTERISTICS OF VARIOUS BIMETAL STRIPS OF THE SAME TEMPERATURE DEFLECTION
AND THE SAME ACTUATING FORCE

Thickness (h)	0.08 cm = 1/32 in.	0.025 cm = 1/100 in.	0.013 cm = 1/200 in.
Lag (α)	0.27 min.	0.09 min.	0.04 min.
Length (L)	10 cm	5.8 cm	4.0 cm
Width (l)	2.5 cm	13 cm	39 cm

Table XI shows the dimensions of bimetal bodies of 1/100 and 1/200 inches for the case that they have the same temperature deflection and actuating force as our present meteorograph bimetals. Already the 1/100 in. element would have to be built as a system of at least five separate strips. The 1/200 in. thermometer would be ideal as to lag. It can, however, hardly be put into a normal meteorograph on account of its excessive width dimensions.

It still is an open question if we actually need as stiff bimetal strips as the ones in use at present. Pen friction and friction in the enlarging mechanism can be brought down to practically nothing by proper construction, even though the instrument has to stand the mechanical stresses during the flight, harsh treatment by inexperienced personnel and exposure to all kinds of weather. The most important factor in deforming the strip is the force of the ventilation current. In the M.I.T. wind tunnel the bending forces of the wind were determined on a normal Bosch strip of 1/32 in. and on a testing piece of 1/100 in. Both strips were exposed to the current in a Bosch meteorograph casing.

Figure 5 shows the results of these tests. First the wind velocity inside the radiation tube of the meteorograph was measured and plotted against the air speed as determined about one foot in front of the meteorograph. The points have some dispersion due to little changes in the position of the pitot tube. But they seem accurate enough to be represented by a straight line relationship, thus showing that the ventilation speed directly on the side of the thermometer is 80 per cent of the airplane speed. Right behind the bimetal strip the velocities are 12% higher than the airplane velocity. The mean

velocity at the bimetal thermometer therefore is only little less than the airplane speed. This is the case however, only if the ventilation current is not throttled down, which in actual flight was done in order to prevent excessive deformations of the thermometers.

The deformations of the strips due to different windspeeds were recorded on the clock-work drum. The deflections, expressed in °C by means of the temperature calibration,

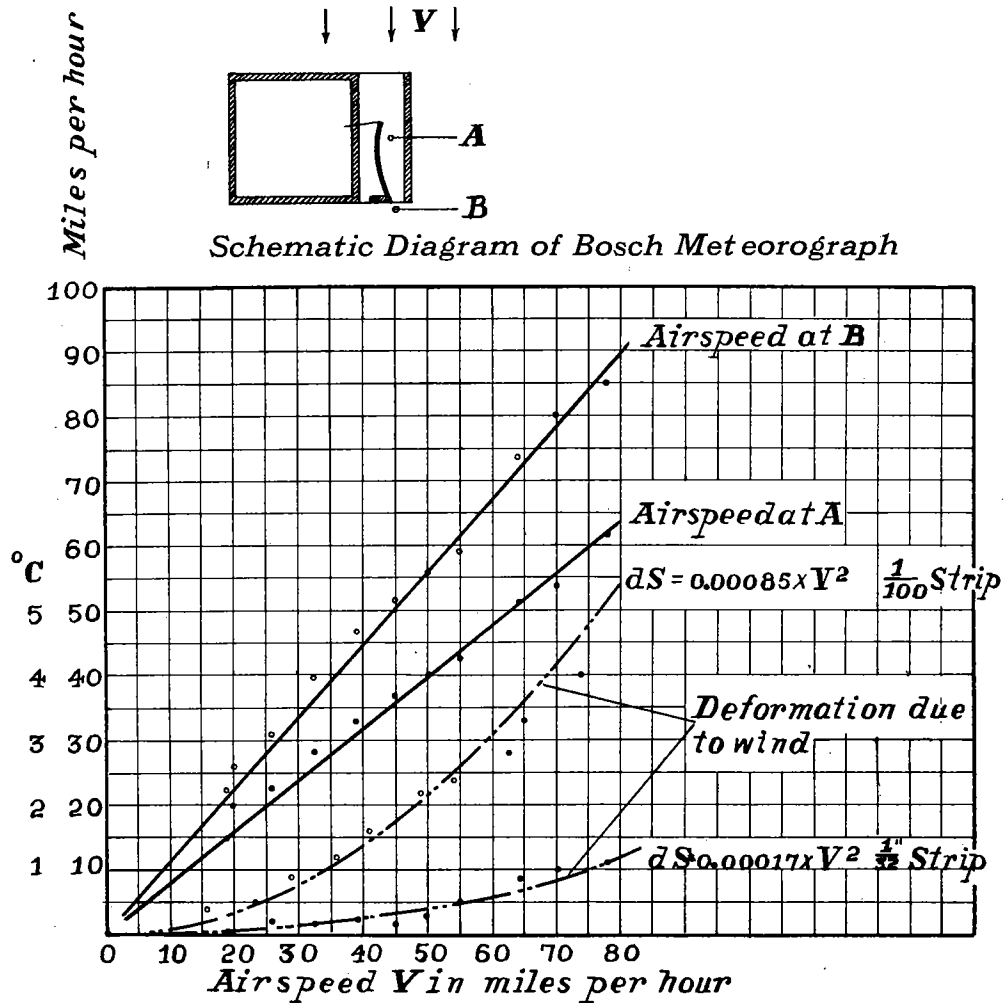


FIG. 5.—Deformation of bimetal thermometers due to wind pressure.

are not steady but oscillate around an average value. This mean value was estimated and plotted in figure 5 against airspeed. These points too show dispersions of fairly large magnitude partly due to fluctuations in the air temperature itself and partly due to difficulties in determining exactly distances of a magnitude of only hundredths of an inch on the smoked record. The results agree reasonably well with tests made at the Zeppelin wind tunnel by Raethjen and Huss. [7a]. One should expect that *the deflections of one and the same strip should increase at a linear rate with dynamic pressure, i.e. with*

the square of the velocity. The points indeed fit fairly well the parabolae, plotted into fig. 5 for reference.

These tests prove that low ventilation speeds permit the use of weak strips of small lag. On the other hand, strong ventilation in itself tends to decrease the lag. In the following a study is made on the relation between lag and ventilation speed. Tests were made with two types of aerographs used in American meteorological ascents: Friez aerograph #8 of the U.S. Weather Bureau, a Friez aerograph owned by M.I.T., Bosch meteorographs #3156 and 3145.

In the equation

$$\alpha = \frac{V}{A} \cdot c \cdot s \cdot \frac{1}{H}$$

H expresses the heat transfer from the air to the thermometer. H depends among other factors on the air density and air speed. The following tests were all made at surface density. A study on the influence of the air density is to be taken up in flight during the next flying period.

The tests were conducted in the M.I.T. open throat wind tunnel of two feet diameter. The air speed was determined by means of a Prandtl tube placed about a foot and a half in front of the meteorograph. The meteorographs were equipped with special 15 min. clockworks in order to obtain the necessary open time scale. They were heated

TABLE XII
LAG OF AIRPLANE METEOROGRAPHS AT DIFFERENT AIRSPEEDS

Instrument	Airspeed		Lag coefficients			Tested by means of
	Miles per hour	Kilometer per hour	Min.	Minutes Mean	Max.	
Bosch #3145 Standard thermometer	28	45	.32	.32	.33	Wind tunnel
	35	56	.23	.27	.29	
	42	67	.25	.27	.29	
	50	80	.23	.26	.27	
	53	85	.23	.27	.30	
	63	100	.26	.27	.29	
	76	121	.23	.26	.29	
	11	18	.72	.82	.90	Ventilation shelter Humidity Calibrator No artificial ventilation
	~ 2	6		~9.5		
	~ 0	0		~34.0		
Friez #8 U. S. Weather Bureau Standard	28	45	2.5	2.60	2.7	Wind tunnel
	35	56	1.7	2.56	3.3	
	42	67	1.9	2.20	2.5	
	50	80	1.4	1.83	2.2	
	63	100	1.00	1.04	1.11	
	72	115	.68	.79	.94	
	77	123	.58	.59	.63	
11	18		5.15		Desk fan	
Friez Original make	63	100	.68	.75	.80	Wind tunnel
	72	115	.80	.83	.85	
	77	123	.72	.76	.85	
Bosch #3156 1/100 in. testing thermometer	53	85	.13	.14	.17	Wind tunnel from Table VII, p. 16)
	68	110	.07	.07	.09	
	(11)	18		.22		
Assmann Hg therm.	11	18	.32	.33	.34	Ventilation shelter

with the help of warm air, produced in a box by an electric stove. Special care was taken to heat the whole instrument uniformly. Through exposure to different ventilation currents the lag traces were obtained and evaluated in the above described graphical manner. Due to little variations of the wind velocities and due to changes in the supposedly constant air temperature, when the tunnel was running, the lag coefficients show dispersions of up to a maximum of 55%.

Table XII shows results of these tests. Each value of the lag coefficient α given represents an average from at least three computations. In order to show the dispersion, maximum and minimum values obtained of α are also given.

The lag coefficients were determined for speeds ranging from 28 miles per hour to 77 miles per hour in the wind tunnel, the meteorographs being in the same position as during ascents. Two additional points for 11 miles per hour were obtained with the help of a desk fan tunnel and finally it was found that the lag coefficient of the Bosch meteorograph is about 34 if there is no artificial ventilation at all.

At all speeds the lag of the Friez instrument is several times that of the Bosch instrument. The actual bimetal elements of the two aerograph types do not seem to be very different from one another. Thus the amazingly small lag of the Bosch meteorograph must be attributed to the more efficient exposure of the thermometer. Fig. 6 contains sketches of the position of the bimetal strip in the three types of meteorographs. It can be seen, that the thermometer of the Bosch meteorograph is directly exposed to the air. The Friez aerographs have their thermometers inside heavy brass cases and thus the thermometers do not get direct benefit of the strong air current of the airplane. On the contrary, the air which finally reaches the thermometers is heated or cooled by the case in front of the thermometers. Thus the lag represents more the lag of the case than that of the thermometer. On the other hand, the air reaching the thermometer of the Bosch meteorograph passes through a wire screen of little heat capacity. This screen protects the strip and the hair against hail and heavy precipitation and tends to smooth the air current. A double screen is provided to throttle the ventilation speed during actual flights.

The influence of parts in front of the thermometer on the lag is rather marked. This came very impressively into appearance on two occasions. Once the attempt was made to place the meteorograph into the large wing-section of a monoplane in order to save drag. Though the thermometer had sufficient ventilation and was well protected against radiation, the temperature curve showed all the characteristics of high lag and had no resemblance with the curve of another meteorograph exposed on the plane in the ordinary way. At the M.I.T. aerological station, which usually sends up two meteorographs with the plane, an attempt was made to carry two Bosch meteorographs, one behind the other in one stream lined case, this to save air resistance. The evaluation of the two records (Jan. 4, '33) showed that at a high rate of climb the second instrument in line read lower in the ground inversion and higher above the inversion than the first one, the top of the inversion being recorded at a higher elevation by the second instrument.

One reason for arranging the thermometer inside the Friez meteorographs may be to protect it from getting wet in clouds and zones of precipitation. But the turbulent flow around the case will carry the water to the thermometer anyway. The process of drying off the water from the strip after the cloud or precipitation zone has been passed, however, will require more time than with the Bosch instrument.

