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External Fuel Vaporization Study

Phase II - Interim Report

by

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Prepared for

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FOREWORD

This report describes the results of a study to determine the effect of reduced quality fuel on external fuel vaporization system requirements in advanced gas turbine engines. The effort was conducted at the United Technologies Research Center under sponsorship of the National Aeronautics and Space Administration, Lewis Research Center under Contract NAS3-21971. The NASA Program Manager was C. E. Baker and the UTRC Principal Investigator was E. J. Szetela. The heat exchanger design calculations were performed by L. Chiappetta of UTRC and the engine performance analysis was made by D. R. Weisel of PWA/CPD.

External Fuel Vaporization Study

Phase II Interim Report

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SUMMARY

An analytical study was conducted to evaluate the effect of variations in fuel properties on the design of an external fuel vaporization system. The fuel properties that were considered included thermal stability, critical temperature, enthalpy at critical conditions, volatility, and viscosity. The design parameters that were evaluated included vaporizer weight and the impact on engine requirements such as maintenance, transient response, performance, and altitude relight.

The baseline fuel properties were those of Jet A. The variation in thermal stability was taken as the thermal stability variation for Experimental Referee Broad Specification (ERBS) fuel. The variation in critical temperature was obtained by using the critical temperature of a hypothetical fuel which had the specific gravity and 10 percent distillation point of No. 2 heating oil and the 90 percent distillation point of Jet-A. The variations in enthalpy and volatility were developed from the properties of other hypothetical fuels and the effect of viscosity was based on the properties of a premium diesel fuel.

The results of the analysis indicate that a change in thermal stability equivalent to that of ERBS would increase the vaporization system weight by 20 percent, decrease operating time between cleaning by 40 percent and make altitude relight more difficult. An increase in fuel critical temperature of 30 K would require a 40 percent increase in vaporization system weight. The assumed increases in enthalpy and volatility would also increase vaporizer weight by 40 percent and make altitude relight extremely difficult. The variation in fuel viscosity would have a negligible effect on the design parameters.

INTRODUCTION

During Phase I of the External Fuel Vaporization Study, an analytical investigation was carried out to select an external vaporizer conceptual design. Also, an analytical determination was made of the feasibility of the use of the vaporizer in an aircraft gas turbine with a lean, premixed, prevaporized combustor. In Phase II, the analytical work was extended to determine the effect of using fuels of a quality poorer than that of current commercial aviation fuel. The results of the analytical evaluation are described in this Interim Report. It covers the design and operation of the external fuel vaporization system with fuel properties that represent possible future changes in aviation fuel.

DEFINITION OF FUEL PROPERTIES

Approach

Discussions were held with several individuals concerning the probable properties of future aviation fuels. Included were R. Lohmann, A. Marsh, and F. Haviland of P&WA/CPD, S. Mosier of P&WA/GPD, C. Baker and G. Reck of NASA LeRC, W. Taylor of Exxon, and A. Vranos of UTRC. Publications dealing with future fuels that may be available in the United States which were reviewed included the papers of P. Cambell of United Airlines and A. Momenthy of Boeing published in Ref. 1, A. Churchill, C. Delaney and H. Lander of AFAPL (Ref. 2) and W. Dukek and J. Longwell of Exxon (Ref. 3). Not surprisingly, there is disagreement among the various interested parties. In most instances, the users feel that the present quality of Jet A can be maintained; the suppliers feel that in order to match jet fuel demands with refinery economics in the future, present fuel quality cannot be maintained. It has been noted that recent literature from communist countries contains discussions of improved quality jet fuels (Refs. 4 and 5).

In view of the unsettled status of future fuels, it was deemed desirable to investigate fuels with lower quality than present-day Jet A in the present program. The fuel properties which are of specific interest are enthalpy, critical pressure and temperature, viscosity, and thermal conductivity; these properties can be estimated from specific gravity and distillation range data. Also required are data on the deposit formation rate at elevated temperatures (the deposit formation rate is a function of the type of compounds in the fuel and the type and quantity of impurities). It is believed that thermal stability of the fuel is the most important fuel property from the standpoint of heat exchanger design. For the heat exchangers designed in Phase 1 (Ref. 6) the thermal resistance of the fuel deposit resulted in a surface area increase of 20 percent in the heat exchanger regions where deposit thickness reached 0.005 cm and 100 percent where the deposit thickness reached 0.020 cm. During cleaning, the heat liberated by the oxidation of a 0.020-cm thick deposit can increase the cleaning air temperature 50 K per cm of length; although some heat release is desirable to overcome loss of heat in the cleaning air to the environment, a rapid air temperature rise can damage the heat exchanger.

Only limited amounts of deposit formation data are available for various fuels. A comparison between deposit thickness after 100 hours for JP-5 (Ref. 7), Jet A (Ref. 1) and No. 2 oil (Ref. 1) is shown in Fig. 1. Linear extrapolation of deposit formation data with time was assumed in the development of the figure. (The validity of such an extrapolation is questionable. According to Ref. 8, a tube with an inner diameter of 0.46 cm had a deposit from No. 2 oil 0.025 cm thick after 50 hours but the tube was plugged in 120 hours.) Because of severe deposits that would be encountered, fuel with the properties of No. 2 oil should not be considered in this program. The limiting properties that should be considered are essentially those for Experimental Referee Broad Specification (ERBS) fuel as documented in Ref. 9.

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Fuel Property Selection

The fuel properties that were considered in this program include thermal stability, critical temperature and pressure, specific heat and volatility, viscosity and thermal conductivity.

