INVESTIGATION OF THE OCCURRENCE OF CONDENSATION IN FLIGHT INSTRUMENTS

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BATTELLE MEMORIAL INSTITUTE

TECHNICAL REPORT SEG-TR-66-2

Code 1

JANUARY 1966

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SYSTEMS ENGINEERING GROUP
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

NOTICES

200 - March 1966 - 773-35-766

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FOREWORD

The Project "Investigation of Condensation Occurring in Flight Instruments" was accomplished by the Polymer Research Branch of the Battelle Memorial Institute, Columbus, Ohio, under the USAF Contract Number AF 33(657)-12462. The contract was initiated under the Project Number 913A-0000-97162. Principal Air Force Project Engineer was 1/Lt George A. Hobe of the Systems Engineering Group, Flight Instruments Branch (SEFIF). This report covers work performed from September 1963 to December 1965. The project research personnel were B. G. Brand, Bailey Bennett, and R. I. Leininger. This report was submitted by B G. Brand, Bailey Bennett, and R. I. Leininger of Battelle Memorial Institute in December 1965.

This technical report has been reviewed and is approved.

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ABSTRACT

This study, conducted under Contract AF 33(657)-12462 for the Aeronautical Systems Division, Wright-Patterson Air Force Base, related to the location and identification of sources of fog formation on the faceplates of hermetically sealed aeronautical instruments.

Two types of fog (moisture and permanent) were found. Moisture fog was shown to be caused by imperfect hermetic sealing of the instrument cases. Permanent (oily) fog was found to be the result of partial decomposition of nonmetallic materials by heat. This decomposition in certain materials results in oily products with appreciable vapor pressure, which may condense on the instrument faceplate, usually the coolest part of the instrument.

Thirteen aeronautical instruments representing seven different types, and made by five different suppliers, were covered by this study.

Included in the report are:

(1) A list of recommended materials

(2) A list of materials shown to contribute to permanent-fog formation

(3) A discussion of the psychrometry of gases

(4) A discussion of desiccants

(5) A critique of the ice-cube test

(6) A recommended modification of the ice-cube test to duplicate more nearly the use conditions

(7) A description of a high-sensitivity fog-potential test

(8) Instructions for the use of the test in Item (7)

(9) Pertinent excerpts from the International Critical Tables.

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I. INTRODUCTION

The condensation of foreign materials on the faceplates of aeronautical flight instruments is a critical problem. Any loss of visibility of the instrument face cannot be tolerated.

A three-phase study was undertaken at Battelle Memorial Institute to investigate the sources of fog-causing materials and preventive measures that might be taken. Phase I comprised a state-of-the-art study of production practices and materials selection for the construction of flight instruments. A summary report on this phase was dated February 24, 1964.

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At the completion of Phase I, work on Phases II and III, "Evaluation and Analysis of Information", was authorized and initiated. These phases covered the examination of flight instruments exhibiting fogging or condensation on their faceplates, and identification of the fogging agents and their source. The exploration of preventive measures and a study of psychrometric principles as they apply to condensation on instrument faceplates was also a part of this study.

The ultimate goal of the study was to develop information and data that could be the basis for the preparation of new and improved performance and/or design specifications for hermetically sealed instruments.

Reports have been prepared on a regular monthly basis during the active periods of the study, indicating progress made on Phases II and III. These reports were dated April 10, May 8, June 8, July 9, August 5, and August 31, 1964. The original contract expired on the latter date, and laboratory work was suspended until the approved supplemental agreement, dated January 6, 1965, was received. Reports for the supplemental period were dated February 15, March 5, April 5, May 7, and June 7, 1965. Data presented in these reports are covered and discussed in this Final Report.

Appended to this report is: (1) a list of nonmetallic materials recommended for use in hermetically sealed aeronautical instruments, (2) a list of nonmetallic materials found in instruments that have been shown to contribute to permanent-fog formation, (3) a discussion of the physical chemistry of gases as it pertains to psychrometry and moisture content of gases, (4) a discussion of the effectiveness of drying agents and their possible use in flight instruments, (5) a description and drawings of the fog-test apparatus with improved sensitivity, and (6) a recommended method for its use. Included also are pertinent excerpts from the International Critical Tables covering vapor-pressure data for water and ice over a broad temperature range. Included in the body of the report is Battelle's analysis of the effectiveness of the ice-cube test as an acceptance test and a suggested substitute test that more nearly duplicates the conditions of instrument use.

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* Phase I consists only of a collection of data on the present state-of-the-art causes and prevention techniques of fogging. Since the study deals only with the development of new techniques for the prevention of fogging in flight instruments, Phase I is not included in this report.

II. SUMMARY

The experimental data of Phases II and III of this study were obtained by dismantling 13 selected aeronautical instruments and studying the individual nonmetallic components. The selection represented seven different types of instruments made by five different suppliers. It is felt that this is a wide enough range of instruments and suppliers to permit drawing several general conclusions regarding the sources of condensation of foreign materials on the faceplates of hermetically sealed flight instruments. The conclusions are:

(1) Two types of fogging (condensation) have been observed in flight instruments: (a) temporary or moisture and (b) permanent or oily-type deposits.

(2) Moisture fogging appears to be more prevalent than does permanent fogging.

(3) Moisture fogging appears to be caused largely by imperfect hermetic seals, allowing the instrument case to "breathe" with temperature fluctuations in humid air.

(4) Redesign of the hermetic seal is recommended to improve its effectiveness and reliability.

(5) Use of drying agents (desiccants) is recommended, provided suitable methods are developed for their inclusion in instruments.

(6) Permanent fog is the result of condensation of a material of low volatility on the faceplate, which does not disappear on warming of the instrument to normal operating temperatures.

(7) Several nonmetallic materials were found in the instruments examined that contribute to permanent-fog formation by loss of volatile ingredients with heat to give an oily-type deposit. These materials are listed in Appendix II section of this report.

(8) Elimination of these materials from the construction of aeronautical instruments is strongly recommended.

(9) The corrosion product in a Type ARU-2B/A instrument was identified as metallic chlorides and traced to possible introduction of trichloroethylene into the instrument case during leak testing.

(10) Use of the fog-test apparatus of high sensitivity in the selection of components to be included in flight instruments is recommended.

(11) Present techniques for baking and purging to remove absorbed moisture from instrument components appear to be satisfactory, provided perfect final sealing of the instrument case is obtained.

(12) The present ice-cube test is judged to be marginally satisfactory for indicating moisture content, but lacking in sensitivity toward permanent or oil-type fogging.

(13) An acceptance test for fog testing assembled instruments is recommended that more nearly duplicates the conditions found in actual instrument use in aircraft.

(14) Several differences in method of design and manufacture between instrument suppliers were noted that could influence the formation of condensation on faceplates. These include sealing materials, bulkhead design, and selection of nonmetallic materials.

(15) Additional work appears desirable to improve the design and definition of allowable materials to further reduce the chances of fog formation on aeronautical instrument faceplates.

III. EXPERIMENTAL RESULTS

Instrument Conditions

A total of 13 instruments was furnished for this study by Olmstead Air Force Base and Wright-Patterson Air Force Base. Practically all of these instruments had been overhauled at some prior date. The inventory list (Table I) shows the serial number, type number where known, and the fog conditions as received as shown by the ice-cube test(1), and by examination of the faceplate for permanent fog after the instrument had cooled to normal room conditions.

TABLE I. INVENTORY AND INSTRUMENT CONDITIONS AS RECEIVED

Instrument	Type	Overhaul Date	Fog[a] Moisture	Fog[a] Permanent
AF60-160	ARU-2B/A	9/10/63	4	4
AF61-234	ARU-2B/A	3/8/63	2	0
AF58-15	MM-4		3	(b)
AF58-579	MM-4		3	0
AF58-648	MM-4	3/20/64	3	0
AF58-1322	MM-4	1/20/59	5+	3
AF60-4018	MM-4	2/9/61	0	0
812	AQU-2/A	--	3	(c)
FY62-209158	--		1	0
FY62-209161	--		2	0
AF62-IM62-51	A/A 24G-15		1	(d)
AF63-261	MS 27150-1		3	0
AF62-4004	ARU-12A	--	1	0

(a) Fog-Evaluation Scale:

0 = No fog
1 = Very slight trace
2 = Slight trace
3 = Moderate fog
4 = Heavy fog
5 = Very heavy fog

(b) No fog visible from outside, but could be seen by transmitted light on dismantling.

(c) White particles on faceplate.

(d) Silvery streaks on faceplate.

Two instruments (AF60-160 and AF58-1322) in the as-received condition had noticeable permanent-fog haze. A third instrument (AF58-15) was found to have a light permanent haze when it was dismantled and the faceplate viewed by transmitted light. One instrument (No. 812) had small flakes of a white material on the inside of the faceplate, and another (AF62-IM62-51) had streaks of silvery material diagonally across the faceplate. Instrument AF60-160 had two areas of permanent fog, each about the size of a half-dollar, on the faceplate in the upper right and upper left areas. This instrument had the tear strip removed when received by Battelle, and showed signs of previous dismantling, since fingerprints were visible on the faceplate interior.

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(1) The ice-cube test was conducted by heating the instrument in an oven at 175 F for 1 hour. The instrument was then removed from the oven, and an ice cube was applied to the faceplate for 2 minutes while the instrument was still warm.

Instrument No. AF58-1322 showed a spotty permanent fog over more or less the entire surface of the faceplate.

All instrument faceplates showed an iridescent, multicolored pattern when viewed at an acute angle. This iridescence is believed to be due to the antireflection coating applied to the faceplate, since it is similar in pattern and degree for all instruments, and is not removed by mild cleaning of both sides of the faceplate.

Instrument FY62-209158 showed some discontinuities in the antireflective coating, when viewed at an acute angle. This condition is probably caused by spotty, imperfect application of the antireflective coating, and not by any fogging property of the instrument contents.

All instruments were dismantled to the extent necessary to remove the nonmetallic components for evaluation of their fogging potential, and for identification of fog, corrosion products, and potential fog sources. Certificates stating that the condition of these instruments is the result of a scientific investigation and not the result of negligence or misuse is packed with each instrument to be returned to the Air Force.

Instruments will be returned to the station from which they were obtained, at the termination of the present study.

Initial Investigations

In the initial phases of this study, it was felt that the lubricant that is applied to various gear trains contained in aeronautical instruments could be a major contributor to the permanent fogging of faceplates. Such lubricants normally contain components having appreciable vapor-pressure at the operating temperature of the instruments. Consequently, some of the potential lubricants were examined for their tendencies to cause fogging. The candidate materials were placed in Thwing-Albert permeability cups in which the usual permeable membranes had been replaced with Pyrex-glass plates. The assemblies were placed in an oven at 185 C (365 F) for 1 hour. They were then removed from the oven and an ice cube was applied for 2 minutes to the glass plates while they were still hot. The assemblies were allowed to stand in the air for 5 minutes after removal of the ice cube. Any fog disappearing during the 5-minute period was called temporary, while that remaining after the 5-minute period was considered permanent. The results are shown in Table II.

After cooling overnight, the cups were reheated and the test repeated. In all cases, the permanent fog disappeared on reheating and did not reappear on application of the ice cube. This test was repeated several times with the same results.

It should be pointed out here that careful examination of the gear trains of dismantled instruments showed, for the most part, no visible indication of the presence of excess lubricant. The only exception was in Instrument AF58-648, where excessive deposits of a hydrocarbon-based lubricant (identified by infrared spectroscopy) were found on the instrument frame. The normal condition, therefore, appears to be a very thin film of lubricant, which would not be expected to contribute significantly to the permanent fogging of instrument faceplates.

TABLE II. FOG TEST OF GREASES AND COMPONENTS

Material in Cup	Fog[a]	
	Temporary	Permanent
Control (empty cup)	2	0
Instrument grease (Aeroshell 11)	3	3
Lithium stearate	3	3
Mineral oil	2	3
Silicone oil (DC-200, 10 cps)	2	2

(a) Fog Evaluation Scale:

0 = No fog
1 = Very slight trace
2 = Slight trace
3 = Moderate fog
4 = Heavy fog
5 = Very heavy fog

It should also be noted that in this test, no attempts were made to dry the air in the test cups. The humid air from the laboratory is doubtlessly the source of at least some of the moisture fog which was noted in all the above results (including the empty-cup control).

In view of the findings relative to the amount of grease on the gear trains and the practice of those instrument suppliers contacted to remove excess grease from the gears by centrifuging, it is believed that, under normal conditions, lubricating greases contribute insignificant amounts of permanent-fogging agents to the final assembled instrument. However, it must be pointed out that most lubricants have a fogging potential, and the quantity permitted in instruments should be carefully controlled to avoid excessive amounts. In at least one instance, a permanent fog was traced to excessive grease content.

The moisture fog shown by the greases and components studied is probably due to the humid air in the cup, and should be largely ignored, although it is known that these materials can sorb moisture, which can be released on heating. Proper baking and purging of the cases during the sealing process should minimize this moisture-fogging potential.

Evaluation of Ice-Cube Test

The ice-cube test, as currently employed as an acceptance test for flight instruments, has at least two shortcomings. First, it is of a low order of sensitivity in indicating moisture content within the instrument. As shown in Appendix III of this report, the calculated sensitivity of the test is 4290 parts moisture vapor per million parts of gas by weight (0.429 percent). Any moisture content under this figure will not give positive results with the test. It is assumed therefore that the ice-cube test would reveal only gross leaks.

Also, as pointed out elsewhere in this report, the permanent or oil-type fog forms much more slowly than does moisture fog, because of comparatively low vapor pressure (volatility) of the oily material. The ice-cube test would tend to cause the formation of a permanent fog, but it is felt that a single cycle would be inadequate to show up the permanent fog which forms much more slowly than does moisture fog.

It should be emphasized, however, that although a more critical and sensitive fog test might indicate some of the instruments that would give trouble later during service, it does not offer any real solution to the problem of preventing fog and, it is felt, would seriously hamper production of instruments by the manufacturer.

The true solution would appear to be the elimination of permanent-fog formation by rigorous control of the materials that are used in the manufacture of instruments, by (1) excluding those materials that have been shown to contribute to fog formation, (2) development of new materials formulated specifically for low fog potential, and (3) rigorous testing of all materials used in each instrument by means of a fog-potential test of high sensitivity, such as that successfully used in this study. Continuous monitoring of nonmetallic materials in each instrument is recommended.

Recommended Acceptance Fog Test

On the basis of the findings of this study, and reported herein, it is apparent that an improved acceptance test is desirable for identifying instruments that could become fogged in service. It is also quite apparent that this method must more nearly duplicate the conditions to which the instruments will be subjected in service. The method should compress the time factor, to permit obtaining meaningful data in a reasonable time period.

Several factors are basic in the design of a fog test, according to the facts presented in this report. It is essential that several cycles of heating and cooling be used to promote the "breathing" of a leaky instrument case and accentuate the ingress of humid air, which causes moisture fog. Cycling, as pointed out elsewhere in this report, also accentuates the formation of permanent fog, which forms much more slowly than moisture fog and is much less visible until the fog has built up to a fairly thick film. It is also important to keep the faceplate of the instrument continuously cooled, since this is the normal operational condition and deposition of fog always occurs to the greatest extent on the coolest portion of the instrument.

It is felt that if proper precautions are taken to eliminate materials known to contribute to fog formation, rigorous pretesting of all components is accomplished, and an improved system of hermetic sealing is developed, manufacturers of aeronautical instruments should not be subjected to undue hardships in producing instruments that would pass an acceptance test designed to more nearly duplicate use conditions.