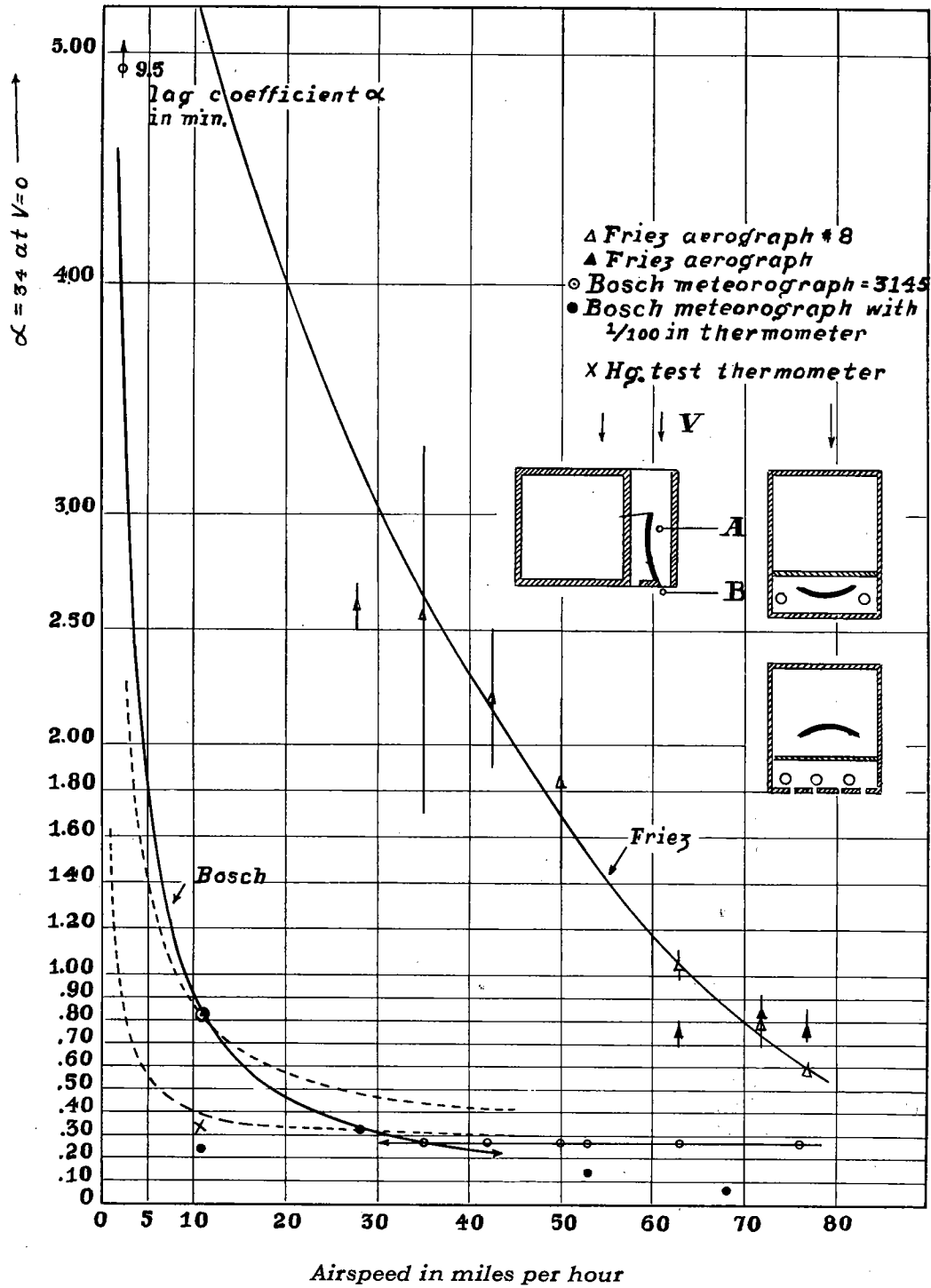


FIG. 6.—Lag of airplane meteorograph thermometers vs. air speed.

Figure 6 is a graphical representation of table XII. There are two curves representing the relations between lag and airplane speed over the entire speed range from 0 to 77 miles per hour. The upper one is the curve of the Friez meteorograph, the lower that of a Bosch meteorograph. The shapes of these two curves are different. The lag of the Bosch instrument reaches a minimum already at an airplane speed of about 35 miles per hour, staying constant at higher speeds. The lag of the Friez instrument still seems to be decreasing rapidly with velocity at 77 miles per hour. From Figure 5 may be seen that the ventilation velocity near the bimetal element of the Bosch instrument is very nearly equal to the airplane speed. The fact that the curve of the Friez thermometer is shaped differently proves, too, that there are other influences active. Either the ventilation speed near the thermometer of the Friez is extremely small compared with the airplane speed or the preheating by the instrument case changes the relation between lag and air speed.

The representation over the entire speed range of the function thermometer lag vs. air speed of the Bosch instrument permits checking and completing of our present knowledge of these relations. It has been found before by Wigand, Robitzsch and Raethjen that the ventilation speed decreases the lag only down to a certain value. Within this range the lag usually is set inversely proportional to the air speed.

In the original formula (page 14) the lag coefficient α equals $\frac{V \cdot c \cdot s}{A \cdot H}$, where H is a factor of heat transfer between air and thermometer. With constant density (surface, room temperature) several other factors will influence H . A certain amount of heat will be conducted through the thermometer support. Some heat is exchanged by radiation. These amounts are probably fairly small and may therefore be considered as minor correction terms at all but very low velocities. The heat exchange thermometer-air may then be set equal to the amount of air passing by the thermometer, i.e., to the air speed. Under these assumptions H is represented by a linear function of the ventilation speed and consequently

$$\alpha = \frac{1}{a + bv} \quad \text{VI}$$

The measurements on the Bosch meteorograph show that α reaches a constant value in the vicinity of 35 miles per hour. It is therefore appropriate to amend the above formula through the inclusion of a constant α_∞ representing the limiting value of the lag for high ventilation velocity. It then takes the form

$$\alpha = \alpha_\infty + \frac{1}{a + bv} \quad \text{VII}$$

Two attempts were made to fit the entire range of measured lag values by formulae of the type VII. In both cases the value for α_∞ was assumed to be 0.27. In one case the curve was required to pass through the points ($\alpha = 34, v = 0$) and ($\alpha = 0.32, v = 28$), in the second case it was required to pass through the points ($\alpha = 34, v = 0$) and ($\alpha = 0.82, v = 11$).

These two curves are represented by broken lines in Fig. 6. It is readily seen that they do not fit the observations. A third attempt was made, assigning again a value of 0.27 to α_∞ but requiring the curve to pass through the points ($\alpha = 0.82, v = 11$) and ($\alpha = 0.32, v = 28$). In this case the value of a becomes negative, so that the lag coefficient would become infinite for a v -value of about 9 miles per hour.

It is evidently impossible to fit the entire range of experimental data by means of a single formula of the type VII. This should not cause much surprise if the complicated nature of the physical processes involved is kept in mind. At low ventilation speeds the heat flow from thermometer to air is very slow; it is probable that due to exchange of radiation between thermometer and shielding (i.e., meteorograph body) both change their temperature at similar rates, whereas in case of strong ventilation, the temperature of the bimetal may change much more rapidly than that of the shielding. In this latter case, the excess heat received by the bimetal through radiation is taken care of by the ventilation current.

It is possible to fit the observations by two equations, one of the form VI and valid in the range $v=0$ to $v=35$,

$$\alpha = \frac{I}{0.03 + 0.105v},$$

and the other,

$$\alpha = 0.27,$$

valid for ventilation speeds in excess of 35 miles per hour. These two curves are entered into Fig. 6 and it is seen that they fit the experimental data very well. The measurements on the Bosch meteorograph equipped with a bimetal test strip of 0.01" seem to indicate that the lag coefficient in this case continues to decrease up to a wind velocity of 68 miles per hour or more. The same statement applies to the Friez meteorograph.

Combining the results of the investigations of the previous pages we are led to the following conclusions regarding general principles to be observed in designing bimetal thermometers for airplane meteorographs:

The lag is given by

$$\alpha = c \cdot s \cdot \frac{V}{A} \cdot \frac{I}{H}.$$

The heat capacity should be made as low as possible through the use of appropriate metals.

The factor V/A may be reduced to the form

$$\frac{V}{A} = \text{const. } h,$$

where h is the thickness of the bimetal.

The term I/H may be expressed by a formula of the type

$$\frac{I}{H} = \frac{I}{a + bv}$$

for ventilation speeds up to a certain critical velocity v_1 , and beyond that value by

$$\frac{I}{H} = \text{constant.}$$

Consequently the lag coefficient is given by

$$\alpha = \text{const. } h \cdot \frac{I}{a + bv} \quad (v < v_1)$$

and by

$$\alpha = \text{const. } h \quad (v > v_1).$$

In order to eliminate one of the independent variables from the above formula we must make use of Kleinschmidt's formula and the expression for the deflection of the bi-metal by wind pressure. We require that the temperature deflection per degree (dS/dt) shall have a certain prescribed value:

$$\frac{dS}{dt} = \text{const. } \frac{L^2}{h} = \text{constant.}$$

Thus

$$L^2 = \text{const. } h.$$

On page 23 it was shown that the necessary actuating force can be obtained by increasing the width and subdividing the strip into several strips. The dynamic pressure of the wind causes a certain deflection ΔS given by

$$\Delta S = \text{const. } \frac{L^4}{h^3} v^2.$$

This deflection must be equal to or less than a certain prescribed value and thus the dimensions of the bimetal and the ventilation speed must be varied in such a fashion that

$$\frac{L^4}{h^3} v^2 = \text{constant.}$$

Substituting in the last equation the relation between L^2 and h one obtains

$$h = \text{const. } v^2.$$

With the aid of this result one finally obtains, for the lag coefficient,

$$\alpha = \text{const. } \frac{v^2}{a + bv} \quad (v < v_1)$$

and
$$\alpha = \text{const. } v^2 \quad (v > v_1).$$

Since a is very small compared with bv , the first of these formulae may be written, except in the vicinity of $v=0$,

$$\alpha = \text{const. } v \quad (v < v_1).$$

These final formulae show that if a certain temperature deflection is prescribed and also a certain resistance against aerodynamic forces, the lag can be kept down by *making the bimetal as thin as possible and at the same time cutting down the ventilation speed to a corresponding extent* ($h = \text{const. } v^2$). The reduction of air speed has to be done in such a way that the air temperature does not undergo changes before reaching the bimetal; for example, by a casing of very thin material of small heat capacity.

The smallest lag attainable in practice is, of course, not zero at no ventilation speed and with an infinitely thin strip. It has been mentioned before that the assumptions which lead to the final formula are incorrect for very small ventilation speeds. The relation between lag and thickness is questionable at very low speeds.

This questionable region of the formulae, however, will not be reached in practice on account of difficulties encountered in the construction of thermometer systems which yield the necessary actuating forces.

When experimental data have become available on the best shape of bimetal strips from the point of view of resistance against bending, the task of obtaining minimum lag must be placed in the hands of a capable instrument builder. He must arrange to get sufficient actuating force by placing a number of thin strips into the meteorograph in such a way that their own weight does not cause trouble. At the same time the frictional forces must be reduced to a minimum. A suitable way of cutting down the air speed has to be found.

While this report is being written the author is cooperating with Mr. R. D. Feiber of Cambridge in the construction of a new airplane meteorograph. The thermometric lag of this new instrument is expected to be a small fraction of the lag of the airplane meteorographs in use at present.

The observation material of the M.I.T. ascents during the period 1931-1933, which will be published in a later report, was obtained with standard Bosch bimetal thermometers. In general, corrections for lag have not been applied. However, there will be tables containing the climbing speed of the airplane for ascents with one or two persons. With the aid of these tables it will be possible to apply lag corrections whenever required.

The temperature curves of the airplane ascents made by M.I.T. were obtained as temperature-time curves on lamp-black aluminum foil. The time scale was chosen in such a fashion that an open and clear record was obtained. The usual clockwork speed of the Bosch meteorograph is one turn in 100 minutes, giving a displacement of 0.27 cm. per min. In case of longer flights the pilot could change the speed to one turn in four hours by means of an electrical contact. The temperature, too, is recorded on a large scale, one degree centigrade giving a deflection of about one millimeter. The arms of the recording pens are very long; they can therefore cover a wide range on the recording drum without change in the contact pressure, which is carefully adjusted to be a minimum. The setting of the pens is changed from time to time so that the normal seasonal temperature range coincides with the most favorable position of the recording pen.

The temperature calibration was, during the first two years, carried out by dipping the meteorograph into a bath of alcohol but keeping the recording drum above the liquid. The temperature of the alcohol was lowered in steps by dissolving dry ice in it. Mixing due to bubbles of escaping carbon dioxide supported by vigorous stirring produces a uniform temperature in about three minutes. Usually temperatures of about -35°C are low enough for the lowest calibration point. In determining the temperature of the bath the use of a mercury thermometer is recommended since it eliminates the need of applying stem corrections which cannot be neglected when toluene thermometers are employed. An additional check is obtained by dipping the instrument into an ice water bath. Every once in a while a temperature calibration is made by raising the temperature of the solution from its lowest temperature by steps; this provides an opportunity for checking the hysteresis and elastic after effect of the bimetal. They were always found to be negligibly small. The aluminum foil of the calibration is fixed with a thin solution of shellac in alcohol; a base line is then drawn parallel to the traces of the two fixed pens and through the zero degree point. The shortest distance between each calibration point

and this base line is taken into a screw divider and transferred to the calibration charts. On this chart a scale of 5 mm for one °C was found to be most convenient. The curve is an almost straight line, deflections at comparatively low temperatures being slightly smaller on account of distortions caused by the enlarging mechanism. The individual check points, usually about 7°C apart, are joined with the help of a spline.

In order to check the liquid bath method some calibrations were conducted in a newly developed temperature-pressure chamber. This instrument will be described later in this paper. During the academic year 1933-1934 all temperature calibrations of the M.I.T. airplane and sounding balloon meteorographs were made with the "T-p chamber." In this calibration chamber the meteorographs are not immersed into any liquid but kept in dry air, which is vigorously stirred by a blower fan. The temperature of the air can be changed at will. With the help of this calibration device, the calibration takes a little more time than the calibration in liquid alcohol. It is, however, a good deal more reliable since the whole instrument undergoes temperature changes similar to those encountered in actual flight. While experimenting with this chamber, we encountered considerable difficulty with regard to the check thermometers. At first, glass thermometers were used, the bulbs being inside the calibration tank while scale and stem were outside the lid. Mercurial thermometers behaved well. With alcohol and toluene thermometers, stem corrections had to be applied. This could not accurately be done as there was always some uncertainty concerning temperature of the stem. Even worse than this was the breaking of the column of the thermometers, which occurred almost regularly. Frequently it occurred inside the tank or in the thermometer mounting so that the break could not be detected until the whole calibration was finished.