In reviewing the influence of these properties on heat exchanger performance it was found that critical temperature significantly effects the size requirements of the heat exchanger while critical pressure has minimal effect on heat exchanger performance. Specific heat is the slope of the enthalpy temperature curve, and hence changes in enthalpy are directly related to changes in specific heat. Thermal conductivity is not appreciably affected by fuel type while viscosity is appreciably affected.

As stated previously, it is felt that the limiting fuel deposit properties that should be considered are those of Experimental Referee Broad Specification (ERBS) fuel. However, only a single deposit data point is available for ERBS and it is derived from the assumption that the deposit thickness for ERBS and Jet A are the same at their respective JFTOT breakpoint temperatures. The breakpoint temperature for ERBS, obtained from Ref. 9 is shown in the deposit curve in Fig. 2. Additional points for the ERBS deposit curve were obtained by assuming that ERBS deposit rates are midway between those of No. 2 heating oil and Jet A. Data for No. 2 oil were obtained from Refs. 1 and 10.

The variation in critical temperature, enthalpy and volatility was defined by comparing Jet A with hypothetical fuels having the properties shown in Table 1. Fuel critical temperature and enthalpy can be calculated (Ref. 11) from specific gravity and the distillation curve; gravity and distillation range of the hypothetical fuels were chosen to obtain an increase in critical temperature and enthalpy

Table 1

Properties of Selected Fuels

	Jet-A	Hypothetical Fuels		
		1	2	3
Gravity (API)	43	33.5	53.5	43
Distillation Range (K)				
10%	464	492	372	492
90%	520	520	575	520
Critical Temperature (K)	683	715	683	694
Enthalpy at Tcrit (KCal/Kg)	319	319	346	341

Hypothetical Fuel No. 1 has the specific gravity and 10 percent distillation point of No. 2 heating oil, the 90 percent distillation point of Jet A, a critical temperature higher than that of Jet A but the same enthalpy at the critical temperature. Hypothetical Fuel No. 2 has the specific gravity and 10 percent distillation point of JP-4, the 90 percent distillation point of No. 2 heating oil, critical temperature the same as that of Jet A, and a higher enthalpy at the critical temperature. Hypothetical Fuel No. 3 is the same as Jet A except that it has the 10 percent distillation point of No. 2 heating oil and a higher critical temperature and enthalpy than those of Jet A.

To obtain the effect of changes in fuel viscosity, data were obtained (Ref. 12) for a premium diesel fuel which has a viscosity that is 50 percent higher than that of Jet A at room temperature. It was assumed that the viscosity-temperature curve for the diesel fuel had the same shape as the Jet A curve.

REVISED CALCULATION PROCEDURE

Prior to starting detailed heat exchanger calculations using varying fuel properties, the calculation procedure was reviewed to determine if a previously observed computational problem could be corrected. The analysis failed when the iteration procedure did not result in a stable combination of wall temperature and deposit thickness for the selected fuel deposit curve such as that shown for Jet A in Fig. 2. It was found that a change in the calculation procedure would stabilize the iteration and the procedure was modified.

In the original calculation procedure, steady state temperature and deposit thickness were assumed at every operating condition being considered and no information concerning the previous flight history was included in the calculation. It is presently felt that a more realistic approach is to assume that the allowable (limiting) deposit buildup of 0.02 cm occurs at the engine cruise condition and that the deposit thickness can be calculated from the wall temperature distribution in a clean heat exchanger. Therefore, a revised procedure has been established in which the analysis of a heat exchanger is made in three steps.

The first two steps in the revised calculation procedure are (1) determine the wall temperatures in a clean heat exchanger at cruise conditions and (2) use the wall temperatures to determine the deposit thickness distribution at 100 hours using the data for Jet A as shown in Fig. 2. The results of these two calculations are stored in the program and recalled in the analysis of subsequent steady-state or transient operating conditions such as Sea-Level Takeoff (SLTO), altitude relight, and engine acceleration and deceleration.

The revised procedure was applied to the analysis reported in Ref. 6 and revealed that additional heat exchanger design options are available; specifically, either the heat exchanger size or the inlet air temperature can be reduced as shown in Table 2.

TABLE 2

Comparison of Heat Exchanger Analyses

	Length (in direction of hot gas flow) cm	Air Inlet Temperature K	Max. Fuel Side Wall Temp. K
Original Procedure			
SLTO	66	1255	1120
Cruise	66	1145	1005
Revised Procedure-reduced size			
SLTO	48	1255	1010
Cruise	48	1185	880
Revised Procedure-reduced temperature			
SLTO	66	1185	930
Cruise	66	1145	825

With the revised procedure, the maximum fuel side wall temperature is lower than previously calculated. This is a significant design advantage since it was concluded in Ref. 6 that corrosion-erosion considerations could limit the allowable wall temperature to a value on the order of 800 K.

The revised calculation procedure was also applied to the other operating conditions that were developed in Ref. 6. Satisfactory steady-state operation at approach and idle are illustrated in Fig. 3 where the heat exchanger exit fuel temperature is plotted against hot gas inlet temperature. The minimum required fuel temperature which is sufficient to obtain completely vaporized fuel downstream of the throttle can be easily attained. However, the corresponding hot gas inlet temperature and related auxiliary burner fuel-air ratio is too low for efficient combustion at the minimum temperature. A higher fuel-air ratio, approximately 0.010, and the corresponding fuel exit temperature, approximately 750 K, would probably be selected at approach and idle.

Acceleration and deceleration were also investigated using the revised operating procedure. It was found that the times required for the transients between idle and sea level takeoff (SLTO) were reduced by a factor of approximately two. As a result, the increase in transient time resulting from the presence of the heat exchanger is calculated to be 1-2 seconds as compared with 2-4 seconds for the original procedure.