The following test procedure is therefore suggested as a replacement for the present ice-cube test:

The instrument to be tested is placed in a chamber in such a manner as to leave the faceplate exposed to the atmosphere. The interior of the chamber is capable of being temperature and humidity controlled. The faceplate is continuously cooled to 34 F. The body of the instrument, containing the hermetic seals, is thus exposed to the conditions inside the test chamber. These conditions should be: 4 hours' cycling at 185 F, followed by 4 hours at 34 F, and the cycle repeated to give 8 hours' total exposure to each temperature. In order to accentuate moisture-fog formation caused by leaky hermetic seals, the atmosphere inside the cabinet should be kept as nearly as possible at 100 percent relative humidity at each temperature. Experience with the fog-potential apparatus has shown that a total of 8 hours' heating will give significant permanent-fog deposits when the fogging component is relatively close to the faceplate. Longer times (additional cycles) may be necessary if the faulty component is remote from the faceplate, or is shielded by bulkheads within the instrument. It is felt that two complete cycles should be adequate for routine acceptance tests and to show up any moisture foggers. However, it is suggested that several instruments from each production group be further tested for approximately 10 cycles to show up any slow-forming permanent fog that might be present. Further acceleration can also be attained by increasing the high-temperature portion of the cycle to 220 F (the temperature used most frequently in the fog-potential test, with good results).

Corrosion Study

During the dismantling of Instrument AF60-160, it was noted that considerable corrosion of the galvanometer needle of the rate-of-turn indicator had occurred. Corrosion products were also noted on the lower portion of the frame of the instrument and on the ring gear and idler gear driving the polycarbonate ball. The corrosion products were soft, and appeared to be slightly moist. Attempts to analyze these products by X-ray diffraction showed them to be too amorphous to obtain any definite pattern, due to a high degree of hydration. Analyses by mass spectroscopy showed the products to be predominantly zinc chloride, with some copper and lead chlorides being present. No trace of fluorides could be found. This finding indicates that the Teflon insulation is not decomposing to cause corrosion. The source of chlorides was felt to be either (1) vinyl chloride possibly used as electrical insulation, (2) chlorinated hydrocarbons used as cleaning and degreasing agents, or (3) acid soldering flux that might inadvertently have been used in soldering.

Examination of the insulation on the wiring inside the instrument by applying a heated soldering iron to each wire showed no melting or softening of the insulation in any case. This behavior indicates that the insulation is all Teflon, and no vinyl chloride insulation appears to be present.

Examination of other nonmetallic components of this instrument gave negative results for the presence of vinyl chloride.

Acid soldering fluxes were ruled out, since they are forbidden by the specification. This was further substantiated by a visit to the manufacturer of this particular instrument, where it was learned that acid fluxes are barred from the plant, and possession of such material is cause for immediate dismissal of the employee.

However, it was learned from this visit that this particular instrument was manufactured either late in 1960 or early in 1961. During that time, leak testing of sealed instrument cases was accomplished by immersing in trichloroethylene and applying an internal nitrogen pressure to the cases to note areas of leakage as indicated by the formation of bubbles. It is not unreasonable to suspect that this process could be responsible for ingress of a significant quantity of trichloroethylene into the instrument case, especially if a partial vacuum existed in the case during immersion. Subsequent purging of the case with helium/carbon dioxide would fail to remove all of the solvent.

Trichloroethylene, in the presence of heat and moisture, can hydrolyze, releasing hydrochloric acid, which is extremely corrosive toward most metals and is probably responsible for the corrosion found in this instrument. This practice was changed by this manufacturer in 1962, and the trichloroethylene was replaced with water. Dangers exist here also in introducing water to give moisture fog.

It should be pointed out that zinc chloride, which was found to be the main corrosion product, is extremely hygroscopic, absorbing large amounts of water from the air, and releasing this water in the form of vapor on heating.

Since aeronautical instruments may be subjected to significant changes in both pressure and temperature, any slight leak in the hermetic sealing of the instrument case will permit ingress of moisture-laden air from the atmosphere. Zinc chloride and other nonmetallic components would therefore absorb this moisture, to be released on heating and lead to formation of moisture fog.

Permanent-Fog Study

In the process of dismantling Instrument AF60-160, the permanent fog, described previously, was found to be not on the outer faceplate, but on the inner surface of an inner, wedge-shaped faceplate which was attached to the instrument frame. Fingerprints were also noted on this faceplate, indicating that the instrument had been opened before Battelle received it. Fortunately, these prints were on the outer surface of the inner plate and could be removed without disturbing the permanent fog on the inner surface.

The haze on the glass plate was dissolved in a small amount of chloroform ($CHCl_3$) and transferred to a salt crystal. The solvent was allowed to evaporate, and an infrared absorption spectrum obtained. This showed the deposit to be practically wholly methyl silane (a volatile pyrolysis product of certain silicone compositions). Only faint traces of other materials could be noted in the spectrum. These could be background responses. It will be shown later in this report that the methyl silane is being released by an RTV silicone sealant which was used in at least two places within this particular instrument. No indication of any hydrocarbons or esters that might originate from lubricants could be detected in the infrared spectrum.

Instrument AF58-1322, being of different design, did not have the wedge-shaped inner plate. The deposit was therefore directly on the outer faceplate. The instrument mechanism was removed, and the deposit was analyzed by infrared spectroscopy as described previously. The deposit in this case proved to be an organic ester with both aromatic and aliphatic constituents. Evidence obtained from the ratio of $-CH_2-$ to $-CH_3$ groups indicates the material to be dioctyl phthalate, a commonly used plasticizer for rubber and plastic materials. No evidence of methyl silane could be noted.

Since the instrument light assembly is constructed differently in this instrument, no RTV silicone putty was found in the front compartment of the instrument. This front compartment is isolated from the gear train and motor stator by a bulkhead.

Incidentally, although a large amount of moisture fog was exhibited by Instrument AF58-1322, no traces of corrosion were found on examination of the mechanism.

Other instruments included in this study showed, in order of the frequency of their occurrence, (1) an impregnated cellulosic cord used to cable electrical wiring, (2) tubing of several types used to cable electrical wiring, (3) Scotch-type tape, (4) excess oil or lubricating grease, (5) epoxy-type cement, and (6) excessive rosin-type soldering flux. All of these can contribute to the formation of permanent fog in aeronautical instruments. These materials are included in the list of materials found to contribute to fogging, given in Appendix II of this report. Use of these materials in the inner portions of hermetically sealed instruments should be forbidden, on the basis of the results obtained in this study.

Temporary-Fog Study

All but one of the instruments examined showed some degree of moisture fog when each was heated for 1 hour in an oven at 175 F, then removed from the oven and an ice cube immediately applied to the face-plate for 2 minutes.

Instrument AF58-1322, Type MM-4, which showed a large amount of condensate on the faceplate, was selected for analysis of the gases within the instrument. Analysis was carried out by mass spectrometry. Instrument AF60-4018, which showed no moisture fog, was treated similarly as a control. Results of the analysis are given in Table III.

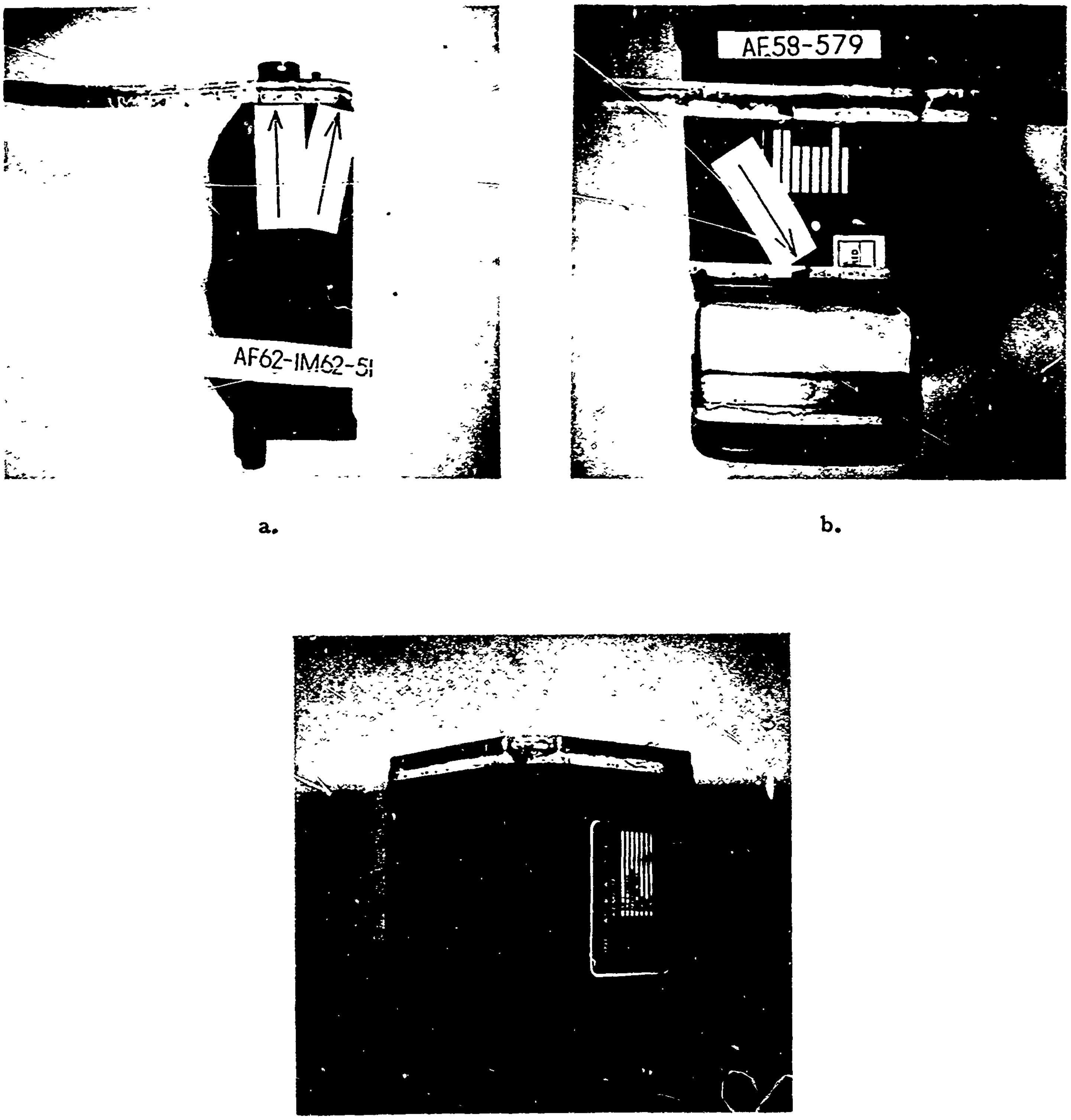
TABLE III. MASS-SPECTROGRAPHIC ANALYSIS OF GASES

(Weight Percent)

Component	Good Instrument (AF60-4018)	Poor Instrument (AF58-1322)
Carbon dioxide	1.28	0.03
Nitrogen	57.4	78.2
Helium	40.9	<0.1
Hydrogen	0.4	--
Oxygen	<0.05	20.9
Argon	--	0.91

The composition of the gases in Instrument AF58-1322 is similar to that of the normal atmosphere within the accuracy of the analytical method used.

The composition of gases in Instrument AF60-4018 is approximately what might be expected, provided no contamination had occurred, since it is the normal practice of the suppliers to carry out the baking operation in a nitrogen atmosphere. If the purging process following the baking were not complete, residual nitrogen would be left in the instrument. The ratio of carbon dioxide to helium is approximately that used by the manufacturer to fill the cases. The almost complete absence of oxygen indicates that no air had entered the case. The hermetic seal of this instrument was therefore complete, and no moisture fog had developed in this case.



a.

b.

c.

FIGURE 1. TYPICAL LEAKY HERMETIC SEALS

Instrument AF58-1322 was pressurized and placed under water. Bubbles could be seen escaping from two points (both on corners) around the tear strip. Removal of the tear strip showed that a proper seal had not been made at the points where leakage was occurring, due to imperfect contact of the strip with the solder on the case.

Examination of the tear strip on other instruments showed similarly poor contact of the strip with the underlying solder, giving a poor seal that could (and probably did) result in leaks in the hermetic seal.

Figure 1 shows some typical examples of defective tear-strip seals. The dark areas in the photographs are places where the solder did not contact the tear strip, thus leaving an opening where humid air could enter or leave the instrument with temperature and pressure changes.

Similarly, Figure 2 shows a tear strip removed from a fogged instrument. Evidence of imperfect seals can likewise be noted here.

FIGURE 2. TEAR STRIP FROM LEAKY HERMETIC SEAL

It is strongly recommended that the seal of these instruments be investigated with the goal of redesigning either the seal or the method of making it, since it is apparent that at least a major portion of the moisture-fog problem can be attributed to humid air entering the imperfectly sealed case, carrying with it an appreciable quantity of moisture vapor.

It should be pointed out that, once moisture enters an instrument, it sorbs on practically all surfaces, and can usually be removed from the case interior only by baking and purging, such as is performed at the time of manufacture and overhaul.

Fogging-Potential Studies

General

In order to investigate the fogging potential of individual components contained within typical aeronautical instruments, and to identify the sources of fogging, it was necessary to construct a special cell and associated apparatus needed for purging and controlling the atmosphere in the cell. The equipment was designed on the basic concept of the molecular still, using a glass plate as the condenser. Details of the apparatus are given in Appendix V.

This cell-type investigation of component parts is based on a generally accepted method. However, radical changes have been made to increase the sensitivity and reproducibility of the system. Important improvements include: (1) redesign of the system to permit control of the atmosphere within the test cell, (2) use of a thermocouple internally mounted and placed near the faceplate, to give accurate temperature control; (3) introduction of an internal heating system to reproduce more nearly the actual instrument conditions, and (4) continuous cooling of the faceplate to increase the sensitivity of the method.

The modified fog-potential apparatus is now sufficiently sensitive to indicate the presence of components having a fogging potential by the analysis of nonfogging components, which have fog sorbed on their surfaces. The fogging component, of course, yields a much greater amount of fog when tested. This, together with a knowledge of the chemical identity of the component and identification of the fog composition, allows a decision to be made regarding the fog potential of each component.

After each instrument (as received) was evaluated and visually examined for evidence of permanent fogging, the instruments were stored in the assembled condition to minimize exposure of the internal parts to the humid atmosphere.

Each instrument was dismantled as completely as necessary, just before it was examined, and individual nonmetallic components and assemblies of the instrument were evaluated in the fog-potential apparatus, to locate possible sources of permanent fog.

The results are presented for each individual instrument.

Instrument AF60-160

This instrument is a Type ARU-2B/A Attitude Indicator. Markings on the case indicated "SMAMA Overhauled October 4, 1963". The tear strip had been removed when the instrument was received. The ice-cube test was therefore meaningless, and was not performed. A definite haze was noted over the entire surface of the faceplate. Two spots of heavy fog about the size of a half-dollar were located in the upper-right and upper-left areas of the faceplate. These spots had the appearance of an oily deposit. On dismantling the instrument, fingerprints were found on the outer side of the inner, wedge-shaped faceplate. These proved to be on the opposite side of the faceplate from the oily deposits, and could thus be removed without disturbing the permanent fog. Considerable corrosion was noted on the frame of the instrument, the rate-of-turn indicator needle, a ring and idler gear operating the ball assembly, and the bottom of the interior of the instrument case. The corrosion products were very hygroscopic and could not be analyzed by X-ray diffraction, as they proved to be completely amorphous. Analysis by mass spectroscopy showed them to be chlorides, predominantly of zinc, copper, and lead. Possible sources of chlorides were considered to be polyvinyl chloride, acid-soldering flux, or trichloroethylene used for cleaning purposes. Examination of electrical insulation showed it to be Teflon throughout. No polyvinyl chloride could be found in the instrument. Acid-soldering flux was ruled out as a possible source, since it is prohibited by the specification.

Evaluation of the individual nonmetallic components of this instrument for fog potential resulted in the data presented in Table IV. Large quantities of cabling cord were found throughout the instrument. No silicone-rubber tubing was found. All cabling tubing was Teflon, even around the main power plug at the instrument rear. Some traces of abrasion were noted on the surface of the polycarbonate ball, but no traces were found of anything that might have caused it. The ball rotated freely, and none of the indicators touched it in any position. It is assumed that the scratching occurred prior to or during overhaul. No foreign materials were found. The tear strips were incompletely sealed in several spots, which explains the source of moisture fog in the instrument.

