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Proceedings of the Eleventh National Conference on Environmental Effects on Aircraft and Propulsion Systems, 1974

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ICING PROBLEMS ON STATIONARY GAS TURBINE POWERPLANTS

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PAPER PRESENTED AT THE ELEVENTH NATIONAL CONFERENCE ON ENVIRONMENTAL EFFECTS ON AIRCRAFT AND PROPULSION SYSTEMS, 21 - 22 MAY 1974, TRENTON, NEW JERSEY.

ICING PROBLEMS ON STATIONARY GAS TURBINE POWERPLANTS

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Mr. Chappell has also carried out analytical and experimental research in axial compressor design, engine cycle calculation techniques, and acoustics. He is a member of the CASI and the ASME, and is currently Senior Research Officer and Chief Projects Officer of the Engine Laboratory.

After graduation from the Hamilton Institute of Technology (Ontario) in 1961, Mr. Grabe joined the National Research Council of Canada. He has since been actively engaged in icing work on a series of aircraft turbine engines. As of recent date, he has assisted in the solution of icing problems arising with stationary gas turbine installations. In addition, he investigated ground effect in connection with VTOL craft, and assisted in gas turbine cycle studies. W. Grabe is a member of the Canadian Aeronautics and Space Institute.

ABSTRACT

The increasing use of industrialized aircraft gas turbine engines for stationary powerplant applications in subfreezing environments has resulted in operational difficulties and occasional catastrophic engine failures caused by ice formations on components within the engine intake system. For many years the icing problem has been the object of considerable study in relation to aircraft gas turbine applications. This background experience provides useful guidance in approaching the icing problems encountered on the more complex intake system configurations of stationary gas turbine powerplants.

The first part of this paper reviews the atmospheric phenomena which can give rise to icing problems. Specific data are given to indicate maximum severities likely to be encountered at stationary gas turbine sites.

The second part of the paper discusses the ice accumulation propensities of typical intake system components in sufficient detail to permit application of the fundamental reasoning to novel system arrangements.

The third part describes several methods of protecting engines and their intake system components from icing conditions, with particular attention being paid to those techniques most appropriate to stationary gas turbine applications. A brief discussion is also given of various types of ice and icing condition detectors and their suitability for use in stationary gas turbine powerplant applications.

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PART I: THE CAUSES

1.0 Introduction

In recent years, aero-derived stationary gas turbine engines have gained popularity in applications such as pipeline and electric power station prime movers. Unlike their more robust industrial-type counterparts, these modified aircraft engines are relatively vulnerable to significant ice formations in the air intake system. In addition, both types of gas turbines are seriously affected by icing of intake air filters which jeopardizes the air supply. In the following paper an attempt will be made to analyse the elements causing icing problems at ground level, and to delineate specific methods of protection against recognized icing hazards.

2.0 The Icing Problem and Icing Conditions

The air intake system of a stationary gas turbine installation must perform two essential tasks - it must provide an adequate flow of clean air to the engine, and it must provide adequate silencing to prevent unacceptable noise levels in the surrounding area. An inlet accordingly comprises large filtering units in series with acoustic splitter elements; after passing through these units, air is normally discharged into a plenum chamber, from whence it passes into the actual engine. Figure 1 illustrates a typical embodiment of these elements, and serves to indicate the somewhat tortuous aerodynamic path upstream of the engine.

An icing situation exists whenever free liquid water droplets or free solid water particles are contained in the engine inlet airstream at temperatures below the freezing point. The icing problem follows when these free water particles strike a surface (such as an inlet screen, filter, or inlet guide vane) and accumulate as ice.

Ice accretions on engine intake components and compressor blading cause performance losses through blockage of the intake area and disfiguration of the aerodynamic passages in the blading rows. The usual symptoms of this condition are increased compressor inlet depression, decreased power output, and increased turbine inlet and outlet temperatures.

The ice accretions can also cause mechanical damage to the engine by inducing vibrations in the compressor blades, which may lead to fatigue failures and considerable secondary damage. Moreover, if ice accumulations within the intake system are allowed to become sufficiently large, these buildups can shed because of vibratory and/or aerodynamic forces and the resulting impact of these pieces of ice can deform and even dislodge sections of compressor blading.

There are two phenomena which can result in the existence of an icing problem in the engine inlet. The terms 'Precipitate

Icing' and 'Condensate Icing' (as defined in Sections 2.1 and 2.2) have been employed in this paper to refer to these two distinct types of icing environment.

2.1 Precipitate Icing Conditions

The term Precipitate Icing is used herein to describe the existence of free water (either in solid or liquid form) in the atmosphere from which the engine draws its air supply. It includes hail, ice crystals, snow, freezing rain, and supercooled water droplets in low level clouds and/or fog. The last condition is synonymous with 'natural icing', a term that is usually applied to flight conditions, and represents the most hazardous form of precipitate icing for the stationary gas turbine powerplant and the aircraft gas turbine engine alike.

2.1.1 Solid Forms

The solid forms of precipitation generally present a less severe hazard to the gas turbine powerplant than does the supercooled liquid precipitation. This phenomenon is primarily attributable to the geometry of typical intake systems and to the non-sticky nature of hail, ice crystals, and snow; i.e., these types of particles will not adhere to cold, forward-facing surfaces in the engine airpath.

The installation of 'snow hoods' over the entry to the intake system (Fig. 1) causes the intake airstream to flow vertically upwards as it enters the system. The velocity under the lower edge of the hood is low, typically of the order of 10 ft/sec, hence large particles with high settling rates (such as hailstones and wet snowflakes) cannot be entrained with the intake air. Some percentage of smaller particles, such as ice crystals and dry snowflakes, may be drawn into the intake system, but generally are removed by the inertial filter elements.

Ambient concentrations of snow or ice crystals can reach relatively high values (of the order of 4 gm/m^3). The effective concentration entering the intake system, however, is usually significantly less for the reasons outlined above. Nevertheless, local wind conditions may augment the concentration entering the intake and, under these conditions, considerable non-uniformity may exist between different sides of the same intake system.

It is perhaps worth reiterating that the relative safety of operation in solid form Precipitate Icing conditions depends greatly on the non-adherence of these particles to <u>cold</u> surfaces. Intentional or inadvertent heating of intake components that are subjected to impingement from solid particle icing conditions may considerably increase the danger of ice accretions forming.

2.1.2 Liquid Forms

A great deal of work has been done to define the meteorological conditions that result in supercooled water droplet icing conditions, and to establish the maximum severity of the hazard in terms of concentrations and extents as functions of temperature and altitude for various cloud types. Most of this work has been oriented toward the aircraft applications, but many of the data gathered and the lore developed can be translated to the ground-based gas turbine powerplant. Reference 1, Section 1, presents a broad outline of this work and an extensive bibliography.

Icing clouds fall into two general categories: stratiform and cumuliform. In stratiform clouds (Fig. 2) icing conditions can prevail for horizontal extents up to 200 miles, and hence this type of icing is usually termed 'Continuous Icing'. Liquid water contents are moderate (0.1 to 0.8 gm/m^3), and the water droplet mean diameter will be in the 5 to 50 micron range. Ambient temperature can vary from -22°F to +32°F, with values above 0°F being most common.

'Intermittent Icing' is found in cumuliform clouds (Fig. 3), and extends horizontally for only 3 to 6 miles. Liquid water contents vary from 0.1 to 3.0 gm/m^3 (i.e. about two and a half times those for Continuous Icing at the same temperature) with occasional peak values as high as 3.9 gm/m^3 for very short distances. Temperature and droplet mean diameter ranges are similar to those for stratiform clouds. The most likely altitude for cumuliform cloud icing is 10,000 ft, whereas that for stratiform cloud icing is only 5,000 ft.

The accepted 'aircraft design standard' variations of liquid water content with temperature for icing conditions in these two types of clouds are shown in Figures 4a and 4b.

For ground installations at altitudes less than 3,500 ft, such as are being considered here, the likelihood of experiencing an 'Intermittent Icing' condition is virtually non-existent, and hence this severity standard need not be taken into consideration in the design of icing protection systems for such units. Moreover, Lewis at NASA has correlated observed low altitude icing conditions with adiabatic lifting theory to show that, even for Continuous Icing conditions in low level stratiform clouds, liquid water contents are reduced at low altitudes (Ref. 1).

Before leaving the discussion of supercooled water droplet icing, it is perhaps worth mentioning the phenomenon of freezing rain. This condition, which definitely can exist at ground level, is an icing condition in that it comprises supercooled water drops in the atmospheric air, usually at temperatures between 25°F and 32°F. However, droplet sizes are very large; about 1,000 microns as compared with a maximum of about 50 microns for a 'true' icing condition. The downward momentum of the falling drops will therefore prevent most of these drops from entering inverted flow intake configurations such as fitted on many stationary gas turbine installations. Moreover, liquid water contents for freezing rain seldom exceed 0.15 gm/m^3, which is only about one-third of the Continuous Icing value at the same temperatures. Thus a protection system that is unaffected by droplet impingement limits will be more than adequate for freezing rain conditions if it is designed for Continuous Icing conditions.

2.1.3 Hoarfrost*

One type of supercooled water droplet icing that has been particularly troublesome on some stationary gas turbine installations is the condition popularly known as "hoarfrost". This condition can occur when moist ambient air cools, for example during daily temperature variations or changes in the weather system. When the total temperature drops below the frost point, quiescent ambient air can become supersaturated. If this quiescent supersaturated air is disturbed or comes into contact with a cold surface, rapid nucleation takes place and the characteristic hoarfrost formations accumulate. The rapidity of hoarfrost accumulation can be quite startling; a 2-inch-mesh chain-link fence has been observed to become completely opaque in less than two hours.

Because the hoarfrost phenomenon is an unstable condition, no known reference has listed observed concentrations as functions of the initial temperature and humidity and the decrease in total temperature. Theoretical maximum concentrations can be calculated by subtracting the saturation humidity at the lower temperature from the absolute humidity at the initial ambient conditions. For example, this procedure predicts a maximum theoretical hoarfrost concentration of 2.64 gm/m^3 if air at 35°F and 100% relative humidity cools to 20°F. From this value the potential severity of this hoarfrost condition can be appreciated as being approximately equal to the concentration of Intermittent Icing conditions or about two to three times the concentration of a Continuous Icing condition.

There are, however, two redeeming features of hoarfrost as compared with other precipitate icing forms. The first is that, because hoarfrost implies a thermodynamically unstable condition in the air, the frost will accumulate on the first disturbing surface. It has been observed, in a typical intake system as shown in Figure 1, that hoarfrost accumulates extremely rapidly on the debris screens, but that little or no accretion forms within the inertial filter elements immediately downstream. On the other hand, if the debris screens are removed for winter operation, the hoarfrost accretions accumulate very rapidly within the filter elements themselves.

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*The classification of hoarfrost as Precipitate rather than Condensate Icing may be questioned. In this paper the term Condensate Icing is reserved for cases where moisture is condensed from the airstream by decreasing the static temperature while the total temperature remains substantially constant. This of course implies acceleration of the airstream to a significant Mach Number such as occurs in the compressor inlet bellmouth. Thus Condensate Icing does not exist as an atmospheric condition per se, but is a situation induced by the engine under certain atmospheric conditions.

The second redeeming feature of hoarfrost is that the accretions that do form are usually sugary rime ice with a high percentage of included air. These lacy ice formations are easily removed (usually by manual mechanical means such as by brushing) and, once dislodged, do not present a severe ingestion hazard even should they negotiate the filter elements. The primary danger to gas turbine operation in hoarfrost conditions is the rapid increase in plenum chamber pressure depression commensurate with the high blockage rates, and the attendant dangers of compressor surge or continued operation with the blow-in doors open.

2.2 Condensate Icing Conditions

If air saturated with water vapour (but containing no liquid water) is accelerated, its static temperature will drop and a portion of the water vapour will condense. If this occurs at a temperature below 32°F, the condensed water will supercool and, if time permits, it will solidify into ice crystals.* This phenomenon is well known in suction wind tunnels, and unless the incoming air is dried to a very low absolute humidity, condensation shock waves can form in supersonic tunnels of this type.

In a stationary gas turbine engine, the Mach Number in the compressor inlet annulus is typically about 0.3 to 0.4 at design operating conditions. This results in a static temperature depression (below inlet total temperature) of the order of 10°F to 15°F at intake total temperatures around the freezing point. Theory predicts that, under atmospheric conditions of moderate temperature (25°F or so) and high humidity, this drop in static temperature results in free water condensate concentrations up to two or three times those for the corresponding Continuous Precipitate Icing condition. However, these Condensate Icing concentration values are appropriate to equilibrium conditions where all the vapour above the saturation limit has condensed (i.e. no supersaturation exists based on the instantaneous static temperature) but none has solidified. In computing these concentrations allowance must be made for the rise in both total and static temperature due to the release of the latent heat of evaporation from the condensate.

In the actual intake system on an engine, several factors combine to make the hazard due to this Condensate Icing less severe. Firstly, the high Mach Number exists only for a very short time at the entry to the inlet guide vanes or the first rotating row of compressor blading. At other positions in the intake system the Mach Number, (and hence the static temperature depression) is lower. This, coupled with the short dwell times for the air/water

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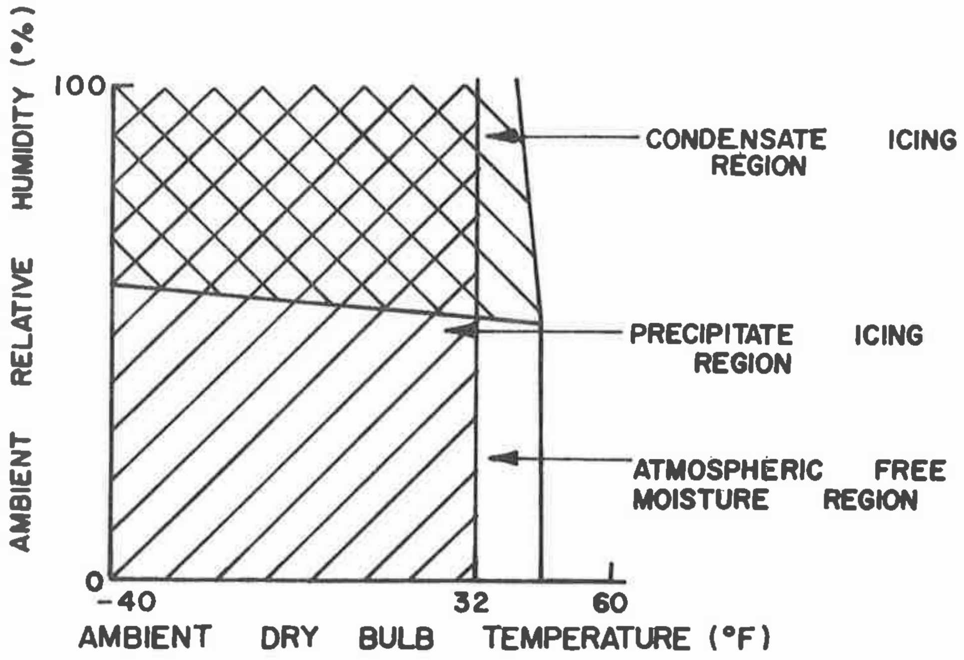
*It is recognized that some of the water vapour may sublimate directly to the solid state, although the literature is not clear on this point; however, in order to establish maximum limits, the pessimistic assumption is made here that all the condensable vapour appears as supercooled liquid water droplets.

mixture in the intake system, will not permit the equilibrium conditions quoted above to be established. Secondly, there is a substantial recovery of total temperature on all forward facing surfaces, thus some of the free water condensate will re-evaporate. Thirdly, condensate droplets formed in this manner are extremely small (of the order of three to five microns in diameter). Thus the effective catch efficiency of any surface is considerably less than for the 'standard' 20 micron droplets of Precipitate Icing.

Because Condensate Icing severity is a function of engine inlet Mach Number, it cannot be expressed as a unique function of temperature as was the case for precipitate supercooled water droplet icing conditions. The next two sections outline a method whereby the icing severity can be calculated as a function of temperature once the inlet Mach Number is known.

2.2.1 Determination of Condensate Icing Region and Severity

Before computing the theoretical icing severities resulting from Condensate Icing conditions, one must delineate the regions within the engine's operating range where these conditions can exist. Whereas Precipitate Icing can exist under appropriate meteorological conditions at any ambient dry bulb temperature less than 32°F, atmospheric free moisture in small droplet form can also exist above the freezing point, typically to temperatures of about 50°F.



The extent of the Condensate Icing region is defined by a maximum ambient temperature and a minimum ambient relative humidity. It is, of course, also dependent on the Mach Number to which the air is accelerated. The maximum static temperature for the existence of supercooled condensate is 32°F. At ambient total temperatures and relative humidities which result in static temperatures greater than 32°F, condensate can still form but cannot adhere as ice to surfaces within the engine intake system. For any given inlet Mach Number, the amount of condensate that forms, due to the acceleration of the moist airstream into the engine inlet, decreases with decreasing ambient relative humidity. Below a certain ambient relative humidity level, the decrease in static temperature due to acceleration of the airstream is insufficient to cause supersaturation, and hence no condensate can form. These two interrelated criteria form the boundaries of the Condensate Icing region depicted in the sketch above. Specific determination of this region is detailed in Appendix A for a typical inlet Mach Number of 0.37, and the severity of Condensate Icing is shown in the form of iso-concentration contours in Figure A-3.

It must be remembered, however, that the data presented in Figure A-3 are theoretical maximum concentrations. Actual concentrations are undoubtedly lower but quantitative differences in severity between the theoretical and actual Condensate Icing phenomena are extremely difficult to predict. It is believed that the theoretical severity may be as high as five times the actual severity, but even this figure is open to considerable doubt. Therefore, as in the case of Continuous Precipitate Icing, the theoretical values can only be used as a design guide and the inherent margin of safety must be kept in mind during the design of the protection system.

2.3 Total Supercooled Water Droplet Icing Severity

Perhaps the most significant factor in determining the design requirements of any icing protection system is the maximum liquid water content for each sub-freezing temperature in the operating range. For a stationary gas turbine engine this total free liquid water content is composed of two parts: maximum Continuous Precipitate Icing concentration (which can be considered a unique function of ambient temperature as shown in Figure 4a), and maximum Condensate Icing concentration (which can be also considered a unique function of ambient temperature once the maximum inlet Mach Number has been determined and if one takes the ambient relative humidity as 100% to obtain the maximum case). Hence, for the typical inlet Mach Number used ($M = 0.37$) the maximum theoretical total liquid water concentration (as a function of ambient temperature) can be found by adding corresponding values of concentration from the 15 micron line of Figure 4a and the 100% relative humidity data from Figure A-3. The result is shown in Figure 5. It should be noted here that this addition has been made irrespective of the droplet size of the two icing conditions. This is permissible for determining total water concentrations, but consideration of droplet size would have to be made in the design of any icing protection system where impingement limits were an important factor.