EFFECT OF FUEL PROPERTIES

Increased fuel deposits affect the size of the heat exchanger because deposits add to the overall resistance to heat transfer. Increased deposits also aggravate the problem of deposit removal. Increased viscosity increases the overall resistance to heat transfer by increasing the fuel film resistance. Critical temperature, enthalpy and volatility (which affects critical temperature and enthalpy) of the fuel significantly affect the size requirements of the heat exchanger. An increase in either property increases the amount of heat that must be added to the fuel, and for a fixed hot gas flow rate, the temperature difference across the heat exchanger is also reduced. A detailed analysis of the effects of critical temperature and enthalpy are shown in the Appendix.

The vaporizer design approach that was used to evaluate the effect of fuel properties consisted of calculating the size and weight of the heat exchanger for each fuel described previously. The required computer program input and the target fuel temperature were identified for each fuel and the heat exchanger size was varied until the target temperature was obtained. Intermediate points were also included in order to present the results in graphical form.

Deposit Thickness

An increase in deposit formation because of the differences in properties between Jet A and ERBS would increase the weight of the heat exchanger by 22 kg as shown in Fig. 4. The maximum wall temperature would also be increased, but the amount (20 K) is not considered to be significant. However, a very significant difference between Jet A and ERBS is the deposit formation rate which would result in a maximum thickness of 0.033 cm with ERBS after 100 hours compared with 0.020 cm with Jet A. A maximum thickness of 0.020 cm is advisable from a cleaning standpoint; therefore, the operating time between cleaning for ERBS would be 61 hours compared with 100 hours with Jet A.

Critical Temperature

An increase in critical temperature would increase the weight of the heat exchanger as shown in Fig. 5. The maximum wall temperature with hypothetical Fuel No. 1 would be 40 K lower than the wall temperature with Jet A. A tradeoff between weight and wall temperature is possible; therefore, the weight penalty of 40 kg can be slightly reduced in a more extensive design effort.

Enthalpy

An increase in fuel enthalpy would increase the weight of the heat exchanger by 40 kg as shown in Fig. 6. Also required would be an increase in hot gas flow of 10 percent to supply the required energy to the fuel. The increased gas flow would be obtained by an increase in the compressor bleed flow. This would not

seriously affect the engine cycle because only a portion of the bleed flow would be utilized in the vaporization system. However, an increased bleed flow of 10 percent slightly affects the auxiliary combustor size and the gas flow distribution system. The maximum wall temperature with hypothetical Fuel No. 2 would be 40 K lower than the wall temperature with Jet A.

Volatility

An increase in volatility exemplified by Hypothetical Fuel No. 3 was defined as an increase in the temperature corresponding to the distillation of 10 percent of the fuel. The critical temperature and the enthalpy at critical temperature of the fuel are also increased (Table 3) which would result in an increase in the heat exchanger weight of 40 kg and the required gas flow rate by 7 percent. These effects are shown in Fig. 7. The maximum wall temperature with hypothetical Fuel No. 3 would be 45 K lower than that with Jet A.

Viscosity

The effect of fuel viscosity on heat exchanger size was found to be negligible. The heat transfer resistance of the fuel film in the heat exchanger would be low compared with the resistance of the air film, and both would be lower than the maximum resistance of the deposit. Therefore, a change in the fuel film resistance resulting from an increased fuel viscosity would not noticeably affect the overall heat transfer rate or the weight of the heat exchanger.

Engine Transient Response and Altitude Relight

The effect of fuel properties on the transient times required between idle and SLTO during acceleration and deceleration was investigated for ERBS and hypothetical Fuels Nos. 1 and 2. Transient times for the three fuels would be approximately one second (slightly lower than for Jet A). Engine transient response would not be substantially affected by the fuel properties.

The effect of fuel properties on altitude relight was investigated for ERBS and hypothetical Fuels Nos. 1 to 3. Altitude relight with Jet A requires the fuel temperature in the heat exchanger be raised to 585 K in order to obtain a dew point of 495 K. The heat exchanger calculations indicated that the target temperature of Jet A can be reached with all of the other fuels with the heat exchanger size and airflow (compressor bleed flow) as specified by the sea level take off design requirements. However, the required fuel temperature of ERBS is estimated to be approximately 40 K higher than for Jet A. If the airflow were to be maintained at the level used with Jet A, the heat exchanger weight would be increased by 100 percent. This would correspond to an increase in vaporization system weight of 90 percent.

Hypothetical Fuels No. 1 and 3 (increased critical temperature and volatility) have the same 90 percent distillation point as Jet A; therefore, the required fuel temperature for these fuels should be close to that of Jet A. The use of Fuel No. 3 would require an increase in airflow and since compressor bleed flow will be difficult to obtain at altitude relight conditions, this fuel will cause relight problems. Hypothetical Fuel No. 2 (increased critical enthalpy) has a higher 90 percent distillation point than Jet A requiring an increase in heat exchanger size for altitude relight. Fuel No. 2 also would require an increase in airflow; therefore, relight problems will be encountered with this fuel.

Engine Performance

In Ref. 6 it was found that the fuel vaporization system would permit an improvement in engine performance because the cooled gas (vitiated air) leaving the heat exchanger can be used more effectively for turbine cooling than hot compressor bleed air at certain turbine locations. Performance improvement included specific fuel consumption, thrust, and thrust/weight ratio when the engine bypass ratio was varied and the engine core remained unchanged. The engine performance results were reviewed to determine if the effect of the external fuel vaporization system on engine weight can be estimated. The results indicated that the improvement in thru weight ratio of approximately 3 percent resulting from the use of heat exchanger exit air for turbine cooling can be applied to engine weight to estimate potential weight reduction in a re-designed engine. The projected E^3 engine weight is at present in the vicinity of 3000 Kg; therefore, the vaporization system with Jet-A has the potential of decreasing that weight by approximately 100 Kg.