TABLE IV. FOG TEST OF INSTRUMENT COMPONENTS

(Instrument AF60-160)

Component	Composition	Temperature, F	Fog[a] Temporary	Permanent	Identity
Pilot-light sealant	RTV silicone	250	1	3	Methyl silane
Motor-stator sealant	RTV silicone	250	1	5	Methyl silane
Plastic shims	Nylon (?)	220	0	0	None
Rubber cement	Nitrile rubber	220	1	3	Dioctyl phthalate
Terminal board	Epoxy-glass	175	3	0	H_2O
Capacitor	C-501	175	0	0	None
Galvanometer assembly	Various	175	2	0	H_2O
Mounting board (galvanometer)	Blue phenolic (?)	175	3	0	H_2O
Choke coil	Wire on plastic bobbin	175	2	0	H_2O
Bushing	Phenolic (?)	175	2	0	H_2O
Wiring harness	Teflon insulation	175	2	0	H_2O
Tear-strip liner	Cured silicone rubber	220	4	0	H_2O

(a) Fog Evaluation Scale:

0 = No fog	3 = Moderate fog
1 = Very slight trace	4 = Heavy fog
2 = Slight fog	5 = Very heavy fog

Instrument AF61-234

This instrument is also a Type ARU-2B/A Attitude Indicator, made by the same supplier as Instrument AF60-160 and mechanically constructed very similarly to it. It had no externally visible permanent fog. The ice-cube test showed a moisture-fog value of 1*. The case was intact when received. A blue dot and the date March 8, 1963, indicated that this instrument had been overhauled. A note dated 3/6/63 indicated that the instrument had operated 200 hours. The elapsed time clock on the rear of the instrument showed only 255 hours. No trace of fog or corrosion was found on dismantling the instrument. However, all surfaces evaluated by the fog-potential test showed traces of permanent fog, which had apparently condensed on them. High permanent fog was shown

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*See Table IV for fog evaluation scale.

by the large areas of Scotch-type adhesive tape, and by the RTV silicone paste used to seal the back of the main instrument light assembly. Infrared analysis of the fogs showed the material from the Scotch-type tape to be a low-molecular-weight aliphatic ester (probably acetate or methacrylate) and that from the RTV silicone paste to be an ether-ester similar to the polyethylene glycol esters of the Carbitol series.

Both compositions are considered typical of the type of materials used to plasticize or soften polymeric materials, and are not unexpected for these applications.

Instrument AF58-15

This is a Type MM-4 Remote Attitude Indicator. It had, as received, a moisture-fog value of 3 by the ice-cube test. A definite flaw in the solder seal of the tear strip was noted on dismantling the instrument. Since it was made by a different supplier, somewhat different construction principles were noted. The bulkhead between front and rear compartments had several large openings, allowing free air or gas circulation between compartments. Wiring was by plugs and sockets, permitting easier dismantling.

A slight permanent-fog haze on the faceplate was noted upon dismantling and viewing by transmitted light. This haze was not visible from the outside of the case before dismantling. The wiring in the instrument was cabled in several places with an amber-colored translucent tubing that was tacky on its surface. Qualitative tests of this material showed it to be a plasticized polyvinyl chloride. Very heavy (value of 5) permanent fog was obtained in the fog-potential evaluation. Analysis of the fog by infrared spectroscopy showed it to be an aliphatic phosphate ester, probably trioctyl phosphate.

Another source of permanent fog was identified as being the cord used in several areas of this instrument to tie together the electrical wiring. This cord appeared to be wax impregnated. Low-boiling components of the wax probably contributed to the permanent-fog formation in this instrument. Very heavy moisture fog was also noted, as might be expected, owing to the tendency of cellulosic materials to sorb water.

Individual fog-potential results of components of this instrument are shown in Table V.

TABLE V. FOG-POTENTIAL STUDY OF COMPONENTS

(Instrument AF58-15)

Component	Composition	Temperature, F	Fog[(a)] Moisture	Fog[(a)] Permanent	Fog[(a)] Identity
Rubber cabling tubing	Plasticized PVC	220	1	5	Dioctyl phthalate
Cabling cord	Wax impregnated cord (linen?)	220	3	1	Wax
Wiring (insulated)	Polyethylene/nylon	220	2	3	Dioctyl phthalate
Potted coils	Asphalt	220	3	2	?
Transformers	Insulating varnish	220	3	2	?

(a) Fog Evaluation Scale:

0 = No fog	3 = Moderate fog
1 = Very slight trace	4 = Heavy fog
2 = Slight fog	5 = Very heavy fog

The results obtained with the components other than the tubing were felt to be due to condensation of DOP from the polyvinyl chloride tubing on their surfaces. Calculations from the weight of tubing found and the expected level of plasticization indicate that over 2 grams of plasticizer was available to contaminate the instrument interior.

Instrument AF58-579

This instrument is also a Remote Attitude Indicator, Type MM-4, and manufactured by the supplier of the two Type ARU-2B/A instruments. It had been SMAMA overhauled October 4, 1963. The ice-cube test showed a moisture-fog value of 3 for the instrument as received. No trace of permanent fog could be seen before dismantling. The rear tear strip appeared to have a good seal. The front tear strip had one area where incomplete sealing could cause leakage. Excessive rosin soldering flux was noted about and under each of the tear strips. Evaluation of the O-rings under the tear strips for fog potential showed a permanent-fog value of 1. No permanent fog could be detected on the faceplate of this instrument. The polycarbonate ball was solvent cemented. A minimum of wiring was found in the front compartment. Other components evaluated showed nothing contributing to permanent-fog formation.

Electrical wiring in this instrument was found to be of two types. One was Teflon-insulated and the other had a two-layer insulation. The inner layer appeared to be polyethylene and the outer sheath containing the coloring was shown to be nylon. Neither type contributed to permanent fog.

Instrument AF58-648

This is a Remote Attitude Indicator, Type MM-4, supplied by the same manufacturer for Instrument AF58-579. It had, as received, a moisture-fog value of 3 by the ice-cube test. It had been SMAMA overhauled March 20, 1964. The rear tear strip was in good condition, but the front strip had several areas near the nameplate where poor contact with the case was noted.

No permanent fog was visible from the front, but viewing of the faceplate by transmitted light showed a permanent-fog value of 2.

Several large smears of grease were found on the frame of this instrument. The grease was analyzed by infrared spectroscopy and shown to be a high-molecular-weight paraffinic hydrocarbon, with no ester groups present.

The polycarbonate ball was solvent cemented. No other materials were found that could contribute to permanent fog. The fog on the faceplate of this instrument must, therefore, have been due to the excessive grease contamination in the instrument.

All components tested showed a high permanent-fog potential, owing to condensation of fog on their surfaces.

Instrument AF58-1322

This is also a Type MM-4 Remote Attitude Indicator, supplied by the same firm as was Instrument AF58-579. This instrument had an extremely heavy moisture content.

The ice-cube test caused moisture to form in puddles at the bottom of the faceplate, and the instrument had a moisture-fog value of 5+. Mass-spectroscopy analysis of the gases inside this instrument showed them to be similar to the composition of air, within the accuracy of the analytical method. Pressurization of the instrument under water showed two areas that leaked badly enough to form a stream of bubbles.

A noticeable general permanent fog was on the faceplate of this instrument. Even though a high moisture content was in the meter, no evidence of corrosion could be seen.

Analysis by infrared spectroscopy of the permanent fog on the faceplate showed it to be an aromatic ester, very probably dioctyl phthalate.

The front and rear compartments were separated by a practically solid bulkhead, restricting circulation of gases in the instrument.

Electrical wiring was cabled with a red tubing that was definitely <u>not</u> Teflon. Evaluation of this tubing in the fog-potential apparatus gave a permanent-fog value of 3. Infrared analysis showed this fog to be similar to that found on the instrument faceplate. The tubing was found to be a silicone-rubber composition. Since pastes of curing compounds in dioctyl phthalate may be used for compounding silicone rubber, it is felt this was the situation here, especially since silicone rubbers from other instruments have shown negative fogging properties. The polycarbonate ball in this instrument had been cemented together with an epoxy-type cement. Fog-potential tests of the epoxy bead gave a permanent-fog value of 3. No permanent fog was noted on pieces of the ball taken from other areas.

Evaluation of two commercial epoxy cements available in Battelle's laboratory showed them to have a definite permanent-fog potential, even after curing by baking at 175 F for 1 week.

Fog-potential values obtained for the individual components of this instrument are given in Table VI.

TABLE VI. FOG-POTENTIAL STUDY OF COMPONENTS

(Instrument AF58-1322)

Component	Composition	Temperature, F	Fog(a) Moisture	Permanent	Identity
Rubber tubing – light	Silicone rubber	220	3	2	Dioctyl phthalate
Rubber tubing – rear	Ditto	220	1	2	Ditto
Light assembly	Unknown plastic	220	0	4	"
Ball	Polycarbonate	220	1	2	"
Ball + adhesive	Epoxy cement	220	3	2	"
Commercial cement	Epoxy	220	3	2	"

(a) Fog Evaluation Scale:

0 = No fog
1 = Very slight trace
2 = Slight trace
3 = Moderate fog
4 = Heavy fog
5 = Very heavy fog

Instrument AF60-4018

This instrument is also a Type MM-4 Remote Attitude Indicator, supplied by the maker of AF58-579. In the as-received condition, it showed no moisture fog by the ice-cube test, and no visible evidence of permanent fog. Analysis of the gases in the instrument showed them to be predominantly nitrogen and helium, with less than 0. 05 percent oxygen, showing that the hermetic seal was still in good shape.

Dismantling of this instrument revealed that it had the most perfect seals of any of the instruments examined.

No traces of permanent fog could be found on the faceplate. Fog-potential examination of components disclosed nothing having a fog potential. All hook-up wire was Teflon-insulated and cabled in silicone-rubber tubing that showed no fog potential.

Instrument No. 812

This is a Type AQU-2/A Horizontal Situation Indicator and was manufactured by a supplier not represented by any other instrument. It had, as received, a moisture-fog value of 3 by the ice-cube test. Small, white, flaky deposits were noted on the faceplate before dismantling. It was found that a white-painted galvanometer needle had been rubbing the wedge-shaped inner faceplate and small particles of the white paint had flaked off and become lodged on the faceplate.

No markings indicating overhaul were found on the instrument. However, the appearance of the tear strip indicated that it had been resoldered. No trace of permanent fog could be found on either the inner or outer faceplates. Electronics were confined to the rear of the instrument. The central compartment was a complicated gear train. All gears appeared clean and relatively free from grease. Three bulkheads with limited openings restricted internal flow of gases.

This instrument was the most complicated of all those examined, and contained the greatest number of nonmetallic parts. However, all parts tested showed no tendency to form permanent fog except for some small pieces of rubber (not silicone) tubing used to insulate the terminals of the main connecting socket on the rear of the instrument. These pieces appeared to have aged considerably, and were tacky and of low tensile strength. Fog-potential tests on this rubber showed a slight trace of permanent fog. It is felt that the rubber had degraded to the point where some low-molecular-weight components having a slight volatility at 220 F (the test temperature) were present, giving the permanent-fog trace.

Instrument FY62-209158

This is a Remote Standby Attitude Indicator. No type number was designated on the instrument case. It is much smaller than the MM-4 or ARU-2B/A instruments, but has the same general type of construction. It had, as received, a moisture-fog value of 1 by the ice-cube test. There was no evidence of permanent fog. Several areas of poor sealing at the tear strip were noted, which could have caused the moisture fog.

All wiring was Teflon insulated. Cabling was accomplished with many pieces of cord which appeared to be wax impregnated. Fog-potential tests of this cord showed a value of 1, and high moisture fog.

Several areas were found where Scotch-type tape was used. Evaluation of these for fog potential resulted in a value of 2. On evaluation, other nonmetallic parts of the instrument showed no tendency to form permanent fog.

Instrument FY62-209161

This is also a Remote Standby Attitude Indicator with no type number. It was supplied by the same maker as was FY62-209158, and is of quite similar construction. Ice-cube test of the instrument, as received, showed a moisture-fog value of 2. The moisture fog persisted in this instrument for at least 2 hours after the ice-cube test, but disappeared on standing overnight. No markings indicating an overhaul were found on the case. Poor hermetic sealing was found at both tear strips.

Slight traces of permanent fog were found for all components tested, indicating the presence of some fogging component in the instrument. This was finally traced to a small piece of plasticized polyvinyl chloride tubing about 1/4 inch in diameter and 1/2 inch long. On evaluation, this small amount of material gave a permanent-fog-potential value of 2. It is believed that the traces of fog found on all components were from this source.

Instrument AF62-IM62-51

This is a Qualitative Unit Attitude Indicator, Type A/A 24G-15. It was manufactured by the maker of AF60-160. Ice-cube test of the instrument as received gave a moisture-fog value of 1. Small silvery streaks diagonally across the faceplate were noted, having the appearance of mercury droplets. Due to the unusual construction of this instrument, it was necessary to destroy the case to remove the mechanism. One small area indicating a poor seal was found on removing the tear strip.

Microscopic examination of the faceplate on removal showed the shiny streaks to be small, unidentified metal flakes, stuck to the glass by what appeared to be lightweight lubricating oil. Examination of the gear trains showed some of them to be badly worn and filled with metal flakes. Signs of abrasion were noted on the polycarbonate ball. It appeared that some foreign metallic body, such as a washer, might have been in the instrument and become caught in the gear trains, although careful examination during dismantling disclosed nothing.

The aluminum gears of the "OFF" flag were badly corroded. Gear trains were found to be composed of several different metals, brass, stainless steel, and aluminum. The corrosion could be galvanic in nature, owing to the contact of dissimilar metals in the presence of moisture.

The only component showing any tendency to form permanent fog was the cord used to cable the electrical wiring. This appeared to be a wax-impregnated cord similar to that found to cause fog in other instruments.

Instrument No. AF63-261

This is a Remote Standby Attitude Indicator, Type MS27150-1. It was supplied by a manufacturer not represented by any other instrument. It showed, by the ice-cube test, a moisture-fog value of 3 as received, with no visible evidence of permanent fog.

The tear strip of this instrument was cemented on with a polysulfide cement, instead of the solder generally used for other instruments. This cement was quite porous, and the seal was incomplete in several areas. It is felt that the polysulfide cement is inferior to solder for hermetic-sealing purposes because of its moisture permeability. Although the moisture permeability is small compared with that of most organic sealants, it is still quite high compared to that of metals.

The electronics of this instrument were sealed in a metal case, and were therefore not evaluated, since they could not contribute to faceplate fogging. Also, a solid bulkhead was inserted between the front and rear compartments, which would restrict the flow of gases inside the instrument.

The only component found in this instrument that had any fog potential was the cord used to cable the electrical wiring. This material was wax-impregnated-cellulosic cord similar to that found to be contributing to permanent fog in other instruments. A value of 2 was obtained from the cord in this instrument.

Instrument AF62-4004

This is an Attitude Indicator, Type ARU-12A. It was furnished by the same maker as was AF60-160. It exhibited, as received, a moisture-fog value of 1 by the ice-cube test. No indication of permanent fog could be noted by external examination.

Construction of this instrument appeared to be very similar to that of the MM-4-type instruments. The hermetic seals appeared to be in fair shape, although the solder was quite porous in some areas.

Many pieces of elastomeric tubing were used throughout the instrument for cabling of electrical wiring.

Two small resistors labeled R-31, mounted on the printed-circuit board, had burned in two. A note on the instrument case indicated that the instrument was no good in pitch.

No indication of any permanent fog could be found on the faceplate on dismantling. A solid bulkhead separated the electronic section from the ball compartment. Scotch-type adhesive tape was used to seal several holes in the bulkhead. These tapes gave a permanent-fog-potential value of 2 on examination. This type of tape has shown similar results when evaluated in other instruments. Similarly, wiring, rubber tubing, instrument-light assemblies, and other parts tested all showed traces of permanent fog.

IV. INTERPRETATION OF RESULTS

General

Results in this study have been obtained on seven different types of instruments, as made by five different manufacturers. Thirteen instruments were covered by the analysis. Several differences in design and manufacturing techniques have been noted between similar instruments. Of course, not enough instruments have been examined to completely cover the field of aeronautical systems, but it is felt that enough samples have been studied to establish certain trends and to form the basis for drafting an improved specification for the procurement of more reliable aeronautical instruments. For example, one good design feature is the isolation of the major portion of nonmetallic components in the rear portion of the instrument, with circulation of the gases within the instrument restricted by a solid bulkhead.

