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A KINETIC MODEL FOR TWO-PHASE FLOW IN HIGH TEMPERATURE EXHAUST GAS COOLERS

John M. Pelton and C. E. Willbanks

ARO, Inc.

June 1972

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An analytical model was developed to describe the thermodynamic and fluid dynamic processes in an exhaust gas cooler employing liquid water injection. The model is based on the solution of the equations of conservation of species, momentum, and energy for the system and the equations for the exchange of these quantities between liquid and gaseous phases. These equations are programmed for solution on an IBM 360 computer. The predictions of the model are compared with measured data from a series of turbojet tests in the Propulsion Development Test Cell (T-1) spray cooler. The comparison showed that the model gave a good agreement with the measured pressure and liquid temperature at various points along the cooler. Parameters such as gas temperature and specific humidity which were not measured are discussed in terms of their relation to the overall cooler performance. From the results of the measurements and predictions, a physical description of the cooling process is presented. Based on the results of one of the tests, a possible method of reducing the pressure loss in a cooler is proposed.

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FOREWORD

The work reported herein was conducted at the request of the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee. Data produced as a result of this research effort has been shared with the Federal Republic of Germany under Annex No. AF-66-G-7406 to the Mutual Weapons Development Plan Master Data Exchange Agreement between the governments of the United States and the Federal Republic of Germany.

The work involved analytical study and experimental testing conducted by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center, AFSC, under contract F40600-72-C-0003. The test data were taken from tests conducted in the Propulsion Development Test Cell (T-1) spray cooler of the Engine Test Facility (ETF) under ARO Project Nos. RW0856, RW2116, and RW2216, and the manuscript was submitted for publication on May 16, 1972.

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This technical report has been reviewed and is approved.

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ABSTRACT

An analytical model was developed to describe the thermodynamic and fluid dynamic processes in an exhaust gas cooler employing liquid water injection. The model is based on the solution of the equations of conservation of species, momentum, and energy for the system and the equations for the exchange of these quantities between liquid and gaseous phases. These equations are programmed for solution on an IBM 360 computer. The predictions of the model are compared with measured data from a series of turbojet tests in the Propulsion Development Test Cell (T-1) spray cooler. The comparison showed that the model gave a good agreement with the measured pressure and liquid temperature at various points along the cooler. Parameters such as gas temperature and specific humidity which were not measured are discussed in terms of their relation to the overall cooler performance. From the results of the measurements and predictions, a physical description of the cooling process is presented. Based on the results of one of the tests, a possible method of reducing the pressure loss in a cooler is proposed.

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APPENDIXES

I. ILLUSTRATIONS

Figures

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NOMENCLATURE

A	Cross-sectional area of cooler as function of distance x along the cooler, ft^2
AA	Fraction of cooler not blocked by piping
A_o	Cross-sectional area of cooler at x = 0, ft^2
C_D	Drag coefficient
c_ℓ	Specific heat of liquid water, Btu/lbm - °R
c_p	Specific heat, Btu/lbm - °R
C_v	Mass fraction of vapor, $C_v = \rho_v/(\rho_v + \rho_{nc})$
D	Particle diameter, ft
D_{ab}	Diffusion coefficient, ft^2/sec
e_d	Internal energy of droplet, Btu
f_ℓ	Ratio of liquid flow rate to noncondensable gas flow rate, $\dot{m}_\ell/\dot{m}_{nc}$
h	Enthalpy, Btu/lbm
$\bar{h}$	Heat transfer coefficient, Btu/ft^2-sec-°R
J	Dimensional constant, 778 ft-lbf/Btu
k	Thermal conductivity, Btu/ft-°R-sec
k_x	Mass transfer coefficient, lb-mole/ft^2·sec
M	Molecular weight, lbm/lb-mole
M_d	Mass of droplet, lbm

$\dot{m}$	Mass flow rate, lbm/sec
Nu	Nusselt number for heat transfer
Nu_{ab}	Nusselt number for mass transfer
P	Pressure, lbf/ft^2
Pr	Prandtl number
R	Gas constant, ft-lbf/lbm-°R
Re	Reynolds number
R_U	Universal gas constant, ft-lbf/lb-mole-°R
Sc	Schmidt number
T	Temperature, °R
t	Time, sec
V	Velocity, ft/sec
x	Distance along cooler, ft
$\bar{x}$	Mole fraction
δ	Incremental distance, ft
μ	Dynamic viscosity, lbm/ft-sec
ρ	Density, lbm/ft^3
σ	Surface tension, lbf/ft
ω	Molar rate of evaporation, moles/sec

