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Engine Laboratory

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Subject: THE DESIGN OF FLUID ANTI-ICING SYSTEMS

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SUMMARY

The method employed in determining fluid requirements for anti-icing is outlined and calculated results for gas turbine engines and for a typical wing are presented. Experimental results verifying the theory are given.

The practical application of fluid anti-icing is discussed with special reference to the gas turbine engine.

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LIST OF SYMBOLS

a	droplet radius - ft.
C_p	specific heat of air at constant pressure = 0.24 CHU/lb. °C.
C_f	skin friction coefficient
D	diffusivity of vapour - ft ² /sec.
e_o	ambient vapour pressure - mm. Hg
e_1	local vapour pressure - mm. Hg
e''_s	vapour pressure at temperature t''_s - mm. Hg
g	gravitational constant = 32.2 ft./sec ²
h	thermal conductivity of air CHU/sec. °C. ft.
J	mechanical equivalent of heat = 1400 ft. lb./CHU
k_e	coefficient of evaporation = $C_f/2(Tr)^{2/3}$ for laminar flow
k_h	heat transfer coefficient = $C_f/2(Pr)^{2/3}$ for laminar flow
L	latent heat of vaporization - CHU/lb.
M	molecular weight of fluid specified by subscript
M_n	Mach number
p	static pressure - mm. Hg
t_o	ambient static temperature - °C.
t_1	local static temperature - °C.
t'_s	surface temperature in clear air - °C.
t''_s	wetted surface temperature - °C.
Tr	Taylor's number = $\mu/D\rho$
U	velocity - ft./sec.
W	weight of fluid evaporated - lb./sec. ft ²
μ	viscosity of air - lb./sec. ft.

LIST OF SYMBOLS CONT'D

ρ weight density - lb./ft³
 γ ratio of specific heats
Pr Prandtl's number = $\mu C_p / k$

Subscripts

o ambient conditions
l local conditions outside the boundary layer
s conditions at the surface
w water
v anti-icing fluid
a air

THE DESIGN OF FLUID ANTI-ICING SYSTEMS

1.0 INTRODUCTION

1.1 General Remarks

Although fluid systems have not been applied widely for aircraft ice protection, they do offer, in some circumstances, unique advantages which make them preferable to other methods. For example, alcohol anti-icing has been applied quite successfully to gas turbine engine installations where the system's ability to protect a fixed intake screen is a considerable advantage.

The following paper outlines the theory of fluid ice protection and presents calculated values for the fluid requirements for anti-icing gas turbine engines and for a typical wing. The practical application of the method is then discussed with particular reference to the gas turbine engine.

1.2 Comparison with Other Methods

Considering for example again the gas turbine engine application, the fluid system has the advantages of a low installed weight, the ability to protect a fixed intake screen, and of a slight increase in power opposed to some power penalty for all other methods.

The disadvantages are that the protection time is fixed by the quantity of fluid carried, and that the compressor air is polluted making it unsuitable for cabin use.

In regard to the total weight penalties involved, Figure 1 indicates the relative total weights (installation plus fuel or other fluid) for a number of systems for a typical fighter installation. It is evident that unless long endurance in icing conditions are contemplated the alcohol system will show, for the assumptions taken, the lowest total weight. It should be noted that this comparison is for a fighter aircraft; for a transport the large weight of additional pressurizing gear that is required with alcohol anti-icing (if compressor air is normally used) may alter the relative weights considerably. The analysis does indicate that for certain applications fluid systems compare favourably with other methods.

2.0 CALCULATION OF THEORETICAL FLUID QUANTITIES

2.1 General Remarks

The quantity of fluid required to prevent ice formation on an exposed surface will be comprised of that amount necessary to form a non-freezing mixture with the water collected on the surface plus an additional amount to cater for evaporation losses. The evaporation losses will include evaporation from the wetted surface plus evaporation from the fluid spray if a spray distribution system is employed. For wick or porous skin systems fluid will be lost by evaporation only from the wetted surfaces.

The method used in this paper follows that developed by Hardy in References 1 and 2, and by Samaras and Bachmeier in Reference 6.

It might be mentioned here that the cyclic shedding of ice accretions has been proposed as a means of reducing the fluid requirement. In this method the fluid is either fed through a porous skin and might detach, the ice or is sprayed on the ice formation and the resulting slush is presumed to blow off at fluid: water ratios lower than that necessary to form a non-freezing mixture. Some saving in fluid weight may be possible with this technique but experimental verification is lacking. The method does show promise as a means of metering fluid flow to suit icing severity as is discussed later in Section 3.1.2.

Ethyl alcohol has been selected as an example anti-icing fluid for the calculations given although calculated results are also given for methyl alcohol and the physical properties of two other suitable fluids are presented.

2.2 Wetted Surface Temperature

Following Hardy (Ref. 1 and 2) the temperature of a thermally isolated surface wetted by a mixture of water and anti-icing fluid is given by:

$$t_s'' = t_s' - \frac{k_{ev} M_v L_v}{k_h M_a C_p} \left(\frac{e_{sv}'' - e_{1v}}{p_1} \right) - \frac{k_{ew} M_w L_w}{k_h M_a C_p} \left(\frac{e_{sw}'' - e_{1w}}{p_1} \right) \quad (1)$$

Now for laminar flow the surface temperature in clear air, t_s' , is given by:

$$t_s' = t_1 + \frac{U_1^2}{2JgC_p} \sqrt{Pr} \quad (2)$$

and the local static temperature is given by:

$$t_1 = t_o + \frac{U_o^2 - U_1^2}{2gJC_p} \quad (3)$$

Substituting equation (3) in equation (2) and putting $\sqrt{Pr} = 0.85$:

$$t'_s = t_o + \frac{1}{2gJC_p} \left(U_o^2 - 0.15U_1^2 \right) \quad (4)$$

Substituting in equation (1) and noting that $k_{ew}/k_h = 1$, i.e., Taylor's number for water vapour near 0°C. equals Prandtl's number, there results:

$$t''_s = t_o + \frac{1}{2gJC_p} \left(U_o^2 - 0.15U_1^2 \right) - \frac{k_{ev}M_vL_v}{k_h M_a C_p} \left(\frac{e''_{sv} - e_{1v}}{p_1} \right) - \frac{M_w L_w}{M_a C_p} \left(\frac{e''_{sw} - e_{1w}}{p_1} \right) \quad (5)$$

It should be noted that the vapour pressures of water and anti-icing fluid on the wetted surface are the partial pressures of the liquids when mixed in the correct proportion to give a non-freezing mixture at temperature t''_s . These data are available in the International Critical Tables although it is necessary to extrapolate from the temperature range given.

The value of p_1 , the local static pressure is related to ambient pressure by the following equation:

$$p_1 = p_o \left(\frac{1 + 0.2M_{n_o}^2}{1 + 0.2M_{n_1}^2} \right)^{\frac{\gamma}{\gamma-1}} \quad (6)$$

The value of e_{1v} will generally be zero while the local water vapour pressure for no change in phase around the body is given by:

$$e_{1w} = e_{ow} \left(p_1/p_o \right) \quad (7)$$

A typical calculation for a gas turbine compressor intake guide vane when wetted with a non-freezing mixture of ethyl alcohol and water is given in the Appendix. Figure 2 presents the results of a number of such calculations for sea level static conditions and for two values of local velocity over the blade. It will be observed that higher velocities result in lower wetted surface temperatures. For a local velocity of 840 ft./sec. it is necessary to supply anti-icing fluid whenever the ambient temperature is lower than +5.5°C. Higher altitudes, i.e. lower ambient pressures, will tend to reduce the wetted surface temperature still further while higher flight speeds will tend to raise the surface temperature.

2.3 Fluid Required to Form a Non-Freezing Mixture

The quantity of fluid required to form a non-freezing mixture on the wetted surfaces will be simply the product of the water, impinging on the surface and the fluid: water ratio required to form a non-freezing mixture at the wetted surface temperature. Figure 3 gives freezing point versus alcohol: water ratio for ethyl alcohol.

For engines, the quantity of water entering the engine is usually taken as that amount which is contained in the engine airflow. For flight conditions where the flight speed exceeds the compressor inlet velocity a somewhat greater quantity of water will tend to enter the engine due to momentum effects. Calculations (Ref. 3) indicate that this effect may increase the water catch by some 20 percent for a flight velocity to inlet velocity ratio of 1.7.

For airframe components the water catch is computed on the basis of that caught by a cylinder which approximates the leading edge contour of the component. Reference 4 presents a series of curves which enable catch efficiencies to be computed with a minimum of computation.

2.4 Evaporation Losses

2.4.1 Surface Evaporation

Again following reference 1, the quantity of anti-icing fluid required to compensate for evaporation losses from the wetted surface is given by:

$$W_v = k_e \rho_a U_o \frac{M_v}{M_a} \left(\frac{e''_{ev} - e_{1v}}{p_1} \right) \quad (8)$$

Figure 4 gives the values of evaporation loss for ethyl alcohol when mixed with water to form a non-freezing mixture on an intake guide vane where the local velocity over the blade is assumed to be uniform at a value of 450 ft./sec. It is observed that the evaporation loss reduces very markedly with lowering ambient temperature.

2.4.2 Droplet Evaporation

For most conditions the evaporation loss from the fluid sprays will be very small although for high vapour pressure fluids such as methyl alcohol and relatively long evaporation distances it is necessary to allow for spray evaporation. Reference 5 enables the evaporation loss to be computed for both the cooling period and for equilibrium conditions. It appears, however, that adequate accuracy is achieved by using only the equilibrium equation which follows:

$$W = 4\pi a D \rho_v \left(\frac{e_v - e_{ov}}{p_o} \right) \frac{M_v}{M_a} \quad (9)$$

where ρ_v is the weight density of the liquid. The vapour pressure at the droplet surface e_v may be taken as that corresponding to the initial droplet temperature and e_{ov} will be zero. The actual vapour pressure at the droplet surface will reduce with lowering droplet temperature but the small value of this loss does not warrant a more precise calculation.