Analysis of the Problem

Fogging of flight-instrument faceplates appears to be a two-phase problem: the deposit of a temporary fog as the result of temperature changes, and the formation of a permanent fog which does not disappear from the faceplate on warming the instrument.

The temporary fog is identified as water which enters the hermetically sealed instrument case as a result of imperfect seals and leaks. Flight instruments may be subjected to wide ranges of temperature and pressure changes, which cause "breathing" or ingress and egress of gases from a leaky case under a pressure differential. Atmospheric air contains a large amount of moisture vapor under normal conditions of humidity. This moisture may be sorbed by the nonmetallic components of flight instruments and a large portion may remain inside the case. Slight warming of the instruments allows release of some of the moisture, which can condense on the faceplate provided it is cooler than the interior of the instrument. This condition usually exists because of the heat generated inside the instrument case.

The most logical cure for this type of fog is the elimination of leaks. Examination of the typical tear strip from a moisture-fogging instrument shows areas of incomplete sealing by solder, as discussed previously, and shown in Figure 1. It is recommended that either improved sealing techniques be developed, or the instrument case be redesigned to incorporate a more positive and dependable seal. Use of a bolted flange sealed by pressure and a relatively wide gasket to decrease chances of permeability is suggested as a possible approach.

Desiccants and Moisture

As discussed in Appendix IV to this report, desiccants (drying agents) can be used to reduce the dew point of gases inside the case to the point where condensation cannot occur at the normally anticipated temperatures of instrument faceplates. Problems involved in this procedure include allowing access of gases to the desiccant without permitting dust from the desiccant to enter the delicate working parts of the instrument, and the usually expected loss of efficiency of the desiccant with age and moisture absorption. One possible method would involve incorporating a high-efficiency desiccant (such as magnesium oxide) in a highly permeable (to moisture vapor) container. This arrangement would permit moisture vapor to pass through and be absorbed by the desiccant, but would not permit dust from the desiccant to escape. It would also permit easy replacement of the desiccant capsule on instrument overhaul. Of course, it must be remembered that desiccants absorb only a limited amount of water, and this method would not be expected to take care of the moisture introduced by major leaks in the instrument seal. Corrosive desiccants should also be avoided.

One instrument (812) was found that contained a desiccant, but its effectiveness is questioned because of the type of container (a molded blotting paper) and the small amount of desiccant. At any rate, the instrument contained appreciable moisture fog as received, before opening the case.

It must be emphasized here that once moisture enters a sealed instrument, it adsorbs on the surfaces of practically all components, and is absorbed within the composition of many nonmetallic components. As such, it can then be released by mild heating, such as by operation of the instrument, to form a high concentration of water vapor inside the case. Since the faceplate is normally the coolest part of the instrument, an ideal situation exists for the condensation of moisture on the glass.

Removal of the moisture, once introduced into the instrument, can be very difficult, and can probably be accomplished only by simultaneous baking and purging of the instrument, such as is performed in the manufacture and/or overhaul of the instrument. It would, therefore, appear that extreme precautions should be taken to insure as good hermetic sealing as possible during the original assembly, and upon overhauling of the instrument.

Permanent Fog

The permanent-fog formation presents a different problem. This fog is formed by the deposit of materials much less volatile than water on the faceplate, usually over a much longer period of time. Because of its low volatility, such fog does not evaporate from the faceplate with warming, and dismantling of the instrument is necessary to remove the deposit.

Several materials that contribute to the formation of permanent fog were found on examination of instrument components.

RTV Silicones

A room-temperature-vulcanizing (RTV) silicone-rubber paste which is used in some instruments to seal the instrument-light assembly and also the motor stator on the rear of the instrument frame, when heated, releases methyl silane which is a transparent, oily liquid of low volatility. This material appears to be the major component of the permanent fog found in the AF60-160, Type ARU-2B/A, instrument checked, as shown by infrared spectroscopic analysis. Silicone rubbers, when heat and pressure cured, do not normally release these silanes. (Witness the negative results obtained with the strip under the tear strip.) It is strongly recommended that RTV silicone putty be eliminated from the instruments and replaced with a sealant that does not cause fogging.

Rubber Cement

The second contributor to permanent fog identified is a nitrile-rubber cement used in some instruments checked to secure various nuts, bolts, screws, washers, etc., throughout the instrument. This material contains an oily liquid plasticizer identified by infrared analysis as dioctyl phthalate. Fog potential tests at 175 F showed a deposit of dioctyl phthalate on the faceplate of the test apparatus from rubber cement taken from the instrument. Although only small amounts of this cement were found in the AF60-160, Type ARU-2B/A instrument, and no positive indication of the presence of dioctyl phthalate could be found by analysis of the permanent fog on the faceplate of this instrument, it is urged that the nitrile-rubber cement in the instrument be replaced with another type of cement that does not fog.

Plasticizers

One of the most plaguing classes of materials found to be responsible for permanent fog in flight instruments is the group of materials used as plasticizers. It is common practice in the compounding of many resins, plastics, and rubbers to include in the composition a low-molecular-weight, oily-type material to impart flexibility, improve low-temperature properties, and make the final composition conform to certain desired characteristics. Although these materials have fairly high boiling points, they also have appreciable vapor pressures, especially at the elevated operating temperatures encountered in flight instruments. They, therefore, volatilize from the major ingredients of a nonmetallic composition in which they are contained and deposit on nearby surfaces, particularly if these surfaces are cooler than the gases in the instrument. This, of course, is frequently the case at the faceplate. Condensation is therefore aggravated at the faceplate, which is the most critical area as it obstructs visibility of the instrument.

Referring to the investigation of the individual instruments, it can be seen that a number of instances were found where volatile plasticizers were contributing to permanent-fog formation. Probably the worst offender was plasticized polyvinyl chloride tubing, used to cable electrical wiring. The fogging ingredient was identified as dioctyl phthalate in one case, and trioctyl phosphate in another. Both materials are commonly used to plasticize polyvinyl chloride compositions. Experience has shown that up to 30 percent of the weight of the composition is frequently plasticizer. Because only a few micrograms of oily material can cause noticeable fogging of a faceplate, the importance of excluding this material is apparent, since only 10 grams of a plasticized compound introduces 3 grams of volatile plasticizer.

Although silicone-rubber tubing was shown in this study to be innocuous in most instances, one instrument was found that contained a silicone-rubber tubing that contributed to fogging. The fog was identified as dioctyl phthalate. A search of available commercial recipes for silicone rubber disclosed one formula that included a curing agent sold in paste form with the liquid composition being dioctyl phthalate. It is conjectured that this was possibly the source of the dioctyl phthalate in this instance. The evidence here indicates the importance of attention to details in method of manufacture and selection of raw materials for components to be used in construction of hermetically sealed flight instruments.

It should be remembered that heat- and pressure-cured silicone rubber would not be expected to release methyl silane on heating. Curing of RTV silicones, on the other hand, is accomplished by catalysis, and the degree of curing is probably not advanced as far as that of the high-temperature-cured materials. Also, it will be recalled that this work has shown that methyl silane results from heating certain RTV silicone pastes.

One unusual situation was disclosed in this study. One of the earlier instruments (AF58-1322) contained a polycarbonate ball, the two halves of which were cemented together with an epoxy-type cement. Fog-potential tests showed this cement to be contributing to permanent-fog formation. Evaluation of a commercial adhesive thought to be of the same general type (Scotch Weld 2158) showed it to behave quite similarly, even after extended curing.

In later-made instruments the ball has been solvent cemented, thus eliminating this particular source of fogging ingredients. However, it must be pointed out that this type of adhesive and/or sealant is used in several other areas of some types of instruments, such as for cementing in field coil assemblies, sealing and potting of electrical coils, etc. The use of this type of material needs to carefully scrutinized to prevent the introduction of materials that will contribute to fog formation.

One additional unusual circumstance was found that merits discussion. In one instrument, elastomeric tubing (not silicone) was found that had apparently deteriorated with age and/or heat to the point that practically all tensile strength had been lost, and the surface had become quite gummy and tacky. This material gave positive results in the fog-potential evaluation. It is reasoned that, since properly formulated and cured elastomeric compounds of low plasticizer content would not normally give positive fog-potential results, those obtained are due to the deterioration of the elastomer to form low-molecular-weight components with sufficient vapor pressure to result in fog formation. It is therefore quite evident that the aging characteristics of nonmetallic components included in flight instruments must be given consideration, and materials that are subject to age and/or heat deterioration should be avoided.

Cabling Cord

Every instrument examined had the electrical wiring cabled together with a tape or cord in certain areas. The Type MM-4 instruments were so constructed that only a small amount of cabling cord was used. Other instruments, particularly the AQU-2/A and some of the smaller "Standby" types, contained significant amounts of the cord. The cord appeared to be made from a linen-type thread and had a waxy appearance, indicating that it had been impregnated with a wax or waxlike material. Evaluation of this material, as removed from the instrument, showed a high tendency both to form moisture fog and to produce traces of permanent fog. Cellulosic materials, in general, are known to have a high affinity for moisture, sorbing large amounts from the atmosphere under normal conditions. This moisture can, of course, be released by mild heating, and thus contribute to the formation of moisture fog. Baking and purging probably remove the greater part of this moisture, but imperfect hermetic seals which permit entrance of moisture vapor allow such materials as this to act as reservoirs, holding moisture until heated. The released moisture then condenses on faceplates, providing the conditions are right. It is suggested that cabling could be accomplished by using materials less likely to sorb moisture, such as polyethylene, nylon, or other similar, less hygroscopic nonmetallics.

Scotch-Type Tape

Practically all instruments dismantled contained various amounts of a cellulosic adhesive tape, similar to the Scotch-type tape. Two instruments (FY62-209158 and AF62-4004) having fairly large areas of this material in several locations in the instrument were found. This tape showed positive fogging-potential results on evaluation. The adhesive used in this type of tape frequently contains rosin and/or plasticizing compounds with appreciable volatility. Under the influence of heat, rosin can degrade, yielding oily materials that could contribute to fogging. Similarly, the plasticizers can volatilize, yielding vapors capable of producing permanent fog, as indicated elsewhere in this report.

Soldering Flux

Instrument AF58-579 was found to contain excessive soldering flux (containing rosin) deposited just inside the tear strips. This material was similarly shown to have an appreciable fogging tendency in the fog-potential test.

It therefore appears evident that rosin and rosin-based materials should be avoided, if at all possible, in the construction of flight instruments. Also, care should be taken to avoid excessive amounts of soldering flux.

Lubricants

Two instruments (AF58-648 and AF62-IM62-51) were found in which excessive amounts of lubricants had contributed to the fogging problem. On dismantling of Instrument AF58-648, several areas of grease deposits were found on the frame of the instrument. This instrument had been overhauled March 20, 1964, and, on dismantling, was found to have an oily deposit on the faceplate which was not visible before dismantling. Analysis of the grease deposits on the frame of the instrument and of the fog deposit on the faceplate showed them to be similar in composition, and to be a long-chain aliphatic hydrocarbon, with no ester groups present. Of course, all materials evaluated for fog potential in this instrument gave positive results, and the grease had therefore appeared to condense oily material on all surfaces within the instrument.

In Instrument AF62-IM62-51, oily streaks were present on the faceplate, which had collected metal flakes from another source. This oil appeared to be a lightweight lubricating oil which may have been inadvertently deposited during overhaul, since no source of this material could be found within the instrument.

The normal practice of sparing use of lubricants and removing excess amounts by centrifuging lubricated parts, as described in Battelle's report covering Phase I of this study, dated February 24, 1964, does not appear to contribute significantly to the formation of permanent fog. However, as pointed out earlier in this report, lubricants do have a definite fog potential. The two cases found in this study appear to have occurred as a result of the application of too much lubricant during overhaul of the instruments in question. Extreme care is strongly recommended in the application of lubricants during overhaul, to avoid excessive use.

Corrosion

As was discussed previously, a major corrosion problem was noted in dismantling Instrument AF60-160. The corrosion products were identified as chlorides of zinc, copper, and lead. The only source of chlorides that could be found to be connected with the instrument was trichloroethylene, which was used to test for leaks in the hermetic sealing. It is understood from the supplier that this practice has now been discontinued, and this particular corrosion problem should disappear.

Although considerable moisture fog was present in Instrument AF58-1322, Type MM-4, no traces of corrosion could be noted. It appears, therefore, that moisture alone does not cause corrosion of instrument interiors, but that other corrosive agents must also be present. This would be expected from Battelle's basic knowledge of corrosion mechanisms, the materials used in flight instruments, and the conditions of use.

V. CONCLUSIONS

The following conclusions have been drawn regarding the fogging of flight instruments:

(1) Two types of fogging are noted in flight instruments: a temporary fog of moisture vapor which is the result of imperfect hermetic sealing and a permanent fog which is a deposit of materials of relatively low volatility that does not disappear from the faceplate on warming. Permanent fog results from the partial decomposition of certain nonmetallic components used in construction of instruments.

(2) The most prevalent type of condensation appears to be moisture fog. This could be largely eliminated by improving the sealing system to make a more positive hermetic seal.

(3) Permanent fog is an oily-type deposit on the faceplate of the instrument that requires an overhaul to effect its removal. Several materials have been identified as contributing to the formation of permanent fog. Redesign of instruments is recommended to avoid use of these materials.

(4) Corrosion of metallic instrument parts is accelerated by the presence in the instrument case of such materials as trichloroethylene. This corrosion can cause an increase in moisture fog, since the corrosion products usually tend to hold water as well as contribute to malfunction of the instrument.

(5) Present baking and purging processes appear adequate to remove moisture *if* the instrument seal is not faulty.

(6) Selection of materials for use in flight instruments can be facilitated by use of the fog-potential test developed in this study.

(7) The ice-cube test has been shown to be satisfactory for disclosing gross moisture-fog conditions, but has a lower threshold sensitivity of about 4,000 parts moisture per million parts of filling gases.

(8) A substitute fog test that more nearly duplicates use conditions is outlined and recommended for use as an acceptance test.

VI. RECOMMENDED FUTURE WORK

The work program as carried out under the present contract has served to indicate some of the sources of fog formation on the faceplates of flight instruments. It is hoped that sufficient information has been obtained to permit the preparation of improved specifications, resulting in more reliable instrumentation for aircraft.

The present study has also served to indicate areas where additional work is required to make even better instruments possible. Some of these areas, as outlined below, represent problems that would be of primary interest to the Air Force. Other areas, similarly outlined, are probably of greatest interest to the instrument manufacturers, in order that they can make instruments that conform to specifications.

(1) The present study should be expanded to include every type of instrument used by the Air Force, as supplied by each maker. This could probably best be accomplished by the careful study of prepurchase prototypes, analyzing each nonmetallic component by means of the high-sensitivity fog-potential test. Purchase of instruments could then be made contingent on production of items identical to approved prototypes.

The alternative procedure would comprise purchase of instruments conforming to specifications which include complete composition requirements for each nonmetallic component of the instrument. It is felt that this latter course is impractical, since it would (1) prohibitively complicate purchase specifications, (2) probably be unacceptable to instrument manufacturers, and (3) restrain technical improvement by the suppliers.

Purchase on a basically performance-type specification is therefore felt to be the preferred course, with careful analysis of prepurchase prototypes being carried out as mentioned above.

(2) A careful study should be made of materials and methods suitable for the inclusion of high-efficiency desiccants in the interior of hermetically sealed instruments. One instrument was included in the present study which contained capsules of desiccant. However, the efficacy of this method in this instance is questioned, since this particular instrument contained the greatest amount of moisture of all instruments examined, as shown by the ice-cube test. This indicates that desiccants effective enough to take care of the humidity introduced by gross leaks in the hermetic seal are not available or are not being used. Therefore, the primary problem still appears to be the reliability of the hermetic seal. Selection of desiccant material, methods for encapsulation to maximize effectiveness and minimize contamination of the instrument by dust, and obtaining sufficient desiccant capacity to last until overhaul are expected to be major problems.

