C

HEAT TRANSFER

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JP-3 FUEL EVALUATION

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1949 INSPECTION OF THE NACA LEWIS LABORATORY

TALK ON HEAT TRANSFER

Presented by Mr. Grele or Mr. Lowdermilk
in Room CW-5, ERB.

(See Stage Photo C-24151)

One of the important functions of the NACA is to provide the basic engineering data required for the design of aircraft engines. Data of this type permit the proper design of engine parts on the first try and eliminate the costly cut and try development process that must be used when design data are not available.

In this talk I will describe a project pertaining to heat transfer which is illustrative of the activity at the NACA on obtaining basic engineering data. This talk will also illustrate a common practice in research, namely, how a small amount of test data can be generalized by the application of theory to apply over a wide range of conditions, far beyond the conditions investigated in the tests.

It is often necessary in the design of an engine to estimate the temperature that certain parts attain as the result of the exposure to the flow of a hot gas in order to determine the amount of cooling required to prevent failure by overheating. For example, in the case of a turbojet engine we are concerned with cooling the turbine blades. Another current problem is the cooling of the turbojet engine tail pipe, when the engine is equipped with an afterburner.

In order to design an engine that will cool properly, a knowledge is required of the heat transfer process from a hot surface to a coolant. Let us consider a simple illustration (C-24180-B) of a fluid flowing through this heated tube. The amount of heat transferred from the tube wall to the fluid is equal to the product of the surface area in contact with fluid, the temperature difference between the tube wall and the fluid, and a factor known as the heat transfer coefficient. Engineering theory indicates that the heat-transfer coefficient depends on the diameter of the tube, the velocity of the coolant, and the following properties of the coolant: density, viscosity, specific heat, and thermal conductivity.

These six quantities are listed merely to illustrate the complexity of the problem. If the effects of these quantities on the heat-transfer coefficient were desired, it would be necessary to make extensive series of tests in which combinations of these quantities were varied in turn, while the remainder were held constant.

Fortunately as a result of studies made by Nusselt in Germany and Reynolds in England it was found that it was possible to group these quantities into two factors, namely Nusselt number and Reynolds number. The Nusselt number is essentially a generalized heat-transfer coefficient, and to emphasize this meaning we will call it the heat transfer factor. This heat transfer factor is equal to the heat-transfer coefficient multiplied by the tube diameter and divided by the thermal conductivity of the fluid. Similarily the Reynolds number is essentially a measure of the fluid flow rate, and therefore we will call it the flow factor. The flow factor is equal to the tube diameter, multiplied by the fluid velocity and density, and divided by the fluid viscosity.

Nusselt showed that all heat-transfer data would fall on a single curve if the heat transfer factor were plotted against the flow factor regardless of what property of the fluid was varied. Only one series of tests in which only one of the properties of the fluid is varied is necessary to establish the curve of heat transfer factor against the flow factor. From this curve the effect of the other five fluid parameters can be predicted.

The next chart (C-24179-D) shows a plot of this type in which heat transfer factor is plotted against flow factor. These data are for the heat transfer from a tube to three fluids; air, water and benzene. The data fall on a single curve in spite of the fact that these fluids differ appreciably in physical properties and that the diameter of the tube was varied. This means that a method was available for predicting cooling performance for a wide variety of conditions.

The data shown on this chart were obtained at moderate tube wall temperatures. The question the NACA undertook to answer was - - could this curve be used to predict the heat-transfer coefficients at the extremely high surface temperatures of current interest?

To answer the question the experimental apparatus shown in this next chart (C-24180-A) was set up. It consisted essentially of an electrically heated metal tube through which air was made to flow. Provision was made for measuring the air flow rate, the air temperature and pressure at the entrance and exit of the tube, and the tube wall temperature. A series of measurements of the heat-transfer coefficient were made for various rates of air flow and at various tube wall temperatures up to 2100° F, and the heat transfer factor was plotted against the flow factor in the conventional manner. Instead of a single curve, a series of curves, one for each surface temperature, was obtained as shown on this next chart (C-24179). The dotted line represents the curve previously shown for the moderate wall temperature data, and it is apparent that this curve represents the present low temperature data reasonably well. However, as the temperature is increased the data fall progressively below the moderate temperature line, and at the highest temperature shown, the heat transfer factor is about 45 percent lower than that predicted by the curve normally used. In other words, the use of the conventional relation between heat transfer factor and flow factor (that is the dotted line) would result in underestimating by 45 percent the engine cooling requirements when the wall temperature is 2100° F.