2.5 Total Theoretical Fluid Requirements

2.5.1 Gas Turbine Engines

Figure 5, based on Figures 2, 3, and 4, presents the total theoretical ethyl alcohol requirements for anti-icing an axial flow gas turbine having a sea level static airflow of 100 lb./sec. and a wetted surface area of 40 ft². The latter figure implies that alcohol is sprayed on all intake surfaces inside the stagnation line on the engine cowling for a nacelle or wing installation where a short intake duct is employed. With a long intake duct the wetted area may increase somewhat depending on the location chosen for the alcohol sprays. The alcohol requirement is observed to increase linearly with liquid water content and about linearly with temperature depression below 0°C. The alcohol requirement for very low liquid water contents represents the evaporation loss from the wetted surfaces.

Figure 6, based on the data in Reference 6, gives corresponding values for methyl alcohol. It is observed that considerably less methyl alcohol is required at low temperatures due to its greater freezing point depressant properties; near 0°C. the higher vapour pressure of methyl alcohol results in lower wetted surface temperatures and greater evaporation losses and the quantities of methyl and ethyl alcohol are about equal.

Figures 7, 8, and 9 indicate the effects of flight speed and altitude presenting methyl alcohol requirements respectively for 300 m.p.h. at sea level; 300 m.p.h. at 20,000 ft.; and 500 m.p.h. at 20,000 ft. Thus the conditions covered represent take-off, beginning at climb, end of climb, and cruise for an operational height of 20,000 feet.

From a comparison of Figures 6 and 7, the alcohol required is observed to decrease with increasing flight speed due to the favourable effect of kinetic heating. Figures 7 and 8 show the unfavourable influence of altitude due to greater evaporation effects with reduced pressure. Figures 8 and 9 again show the beneficial effect of increasing airspeed at constant altitude.

It will be observed that the engine airflows assumed in Figures 5 to 9 are appropriate to the flight speed and altitude shown for an engine having a sea level static airflow of 100 lb./sec., but that the airflows within each figure have been held constant for convenience of application to different size engines. Thus, for a given figure, the alcohol requirement corresponds to constant engine airflow and thus to decreasing r.p.m. with lowering temperature. Actual alcohol requirements for a given flight speed and altitude at constant observed r.p.m. will increase above those shown in very nearly the same proportion as engine air weight flow.

2.5.2 Airframe Components

As a typical example, the quantities of methyl and ethyl alcohol to anti-ice the main plane of a modern 115-foot span transport aircraft have been computed and are shown in Figure 10. The results are given for ICAN* temperature only (-24°C.) but Figure 8 may be used in conjunction with Figure 10 to determine the requirements for other temperatures. Wetted surface temperature has been computed for a region where the local velocity equals the flight velocity and water catch was determined from Reference 4. The area for surface evaporation

*International Convention for Air Navigation.

was taken, rather arbitrarily, as equal to half the circumference of the equivalent leading edge cylinder. However this assumption is not critical since the evaporation loss for laminar flow is very small (0.35 lb./hr. ft² for ethyl alcohol).

It is of interest to note that the fluid quantities given in Figure 10 are very much lower than those computed by Hardy in Reference 2. Three factors contribute to this difference: (1) The freezing point depressant properties of methyl alcohol are superior to ethylene glycol, although this difference will be less noticeable near 0°C. due to evaporation effects, (2) The smaller leading edge radii of modern airfoils result in lower water catch rates per foot of span, (3) The water catch rates computed from Reference 4 are considerably lower than values given by Hardy in the example on page 36 of Reference 2.

3.0 PRACTICAL APPLICATION OF FLUID SYSTEMS

3.1 Gas Turbine Anti-Icing

3.1.1 Correlation of Theory and Experiment

As is well known the main difficulty in applying fluid anti-icing is the achieving of effective fluid distribution. In the case of gas turbines numerous fixed and rotary spray systems have been proposed and a number of these have been tested in the Engine Laboratory of the National Aeronautical Establishment. Some typical test results are shown in Figure 11 where the ratio of experimental to theoretical alcohol requirement is plotted against alcohol flow, i.e. icing severity, for two distributor types. It is observed that when a fixed distribution system, such as a number of stationary nozzles or a drilled spray ring, is used the ratio of experimental to theoretical alcohol flow is quite high at low flows but reduces to a value of about 2 near the maximum flow or design point for the system. This deterioration in distribution at low flows results from the low system pressure and consequently poor atomization and spray penetration. The hydrostatic head effect also causes more fluid to be forced out of the lower nozzles in the system at low spray pressures.

When some type of rotary spray is used, such as spray nozzles on the propeller hub for turboprop engines, it is possible to anti-ice with approximately the theoretical alcohol flow over a wide range of flows. Distribution is simplified here since the spray nozzles are required to cover only one dimension rather than two. Some deterioration in distribution of low flows is evident due to reducing pressure with flow at the nozzle.

In general the data in Figure 11 would appear to verify the theoretical calculations for anti-icing fluid requirements.

3.1.2 Mechanical Design

Considering distributors first, it is quite clear that for turboprops some type of rotary spray mounted on the propeller spinner will be best for engines having annular air intakes. Distribution is usually improved by facing the nozzle forward and, in addition, the nozzle is then self-protecting.

For the turbojet, the problem is complicated by the absence of a rotating member such as the propeller spinner. However, the improved distribution possible probably justifies the complication of either an aerodynamically or a mechanically driven slinger distributor. If two nozzles are employed, they should be placed at different radii to reduce the radial distance that must be covered by each.

If simplicity dictates a fixed fluid distributor, reasonably good coverage can be attained at high flows but special measures will be necessary if large excesses of fluid are to be avoided at low flows. For example the system might employ two distributing rings or sets of nozzles, only one of which would be used at low flows to maintain spray pressures relatively high compared to the hydrostatic head. Any fixed system will be a compromise between a large number of small holes to obtain good distribution without excessive fluid quantities and a small number of large holes to avoid blocking difficulties. The optimum distributor configuration is presently determined by trial and error experiments on the test bed. Figure 12 shows typical examples of rotary and fixed fluid distributors.

In regard to supply systems, if a slinger ring is employed in conjunction with a rotary distributor, the necessary spray pressure is developed by centrifugal force and the fluid may therefore be supplied to the slinger by simply pressurizing the alcohol storage tank.

If fixed spray nozzles are used, the supply pressure will increase as the square of the fluid flow, becoming fairly high at high flows. Under these conditions, a fluid pump will usually be required, and care must be taken to avoid corrosion problems such as have occurred with methyl alcohol and light alloy pumps. The addition of five percent water to methyl alcohol has been found to be effective in reducing corrosion.

The control of fluid anti-icing systems presents a rather difficult design problem. As indicated in Section 3.3 under Meteorological Conditions, severe icing is generally of very short duration and for this reason large savings in fluid weight are available if some metering device is provided.

A system of cyclic control for fluid systems has been proposed by Fraser (Ref. 7). This system employs an ice detector mounted aft of the fluid sprays which acts as a sensing device for a servo-mechanism which turns the fluid on and off for brief periods as required. The system has the dual advantage that it meters the fluid according to icing severity, and further that, if used with a fixed distributor, it would eliminate the problem of poor distribution at low fluid flows since the system would operate intermittently at maximum flow. Operation will be more or less satisfactory, depending on the de-icing properties of the fluid used.

Various methods of control for continuous systems have been proposed but an operational one is not known to the author. For screened engines it would appear that the pressure drop across the screen might be employed as an indicator, but some integration with airflow and altitude will likely be necessary since intake dynamic head will vary with changes in r.p.m. and altitude. Jet pipe temperature does not appear to be a useful icing indicator since engines can collect quite large ice quantities for a few degrees rise in jet pipe temperature.

3.1.3 Choice of Fluid

Desirable anti-icing fluids should possess good freezing point depressant properties and, at the same time, have low vapour pressures so that a minimum of evaporative cooling occurs on wetted surfaces. Unfortunately these two properties generally show opposite trends for various molecular weights with the lighter fluids giving the greatest freezing point depression.

Figure 13 presents the freezing points of aqueous solutions of three common alcohols and of ethylene glycol. It is observed that methyl alcohol is most effective while iso-propyl alcohol and ethylene glycol give the least depression. Somewhere below -20°C . iso-propyl alcohol has a transformation point below which the percentages to form a non-freezing mixture increase rapidly. (It should be noted that the abscissa in Figure 13 is percent depressant in the mixture while the abscissa in Figure 3 is alcohol : water ratio.)

Figure 14 gives vapour pressure trends with temperature for the three alcohols (the vapour pressure of ethylene glycol is very low in this temperature range). The higher

vapour pressure of methyl alcohol compared to say ethyl alcohol results in lower wetted surface temperatures and greater evaporation losses. For these reasons the two alcohols are of about the same effectiveness near 0°C. where vapour pressure effects become important (refer to Fig. 5 and 6).

In regard to experimental comparisons among fluids, a series of tests was conducted on an axial flow turbojet to compare the effectiveness of methyl, denatured ethyl*, and isopropyl alcohols. The tests were conducted in the temperature range -20 to -30°C. Both anti-icing properties, i.e. ability to prevent ice formation, and de-icing properties, i.e. ability to remove ice accretions, were investigated.

Denatured ethyl alcohol and methyl alcohol were found to have roughly the same anti-icing properties but the de-icing ability of denatured ethyl alcohol was somewhat less than methyl alcohol.

Isopropyl alcohol was definitely inferior with regard to both anti-icing and de-icing. It was found that even double the amount of methyl alcohol was insufficient for satisfactory anti-icing. It should be noted, however, that these tests were conducted below the transformation point for isopropyl alcohol. Somewhat more positive results were shown for isopropyl alcohol in another series of tests in the temperature range 0 to -11°C.

Finally, apart from the over-riding consideration of availability, the corrosive effects of various anti-icing fluids should be considered. Little information appears to be available concerning these corrosive effects but it is known that alcohols attack some light alloys; for example, anhydrous methyl alcohol attacks magnesium very actively. The addition of water slows down this process considerably.