(3) Adhesives, sealants, and elastomeric materials (rubber) have all been shown to be problem areas. A research study is needed to develop satisfactory material formulations or recipes that can be approved for use in order to produce nonfogging instruments. This study can be expected to require considerable attention to the detailed evaluation of raw materials and aging characteristics of the finished product.

(4) The new fog-potential test, based on a sound and practical scientific principle, has resulted in greatly increased sensitivity toward fog formation. However, it requires the evaluation of each individual nonmetallic component. It is possible that methods for the acceptance testing of instruments can be devised that will give more reliable results than those now in use. For example, it is believed that multicycling of the instrument under pressure and temperature changes would increase both the moisture- and permanent-fog sensitivity of the ice-cube test. Analysis of the latter test as presented in this report shows it to be only marginally satisfactory. Increasing the temperature range of the test may also prove to be advantageous.

(5) Use of thermal-gravimetric analysis and/or differential thermal analysis for the study of fogging potential of nonmetallic components may be fruitful, since it can give quantitative data on weight loss, etc., due to the effect of mild heating. Studies of this nature were judged to be beyond the scope of the present contract.

(6) Twelve of the 13 instruments examined in this study contained enough moisture to give positive results in the ice-cube test. All twelve instruments had faulty sealing at the tear strip, destroying the hermetic sealing of the instrument and allowing ingress of humid air. This is quite strong evidence of the need of an improved method of sealing for instrument cases. This is felt to be a design engineering problem and is not considered to be insoluble. Better hermetic sealing would do much toward eliminating moisture-fog formation in instruments and, if properly designed, could facilitate overhaul and minimize resealing problems. Present baking and purging practices appear to be satisfactory, provided hermetic conditions can be maintained in the instrument.

(7) The list of materials recommended for use in hermetically sealed instruments is a result of the examination of a limited number of materials found in the instruments examined. It is believed that the Air Force would benefit greatly by the expansion of this list. A research study should be undertaken to evaluate a wide range of nonmetallic materials for approved use by the Air Force, which are identified by commercial trade names and grades. This list could then be supplied to the instrument manufacturers, for use according to their engineering requirements.

APPENDIX I

NONMETALLIC MATERIALS RECOMMENDED FOR USE

TABLE VII. NONMETALLIC MATERIALS RECOMMENDED FOR USE IN FLIGHT INSTRUMENTS BASED ON FOG-POTENTIAL EVALUATIONS

1. Teflon (polytetrafluoroethylene)
2. Nylon (polyamid resin)
3. Polyethylene
4. Silicone rubber (well cured by heat and pressure)
5. Epoxy-glass laminates (for circuit boards)
6. Polycarbonate resins
7. Paints in those instruments evaluated
8. Polysulfide resins
9. Phenolic-paper laminates (for circuit boards)
10. Phenolic-resin molded parts
11. Epoxy molded parts

APPENDIX II

NONMETALLIC MATERIALS NOT RECOMMENDED FOR USE

TABLE VIII. NONMETALLIC MATERIALS NOT RECOMMENDED FOR USE IN FLIGHT INSTRUMENTS BASED ON FOG POTENTIAL EVALUATIONS

1.	Excessive amounts of lubricants
2.	Plasticized polyvinyl chloride
3.	Rubber cements
4.	RTV silicone putties
5.	Rubber (other than silicone)
6.	Epoxy cements containing plasticizers
7.	Cellulosic cords, particularly if wax impregnated
8.	Excessive amounts of soldering flux (rosin based)
9.	Scotch-type tapes

APPENDIX III

PSYCHROMETRY OF FILLING GASES

A brief and simplified discussion of certain phases of the physical chemistry of gases may lead to a better understanding of the principles involved in the fogging of instrument faceplates.

Dalton's law of partial pressures states that the total pressure of a mixture of gases is equal to the sum of the partial pressures of the constituent gases. That law is stated in equation form as:

$$P = p_1 + p_2 + p_3 + \cdot \cdot \cdot \cdot \, p_n \; .$$

It also follows from the Maxwell relationship of kinetic energy that the mole fraction of any component in a mixture of gases is given by:

$$p_c = x_c P \; .$$

where

p_c = the partial pressure of any component

x_c = the mole fraction of that component

P = the total gas pressure.

(The mole fraction of any constituent in a mixture is defined as the number of molecules of that constituent divided by the total number of molecules in the mixture.)

Now let us consider the case where liquid water is in contact with air (or any other gas or mixture of gases). The water molecules tend to escape from the surface of the liquid water at a rate proportional to their kinetic energy. As the molecules escape from the liquid surface, they become a vapor and exert a partial pressure in the area above the liquid. When this partial pressure reaches a steady state, the same number of molecules are condensing back into the liquid as are escaping from it. The value of the partial pressure at this point, which is exerted by the vaporized molecules, is known as the vapor pressure of the liquid.

As is the case with all equilibrium conditions, the vapor pressure is temperature dependent. An increase in the temperature of the liquid causes a greater number of molecules to attain the critical kinetic energy to permit them to escape, and the vapor pressure consequently increases. A decrease in temperature lowers the kinetic energy of the gaseous molecules, and they condense back into the liquid form. This form of condensation can cause fogging of aeronautical instrument faceplates when sufficient moisture is present and the faceplate is cooler than the gases in the instrument case.

When the steady state referred to above is reached and liquid water and water vapor are both existing simultaneously, the gas (air) is said to be at 100 percent relative humidity.

The dew point of moisture-containing gases is defined as the temperature at which condensation occurs.

It is apparent from the discussion above that the composition of the basic dry gases used in filling aeronautical instrument cases is unimportant from the standpoint of moisture fogging. Aqueous fogging is purely a function of the amount of moisture (number of molecules) present in the instrument and the temperature relationships. When the temperature of the faceplate falls below the dew point of the gases inside the instrument, condensation (and hence fogging) will occur.

It must be remembered that the above discussion is simplified. For extremely accurate work, certain correction factors, which are disregarded here, are necessary. For example, in the case of the vapor pressure of water in a closed container (constant volume), the pressures are additive (atmosphere plus vapor) and the pressure relationship with mole fraction becomes:

$$p_c = X_c (P + p_c) \ .$$

However, for most practical purposes, these correction factors can be ignored, except where extreme accuracy is necessary.

The following simplified calculation will serve to illustrate the above discussion of psychrometric principles:

Let us assume that an instrument case with 1.0-liter free volume is filled with air of 50 percent relative humidity at 1 atmosphere (760 mm mercury) and 70 F (21 C). From Peabody's Steam and Entropy Tables, the vapor pressure of water at 70 F (21 C) is 18.62 mm of mercury. Since the water is already in vapor form, the correction above can be ignored and P = 760 mm. If the air had been saturated (100 percent relative humidity),

$$p_c = x_c P$$

$$18.62 = x_c \times 760$$

$$x_c = \frac{18.62}{760} = 0.0245 \ .$$

Thus, 2.45 percent of the molecules would be water-vapor molecules if the air had been saturated (100 percent relative humidity). Since the relative humidity was only 50 percent, the concentration would be

$$x_c = 0.0245 \times 0.50 = 0.01225 \ .$$

The partial pressure of the moisture vapor would, similarly, be

$$p_c = 0.01225 \times 760 = 9.31 \text{ mm of mercury.}$$

Referring again to Peabody's Steam and Entropy Tables, the temperature corresponding to a vapor pressure of water of 9.31 mm of mercury is approximately 10 C (50 F). Thus, if the temperature of the faceplate dropped below 50 F, condensation of water would occur in this case.

In order to prevent condensation of moisture on instrument faceplates, it is quite apparent, therefore, that the dew point of the gases inside the case must be maintained below the minimum expected temperature to which the instrument faceplate will be exposed.

Let us examine what happens to the moisture content of air (or any gas) when it is passed through a liquid-nitrogen trap to lower the dew point. The temperature of boiling liquid nitrogen is -195.8 C (-320.4 F). The International Critical Tables contain data on the vapor pressure of water (ice) only to -90 C. For temperatures in the region of the boiling point of liquid nitrogen, it is therefore necessary to extrapolate existing data to estimate the water content of gases at these conditions.

A reasonably accurate approximation of the relationship of the vapor pressure of ice at very low temperatures is given by the equation:

$$\log p = c - \frac{a}{T} ,$$

where

p = the partial pressure

T = absolute temperature (K)

c and a = constants, depending on the material under consideration.

Applying the above equation to the data for the vapor pressure of water over ice at -70, -80, and -90 C, found in the International Critical Tables, the value of c is calculated to be 11.378 and that for a is 2.86×10^3. If these values are now used in the same equation, and the vapor pressure of water vapor over ice at -195.8 C (77.4 K) is calculated, a value of 2.7×10^{-26} mm of Hg is obtained. This should be considered only as a rough approximation, since it is based on the supposition that a log p versus temperature plot is a straight line down to -195.8 C. It is known, however, that this plot deviates slightly, in the direction that gives slightly lower real values than those calculated by using the above equation. For want of a better method, this approximation is adequate for present purposes, and should be considered as an upper limit to the real value.

If the above figure is used to calculate the actual concentration of water vapor in a gas or mixture of gases by using the formula:

$$p_c = x_c P ,$$

it is found that

$$\text{mole fraction} = x_c = \frac{p_c}{P}$$

$$x_c = \frac{2.7 \times 10^{-26}}{760}$$

$$x_c = 0.35 \times 10^{-30} ,$$

which means that about 1 molecule of water vapor exists in 3×10^{30} molecules of gas, or 1 molecule per 5 million liters. In essence, water vapor can be considered to be nonexistent in such a gas at liquid-nitrogen temperatures.

Let us now consider the physical chemistry of the ice-cube test. If we assume that the ice cube in contact with the faceplate lowers its temperature to 0 C, then moisture condensation will occur on the faceplate if the dew point of the gases inside the instrument case is above 0 C. (Actually, the temperature of the faceplate will be slightly above 0 C, because of the thermal conductivity of the glass.)

From the International Critical Tables, the vapor pressure of liquid water at 0 C is 4.58 mm of mercury. Using the equation:

$$p_c = x_c P$$

or

$$x_c = \frac{p_c}{P}$$

$$x_c = \frac{4.58}{760} = 6.04 \times 10^{-3}$$

$$\text{Mole per cent} = x_c \times 100 = 0.604 \text{ percent.}$$

Using 18.0 as the molecular weight of undissociated water and 26.74 as the apparent molecular weight of air,

$$0.604 \times 18.0 = 10.9 \text{ g } H_2O$$

$$99.4 \times 26.74 = \frac{2560.0 \text{ g air}}{2570.9 \text{ g total weight}}$$

$$\frac{10.9}{2570.9} \times 100 = 0.429 \text{ percent by weight water}$$

or 4290 ppm .

The lower sensitivity of the ice-cube test is therefore 4290 ppm water. If the concentration of water is below this figure, no condensation will occur, and negative results will be obtained, even though appreciable moisture might be present.

Using calculations similar to those above, it is possible to calculate the concentrations of moisture vapor in air at which condensation will occur in relation to the faceplate temperature, as shown in Table IX.

The following table may be used to calculate the water content of gases if the fogging temperature (dew point) is known, or vice versa. A plot of the above data, shown in Figure 3, reveals almost a straight-line function on semilog paper, showing that water content is an exponential function of temperature.

It must be remembered, of course, that the presence of any liquid water inside an instrument case insures 100 percent humidity, or saturation of the gases inside the case, and any decrease in temperature will cause fogging of the faceplate.

TABLE IX. MOISTURE CONTENT OF GASES AND FOGGING TEMPERATURE

Faceplate Temperature,		Vapor Pressure of H_2O, mm of Hg	H_2O, mole percent	H_2O, weight percent
C	F			
-30	-22	0.286	0.038	0.027
-20	-4	0.776	0.102	0.066
-10	+14	2.15	0.283	0.192
0	+32	4.58	0.604	0.429
+10	+50	9.21	1.21	0.81
+20	+68	17.54	2.31	1.57
+30	+86	31.82	4.19	2.85
+40	+104	55.32	7.28	5.23
+50	+122	92.51	12.15	8.82
+60	+140	149.4	19.65	14.65

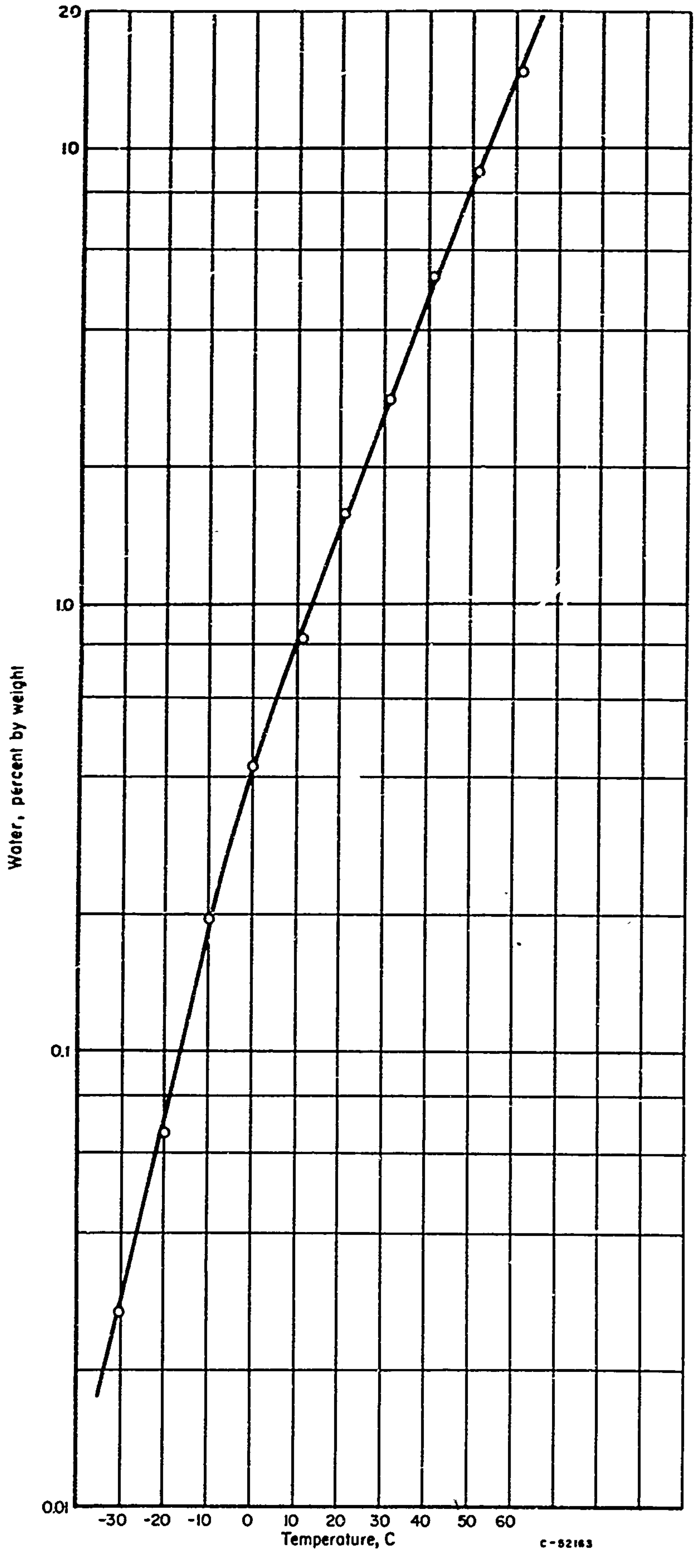


FIGURE 3. MOISTURE CONTENT OF GASES VERSUS FOGGING TEMPERATURE

APPENDIX IV

EFFECTIVENESS OF DRYING AGENTS

According to data compiled by John H. Yoe, and included in the Handbook of Chemistry and Physics, published by the Chemical Rubber Publishing Company, granular calcium chloride will reduce the water content of moist air to about 0.25 mg (0.00025 g) water per liter of air. This is equivalent to $\frac{0.00025}{18}$ mole of water (or 1.4×10^{-5} mole). One liter of air is $\frac{1}{22.4}$ or 0.0447 mole. The mole fraction of water vapor is therefore:

$$\frac{1.4 \times 10^{-5}}{4.5 \times 10^{-2}} = 3.1 \times 10^{-4} = x_c ,$$

since

$$p_c = x_c P,$$

$$p_c = 3.1 \times 10^{-4} \times 760$$

$$p_c = 0.24 \text{ mm of mercury} .$$

From the International Critical Tables, the temperature at which water (ice) has a vapor pressure of 0.24 mm of mercury is approximately -32 C (-25.6 F). Thus, calcium chloride (until it became saturated) would lower the temperature at which fogging occurred (dew point) to -25.6 F. It must be remembered, however, that calcium chloride is extremely corrosive for metals and should be avoided. Most of the drying agents that are more efficient than calcium chloride (lower residual water) are similarly quite corrosive (examples: phosphorus pentoxide, KOH, H_2SO_4, NaOH, and $CaBr_2$). Alumina and silica gels dry by physical action, and therefore the efficiency of these materials depends upon their moisture content.