This dispersion of the high temperature heat-transfer data from a single line is undesirable because it reduces the ability to generalize the results. That is, if a single curve had been obtained it would have been possible to accurately predict heat-transfer performance beyond the range of the tests. Therefore, the conventional method of correlating heat-transfer data was re-examined to determine whether it could be revised in such a way as to bring the high temperature and low temperature data together.

Now the various properties of the fluid such as density, viscosity, specific heat, and thermal conductivity depend on temperature. In the conventional method of correlation these quantities are evaluated at the average temperature of the fluid in the computation of the heat transfer factor and the flow factor. After some consideration it was decided that inasmuch as the flow region next to the wall offered the greatest resistance to the transfer of heat, the heat transfer process would be better defined if the fluid properties were evaluated at the temperature of this region or namely the tube wall temperature. When the heat transfer and flow factors were determined in this way, the following plot (C-24180-D) was obtained. It is seen that all of the points now fall on a single curve regardless of surface temperature and agree with the moderate surface temperature data of previous investigators. This means that a procedure is now available for predicting heat-transfer coefficients at very high surface temperatures, from data obtained at moderate temperatures.

Equally as important as the accurate predicting of heat transfer is the prediction of the pressure drops associated with flowing fluids under conditions of heat transfer, that is, a pressure drop across the tube is required to force the fluid through the tube to overcome friction. Generally, increased heat transfer is accompanied by increase in this pressure drop, so that if the permissible pressure loss is limited, as it generally is in aircraft application, the heat transfer may also be limited. Accordingly, pressure losses were obtained simultaneously with the heat-transfer data, and were used to calculate the pressure drop coefficients. This coefficient is a quantity relating the pressure loss due to friction, to the fluid flow rate.

Past work, both theoretical and experimental, has shown that pressure drop coefficients, for conditions of no heat transfer, can be correlated by plotting them against the flow factor previously described (C-24179-A).

Again it was found that with the conventional method of presentation there was a dispersion of the data from a common correlation line as the surface temperature increased.

However, by slightly modifying the pressure drop coefficient, and plotting it against the same modified flow factor used to make the high temperature heat-transfer data fall on a single line, these coefficients could also be made to fall together. This result is illustrated in the next chart (C-24180-C) where the modified pressure drop coefficient is plotted against the modified flow factor. All of the data points now fall on a single line, and hence simplify the calculations of pressure drops accompanying flow with heat transfer.

There is an additional step that might be desirable, and that is the use of a single equation or curve to predict either heat-transfer or pressure drop coefficients. Various investigators have indicated that there is an analogy between heat transfer and pressure loss, which has been experimentally verified at low temperatures. That this analogy also applies at high temperatures is illustrated in this next chart (C-24179-B) which shows the modified pressure drop coefficient, (plus symbols) and a heat-transfer factor, (circle symbols) plotted against the modified flow factor. This heat-transfer ordinate is a modification of the previous heat transfer factor divided by the flow factor. The data fall together and can be represented quite well by a single line over most of the flow factor range. The line drawn is that previously used to represent the pressure drop correlation. Hence both the amount of the heat-transfer and the corresponding pressure drop can be obtained from the same curve. One implication of this result is, that it is possible from pressure drop tests on a fluid flowing through an unheated tube, to establish a curve which may then be used, to predict heat transfer coefficients over a wide range of surface temperatures.

In summary this investigation has provided basic high temperature heat transfer and pressure drop data that are required for the design of engine cooling systems.

Of more fundamental importance, the conventional method of correlating heat transfer data has been modified to include the effects of high temperatures, so that the results of a few tests can be plotted on a single curve to cover a wide range of operating and design conditions.

1949 INSPECTION OF THE NACA LEWIS LABORATORY

TALK ON JP-3 FUEL EVALUATION

Presented by Mr. H. Barnett or Mr. E. R. Jonash
in Room CW-5, ERB.

(See Stage Photo C-24152 and Color Photo)