As pointed out previously, the theoretical maximum concentrations shown in Figure 5 are in excess of the expected actual maximum concentrations by a factor of at least two (and probably more). Therefore, any icing protection system designed to withstand these concentrations will have an inherent margin of safety of the same order.

PART II: THE EFFECTS

3.0 Ice Accumulation Areas in the Engine Inlet System

3.1 General

Figure 1, as noted above, illustrates a generalized configuration for a stationary gas turbine powerplant installation and contains all the intake elements found in most pumping and generating station applications. The icing propensities of these elements will be considered in the following sections for each of the icing environments discussed in Section 2. Following the detailed discussions of the icing characteristics of the individual intake components, a table is presented wherein the relative likelihood of each component to accumulate ice under each of the icing environments is summarized. These assessments are based on the type of intake configuration shown in Figure 1. Installations which differ substantially from the type illustrated (e.g. ground-level forward-facing configurations) will undoubtedly exhibit different characteristics. Nevertheless, the reasoning presented in the following sections can be applied to estimate ice accumulation tendencies for any reasonable configuration.

3.2 Snow Hoods

Although these components are not likely to accrete ice on the engine airflow side under any environmental conditions, their fitment has a significant effect on the icing characteristics of some of the downstream intake components. Hence, their function will be discussed here, and their effects on the icing tendencies will be discussed with the individual components in the following sections.

The installation of snow hoods (Fig. 1) over the entry to the intake system causes the inlet airstream to flow vertically upwards as it enters the system. Velocity under the lower edge of the hood is low, typically of the order of 10 ft/sec, hence large particles with high settling rates cannot be entrained by the intake air. Such particles include hailstones, raindrops, freezing raindrops, and heavy wet snowflakes. Small particles that may be entrained, even at 10 ft/sec, include dry snow, fog, some ice crystals, and, of course, supercooled liquid water droplets. In the case of large icing particles (e.g. freezing rain, hail), the snow hood protects primarily the debris screens and the filter elements, as particles of this size cannot penetrate the filter elements in any case. In addition, the location of blow-in door openings relative to snow hood position can be of considerable importance as discussed in Section 3.5

3.3 Debris/Bird Screens

These screens are fitted to prevent large debris (such as leaves) from entering and plugging the filter elements. They also serve to prohibit birds and rodents from entering and/or nesting in the filters. These screens usually comprise grids of 1/16" to 1/8" diameter wires at 1/2" centers or less. Throughflow velocities are about 20 ft/sec, too low for Condensate Icing to be of concern.

As mentioned previously, snow hoods effectively protect the debris screens from heavy particle precipitate icing. Without the snow hood, freezing rain or drizzle could result in significant ice accretions which would lead to increasing screen blockage until an unacceptable pressure drop was reached. Wet snow could give rise to similar blockage although the ice accretions are likely to be somewhat easier to dislodge and some self clearing may occur before the plenum depression becomes intolerable.

Dry powdery snow, even though it may be drawn in under the snow hood, should offer no problem as the solid snowflakes will not adhere to the cold wires of the screen. However, if some portions of the screen are warmed to slightly above freezing (e.g. by proximity to some heat source such as the compressor house or a hot vent pipe) then some ice accretions may form in the fringe zones between the warm and cold areas of the screen. It is unlikely that these fringe areas would be large enough to cause a significant plenum pressure depression even if they iced over completely, however, under these melt-refreeze conditions there is always a danger of large glaze (runback) ice accretions forming in local areas behind the screen and thus constituting a possible ingestion hazard to the filter elements if not to the engine itself.

With snow hoods fitted, the primary cause of ice accretions on the debris screens is supercooled water droplets in the ambient air stream. In a classical icing cloud or in freezing fog the ice buildups will grow gradually on the screen wires and excessive blockage will occur only after several hours of operation in even the most severe icing conditions. Recent tests at the National Research Council (Ref. 5) resulted in ice accretions of 5/8" deep by 3/16" wide on a 1/2" mesh of 1/16" diameter wires after two hours of 0.75 gm/m^3 (Fig. 6). Pressure loss increased from 0.1" to 1.1" H_2O during the test period even though the screen was inclined at 45° to the airflow (Fig. 7). This liquid water concentration is at least twice as severe as the worst concentration likely to be met in the field and hence the test period of two hours can be equated to at least four hours of actual operating time. The accretions formed were hard rime ice (at -5.0°C) and were firmly attached to the screen, showing no self-shedding tendencies at the 25 ft/sec tunnel velocity used in the test.

Probably the most rapid blockage of debris screens by ice accumulations will occur under the hoarfrost type of precipitate icing described in Section 2.1.3. Field observations under these conditions indicate the pressure loss across the screen may reach intolerable levels in as little as 30 minutes, and that almost continual removal of the soft powdery ice buildups (usually by brushing) is required to keep the plenum depression within acceptable limits without the blow-in doors opening. These high buildup rates are caused by the unstable nature of the supersaturated inlet air and the subsequent 'avalanche' nucleation effect as the air is disturbed on its way through the debris screen. There is some evidence to suggest that the nucleation and deposition of this moisture on the debris screens prevents or substantially decreases the subsequent deposition on the inertial filter elements downstream.

3.4 Filters

Experience with media filters has shown that this type of element plugs so rapidly under all icing conditions that they are seldom used during winter operation.

Intertial or momentum separation filters function on the principle of accelerating the airstream and turning it rapidly, thus 'centrifuging' entrained particles to a local area of the flow where they can be removed and discharged away from the engine airstream (Fig. 8). Typical velocities are still below those that give rise to severe Condensate Icing problems; however, some ice formations may accumulate on the filter turning vanes under extremely high humidity conditions.

In Precipitate Icing conditions the icing particles are effectively segregated in the small tortuous passages of the filter elements. If these particles are 'dry', such as ice crystals or dry snow, and the filter elements are cold, then the entrained icing particles will respond to the inertial separation process in much the same manner as would large dust particles. They will not stick to the filter elements and will be discharged overboard along with the filter bleed air. Indeed, operators have reported observing considerable quantities of dry snow being discharged from the filter bleed ducts under these conditions.

If, on the other hand, the Precipitate Icing particles are 'wet', such as supercooled water droplets or wet snow, then they will adhere to the small passages in the filter elements and the pressure drop across the filter system will increase rapidly to an unacceptable level.

Again, the fitment of snow hoods will prevent the larger Precipitate Icing particles from reaching the filter elements. Nevertheless, there is still appreciable likelihood of the classical icing condition presenting some difficulties, the frequency and severity of which depend greatly on local weather conditions at the gas turbine site.

Recalling the discussion of hoarfrost in Sections 2.1.3 and 3.3, one can readily appreciate that if unstable supersaturated air is permitted to enter the filter elements, then blockage by ice accumulations will be extremely rapid. One case reported during the winter of 1971/1972 suggested 10 minutes maximum running time between filter cleanings. It might also be noted here that cleaning ice accretions from inside inertial filter elements is considerably more difficult (and hence time consuming) than cleaning similar deposits from debris screens. Frost buildups brushed from the filters or debris screens while the unit is operating are usually separated by the inertial filter and discharged from the intake system, hence very little danger to the engine exists during these scraping-off exercises. The relative difficulty of removing hoarfrost accumulations from the filter elements encouraged the investigation of the debris screen's possible role as a 'deposition trigger' in hoarfrost conditions.

3.5 Blow-in Doors

Increasing the pressure drop across the debris screen and filter unit decreases the pressure in the engine intake plenum. If this trend continues unchecked, the gas turbine engine compressor may surge or the plenum itself may implode. Blow-in doors are provided to prevent these eventualities. However, once the blow-in door has opened, the engine is no longer protected by the inlet filter system, and hence suffers the potential hazards associated with an unprotected inlet.

Under winter operating conditions there is another hazard associated with the operation of the blow-in door. Because this door is usually closed, ice and snow deposits can accumulate around its edges, especially if there are horizontal ledges on its exterior frame. Figure 9 gives an illustration of this potential hazard. This horizontal-louvre type of door maximizes the number of surfaces that would be prone to accumulating ice and snow deposits. When the door is opened, these deposits may very easily be swept into the plenum with the inrushing airstream. Moreover, there is also the danger that these accretions may be bonded to the door and doorframe strongly enough to prevent the blow-in door from opening when it is required. Strong motorized actuators have been fitted to many installations specifically to avoid this danger.

In addition to designing the blow-in door flush with the exterior surface of the filterhouse, it is clearly an advantage to position it under the snow hood so that, should operation with the door open be required, the engine would still receive the protection from certain Precipitate Icing conditions afforded by the hood. Such an arrangement is shown in Figure 10.

For units with potentially hazardous blow-in door designs, it may be wise to trigger an alarm slightly below the pressure drop which would cause automatic actuation of the blow-in door, and to instruct operating personnel to check that the door and doorframe areas are free of hazardous accumulations of ice and snow before opening the door.

3.6 Silencer Elements, Walkways, and Enclosures within the Plenum

These intake system elements are usually in very low velocity areas downstream of the debris screen and filter assembly. Condensate Icing is not a problem in these low velocity regions. The severity of Precipitate Icing conditions which can reach these components depends greatly on the type and effectiveness of the components upstream. For example, in an installation equipped with snow hoods, debris screens, and inertial filters, there will be little chance of any significant icing conditions reaching the silencer elements or other enclosures within the plenum. The few powdery snowflakes which do penetrate the filter elements usually pass harmlessly through the plenum and the engine itself.

The primary circumstance under which ice accretions can form on the walkways and silencer elements is during operation with the blow-in door open. Then, some or all of the Precipitate Icing particles can reach these components, depending on the location of the blow-in door and its possible protection by a snow hood. Here again, 'dry' icing particles will not adhere to the cold surfaces. However, wet snow and the various forms of supercooled water droplets can, and will, accrete as ice on these surfaces if they reach this part of the intake system. Fortunately, catch efficiencies are very low at velocities typical of these areas and accretions will grow very slowly and are most unlikely to cause blockage problems. Nonetheless, as in the case of the blow-in doors, horizontal ledges, where local vortices can deposit ice and snow accumulations, should be avoided in the design.

Notwithstanding the foregoing remarks, it is of considerable importance how ice accretions that do form after prolonged operation in icing conditions dissipate. Ideally, the buildups should sublimate gradually as, for example, the ambient temperature rises. If, on the other hand, heat transfer through the metal elements weakens the ice/metal interface, large 'plates' of ice can shed and may be drawn into the engine causing severe ingestion damage. Designing for protection against this occurrence is awkward, and perhaps the two best methods are provision of a relatively long horizontal path between the silencer trailing edges and the engine flare, and/or fitment of an 'ingestion protection' screen directly in front of the engine bellmouth. This latter suggestion involves some additional hazard as discussed in Section 3.8.

Engine starters are often placed remote from the compressor inside an enclosure (Fig. 1). A tendency exists to slope the roof of the enclosure towards the engine intake, presumably to have it double as a crude aerodynamic fairing. From an icing point of view, this slanting is undesirable, because falling ice pieces which impinge on it are liable to bounce in the direction of the engine inlet. Depending on the geometry of the plenum, entrainment of the ice into the air stream and subsequent ingestion could be a possibility.

3.7 Plenum Chamber

A typical stationary gas turbine installation places the engine intake inside a plenum chamber. Besides providing a structure for the protective intake components discussed in this Part its main purposes are to contain the compressor noise and to keep the elements from the engine. This enclosure is attached to the engine/compressor house, which means that three walls and the roof form the sound barrier to the surroundings while the fourth wall is provided by the main compressor building wall, also referred to as the bulkhead wall.

In designing this plenum chamber, often little attention is paid to icing phenomena. During the course of winter, snow settles on the roof. Subsequent melting because of rises in ambient temperature or radiative heating may lead to seepage of water into the intake plenum, assisted by the static depression inside. Here it may collect and freeze to hard glaze icicles. It is easy to visualize that if these ice formations are suspended above the engine inlet, serious compressor damage is risked. Therefore, it is absolutely imperative that the intake housing be waterproof, at least above the centerline of the engine intake. Unfortunately, this requirement has often been neglected in past designs. A common problem area is also the joint between intake enclosure and engine/compressor building.

As has been pointed out earlier, dry snow and water vapour may pass through the filters into the plenum. Dry snow and ice crystals can be rendered harmless by keeping all surfaces cold. The alternative would be heating all parts of the intake system to temperatures above freezing - an extremely costly proposition. Partial heating of selected components or areas should definitely be avoided since it could lead to melting of the flakes and subsequent freezing into glaze ice. The outside walls are being kept cold by ambient air. Significant heat transfer can take place, however, through the bulkhead wall, the very wall which contains the engine intake bellmouth. Insulation of this wall is relatively simple, and can be done, in existing installations, conveniently from the engine side (Fig. 11).

If insulation is successful, snow and ice crystals will either be ingested by the engine or collect on protrusions from the wall and/or on the floor. Because of the danger of eventual melting and refreezing, protrusions near the bellmouth and above the floor should be avoided. Snow that settles on the floor should not present a hazard providing the intake bellmouth is positioned sufficiently high off the floor, say 1 1/2 intake diameters from centerline to ground. Eventually, snow accumulations on the floor melt. In the absence of proper drainage, puddles may freeze to sheet ice which could conceivably be lifted by the inlet air stream and be ingested. Although the chance for this to happen is remote, one should drain any water from the floor, if only for personnel safety.

Condensate Icing is, generally, not a problem in the plenum because air velocities are too low for significant static temperature depressions. Exceptions to this generalization are high-velocity vortices which have been observed near the bellmouth, sometimes in corners of the bulkhead wall. If meteorological conditions described in Section 2.2 prevail, Condensate Icing may take place in these areas. In that case aerodynamic fairings or cascades may have to be installed.

Considering that ice formations on the plenum walls and ceiling are eliminated by proper sealing, ice may still form on the filter elements and the silencers (Fig. 1). This ice is harmless as long as the horizontal distance to the engine intake is great enough to prevent ingestion.

Finally, properly located inspection windows and adequate illumination of the plenum chamber should be provided. Care must be taken, though, that no 'hot spots' are created by the lamps.

3.8 Ingestion Protection Screen

If the precautions expounded in the foregoing sections are taken, the engine intake should be sufficiently protected against destructive ice ingestions. Often it has been found to be difficult, however, to seal existing older intake housings without great expenditure. In such a case, protective screens mounted in front of the bellmouth have been suggested. One possible configuration is illustrated in Figure 12.

A screen immediately in front of an engine intake would be simply a debris screen where the debris would primarily, but not exclusively, consist of ice formations of significant size. It would also provide protection against larger rivets, loosened pieces of concrete, misplaced hand tools, etc. While the design and installation of such a screen seems to be a straightforward matter, some important criteria must be taken into consideration.

Although, from an icing point of view, the screen would be located in a rather 'clean' environment, it is still possible for ice to form on the mesh. Condensate Icing should not be a problem because of the low air velocities through the screen. Most supercooled water droplets would be caught in the inertial filter passages, although some smaller droplets may reach the screen. Dry snow will pass harmlessly through the mesh, providing that its wires are kept cold. Extensive operation with an open blow-in door, however, could lead to significant icing of the engine screen. In that event, supercooled water and wet snow would constitute the most hazardous elements.

In case of ice formations on the screen wires, two problems could arise: shedding of ice into the intake, and aerodynamic blockage. If ice formed on the upstream side of the mesh, pieces no longer than the mesh pitch could break off and pass through. One remote possibility would be the case of melting of the ice buildup, followed by refreezing of the melt on the inside of the screen, and subsequent ingestion. In order to get a better understanding of the icing processes speculated on, a series of tests was conducted on various likely screen samples, see Reference 5. The icing severity of supercooled water was chosen so as to represent at least 10 hours of actual operation under the worst environmental conditions. In essence it was found that:

(a) the ice formed a very strong lattice firmly attached to the wire, which could be breached by hand only with great effort;

(b) even extensive ice formations did not increase the screen pressure drop measurably under representative air flow conditions; the sole exception was a heavily iced 1/2-inch pitch screen (Figs. 6 and 7);

(c) it was not possible to form ice on the inside of the screen.

Even though the pressure drops in the above tests were found to be insignificant, one should provide a bypass opening by leaving the bottom section of the screen envelope open. Thus, even a fully blocked screen would not starve the engine of air. It would have to be established, though, whether the engine's compressor would be affected adversely by any inflow distortion from a clear or iced asymmetric screen.

Although the shape and positioning of any intake screen would be largely governed by the plenum layout, certain design criteria should be taken into consideration. In order to keep the velocity through the screen low (low losses, prevention of Condensate Icing), it should not be placed in the immediate engine intake. Making the screen too large would increase the price and create an unnecessary obstacle inside the plenum. It is important though, that the configuration of the screen be such that all areas of potential ice formation be outside the screen.

With respect to the construction of the intake screen, a few simple rules ought to be observed. The selection of the mesh should strike a balance between maximum protection and minimum losses. The screen must be sturdy enough to withstand the impact of a large ice formation dropped from the greatest possible height. A strong frame might prove helpful towards this end. Since fretting of the wires, caused by the combined effects of wire frequencies and vortex shedding frequencies, is a possibility, the use of welded screen material is recommended.

Finally, attention is drawn briefly to the thermal insulation of the screen mountings. The earlier recommendation for keeping components in the intake housing cold is to be extended to the engine screen. If the screen is attached directly to the bulkhead wall, with anchor bolts or brackets extending through this wall, heed should be paid to possible heat conduction from the warm side of the wall. Dry snow in the plenum could be a source of glaze ice formation in a most sensitive area, viz. immediately adjacent to the air intake.

3.9 Inlet Flare/Bellmouth

Air is accelerated into the engine intake through an inlet flare or bellmouth. The two terms are synonymous; the former one being widely used by stationary engineers while the latter term is preferred by aviation engineers.

The surface of the bellmouth, if kept cold, should not present any problems from an icing point of view. The bellmouth often consists of a single piece of fibreglass mold with a very smooth finish. Its positioning relative to the wall may vary basically, in three different ways, it can be: extended with recess, extended, or flush mounted, see Figure 13.

A recess, as shown in Figure 13a, can lead to icing problems, especially if heat is conducted from the compressor house. In one actual case, dry snowflakes, which had entered the plenum, collected behind the bellmouth lip, melted, and froze to glaze ice on the lip. Since a recess of this kind has no obvious virtue, but poses a potential icing hazard, its elimination was recommended. In addition, the cavity was filled with insulating material.

A projecting inlet flare has the advantage that ice formations on the bulkhead wall will not pass in front of the intake when sliding or falling to the floor. The projection is, typically, six to eight inches from the wall (Fig. 13b). Furthermore, the flare has a clean lip, i.e. no clamps which could collect ice. Although it would be possible for snow and ice, with an opened blow-in door, to collect between lip and wall, the danger is greatly reduced with proper insulation in this area.