The only exception is magnesium oxide (MgO). According to the tabulation compiled by Yoe, MgO dries gases (air) to a residual moisture content of 0.008 mg per liter of air, or about 1/30 the amount left in air by calcium chloride. It is proposed that MgO be investigated for incorporation in aeronautical instruments. Similar calculations for efficiency of MgO are shown below:

$$0.008 \text{ mg } H_2O = 8 \times 10^{-6} \text{ g}$$

$$\frac{8 \times 10^{-6}}{18} = 0.45 \times 10^{-6} \text{ mole } H_2O$$

$$\text{Mole fraction, } x_c = \frac{4.5 \times 10^{-7}}{4.5 \times 10^{-2}} = 1 \times 10^{-5} ,$$

since

$$p_c = x_c P$$

$$p_c = 1 \times 10^{-5} \times 760 = 7.6 \times 10^{-3} \text{ mm of mercury.}$$

The corresponding temperature at which water (ice) has a vapor pressure of 0.0076 mm of mercury is approximately -61 C (-78 F).

It must be remembered that the use of drying agents in aeronautical instruments involves considerable mechanical problems of preventing clogging of gear trains by dust from the material, dusting of faceplates and obscuring vision, etc. Considerable study of the problem is needed before a recommendation of materials and methods can be made.

APPENDIX V

DESCRIPTION OF HIGH-SENSITIVITY FOG-TEST APPARATUS

The fog-potential test apparatus design is based on the tendency of vapors that are released by heat, or the volatile products of mild pyrolysis, to condense on a cooled glass plate located near the heated item.

It was found desirable to incorporate improvements in the method and technique as the study progressed, in order to simulate more nearly the actual conditions found in aeronautical instruments, and to obtain increased sensitivity for the method. Improvements found to be desirable included: (1) redesign of the equipment to permit control of the atmosphere inside the test cell, (2) use of a thermocouple internally mounted near the faceplate, connected electrically to a temperature controller, to give accurate control of specimen temperature; (3) introduction of an internal heating system, connected to the temperature controller, to give closer temperature control than is possible when the cell is placed in an oven and to simulate more nearly actual use conditions by having the material at a temperature higher than that of the faceplate; (4) use of continuous cooling of the faceplate by circulation of tap water, with frequent chilling of cold (34 F) water, to increase the sensitivity of the method; and (5) filtering and chilling of the gas (high-purity helium) used to fill the test cell, to remove dust and moisture.

Engineering drawings of the cell and its parts are given in Figure 4, Parts A through G.

Cell parts are made of cold-rolled steel, and are chromium plated to give a smooth surface, thus minimizing sorption of volatile materials on the cell surfaces.

The faceplates are cut from 1/8-inch Pyrex-glass plate, to obtain a smooth surface, which increases the visibility of any condensed film and decreases the probability of breakage due to thermal shock and strains.

The seal around the faceplate was made with a silicone-rubber O-ring, size 2-40. This permits removal of the glass plate for analysis of permanent fog, and closer visual examination for the detection of the presence of fog. Support of the glass plate was accomplished by a brass spacing ring 3-1/4-inch in outside diameter, 2-3/4 inch in inside diameter, and 1/2 inch high. This gave a positive seal by compressing the O-ring.

A ring-type Chromalox heater (A-10, 200 watt) was mounted in a groove cut in the inner support (Figure 4, Part D) and connected to the AN/MS connector.

A copper-constantan thermocouple was connected to the AN/MS connector in such a manner that the head of the thermocouple was about 1/8 inch from the glass faceplate.

A Type 8-732 aluminum weighing dish (Fisher Scientific Company) was used to hold the sample. A 1/4-inch-diameter hole was punched in the center of the dish to allow the thermocouple to extend above the sample. This dish prevented direct contact of the sample with the source of heat, and facilitated cleanup after an evaluation.

The thermocouple was supported by means of a ceramic tube, so that it remained erect and properly positioned.

The thermocouple leads from the cell to the reference junction were identical to the wires used to make the couple, as shown in Figure 4. The reference junction consisted of a copper-constantan and a copper-copper couple. Thus the leads from the reference junction to the controller were both copper wires. This procedure was necessary since the controller had no built-in reference couple.

The controller employed was a Thermo-Electronic controller, manufactured by Thermo Electric Company, Saddle Brook, New Jersey, and controlled to a millivolt setting.

The reference junction was encased in a stainless steel protection tube and immersed in a large jar of water kept at room temperature (75 F). The apparatus was located in an air-conditioned laboratory, which kept the water temperature reasonably constant (±2 F). Since the reference junction was at 75 F instead of 32 F, the standard tables for copper-constantan thermocouples had to be corrected by subtracting 43 F from each temperature. Figure 5 is a graph of the corrected relationship of millivolts to temperature, used in this work. Salient points were: 175 F = 2.45 mv, 220 F = 3.38 mv, and 250 F = 4.15 mv.

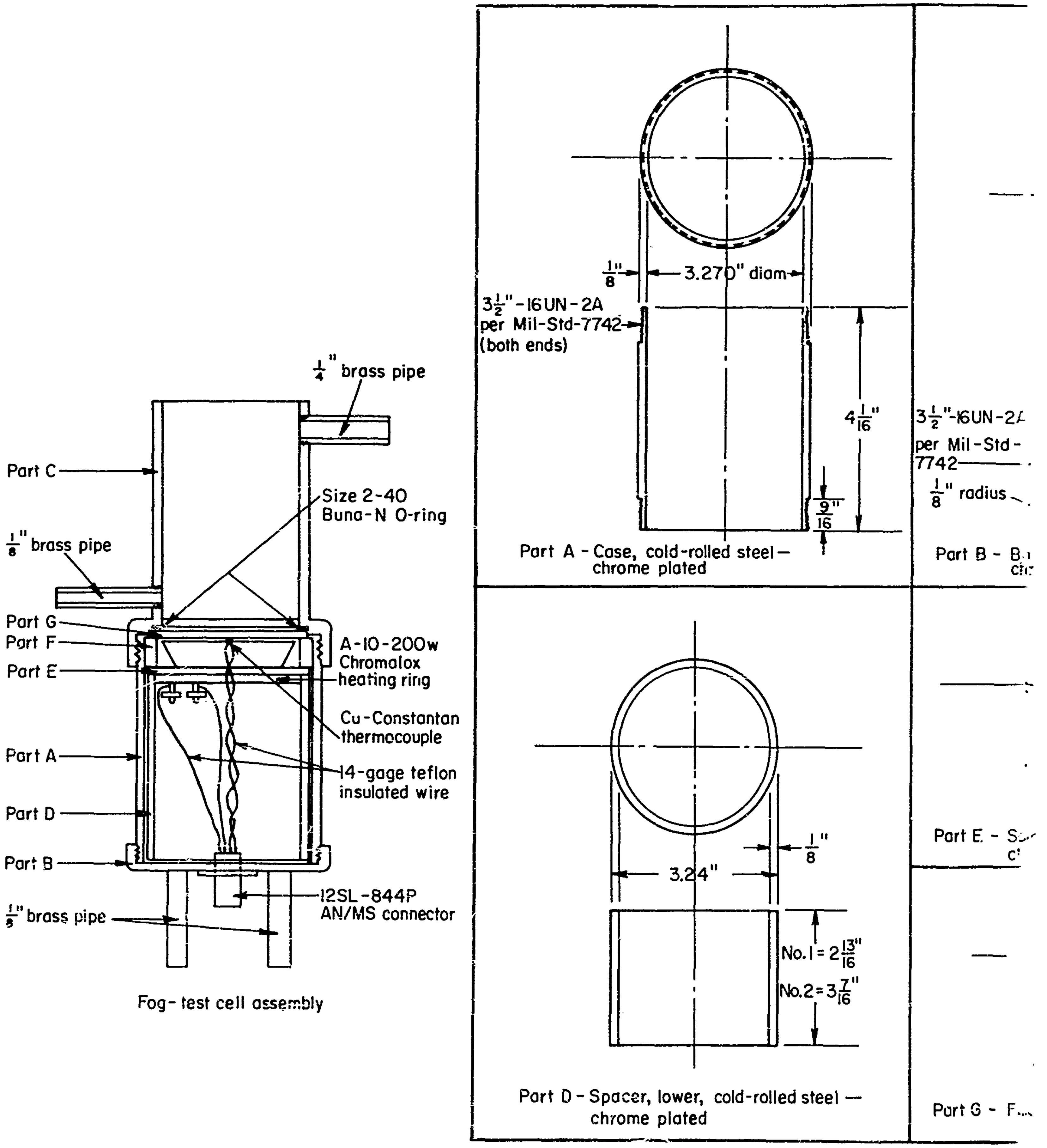
The cell was connected to a piping system as shown in Figure 6. This system permitted evacuation of the test cell and filling with either helium or air which was passed through a liquid-nitrogen trap (-319 F) to lower its dew point as much as possible. The second liquid-nitrogen trap was installed to prevent contamination of the vacuum gage and the vacuum pump.

All gas inlets were fitted with tightly packed glass-wool filters to prevent dust, etc., from entering the system.

All joints in the piping system were sealed with rosin-fluxed solder to minimize leakage.

The liquid-nitrogen traps were of Pyrex glass, and were immersed in Dewar flasks holding the liquid nitrogen. Joints to the brass pipe were made with standard vacuum-type heavy rubber tubing. These joints were kept as short as possible to minimize outgassing of the rubber and the diffusion of moisture-laden air through the tubing.

The entire system was outgassed at maximum vacuum for 1 week before any experimental runs were carried out.

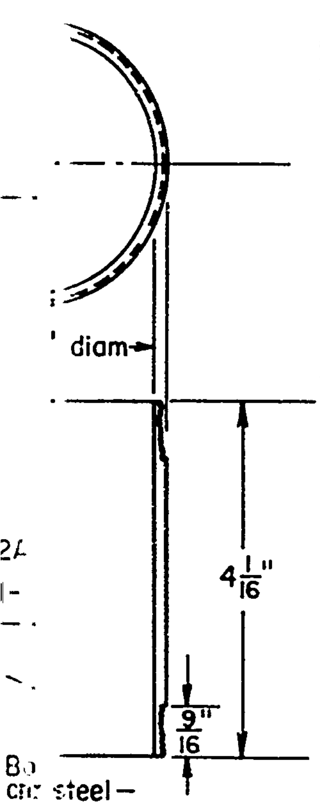


Fog-test cell assembly

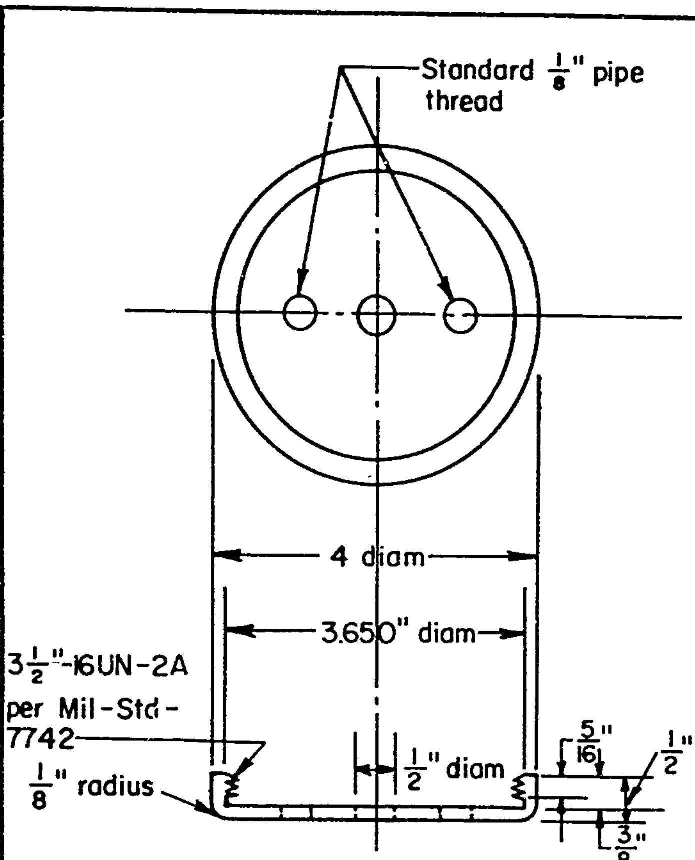
Part A - Case, cold-rolled steel — chrome plated

Part D - Spacer, lower, cold-rolled steel — chrome plated

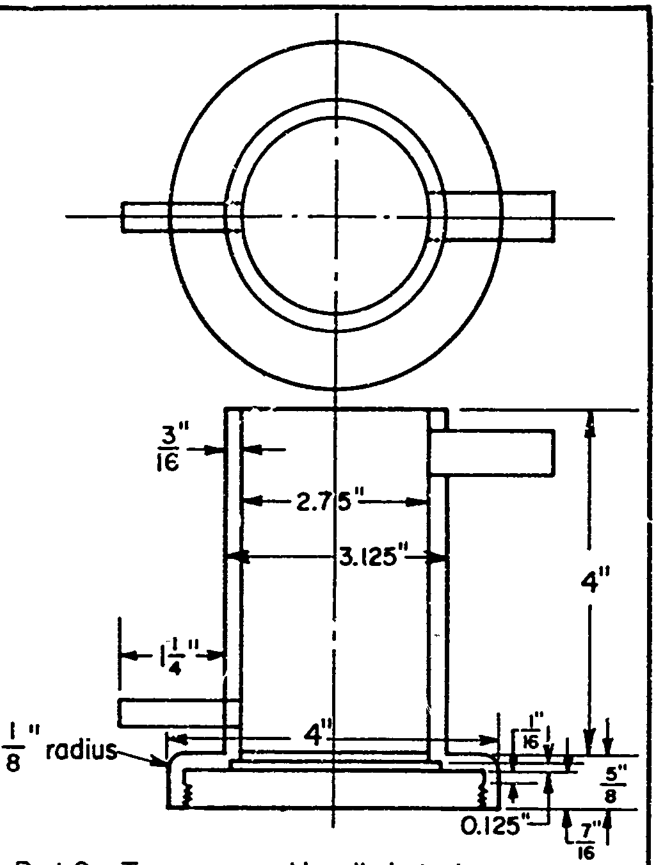
FIGURE 4. HIGH-SENSITIVITY FOG-TEST CELL



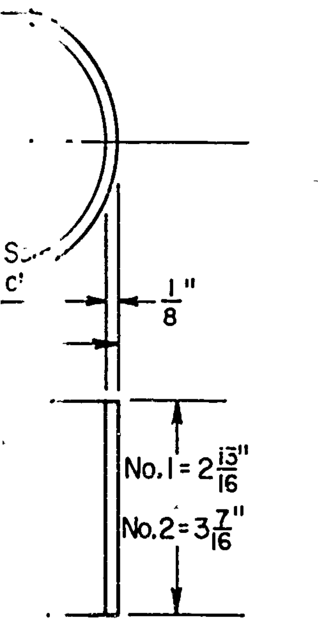
Bo… cr… steel —



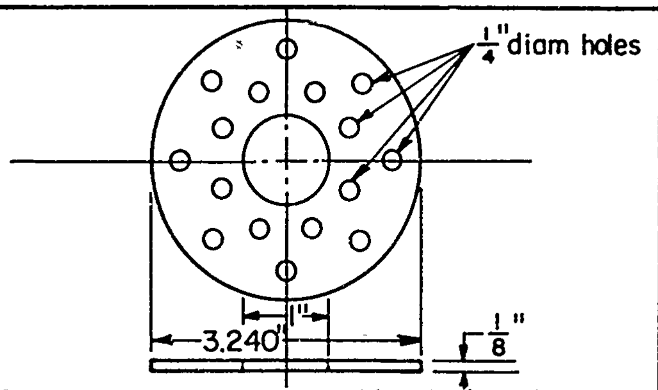
Part B - Bottom cover, cold-rolled steel — chrome plated