Sounding balloon meteorographs must be carefully standardized down to -75°C. That means that the choice of liquid thermometers is restricted to toluene thermometers. Since 1934 the airplane ascents of M.I.T. have been carried out in cooperation with the U. S. Army. The Fairchild plane which is now flown for this purpose permits easily ceilings of 7 kilometers. Temperatures over Boston at this altitude are occasionally far below the range of mercurial thermometers. For this reason the glass thermometers were replaced by electrical thermometers. Resistance thermometers probably would be the most convenient ones. The M.I.T. chamber, however, is equipped with thermocouples since their lag is so small that they permit checking of the uniformity of temperature within the tank. Three copper-constantan junctions are provided, which can be placed at any point inside the chamber. If they are arranged in series and connected to a special potentiometer indicator (assembled by Leeds & Northrop for our purpose), readings from +80°C. to -80°C. corresponding to +9 to -9 millivolts, are obtained with an accuracy of 0.1°C.

A daily check on the temperature calibration of the meteorograph is carried out in connection with each meteorological ascent by taking check readings of mercurial thermometers in the ventilation shelter. This shelter also serves the purpose of keeping the meteorograph at true air temperature before take-off and of storing it between ascents.

During the history of the M.I.T. Aerological Station, several ventilation tunnels have been used. The latest model is shown in Figure 7.

It is formed by two concentric metal cylinders of a length of 31 inches and 11 and 13 inches in diameter, sprayed with silver paint. An electric fan draws the air through the tunnel at a rate of 6 meters per second, ventilating two meteorographs and the dry and wet bulb of two mercurial thermometers. Thin metal shields cut down the ventilation

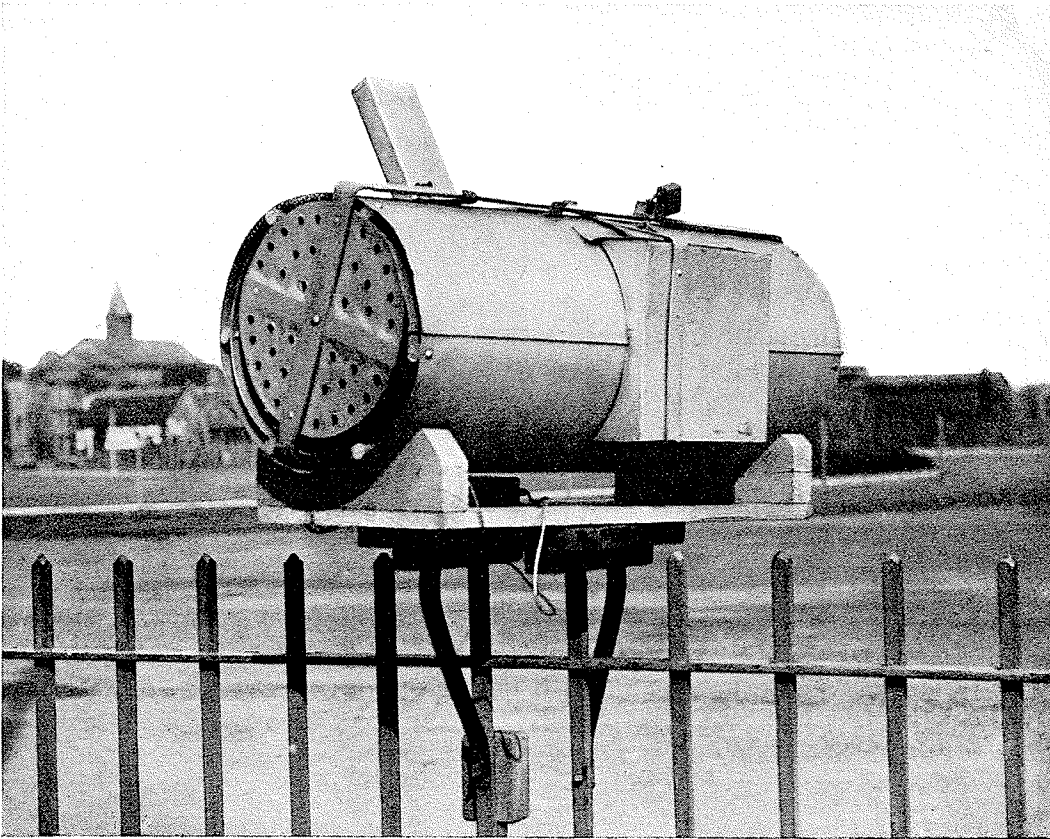


FIG. 7.—Massachusetts Institute of Technology ventilation shelter.

speed at the check thermometers so that their lag comes near to that of the meteorograph thermometers. The whole arrangement can be turned into the wind in order to increase the ventilation of the fan. Electric time marks permit the marking of the exact moment when check readings on temperature and relative humidity are taken.

Readings are taken before and after the flight. Since normally, the ascents are carried out at early morning hours the diurnal temperature change causes two different readings, which are used as a check on the temperature calibration. From the calibration chart the two distances corresponding to the check temperatures are taken and laid into the lamp blacked foil. A line drawn tangent to the two circles must be parallel to the traces of the fixed pens and must have a constant distance from them. This line then serves as the base line from which the temperatures of significant points are measured.

The meteorographs stay in this shelter until the very moment of take-off. Protected against radiation and ventilated with at least ten to fifteen miles per hour, they will assume true air temperature. Experience has shown that even a meteorograph with double protection against radiation, such as the Bosch instrument, will get warmed up if not ventilated. On hot, calm days considerable errors are caused. As a result, not only the starting temperature but also the lapse rate of the layer near the ground are recorded incorrectly. A case was reported to the author where an airplane station registered a

lapse rate of more than 2°C . per 100 m. in a layer of more than 1 kilometer! Aerological measurements of this kind are of course worthless in view of the significance of the layer near the ground for meteorological problems.

On the occasion of the meteorological ascents at Elmira, N.Y. and Twin Mountains, N.H., made with the equipment of the M.I.T. Station, it was found inconvenient to operate with this ventilation shelter on account of transportation difficulties. A new portable arrangement is therefore being developed. A short tube of 4 inches diameter containing the check thermometers and a fan will be attached directly to the radiation tube of the Bosch meteorograph. This is to be done while the meteorograph hangs on the plane or on a special gallow where the meteorograph can be placed before and after the flight. When this new arrangement is perfected, it will probably replace the ventilation shelter.

C. MEASUREMENTS OF AIR PRESSURE

Measurements of the static pressure of the free atmosphere serve two main purposes. In the first place, when combined with temperature and humidity measurements they permit the computation of altitudes of significant points in the temperature and humidity curves. In addition, if pressures from a sufficient number of well distributed ascents are available, isobaric charts may be plotted for several levels instead of for the surface only. Our present meteorographs record the pressure with errors of the magnitude of several millibars. For the first mentioned purpose of coordinating temperature, humidity and altitude at significant points, the inaccuracy in the pressure readings may result in errors of 50 to 100 meters in the calculated altitude of a certain characteristic point (for instance a given temperature), which however, is sufficiently accurate for most synoptic purposes. In special studies such as the determination of the thickness of the turbulent layer in the atmosphere, errors of this magnitude may be disturbing. For the second purpose, i.e., the determination of the pressure at fixed levels, the present accuracy is sufficient. The pressure at a certain level can be calculated quite accurately if the surface pressure and the mean temperature between the surface and this level are known. The inaccuracy in the pressure readings has the effect of distorting the temperature-pressure relationship between the ground and the level for which the pressure is sought. This will produce an error in the mean temperature upon which the pressure calculation is based, but the resulting error in the pressure at the fixed upper level will be less than the error in the recorded pressure corresponding to any definite characteristic point in the temperature record.

Practically all instruments to indicate or record atmospheric pressure at high levels are based on the principle of the aneroid (Vidi chamber) or the Bourdon tube. The actuating forces of these devices are large enough to permit a mechanical enlarging and recording of the original deflections on a suitable scale. Both the aneroid and the Bourdon tube are elastic systems which deform with the external pressure. They possess the usual disadvantages of elastic systems, such as elastic after effect, hysteresis and temperature influence. A large number of scientific papers have been published on this subject [11, 12] and very successful efforts have been made by certain manufacturers of altimeters to decrease these effects. There is no doubt that the aneroids of our common meteorographs do not at all compare with the high standard which could now be obtained. More refined pressure elements in the meteorographs would appreciably facilitate the evaluation of the records and also save time, but there is no absolute need for more refined pressure

element in the meteorographs since the aerologist is, or at least should be, able to correct most of the errors which occur in the readings of our present instruments.

Other errors in the pressure readings are frequently introduced by dynamic pressure effects. The meteorograph which is carried with high speed through the air, forms its own field of dynamic pressure. If carried by plane, the meteorograph hangs in the pressure field of the craft. According to the position of the aneroid in these fields, errors of the magnitude of several millibars may be caused.

The *elastic after effect* becomes visible when a meteorograph which has not been used for a while is recalibrated. The new curve will not coincide with the previous calibration and will differ also from subsequent calibration curves. Having been exposed to low pressure the unused aneroid returns to its original position very slowly. Traces of the elastic after effect have been noticed by some investigators after a period as long as one year. According to Kleinschmidt [6], the elastic after effect disappears approximately logarithmically. Thus, during the first few days after a first exposure, the action of the aneroid starts from a different position. This effect, although numerically small, could easily be shown through tests with Bosch and Friez meteorographs in the laboratory. It was not noticeable with Jaumotte sounding balloon meteorographs. Kleinschmidt [6] states that the elastic after effect increases with increasing temperature. Kohlrausch [14] finds that it is approximately proportional to the amount of pressure change exerted on the instrument. If the aneroid is used in regular ascents, as is the case at most aerological stations, the significance of the elastic after effect is greatly reduced. The after effect can be considered the same for each ascent on account of the similar period of time between flights. In order to avoid appreciable errors due to the elastic after effect, all records of regular ascents at Boston were evaluated by means of calibration charts obtained after repeated "massages" of the instrument. The meteorograph was never sent up nor the record evaluated with the ordinary calibration chart unless the after effect had been eliminated by a previous flight or by an evacuation under the bell jar down to the pressure of the average altitude of the flights. If this procedure cannot be followed, as is the case with sounding balloon instruments, it is advisable to prepare both the virginal and the hysteresis curves and use them in accordance with the conditions prevailing at the ascent. The sounding balloon instruments used by M. I. T. are calibrated and sent up with a long time intervening period of rest, so that the virginal curve has to be used.

Hysteresis, although rather neglected by meteorologists, is of greater practical significance than the elastic after effect. If an aneroid is exposed to pressure changes, its deflections in ascent differ from the ones in descent. In the calibration chart this is expressed by different curves for ascent and descent. As mentioned before, the curve representing the first descent does not come back to the initial point from which the ascent began, because of the elastic after effect. After the process of lowering and increasing the pressure has been repeated often enough, two branches are obtained which do not change any more. According to tests made by L. Scriba [12] on a large number of aneroids of different makes, this state is usually reached after three evacuations. The two curves coincide in the points of surface pressure and lowest pressure. In the middle of the pressure range the distance from one curve to the other is largest. It is 5 to 20 mb. with our aerograph aneroids when the pressure range corresponds to an altitude of about four miles. The cycle formed by these two curves is called the hysteresis cycle. It represents work which appears in the form of heat raising the aneroid temperature during the deformation.

The amount of hysteresis is usually expressed as the maximum distance between the two curves. It depends on the pressure interval and on temperature. Kleinschmidt cites a formula for the width w of the hysteresis cycle as function of the pressure interval i of the following kind:

$$w = a \cdot i + b \cdot i^2.$$

From a number of careful experiments by L. Scriba, it seems rather certain that the width of the hysteresis cycle can be expressed as a linear function of the pressure interval. Unfortunately, Scriba's tests cover only pressure changes up to about 350 mb, thus preventing a very accurate check of the formula. At any rate the tests show that the constant b must be so small that it can be neglected in meteorological practice.

Tests at the Deutsche Versuchsanstalt für Luftfahrt give information on the influence of temperature on hysteresis. All aneroids have larger hysteresis at high than at low temperatures. The relation can be expressed by

$$w = (a \cdot T + b \cdot T^2)i,$$

where T represents absolute temperature and a and b are constants of the individual aneroid. At -10° the hysteresis is frequently only $\frac{1}{2}$ to $\frac{2}{3}$ of the hysteresis at room temperature.