In recent years the number of aircraft powered by turbojet engines has increased rapidly. The question arises, then, what type of fuel will be available in sufficient quantity for operation of these aircraft in time of emergency. Current turbojet engines have been developed on aviation gasoline and kerosene type fuels but there are several reasons why these fuels are not suitable. First, it is undesirable to burn highly refined gasolines in engines that will effectively utilize less refined products. Second, kerosene type fuels are not available in the quantity that would be needed in an emergency. It is also desirable to select now the fuel that will be available in sufficient quantity in order to have this fuel around which our future turbojet engines can be developed. As a result of this problem representatives of the petroleum industry were asked to suggest the fuel that would be available in sufficient quantities for operation of turbojet engines in an emergency. The method by which this was done is illustrated in the first chart (C-24172-B). Here is shown a barrel of crude petroleum and from this crude we can obtain by our various refining processes 40 percent gasoline, 6 percent kerosene, 17 percent Diesel and heating oil, 24 percent Bunker fuels, 3 percent lubricating oil and 10 percent of other products. If we consider that certain physical properties may be limiting insofar as aircraft performance is concerned, and one such property is freezing point, then only a certain portion of the original crude can be used in aircraft. In other words, the freezing point of aviation fuels is restricted to a maximum of -76°F. In order to meet this limitation we could use all of the gasoline, all of the kerosene and about one-fourth of the Diesel and heating oil. These three components could be combined to give us a fuel representing 50 percent of the original crude and, as you see on the chart, this fuel has been designated JP-3. In this way we have decided what fuel would represent maximum availability in the event of an emergency. The next question to answer is how does this fuel perform in current turbojet engines which have been developed on gasoline and kerosene type fuels. The NACA was asked by the Air Forces and the Navy Department, Bureau of Aeronautics, to evaluate this JP-3 in our current engines and the plan by which this evaluation was achieved is shown on the backdrop (C-24152-). On the backdrop the first item we have listed shows the performance characteristics which were investigated -- carbon deposition, starting, combustion efficiency and altitude operational limits. These factors were studied in four designs of single burners of both the can type and the annular type. They were also evaluated in four full-scale engines of both the can type and annular type in our altitude tanks and our altitude wind tunnel and in flight. The fuels considered in the performance studies are shown in the second chart (C-24171-A). On this chart we have indicated two properties that describe the fuels investigated -- the boiling temperatures and the aromatic content. An aromatic is one of many components which appear in petroleum fuels and is costly to remove. Aromatics have been found to be detrimental to combustion efficiencies and altitude operational limits and show greater tendencies than other components to form carbon in the burners of the engine. The first two fuels shown on this chart are aviation gasoline and JP-1 which is a kerosene type fuel. The gasoline boils between 100° and 350° F and the JP-1 fuel between 325° and 450° F. These two fuels were used in the development of our current engines and were included in the investigation for comparative purposes. The JP-3 fuels investigated cover a range of boiling temperatures and aromatic content. These were selected inasmuch as the JP-3 specification is quite broad and it was our intention to see what effect variations in the fuels under the specification would have in performance. The first fuel boils between 100° and 550° F and has an aromatic content of 19 percent. This fuel is just as it was obtained from the refinery. The boiling range was extended to 600° F for the second fuel without altering the aromatic content. The third fuel has the same boiling range as the second fuel but the aromatic content was changed from 19 percent to 29 percent. The results of studies of carbon deposition are shown in the next chart (C-24171-B). On the ordinate of this chart we have indicated the relative carbon formed. The same five fuels shown in the preceding chart are shown here. Aviation gasoline deposited less carbon in the burners of the engines than any of the other fuels and the JP-3 fuel, with the boiling range of 100° to 600°F and an aromatic content of 29 percent, formed the largest carbon deposit. The JP-1 fuel, the kerosene type, is slightly less than this JP-3 fuel. The remaining two JP fuels formed considerably less carbon than the JP-1 and we can conclude from this that insofar as carbon deposit is concerned any engine that performs satisfactorily with JP-1 would perform satisfactorily with these two JP-3 fuels. The fact that the high aromatic JP-3 fuel formed more carbon than any other JP fuel indicates that some control must be maintained in the specification of the quantity of aromatic that may be in the fuel in order to avoid excessive engine deposits. The next chart (C-24172-A) illustrates the results of altitude starting tests. Altitude starts may be necessary in the case of bomber-type aircraft in which one or more engines may be inoperative during a flight and started at some time during the flight for increased speed or it is important in the case of fighter aircraft when altitude operational limits have been exceeded and burner blowout occurs. The results shown on this chart indicate that the altitude starting limit is about 75 percent higher than JP-1 fuel. This result was obtained in one of our current engines. It is emphasized however, that these starting limits will vary from one engine to another. Consequently the results on this chart are merely an indication of differences in fuel starting characteristics in a specific engine at a specific set of conditions. In summarizing performance data obtained on the JP-3 fuels I should like to refer once again to the backdrop (See also C-24172-C). I have just shown that the carbon deposition and starting characteristics of JP-3 fuels in current engines designed for JP-1 are equal to or better than those of the JP-1 fuels. In the case of combustion efficiencies and altitude operational limits it was also found that JP-3 fuel was equal to or better than JP-1 fuel. There are other factors aside from performance characteristics that must be considered before a fuel is acceptable. These are related to handling problems both in flight and on the ground. One such factor to be considered is vapor loss. As you know, with gasoline, vapor will be lost by boiling of the fuel as an airplane is taken to altitude. In the case of gasoline in which the fuel temperature is 100° F the loss by evaporation in going to 40,000 feet would be about 8 percent. More important than the boiling losses, however, are the surging losses that occur during rapid climb with full tanks. Since these factors were true for aviation gasoline they would also be true for JP-3 fuels since JP-3 fuels include the gasoline range of components. We have here a demonstration - -