The corrosion problem is complicated by the tendency of some denaturing agents or impurities to be corrosive and also by the tendency of water to either induce or suppress corrosion. The application of corrosion inhibitors, as applied in reciprocating engine cooling systems, may alleviate this problem.

It appears that corrosion of compressor blades will be insignificant, even if they are made of light alloys, because the exposure time will be very short. The problem may occur in tanks, pumps, connecting lines or any part of the system exposed to the anti-icing fluid for long periods.

* 90 percent by volume of 96 percent ethyl and 10 percent methyl alcohol.

It is concluded that, in the absence of more information, direct tests on fluid anti-icing systems will be required. Care must be taken to insure that corrosion products do not clog the distributor when the system is operated after a long period of idleness.

3.1.4 Performance Effects

Although theoretical calculations (Ref. 6) have indicated thrust boosts up to 6 percent, when sufficient alcohol is injected for anti-icing, experimental results indicated negligible thrust boosts for an axial engine (for low temperatures at least) and boosts of the order of one percent for a centrifugal engine.

Fuel consumption at cruise r.p.m., for an axial engine, was found to decrease by roughly $1/4$ of the alcohol injected. Thus, for alcohol anti-icing fluid, fuel reserves may be reduced by $1/4$ of the weight of alcohol carried.

3.2 Airframe Application

It is not proposed to treat in any detail here the practical aspects of airframe protection since the author has no intimate knowledge of this work.

In regard to the correlation of theory and experiment, work done at the R.A.E. and reported by Hardy (Ref. 2) indicates a very close correlation between experimental requirements and theoretical predictions. Further investigation of the test data reported indicates fair agreement with Reference 4 for water catch rates. It thus appears that, providing effective distribution can be achieved, the calculation procedure described herein will give a good estimation of fluid requirements.

References 2 and 10 give brief descriptions of the mechanical design of fluid systems. Of particular interest is a porous panel development mentioned in the latter reference which is reported to reduce the fluid requirement considerably from that necessary with the conventional system employing two porous slots. It is also of interest to note that the recommended operating technique is to use the system for anti-icing rather than de-icing.

3.3 Meteorological Conditions

Figure 15 presents the meteorological design requirements proposed by the Low Temperature Laboratory of the N.A.E. It is observed that severe icing is not predicted over large areas. These curves may be cross-

plotted on fluid requirement curves (for example, Figures 7 to 10), assuming constant meteorological conditions to 20,000 ft., to determine the fluid requirements at various flight speeds and altitudes. If a control for fluid flow is provided, then the 3-mile extent curve will simply specify the maximum flow required, while the lower curves enable a prediction to be made of the maximum total quantity of fluid required for a given flight.

4.0 CONCLUSIONS

(1) Comparisons between theory and experiment indicate that the method outlined for calculating fluid requirements gives a good estimation of that actually required (Fig. 11 and Section 3.2). Typical calculated fluid requirements for various applications are given in Figures 5 to 10.

(2) Distribution problems for some applications will necessitate supplying excess fluid quantities. For example, while for gas turbine engines employing a rotating distributor, the theoretical fluid quantity is adequate, engines with a fixed fluid distributor may require twice the theoretical fluid flow at high flows and three times the theoretical flow at one-third of the maximum system flow.

(3) For some applications, particularly short endurance aircraft, fluid anti-icing may be the most desirable method of protecting gas turbine engines (Fig. 1). The fluid quantities calculated for wings suggest that this aspect of fluid anti-icing is worthy of more attention than it has received previously.

(4) The tendency for severe icing to be of only short duration (Fig. 15) emphasizes the need for flow control for fluid systems.

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/MMR

FIG. 1.

VARIATION OF WEIGHT WITH PROTECTION TIME
FOR SEVERAL ENGINE ANTI-ICING SYSTEMS.

CONDITIONS :

ALTITUDE - 20,000 FT
FLIGHT VELOCITY - 530 M.P.H.
TEMPERATURE - -30 °C
LIQUID WATER - 1 GM/M³

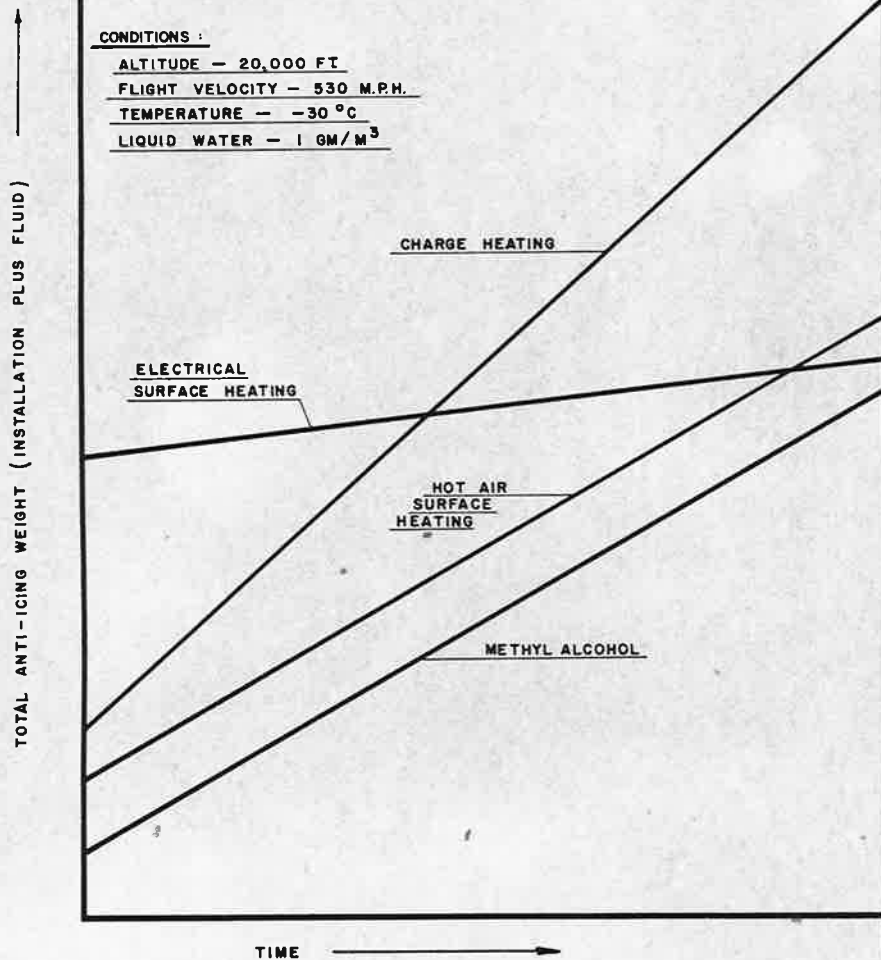


FIG. 2.