Estimates of the effect of fuel properties indicate that use of any of the oth fuels being considered in this program would result in a weight saving which is approximately the same as that with Jet-A. The use of any of the other fuels in conjunction with an external fuel vaporization system would produce the same reduction in specific fuel consumption as Jet-A (0.5 percent at cruise, based on an increase in turbine inlet temperature).

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CONCLUSIONS

The assessment of the effect of fuel properties indicated that in comparison with Jet-A, future aircraft fuels will impose more stringent design requirements on the external fuel vaporization system. Maintenance of the engine will be more frequent; the allowable operating time between cleaning will be decreased with fuels having a greater tendency for deposit formation. Vaporization system weight will be increased by 20 to 40 percent (0.5 to one percent of engine weight). Although engine transient response and engine performance will not be appreciably affected, altitude relight will be considerably more difficult. The calculated gains in engine performance attributable to the use of Jet-A with an external fuel vaporization system are retained with lower quality fuels.

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APPENDIX

Impact of Fuel Properties

The effects of fuel critical temperature and enthalpy at the fuel critical temperature can be shown using the following simplified analysis. The heat required to raise the fuel temperature to a specified outlet temperature is:

$$\dot{Q} = (\dot{W}Cp)_F \, (T_{F_{OUT}} - T_{F_{IN}}) \tag{1}$$

This heat is supplied by the hot gas products of combustion:

$$\dot{Q} = (\dot{W}Cp)_A \, (T_{A_{IN}} - T_{A_{OUT}}) \tag{2}$$

The heat gained by the fuel (and lost by the hot gas) can also be expressed in terms of the overall heat transfer coefficient for the heat exchanger:

$$\dot{Q} = UA_W \, (\overline{T}_A - \overline{T}_F) \tag{3}$$

where

$$\overline{T}_A = \frac{1}{2} (T_{A_{IN}} + T_{A_{OUT}}) \tag{4}$$

and

$$\overline{T}_F = \frac{1}{2} (T_{F_{IN}} + T_{F_{OUT}}) \tag{5}$$

These equations may be combined to yield an expression for the product of overall heat transfer coefficient and surface area, a measure of the size of the heat exchanger:

$$UA_W = \frac{2(\dot{W}Cp_F)\,\Delta T_F}{D_1} \tag{6}$$

where

$$\Delta T_F = T_{F_{OUT}} - T_{F_{IN}} \tag{7}$$

and

$$D_1 = 2(T_{A_{IN}} - T_{F_{IN}}) - \Delta T_F \left[1 + \frac{(\dot{W}Cp)_F}{(\dot{W}Cp)_A} \right] \tag{8}$$

As the critical temperature is increased while all other parameters are held constant, the required fuel outlet temperature is increased. The amount of heat that must be supplied to the fuel is increased (Eqn. 1). Differentiating Eqn. (6) with respect to ΔT_F yields

$$\frac{\partial(UA_W)}{\partial(\Delta T_F)} = \frac{4(\dot{W}Cp)_F\,(T_{A_{IN}} - T_{F_{IN}})}{D_1^2} > 0 \tag{9}$$

since necessarily $T_{A_{IN}} > T_{F_{IN}}$. Thus, as the fuel critical temperature is increased the heat exchanger must become larger.

As the enthalpy of the fuel at the critical temperature is increased while the critical temperature is held constant, the average fuel specific heat is increa and therefore the product $(\dot{W}Cp)_F$, is increased. Thus, the amount of heat that must be supplied by the fuel is increased (Eqn. 1). Differentiating Eqn. (6) with respect to $(WCp)_F$ yields:

$$\frac{\partial(UA_W)}{\partial(\dot{W}Cp)_F} = \frac{2\Delta T_F}{D_1^2}\left[T_{A_{IN}} - T_{F_{IN}} + T_{A_{IN}} - T_{F_{OUT}}\right] > 0 \tag{10}$$

since $T_{A_{IN}} > T_{F_{OUT}} > T_{F_{IN}}$. Thus, as the enthalpy at the fuel critical temperature is increased, the heat exchanger must become larger.

The effects of fuel critical temperature and enthalpy may also be examined in terms of the mean temperature difference across the heat exchanger. Defining

$$\Delta\bar{T} = \bar{T}_A - \bar{T}_F \tag{11}$$

then Eqns. (1) through (5) may be combined to obtain:

$$\Delta\bar{T} = \frac{T_{A_{IN}} - T_{F_{IN}}}{D_2} \tag{12}$$

where

$$D_2 = 1 + \frac{UA_W}{2}\left[\frac{1}{(\dot{W}Cp)_A} + \frac{1}{(\dot{W}Cp)_F}\right] \tag{13}$$

Upon differentiating (Eqn. 12) with respect to ΔT_F and using Eqn. (9) in the resulting expression, it can be shown that:

$$\frac{\partial(\Delta\bar{T})}{\partial(\Delta T_F)} < 0 \tag{14}$$

Upon differentiating (Eqn. 12) with respect to $(\dot{W}Cp)_F$ and using Eqns. (6) and (10), it can be shown that

$$\frac{\partial(\Delta\bar{T})}{\partial(\dot{W}Cp)_F} < 0 \qquad (15)$$

Thus, an increase in either the fuel critical temperature (T_F) or critical enthalpy ($\dot{W}C_p$) results in a decrease in the mean temperature difference across the heat exchanger.

This simplified analysis is presented only for illustrative purposes. A more rigorous analysis is contained in the computer program that is used for heat exchanger performance analysis and design.