SUBSCRIPTS

A	Average
f	Film value
g	Gas phase—vapor plus noncondensable
i	Liquid originating at injection station i
ℓ	Liquid phase
nc	Noncondensable
ref	Reference
s	Droplet surface

v	Vapor
1, 2, 3, etc.	Spraybank number

SUPERSCRIPT

m	Molar

SECTION I
INTRODUCTION

Testing of turbojet engines and rocket motors at simulated altitude in ground test facilities requires cooling of the high temperature exhaust gas to a relatively low temperature before the gas enters the exhaust gas pumping system. Cooling of the gases by water spray with direct heat and mass exchange between the water and the exhaust gas has been utilized in many test facilities. This method of cooling is often called spray cooling.

Many of the spray coolers used in the Engine Test Facility (ETF) at the Arnold Engineering Development Center (AEDC) receive exhaust gas from a rocket or turbojet engine. The cooling process reduces the temperature from approximately 4000°R (maximum temperature of a turbojet engine exhaust gas) to approximately 550°R. By means of an atomizing water spray, the exhaust gas is cooled and humidified. The cooling produces a temperature compatible with the ducting, control valves, and pumping system material limits. Water conservation is an important consideration in operation because of the large quantities of spray water required.

Previous work has developed computer models for spray coolers based on the assumption of a homogeneous two-phase flow with kinetic and thermodynamic equilibrium (Refs. 1, 2, and 3). The investigations contained in this report cover the development of a computer model of a spray cooling process that follows a typical liquid water droplet in the cooler ducting. No assumptions of kinetic or thermodynamic equilibrium between the gas and liquid are made. The model is then compared with measurements made in a spray cooler during operation. The approach approach is similar to that used by Shapiro (Ref. 4).

SECTION II
EXHAUST GAS COOLING SYSTEM

2.1 CONFIGURATION

The configuration of the Propulsion Development Test Cell (T-1) spray cooler consists of a diverging conical inlet section followed by a constant-area duct to the end of the spray cooler (Fig. 1a, Appendix I). The cooling water is introduced through a group of nozzles arranged in a series of banks, in which the first three banks of sprays consist of nozzles projecting a fan-type spray directed downstream along the wall to protect the ducting (Fig. 1b). The remaining banks are arranged in a wagon-wheel configuration with several spokes, each "spoke" containing several spray heads. Each spray head contains several fixed-geometry, conical spray nozzles (Figs. 1b and c) directed generally downstream. The water to each spray bank is supplied by a large header, and the flow rate to each spray bank is controlled by a valve between the header and the spray bank.

2.2 INSTRUMENTATION

Instrumentation was provided to measure flow rates and pressures of the exhaust gas stream entering the cooler, and the temperature and composition were calculated using the method of Ref. 5. Exhaust gas static pressure and liquid water temperature measurements were also made at five axial stations along the cooler. The temperature of the cooling water before injection was measured, and the flow rate was calculated from pressure measurements made across an orifice or at the control valve. The location of this instrumentation is shown in Fig. 2. Measurements taken by this instrumentation provided experimental correlation with the analytical results from the mathematical model.

The millivolt outputs from the thermocouples and strain-gage-type pressure transducers were recorded on either magnetic tape or by a photographically recording galvanometer-type oscillograph. The magnetic tape data were reduced on a digital computer, and the oscillograph data were reduced manually using electrical calibrations taken prior to testing.

SECTION III
DEVELOPMENT OF THE ANALYTICAL MODEL

The analytical model is based on the equations of conservation of energy, momentum, and species for the exhaust gas cooler and the exchange of these quantities between phases. The model considers the behavior of a typical drop down the length of the cooler and calculates the changes in thermodynamic properties over a series of small incremental distances. The equations were programmed for solution on a digitial computer.

Some of the key assumptions in the analysis are as follows:

1. All gases including water vapor obey the perfect gas equation of state.
2. The flow is steady and one dimensional.
3. The gas mixture at any section is homogeneous.
4. The droplets from each injection station are uniformly distributed over the cross-sectional area of the cooler.
5. The droplets are injected parallel to the gas flow and maintain this direction throughout the cooler. The influence of gravity on the droplets is considered negligible.
6. There is no aerodynamic breakup or agglomeration of the drops.
7. The drops injected at any injection station are uniform in size.
8. The maximum number of injection stations is nine, and their spacing is arbitrary.
9. The internal resistance of the drops to heat distribution is negligible, thus the temperature is uniform through the drop.
10. The drops injected at each injection station are accounted for separately.
11. Heat transfer and friction at the duct walls and piping are negligible.
12. Cross-sectional area of the cooler is a prescribed function of distance along the cooler.