VARIATION OF WETTED BLADE SURFACE
TEMPERATURE WITH AMBIENT TEMPERATURE

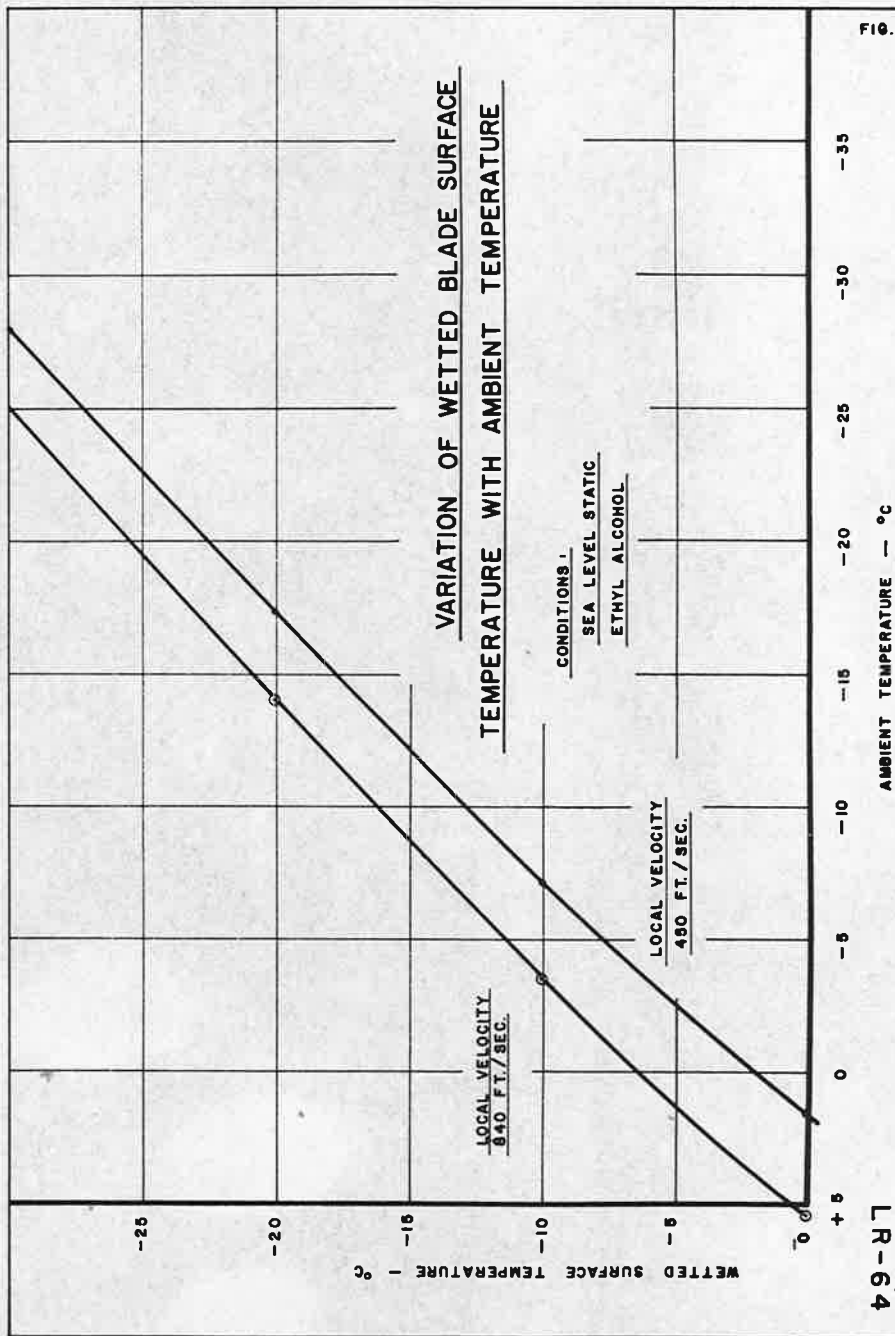
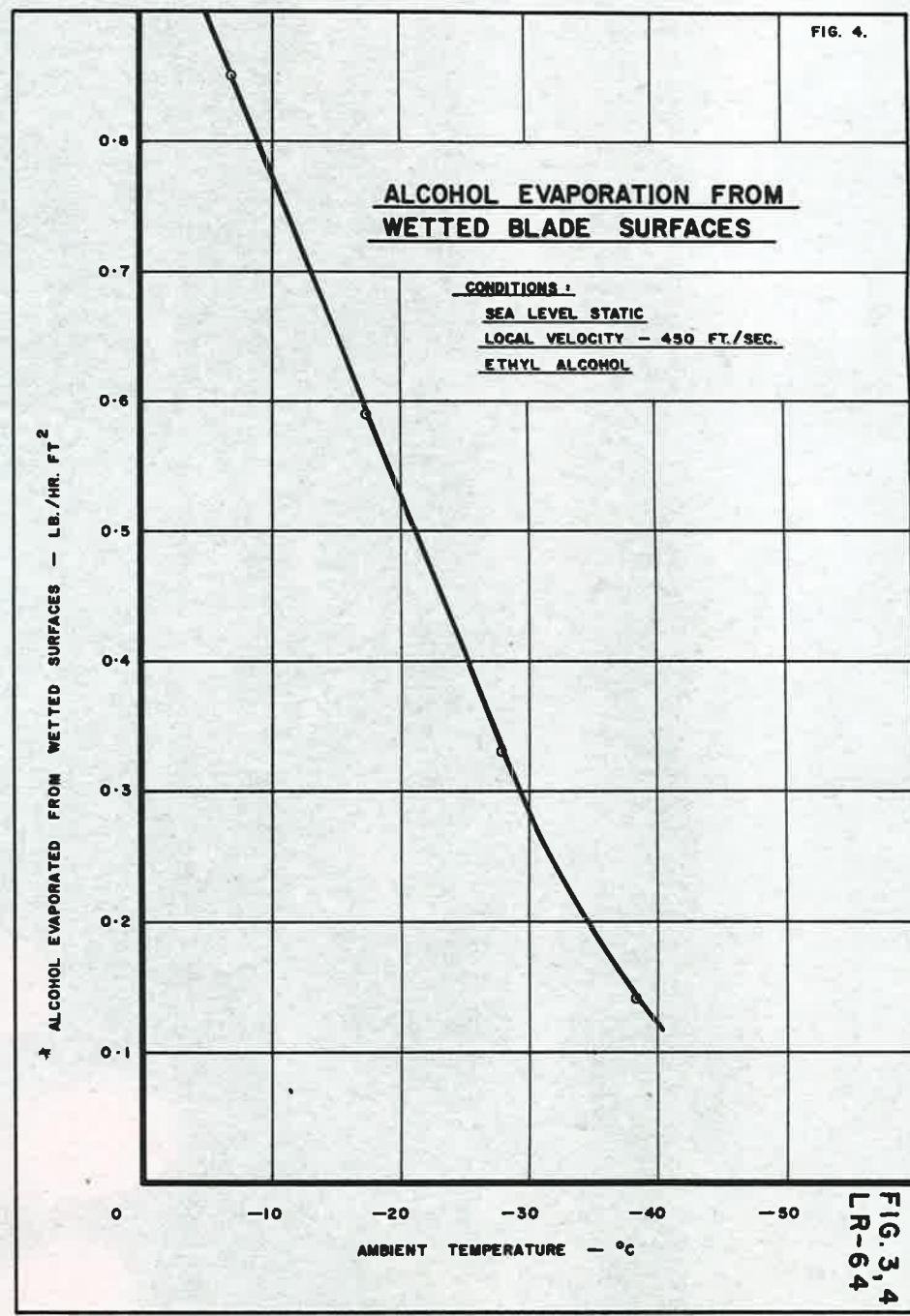
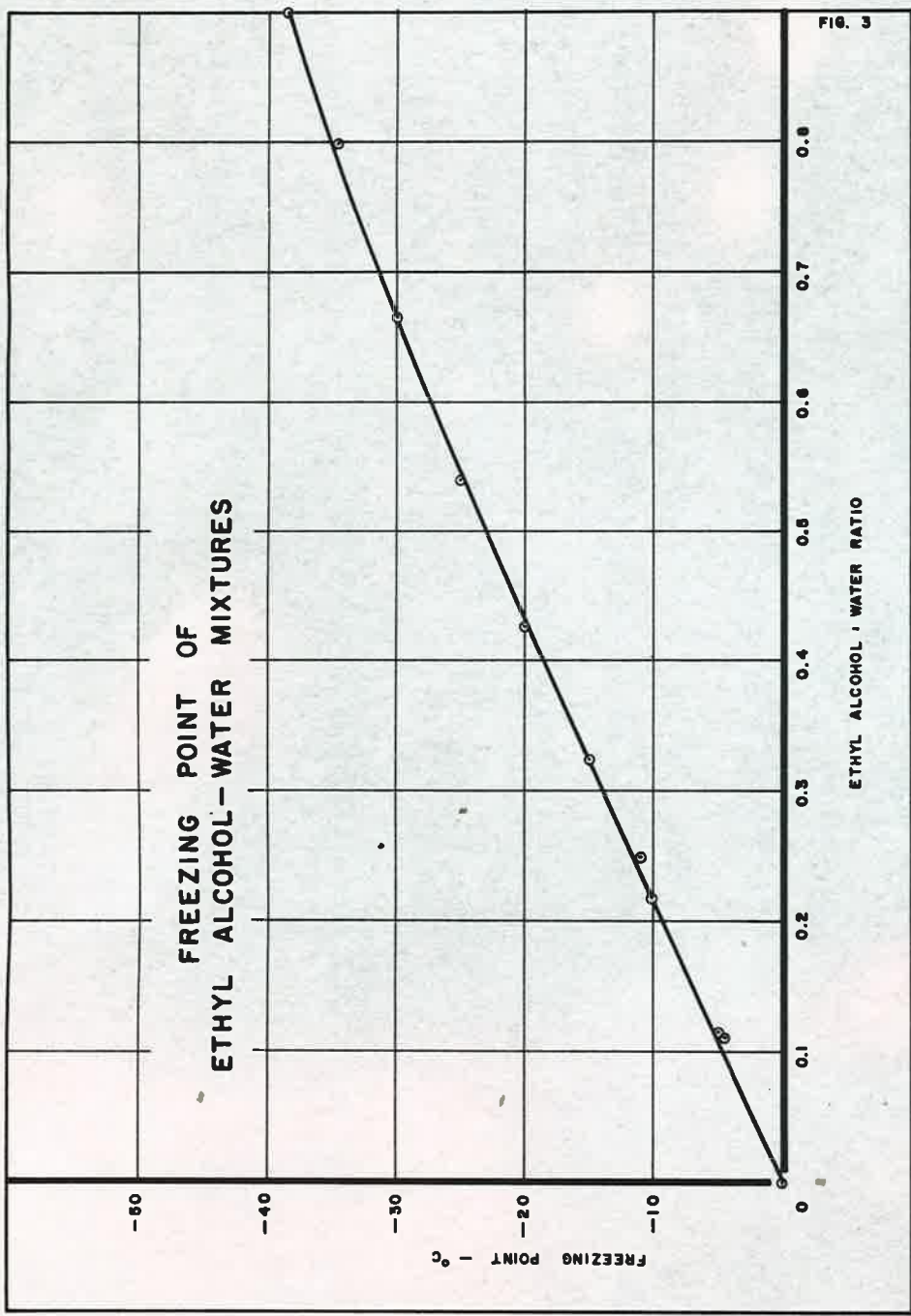
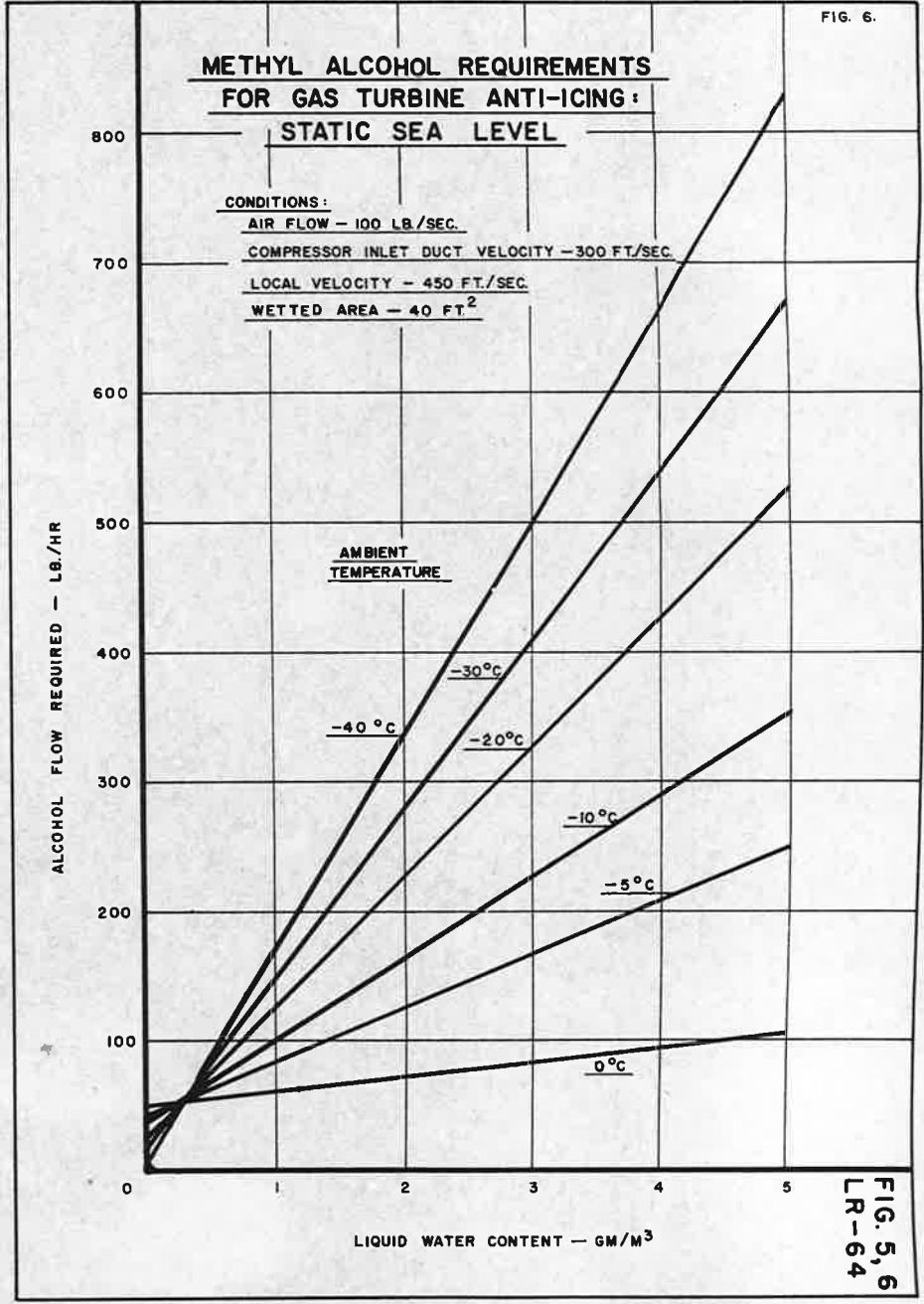
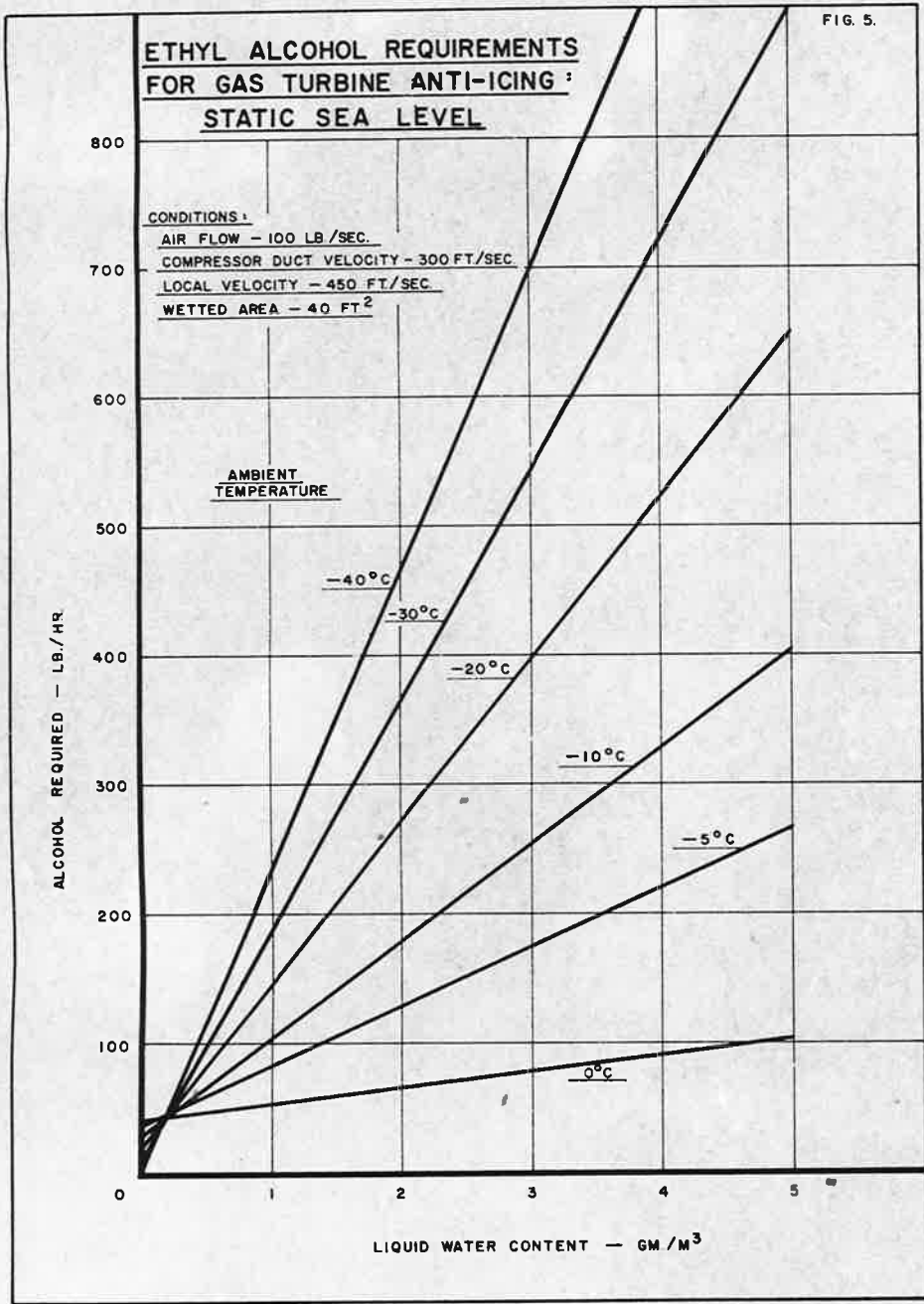