List of Symbols

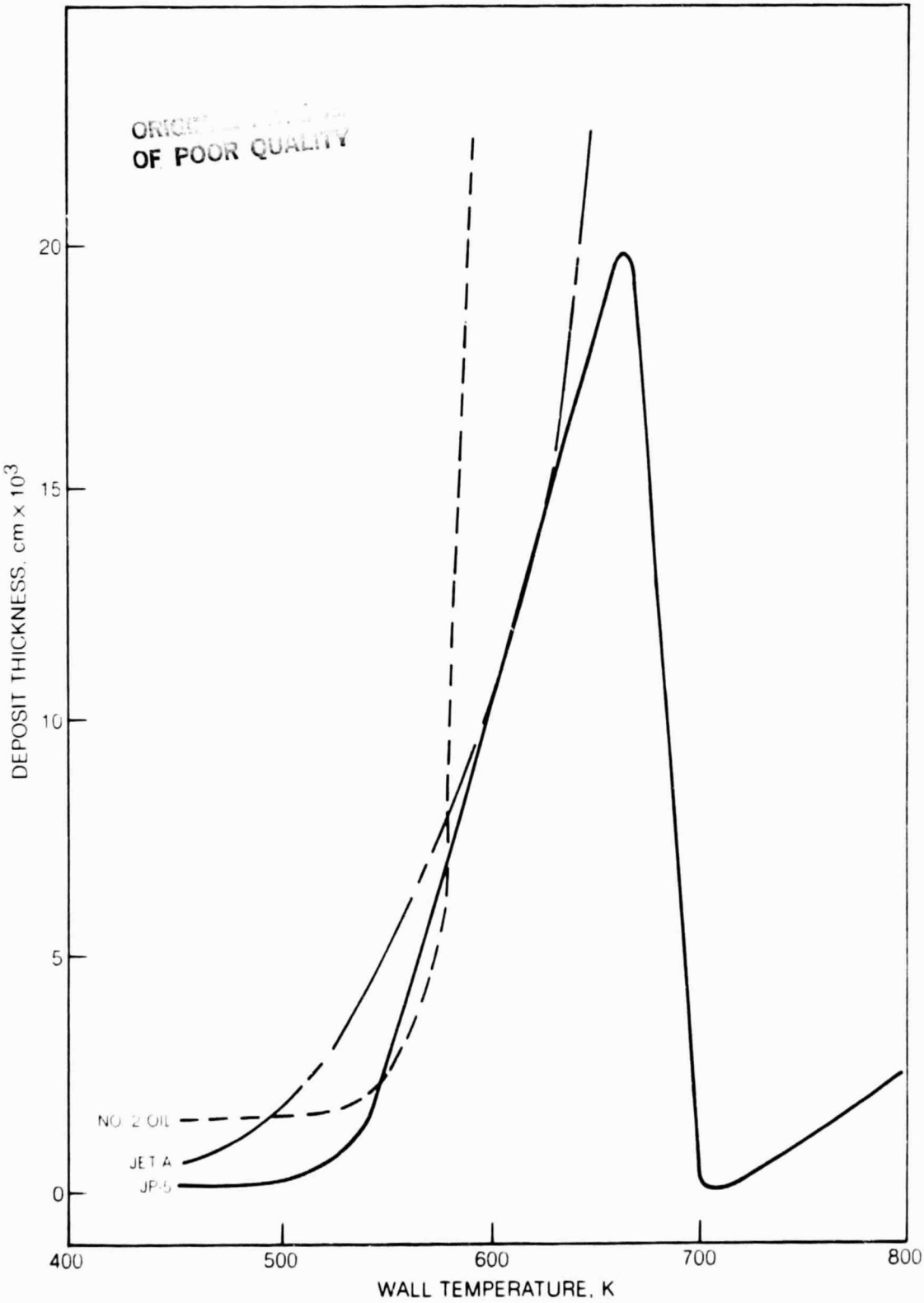
A	Surface Area, m^2
Cp	Specific heat at constant pressure, cal/g-K
$\dot{Q}$	Heat transfer rate, cal/hr
T	Temperature, K
U	Overall heat transfer coefficient, cal/hr-m^2-K
$\dot{w}$	Weight flowrate, g/hr