3.1 EQUATION FOR THE CONSERVATION OF SPECIES FOR ONE INJECTION STATION

The conservation of species written for the exhaust gas and water (in both liquid and vapor form) over an incremental distance δx is

$$\dot{m}_v + \dot{m}_\ell + \dot{m}_{nc} = \dot{m}_v + \frac{d\dot{m}_v}{dx}\delta x + \dot{m}_\ell + \frac{d\dot{m}_\ell}{dx}\delta x + \dot{m}_{nc} + \frac{d\dot{m}_{nc}}{dx}\delta x \quad (1)$$

If the noncondensable flow rate is assumed constant and insoluble in water, Eq. (1) may be simplified:

$$\frac{d\dot{m}_v}{dx} + \frac{d\dot{m}_\ell}{dx} = 0 \quad (2)$$

The mass fraction of vapor may be written

$$C_v = \frac{\dot{m}_v}{\dot{m}_v + \dot{m}_{nc}} \quad (3)$$

and the mass fraction of noncondensable gas is

$$C_{nc} = \frac{\dot{m}_{nc}}{\dot{m}_v + \dot{m}_{nc}} = 1 - C_v \quad (4)$$

In addition, the specific humidity may be defined as

$$\frac{\dot{m}_v}{\dot{m}_{nc}} = \frac{C_v}{1 - C_v} \quad (5)$$

and the liquid water ratio (f_ℓ) as

$$f_\ell = \frac{\dot{m}_\ell}{\dot{m}_{nc}} \quad (6)$$

3.2 EQUATION FOR THE CONSERVATION OF ENERGY FOR ONE INJECTION STATION

The energy equation is developed to equate the total energy of the exhaust gas and liquid water as they pass two planes an incremental distance (δx) apart.

$$\dot{m}_{nc}\left[h_{nc} + (V_{nc}^2/2)\right] + \dot{m}_v\left[h_v + (V_{nc}^2/2)\right] + \dot{m}_\ell\left[h_\ell + (V_\ell^2/2)\right]$$
$$= \left[\dot{m}_{nc} + (d\dot{m}_{nc}/dx)\delta x\right]\left\{h_{nc} + (dh_{nc}/dx)\delta x\right.$$
$$\left. + \left[V_{nc} + (dV_{nc}/dx)\delta x\right]^2/2\right\} + \left[\dot{m}_v + (d\dot{m}_v/dx)\delta x\right]\left\{h_v\right.$$
$$\left. + (dh_v/dx)\delta x + \left[V_{nc} + (dV_{nc}/dx)\delta x\right]^2/2\right\}$$
$$+ \left[\dot{m}_\ell + (d\dot{m}_\ell/dx)\delta x\right]\left\{h_\ell + (dh_\ell/dx)\delta x\right.$$
$$\left. + \left[V_\ell + (dV_\ell/dx)\delta x\right]^2/2\right\} \quad (7)$$

By expanding and simplifying the above and expressing the mass flow rates of the various components in terms of Eqs. (5) and (6), Eq. (7) becomes

$$\frac{dh_{nc}}{dx} + V_{nc}\frac{dV_{nc}}{dx} + \frac{C_v}{1 - C_v}\frac{dh_v}{dx} + V_{nc}\frac{dV_{nc}}{dx} + \left[\frac{h_v + (V_{nc}^2/2)}{(1 - C_v)^2}\right]\left[\frac{dC_v}{dx}\right]$$
$$+ f_\ell\left(\frac{dh_\ell}{dx} + V_\ell\frac{dV_\ell}{dx}\right) + \left(h_\ell + \frac{V_\ell^2}{2}\right)\frac{df_\ell}{dx} = 0 \quad (8)$$