FIG. 1, 2
LR-64





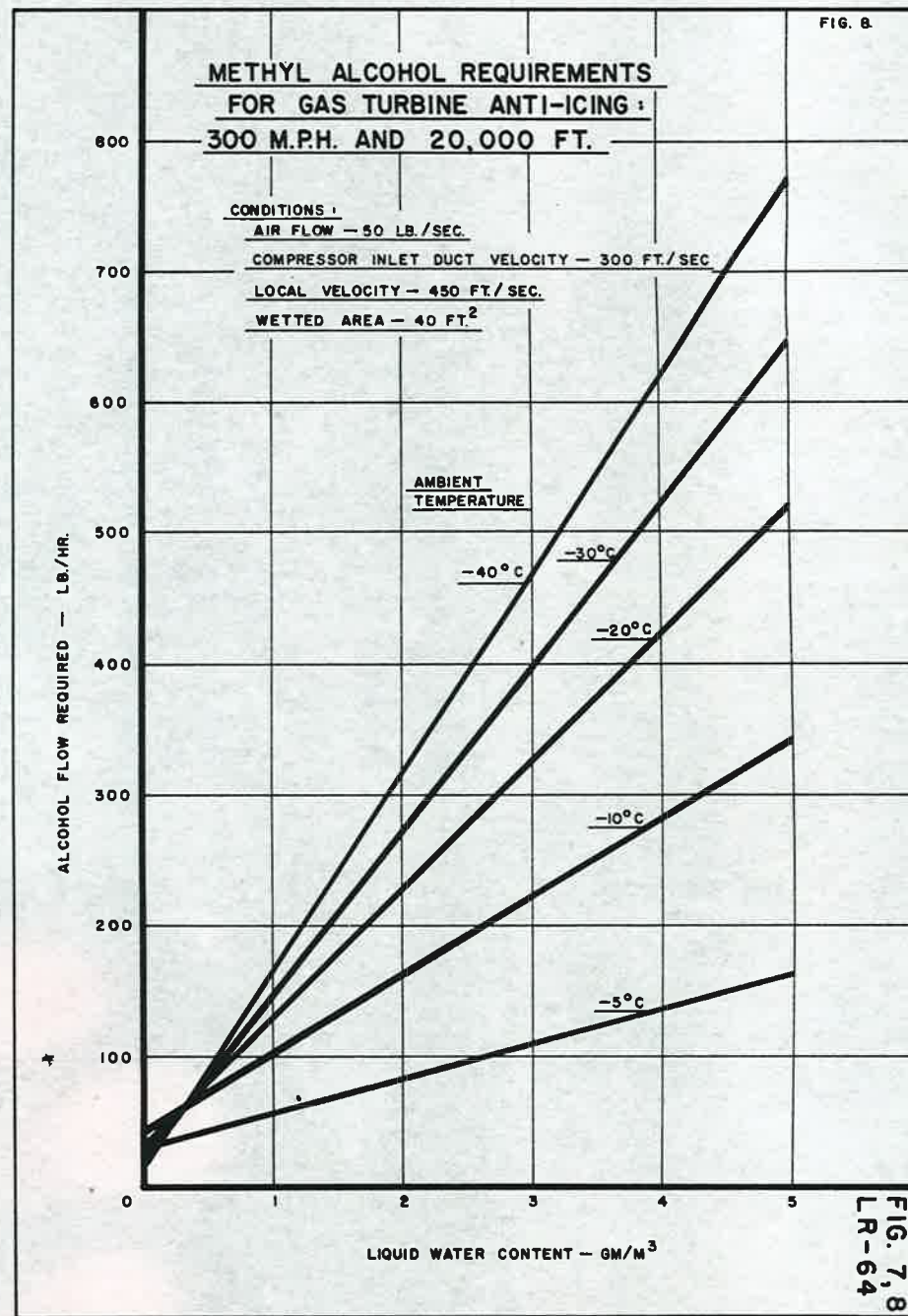
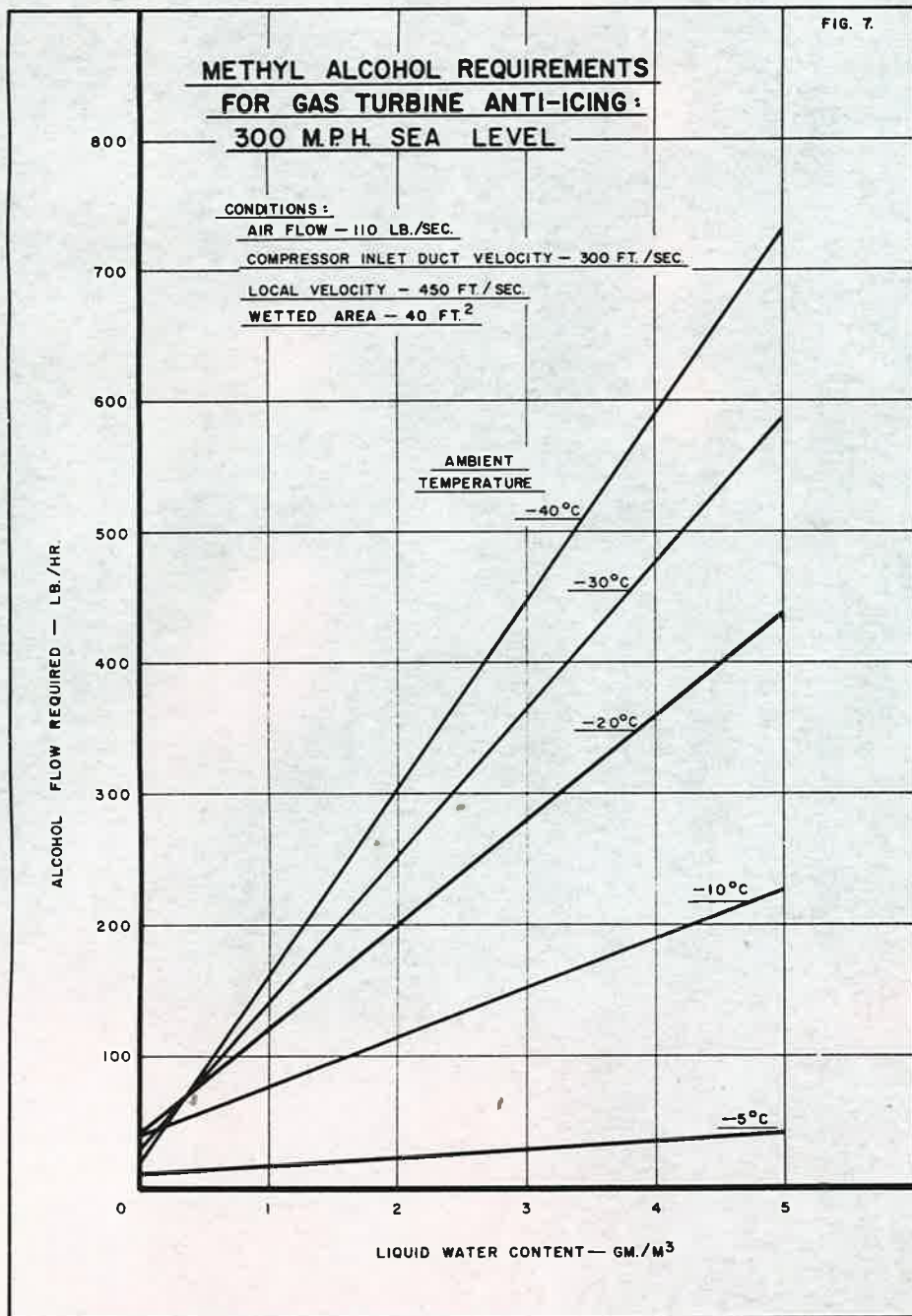