In our calibration chamber the hysteresis of the aneroids of several meteorographs was determined at room temperature and at lower temperatures for a pressure range from about 1000 mb to about 400 mb. Table XIII shows the maximum widths of the hysteresis cycles. The data cannot be considered very exact since they have been obtained from the standard pressure calibrations in steps of about 50 mb. The steps most likely modify the hysteresis somewhat. Furthermore, it is impossible to reveal such small pressure differences with great accuracy from ordinary records.

TABLE XIII

Temperature	Friez	Bosch	Bosch	Bosch	Richard
21°C		10 mb			
-40°C		6 mb			
24°C	3 mb		7 mb	7 mb	11 mb
-28°C	1 mb		5 mb	4 mb	7 mb

In spite of this rather rough method of determination, the data present the temperature effect on the hysteresis quite clearly. Errors caused by this effect will be approximately the same in successive ascents when the temperatures do not change too much. Variations in the height of phenomena recorded against pressure will thus be correctly determined although the absolute heights are incorrect. Should certain investigations necessitate extreme accuracy, it is essential to apply temperature corrections for hysteresis. It should be mentioned that the hysteresis of the aneroid does not depend on the speed of the pressure change.

The lag of aneroids and Bourdon tubes is negligible according to investigations by De Quervain [15].

Most important of all errors is that caused by the *temperature influence* on the aneroid. To the author's knowledge none of the meteorographs in use at present is equipped with an aneroid which is completely compensated against temperature at all pressures encountered during aerological soundings although many efforts have been made to

construct such an element. At present the only way of getting correct pressure readings is to determine a correction and, if necessary, to apply it. For the future the question is whether to concentrate all efforts on the construction of temperature-compensated aneroids or to supply calibration equipment which permits accurate and quick determinations of the corrections.

For practical reasons it was decided to develop such a calibration device at M. I. T. In the first place it is needed for our present meteorographs, which will have to serve for several years yet.

We started the development of a "Temperature-Pressure-Chamber" with the aero-

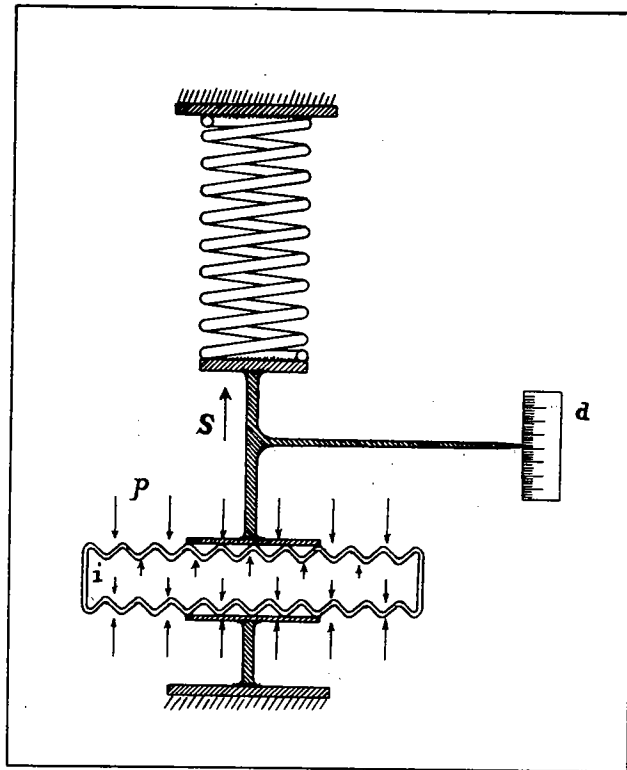


FIG. 8.—Sketch of aneroid.

logical ascents in 1931. Successive constructions of three chambers led to a calibration device that is now available commercially. It will be described later in this paper. With this chamber the routine calibrations of our station are made. The temperature corrections of the meteorographs are determined and, since the flying period of 1932-1933, applied in all evaluations of flight records. During the Third, Fourth and Fifth National Glider Contests all official barograph calibrations, sanctioned by the National Aeronautic Association, were executed with these chambers. Other meteorological institutions in the United States and Canada have obtained such chambers for their aerological work.

Aneroids are generally composed of one or more evacuated chambers or bellows of thin corrugated metal and a spring counterbalancing the air pressure upon the chambers

or bellows. Figure 8 shows the principle of the aneroid. It makes but little difference whether the spring is inside or outside the chamber or whether there is any spring at all, since the chambers themselves act as such. In the sketch, the spring tension (S) is in equilibrium with the air pressure (p). If the air pressure decreases, the chamber will deform until the spring tension is released to a new value corresponding to the new air pressure. The deflection gives a measure of the pressure change. These deflections usually are proportional to the pressure changes, as the spring changes its form proportional to the load, which is the air pressure.

Whether or not this be true is shown by the calibration curve of the individual instrument. Usually it is a practically straight line, with a slight curvature caused by the distorting influence of the enlarging mechanism. In such cases it is justified to assume, as a first approximation,

$$p = c \cdot d,$$

where d is the deflection of the chamber from the position $p = 0$ to the actual pressure and c is a factor expressing the elasticity of the spring at room temperature (t_0). The stiffness of a spring varies with temperature, the tension of common springs decreasing with increasing temperature. At higher temperatures equilibrium between the spring force on one side and a constant air pressure upon the chambers on the other side will be reached in a position where the chamber is slightly more compressed. This indicates an increase of pressure which actually does not exist. The deflection d_t at a slightly higher temperature, $t = t_0 + \Delta t$ can therefore be expressed in the form

$$p = c(1 - \alpha \Delta t)d_t,$$

where α expresses the change of Young's modulus for the whole aneroid system on account of temperature. The difference Δd between the two deflections d_t and d represents the error due to temperature

$$d_t - d = \Delta d = d_t - d_t(1 - \alpha \Delta t) = d_t \alpha \Delta t.$$

This means that all deflections d_t obtained at temperatures differing from the calibration temperature have to be increased by the amount

$$\Delta_c d = -d_t \alpha \Delta t,$$

in order that they may be expressed in pressure units by means of the original calibration. As the calibration curve is practically a straight line, it is more convenient to go in with the deflection d_t , obtain the corresponding p and correct p . This correction follows from

$$\Delta_c d = -d_t \alpha \Delta t$$

and

$$d_t \sim d = \frac{p}{c}.$$

The result is

$$\Delta_c p = -\alpha \Delta t p$$

Table XIV was prepared to show the large range of α in ordinary meteorographs. From the table may be seen that the constant α ranges from $+0.00164$ to -0.000173 for various aneroids. With our present meteorographs α is of the magnitude of $.0004$. This means that each 10°C off the calibration temperature would cause discrepancies of

TABLE XIV

Make	Determined by	Individual measurement	Means of series of measurements on the same type	Maximum derivation from the means in %
<i>A) Aneroids</i>				
German Silver, steel spring	L. Scriba (12)	+0.000051		
German Silver, steel spring	L. Scriba (12)	+0.000202		
German Silver, steel spring	L. Scriba (12)	+0.00046		
Invar, steel spring	L. Scriba (12)	+0.00028		
German Silver, no spring	L. Scriba (12)	+0.00061		
Steel, no spring	L. Scriba (12)	+0.000164		
Monelmetal, no spring	L. Scriba (12)	+0.00043		
Monelmetal, no spring	L. Scriba (12)	+0.000323		
Steel, no spring	L. Scriba (12)	-0.000173		
Bosch	M. I. T.	+0.00053		
Bosch	M. I. T.	+0.00038		
Bosch	U. S. Weather Bureau*	—	0.00013	
German Silver, steel spring	Kleinschmidt (6)	—	0.0003	
<i>B) Bourdon Tubes</i>				
Friez	U. S. Weather Bureau (Ballard)	—	0.00052	
Bosch	Hergesell, Kleinschmidt (16)	—	0.000457	11 (26)
Richard	Hergesell, Kleinschmidt (16)	—	0.000637	69

* As given in the manuscript of the U. S. Weather Bureau instructions for aerological ascents.

about 4 millibars at sea level and about 2 millibars at the five kilometer level. A good many of these errors can be eliminated by the method of evaluation of the flight records. If a printed chart is used on the meteorograph drum, the pressure indications at the surface will be erroneous if the temperature is different from the temperature for which the chart is graduated. The same thing holds for higher altitudes. On the other hand, if the deflections are measured from a known base line (surface barometer reading) irrespective of the position of this base line on the chart, the initial discrepancy will disappear. In case the calibration curve is a true straight line, it makes no difference in which part of it the pressure is determined, or, in other words, the initial error is completely taken care of for the whole ascent. As the displacement ordinarily is very small, even our slightly curved calibration curves may often be considered straight lines. This method, however, can not eliminate the errors due to the temperature lapse rate between starting point and ceiling. An average temperature drop of 30°C results in an error of about 6 millibars or 100 meters on the basis of $\alpha = .0004$. The goal is, of course, to construct an aneroid with $\alpha = 0$, because in this case any temperature influence on the aneroid would be eliminated. The fact that some aneroids now in use have positive α -values, others negative α -values shows that this is not impossible.

A steel alloy tested by Kleinschmidt [13] proved to increase the spring tension with increasing temperature. Kleinschmidt concludes from this that it must be possible to make a special steel the elastic properties of which do not change with temperature. A combination of two springs, one with increasing, one with decreasing elastic tensions might lead to the desired result. In this case one of the springs could be represented by the Vidi chamber or the bellows themselves.

The Deutsche Versuchsanstalt für Luftfahrt has built aneroids without special springs by bracing membranes on a stiff ring of brass. The temperature expansion of this ring causes small deformations of the aneroid which act in the opposite sense to the temperature effect on the elastic deformation. Different test pieces showed α on both sides of zero. Proper choice of materials must lead to a compensated aneroid.

Another way of compensation is the use of bimetal members in the enlarging mechanisms and mountings. In fact instruments of this kind have been built commercially, without coming into general use, however. Recent new suggestions in this direction by the Bureau of Standards and the U. S. Weather Bureau are expected to lead to a more successful solution.

Our present meteorographs and barographs are not equipped with aneroids compensated in one of the above mentioned ways. Most of them are partly compensated with a gas filling. The chambers or bellows are not completely evacuated but a small quantity of air is left inside. Its pressure of, say 2 inches, is indicated by arrows i in Figure 8. Changes of this inside pressure cause small deformations of the aneroid which can be used to partially compensate the thermo-elastic effects.

The inside pressure varies according to the temperature of the aneroid and according to the volume changes of the chambers, caused by the deformation at different air pressures. The gas filling follows the gas laws as long as no condensation takes place. This, however, happens easily if the inside air is damp from soldering fluid that may penetrate when sealing the chambers. The inside pressure at calibration temperature T_0 and surface pressure p_0 is given by

$$i_0 = \frac{RT_0}{V_0}.$$

(R = gas constant, V_0 = chamber volume)

At any other pressure p during the calibration it is given by

$$i = \frac{RT_0}{V}.$$

At a temperature $T_0 + \Delta t$ and a chamber volume V' , corresponding to the external pressure p , the inside pressure is

$$i' = \frac{R(T_0 + \Delta t)}{V'}.$$

The difference $i' - i$ causes a deformation of the chambers relative to the position they occupied at the calibration temperature T_0 and the air pressure p . The pressure ($i' - i$) pushes from the inside. The effect will be the same as if the air pressure p had been reduced by an amount ($i' - i$)

$$-\Delta p = i' - i = \frac{R(T_0 + \Delta t)}{V'} - \frac{R \cdot T_0}{V}.$$

If one could arrange the amount ($i' - i$) to vary with air pressure p and temperature t in such a way that it would exactly counteract the thermo-elastic errors, a completely compensated aneroid would be obtained. The thermo-elastic error as given above is

$$\Delta p = \alpha \cdot p \cdot \Delta t.$$

The combination of the two components of Δp is to furnish V as a function of p for a completely compensated system:

$$\alpha \cdot p \cdot \Delta t = \frac{R \cdot T_0}{V'} + \frac{R \cdot \Delta t}{V'} - \frac{R \cdot T_0}{V}.$$

If $V' - V$ is negligibly small it follows that

$$V = \frac{R}{\alpha p}$$

Since the inside volume of the chambers varies both with temperature and with pressure an absolutely compensated aneroid can not be built on this principle. However, the volume changes due to temperature ($V' - V$) are rather small in comparison with the volume changes due to variations in air pressure. They may be neglected. Thus it follows that compensation can be obtained if the chambers are built in such a way that their volume changes inversely with the air pressure.

Very few aneroids are built this way. In most cases the inside volume is so large and the deformation over the whole pressure range so small that one may assume that the volume is the same under all conditions. In this case

$$\begin{aligned} -\Delta p = i' - i &= \frac{R(T_0 + \Delta t)}{V_c} - \frac{RT_0}{V_c} = \frac{R}{V_c} \Delta t \\ &= \frac{i}{T_0} \Delta t = A \Delta t. \end{aligned}$$

The complete correction formula is

$$\Delta_c p = (A - \alpha p) \Delta t,$$

where $\Delta_c p$ is the correction to be applied to readings of p if the aneroid has a temperature which exceeds the calibration temperature by the amount Δt . Normally, Δt is negative during meteorological ascents. The readings of the meteorograph thermometer are taken as measures of the aneroid temperature. A is the gas filling constant and α the elastic constant.