Subscripts

A	Hot gas
F	Fuel
IN	Inflow condition
OUT	Outflow condition
w	Wall

FIG. 1

DEPOSIT THICKNESS AFTER 100 HOURS



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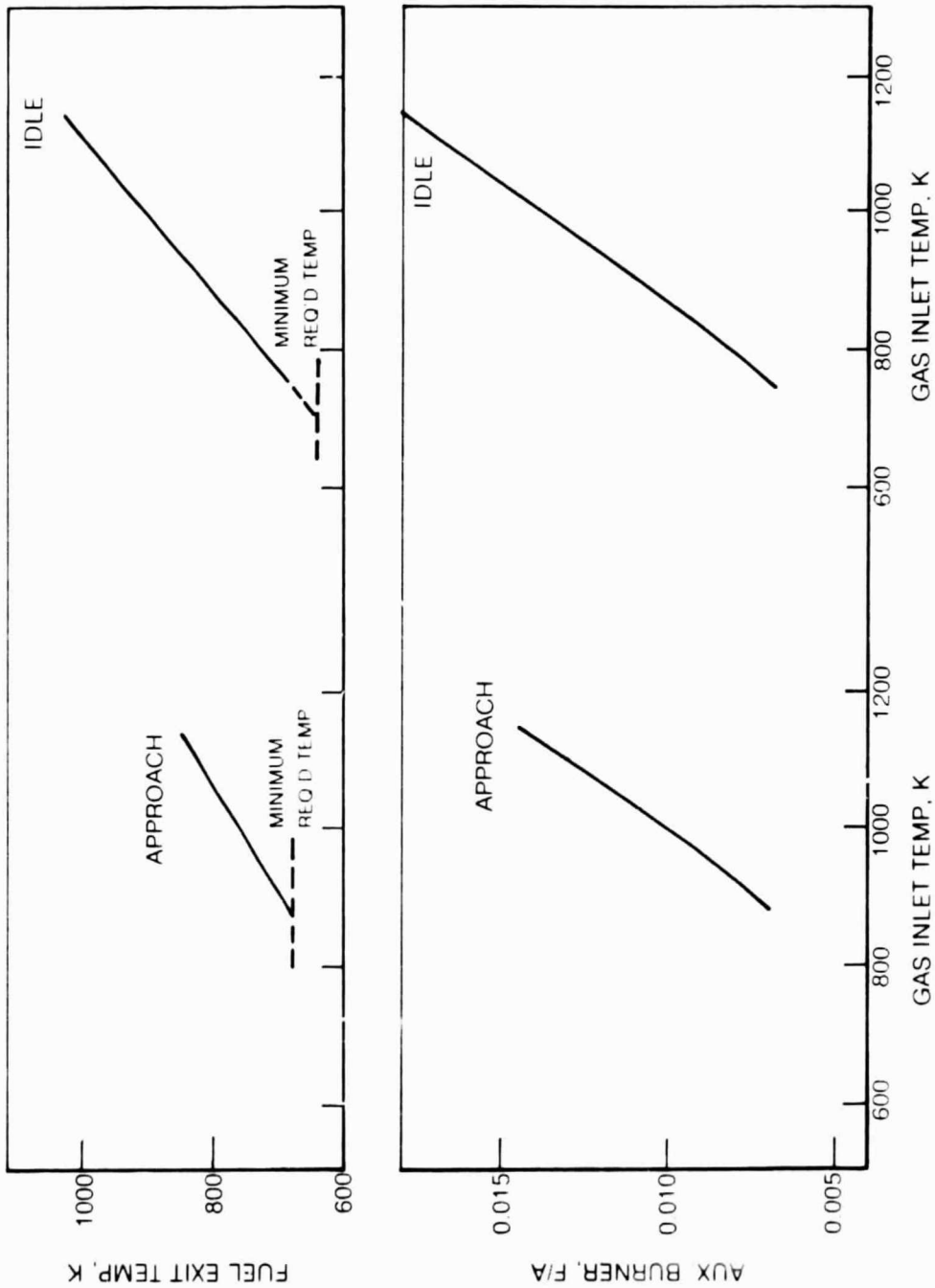
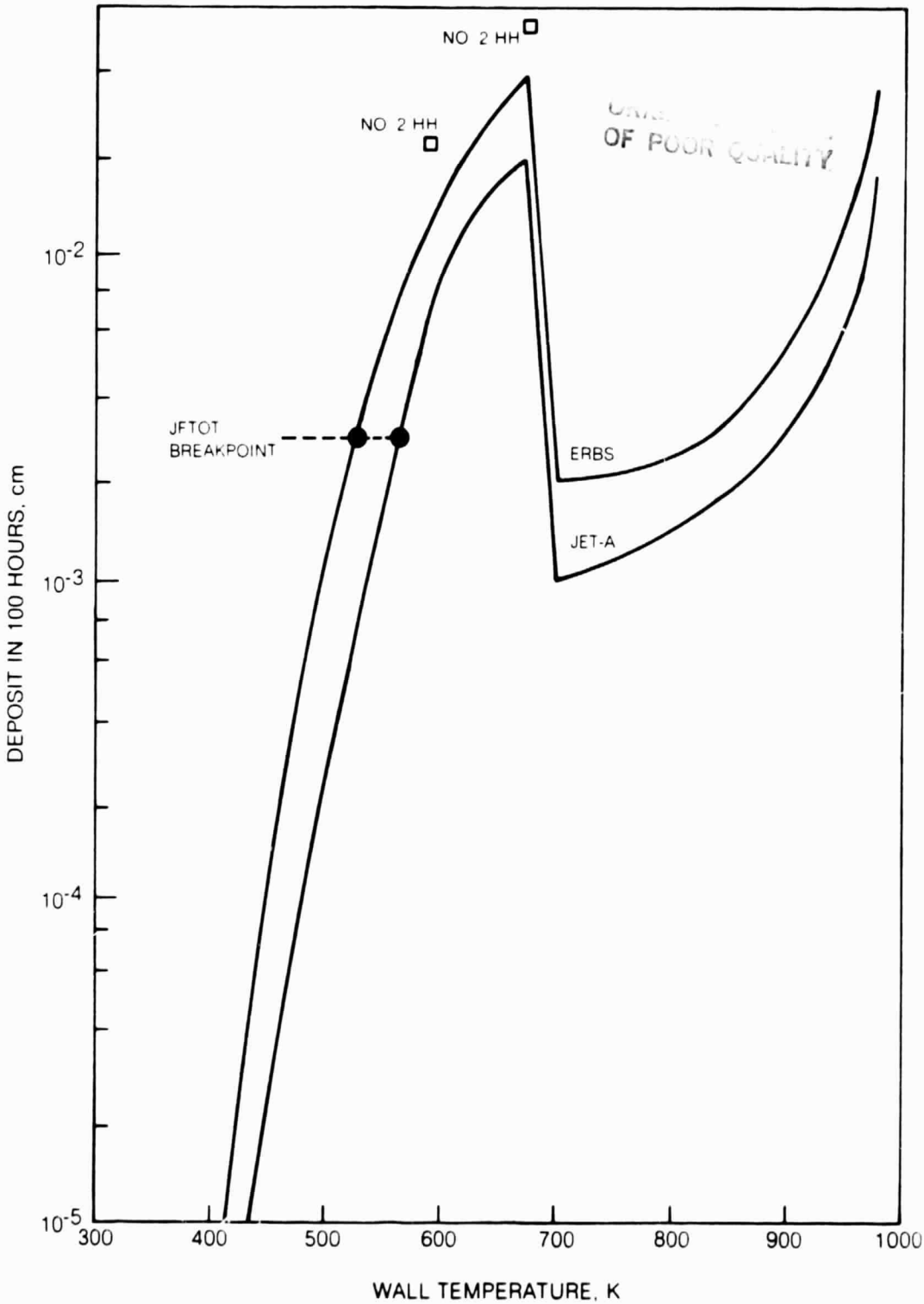
HEAT EXCHANGE PERFORMANCE AND AUXILARY BURNER REQUIREMENTS