3.3 EQUATION FOR THE CONSERVATION OF MOMENTUM FOR ONE INJECTION STATION

The momentum equation expressing the total momentum passing two planes (δx) apart is:

$$\dot{m}_{nc}V_{nc} + \dot{m}_v V_{nc} + \dot{m}_\ell V_\ell + PA = \left[\dot{m}_{nc} + (d\dot{m}_{nc}/dx)\delta x\right]\left[V_{nc}\right.$$
$$\left. + (dV_{nc}/dx)\delta x\right] + \left[\dot{m}_v + (d\dot{m}_v/dx)\delta x\right]\left[V_{nc} + (dV_{nc}/dx)\delta x\right]$$
$$+ \left[\dot{m}_\ell + (d\dot{m}_\ell/dx)\delta x\right]\left[V_\ell + (dV_\ell/dx)\delta x\right]$$
$$+ \left[P + (dP/dx)\delta x\right]\left[A + (dA/dx)\delta x\right] \quad (9)$$

Expanding and simplifying give

$$\dot{m}_{nc}(dV_{nc}/dx) + V_{nc}(d\dot{m}_{nc}/dx) + \dot{m}_{v}(dV_{nc}/dx) + V_{nc}(d\dot{m}_{v}/dx) + \dot{m}_{\ell}(dV_{\ell}/dx) + V_{\ell}(d\dot{m}_{\ell}/dx) + P(dA/dx) + A(dP/dx) = 0 \qquad (10)$$

By dividing by $\dot{m}_{nc}$ and incorporating the specific humidity and liquid water ratio in terms of Eqs. (5) and (6), respectively, Eq. (10) may be expressed as

$$\frac{dV_{nc}}{dx} + \frac{C_v}{1 - C_v}\frac{dV_{nc}}{dx} + \frac{V_{nc}}{(1 - C_v)^2}\frac{dC_v}{dx} + f_{\ell}\frac{dV_{\ell}}{dx} + V_{\ell}\frac{df_{\ell}}{dx} + \frac{P}{\dot{m}_{nc}}\frac{dA}{dx} + \frac{A}{\dot{m}_{nc}}\frac{dP}{dx} = 0 \qquad (11)$$

Multiplying by $V_{nc}(1 - C_v)^2$ and assuming that the change in area over the increment δx is negligible give

$$(1 - C_v)V_{nc}\frac{dV_{nc}}{dx} + V_{nc}^2\frac{dC_v}{dx} + (1 - C_v)^2 V_{nc}\left[f_{\ell}\frac{dV_{\ell}}{dx} + V_{\ell}\frac{df_{\ell}}{dx}\right] + \frac{(1 - C_v)^2}{\rho_{nc}}\frac{dP}{dx} = 0 \qquad (12)$$

3.4 EQUATIONS FOR MULTIPLE INJECTION STATIONS

Exhaust gas coolers similar to those shown in Fig. 1a consist of a series of spray banks or water injection stations, whereas the equations previously developed indicate that the water is injected uniformly at one station. The equations are easily expanded to include multiple injection stations by adding a term to describe the liquid injection conditions at each spray bank and the location of each bank. The previously developed equations (Eqs. (2), (8), and (12)) are modified as shown below. Equation (2) becomes

$$\frac{d\dot{m}_v}{dx} + \sum_n \frac{d\dot{m}_{\ell_i}}{dx} = 0 \qquad (13)$$

Equation (8) becomes

$$\frac{dh_{nc}}{dx} + V_{nc}\frac{dv_{nc}}{dx} + \frac{C_v}{1 - C_v}\left(\frac{dh_v}{dx} + V_{nc}\frac{dV_{nc}}{dx}\right) + \left[\frac{h_v + (V_{nc}^2)}{(1 - C_v)^2}\right]\left[\frac{dC_v}{dx}\right]$$

$$+ \sum_n \left[f_{\ell_i}\left(\frac{dh_{\ell_i}}{dx} + V_{\ell_i}\frac{dV_{\ell_i}}{dx}\right)\right] + \sum_n \left[\left(h_{\ell_i} + \frac{V_{\ell_i}^2}{2}\right)\frac{df_{\ell_i}}{dx}\right] = 0 \tag{14}$$

and Eq. (12) becomes

$$(1 - C_v)V_{nc}\frac{dV_{nc}}{dx} + V_{nc}\frac{dC_v}{dx} + (1 - C_v)^2 V_{nc}\sum_n \left[f_{\ell_i}\frac{dV_{\ell_i}}{dx} + V_{\ell_i}\frac{df_{\ell_i}}{dx}\right]$$