This formula shows that the aneroid is compensated for one pressure only. This pressure (p_c) is called the compensation pressure and is given by

$$p_c = \frac{A}{\alpha}$$

The corrections in the region near p_c are small. This method of compensating aneroids, therefore, is appropriate for station barographs which record pressures varying only slightly around a certain mean pressure. However, care should be taken that a barograph that is intended for use at sea level is not used at a high mountain observatory. The air filling which is needed for a certain purpose can be determined from the two formulas above.

Since

$$p_c = \frac{A}{\alpha}, \quad A = \frac{i}{T_0}$$

it follows that

$$i = T_0 \cdot \alpha \cdot p_c$$

or, roughly,

$$i = 290 \cdot \alpha \cdot p_c.$$

An aneroid for use at sea level, having $\alpha = .0004$, should have an inside pressure of

$i = 290 \cdot 0.0004 \cdot 30$ inches = 3.5 inches. If the same aneroid were to be used 5 kilometers above sea level it should have a filling of only 1.5 to 2 inches.

Airplane meteorographs are frequently compensated at sea level pressure or even higher pressure. The correction formula,

$$\Delta_c p = A\Delta t - \alpha p \Delta t,$$

shows that this is undesirable. The last term of this equation has a tendency to remain constant during an ascent, since p decreases and $|\Delta t|$ increases with elevation. The expression $|A\Delta t|$, however, increases with elevation. If A is large, that is, if the aneroid is compensated for a high air pressure, the correction changes considerably during the ascent. If the air filling is small, $\Delta_c p$ remains more nearly constant during the whole ascent. Since the constant part of the error may be eliminated by the proper evaluation procedure, one may frequently neglect the correction completely. An example may show this. Two aneroids, (1) and (2), have a value of $\alpha = 0.0004$. Aneroid (1) is compensated for 1000 mb; $A = 0.4$. Aneroid (2) is compensated for 400 mb; $A = 0.16$. Two ascents are considered. The first begins at 1000 mb and 20° and ends at 400 mb and -10°C . The corrections in this case are

	Δp at 1000 mb	Δp at 400 mb
(1) Aneroid (compensated at 1000 mb)	0	-7.2
(2) Aneroid (compensated at 400 mb)	0	0

Another ascent may start at 1000 mb with -10°C and go to 400 mb with -40°C .

	Δp at 1000 mb	Δp at 400 mb
(1) Aneroid (compensated at 1000 mb)	0	-14.4
(2) Aneroid (compensated at 400 mb)	7.2	0

The preceding discussion indicates the proper way of calibrating aneroids. The calibration curve for room temperature can most easily be obtained under a bell jar. In fact any container which can accommodate a meteorograph and can stand evacuation may be used. The container has to be tapped for the pressure hose. With the help of a glass— T , a mercurial manometer and a vacuum pump can be connected. A water jet pump may be used instead of an expensive oil pump if there is sufficient water pressure. A good manometer, however, is an essential part of the calibration equipment. All inherent errors of the manometer will of course appear as errors in the calibration. Manometers, with wooden scales are especially undesirable, since the scale changes with the humidity of the air. If the calibration has to be done in a container without a window, it is advisable to determine the range of the barograph by a preliminary evacuation to a pressure about 100 millibars below room pressure.

At M. I. T. a pressure calibration of airplane meteorographs begins with three cycles from surface pressure to the pressure of the ceiling of the daily weather flights. This is to eliminate elastic after effects and to obtain the hysteresis curve. Then follows evacuation in steps of about 100 millibars and again an increase of pressure in steps of about 100 millibars. Care has to be taken that no readings are taken until the adiabatic temperature changes, taking place with the pressure changes, are equalized. They appear as little hooks on the meteorograph record.

Sounding balloon meteorographs are calibrated from high to low pressure only. The steps are smaller, about 60 mb. As the virginal curve is wanted, the instruments are kept

from large pressure changes for at least one week prior to the calibration. For the sounding balloon work, M.I.T. uses Jaumotte meteorographs. They are not equipped with a clock work, temperature and humidity being recorded directly against air pressure. It is, therefore, necessary to mark the pressure steps during a calibration with the help of either the temperature or humidity pointer. This is done by placing the forty meteorographs, which can be accommodated by the calibration chamber, around two 60 watt light bulbs. The bulbs are operated from the outside. A clear mark by the temperature pointer is obtained by an illumination of about 15 sec. at room temperature and of about 25 sec. at a temperature of -70°C .

In order to determine the temperature corrections, the temperature is lowered, usually to -40°C , immediately after the calibration at room temperature. A similar calibration procedure is followed, that is steps of about 100 mb are obtained from high to low to high pressure. Both experiments are made on the same foil in order to avoid any possible displacements. It is not advisable to go to a temperature much below -40°C , as many clock works will stop running at lower temperatures. The air has to be absolutely dry. If it is not, condensation and sublimation take place in the clock work housing, thus even stopping clocks that are built for extremely low temperatures.

The deflections of the pressure pointer can now be plotted into a calibration chart. They are measured as vertical distances from any base line parallel to the traces of the reference pointers. It is convenient to choose a base line at about 700 mb because then the distances above and below the line are short enough to be taken into a screw divider of small size.

On the calibration chart, which has a division of 5 millimeters per 10 millibars, the hysteresis cycles, one at room temperature, one at -40°C are obtained. The temperature corrections may now be taken at any desired pressure. These corrections are plotted once more vs. pressure. If the above correction formula is correct, a straight line should be obtained. Within the accuracy of reading, this is usually the case with Bosch and Friez meteorographs, as their aneroids have a large volume and small displacements. If there is reason to believe that the relation between correction and temperature is nonlinear, further calibrations at different temperatures have to be made. Otherwise, the corrections for different temperatures may now be computed and represented in graphical form. Where no temperature-pressure chamber is available, the correction formula has to be considered correct. The constant A can be determined, provided we know α , by submitting the instrument at surface pressure to two widely different temperatures.

A more satisfactory method is to measure Δp for widely different temperatures once at surface pressure and once at a low pressure. This requires a pressure chamber, the temperature of which can be varied greatly. A number of meteorological institutions carrying on sounding balloon research are equipped with such a chamber, mostly designed for the calibration of sounding balloon meteorographs. If these chambers have no inside ventilation many hours are required for one calibration; thus they are not suitable for aerological stations which use their instruments every day. The meteorographs should be checked at frequent intervals, since there is always the possibility that the constants change. The compensation pressure of one of the Bosch aneroids of M.I.T., for example, went from about 400 mb to about 1000 mb in the course of three years.

A sketch of the temperature-pressure-chamber is shown in Figure 9. It consists of an aluminum tank which can accommodate either two airplane meteorographs or forty

Jaumotte instruments in the same position as during ascents. A six inch window in the lid and electrical illumination, mounted inside and switched from the dashboard permits seeing the traces of at least one instrument during the calibration. A blower fan, operated through a stuffing box by an outside motor causes vigorous stirring of the air in the tank. Measurements with thermocouples have shown that there are no temperature

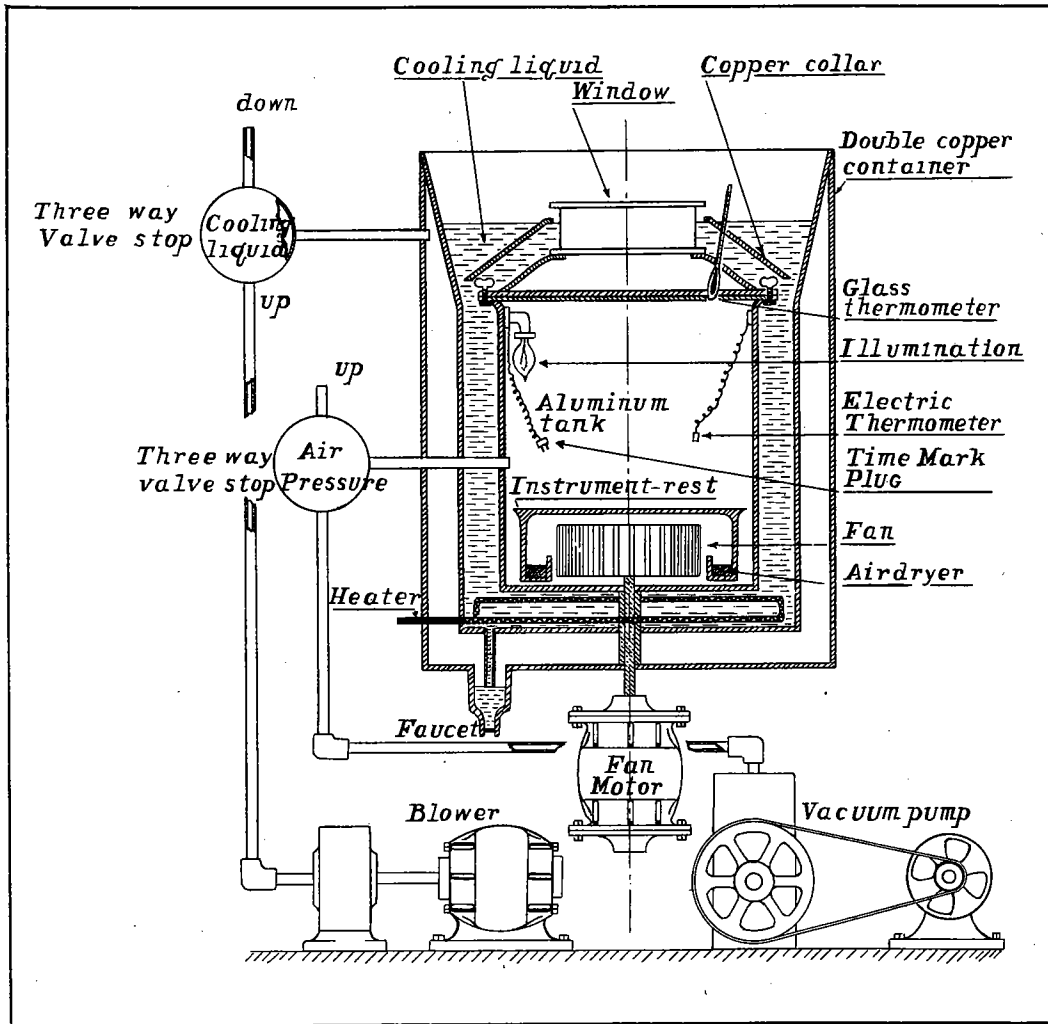


FIG. 9.—Massachusetts Institute of Technology temperature-pressure-chamber.

gradients in the tank except when it is completely filled with instruments. Even then it was possible to obtain a temperature of around -75°C , uniform to within one degree, which is sufficient for pressure calibrations. The instruments are placed on a rest on which are mounted trays of phosphor pentoxide which absorbs all moisture in the tank. The tank is wired for thermocouples, resistance thermometers and time marks. In addition, two mountings are provided in the lid, which accommodate either glass thermometers or additional electric thermometers. A pipe line goes from the tank to a three-way air

valve which is also connected with a vacuum pump and with a line into the room, either directly or through a gas washing bottle. The handle of this valve may be turned to three positions. If turned to "air pressure-down," the tank connects with the vacuum pump. The pump motor is automatically switched on and evacuation begins. In position "stop" the tank is sealed, the pump motor switched off. In position "air pressure-up," the tank

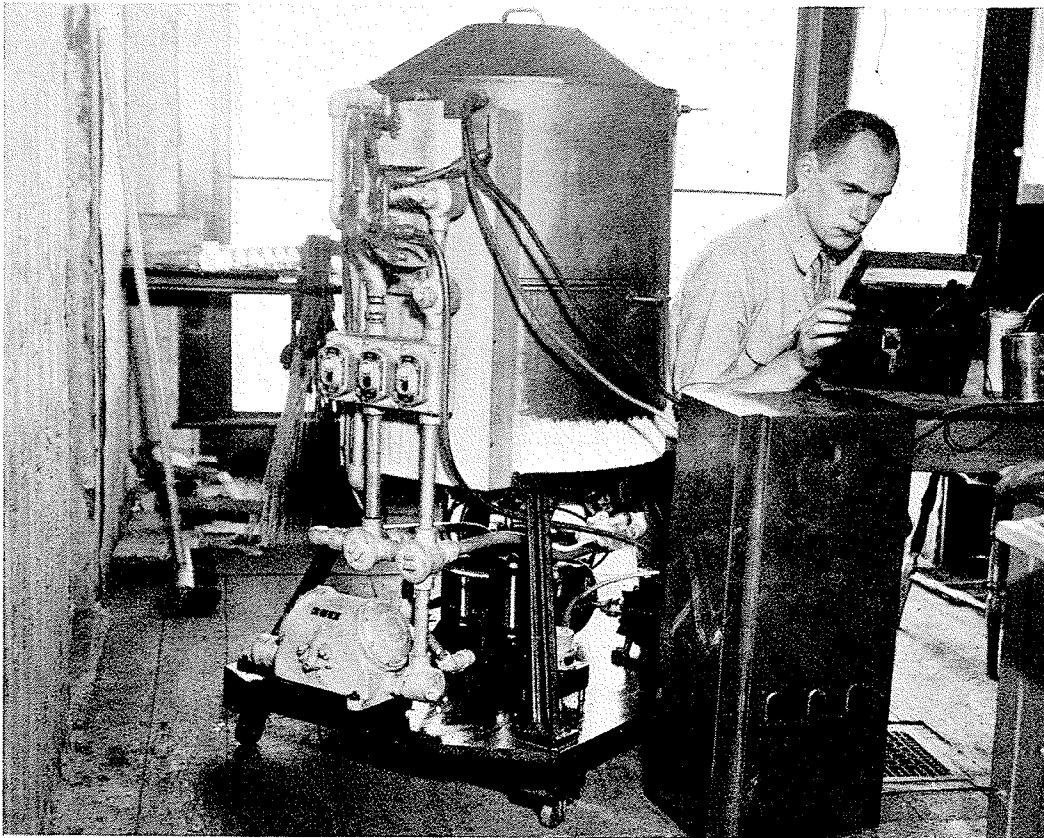


FIG. 10.—Massachusetts Institute of Technology temperature-pressure-chamber.

line opens to the room. If it is intended to increase the inside pressure while the chamber is at low temperature, a gas washing bottle to dry the air is essential since otherwise its moisture would be deposited on the instruments in the tank.