One possible solution to the vapor loss problem is pressurization of tanks. However, this imposes a weight penalty on aircraft and also increases the difficulties in the design of self-sealing fuel tanks. Still another possible solution is the removal of the more volatile components from the fuel since these components will belost anyway. Considering a JP-3 fuel which has a volatility as indicated by its vapor pressure of 7 pounds per square inch, if we remove a portion of the more volatile components and reduce the vapor pressure to a lower value, for example, 1 pound per square inch, we would minimize the loss through boiling. At the same time the availability of the fuel would be reduced by about 15 percent and other problems would result as indicated on the next chart. On this chart (C-24171-C) we show the inflammability limits of three fuels. On the ordinate we have plotted altitude and on the abscissa fuel temperature. Considering JP-3 fuel the zone which is colored red on this chart shows the region of altitude and temperatures in which the fuel and air mixture over the liquid surface of the fuel in an aircraft tank will be inflammable. At sea level inflammable mixtures will exist in the tank with JP-3 fuel between temperatures of -40° F and +15°F. However, this range of temperatures will vary with altitude. If, at 0°F, we were to hold the fuel temperature constant and increase the altitude up to about 15,000 feet we would still have inflammable mixtures within the tank. Increasing the altitude still further we would pass out of the zone of inflammability and on this side of the zone there would be too much vapor present for the quantity of air present and the mixture would be too rich to burn. On the left side of the zone we would have a reverse situation where the mixtures would be too lean to burn. The next fuel shown is a cut JP-3 fuel and this is the same as the JP3 fuel except that the more volatile components have been removed. When this happens the zone of temperatures in which the flammable mixtures occur in the tank is raised to a higher temperature level at sea level of +30° to +100° F and this range of temperatures is more frequently encountered in service. The inflammability zone of JP-1 fuel, the kerosene type fuel, is in still a higher temperature region. It is fairly obvious that with all three of these fuels during certain conditions of operation we will be in and out of these zones of inflammability. We have here a demonstration --

These two demonstrations have shown the type of problems we must face aside from problems of performance in the engines and in summarizing we can see that JP-3 fuel is available in sufficient quantity for an emergency and that it performs satisfactorily in our current engines which have been designed for JP-1 fuel. On the other hand we have the problem of vapor loss and in turn the problem of inflammable mixtures in tanks and for this reason the final fuel must necessarily be a compromise from consideration of both the advantages and disadvantages. Research results that I have described and the research continuing at this Laboratory will ultimately lead to the selection of a fuel that will be optimum from considerations of availability and over-all performance. Around such a fuel our future engines can be developed.

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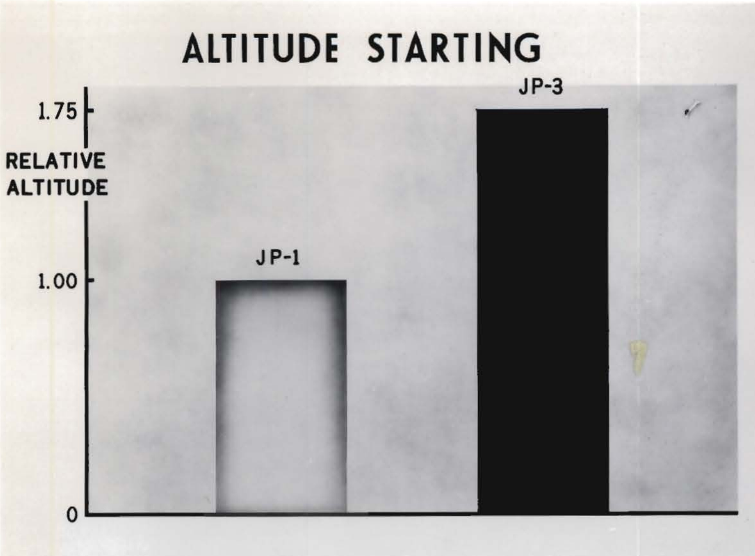
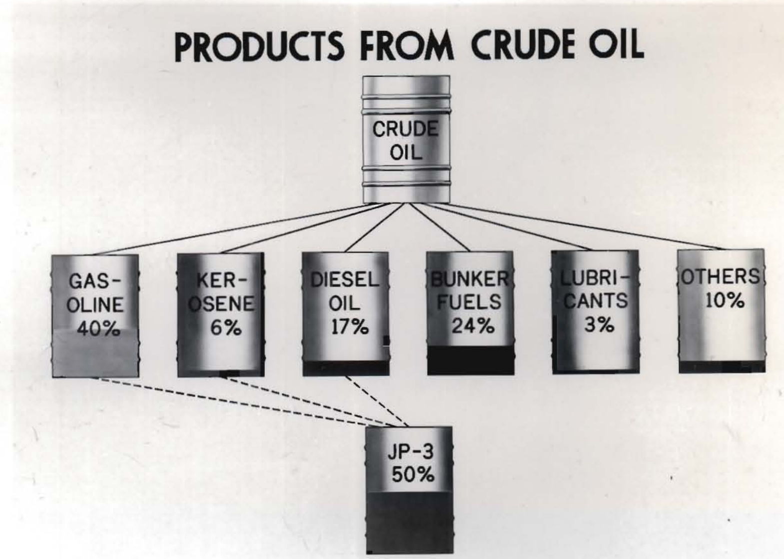