FIG. 9

**METHYL ALCOHOL REQUIREMENTS
FOR GAS TURBINE ANTI-ICING:
500 M.P.H. AND 20,000 FT.**

CONDITIONS:

AIR FLOW - 60 LB/SEC

COMPRESSOR INLET DUCT VELOCITY - 300 FT/SEC

LOCAL VELOCITY - 450 FT/SEC

WETTED AREA - 40 FT²

ALCOHOL FLOW REQUIRED - LB / HR.

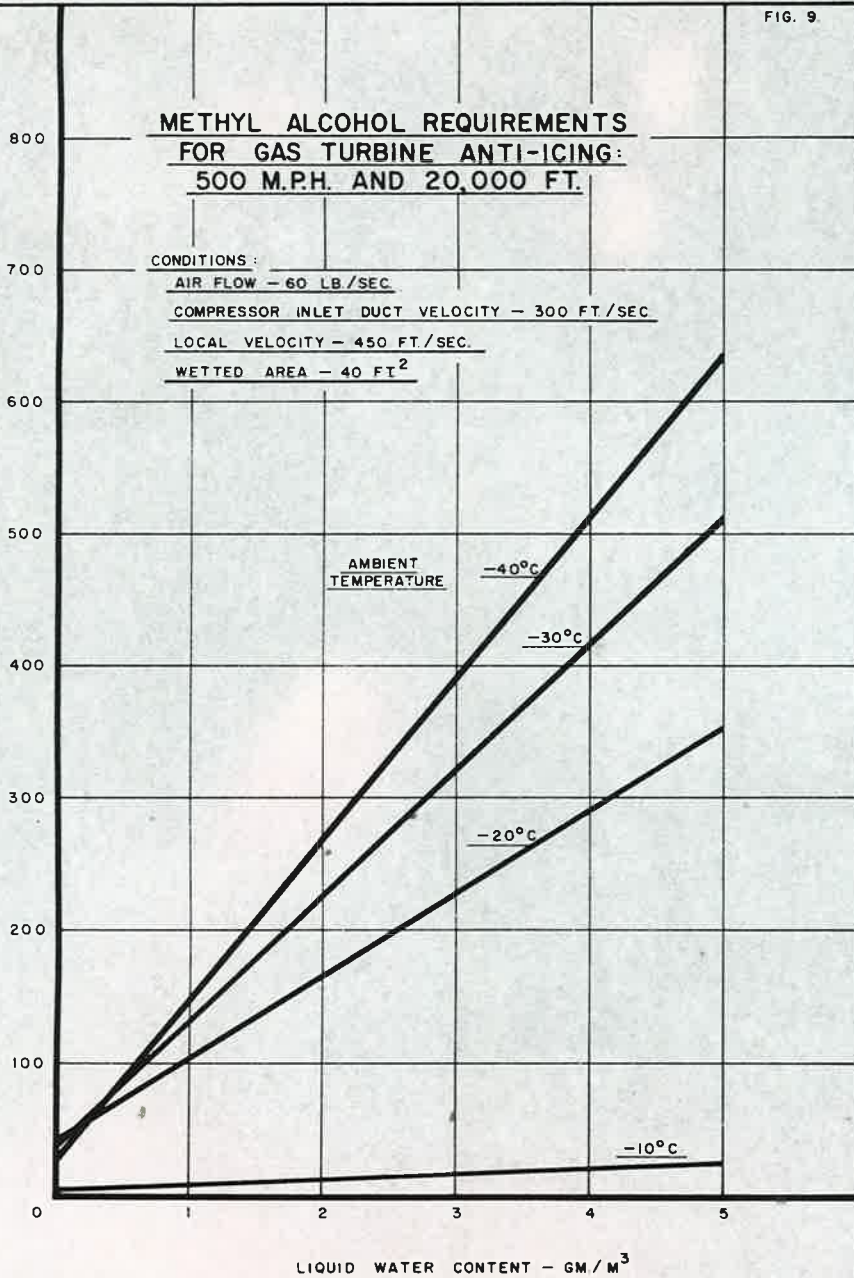


FIG. 10

**ALCOHOL REQUIREMENTS
FOR WING ANTI-ICING**

AIRCRAFT:

SPAN - 115 FT.

LEADING EDGE RADIUS - ROOT - 2.0 IN.
TIP - 1.2 IN.

CONDITIONS:

ALTITUDE - 20,000 FT.

FLIGHT VELOCITY - 300 M.P.H.

AMBIENT TEMPERATURE - -24 °C

DROPLET SIZE - 20 μ

ALCOHOL FLOW REQUIRED - LB / HR.

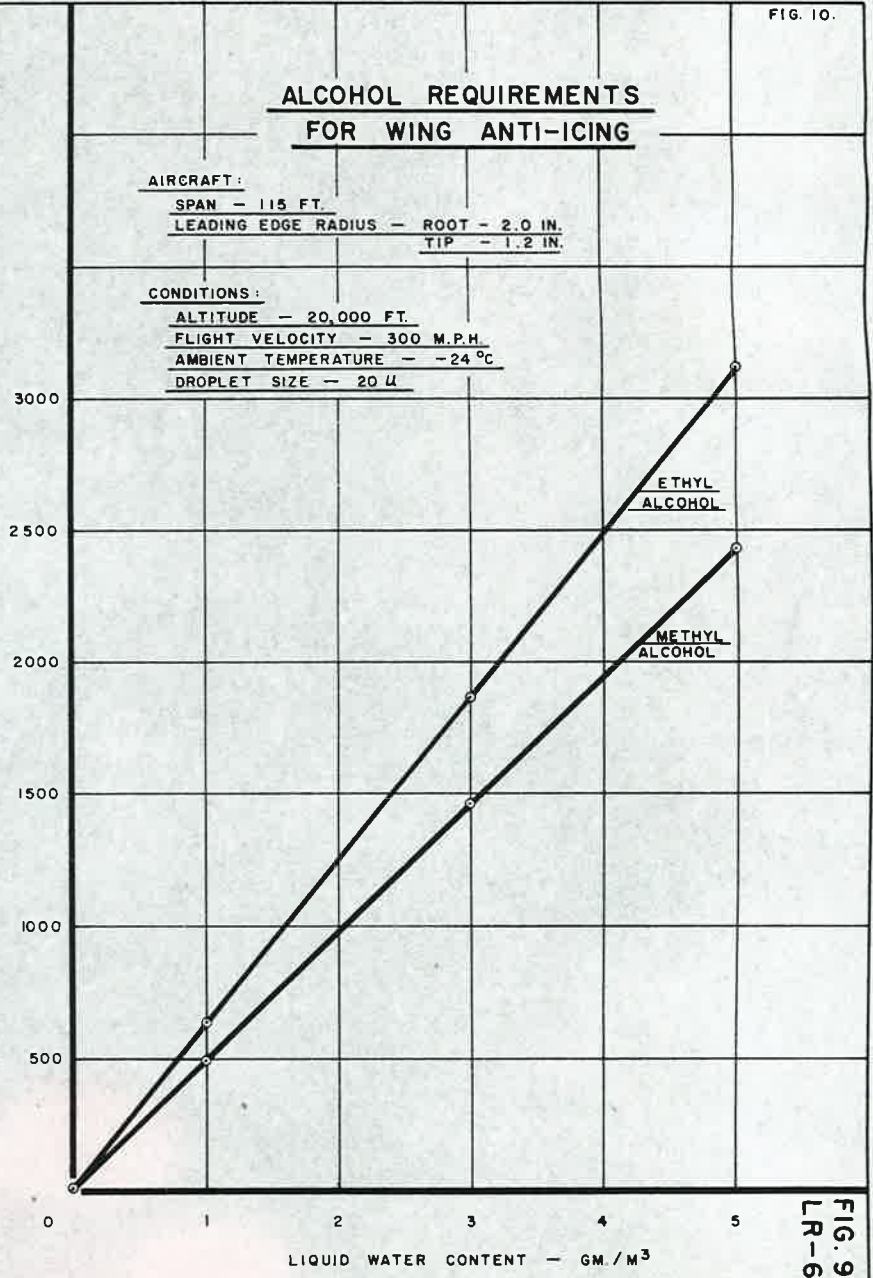


FIG. 9,10
LR-64

FIG. 11.