Another pipe line connects the tank with a manometer. The aluminum tank is placed in a double metal container, soldered air tight. When not in operation the lower part of this double container holds about seven gallons of alcohol or gasoline. The lid of the aluminum tank may be opened in this position. When this lid is screwed tight, air may be pumped into the outer part of the double container forcing the cooling liquid up until it completely surrounds the aluminum tank. Further pumping bubbles air through the alcohol, thus stirring it. The outer room now is filled with air and serves as an insulator. This is the position shown in Fig. 9. A three-way valve serves to operate the liquid level. In position "liquid level up" the outer container is connected with a blower, the motor

of which is automatically switched on. In position "stop" the level is maintained in a steady position save for small variations caused by temperature changes of the air in the outer container. They cause pressure changes which push the liquid up or down. In position "liquid level down," the outer container is opened to the room, whereby the liquid in the inner container drops below the lid of the instrument tank. A faucet is provided to empty the device.

If the temperature inside the tank is to be lowered, dry ice (solid carbon dioxide) has to be dissolved in the cooling liquid. The heavy gas development occurring during this procedure causes intense stirring of the alcohol and often "overboiling." For this reason the edges of the container are drawn up rather high. In addition a metal collar is placed on top of the aluminum tank. The bubbles break on this collar and the carbon dioxide escapes without spilling alcohol. It is, however, necessary to crush the dry ice into pieces of nut size before putting them into the solution. If larger pieces are immersed the gas development is too vigorous. Besides, it requires more time to lower the temperature, since big pieces do not dissolve quickly enough. A shoot is provided on the copper collar for the dry ice.

The temperature can be lowered in steps according to the quantity of ice dissolved in the cooling liquid. We have been using steps of about 7°C in the calibration. Approximately 15 minutes are required for each step to obtain steady conditions when calibrating airplane meteorographs. Jaumotte instruments require less time.

In order to make a temperature calibration from room temperature to about -40°C , one 50-pound block of dry ice is sufficient. With two blocks of dry ice temperatures of -75° to -78°C can be reached. The time required to lower the inside temperature from room temperature to -75°C is less than one half hour, provided no time has to be spent in obtaining intermediate readings. If no further ice is added, the temperature of -75°C rises at a rate of approximately 1°C per 12 minutes on account of heat conduction and radiation. An electric heater is built into the chamber to accelerate this rate of heating and permit temperature calibrations from low to high.

With this calibration chamber pressure calibrations can be executed at any temperature. On account of imperfect insulation, the temperature always rises slowly. Although this change is but very small, the corresponding change of pressure in the tank is inconvenient. With an ordinary manometer two settings are necessary. It requires some practice either to keep the temperature absolutely constant by adding small amounts of dry ice or to make the manometer settings very quickly.

A manometer that necessitates only one reading would certainly contribute toward more accurate check readings. If, in addition, a manometer could be built so that temperature corrections of the mercury are automatically eliminated, most of the inconvenient calculations now connected with a pressure calibration could be saved. Figure 11 shows such a manometer. The left limb has a large diameter R , the right limb a diameter r which must be wide enough not to cause excessive capillary depression. At least 8 mm width should be considered. The vacuum is connected to the right limb. At 0°C and no pressure difference, the two mercury levels are equally high. The scale is attached so that its zero point coincides with this level. If a pressure difference b is applied the mercury rises h mm in the right arm and falls H mm in the left arm. h can be determined by one reading on the scale. b can be computed from

$$b = H + h, h \cdot \pi r^2 = H \cdot \pi R^2.$$

Thus

$$b = h \left(1 + \frac{r^2}{R^2} \right).$$

At $t^\circ\text{C}$ the reading on the scale would be $h' = h(1 + \gamma t)$ where γ is the expansion coefficient of mercury minus the expansion coefficient of the scale. With a brass scale this would be 0.000162. By substitution one finds

$$b = h' \frac{1 + \frac{r^2}{R^2}}{1 + \gamma t}.$$

Thus, if the diameter R of the left leg is chosen so that at room temperature ($t_0 = 20$)

$$R = \frac{r}{\sqrt{20\gamma}},$$

one reading from the scale would furnish the pressure difference already corrected for room temperature.

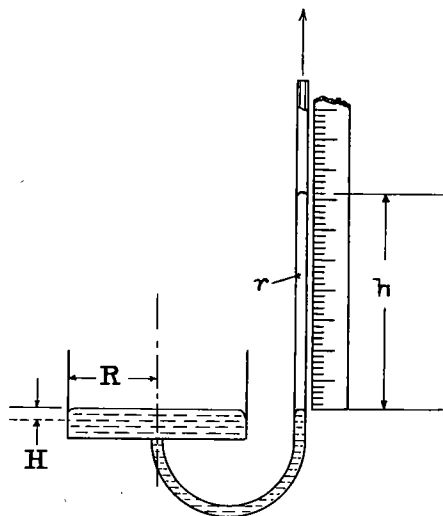


FIG. 11.—Sketch of a compensated manometer.

D. CALIBRATION OF HYGROMETERS

In modern meteorology the humidity of the free atmosphere plays a rôle as important as that of pressure and temperature. Nevertheless, present day aerological humidity measurements do not conform to our needs. Specific humidity is considered a conservative property of individual air masses; it is especially important to obtain reliable upper air data on humidity for the routine analysis of the various air masses depicted on our daily weather maps. Considerable time has, therefore, been devoted towards improving the methods of observing air humidity. This work is to be continued on a larger scale in the near future. A detailed account will be given in a separate report after the investigations have been completed.

In the following is given a short outline of some experiments during flight with psychrometers and dew point indicators and a description of our calibration chamber for hair hygrometers. From the beginning the use of recording dry and wet thermometers was not promising. It was to be expected that on practically each flight the wet bulb would freeze. Although it usually is possible to see from the record whether there is water or ice on the wet bulb, no humidity record can be obtained while the water is freezing. This usually takes place just below the freezing point, so that those conditions are not recorded, which are of special interest in connection with ice formation on aircraft. Nevertheless experiments of this type were carried out. The thermometer of one of two meteorographs was covered with cloth, which was kept wet by means of a wick and an oval aluminum container with water. The evaluation of the records showed that the lag of the covered thermometer was such that all the way up it recorded higher temperatures than the dry thermometer.

Assmann psychrometers were carried up and attempts were made to read them at the top level in order to check the indication of the hair hygrometer at that point. The temperatures there, however, were always so low that the computation of the relative humidity from the dry and wet bulb readings were inaccurate. They could hardly be used as a check. Readings with the same instrument inside the cabin were more successful, as the inside temperature usually was 10°C . to 15°C . higher. By computing the specific humidity from both the psychrometer and the hair hygrometer of the meteorograph, a comparison of the two measurements is possible. The tests, however, showed that the humidity inside the cabin was always much higher. This is easily explained by the presence of two persons in this small space.

Experiments were then carried out with an Assmann psychrometer with preheating of the air. Willett, following a suggestion by Köhler, had prepared such an instrument for measurements of the total water content in fog. The air was sucked from the outside of the airplane by a large tubing into the psychrometer. Before reaching the bulbs, the air was drawn past a heating wire system which was connected to a six volt battery. In this way the air temperature was raised about 30°C . The result was that the humidities became so low that the sleeve of the wet bulb usually dried off before the equilibrium depression of the thermometer was reached. When it was reasonably certain that the minimum position of the wet bulb was reached, the depression usually was so large that there seemed to be some doubt regarding the propriety of applying Sprung's formula for the computation of vapor pressure or relative humidity. The checks obtained in this way were poor. This psychrometer with preheating was later brought to Mount Washington observatory. There its readings were compared with those of an ordinary psychrometer, a hair hygrometer and a dew point indicator. The test on the mountain showed that the principle of the preheated psychrometer is sound.

By far the most promising results were obtained with a dew point indicator. A standard Lambrecht dew point mirror was mounted in front of a cabin window of the Robin plane in such a way that it could be read from the inside. The Lambrecht dew point indicator normally is operated by blowing air through sulphuric ether. For use in the plane, the exhaust nozzle of the dew point indicator was connected to a hose system which ended in a Venturi tube. By means of a stop-cock, the air flow could be regulated in order to cool the mirror to the dew point. Another circuit was used to refill the indicator with ether from a large bottle. This contraption gave excellent results at low altitudes. The dew point was determined very quickly and accurately and checked reasonably well

with the indications of the hair hygrometer. At higher altitudes, however, the ether in the bottle evaporated, although the pressure did not come near the vapor pressure of ether.

From these tests one must conclude that it is possible to measure humidities during aerological flights more accurately than the hair hygrometer does. A better method of cooling the dew point indicator, however, has to be found. Experience has taught us that the effect of the ether fumes on the human body are much more serious at high altitudes than on the ground.

The human hair is used as an indicator of relative humidities since the introduction of its use by Saussure in 1783. If proper care is taken, it gives excellent results at temperatures above the freezing point and at high relative humidities. At low temperatures and low humidities, its lag is quite large. Aerological ascensions always encounter these conditions. The accuracy of our upper air humidity data, therefore, is often very poor. To the author's knowledge, there exists no complete study of the lag in the hair hygrometer. It is, therefore, impossible to apply accurate corrections for lag to the humidity records of our meteorographs.

The hair lengthens if the humidity increases. The total displacement of 100% *RH* varies from hair to hair. The changes of length relative to this total displacement follow a certain law. Already Saussure gave the correlations between these changes and relative humidity. They were checked by other investigators but no physical law has been found to explain them. With the help of this empirical law it should be possible to calibrate a hair hygrometer by simply determining the deflections at two different relative humidities. One measurement may be obtained on a day with low relative humidity, another under a bell jar, the walls of which are covered with damp cloths. Bongards [17], in his excellent and complete study on humidity measurements, has pointed out that it is not easy to obtain 100% *RH* accurately. This method of calibrating the hair therefore usually introduces an error of a few % *RH* from the very beginning.

Saussure's data on the relation between relative humidity and deflections of the hair may be correct for all hairs. In all our meteorographs, however, the indications of the humidity stylus are somewhat distorted from Saussure's relations, on account of the enlarging linkage which is necessary to present the deflections of the hair in a suitable size. Assuming that the linkage tends to enlarge the deflections of the hair in a linear fashion one additional calibration point is necessary. This assumption seems to be correct as far as the Bosch meteorograph is concerned.

A calibration chamber was built, therefore, which permitted the establishment of three widely different relative humidities. This device consisted of a metal chamber capable of accommodating two meteorographs. A pipe line connected the chamber to an air pump. The pump sucked the air from the chamber into a gas washing bottle filled with distilled water. Here the air was enriched with water vapor and pressed back into the chamber. A high relative humidity was established which could be measured by dry and wet bulb thermometers, mounted into the line between chamber and pump. The water bottle could be replaced by two other bottles containing sulphuric acid solutions. According to the concentration of these solutions, two different humidities were established.

This device represented an improvement compared with the first mentioned calibration method. However, it was not possible to obtain absolutely constant relative humidities on account of temperature changes taking place in the system. About an hour was required to obtain asymptotic values of the humidity records. If, during this time, the

room temperature changed somewhat, the relative humidity in the chamber changed too. Adiabatic temperature changes in the pump lines, heating by the pump and temperature changes due to evaporation or absorption of water in the bottles added to the lack of constancy of the temperature.

The calibration points obtained seldom fell exactly on the curve given by Saussure's data. It was not possible to say whether this was due to the hair or due to erroneous calibration of the chamber.