$$+ \frac{(1 - C_v)^2}{\rho_{nc}}\frac{dP}{dx} = 0 \tag{15}$$

The piping necessary for the spray banks in an exhaust gas cooler similar to the one shown in Fig. 1a can occupy a significant portion of the cross-sectional area of the duct. In the cooler of test cell T-1, the frontal area of the piping at each injection station is approximately 12 percent of the total cross-sectional area. Because of the large amount of liquid normally used for cooling and the blockage caused by water piping, the equations describing the cooling process must be further modified to incorporate terms necessary to account for the loss in momentum of the liquid that strikes this piping. This modification is made 0.25 ft upstream of each spray bank where the liquid properties from all previous stations are mass averaged to produce two new streams, one of which represents the liquid passing a spray bank without interference and a second stream which strikes the piping, losses its momentum, and is then reaccelerated. The fraction of liquid striking the piping is equal to the fraction of area occupied by the piping. Therefore, the new liquid properties passing the spray bank will be

$$f_{\ell_A} = (AA)(f_{\ell_1} + f_{\ell_2} + f_{\ell_3} + \cdot \cdot \cdot) \tag{16}$$

$$V_{\ell_A} = \frac{V_{\ell_1} f_{\ell_1} + V_{\ell_2} f_{\ell_2} + V_{\ell_3} f_{\ell_3} + \cdot \cdot \cdot}{\sum_n f_{\ell_i}} \tag{17}$$

$$T_{S_A} = \frac{T_{s_1} f_{\ell_1} + T_{s_2} f_{\ell_2} + T_{s_3} f_{\ell_3} + \cdots}{\sum_n f_{\ell_i}} \tag{18}$$

$$D_A = \frac{D_1 f_{\ell_1} + D_2 f_{\ell_2} + D_3 f_{\ell_3} + \cdots}{\sum_n f_{\ell_i}} \tag{19}$$

The properties of the liquid that strikes the piping will be

$$V_{\ell_B} = 1.0 \tag{20}$$

$$T_{S_B} = T_{S_A} \tag{21}$$

$$D_B = \frac{13\sigma}{\rho_g \left(V_{nc} - V_{\ell_B}\right)^2} \tag{22}$$

The velocity (V_{ℓ_B}) is arbitrarily set at a small value but not zero because it appears in the denominator of several calculations; T_{S_B} is assumed equal to T_{S_A} since the system is adiabatic and no heat is lost to the piping. The diameter of the reaccelerated drop (D_B) is based on Eq. (12.6) of Ref. 6. The equation has been modified by neglecting the second term on the right side since it is almost negligible for the conditions encountered in this program. The final form of the equation for the drop diameter is basically a solution to the Weber number for a critical value of 13.

3.5 EQUATIONS FOR THE EXCHANGE OF MASS, ENERGY, AND MOMENTUM BETWEEN PHASES

It is now necessary to develop the equations to relate the transfer of mass, energy, and momentum between phases. Since the mass flow rate of the noncondensable portion of the exhaust stream is considered constant and negligibly soluble in water, the only exchange of mass occurs between the liquid water and vapor. The conservation of water was expressed earlier in Eq. (2) and is

$$\frac{d\dot{m}_v}{dx} + \sum_n \frac{d\dot{m}_{\ell_i}}{dx} = 0$$

Furthermore the mass transfer to or from a single drop may be developed from Eq. (21.2-26) of Ref. 7 which expresses the molar rate of evaporation as

$$\omega_{v_i}^{(m)} = k_{x_i} \pi D_i^2 \frac{\bar{x}_{vs_i} - \bar{x}_v}{1 - \bar{x}_{vs_i}} \tag{23}$$

By multiplying by the molecular weight of vapor (M_v), the results in terms of the mass rate of evaporation may be expressed as

$$\omega_{v_i}^{(m)} M_v = k_{x_i} \pi D_i^2 M_v \frac{\bar{x}_{vs_i} - \bar{x}_v}{1 - \bar{x}_{vs_i}} \tag{24}$$

Since the mass rate of evaporation is equal to the decrease in the mass of a drop per unit time, then

$$-\frac{dM_{d_i}}{dt} = k_{x_i} \pi D_i^2 M_v \frac{\bar{x}_{vs_i} - \bar{x}_v}{1 - \bar{x}_{vs_i}} \tag{25}$$

Since the equations developed will be solved for incremental distances (dx), the equation above will be more useful in terms of the distance (dx):

$$V_{\ell_i} \frac{dM_{d_i}}{dx} = k_{x_i} \pi D_i^2 M_v \frac{\bar{x}_v - \bar{x}_{vs_i}}{1 - \bar{x}_{vs_i}} \tag{26}$$