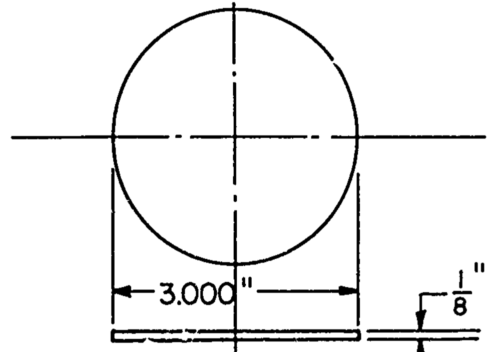
Part C - Top cover, cold-rolled steel — chrome plated



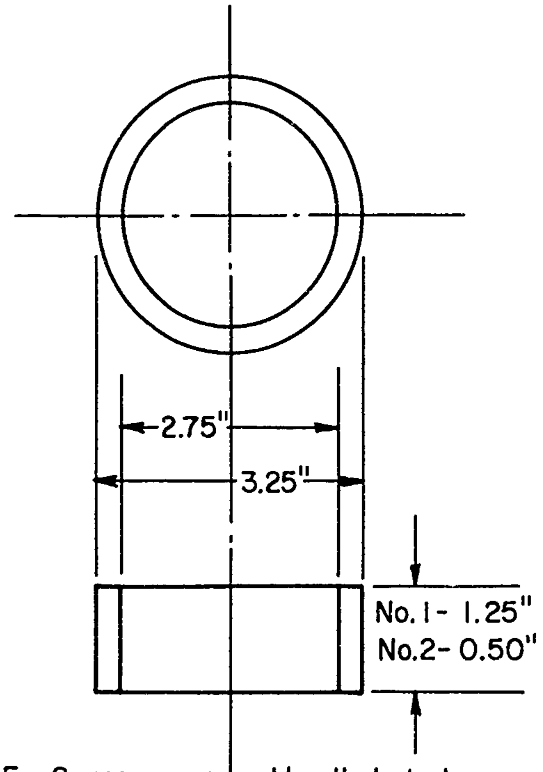
F…-rolled steel —



Part E - Sample support, cold-rolled steel — chrome plated



Part G - Face plate, 1/8" Pyrex plate glass



Part F - Spacer, upper, cold-rolled steel — chrome plated

C-52164

B

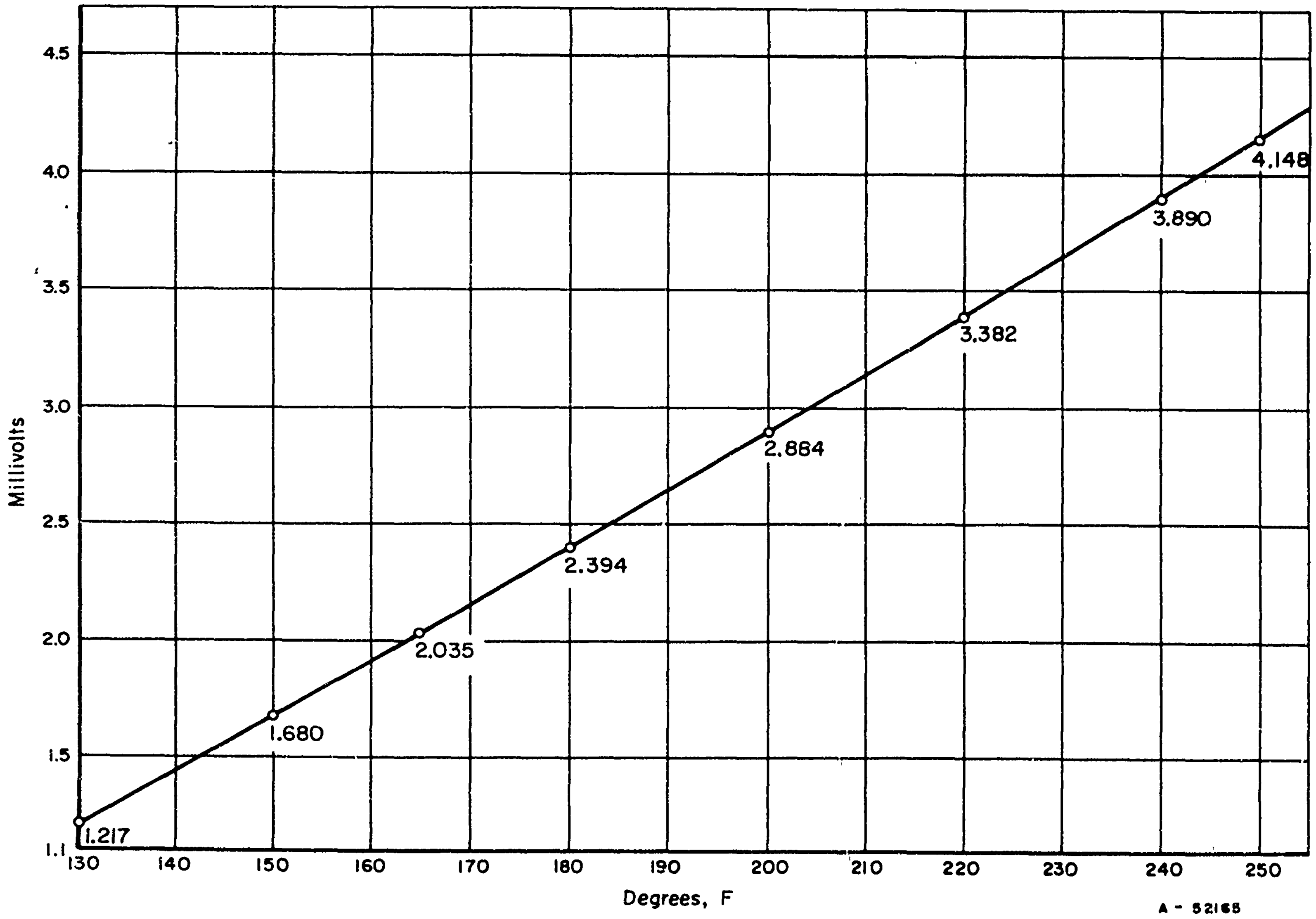


FIGURE 5. REVISED COPPER-CONSTANTAN CALIBRATION

Reference Junction – 75 F.

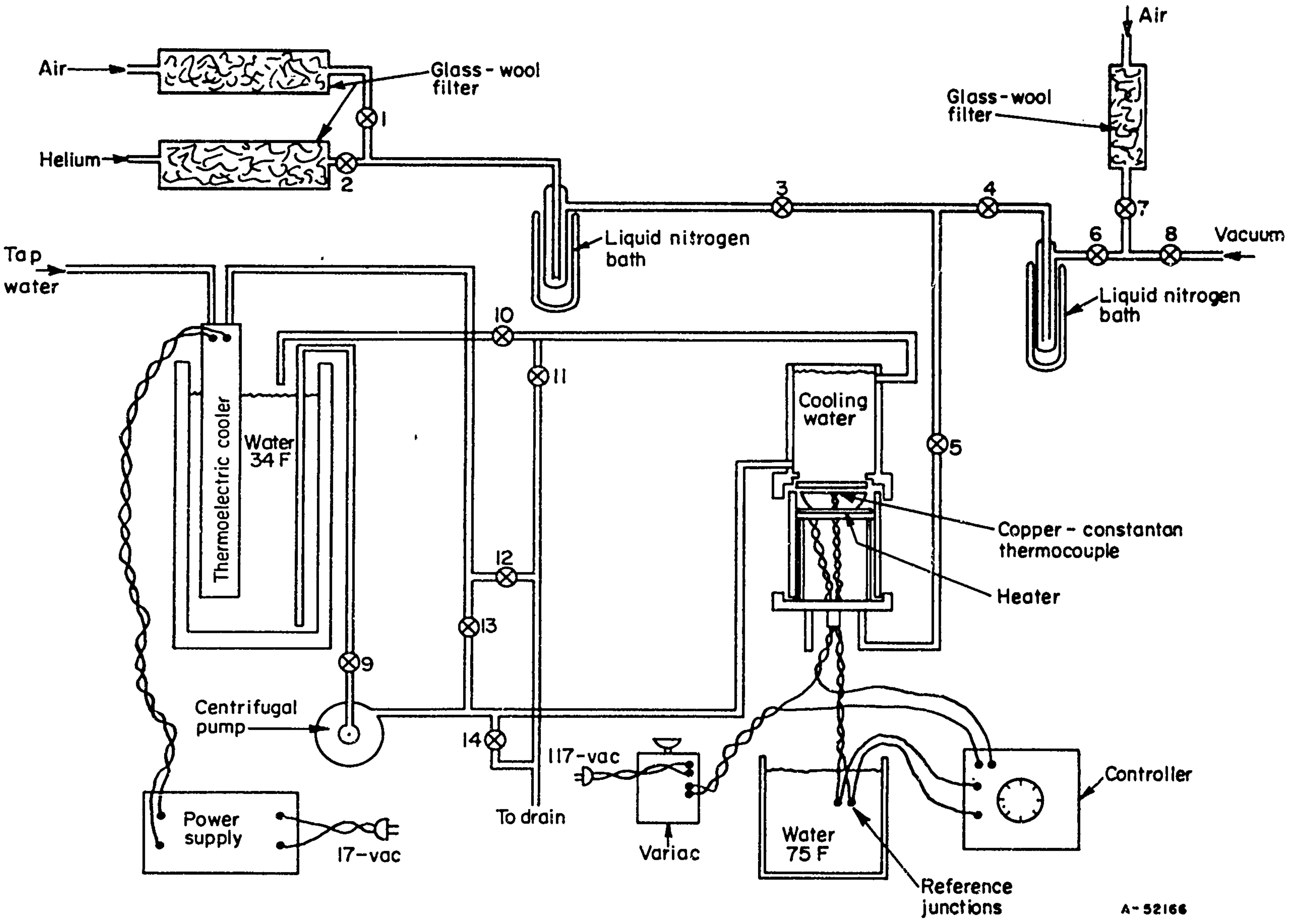


FIGURE 6. REVISED FOG-POTENTIAL APPARATUS

APPENDIX VI

METHOD OF USING THE HIGH-SENSITIVITY FOG-TEST APPARATUS

Reference should be made to Figure 6 for labeling of parts, valves, etc.

Before making an experimental evaluation, the entire system is assembled and outgassed at a temperature higher than that to be used in the test (275 F was used in this study), with a pressure of approximately 0.1 mm of mercury. After the original outgassing, about 48 hours' heating appeared adequate, except in those cases where silicones contaminated the cell with silane decomposition products.

An experimental evaluation is made by the following procedure.

The sample to be evaluated is placed in the aluminum dish. The cell is fitted with the liner and spacer that gives the smaller space above the heating unit, if the sample is small enough to permit it. The aluminum dish is placed in the cell, allowing the thermocouple head to protrude through the hole in the dish. The threads of the cell are covered with Permacel Ribbon Dope Thread Sealant (Teflon tape). The Pyrex faceplate is carefully cleaned until no water break is noted. Scrubbing with Bon Ami powder has been found to give good results. The plate is rinsed with distilled water and dried with a fresh tissue. The glass plate is temporarily held in place over the O-ring with Scotch tape. The cell cover is tightened with a strap wrench to compress the O-ring and prevent leakage.

The cell is connected to the purging and cooling system by means of three unions. The cooling traps are filled with liquid nitrogen. The electrical connections are made at the bottom of the cell. The controller is set at the proper value to give the desired test temperature. Valve 3 is closed, and Valves 4, 5, 6, and 8 are opened. The cell is evacuated for 10 minutes. While this is being done, Valves 1 and 2 are opened and helium flow is adjusted to give a slow exit of helium gas from the air inlet. Valve 1 is then closed. The cell is flushed 10 times by closing Valve 4 and opening Valve 3 to fill the cell with helium, then reversing the procedure by closing Valve 3 and opening Valve 4 to re-evacuate the cell. The cell is filled with dry helium and Valves 3 and 1 are opened; Valves 2 and 4 are closed. Valve 6 may now be closed, and the vacuum pump turned off. Valves 9, 10, 12, and 14 are closed, and Valves 13 and 11 are opened, to permit cooling water to circulate over the faceplate. Chilling of the faceplate is performed hourly by circulating the 34 F water over the faceplate. This is accomplished by the following sequence: open Valve 12, close Valve 13, close Valve 11, open Valves 9 and 10, and start centrifugal pump. After water has warmed up to 45 to 50 F, Valve 9 is closed and the pump can be turned off. Tap-water cooling may then be restored by opening Valve 13, closing Valves 10 and 12, and opening Valve 11.

After heating has been maintained for 8 hours, the heat is turned off, and the cooling water is drained from the cell cover by opening Valves 12 and 14, and closing Valve 13. As soon as the cell is cool (usually overnight), the cover is removed and the cover glass examined for traces of permanent fog. The presence of permanent fog is graded according to the following scale:

0 = No fog
1 = Very slight trace
2 = Slight fog
3 = Moderate fog
4 = Heavy fog
5 = Very heavy fog

A permanent record of moisture fog may be made by photographing the top of the cell under illumination of a single 375-watt photoflood bulb placed at an angle of about 45 degrees with the faceplate, and at a distance of 2 feet from the plate, immediately after making an ice-cube test. However, it should be pointed out that permanent fog does not show in photographs of this type. No successful method has been devised for photographing permanent fog satisfactorily.

APPENDIX VII

EXCERPTS FROM THE INTERNATIONAL CRITICAL TABLES

THE VAPOR PRESSURES OF ICE AND WATER UP TO 100°C

E. W. Washburn

In the following tables, the values given are the vapor pressures for the condition that the solid or liquid phase is under its own vapor pressure. If the solid or liquid phase is in contact with the atmosphere, the corresponding vapor pressures will be somewhat higher, and can be obtained by adding to the value given in the table a small increment, Δp, computed by means of the following equations:

Dans les tables suivantes, les valeurs données sont les tensions de vapeur dans la condition de la phase solide ou liquide se trouvant sous la pression de sa propre vapeur. Si la phase liquide ou la phase solide se trouve en contact avec l'atmosphère, les tensions de vapeur correspondantes seront un peu plus élevées, et elles peuvent être obtenues en additionnant aux valeurs données dans les tables un petit accroissement, Δp, calculé au moyen des équations suivantes:

Die in den folgenden Tafeln angegebenen Werte für die Dampfdrucke gelten für den Zustand, dass die feste oder flüssige Phase unter dem eigenen Dampfdruck steht. Ist die feste oder flüssige Phase mit der Atmosphäre in Verbindung, so werden die entsprechenden Dampfdrucke etwas höher sein. Man erhält sie, wenn man zu dem in der Tafel angegebenen Wert das Inkrement Δp addiert, das sich nach den Gleichungen berechnen lässt:

Nelle tabelle seguenti le tensioni riportate sono quelle del solido o del liquido a contatto col solo vapore proprio. Quando il solido o il liquido si trovano in contatto con l'atmosfera, le tensioni di vapore corrispondenti sono un po' più alte e si possono avere aggiungendo al valore della tabella, un incremento Δp, calcolato per mezzo della seguente equazione:

For ice and for water below 0°C:

$$\frac{100\Delta p}{p} = \frac{20}{t + 273}$$

For water above 0°C:

$$100\,\frac{\Delta p}{p} = 0.0775 - 3.13 \times 10^{-4}t \text{ (valid up to } t = 40°\text{C)}$$

and

$$100\,\frac{\Delta p}{p} = 0.0652 - 8.75 \times 10^{-4}p \text{ (valid above } 50°\text{C)}$$

The Vapor Pressure of Ice

Computed from the equation

$$\log_{10}p = \frac{-2445.5646}{T} + 8.2312\log_{10}T - 0.01677006T + 1.20514 \times 10^{-5}T^2 - 6.757169, \text{ mm Hg}$$

Based upon the measurements of Weber (²) and Scheel and Heuse (¹); see Washburn (³).