An improved chamber on the same principle was then built. This second device was also equipped with three gas washing bottles, but this time flat containers were used, which were arranged in such a way that they formed the three side walls of the chamber, in front being a glass door. All pipe lines were made as short and as wide as possible. The dry and wet bulbs were placed into the chamber in front of the exhaust tube. As a check on the relative humidity not only the psychrometer but also a standard hair hygrometer and a dew point indicator were used. A fourth check was obtained through hydrometer readings in the acid solutions. Repeated operations showed that a maximum of 96% could be reached when bubbling air through water. About 60% and about 25% were obtained with the acid solutions. At these humidities, psychrometer, dew point indicator and hydrometer furnished readings of the relative humidity which agreed to within 1% RH. The standard hair hygrometer was about 2% off at 25% RH.

The deflections of the humidity stylus of the meteorographs which were calibrated in this chamber again did not fall on Saussure's curve. The three fold check readings left little doubt as to the correctness of the calibration. The conclusion was inescapable that Saussure's relations cannot be used in the preparation of humidity curves for our meteorographs. Additional calibration points are needed.

The daily check readings of the humidity before and after the flights showed that there was a pronounced error due to temperature. Temperature corrections of hair hygrometers are given by Kleinschmidt [6]. They were applied during the first year of operating the M.I.T. aerological station. Even with these corrections the two readings practically never checked completely. A discrepancy of several % was frequently found and had to be ascribed to lag or some other unknown effect. The humidity values which are given in the adiabatic charts are based on the check reading which seemed to be the more reliable. An attempt was made to find more accurate corrections by computing corrections of hair hygrometers mounted in an aluminum frame (Kleinschmidt's corrections are based on a brass frame). No obvious improvement was gained, so that during the last two flying periods no corrections whatsoever were applied.

Investigations by Griffith [18] resulted in temperature corrections for hygrometers that are entirely different from Kleinschmidt's data. For this reason it was considered essential to design a calibration chamber which not only permits the establishment of at least six different states of humidity but also their establishment at different temperatures.

The principle of this device is sketched in Fig. 12. A copper lined wooden box of about 2-1/2 by 2 feet and about 1-1/2 foot high can be filled with water of any desired temperature between 0°C and 100°C. It contains the copper calibration chamber which is then surrounded by water on five sides. The chamber is open to the front and can be closed air-tight by an insulating glass door. On both sides of the calibration chamber there are six gas washing bottles, also completely surrounded by water. The pump, which at present is mounted on top of the wooden box, will be set down so that it, too, will be im-

mersed in water. All pipe lines are surrounded by water except the short pieces which serve as connections to the different bottles. These are insulated. On account of the large heat capacity of water, temperature changes are practically eliminated. During recent calibrations at room temperature the dry bulb indicated a change of $.2^{\circ}\text{C}$ during three hours.

At room temperature and high humidities about 10 minutes are required to go from

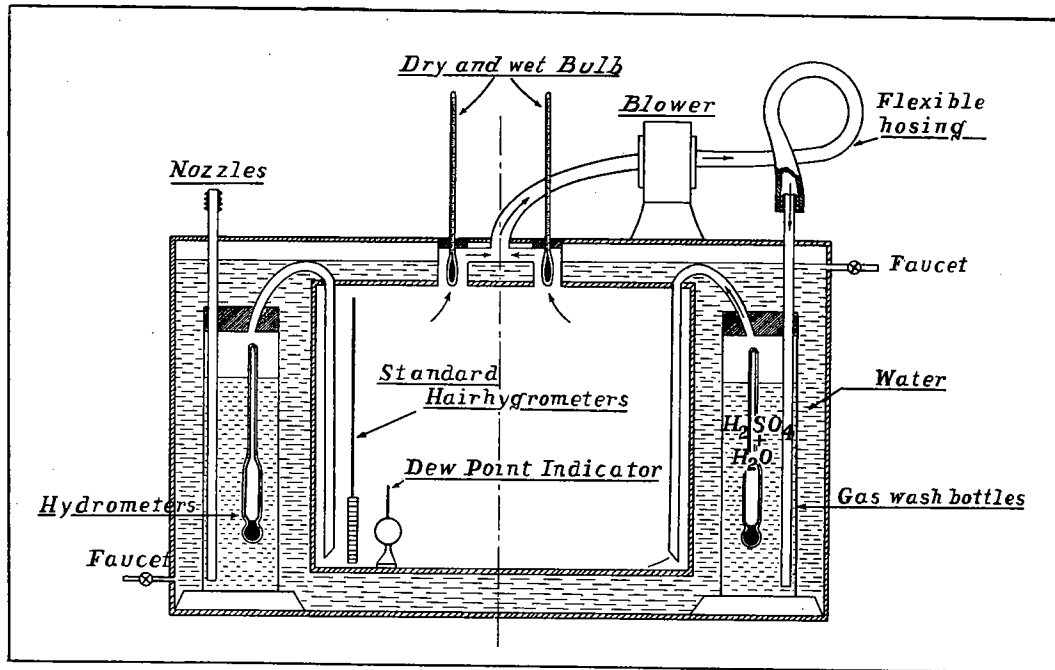


FIG. 12.—Massachusetts Institute of Technology hygrometer calibration chamber.

one reading of a Friez meteorograph to another reading, about 15% RH lower or higher. At low humidities about 20 minutes are needed. At a temperature of 5°C , twice to three times the time is required for the same steps. The calibration points obtained in this chamber fitted well a smooth curve. The calibration from high to low humidity agreed to 1% with the calibration from low to high humidity. After some details have been perfected, this calibration chamber will serve the weekly routine calibrations of the M.I.T. meteorographs. At room temperature a calibration in steps from high to low to high requires slightly more than two hours. In order to find accurately the temperature correction a calibration at a temperature lower than room temperature has to be made. This requires too much time for routine calibrations. Tests will have to prove whether or not a second calibration at higher temperature will furnish the same temperature corrections of the hygrometer. In this case the whole calibration of the hair hygrometer can conveniently be done between daily ascents.

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II. AIRCRAFT INSTRUMENTS IN METEOROLOGICAL FLYING

BY C. S. DRAPER

Any undertaking which requires flights under conditions of no visibility, must of necessity employ instrumental aids to flying. It is the purpose of the present section to outline briefly the application of instruments to the problem of meteorological flights.

In general the tachometers, pressure gauges, thermometers and fuel level gauges used in checking aircraft engine operation present no special difficulties for meteorological flying. On the other hand the flight control instruments introduce several problems.

A convenient classification of flight instruments may be made, using as the basis the various geometrical displacements possible to an aircraft and their time rates of change. Such an arrangement has been given by Bassett [5] in the table reproduced below.*

The airplane used in the present series of flights was equipped with each of the instruments listed in this table except the drift indicator and the pitch indicator. The function of the drift indicator was taken over to a certain extent by a radio set operated in conjunction with the Department of Commerce radio beacon station at the Boston Airport. The other instruments will be considered below.

TABLE I
AIRCRAFT INSTRUMENT CLASSIFICATION

AXES	MOTION	RATE INSTRUMENTS	AMOUNT INSTRUMENTS
Translation			
1. Longitudinal	Forward	Air Speed Indicator	Radio
2. Lateral	Sideways	Drift Indicator	Radio
3. Vertical	Up and down	Rate of Climb Indicator	Altimeter
Rotation			
4. Longitudinal	Roll or Bank	Bank Indicator	Sperry Horizon
5. Lateral	Pitch	Pitch Indicator	Sperry Horizon
6. Vertical	Turn	Turn Indicator	Directional Gyro Magnetic Compass

Two air speed meters were installed as permanent equipment on the meteorological plane. One air speed meter was of the conventional pitot-static type as supplied by the Pioneer Instrument Company. This instrument operated well except under certain atmospheric conditions leading to ice formation on the externally mounted pitot-static pressure head. This trouble may be reduced by use of an electrically heated pressure head. Such heated units are now commercially available and would certainly prove of value in meteorological flying. The second air speed meter was of the rotating cup anemometer type. The cup anemometer has the ability to remain in operation under the most severe conditions of ice formation and will, besides, give a speed indication unaffected by atmospheric density changes.

A Pioneer Rate of Climb meter was found to be useful in maintaining the optimum condition of climb during the ascents. This device gave satisfactory results throughout the work.

The functions of the pitch indicator were taken over by the Sperry Artificial Horizon.

Indications of rate of rotation in yaw and of roll under conditions of straight flight were furnished by a Pioneer Bank and Turn Indicator of the usual type.

* As general references on the subject of Aircraft Instruments the books by Stewart [1] and Eaton [2] may be mentioned. The Specialized study of blind flight is treated by Ocker and Crane [3] and by Stark [4].

Radio receiving equipment was found to be indispensable for consistent operation under conditions requiring long ascents through cloud layers. The receiver used was manufactured by the Radio Marine Corporation of America. The use of sensitive radio apparatus necessitated careful electrical shielding of the ignition system of the engine. A complete shielding system was made up to special order by the Breeze Corporation of Newark, New Jersey.

Several experiments were carried out to determine the most suitable type of radio antenna. A single trailing wire was found to produce satisfactory results. As supplementary equipment a single wire flat top antenna was mounted below the fuselage.

The altimeter used was of the "sensitive" type capable of indicating differences of barometric pressure corresponding to altitude changes of ten to twenty feet. This instrument was supplied by the Kollsman Instrument Company of Brooklyn, New York. In practice the altimeter was found to be reliable and in general gave excellent results.

A Sperry Artificial Horizon served to establish a horizontal reference plane within the aircraft. The mechanism of this instrument is so arranged that the pilot may easily interpret its indications in terms of pitch and roll of the airplane. A gimbal mounted gyro wheel is so controlled that its axis is made to coincide with the average direction of the resultant of gravity and inertia forces acting on the airplane. This is attained through the action of a set of four small, pendulum-controlled air jets. Any deviation of the axis from the direction of the resultant acceleration introduces a moment in the proper sense to precess the gyro back into position. The angular velocity due to these restoring moments is small so that in practice the gyro will assume a satisfactory average position. Whenever the pilot desires to maintain straight flight the direction of the resultant force on the airplane is nearly enough along the direction of gravity for the unit to establish a satisfactory horizontal reference plane.

Directions in azimuth were indicated as usual by a magnetic compass, the particular instrument used being a conventional aircraft compass supplied by the Pioneer Instrument Company. A Sperry Directional Gyro was installed as an auxiliary azimuth instrument. This device possesses the great advantage of being free from the inertia errors inherent in the magnetic compass. The instrument consists of a air driven gyro wheel mounted in a free gimbal system. The high angular momentum of the wheel, combined with the small disturbing torques transmitted by the nicely made gimbal bearings, result in negligible deviations from a set direction over time periods up to thirty minutes. The gyroscopic assembly is fitted with an azimuth scale and an arrangement for making at will any desired directional setting.

As units the gyroscopic devices gave satisfactory service, but the necessity of supplying air for driving the rotors introduced difficulties which were accentuated by the type of service required in meteorological flying. This matter of gyro air supply will be discussed somewhat at length in the succeeding paragraphs.

The usual method of driving the gyro instruments is by means of a double Venturi unit furnished as part of the equipment [6]. Theoretically such a device should give a pressure difference depending directly upon $1/2\rho v^2$, where ρ is the air density and v is the relative velocity of the venturi with respect to the airstream. In practice there are variations due to changes of Reynold's Number with temperature and density and to the introduction of air at the throat of the venturi. Experiments were actually carried out over an altitude range of 15,000 feet and showed that for a constant pitot-static air speed meter reading, the suction supplied by a venturi is approximately constant. It

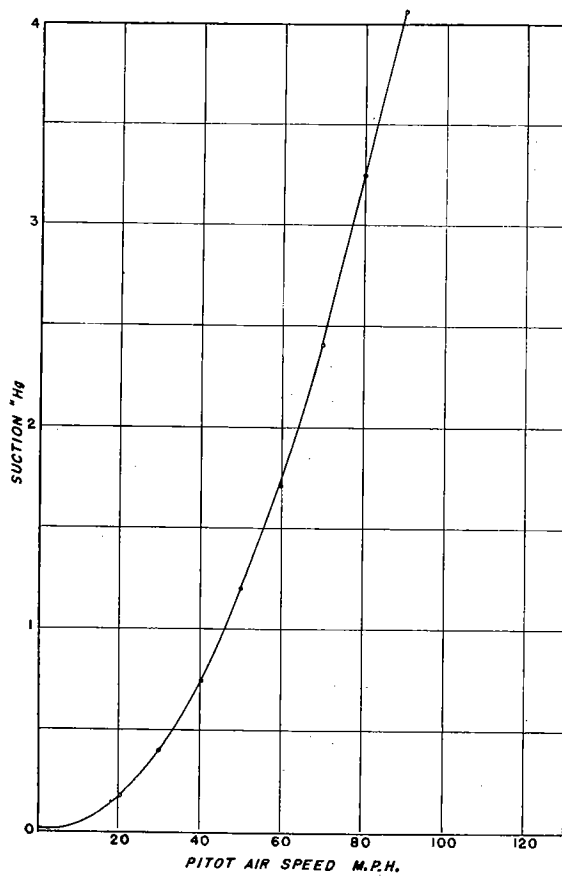


FIG. 1.