DEPOSIT FORMATION FOR JET-A AND ERBS



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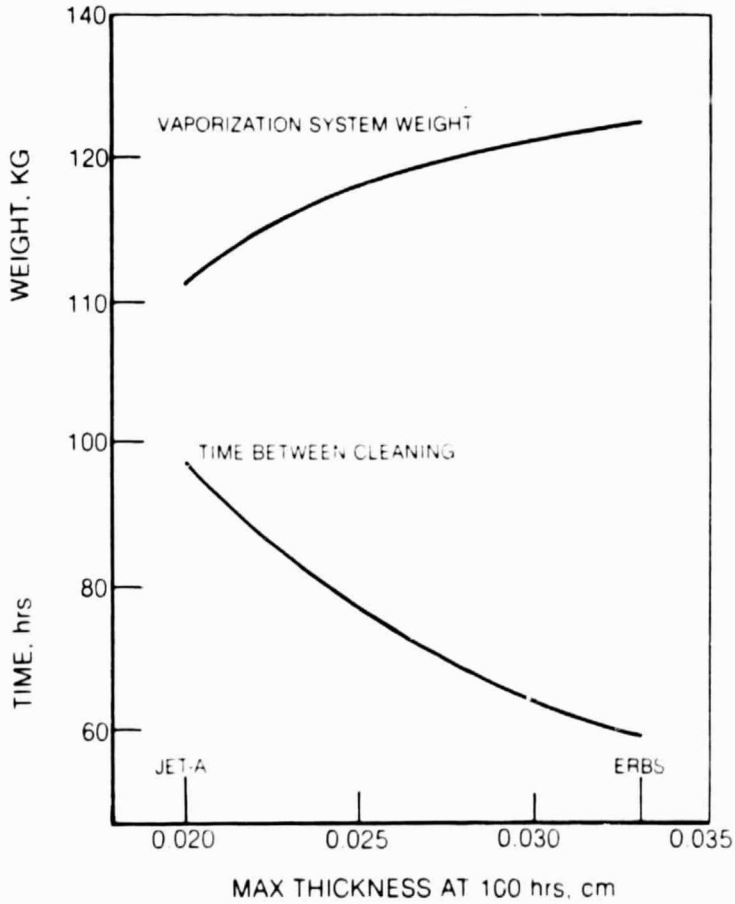
EFFECT OF MAXIMUM DEPOSIT THICKNESS

HEAT EXCHANGER DESIGN PARAMETERS



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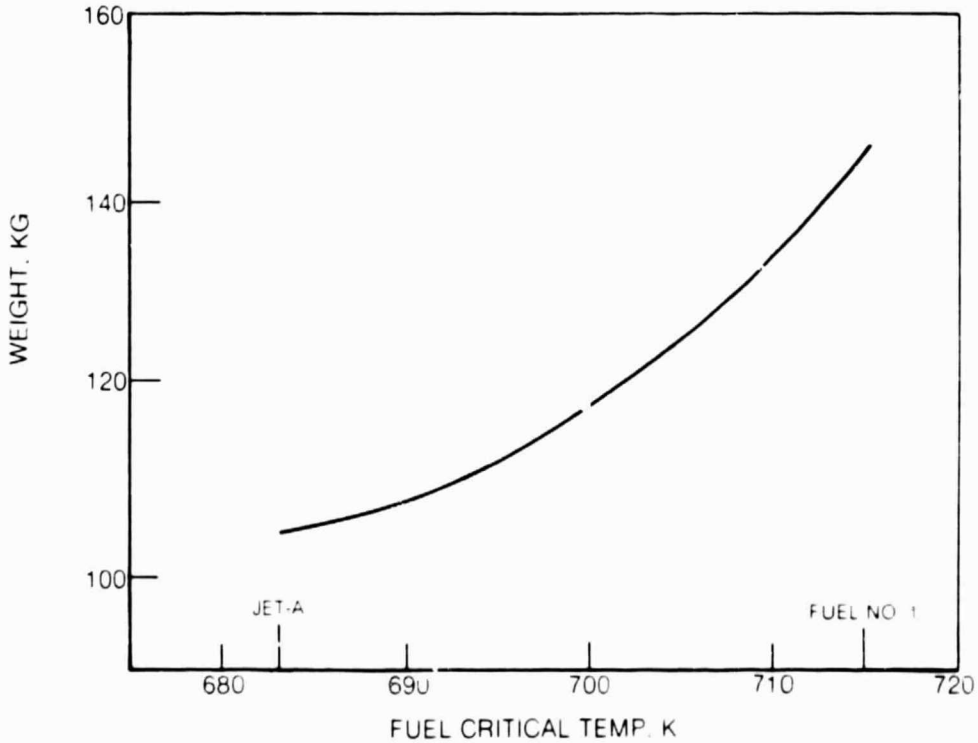
EFFECT OF CRITICAL TEMPERATURE ON WEIGHT