Flush mounted bellmouths present a rather clean intake in that they do not provide a stagnant space for possible snow collection and subsequent ice formation. Some care must be taken, however, with respect to the fastening methods. One common design uses a series of clamps around the periphery of the flare (Figs. 13c and 14). Since the clamp bolts probably extend through the bulkhead wall, heat transfer along the bolt may lead to the aforementioned snow-melting-glaze ice sequence on these protrusions. Therefore, one should fasten existing flush mounted flares by a ring which forms a smooth transition between wall and bellmouth (Fig. 13d). In new designs, this mounting ring may become an integral part of the inlet flare.

In general, discontinuities in smooth surfaces aid the formation of ice in a suitable environment. Because Condensate Icing conditions may well exist at the small section of the bellmouth, a smooth transition to the compressor case must be assured. In addition to eliminating the chances for the formation of undesirable ice ridges, a clean transition benefits the air flow into the compressor aerodynamically.

One method of cleaning compressor blades is by liquid spray from a wash rig (Fig. 14). When not in use, the two articulated arms are folded away from the intake, as shown. In line with the previous statement that protrusions of any kind ought to be avoided, this type of wash rig should be replaced by one which is built into the bellmouth (Fig. 13b).

4.0 Ice Accumulation Areas Within the Engine Intake

4.1 General

Unprotected engine intake components are susceptible to ice formation. Depending on their relative location in the inlet and on atmospheric conditions in the plenum, Condensate and/or Precipitate Icing may take place. In the following sections these intake components will be discussed briefly with respect to their relative vulnerability to ice formation. Protective measures will be treated in Part III.

4.2 Nose Bullet and Starter Shafting

Nose bullets of modified aero engines are, generally, non-rotating. Inlet air velocities are not high enough in this region to cause Condensate Icing of any consequence; the possibility of Precipitate Icing presents the only problem, albeit a small one. If runback ice were to form on the bullet surface, it would pose a considerable threat to the compressor blade. Therefore, thermal protection is usually provided, as discussed in Section 5.2.

The starter shaft of remote starter installations could be susceptible to precipitate or 'leakage' icing. By 'leakage' icing is meant the formation of ice resulting from melting water dripping onto the shaft from the roof. The shaft rotates only during the starting cycle; after light-up it is disengaged from the engine. The potentially most hazardous ice formation is glaze ice growing from the lower surface of this shaft at rest. On start-up, centrifugal force detaches the accretion, leading, possibly, to entrainment and ingestion. Inspection of the starter shaft should, therefore, form part of the visual pre-start inspection of the plenum chamber during winter season.

4.3 Compressor Front Frame

A small number of radial support struts is often placed between nose bullet and first stage rotor (Fig. 14). They are of large pseudo-airfoil cross-section with moderately high catch efficiency. Condensate Icing is the primary icing hazard in this region, with Precipitate Icing presenting a lesser problem. Because of the large surface of these struts, runback icing, if its takes place, may be sizeable and present a considerable problem. This type of icing may conceivably be caused by inadvertent heating from service pipes placed inside the struts, e.g. oil feed and oil scavenge lines for the front compressor bearing which is supported by the struts. For these reasons, support struts are usually protected thermally (see Section 5.2).

4.4 Inlet Guide Vanes

Certain types of modified aero engines are provided with inlet guide vanes which direct the air flow onto the first stage compressor rotor. Even though these vanes are rather thin, their catch efficiency is fairly high. Both Condensate and Precipitate Icing may take place at this inlet plane. Condensation produces very small droplets which are likely to form rime ice. This type of ice is very soft and brittle and, typically, builds up in spear-head form (Fig. 15a). Glaze ice, on the other hand, is hard and forms into a hammerhead shape (Fig. 15b). If runback ice should form, it could conceivably grow beyond the vane trailing edges, interfering with the first stage compressor rotor. Like the support struts, the inlet guide vanes are generally protected by the inlet anti-icing system.

4.5 First Stage Compressor Rotor

Icing conditions experienced by first stage compressor rotor blades are less severe than those of preceding intake components. The reasons for this are twofold: upstream components will have collected a certain fraction of the free icing particles, and also ice formations on the compressor blades are subjected to centrifugal and aerodynamic forces which will induce periodic shedding. Uneven shedding of ice buildups around the rotor may lead, however, to increased vibration which can be used as an indication of compressor rotor icing. If preset vibration limits are exceeded for a longer period, the engine may have to be shut down for inspection.

Ingestion of larger ice pieces into the engine presents a particular hazard to the first rotor stage of the compressor. Since the spacing between the trailing edge of the inlet guide vanes and the leading edge of the rotor blades is fairly small, ice chunks may be jammed in this gap. Depending on size and hardness of the ice, the affected blade(s) may be deflected rearwards far enough to make contact with the stator. The resulting damage may be severe. In the absence of inlet guide vanes, the impact of ice pieces causes tearing and bending of first stage blades; deflection is usually less than in the former case.

4.6 Subsequent Compressor Stages

Subsequent compressor stages, both rotor and stator, are seldom affected by icing and are, therefore, not protected. The possible exception is the first stage stator which follows the first stage rotor. At particularly low intake temperatures, the total temperature rise through the rotor may produce the conditions necessary for glaze ice formation on this stator. Because a certain minimum amount of liquid water content is required for this process, however, the chances for it to take place are small. Spacings between higher order rotors and stators are small which means that any glaze ice pieces which managed to proceed this far may cause extensive damage.

4.7 Summary of Ice Accumulation Tendencies

Part II has presented detailed discussions of the icing tendencies of each major component in the engine intake system. The following table attempts to summarize these tendencies for the various types of icing environments described in Part I.

PART III: THE SOLUTIONS

5.0 Icing Protection Systems

5.1 General

The primary objective of an icing protection system is to prevent, or limit to a tolerable size, ice accretions within the engine intake. The size and complexity of inlet systems for

ICE ACCUMULATION TENDENCIES OF INTAKE COMPONENTS IN A TYPICAL STATIONARY GAS TURBINE INSTALLATION AS SHOWN IN FIGURE 1

SECTION NO.	INTAKE COMPONENT		PRECIPITATE ICING						HOAR-FROST	COND. ICING
			HAIL	ICE CRYSTALS	SNOW		FREEZING RAIN	SCW DROPLETS		SCW DROPLETS
					DRY	WET				
3.1	Snow Hoods		1	1	1	1	1	1	1	1
3.2	Debris/Bird Screens		1	1	1	2(1)	3(1)	3	3	1
3.3	Filters	Inertial	2(1)	1	1	2	3(1)	3	3	2
		Media	2(1)	3	3(1)	3(1)	3(1)	3	3	1
3.4	Blow-in Doors		2(1)	2(1)	2(1)	2(1)	3(1)	3(1)	1	1
3.5	Silencers, Walkways, Enclosures		1	1*	1*	1*	1	1*	1	1
3.6	Plenum Chamber		1	1*	1*	1*	1	1*	1	1
3.7	Ingestion Protection Screen		1	1*	1*	1*	1	2	1	1
3.8	Inlet Flare/ Bellmouth		1	1*	1*	1*	1	1*	1	1
4.2	Nose Bullet/ Starter Shafting		1	1	1	1	1	2	1	1
4.3	Compressor Front Frame		1	1	1	1	1	2	1	2
4.4	Inlet Guide Vanes		1	1	1	1	1	2	1	3
4.5	First Stage Compressor Rotor		1	1	1	1	1	2	1	2
4.6	Subsequent Compressor Stages		1	1	1	1	1	1	1	1

LEGEND:
1 = Little or no tendency
2 = Moderate tendency
3 = Strong tendency
( ) = Snow hood fitted
* = Without intentional or unintentional heating

stationary gas turbine applications often prohibit provision of an icing protection system capable of guaranteeing ice-free conditions everywhere ahead of the engine compressor blading. Therefore, in stationary gas turbine powerplants, the total protection of the engine often comprises a combination of ice ingestion protection and icing protection systems. Two ice ingestion protection schemes, viz. extending the horizontal airpath immediately in front of the engine,and fitment of a screen directly ahead of the compressor face, have been discussed in Sections 3.7 and 3.8,respectively. In the current section, the four major categories of icing protection systems will be described and compared. The discussion will include all systems, although some of them are rarely, if ever, applied to stationary installations.

Two terms that occur frequently in discussions of icing protection systems are 'anti-icing' and 'de-icing'. 'Anti-icing' embrances all icing protection schemes that prevent the formation of hazardous ice accretions. 'De-icing', on the other hand, refers to icing protection systems that permit a certain (tolerable) ice accretion to form and then promotes its removal before it can reach hazardous proportions. The latter category usually operates cyclically, and the cycle's off/on time ratio is determined by the engine ingestion tolerance under the ambient conditions which will result in the severest ice accumulation rate. Some of the icing protection systems discussed in the following sections can operate in either the anti-icing or the de-icing mode. An in-depth treatment of protective systems can be found in Reference 1.

Stationary gas turbine engines can be divided, basically, into two categories: industrial-type engines and modified aircraft engines. In general, industrial-type engines are designed specifically for their application. They are heavy and robust, and work at relatively low speeds. For these reasons, compressor blades are usually not protected against icing or ice ingestion at all; the strong blades simply 'chew up' any ice formations which might be ingested.

Modified aero engines are characteristically of lightweight, and their compressor blades must be protected from ice formations. The following sections will, therefore, deal primarily with the protection of inlet components of this type of stationary turbine engine.

5.2 Thermal Systems

5.2.1 Charge Heating

Charge heating, as applied to anti-icing work, means the raising of intake air temperature by mixing hot gases into the cold airstream. Either HP compressor bleed air or engine exhaust gases are admitted into the intake stream in front of the bellmouth. The static temperature of the resultant gas mixture must be above freezing at all inlet planes if Condensate, as well Precipitate, Icing is to be prevented. The advantage of charge heating is that, if the temperature is raised sufficiently, icing cannot take place anywhere in the engine intake. The price for this protection, however, may be high. As is well appreciated, the output of a gas turbine increases with decreasing temperatures. If the driven equipment is not power limited, the installation will operate below maximum capacity with a raised intake air temperature. Furthermore, compressor bleed air is expensive which should, for all practical purposes, rule out its use for charge heating.

Engine exhaust gases, a waste material, seem to be a more logical source of heat. The major disadvantages to be considered are: pressure losses and inlet air pollution. Combustion products are expanded through a series of turbines to slightly above atmospheric pressure. Any piping system beyond the exhaust stack would incur a pressure loss, leading to a certain back pressure at the power turbine exit which, in turn, would decrease the useful work output. With respect to intake air pollution, two detrimental effects come to mind. The exhaust gases will foul the compressor blades, thus increasing the cleaning frequency. In addition, approximately three percent water vapour is contained in the combustion products, leading to possible inlet icing problems, if the ambient air temperature is sufficiently low.

In a field experiment, compressor vent air, which normally was bled to atmosphere, was discharged from a piccolo pipe mounted upstream of the debris screen. The scheme's purpose was the prevention of hoarfrost formation on part or all of the screen. This partial heating of intake air could lead to cold streaks, and to the creation of runback ice in intermediate zones in the inertial separator.

In any applications of charge heating, an even distribution of the hot gases is important. Improper mixing may result in the above mentioned cold streaks and, possibly, in local icing in the engine intake region.

5.2.2 Component Heating

Component heating is by far the most popular method of engine intake protection against icing. It is economical, because the amount of heat for each component can be closely controlled, and clean. Most aero-derived engines come equipped for component heating, invariably with greater capacity than is required for ground installation. Basically, two heat sources are used: electricity and compressor bleed air.

For electrical anti-icing, resistance wires are imbedded in rubber pads which are mounted on the surface to be protected. Aircraft wing and empennage leading edges and propeller roots are common locations for electrical pads. In stationary installations they are rarely, if ever, encountered.

Compressor bleed air is nearly exclusively the source of energy for component heating. HP compressor air is bled through passages provided in components to be protected. These usually include the nose bullet, starter shaft, struts, inlet guide vanes, and sometimes the first stage stator. The spent air is discharged either to the outside or into the air intake stream. The protection is selective, i.e. the components are heated only when icing actually takes place or a potential icing environment exists. The selection is made either by an icing detector or icing condition detector (see Section 6.0) or manually by station personnel. Component heating is usually based on the anti-icing, rather than de-icing, principle. In designing the system and in metering the bleed flow rate care must be taken that no runback icing occurs. As mentioned above, runback water forms hard glaze ice, the most hazardous type for the compressor. The bleed flow for the engine inlet components, without starter shaft, is of the order of one percent of compressor flow rate. The starter shaft takes a negligible amount of air, and, for that reason, is often heated continuously.

5.3 Chemical Systems

In a chemical anti-icing system, the liquid water in the intake air is mixed with a freezing point depressant, e.g. ethylene glycol or isopropyl alcohol. A relationship between freezing points of some depressant/water solutions and their strengths is given in Figure 16. The chemical anti-icing method is rarely used. In one case, an intake screen was kept free of ice by spraying alcohol onto it. One of its drawbacks is the logistics involved, especially for isolated installations. Another one is the cost, if one considers extending the engine's protection over longer periods of potential icing environments.

5.4 Mechanical Systems

In contrast with the methods discussed above, mechanical systems de-ice components at intervals rather than keep them free of ice constantly (anti-icing). In aircraft applications, the most prominent mechanical de-icer is the pneumatic boot, used on cowl intake lips and wing leading edges. Mechanical de-icing at stationary installations takes the form of manual brushing of hoarfrost from debris screens or out of inertial separator passages. Automatic brushing systems have been considered.

5.5 Inertial Systems

Inertial separation of particles from an airstream that carries them takes place when the stream is forced to change direction drastically, at sufficiently high velocity (see Section 3.4 and Fig. 8). Inertial separators are widely used in stationary installations for dust and sand protection. In wintertime, they will handle dry snow and ice crystals without problem. Wet snowflakes and supercooled water droplets, however, while being separated from the air, will impinge on the separator walls and form slush or ice. Thus, it becomes only a matter of time before the rather small passages become plugged. One might say that this type of inertial separation of icing elements is unintentional, and it certainly can cause problems. Hoarfrost which forms inside inertial separators can usually be removed by brushing and scraping.

The best known intended separator of icing particles is the snow hood (Fig. 1). The relatively high momentum of free falling snowflakes or freezing rain droplets will keep them from being entrained by the low velocity intake airstream. The hood offers little protection against windblown snow and ice crystals.

6.0 Detectors

6.1 General

Thermal and chemical anti-icing protection is, generally, controlled by a detector. The detectors used in stationary gas turbine installations can be divided into two groups: icing detectors and icing condition detectors. A brief description of the two principles involved, with reference to typical detectors belonging to these two categories, follows.

6.2 Icing Detectors

An icing detector indicates any icing which actually takes place at its particular location. A sensing element is exposed to the airstream, i.e. to icing. Ice formation on it is recognized by the detector system and relayed to the anti-icing control.

A typical detector which demonstrates this kind is the Rosemount probe (Fig. 17 and Refs. 6 and 7). A rod, exposed to airstream, is excited to a particular frequency. As small amounts of ice buildup on its leading side, the frequency is changed, which initiates two actions. A signal is given to the anti-icing system control of the engine, and the probe itself is de-iced, preparing it for a new cycle. The engine anti-icing system is kept active until icing of the detector has ceased for a specific time interval.

The advantage of this type of detector is that the anti-icing system is activated only when actual icing at the location of the probe takes place. It is obvious that judicious positioning of the probe is important, and more than one probe may be required. In order to cover Condensate Icing, the probe has to be placed well inside the engine inlet, near the components to be protected. Some people consider the close proximity to the compressor a disadvantage. The fact that this type of detector will not indicate the presence of snow is not a shortcoming, because it is advisable to keep inlet components cold in snow. It should be noted that a certain minimum air velocity is required for this ice detector to function.

6.3 Icing Condition Detectors

The icing condition detector senses an atmospheric condition which potentially could cause Condensate Icing in the engine intake. Condensate Icing depends, primarily, on ambient temperature, relative humidity, and the static temperature depression in the inlet, which is a function of the local Mach Number (see Section 2.2). A potential Condensate Icing condition causes the sending of a signal to the anti-icing control.

Representative for this group is the Holley ice condition detector (Fig. 18 and Ref. 8). The detector head, which is, typically, mounted on the bulkhead wall adjacent to the bellmouth, senses temperature and relative humidity. The measured quantities are compared with reference values by an electronic logic circuit. If the measured temperature is below that of the selected reference temperature, e.g. 41°F, and the relative humidity above the reference one, e.g. 85 percent, the anti-icing system will be activated. In a strict sense, this kind of detector is designed to protect the intake components only against Condensate Icing. In actual fact, however, it probably covers most Precipitate Icing situations as well. The temperature cut-off level is unquestionable high enough, and Precipitate Icing conditions are usually accompanied by high relative humidities. Unfortunately, this is also the case in most snow conditions, which means that the anti-icing system will be triggered when it would be safer to have it inactive.

In most ground installations, a manual control permits station personnel to override the detector control in a positive sense, i.e. to switch the anti-icing system on even though the detector does not demand it. Personnel are known to have taken advantage of this provision when they suspected the detector or when they felt that atmospheric conditions warranted extended periods of protection.

7.0 Design Considerations and Operational Aspects

7.1 Assessment of Required Protection

In designing a stationary gas turbine installation for icing protection, certain criteria should be considered. A thorough study of the meteorological conditions during winter months at the proposed site is strongly recommended. Nearby meteorological stations should be able to supply that information. Of importance are patterns of:

(a) precipitation, i.e. freezing rain, non-freezing rain at low temperatures, hail, and snow;

(b) temperature;

(c) humidity;

(d) wind strength and direction;

(e) the duration of certain weather conditions;

(f) ground-level ice crystal and icing clouds (at high altitude stations);

(g) fog and freezing fog; and

(h) hoarfrost.

Combinations of two or more of the above elements may lead to specific problems. For example, freshly fallen snow, low temperatures, and a strong wind across open land may result in blowing snow, an icing hazard discussed above.

Icing problems vary drastically from location to location. It was found, for instance, that hoarfrost represented a serious problem at one installation, while it was only a mild one at an adjacent site. Even within one site, neighbouring units may be affected differently by a certain icing element. In one case, because of the particular layout of the site and the prevailing winds, blowing snow frequently blocked the inertial filters of one unit, but those of an identical unit alongside it were unaffected.

Given certain meteorological conditions, the degree of icing protection depends to a large extent on the installation's characteristics and design features. If intake air filtration is required because of dust and sand conditions during the non-icing seasons, then free air passage through the filters must be assured in wintertime. With respect to the engine itself, industrial-type engines, as was pointed out above, require only the crudest form of ice protection, while that for aero-derived types has to be fairly sophisticated.

In brief, the level of ice protection for a stationary gas turbine installation depends on meteorological conditions prevailing in that area and on the engine's tolerance to icing and ice ingestion.