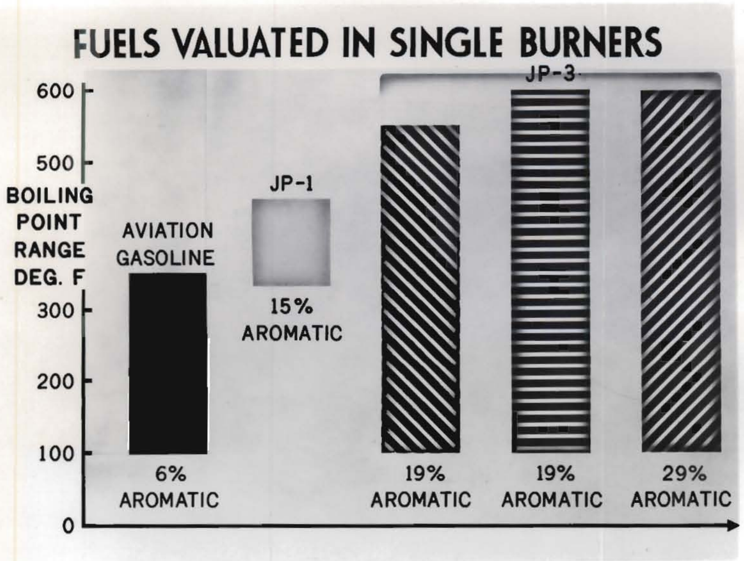


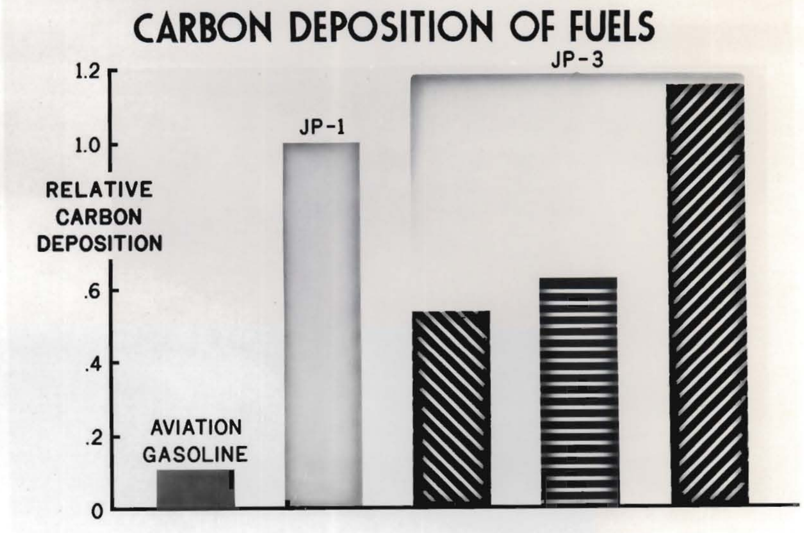
TURBOJET FUEL CONSIDERATIONS

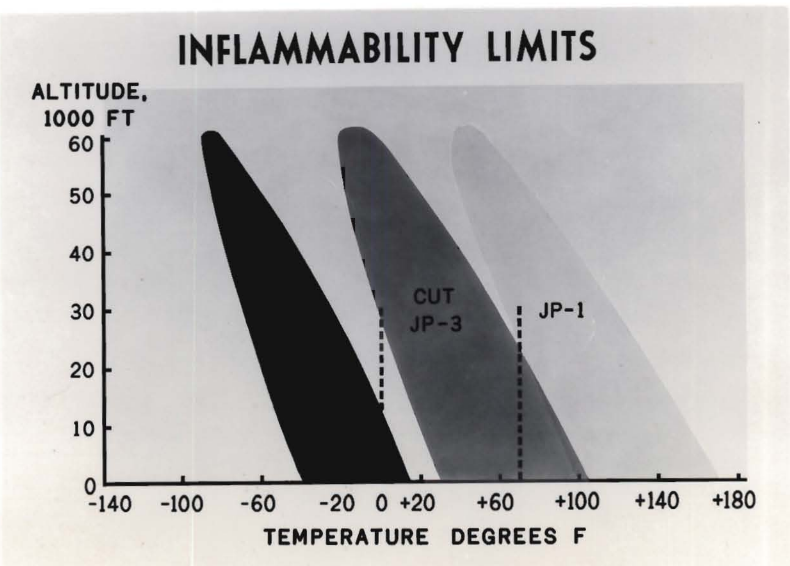
1. AVAILABILITY
2. FLIGHT RANGE
3. AIRCRAFT PERFORMANCE

(A) ENGINE PERFORMANCE
- (1) COMBUSTION EFFICIENCY
- (2) ALTITUDE LIMITS
- (3) CARBON FORMATION
- (4) MAX. STARTING ALTITUDE

(B) FUEL SYSTEM PERFORMANCE
- (1) VAPOR LOSS
- (2) VAPOR LOCK
- (3) COMBUSTIBLE MIXTURE IN TANKS







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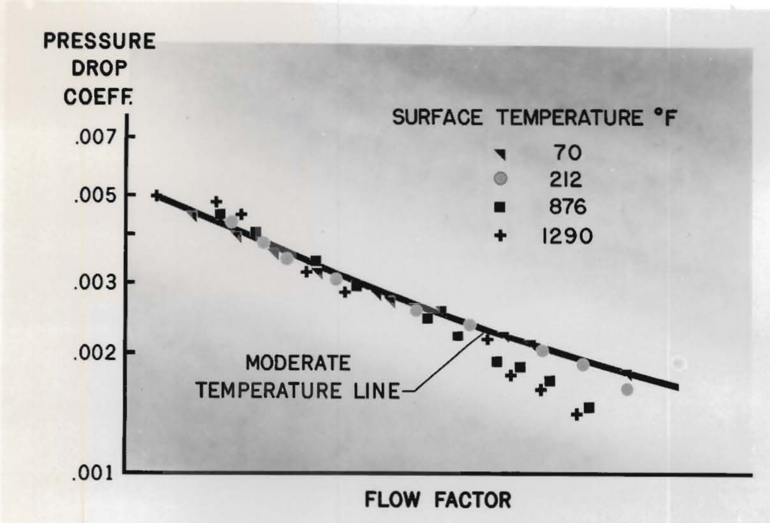