For a mixture of perfect gases, the molar concentration ($\bar{x}_{vs_i}$) can be expressed in terms of the pressure where

$$\bar{x}_{vs_i} = \frac{P_{vs_i}}{P} \tag{27}$$

is the mole fraction of vapor at the drop surface and P_{vs} is the vapor saturation pressure computed at the drop surface temperature. While this method of evaluating $\bar{x}_{vs}$ is exact only for zero mass transfer, it can be shown to give satisfactory results even at relatively high mass transfer rates. The mole fraction ($\bar{x}_v$) of the free stream is

$$\bar{x}_v = \frac{\dot{m}_v/M_v}{(\dot{m}_v/M_v) + (\dot{m}_{nc}/M_{nc})} = \frac{C_v/M_v}{(C_v/M_v) + (1 - C_v/M_{nc})} \tag{28}$$

The change in the total amount of liquid may be expressed in terms of the change for one drop and the number of drops

$$\frac{df_{\ell_i}}{dx} = \frac{f_{\ell_i}}{M_{d_i}} \frac{dM_{d_i}}{dx} \tag{29}$$

The transfer of energy between phases is related to the thermodynamic state of the exhaust gas stream and the liquid drops. Since the system is adiabatic and at a constant area over the distance (dx), any change in the gas stream will necessarily result in a change in the drops; therefore, the exchange of energy between phases will be expressed as a change in internal energy of a single drop, and this will then be related to the change in energy of all the liquid. The change in internal energy for a single drop over the distance (dx) is

$$V_{\ell_i} \frac{de_{d_i}}{dx} = \bar{h} \pi D_i^2 \left(T_g - T_{s_i}\right) + h_{v_{s_i}} V_{\ell_i} \frac{dM_{d_i}}{dx} \tag{30}$$

where the first term on the right expresses the convective heat transfer and the second term expresses the heat transfer accompanying the mass transfer and change in phase. From the known energy transfer for one drop, the total energy transfer may be expressed as

$$\frac{d}{dx}\left(h_{\ell_i} \dot{m}_{\ell_i}\right) = \frac{\dot{m}_{\ell_i}}{M_{d_i}} \frac{de_{d_i}}{dx} \tag{31}$$

It is assumed that the resistance to heat distribution within the droplet is negligible compared with the resistance to heat transfer at the surface, that is, the temperature within the drop is uniform. Thus,

$$e_{d_i} = c_\ell (T_{s_i} - T_{ref}) \tag{32}$$

for a constant specific heat of liquid (c_ℓ).

The momentum transfer between phases will be expressed using Newton's Second Law where the force on the drop is due only to the droplet drag. Therefore, expressed in this manner,

$$V_{\ell_i} \frac{d}{dx}\left[M_{d_i}\left(V_{nc} - V_{\ell_i}\right)\right] = \rho_g \frac{\pi D_i^2}{4} \frac{C_{D_i}\left|V_{nc} - V_{\ell_i}\right|\left(V_{nc} - V_{\ell_i}\right)}{2} \tag{33}$$

which may be simplified to

$$\left(V_{nc} - V_{\ell_i}\right) V_{\ell_i} \frac{dM_{d_i}}{dx} + M_{d_i} V_{\ell_i} \frac{dV_{\ell_i}}{dx} = \rho_g \frac{\pi D_i^2}{4} \frac{C_{D_i}\left|V_{nc} - V_{\ell_i}\right|\left(V_{nc} - V_{\ell_i}\right)}{2} \tag{34}$$

where ρ_g is the density of the combined noncondensable gas and vapor in the stream.