7.2 Symptoms of Icing and Incipient Trouble

It is of great importance that icing, in any of its various forms, be detected as early as possible for protective measures to be taken. Icing and icing condition detectors (see Section 6.0) are widely used to activate anti-icing and de-icing systems. These detectors may also transmit a warning signal to the crew, alerting it to the icing situation. Ice formation of significant size on rotating components can sometimes be monitored through vibration instrumentation. Uneven shedding of accretions could show up in the form of increased vibration levels.

To guard against excessive depression, plenum chambers are, usually, equipped with static pressure taps. At a selected pressure differential, e.g. 2.5 inches WG, an alarm signal is given to the station personnel. Depending on engine tolerance and operating policy, a blow-in door may be opened automatically, either simultaneously with the alarm signal or at a somewhat greater depression. Hoarfrost has been known to cause serious plenum chamber depression by extensive buildup in the inertial separator passages or on the preceding debris screen. Manual brushing and scraping usually clears the filter passages and/or the screen mesh.

Once the station personnel is alerted to an icing condition, periodic inspection of the plenum chamber is often ordered. To facilitate this inspection, good lighting and properly situated windows are a necessity.

7.3 Identification of Icing Damage

If damage has been caused by icing, it is important to identify it as such, if only to take the necessary remedial steps. In the majority of cases, one observes compressor rotor blade damage, accompanied, perhaps, by lesser damage to adjacent stator blades.

In a case of high-speed impact damage it is not always easy to come to a definite conclusion as to the kind of object which was ingested. Generally, it can be said, however, that ice and slush will cause smooth deformations, as can be seen in Figure 19. These fan blades, which were damaged by ice, are not too different from typical first stage compressor blades. Solid foreign objects, like rivets, stones, nuts, etc., will leave ragged tears. Further, damage from solid, hard objects will usually extend through more than one compressor stage, while ice is smashed by the initial rotating stage.

However, identification of engine damage is largely a matter of experience since every ingestion is a unique occurrence, and cannot be easily classified.

8.0 Concluding Remarks

Icing problems at stationary gas turbine installations arise from the peculiar interaction of certain meteorological conditions and deficiencies in intake protection. Since no two atmospheric conditions are exactly alike, icing encounters often do not form a unique pattern, even at a given location, which would facilitate the provision of a universal icing protection system. For this reason, improvements in the defence against icing problems have hitherto, more often than not, been on an ad hoc basis, undertaken at individual installations.

Nevertheless, recurring basic icing elements have been analysed, the resulting icing problems have been demonstrated, and some general guidelines for improvement of the intake protective systems have been delineated. Specifically, solutions have been proposed for the hoarfrost blockage of inertial filter passages and debris screens, for the glaze ice formation inside the plenum chamber caused by water leakage from the outside, and for the formation of ice inside the engine air intake. The principles of available anti-icing and de-icing systems, together with icing and icing condition detectors, were discussed in some detail.

For future installations, the designer of the air intake system is advised to pay special heed to the icing environment of the area, and to incorporate all necessary protection against the winter elements in his initial design. A careful approach to potential icing problems should minimize surprises during operation, considerably reduce the extent of on-site improvements to be undertaken, and decrease unscheduled downtime with ensuing loss in production.

9.0 References

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8.	Ciemochowski, M.F.	Ice Detector System Detects Frost and Ice Conditions on Stationary Gas Turbine Inlet Surfaces, SAE National Combined Farm Construction and Industrial Machinery, Powerplant, and Transportation Meeting, Milwaukee, Wisc., 9-12 Sept. 1968, SAE 680558.

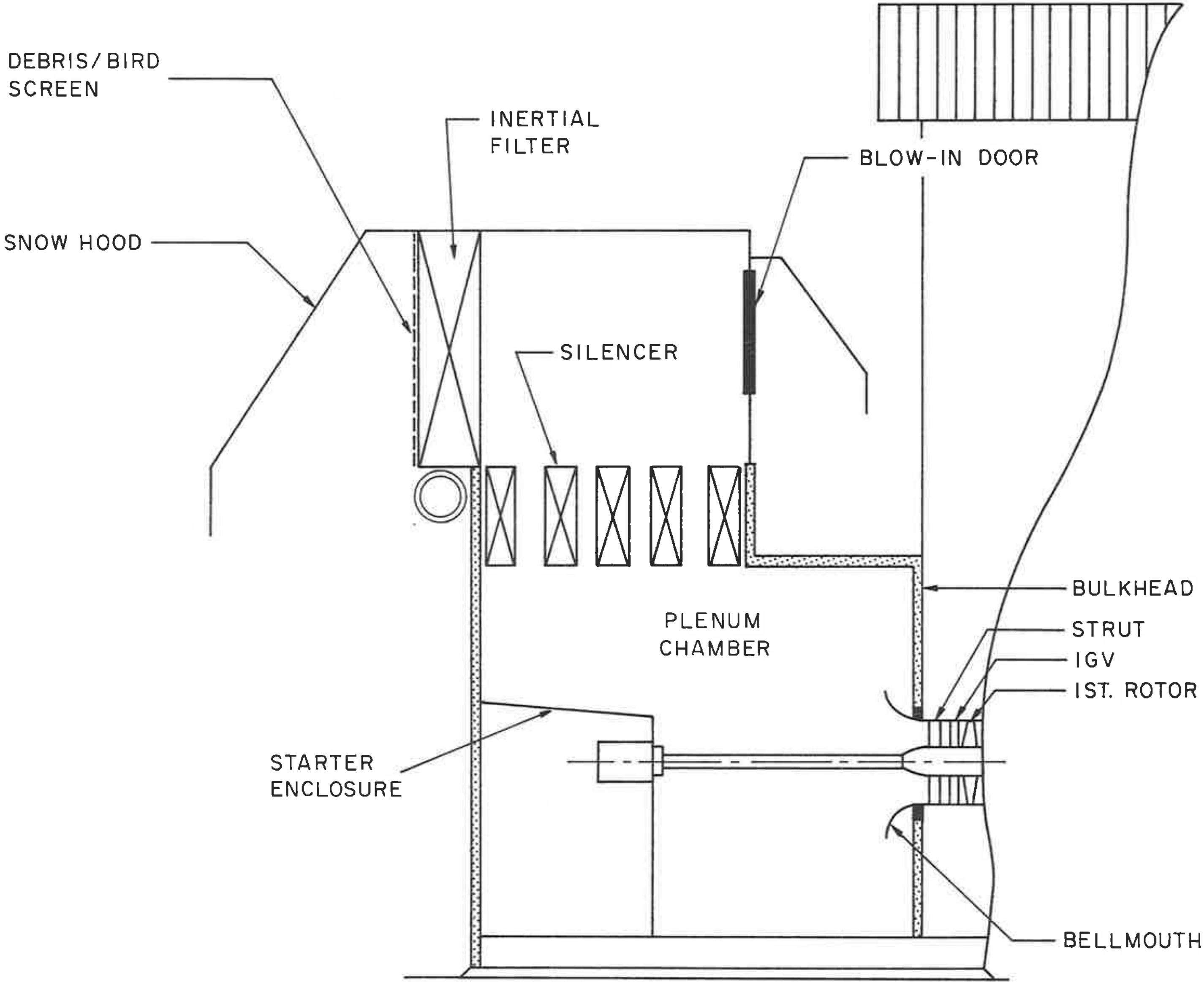


FIG.1 : TYPICAL STATIONARY GAS TURBINE INTAKE SYSTEM

FIG. 2 : STRATIFORM CLOUDS

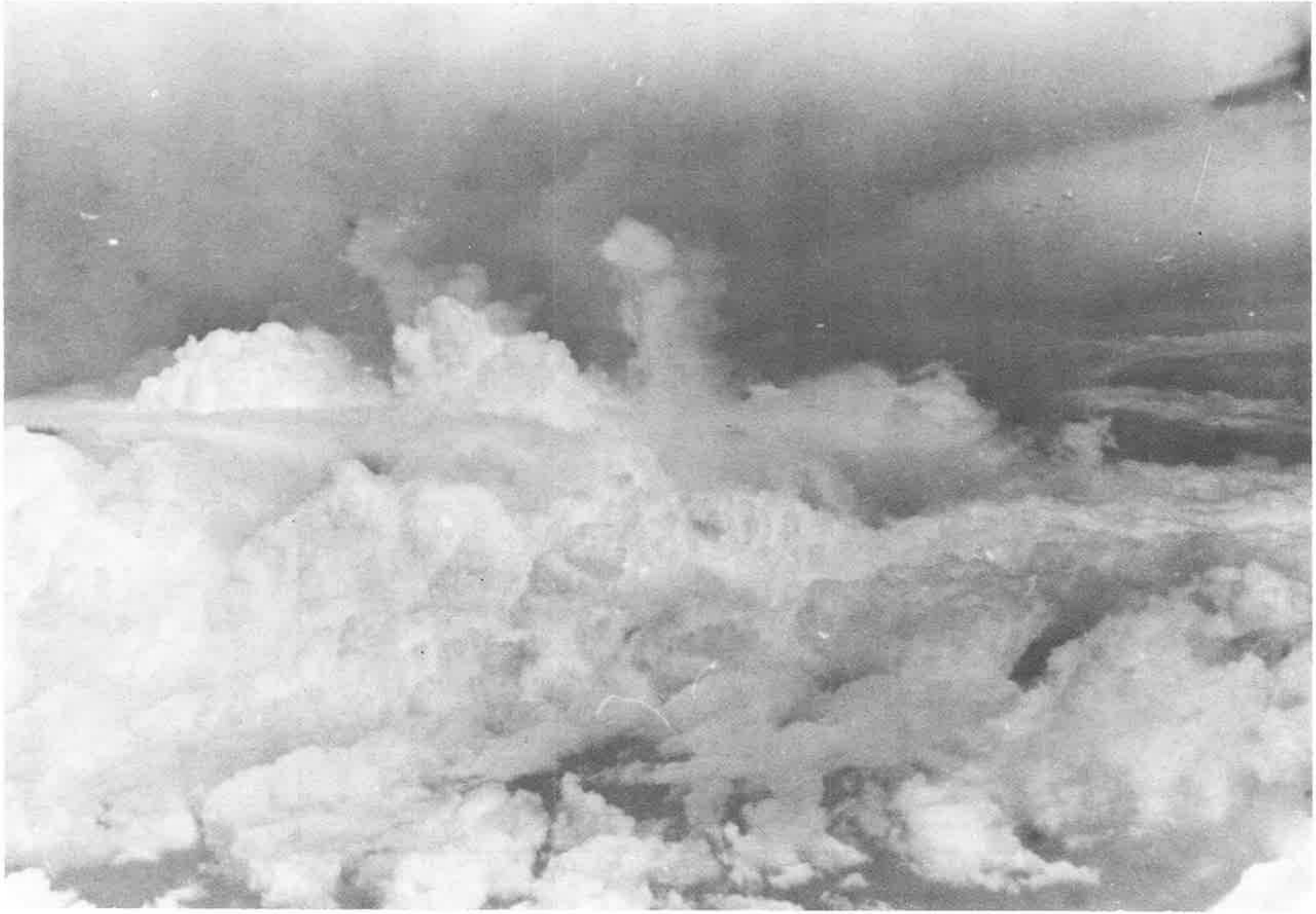
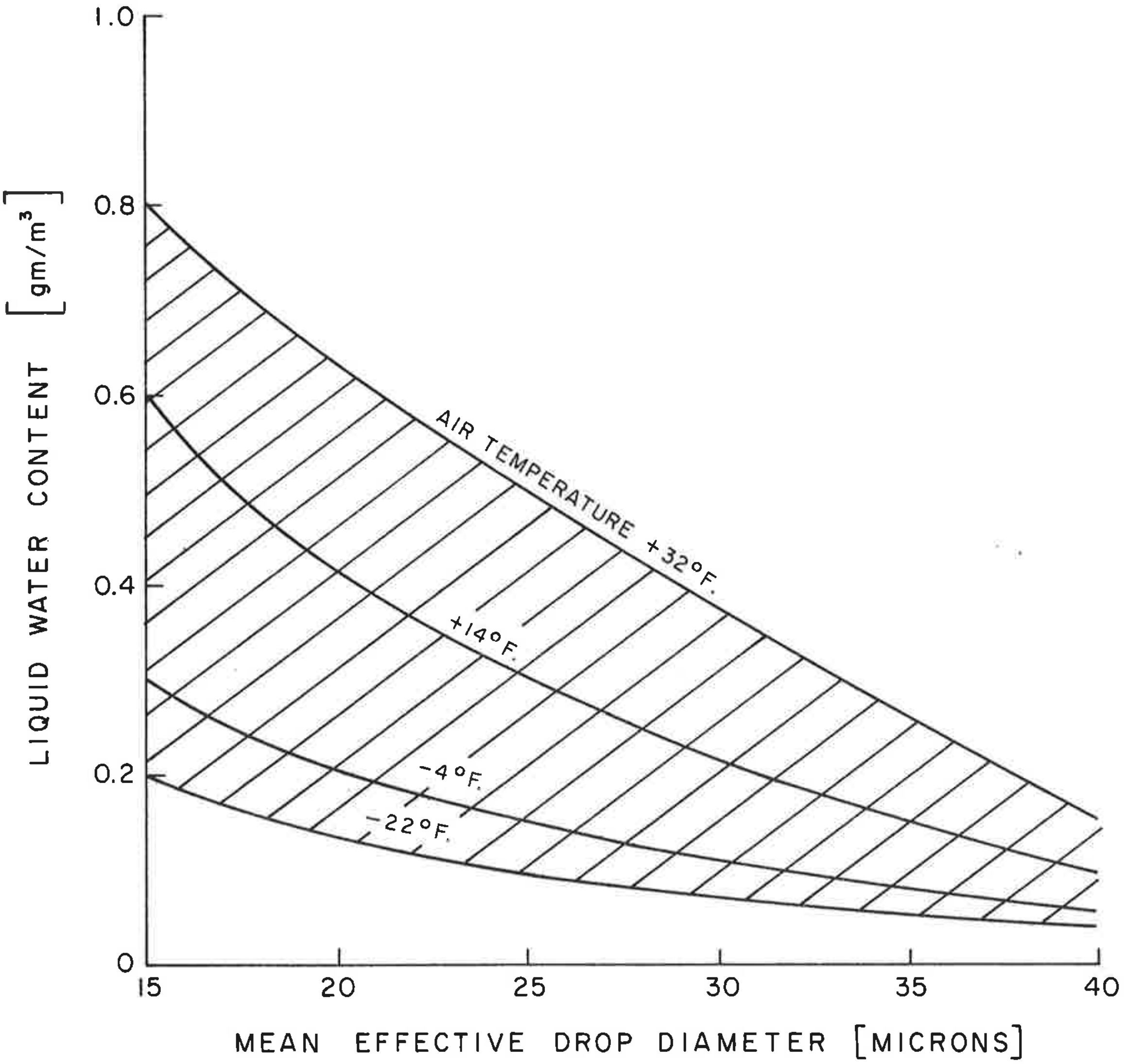


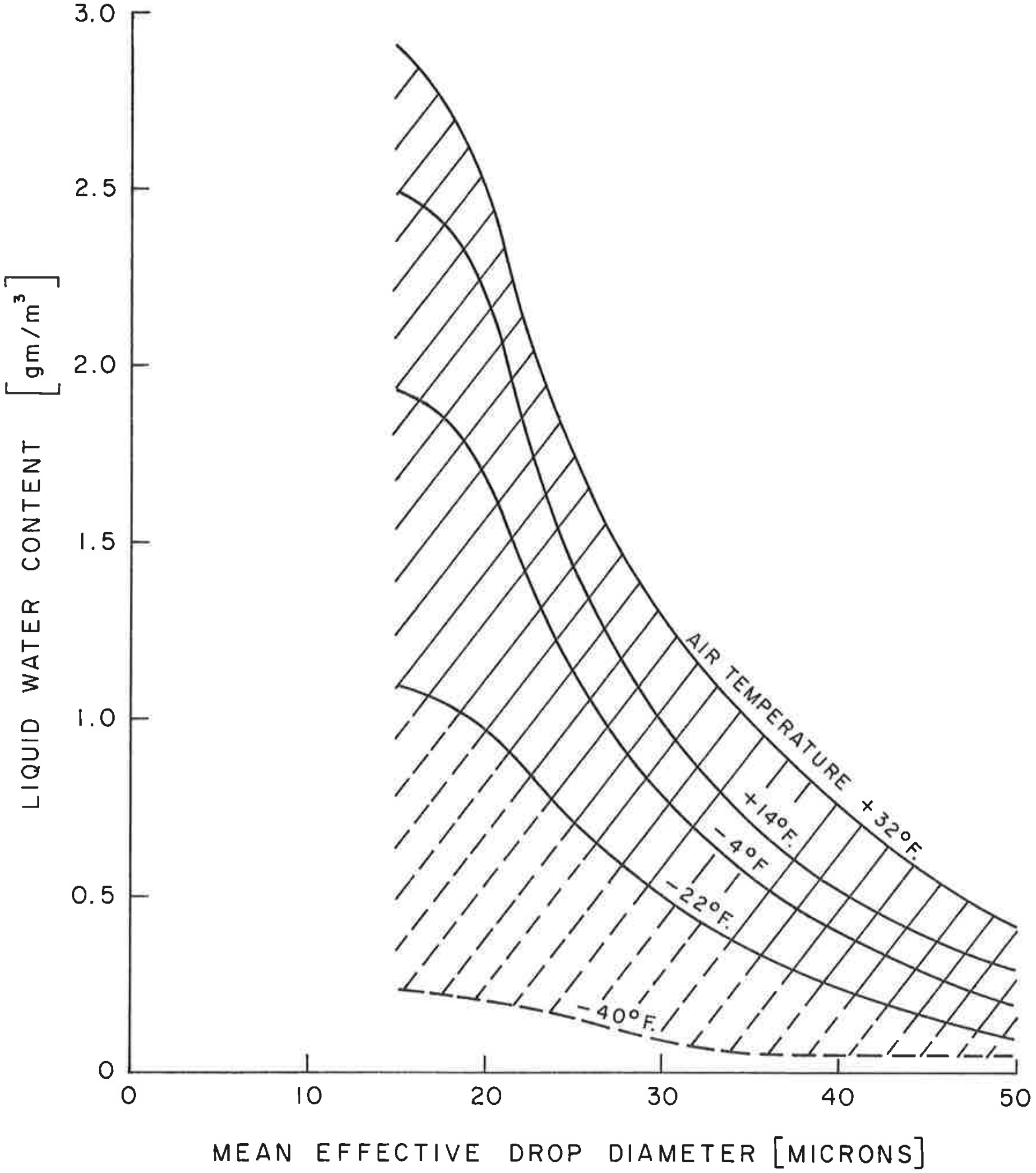
FIG. 3 : CUMULIFORM CLOUDS



PRESSURE ALTITUDE RANGE, S.L. TO 22,000 FT.
MAXIMUM VERTICAL EXTENT 6,500 FT.
HORIZONTAL EXTENT, STANDARD DISTANCE OF 20 MI.