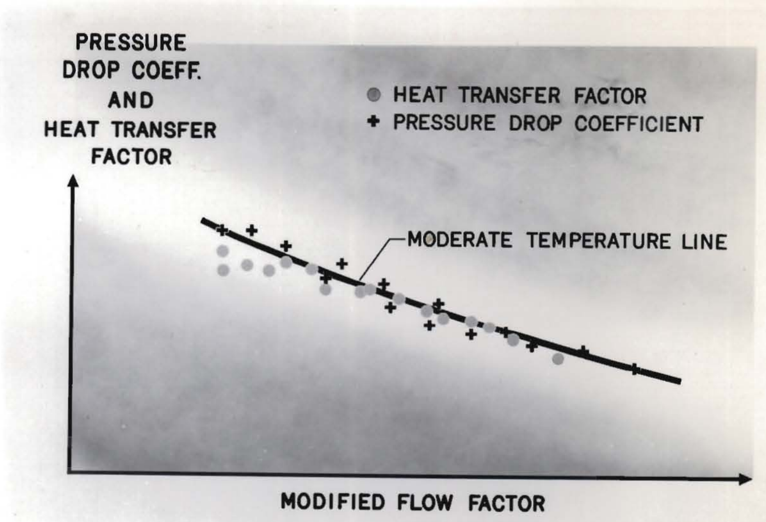

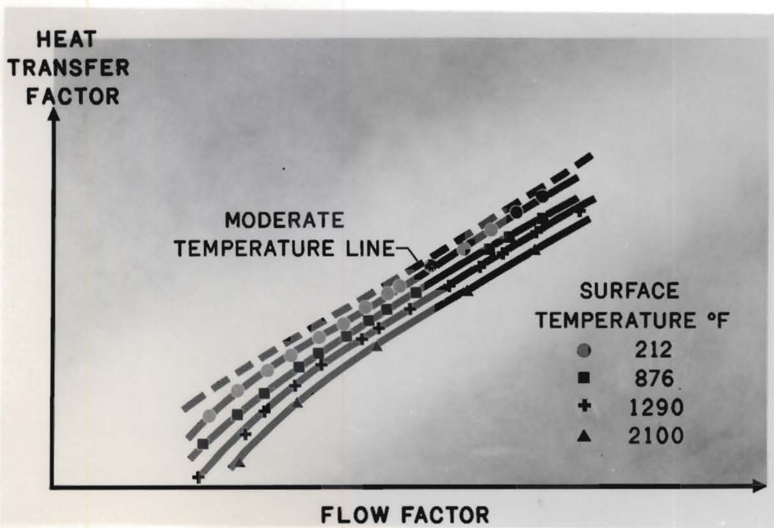

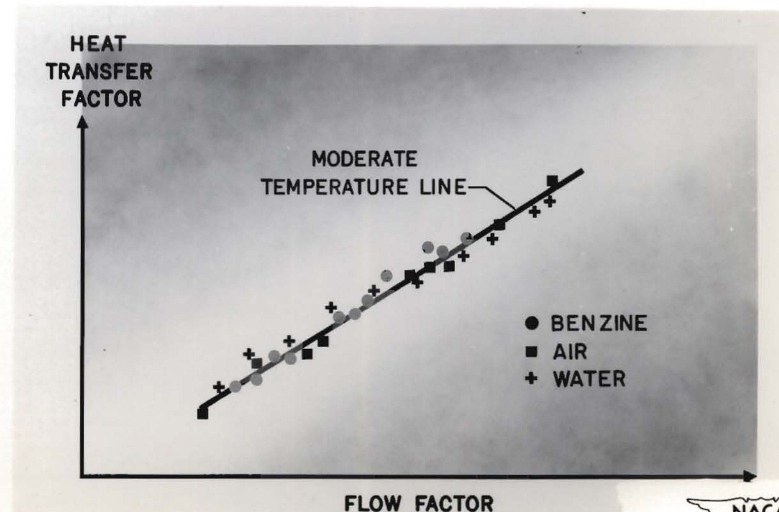

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