CORRELATION OF THEORY AND EXPERIMENT
FOR GAS TURBINE ANTI-ICING SYSTEMS.

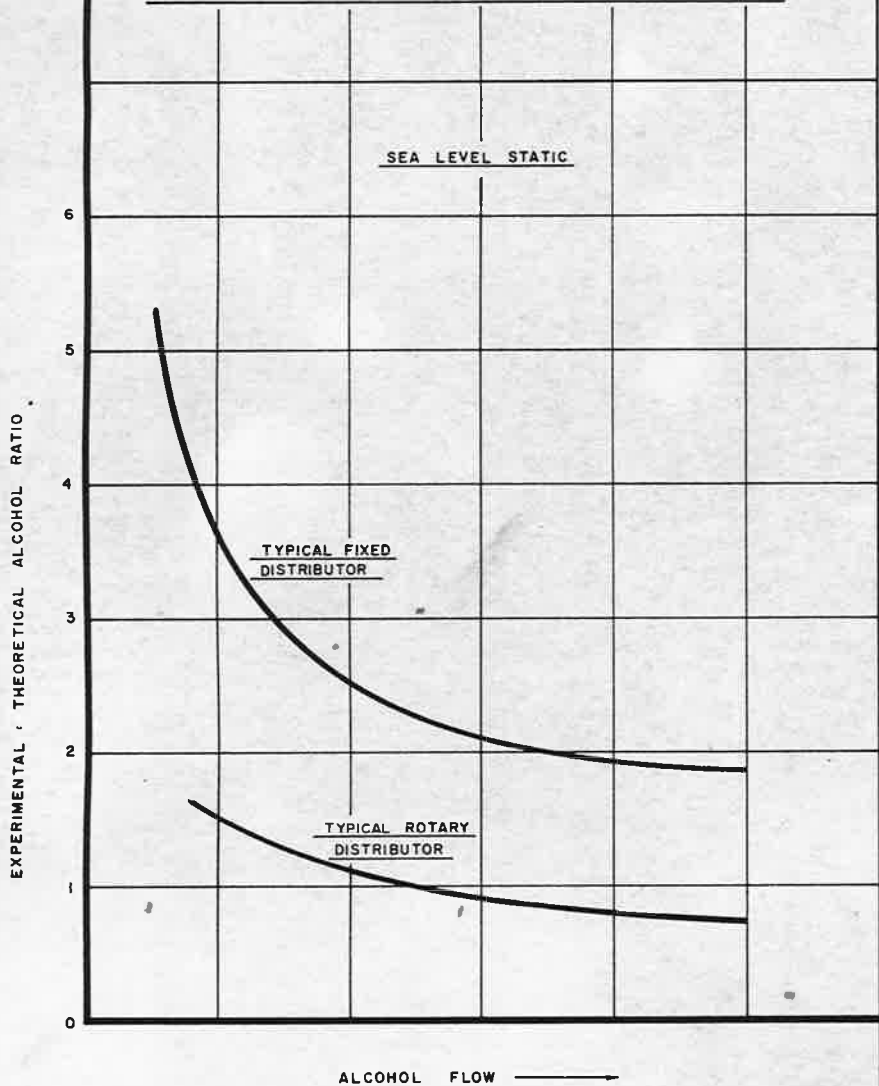
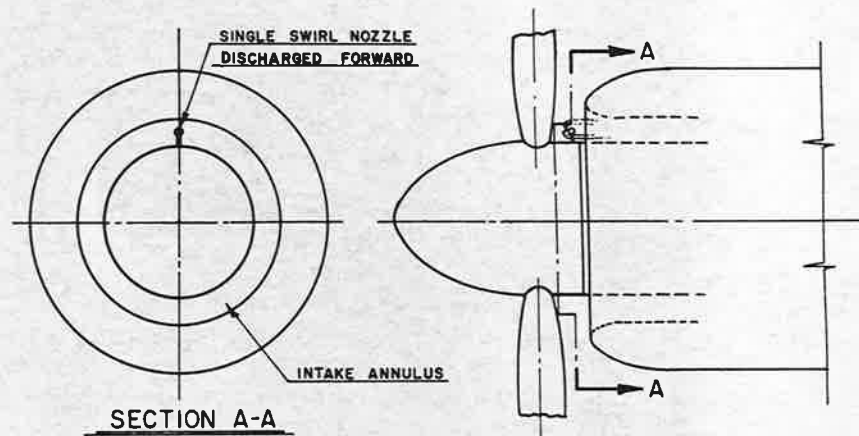
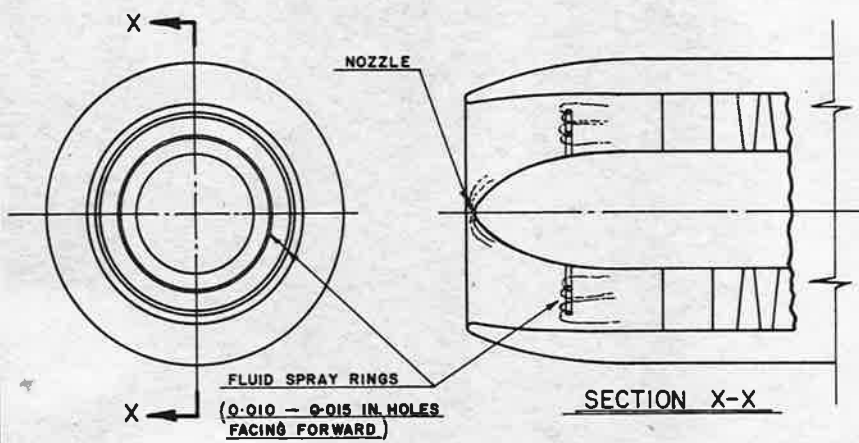


FIG. 12.



TYPICAL ROTARY FLUID SPRAY SYSTEM



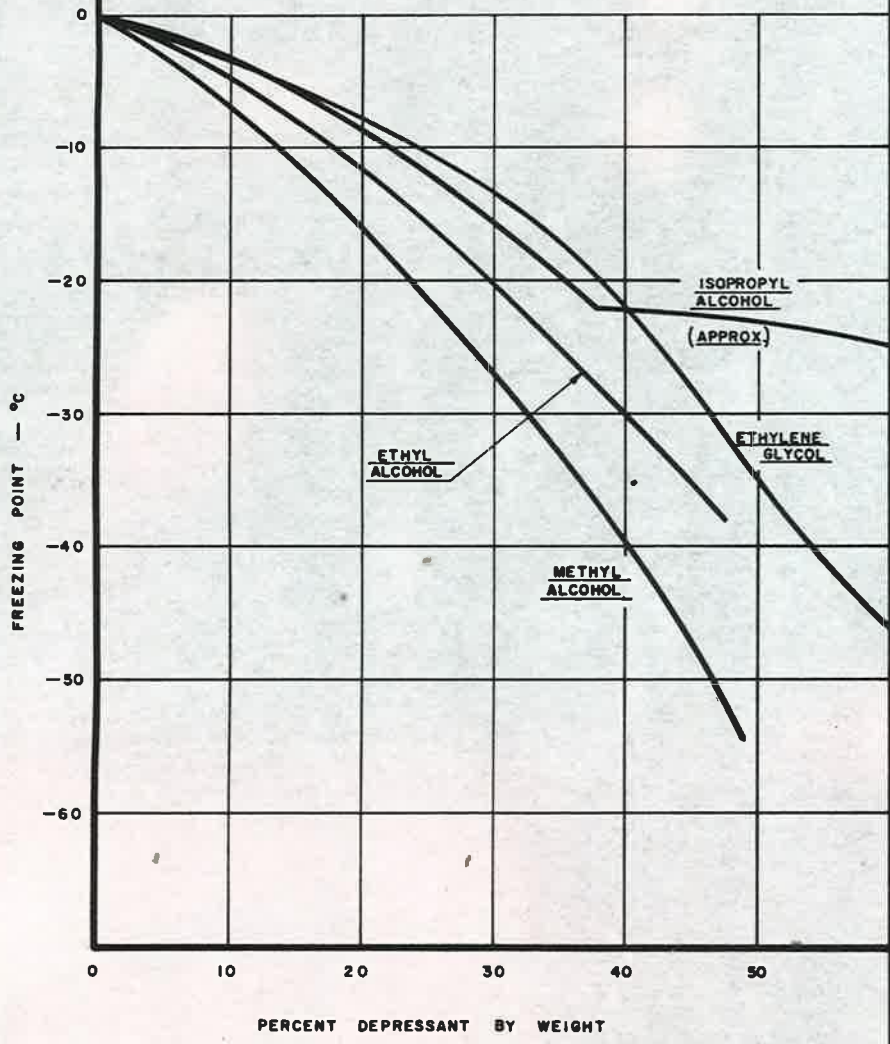
TYPICAL FIXED FLUID SPRAY SYSTEM

GAS TURBINE FLUID ANTI-ICING SYSTEMS.