SOURCE: NACA TN 1855
CLASS III-M CONTINUOUS MAXIMUM

FIG. 4a: CONTINUOUS MAXIMUM ATMOSPHERIC ICING CONDITIONS STRATIFORM CLOUDS



PRESSURE ALTITUDE RANGE
4,000 TO 22,000 FT.

HORIZONTAL EXTENT, STANDARD
DISTANCE OF 3 MI.

SOURCE OF DATA:
NACA TN 1855

NOTE: DASHED LINES INDICATE
POSSIBLE EXTENT OF LIMITS

FIG. 4b: INTERMITTENT MAXIMUM ATMOSPHERIC ICING CONDITIONS
CUMULIFORM CLOUDS

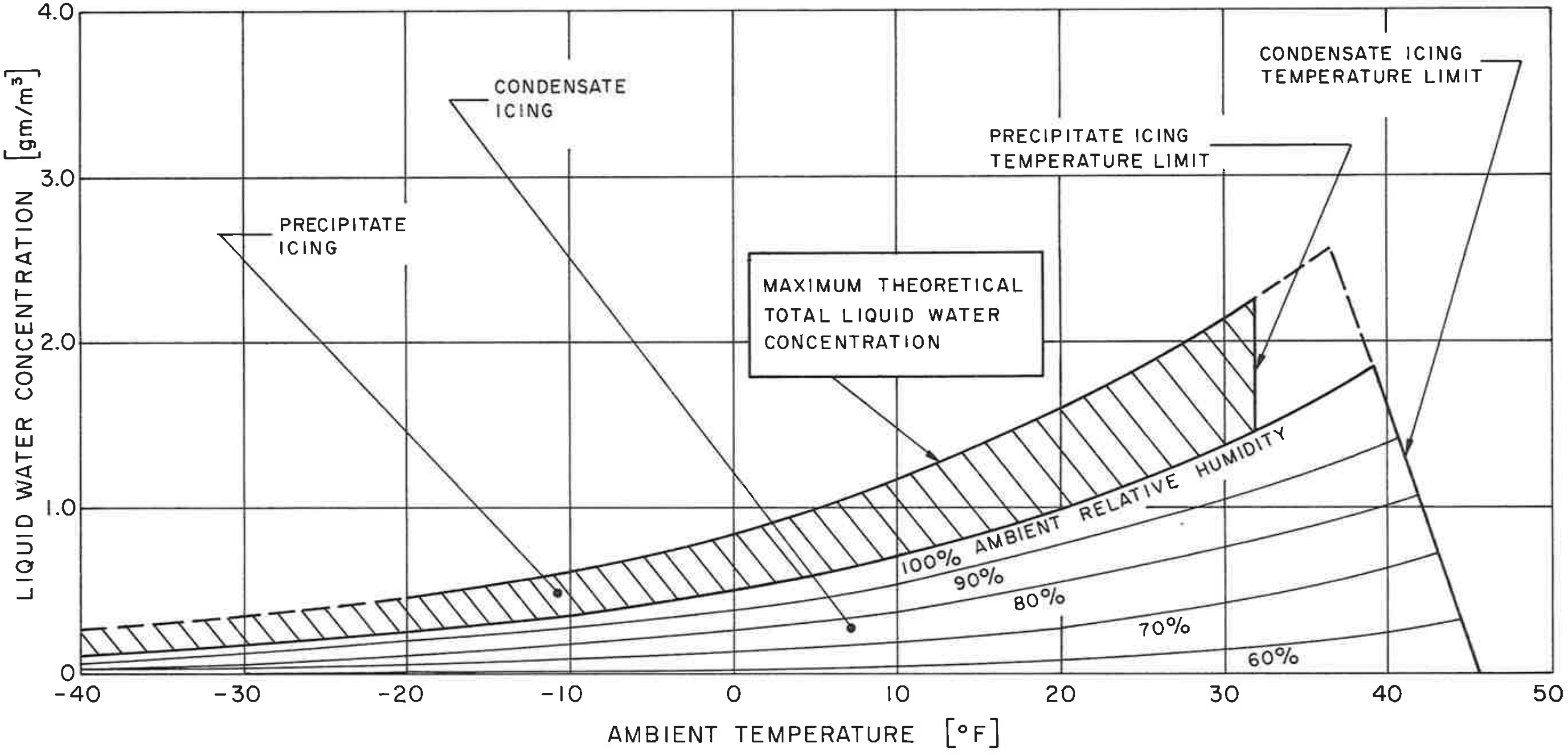


FIG.5 : MAXIMUM THEORETICAL LIQUID WATER CONCENTRATION

INLET MACH NO. = 0.37

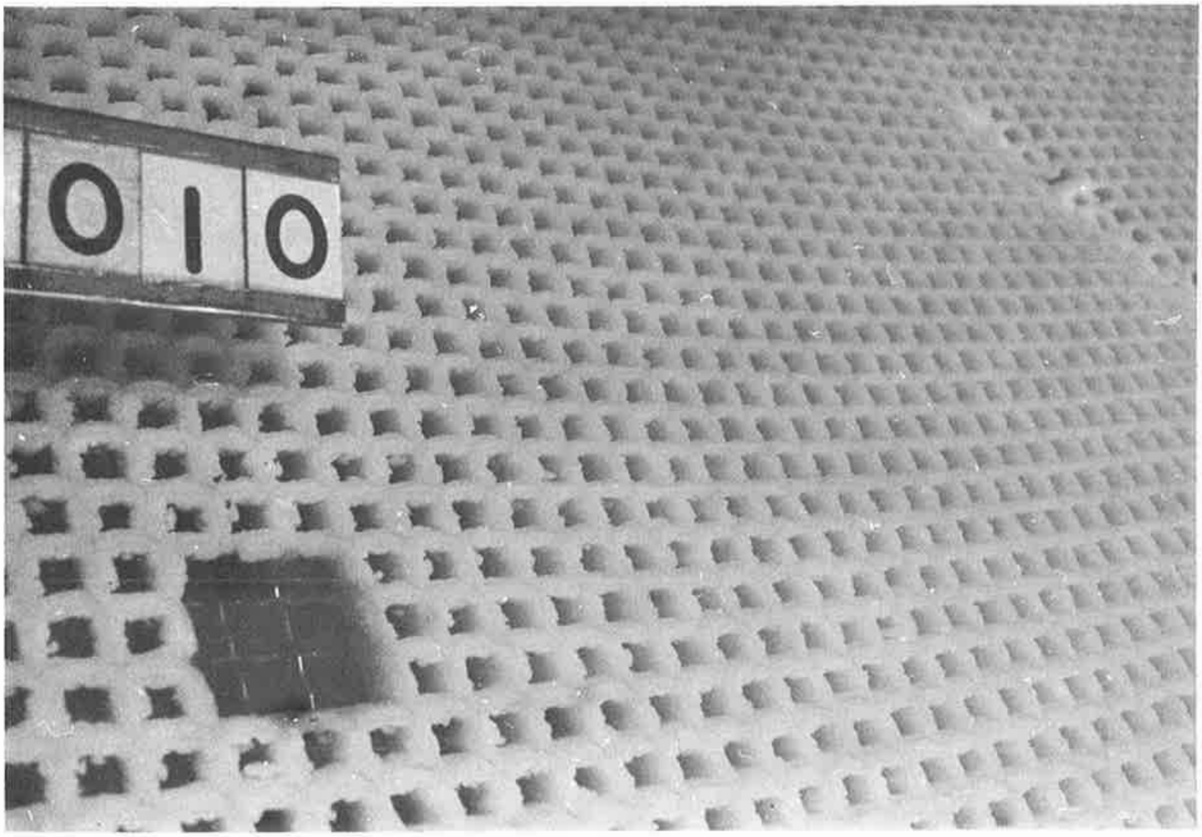
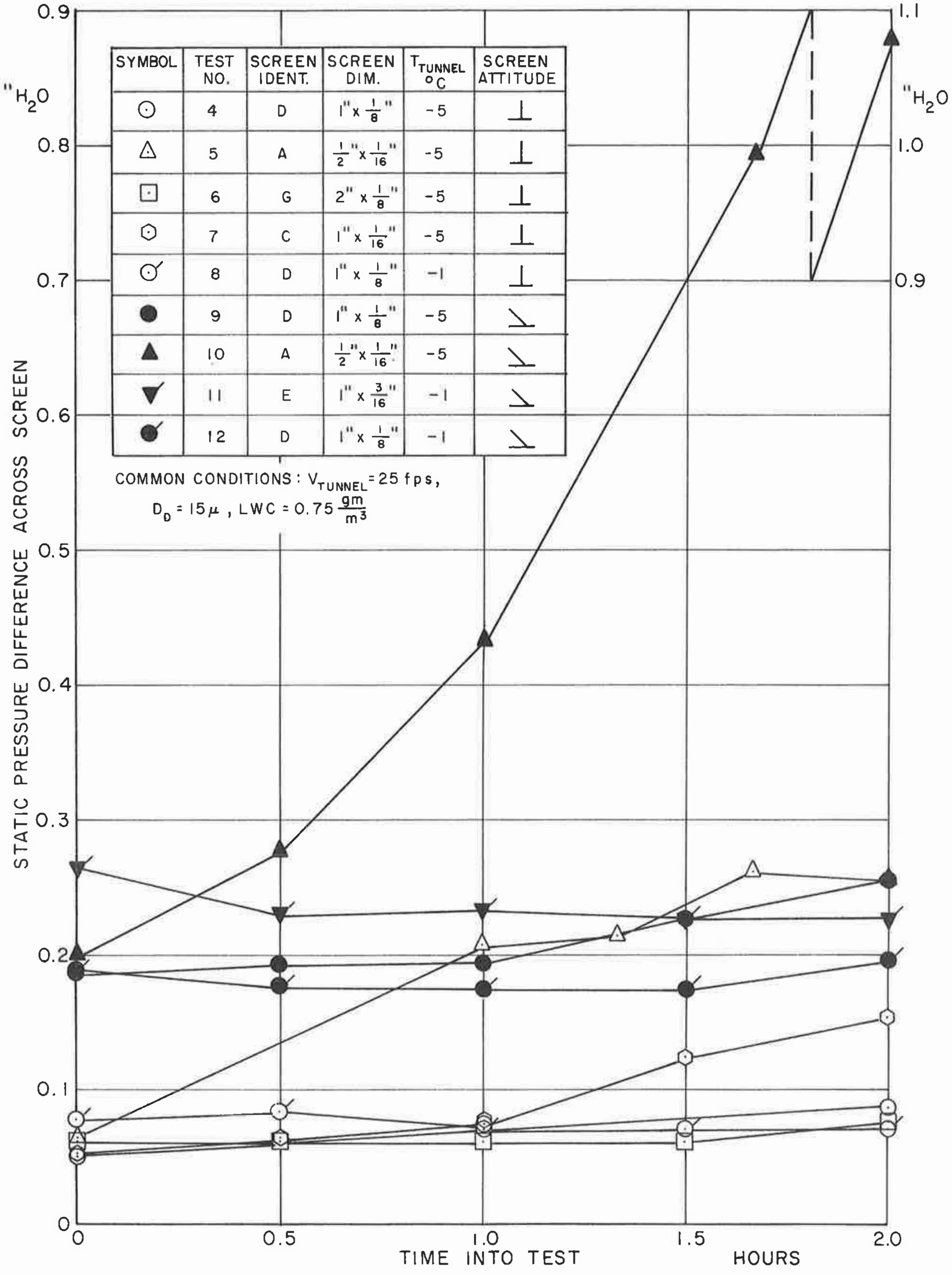


FIG. 6: HEAVY RIME ICE BUILD-UP ON INCLINED 1/2-INCH SCREEN AFTER 2 HOURS OF TESTING



SYMBOL	TEST NO.	SCREEN IDENT.	SCREEN DIM.	T_{TUNNEL} °C	SCREEN ATTITUDE
⊙	4	D	$1'' \times \frac{1}{8}''$	-5	⊥
△	5	A	$\frac{1}{2}'' \times \frac{1}{16}''$	-5	⊥
⊡	6	G	$2'' \times \frac{1}{8}''$	-5	⊥
⬡	7	C	$1'' \times \frac{1}{16}''$	-5	⊥
⊙	8	D	$1'' \times \frac{1}{8}''$	-1	⊥
●	9	D	$1'' \times \frac{1}{8}''$	-5	∠
▲	10	A	$\frac{1}{2}'' \times \frac{1}{16}''$	-5	∠
▼	11	E	$1'' \times \frac{3}{16}''$	-1	∠
●	12	D	$1'' \times \frac{1}{8}''$	-1	∠

COMMON CONDITIONS : $V_{TUNNEL} = 25$ fps, $D_D = 15\mu$, LWC = $0.75 \frac{gm}{m^3}$

FIG. 7 : STATIC PRESSURE DIFFERENCE ACROSS SCREEN vs TIME INTO TEST

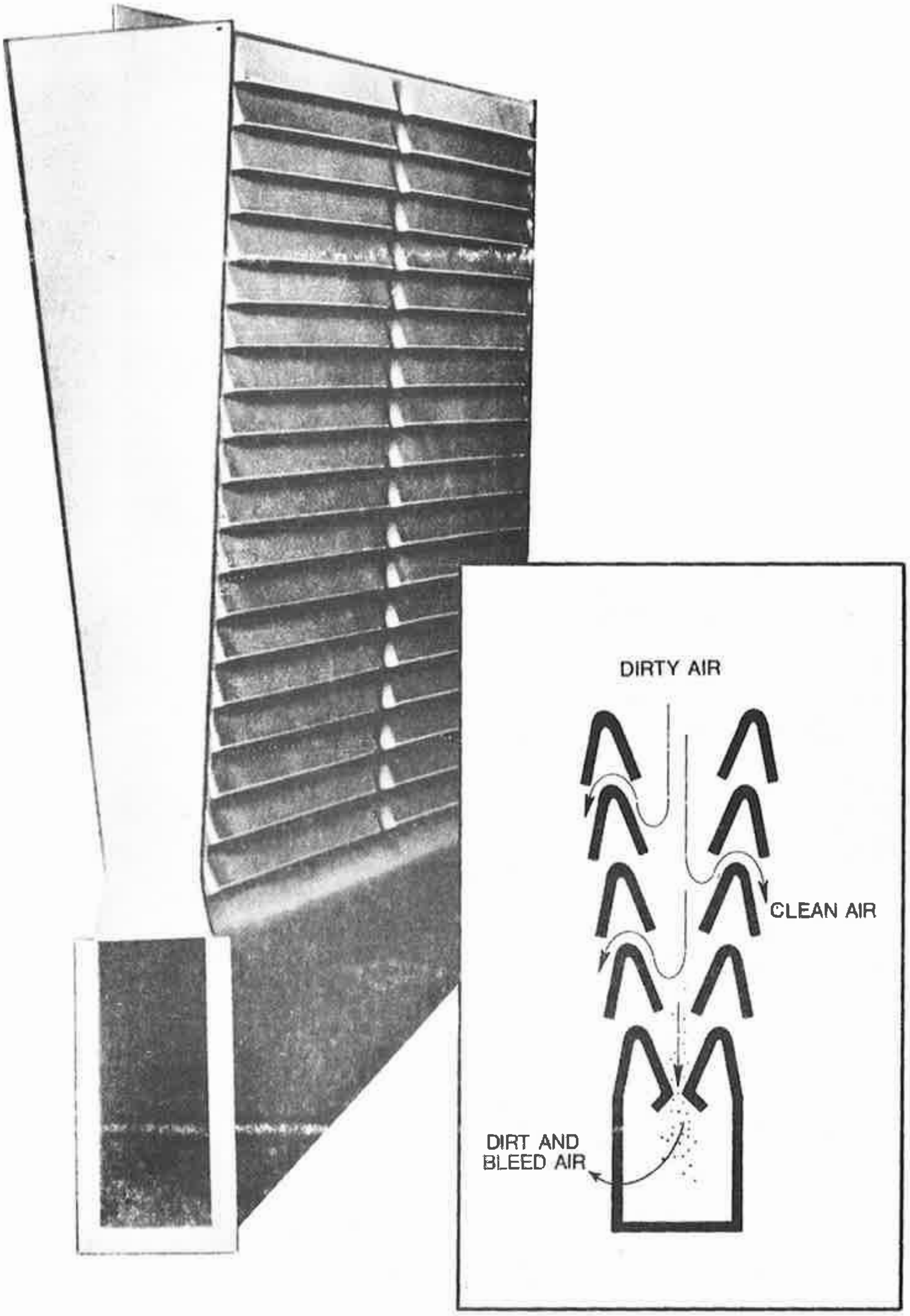
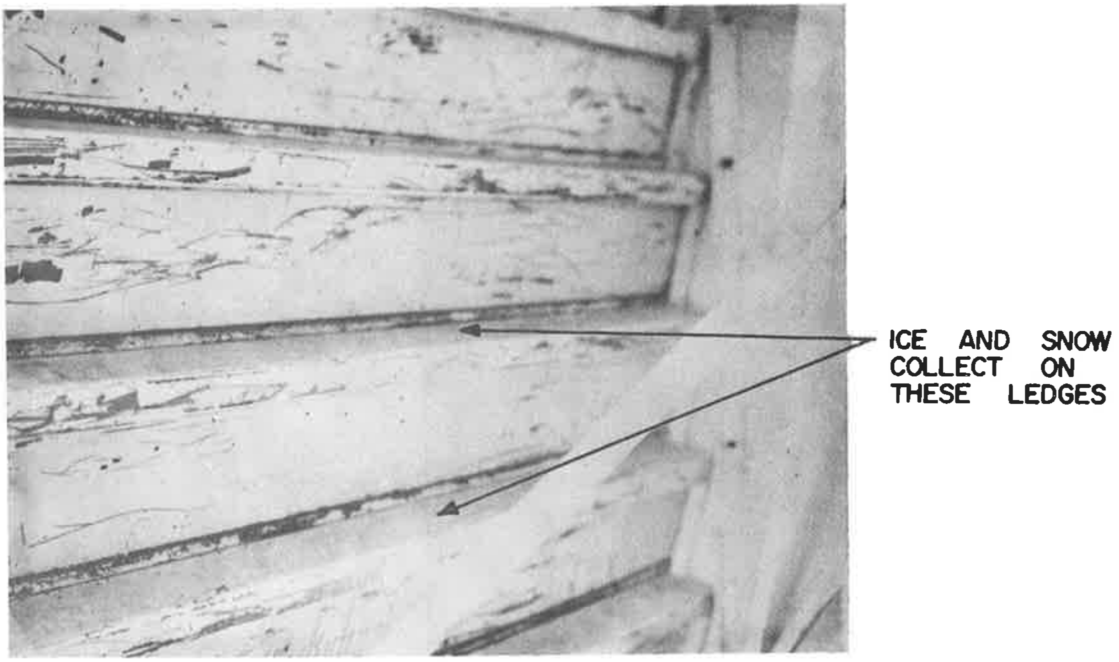
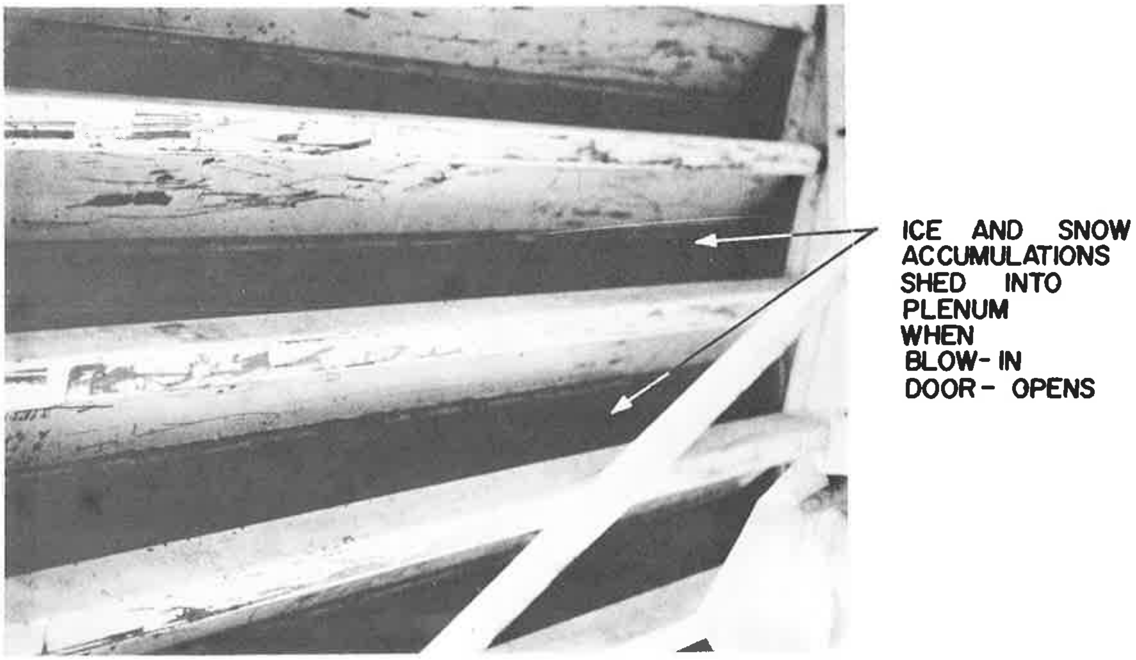