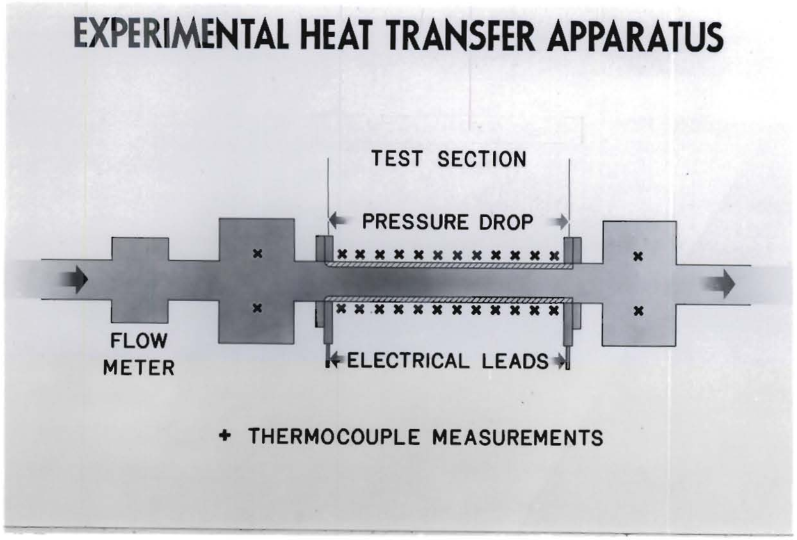
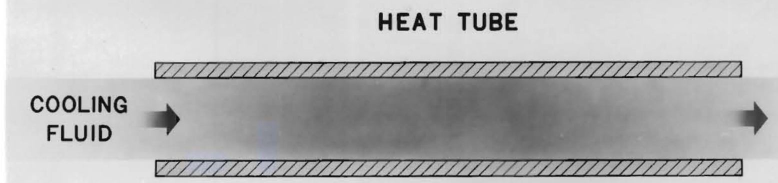
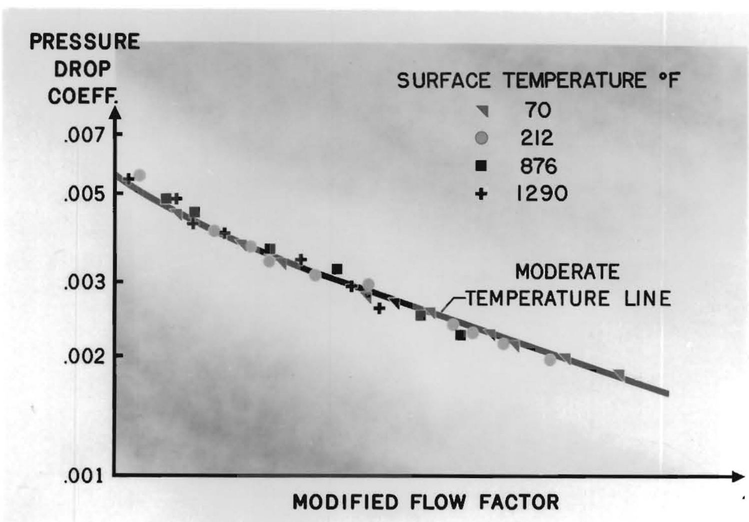
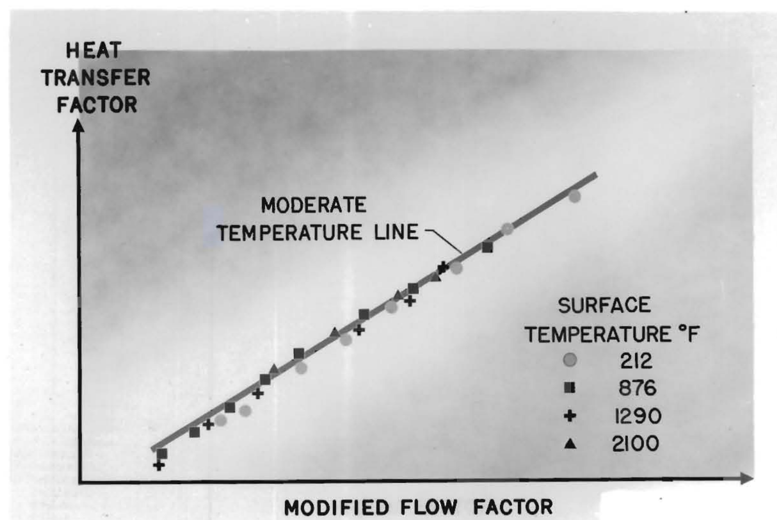