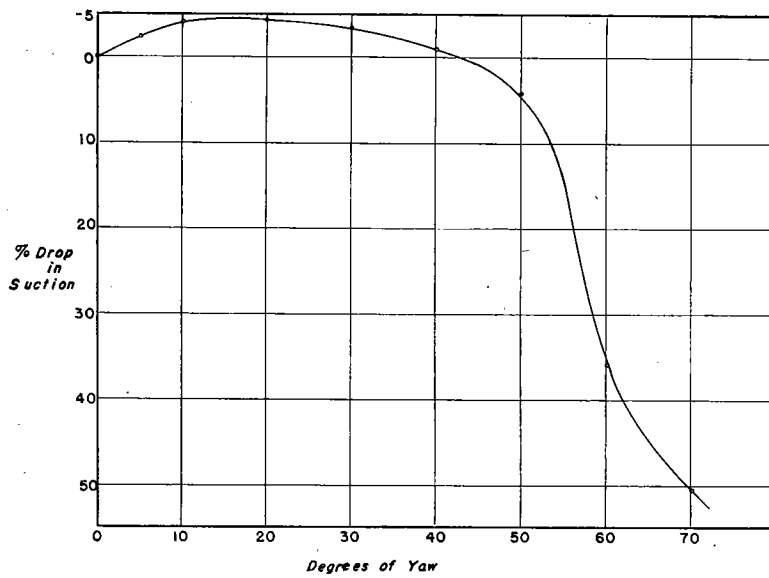


FIG. 2.

follows that in general a venturi furnishing the required pressure difference of three and one half to four inches of mercury for a certain pitot-static meter reading at sea level will give almost the same pressure difference at any other altitude for a like pitot-static reading.

The venturi as a source of power for instrument drive has two serious disadvantages in meteorological work. In the first place, the suction supplied falls off with the square of the pitot-static air speed meter reading and in the second place a small amount of ice formation seriously impairs operation. Figure 1 shows the relation between venturi suction and pitot-static air speed as determined from wind tunnel tests by A. Spilhaus under the writer's direction [7].

The curve indicates that under wind tunnel conditions an air speed of over eighty miles per hour is necessary to give the required pressure difference for instrument drive work. In practice, sufficient vacuum may be obtained under conditions of climb down to pitot-static air speeds of fifty to sixty miles per hour by using a venturi location within the slip stream.

A second series of wind tunnel tests was made to determine the effect of yaw on venturi performance [7]. The experimental results are given in Figure 2.

This plot indicates plainly that there is no necessity of carefully adjusting the venturi along the air stream.

A number of flight tests were carried out to study the effect of venturi location on the suction supplies. It was found that a position on the upper side of the wing near the outer portion of the slipstream and over the front wing spar gave much better results than locations below the wing or on the fuselage. A venturi placed above the wing also proved to be much less affected by skidding or slipping of the airplane than a similar venturi placed below the wing.

Since the high angle of attack maintained during rapid ascent is unfavorable for venturi operation, it is important to reduce pressure losses in the supply lines and fittings as far as possible by using large tubing with bends of relatively large radius. A vacuum gauge with a range of six inches of mercury was a permanent part of the installation on the M.I.T. airplane and served to check ordinary operation in addition to supplying warning of a drop in suction due to ice formation in the venturi.

The matter of ice formation is an integral part of the instrument problem if full use is to be made of the airplane as a means of collecting meteorological data. It is possible to reduce the difficulty by mounting the venturi on the engine exhaust manifold. Reports made by the pilots indicate that under severe conditions even this heating is not sufficient to prevent ice formation.

There is the possibility of utilizing the engine intake manifold vacuum for driving the gyro instruments. A complication is introduced by the variation of suction as engine output is changed. At full throttle the manifold vacuum may drop to a value less than one inch of mercury while under idling conditions the depression may amount to twenty inches of mercury. Thus in climb with full throttle, the vacuum is lower than the required amount, while in descent with closed throttle the reverse would be true. A suitable automatic pressure control might be used to advantage here for conditions giving more than the necessary three inches of mercury. It is apparent that the present instruments will not operate properly from the manifold vacuum of an engine subjected to full throttle operation for long periods of time. This makes the manifold connection of no use in most meteorological ascents.

The difficulties of low speed operation and ice formation led to the purchase of a Deslauriers propeller driven pump as the vacuum supply for the two Sperry instruments. This pump gave certain mechanical difficulties and was therefore used as emergency equipment only. Lately a number of companies are making displacement pumps which are either driven directly from the engine or by an auxiliary supply of power.

Mr. Spilhaus [7] has studied theoretically the operating characteristics of a displacement pump supplying power for an air driven gyro rotor and checked his results by experiments on a displacement pump.

The theoretical treatment considers the variation in the pressure difference maintained across a fixed orifice by a pump operating at a known displacement per unit time as atmospheric density changes. The method of treatment is outlined below.

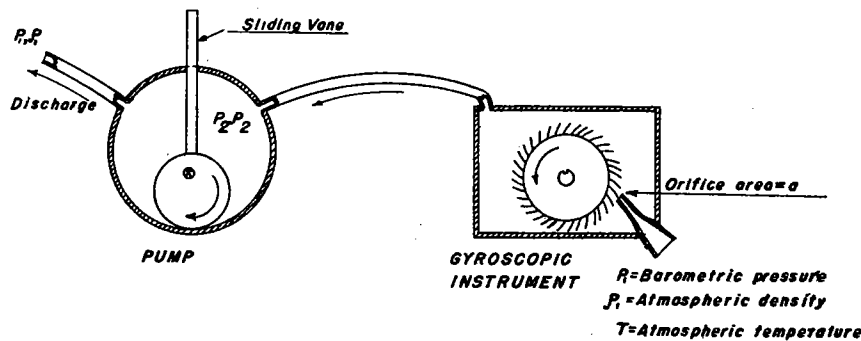


FIG. 3.

The volume (v), of fluid flowing through an orifice of area a per unit time, under a pressure difference of Δp is given by the formula

$$v = (a\alpha) \sqrt{\frac{2\Delta p}{\rho}}, \quad (1)$$

where α is the orifice coefficient and ρ is the air density outside. Let n be the speed of the pump in revolutions per second and d be the displacement per revolution so that the displacement per second V is given by the expression

$$V = nd. \quad (2)$$

By the principle of continuity the mass of air handled per second by the pump must be equal to the mass of air flowing through the orifice in the same time, i.e.,

$$\rho_2 V = \rho_1 (a\alpha) \sqrt{\frac{2\Delta p}{\rho_1}}. \quad (3)$$

There will be a relation between ρ_1 and ρ_2 depending upon the type of process involved in the flow through the orifice and tubing to the pump. The two extreme cases will be isothermal flow on one hand and adiabatic flow on the other. In general the relation between the densities may be expressed as

$$\rho_2 = \rho_1 \left(\frac{p_2}{p_1} \right)^{1/\gamma} \quad (4)$$

where $\gamma = 1$ for an isothermal process and becomes equal to the ratio of the specific heat at constant pressure to the specific heat at constant volume for an adiabatic process.

Substituting this relation into the equation of continuity gives

$$\left(\frac{p_2}{p_1}\right)^{1/\gamma} = \left(\frac{a\alpha}{V}\right) \sqrt{\frac{2\Delta p}{\rho_1}}. \quad (5)$$

Now, in the present case, $p_2 = p_1 - \Delta p$, and substitution of this expression for p_2 gives

$$\left(\frac{p_1 - \Delta p}{p_1}\right)^{1/\gamma} = \left(\frac{a\alpha}{V}\right) \sqrt{\frac{2\Delta p}{\rho_1}}. \quad (6)$$

Solving for Δp results in the expression

$$\Delta p = \frac{\rho_1}{2\left(\frac{a\alpha}{V}\right)^2} \left(1 - \frac{\Delta p}{p_1}\right)^{2/\gamma}. \quad (7)$$

Expanding by the binomial theorem and neglecting powers of $\Delta p/p_1$ higher than the first one obtains

$$\Delta p \left(1 + \frac{1}{\left(\frac{a\alpha}{V}\right)^2 \frac{\gamma p_1}{\rho_1}}\right) = \frac{\rho_1}{2\left(\frac{a\alpha}{V}\right)^2}. \quad (8)$$

Thus, finally

$$\Delta p = \frac{\gamma p_1}{2} \left(\frac{1}{1 + \frac{(a\alpha)^2 \gamma p_1}{V^2 \rho_1}}\right). \quad (9)$$

This expression is valid if $\Delta p/p_1$ is sufficiently small. In the usual case where the instrument case and piping are well cooled the process will be nearly enough isothermal that γ may be taken equal to unity. Under this assumption the vacuum supplied to the instrument by the displacement pump is given by the expression

$$\Delta p = \frac{p_1}{2} \left(\frac{1}{1 + \frac{(a\alpha)^2 RT}{V^2}}\right). \quad (10)$$

Here R is the gas constant and T is the absolute temperature of the outside air. This equation involves two parameters, $(a\alpha)$ which depends upon the performance of the gyroscopic instrument as an orifice and V which depends upon the size and speed of the pump.

A series of experiments was carried out to check the validity of the theoretical result. This work was divided into two parts, the first part being carried out during actual ascents and the second part performed at sea level with an auxiliary pump as a means of controlling the intake and exhaust pressures on the pump under test. A gas meter was used to measure the flow through the pump during the sea level tests so that the parameter V was determined for each condition.

The test results showed that the gyroscopic instruments behave nearly enough as plain orifices if account is taken of the effect of temperature on the bearing friction of the gyro rotor [8]. The curve below shows the agreement between theory and experiment for a displacement pump operating the two Sperry instruments.

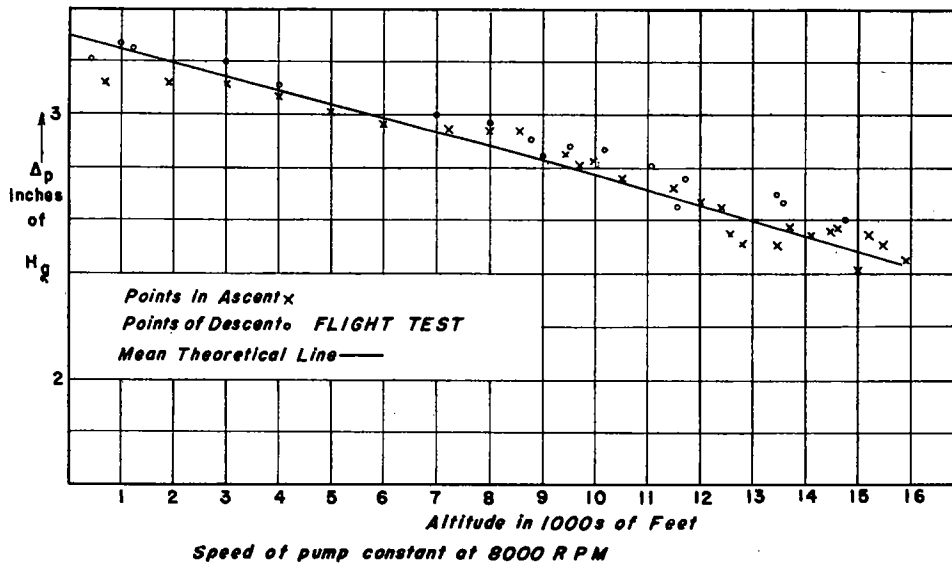


FIG. 4.

The plot indicates that Δp decreases with increasing altitude. There is, however, for a constant Δp , a speeding up of the gyro wheel with decreasing density due to reduced windage losses [8]. This statement is based on experiments made by the Sperry Company in a variable density chamber. In practice the reduced wheel losses should render unimportant the suction decrease of a displacement pump with altitude.

In conclusion it is fitting that an expression of thanks be extended to those manufacturers of aircraft equipment who have cooperated in making successful the meteorological flights at M.I.T.

Many favors have been extended by the personnel of the Sperry Gyroscope Company. In particular the kindness of President R. E. Gillmor in loaning a Directional Gyro and venturi equipment was very helpful. The interest of Mr. C. D. Jobson in the inspection and annual servicing of the instruments has also been of great assistance.

Mr. Frank Gardner of the Breeze Corporation greatly facilitated the radio installation by supervising the design and construction of a system of Breeze Radio Shielding for the Curtiss Challenger engine.

Thanks are due to Mr. J. D. Peace, Jr. formerly of the Pioneer Instrument Company for much useful assistance in the general field of aircraft instruments.

Mr. Paul Kollsman of the Kollsman Instrument Company made possible the installation of a Kollsman Sensitive Altimeter as part of the instrument equipment.

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