FIG. 8: SINGLE CELL DYNAVANE INERTIAL SEPARATOR



(a) LOUVRES CLOSED



(b) LOUVRES OPEN

FIG. 9: BLOW - IN DOOR
POOR DESIGN

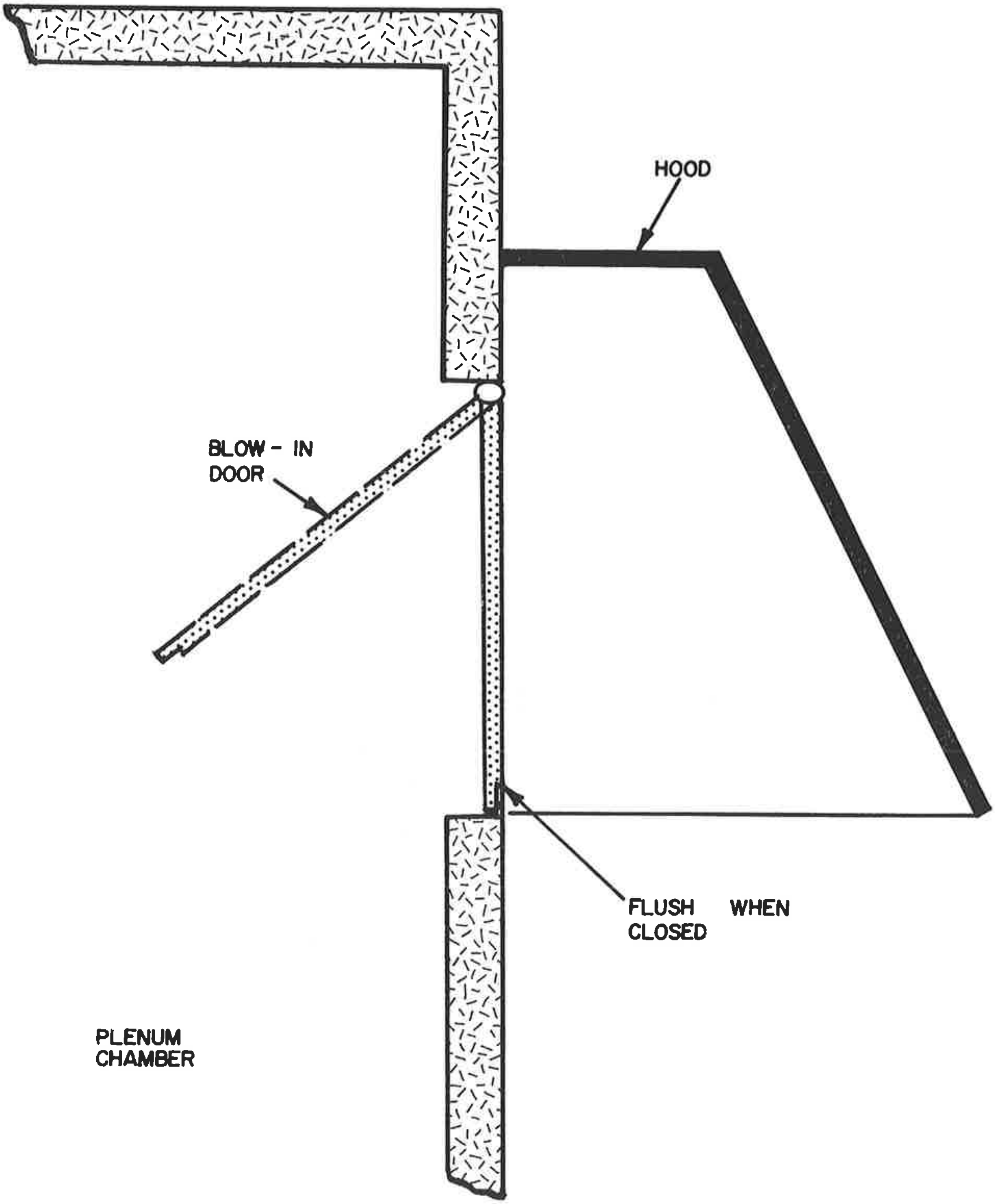


FIG. 10: BLOW — IN DOOR
SATISFACTORY DESIGN

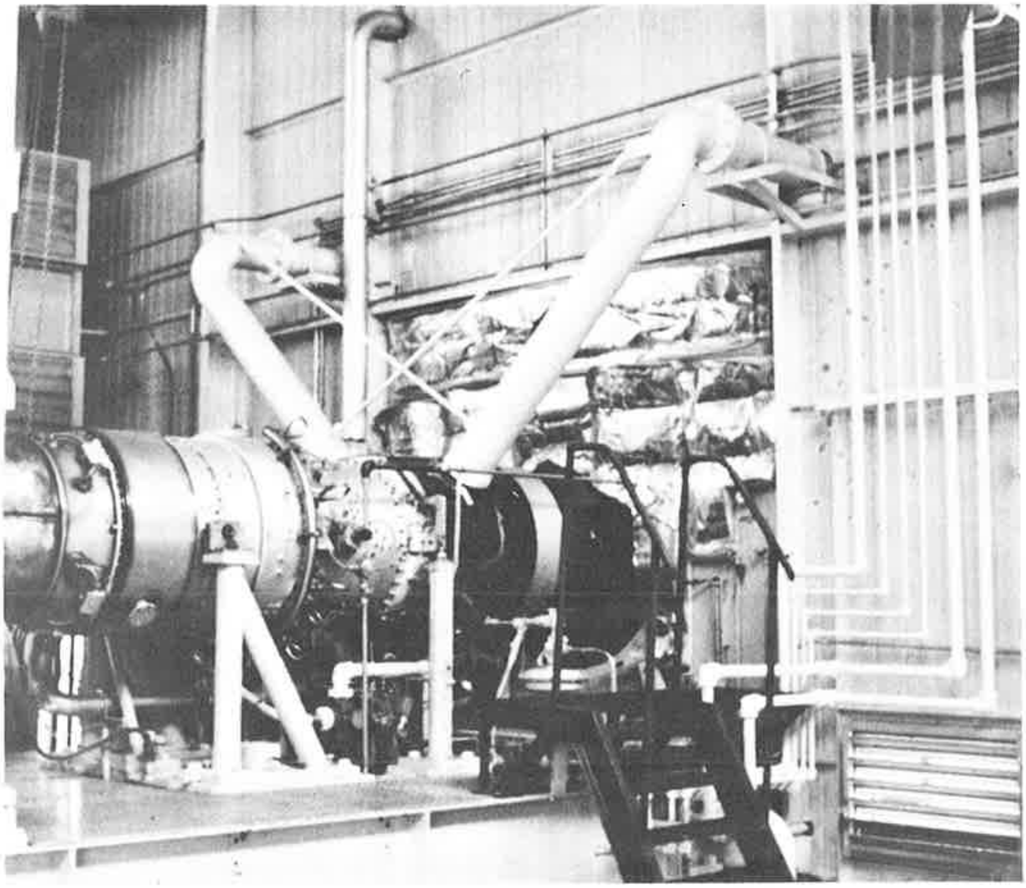


FIG.11 : INSULATION ON BULKHEAD WALL, APPLIED ON COMPRESSOR HOUSE SIDE.

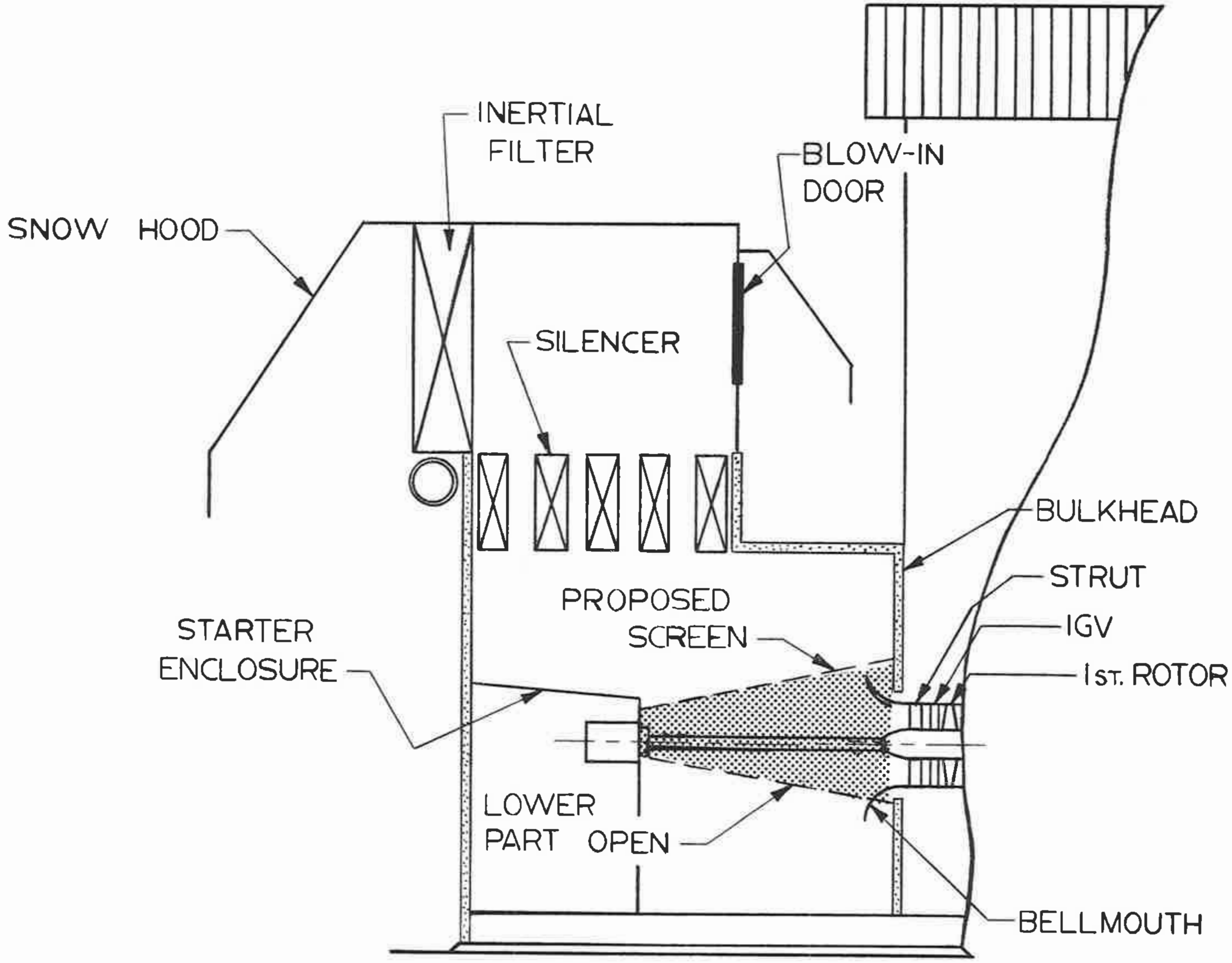
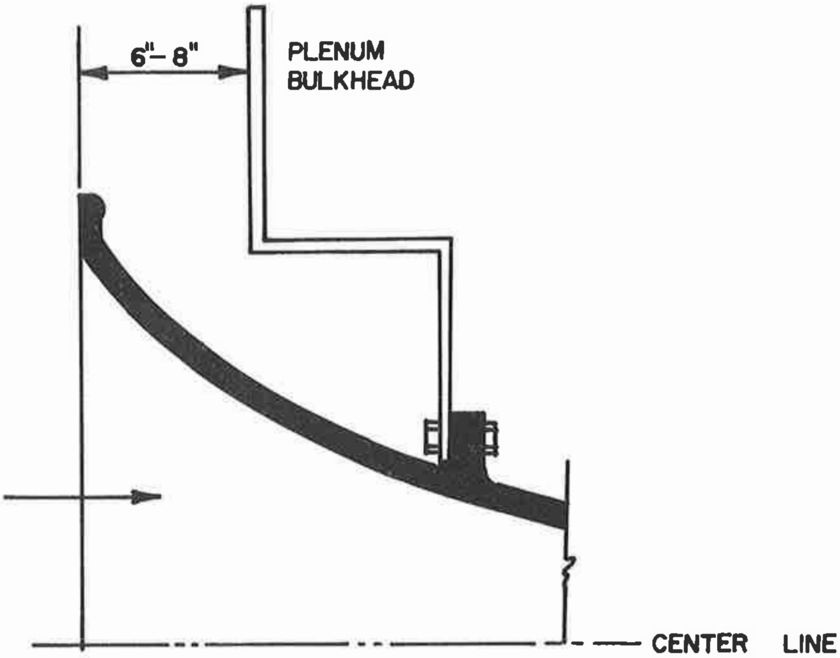
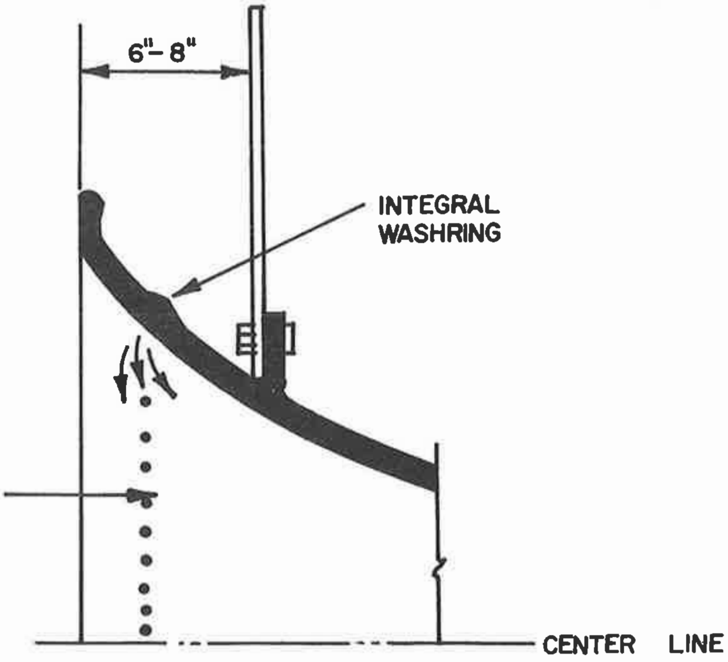