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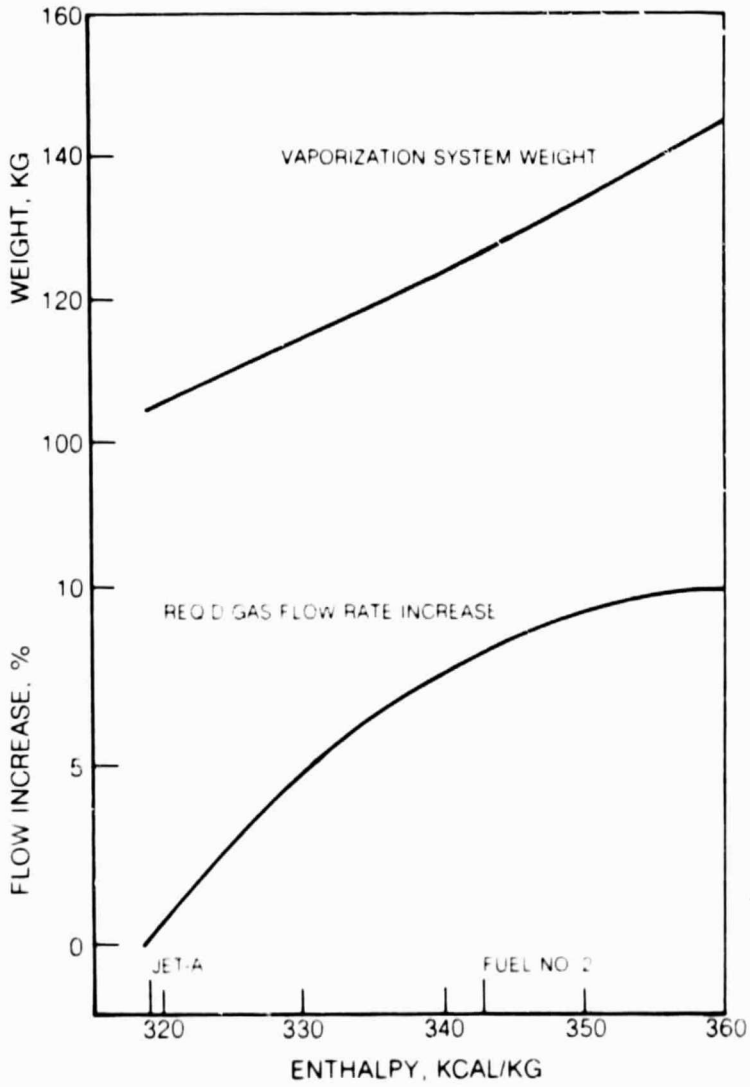
EFFECT OF ENTHALPY AT THE CRITICAL TEMPERATURE ON WEIGHT



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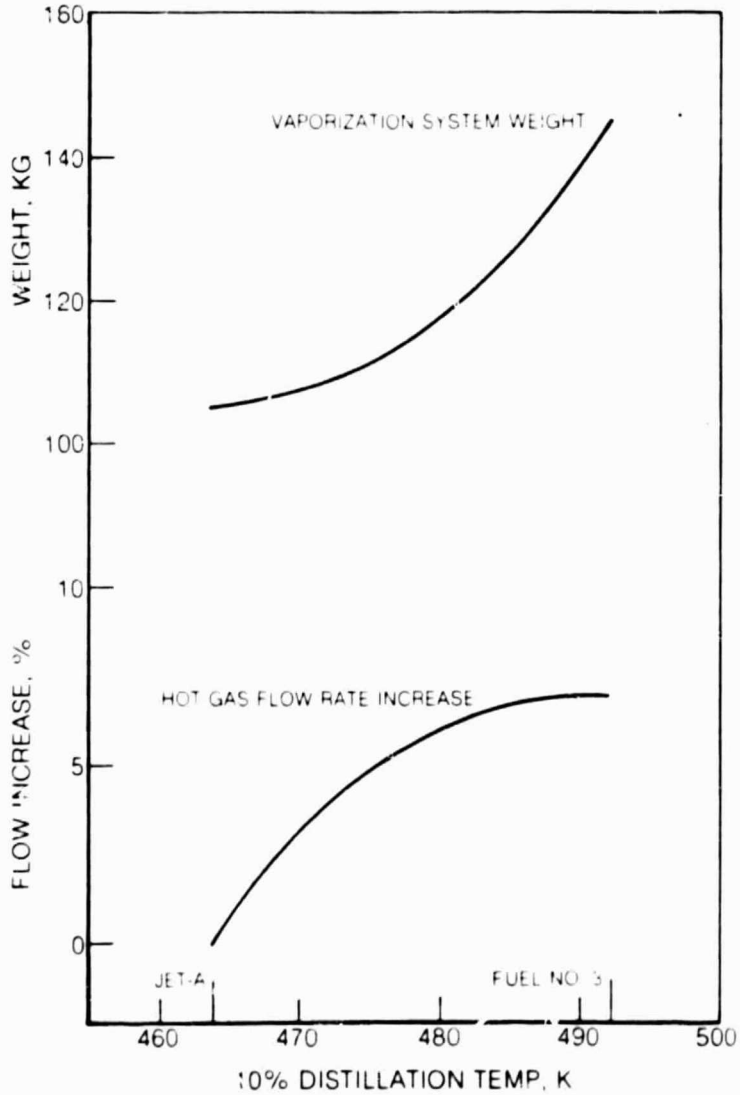
EFFECT OF FUEL VOLATILITY ON WEIGHT