HEAT TRANSFER TERMS



HEAT TRANSFER COEFF. . . h
TUBE DIAMETER . . . . . D
VELOCITY OF COOLANT . . V
DENSITY OF COOLANT . . ρ
VISCOSITY OF COOLANT . μ
SPECIFIC HEAT OF COOLANT . C
THERMAL CONDUCTIVITY OF COOLANT . . . . . . κ
HEAT TRANSFER FACTOR . . $\frac{hD}{\kappa}$
FLOW FACTOR . . . . . . $\frac{\rho VD}{\mu}$





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JP-3 FUEL EVALUATION
PERFORMANCE CHARACTERISTICS
1 CARBON DEPOSITION
2 STARTING
3 COMBUSTION EFFICIENCY
4 ALTITUDE OPERATIONAL
CAN TYPE BURNER
ANNULAR TYPE BURNER
SINGLE BURNERS
ALTITUDE TEST CHAMBER
FULL SCALE ENGINES
FLYING TEST BED
JP-3 VP-7 PSI 0° F
CUT JP-3 VP-1 PSI 0° F
HEAT TRANSFER & FUELS
FUELS VALUATED IN SINGLE BURNERS
BOILING POINT RANGE DEG F
AVIATION GASOLINE
JP-1
15% AROMATIC
6% AROMATIC
19% AROMATIC
19% AROMATIC
29% AROMATIC
ALTITUDE
50,000
40,000
30,000
20,000
10,000


JP-3 FUEL EVALUATION
PERFORMANCE CHARACTERISTICS
1 CARBON DEPOSITION
2 STARTING
3 COMBUSTION EFFICIENCY
4 ALTITUDE OPERATIONAL LIMITS
SINGLE BURNERS
FULL SCALE ENGINES
JP-3 VP-7 PSI 70° F
CUT JP-3 VP-1 PSI 70° F
JP-3 VP-7 PSI 0° F
CUT JP-3 VP-1 PSI 0° F
HEAT TRANSFER & FUELS
PRODUCTS FROM CRUDE OIL
CRUDE OIL
GAS-OLINE 40%
KER-OSENE 6%
DIESEL OIL 17%
BUNKER FUELS 24%
LUBRI-CANTS 3%
OTHERS 10%
JP-3 50%
ALTITUDE
50,000
40,000
30,000
20,000
10,000
C-24152
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