FIG.12: INTAKE SYSTEM WITH INGESTION PROTECTION SCREEN

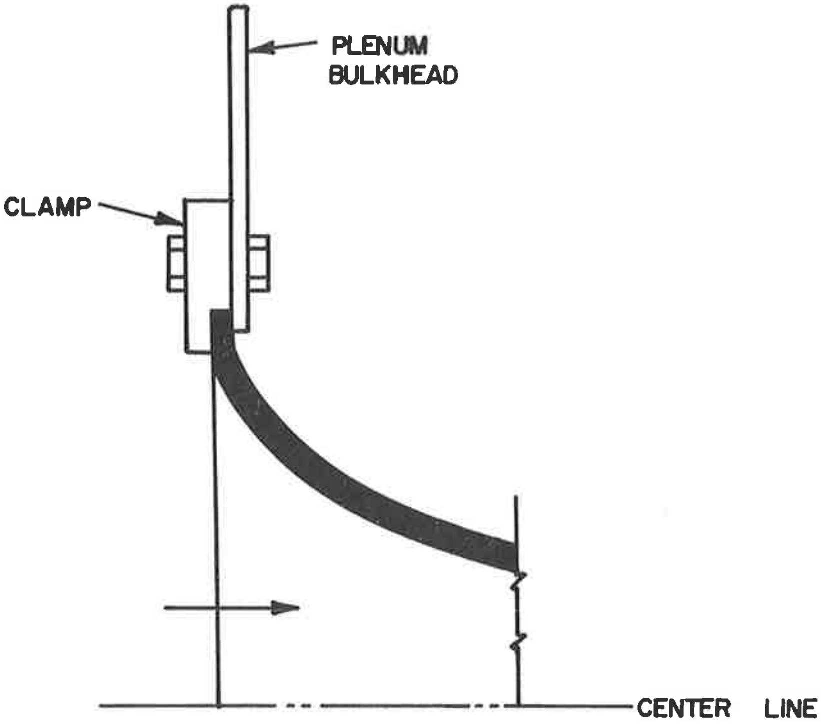


(a) EXTENDED BELLMOUTH WITH RECESS

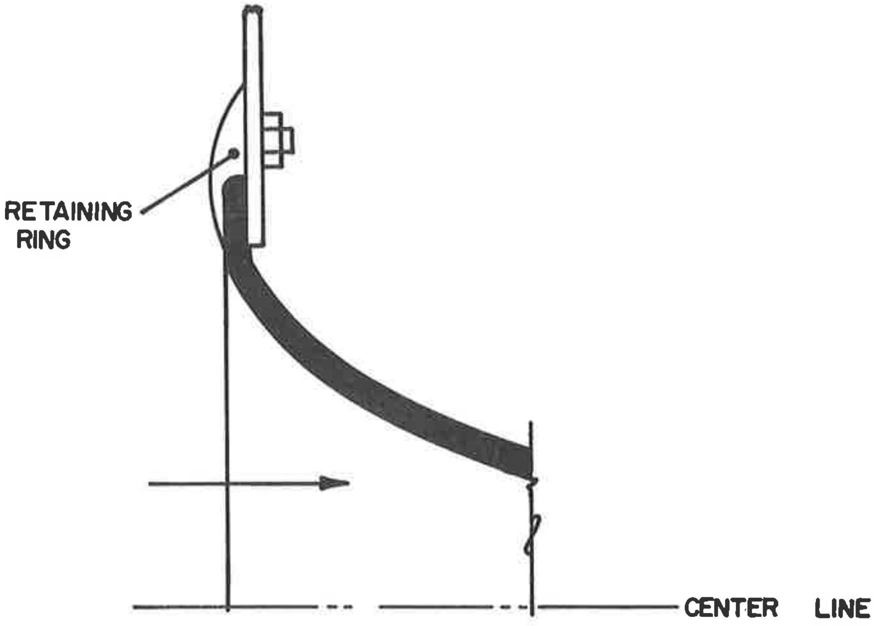


(b) EXTENDED BELLMOUTH

FIG. 13: TYPES OF BELLMOUTH MOUNTINGS



(c) FLUSH MOUNTED WITH CLAMPS



(d) FLUSH MOUNTED WITH RETAINING RINGS

FIG. 13 : TYPES OF BELLMOUTH MOUNTINGS

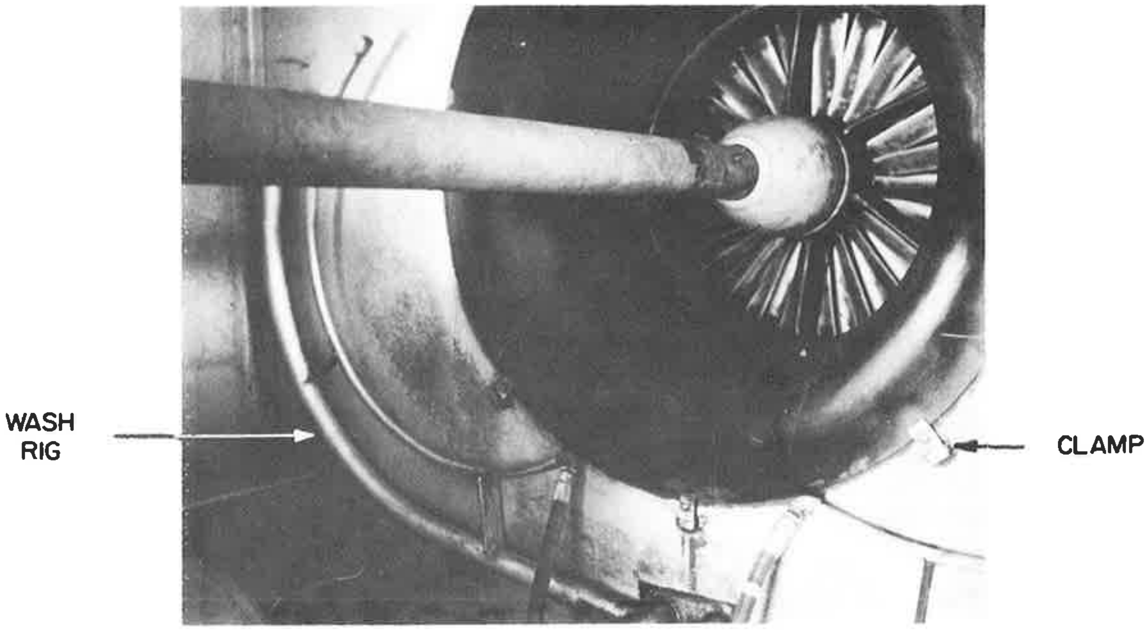
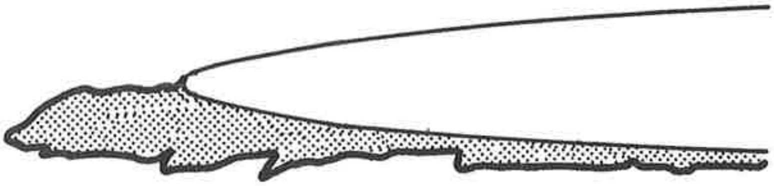
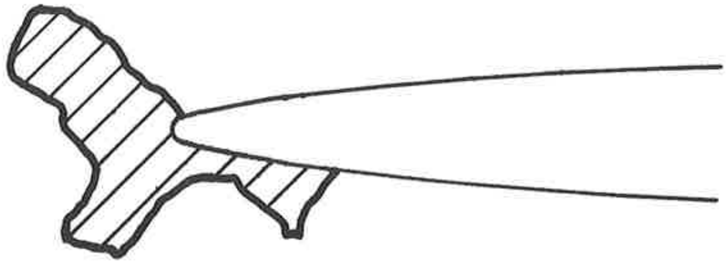


FIG. 14: FLUSH MOUNTED BELLMOUTH HELD BY CLAMPS



(a) RIME ICE



(b) GLAZE ICE

FIG. 15: TYPICAL ICE FORMATIONS ON AN AIRFOIL-SHAPED MEMBER

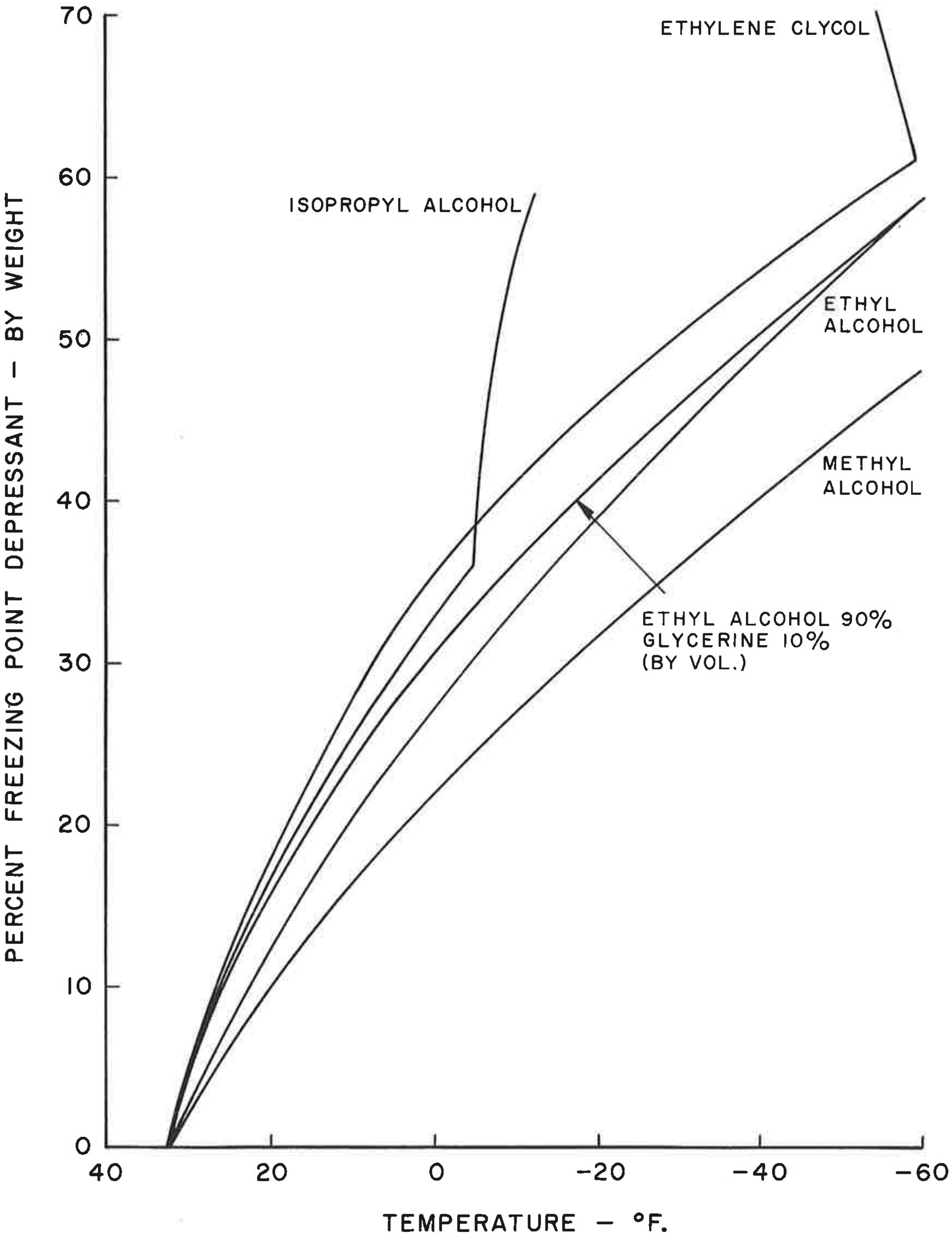


FIG. 16:

FREEZING POINT PLOTS FOR AQUEOUS SOLUTIONS OF SEVERAL FREEZING POINT DEPRESSANT FLUIDS

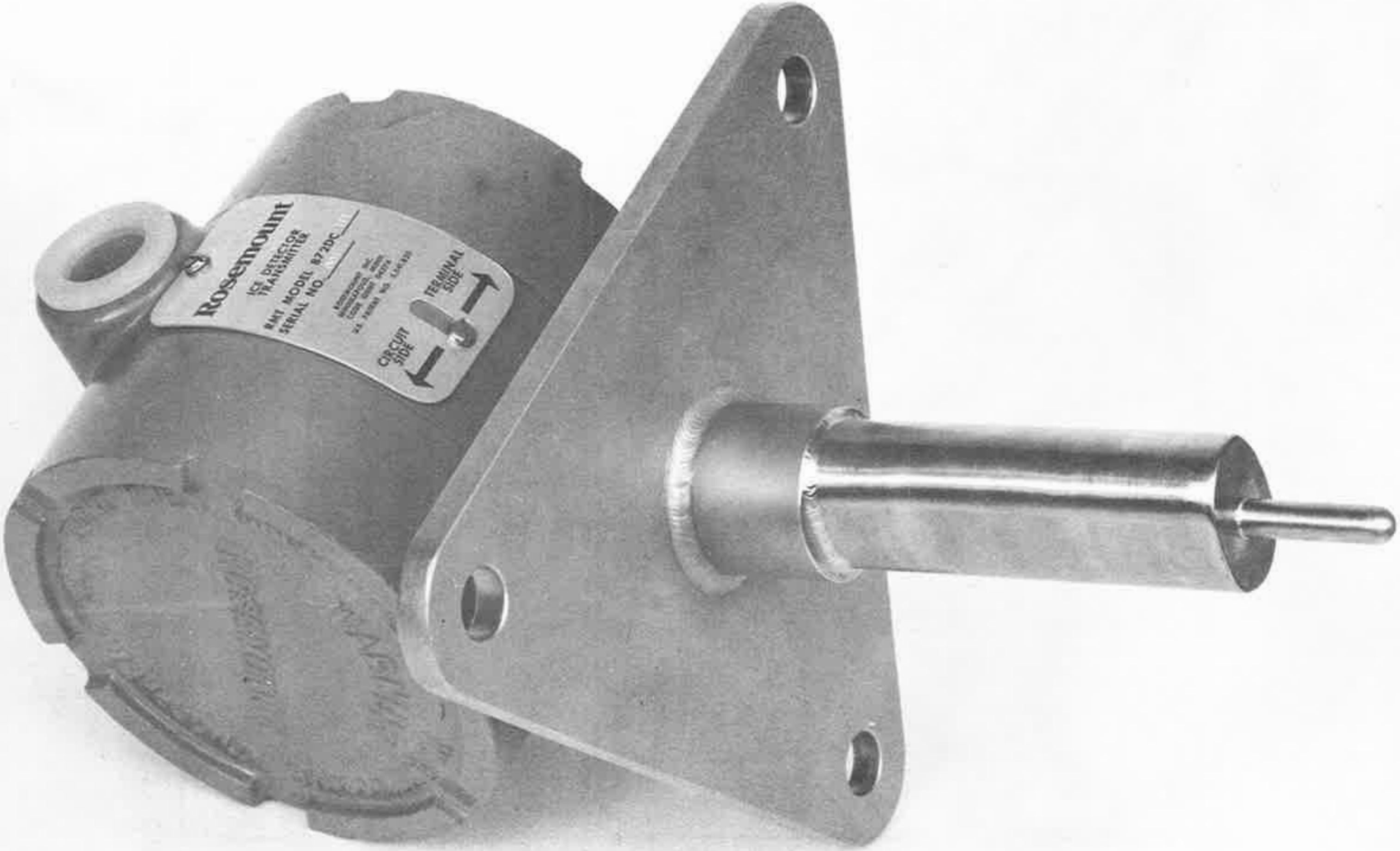


FIG. 17 : ICE DECTECTOR

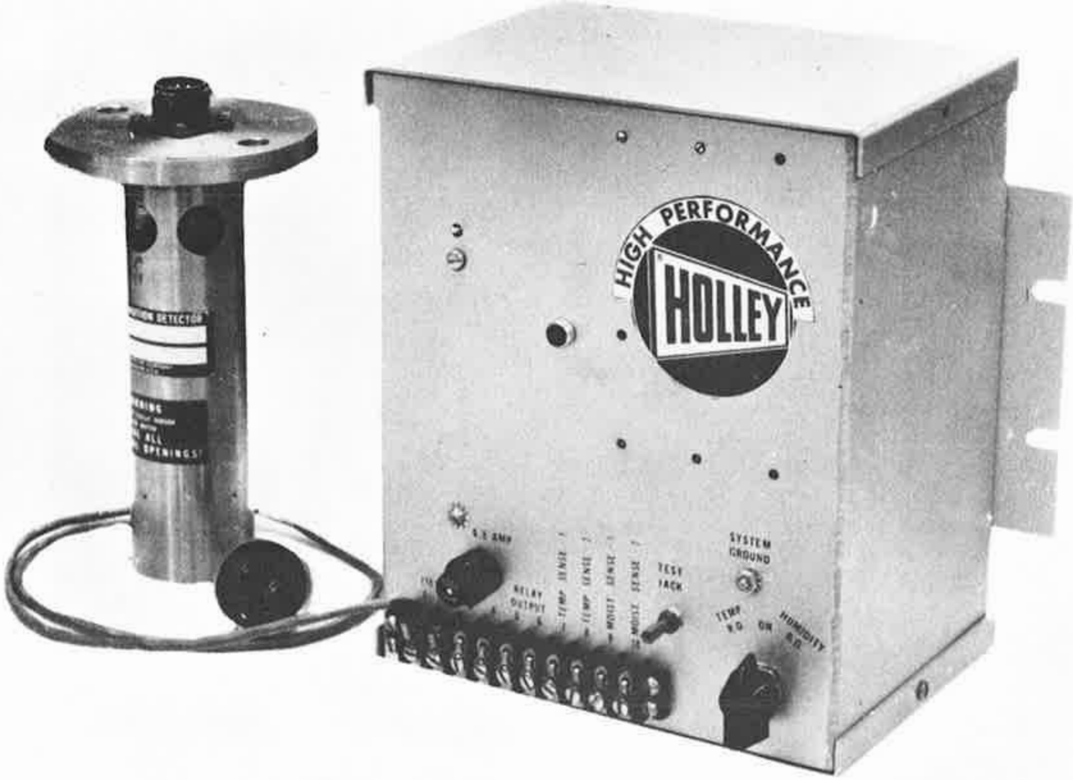


FIG. 18 : ICE CONDITION DETECTOR
SENSING HEAD AND INSTRUMENT BOX

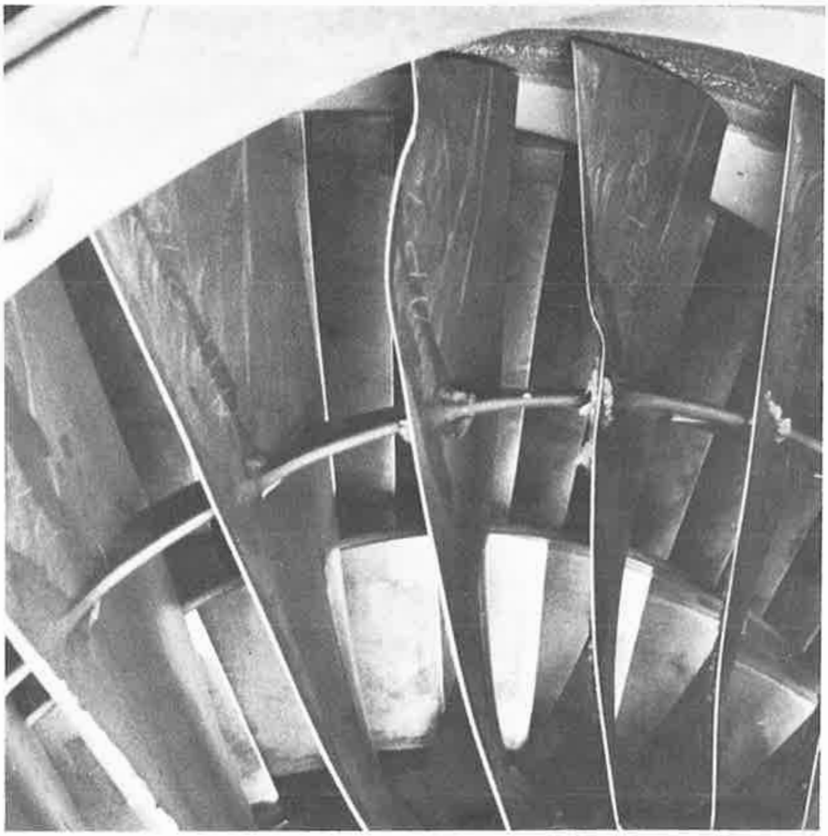


FIG. 19: BLADE DAMAGE FROM ICE INGESTION

APPENDIX A

Determination of Condensate Icing Region

and

Calculation of Condensate Icing Concentrations

The severity of Condensate Icing conditions within the region shown on the sketch depends on the following parameters:

(a) Engine Inlet Mach Number

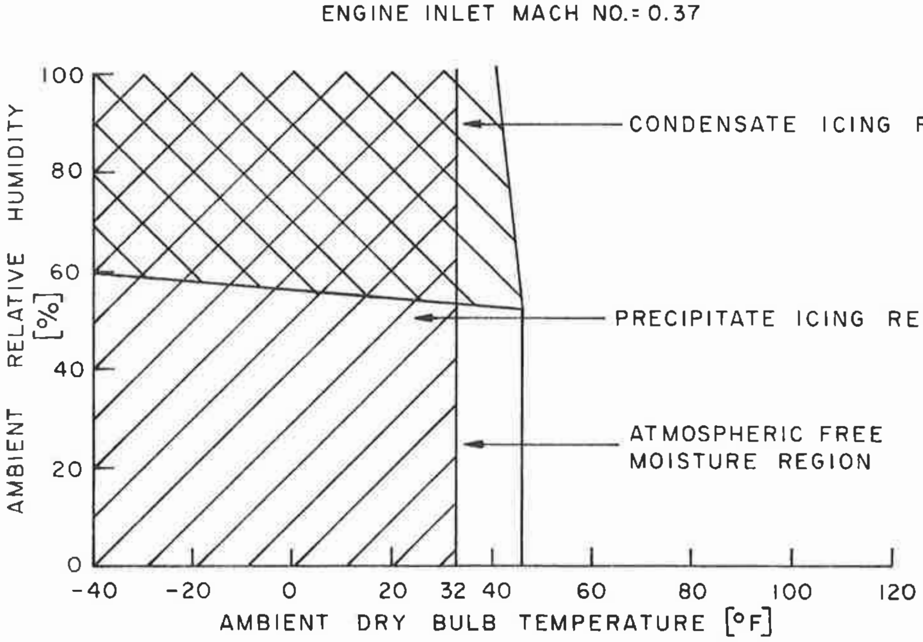
The higher the engine inlet Mach Number, the greater the static temperature depression and hence the more condensate will form within any given inlet airstream.