$T = 273.1 + t$

−90° to −30°; unit, 0.001 mm Hg

t, °C	0	1	2	3	4	5	6	7	8	9
−90	0.07_0	0.05_8	0.04_8	0.04_0	0.03_3	0.02_7	0.02_2	0.01_8	0.01_5	0.01_2
−80	0.40	0.34	0.29	0.24	0.20	0.17	0.14	0.12	0.10	0.08_6
−70	1.94	1.67	1.43	1.23	1.05	0.90	0.77	0.66	0.56	0.47
−60	8.0_8	7.0_3	6.1_4	5.3_4	4.6_4	4.0_3	3.4_9	3.0_2	2.6_1	2.2_5
−50	29.5_5	26.1	23.0	20.3	17.8	15.7	13.8	12.1	10.6	9.2_3
−40	96.6	86.2	76.8	68.4	60.9	54.1	48.1	42.6	37.8	33.4
−30	285.9	257.5	231.8	208.4	187.3	168.1	150.7	135.1	120.9	108.1

−30° to 0°; mm Hg

t, °C	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
−29	0.317	0.314	0.311	0.307	0.304	0.301	0.298	0.295	0.292	0.289
−28	0.351	0.348	0.344	0.341	0.337	0.334	0.330	0.327	0.324	0.320
−27	0.389	0.385	0.381	0.377	0.374	0.370	0.366	0.362	0.359	0.355
−26	0.430	0.426	0.422	0.418	0.414	0.409	0.405	0.401	0.397	0.393
−25	0.476	0.471	0.467	0.462	0.457	0.453	0.448	0.444	0.439	0.435
−24	0.526	0.520	0.515	0.510	0.505	0.500	0.495	0.490	0.486	0.481
−23	0.580	0.574	0.569	0.563	0.558	0.552	0.547	0.541	0.536	0.531
−22	0.640	0.633	0.627	0.621	0.615	0.609	0.603	0.597	0.592	0.586
−21	0.705	0.698	0.691	0.685	0.678	0.672	0.665	0.659	0.652	0.646
−20	0.776	0.769	0.761	0.754	0.747	0.740	0.733	0.726	0.719	0.712
−19	0.854	0.846	0.838	0.830	0.822	0.814	0.806	0.799	0.791	0.783
−18	0.939	0.930	0.921	0.912	0.904	0.895	0.887	0.879	0.870	0.862
−17	1.031	1.021	1.012	1.002	0.993	0.984	0.975	0.966	0.956	0.947
−16	1.132	1.121	1.111	1.101	1.091	1.080	1.070	1.060	1.051	1.041
−15	1.241	1.230	1.219	1.208	1.196	1.186	1.175	1.164	1.153	1.142

−30° to 0°; mm Hg.—(*Continued*)

t, °C	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
−14	1.361	1.348	1.336	1.324	1.312	1.300	1.288	1.276	1.264	1.253
−13	1.490	1.477	1.464	1.450	1.437	1.424	1.411	1.399	1.386	1.373
−12	1.632	1.617	1.602	1.588	1.574	1.559	1.546	1.532	1.518	1.504
−11	1.785	1.769	1.753	1.737	1.722	1.707	1.691	1.676	1.661	1.616
−10	1.950	1.934	1.916	1.899	1.883	1.866	1.849	1.833	1.817	1.800
−9	2.131	2.112	2.093	2.075	2.057	2.039	2.021	2.003	1.985	1.968
−8	2.326	2.306	2.285	2.266	2.246	2.226	2.207	2.187	2.168	2.149
−7	2.537	2.515	2.493	2.472	2.450	2.429	2.408	2.387	2.367	2.346
−6	2.765	2.742	2.718	2.695	2.672	2.649	2.626	2.603	2.581	2.559
−5	3.013	2.987	2.962	2.937	2.912	2.887	2.862	2.838	2.813	2.790
−4	3.280	3.252	3.225	3.198	3.171	3.144	3.117	3.091	3.065	3.039
−3	3.568	3.539	3.509	3.480	3.451	3.422	3.393	3.364	3.336	3.308
−2	3.880	3.848	3.816	3.785	3.753	3.722	3.691	3.660	3.630	3.599
−1	4.217	4.182	4.147	4.113	4.079	4.045	4.012	3.979	3.946	3.913
−0	4.579	4.542	4.504	4.467	4.431	4.395	4.359	4.323	4.287	4.252

THE VAPOR PRESSURE OF LIQUID WATER FROM −16 TO 0°C (IN MM HG)

Computed from the above table with the aid of the thermodynamic equation

$$\log_{10}\frac{p_w}{p_i} = \frac{-1.1489t}{273.1+t} - 1.330 \times 10^{-5}t^2 + 9.084 \times 10^{-8}t^3$$

t, °C	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
−15	1.436	1.425	1.414	1.402	1.390	1.379	1.368	1.356	1.345	1.334
−14	1.560	1.547	1.534	1.522	1.511	1.497	1.485	1.472	1.460	1.449
−13	1.691	1.678	1.665	1.651	1.637	1.624	1.611	1.599	1.585	1.572
−12	1.834	1.819	1.804	1.790	1.776	1.761	1.748	1.734	1.720	1.705
−11	1.987	1.971	1.955	1.939	1.924	1.909	1.893	1.878	1.863	1.848
−10	2.149	2.134	2.116	2.099	2.084	2.067	2.050	2.034	2.018	2.001
−9	2.326	2.307	2.289	2.271	2.254	2.236	2.219	2.201	2.184	2.167
−8	2.514	2.495	2.475	2.456	2.437	2.418	2.399	2.380	2.362	2.343
−7	2.715	2.695	2.674	2.654	2.633	2.613	2.593	2.572	2.553	2.533
−6	2.931	2.909	2.887	2.866	2.843	2.822	2.800	2.778	2.757	2.736
−5	3.163	3.139	3.115	3.092	3.069	3.046	3.022	3.000	2.976	2.955
−4	3.410	3.384	3.359	3.334	3.309	3.284	3.259	3.235	3.211	3.187
−3	3.673	3.647	3.620	3.593	3.567	3.540	3.514	3.487	3.461	3.436
−2	3.956	3.927	3.898	3.871	3.841	3.813	3.785	3.757	3.730	3.702
−1	4.258	4.227	4.196	4.165	4.135	4.105	4.075	4.045	4.016	3.986
−0	4.579	4.546	4.513	4.480	4.448	4.416	4.385	4.353	4.320	4.289

THE VAPOR PRESSURE OF LIQUID WATER FROM 0°C TO 100°C (IN MM HG)

From the Physikalisch-Technische Reichsanstalt "Wärmetabellen," Holborn, Scheel and Henning, Vieweg und Sohn, Braunschweig, 1909. By permission

t, °C	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	4.579	4.613	4.647	4.681	4.715	4.750	4.785	4.820	4.855	4.890
1	4.026	4.962	4.998	5.034	5.070	5.107	5.144	5.181	5.219	5.256
2	5.294	5.332	5.370	5.408	5.447	5.486	5.525	5.565	5.605	5.645
3	5.685	5.725	5.766	5.807	5.848	5.889	5.931	5.973	6.015	6.058
4	6.101	6.144	6.187	6.230	6.274	6.318	6.363	6.408	6.453	6.498
5	6.543	6.589	6.635	6.681	6.728	6.775	6.822	6.869	6.917	6.965
6	7.013	7.062	7.111	7.160	7.209	7.259	7.309	7.360	7.411	7.462
7	7.513	7.565	7.617	7.669	7.722	7.775	7.828	7.882	7.936	7.990
8	8.045	8.100	8.155	8.211	8.267	8.323	8.380	8.437	8.494	8.551
9	8.609	8.668	8.727	8.786	8.845	8.905	8.965	9.025	9.086	9.147
10	9.209	9.271	9.333	9.305	9.458	9.521	9.585	9.649	9.714	9.779
11	9.844	9.910	9.976	10.042	10.109	10.176	10.244	10.312	10.380	10.449
12	10.518	10.588	10.658	10.728	10.799	10.870	10.941	11.013	11.085	11.158
13	11.231	11.305	11.379	11.453	11.528	11.604	11.680	11.756	11.833	11.910
14	11.987	12.065	12.144	12.223	12.302	12.382	12.462	12.543	12.624	12.706

THE VAPOR PRESSURE OF LIQUID WATER FROM 0°C TO 100°C (IN MM HG).—(*Continued*)

t, °C	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
15	12.788	12.870	12.953	13.037	13.121	13.205	13.290	13.375	13.461	13.547
16	13.634	13.721	13.809	13.898	13.987	14.076	14.166	14.256	14.347	14.438
17	14.530	14.622	14.715	14.809	14.903	14.997	15.092	15.188	15.284	15.380
18	15.477	15.575	15.673	15.772	15.871	15.971	16.071	16.171	16.272	16.374
19	16.477	16.581	16.685	16.789	16.894	16.999	17.105	17.212	17.319	17.427
20	17.535	17.644	17.753	17.863	17.974	18.085	18.197	18.309	18.422	18.536
21	18.650	18.765	18.880	18.996	19.113	19.231	19.349	19.468	19.587	19.707
22	19.827	19.948	20.070	20.193	20.316	20.440	20.565	20.690	20.815	20.941
23	21.068	21.196	21.324	21.453	21.583	21.714	21.845	21.977	22.110	22.243
24	22.377	22.512	22.648	22.785	22.922	23.060	23.198	23.337	23.476	23.616
25	23.756	23.897	24.039	24.182	24.326	24.471	24.617	24.764	24.912	25.060
26	25.209	25.359	25.509	25.660	25.812	25.964	26.117	26.271	26.426	26.582
27	26.739	26.897	27.055	27.214	27.374	27.535	27.696	27.858	28.021	28.185
28	28.349	28.514	28.680	28.847	29.015	29.184	29.354	29.525	29.697	29.870
29	30.043	30.217	30.392	30.568	30.745	30.923	31.102	31.281	31.461	31.642
30	31.824	32.007	32.191	32.376	32.561	32.747	32.934	33.122	33.312	33.503
31	33.695	33.888	34.082	34.276	34.471	34.667	34.864	35.062	35.261	35.462
32	35.663	35.865	36.068	36.272	36.477	36.683	36.891	37.099	37.306	37.518
33	37.729	37.942	38.155	38.369	38.584	38.801	39.018	39.237	39.457	39.677
34	39.898	40.121	40.344	40.569	40.796	41.023	41.251	41.480	41.710	41.94
35	42.175	42.409	42.644	42.880	43.117	43.355	43.595	43.836	44.078	44.320
36	44.563	44.808	45.054	45.301	45.549	45.799	46.050	46.302	46.556	46.811
37	47.067	47.324	47.582	47.841	48.102	48.364	48.627	48.891	49.157	49.424
38	49.692	49.961	50.231	50.502	50.774	51.048	51.323	51.600	51.879	52.160
39	52.442	52.725	53.009	53.294	53.580	53.867	54.156	54.446	54.737	55.030
40	55.324	55.61	55.91	56.21	56.51	56.81	57.11	57.41	57.72	58.03
41	58.34	58.65	58.96	59.27	59.58	59.90	60.22	60.54	60.86	61.18
42	61.50	61.82	62.14	62.47	62.80	63.13	63.46	63.79	64.12	64.46
43	64.80	65.14	65.48	65.82	66.16	66.51	66.86	67.21	67.56	67.91
44	68.26	68.61	68.97	69.33	69.69	70.05	70.41	70.77	71.14	71.51
45	71.88	72.25	72.62	72.99	73.36	73.74	74.12	74.50	74.88	75.26
46	75.65	76.04	76.43	76.82	77.21	77.60	78.00	78.40	78.80	79.20
47	79.60	80.00	80.41	80.82	81.23	81.64	82.05	82.46	82.87	83.29
48	83.71	84.13	84.56	84.99	85.42	85.85	86.28	86.71	87.14	87.58
49	88.02	88.46	88.90	89.34	89.79	90.24	90.69	91.14	91.59	92.05
50	92.51	97.20	102.09	107.20	112.51	118.04	123.80	129.82	136.08	142.60
60	149.38	156.43	163.77	171.38	179.31	187.54	196.09	204.96	214.17	223.73
70	233.7	243.9	254.6	265.7	277.2	289.1	301.4	314.1	327.3	341.0
80	355.1	369.7	384.9	400.6	416.8	433.6	450.9	468.7	487.1	506.1
90	525.76	527.76	529.77	531.78	533.80	535.82	537.86	539.90	541.95	544.00
91	546.05	548.11	550.18	552.26	554.35	556.44	558.53	560.64	562.75	564.87
92	566.99	569.12	571.26	573.40	575.55	577.71	579.87	582.04	584.22	586.41
93	588.60	590.80	593.00	595.21	597.43	599.66	601.89	604.13	606.38	608.64
94	610.90	613.17	615.44	617.72	620.01	622.31	624.61	626.92	629.24	631.57
95	633.90	636.24	638.59	640.94	643.30	645.67	648.05	650.43	652.82	655.22
96	657.62	660.03	662.45	664.88	667.31	669.75	672.20	674.66	677.12	679.59
97	682.07	684.55	687.04	689.54	692.05	694.57	697.10	699.63	702.17	704.71
98	707.27	709.83	712.40	714.98	717.56	720.15	722.75	725.36	727.98	730.61
99	733.24	735.88	738.53	741.18	743.85	746.52	749.20	751.89	754.58	757.29
100	760.00	762.72	765.45	768.19	770.93	773.68	776.44	779.22	782.00	784.78
101*	787.57	790.37	793.18	796.00	798.82	801.66	804.50	807.35	810.21	813.08

* For higher temperatures, v. p. 233.

LITERATURE

(For a key to the periodicals see end of volume)

(1) Scheel and Heuse, *16*, 29: 731; 09. (2) Weber, *168*, No. 180: 37; 15. (3) Washburn, *406*, 88: 488; 24.

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*

Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201

2a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b GROUP

3. REPORT TITLE

INVESTIGATION OF THE OCCURRENCE OF CONDENSATION IN FLIGHT INSTRUMENTS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Final Technical Report March 1, 1964 to June 30, 1965

5. AUTHOR(S) *(Last name, first name, initial)*

Brand, Benson G., Bennett, Bailey, and Leininger, Robert I.

6. REPORT DATE
January 1966

7a. TOTAL NO. OF PAGES
53

7b. NO. OF REFS
0

8a. CONTRACT OR GRANT NO.
Contract No. AF33(657)-12462

b. PROJECT NO.

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
SEG-TR-66-2

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11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Systems Engineering Group, Research and
Technology Division, Air Force Systems
Command, WPAFB, Ohio 45433

13. ABSTRACT

This study concerned the location and identification of sources of fog formation on the faceplates of hermetically sealed aeronautical instruments.

Two types of fog (moisture and permanent) were found. Moisture fog was shown to be caused by imperfect hermetic sealing of the instrument cases. Permanent (oily) fog was found to be the result of partial decomposition of nonmetallic materials by heat. This decomposition in certain materials results in oily products with appreciable vapor pressure, which may condense on the instrument faceplate, usually the coolest part of the instrument.

Thirteen aeronautical instruments representing seven different types, and made by five different suppliers, were covered by this study.

Included in the report are:

1. A list of recommended materials
2. A list of materials shown to contribute to permanent fog formation
3. A discussion of the psychrometry of gases
4. A discussion of desiccants
5. A critique of the ice-cube test
6. A recommended modification of the ice cube test
7. A high-sensitivity fog potential test
8. Instruction for use of the fog potential apparatus
9. Excerpts from the International Critical Tables.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Instrument Fog						
Desiccants						
Sealing						
Fog Potential						
Aeronautical Instruments						

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