FIG. 11,12
LR-64

FIG. 13

FREEZING POINTS OF AQUEOUS SOLUTIONS OF VARIOUS FLUIDS



BASED ON REFERENCES 8 & 9

FIG. 14

VAPOUR PRESSURES OF PURE ALCOHOLS

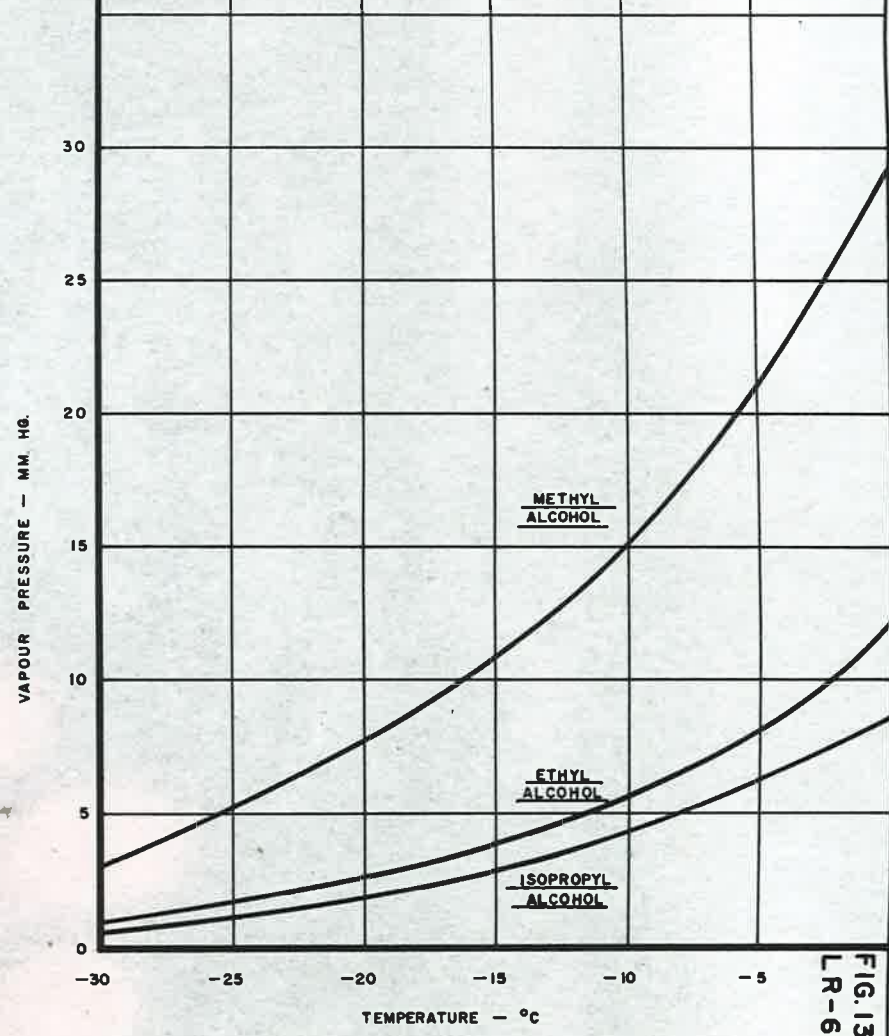
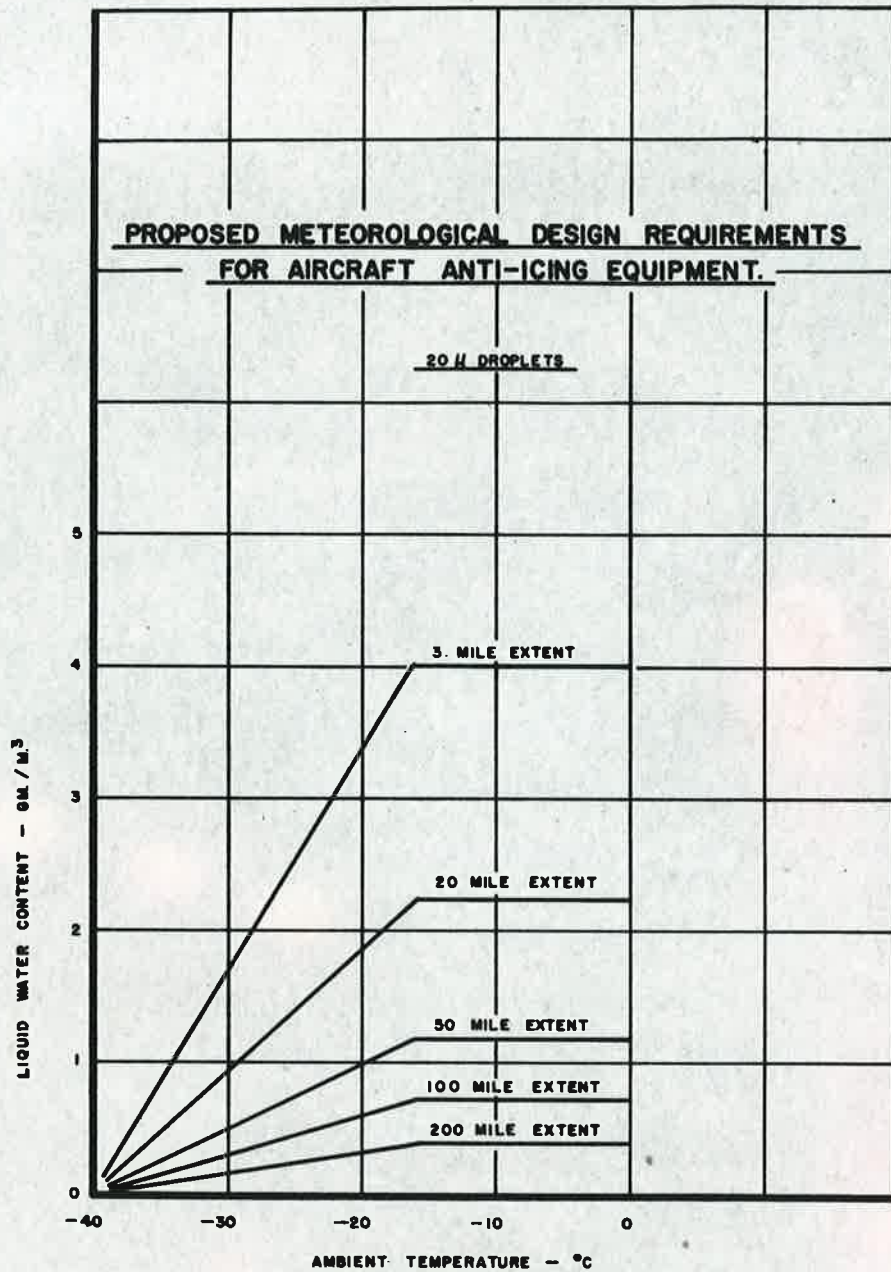


FIG. 13,14
LR-64



LOW TEMPERATURE LABORATORY

APPENDIX A

CALCULATION OF WETTED BLADE SURFACE TEMPERATURE
FOR ETHYL ALCOHOL ANTI-ICING

As an example assume the following:

$$\begin{aligned} t_o &= -7.4^\circ\text{C.} \\ U_o &= 0 \\ U_1 &= 450 \text{ ft./sec.} \\ p_o &= 14.7 \text{ lb./in}^2 \end{aligned}$$

Rewriting equation (5):

$$\begin{aligned} t_s'' &= t_o + \frac{1}{2gJc_p} \left(U_o^2 - 0.15U_1^2 \right) - \frac{k_{ev}M_vL_v}{k_hM_aC_p} \left(\frac{e_{sv}'' - e_{1v}}{p_1} \right) \\ &\quad - \frac{M_wL_w}{M_aC_p} \left(\frac{e_{sw}'' - e_{1w}}{p_1} \right) \end{aligned}$$

and making the following substitutions

$$\begin{aligned} \frac{k_{ev}}{k_h} &= \left(\frac{P_r}{T_r} \right)^{2/3} = \left(\frac{D\rho C_p}{k} \right)^{2/3} \\ &= \left(\frac{1.15 \times 10^{-4} \times 0.073 \times 0.24 \times 3600}{0.0135} \right)^{2/3} = 0.66 \end{aligned}$$

$$M_v = 46$$

$$M_a = 29$$

$$L_v = 221 \text{ CHU/lb.}$$

It is now necessary to estimate a value for t_s'' and then to substitute appropriate values for e_{sv}'' and e_{sw}'' . Assume $t_s'' = -10^\circ\text{C.}$

Then:

$e''_{sv} = 0.26 \times 5.6 = 1.45$ mm. Hg where the number 0.26 is the fraction of pure liquid vapour pressure for a mixture 18 percent alcohol (freezing point $-10^{\circ}\text{C}.$).

And:

$$e''_{sw} = 0.92 \times 2.1 = 1.94 \text{ mm. Hg}$$

$$p_1 = 760/1.13 = 670 \text{ mm. Hg}$$

$$e_{1w} = 2.65/1.13 = 2.35 \text{ mm. Hg}$$

$$M_w = 18$$

$$L_w = 603 \text{ CHU/lb.}$$

Thus:

$$\begin{aligned} t''_s &= -7.4 - 1.4 - \frac{0.66 \times 46 \times 221}{29 \times 0.24} \left(\frac{1.45 - 0}{670} \right) \\ &\quad - \frac{18 \times 603}{29 \times 0.24} \left(\frac{1.94 - 2.35}{670} \right) \\ &= -7.4 - 1.4 - 2.1 + 0.9 \\ &= -10^{\circ}\text{C}. \end{aligned}$$

which agrees with the initial guess.

If a range of wetted surface temperatures is required the calculation is simplified by assuming values for t''_s and calculating t_o .