(b) Ambient Relative Humidity

Clearly, ambient air closer to saturation will produce more condensate for a given static temperature depression than will drier ambient air.

(c) Ambient Temperature

Because the saturation water content of air is non-linearly temperature dependent, more condensate will form from warm air than from cold air for given initial relative humidity and specified static temperature depression.



This section presents the equations required to compute the condensate concentration resulting from acceleration of a specified stream of moist air to a given Mach Number. Equilibrium conditions are assumed to pertain throughout.

In the calculation procedure outlined below, the actual condensation process has been replaced by two consecutive sub-processes, viz. 'overcondensation' and 're-evaporation'. The first sub-process assumes the static temperature drops to the dry air value, resulting in greater condensation than actually forms. The second sub-process corrects this initial estimate by allowing the latent heat of evaporation to raise the static temperature and thus re-evaporate some of the condensate. These two sub-processes are computed iteratively to converge on the true static temperature and condensate concentration at the end point of the actual process.

The independent variables required as inputs to the iterative calculation routine are:

	the inlet Mach number	(M)	[-]
	the ambient total temperature	(T)	[°F]
and	the ambient relative humidity	(RH)	[%]

1. Assuming initially that no condensate forms, the static temperature is given by:

$$t_{dry}[^\circ F] = \frac{T + 460}{1 + \left(\frac{\gamma-1}{2}\right)M^2} - 460 \qquad (1)$$

where $\gamma = 1.40$*

t_{dry} is used as the initial estimate for the converged value of static temperature with condensation.

$$t = t_{dry}$$

2. The absolute humidity can be obtained for given values of T & RH from tables such as in Reference 2. For convenience in computer evaluation, saturation humidity values from Table 7 of Reference 2 were approximated by:

$$SH = e^{(.043636T-7.002236)} \left[\frac{lb_{H_2O}}{lb_{dry\ air}}\right] \qquad (2)$$

as shown in Figure A-1.

---

*It can be demonstrated that, even for saturated air at the highest temperature of interest in these calculations, the water vapour in the air makes no significant change in the ratio of specific heats (γ) from the dry air value.

Thus the ambient humidity can be evaluated directly from:

$$H_{amb} = \frac{RH}{100}\left\{e^{(.043636T-7.002236)}\right\}\left[\frac{lb_{H_2O}}{lb_{dry\ air}}\right] \tag{2a}$$

and likewise the saturation humidity at the current estimate of static temperature

$$SH_t = e^{(.043636t-7.002236)}\left[\frac{lb_{H_2O}}{lb_{dry\ air}}\right] \tag{2b}$$

3. The difference between these two humidities represents the initial estimate of the specific condensate (i.e. the 'over-condensation').

$$COND = H_{amb} - SH_t\left[\frac{lb_{H_2O}}{lb_{dry\ air}}\right] \tag{3}$$

4. If this amount of condensate did condense, the temperature rise due to the latent heat of evaporation released would be:

$$\Delta t = \frac{h_{fg}}{C_{P_a}} \times COND = \frac{1065.4}{.24} \times COND$$

$$\text{i.e.}\quad \Delta t = 4439.2 \times COND\ [°F] \tag{4}$$

5. The accuracy of the initial estimate of static temperature can be checked by forming the difference:

$$DIFF = t_{dry} + \Delta t - t[°F] \tag{5}$$

If the absolute value of DIFF is greater than an arbitrary tolerance (say 0.1°F) a better estimate of t can be obtained by applying the difference to the previous estimate. Thus

$$t_{n+1} = t_n + DIFF\ [°F] \tag{6}$$

A new saturation humidity, appropriate to this revised estimate of static temperature, can be generated from Equation 2b. The calculation procedure is then repeated until satisfactory convergence has been obtained.

After the iterative process yields final values for t and COND, it remains only to convert the latter into the common icing concentration units of gm/m³.

The specific volume of the saturated mixture can be obtained from Table 1 of Reference 2. As previously in step 2, these data have been approximated for convenience by

$$v_{mix} = 11.6143 + .027143\ T \left[\frac{ft^3_{mix}}{lb_{\substack{dry\\air}}}\right] \tag{7}$$

as shown in Figure A-2.

Thus at the converged static temperature

$$v_{mix} = 11.6143 + .027143\ t \left[\frac{ft^3_{mix}}{lb_{\substack{dry\\air}}}\right] \tag{7a}$$

And finally the Condensate Icing concentration is given by:

$$CONC = \left(\frac{COND}{v_{mix}}\right) \left[\frac{lb_{H_2O}}{ft^3_{mix}}\right] \times 16018.5 \left[\frac{gm/m^3}{lb/ft^3}\right]$$

$$CONC = \frac{16018.5 \times COND}{v_{mix}}\ [gm/m^3] \tag{8}$$

A FORTRAN IV program was written to perform this calculation procedure for a specified interval and range of ambient temperatures at a given inlet Mach Number. It automatically decremented the ambient relative humidity in 5% steps until the minimum humidity boundary was reached at each temperature. Thus a grid of Condensate Icing concentration values was produced and these values were then cross plotted to yield the iso-concentration contours and the minimum humidity boundary shown on Figure A-3. The maximum temperature boundary was obtained by interpolating between the output values of static temperature adjacent to 32°F.

It must be remembered, however, that the data presented in Figure A-3 are theoretical maximum concentrations. Actual maximum concentrations are undoubtedly lower but quantitative differences in severity between the theoretical and actual Condensate Icing phenomena are extremely difficult to predict. It is believed that the theoretical severity may be as high as five times the actual severity, but even this figure is open to considerable doubt. Therefore, as in the case of Continuous Precipitate Icing, the theoretical values can only be used as a design guide and the inherent margin of safety must be kept in mind during the design of the protection system.

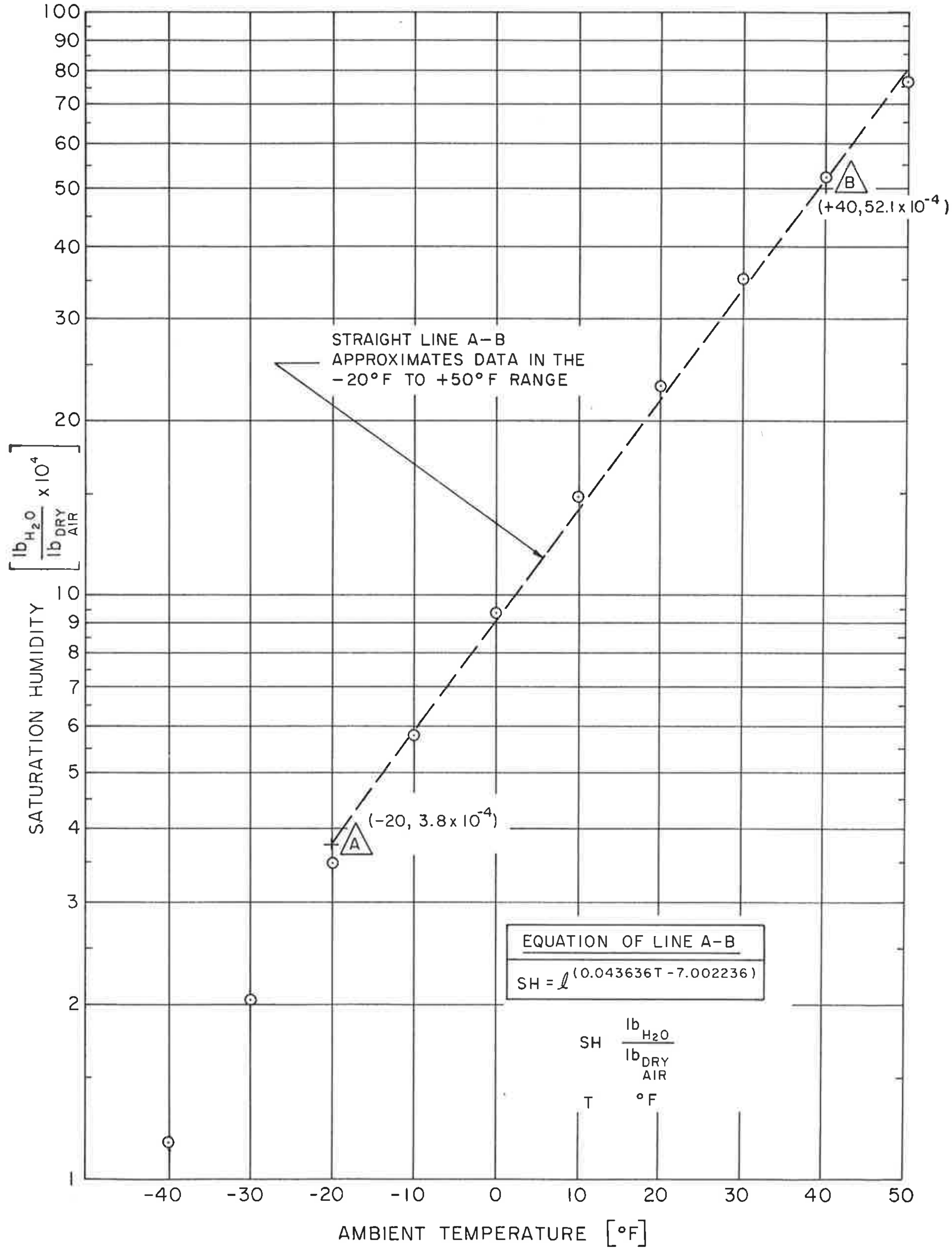


FIG. A1: SATURATION HUMIDITY vs TEMPERATURE IN THE ICING REGIME

REF. 2 TABLES 6 & 7

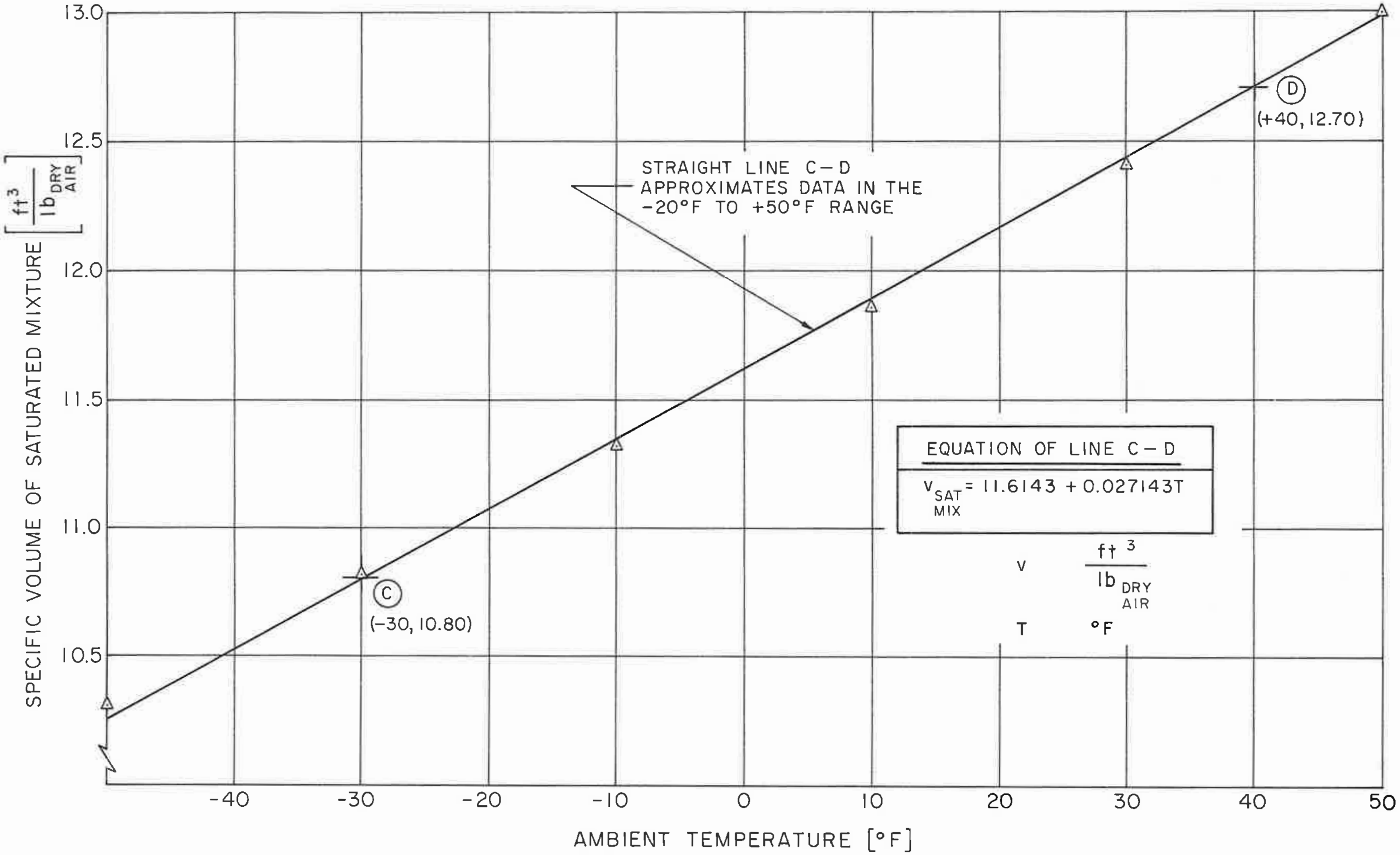


FIG.A2: SPECIFIC VOLUME OF SATURATED AIR vs AMBIENT TEMPERATURE IN THE ICING REGIME

REF. 2 TABLE I

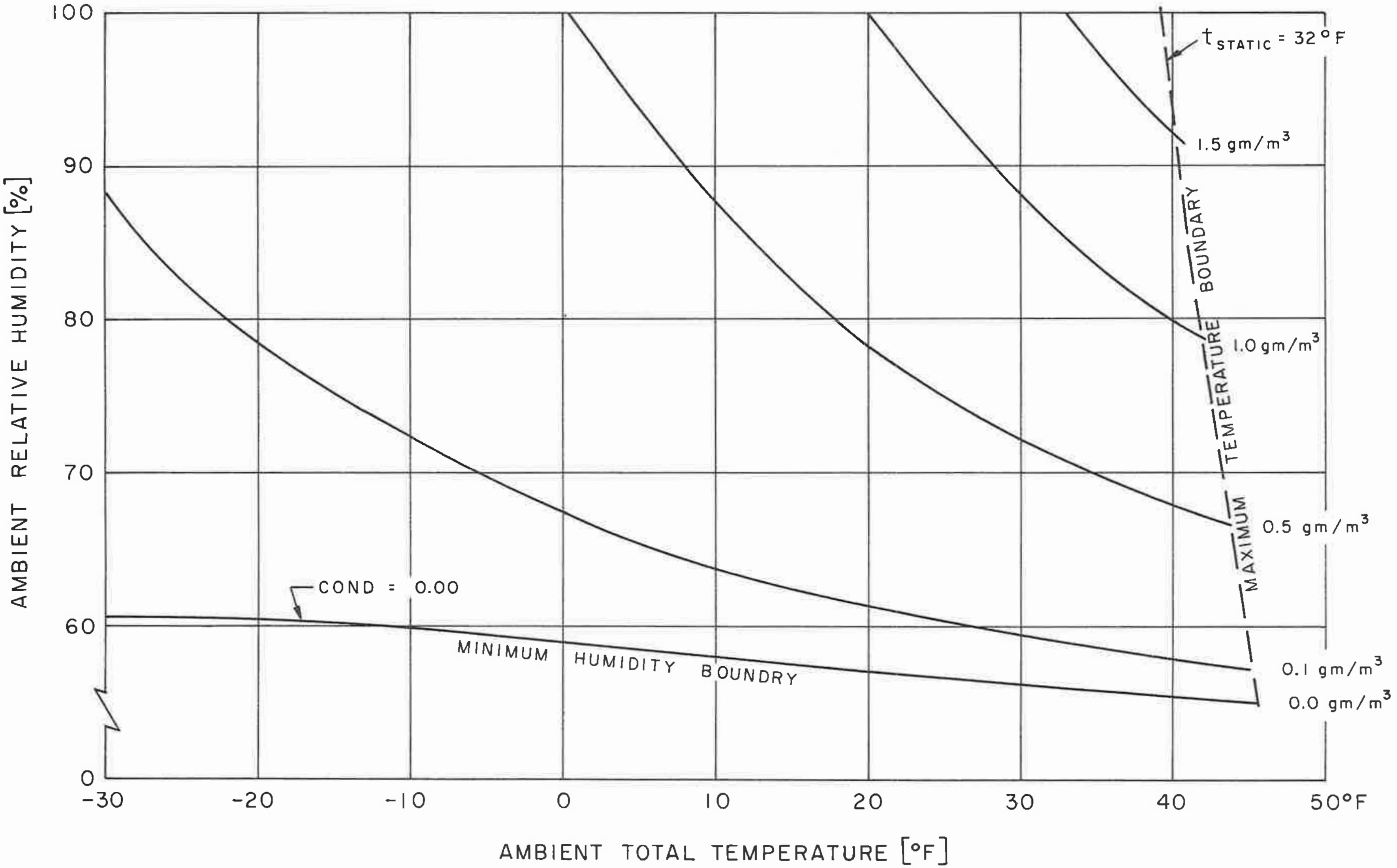


FIG. A3 : CONDENSATE ICING CONCENTRATIONS

(INLET MACH NO. = 0.37)