The equation of state for the exhaust gas stream is

$$P = (\rho_{nc} + \rho_v) R_g T_{nc} \tag{35}$$

where

$$R_g = \left(\frac{1 - C_v}{M_{nc}} + \frac{C_v}{M_v}\right) R_u \tag{36}$$

3.6 COMPUTER SOLUTION OF THE EQUATIONS

The conditions in the cooler are determined by first computing the changes to the liquid and then incorporating these changes into the solution of the conservation equations for the complete system. The computer solution is based on the modified Euler method. The changes in the liquid properties are calculated from the derivatives given in Eqs. (26), (29), (30), and (34) and a known step size (dx). These changes are calculated for each liquid stream. The sum of the changes in mass, energy, and momentum are then incorporated into Eqs. (13), (14), (15), and (35) to solve for the new gas properties. An iteration technique is used for the solution to the last three equations. The calculation procedure continues down the cooler until a point is reached 0.25 ft upstream of a spray bank. At this point, the liquid properties are averaged as discussed in Section 3.4 (Eqs. (16) through (22)). By using the gas properties last calculated and the liquid properties of stream "a" only, the calculation procedure discussed above is completed for one step (dx). At this point, stream "b" (the liquid that has impinged on the piping) is added to the calculation, and the changes to Eqs. (26), (29), (30), and (34) are calculated for the two streams separately. These changes in mass energy and momentum are included in this iterative solution to Eqs. (13), (14), (15), and (35). The calculation procedures continue until a new spray bank is reached and then these liquid properties are included in the calculation routine.

The step size (dx) is variable in this program. The initial value used is 0.0001 ft, but if convergence is achieved quickly (less than 3 iterations), the step size is increased for the next series of calculations. The step size will vary between 0.0001 and 0.01 ft depending on the number of iterations necessary for convergence in the previous set of calculations. A computer listing of the program is given in Appendix III.

The frequency of printout for the calculations may also be varied, but experience has shown that for most conditions printing the results every 0.25 ft is sufficient to see the changes in the exhaust gas cooler conditions.

Typical input for a computer run is shown in Tables Ia and b (Appendix II). Special note should be taken of the spray banks in which no water is injected ($f_\ell = 0$). The spray banks are included in the input because they will contribute blockage to the system and their location must be known. In each case, a fictitious velocity, temperature, and drop size is also included to prevent division by zero during the solution, but since these properties are also multiplied by f_ℓ, they become zero and do not affect the final solution.

For conditions where two-phase flow exists, but the piping for injecting the liquid does not occupy a significant portion of the cross-sectional area, a variation of the analytical model may be used. This variation involves only the solution of Eqs. (13), (14), (15), (26), (29), (30), (34), and (35) without the averaging of the liquid properties discussed in Section 3.4 (using Eqs. (16) through (22)). In addition, a drop size distribution may be simulated in this variation of the model by inputing the various drop diameters and their respective quantities (f_{ℓ_i}) as spray stations but with the stations at the maximum dx distance apart. A computer listing for this model variation will be found in Appendix IV.

SECTION IV
EVALUATION OF THE ANALYTICAL MODEL

An evaluation of the computer model was made by comparing the predicted exhaust gas pressure with measured data and also the predicted liquid water temperature with the value measured by an exposed junction thermocouple at several points in the exhaust gas cooler. In addition, the calculated exhaust gas temperature and the specific humidity are discussed to determine how these parameters are influenced by test conditions.

Six typical data points taken during the testing of a turbojet engine are used to evaluate the model. The input conditions for use in the computer program are shown in Tables I and II. Also shown in the tables are the inlet conditions to the spray cooler which were calculated using the method of Ref. 4 which has been included as a part of the model. These data show that, for the runs in Table I, the cooler inlet conditions are constant and the difference is in the spray banks that are in use, whereas the data in Table II show the cooling water parameters to be constant and the exhaust gas temperature and velocity to vary. Two other items of importance that should be noted are:

1. The cooling water flow rate from the individual "wagon-wheel" spray banks was kept constant, and only the number of spray banks was varied, and
2. The cooling water from the wall sprays of spray banks No. 2 and 3 were not normally included in the calculation, whereas the water from spray bank No. 1 was included.

The flow rate from the individual spray banks was kept constant to minimize the effects of variations in cooling water velocity, drop size, and distribution from the individual nozzles. The cooling water from spray banks 2 and 3 was not included because it was believed that these wall sprays would not contribute significantly to the cooling of the exhaust gas. Calculations show that the pressure change in the ducting to the first wagon-wheel can generally be adequately described by assuming a one-dimensional isentropic flow with no cooling water present. The cooling water from spray bank No. 1 was included because liquid water must be present at the start of the computer program (i.e., $f_{\ell_1} \neq 0$), and the difference between the isentropic value of pressure and that calculated using the initial spray bank was not significant.

The measured and calculated values of pressure as a function of distance along the cooler are shown in Fig. 3; the liquid water temperatures are shown in Fig. 4. The increase in pressure during the first 9 ft (the diverging portion of the ducting) followed by a drop in pressure for the constant area portion of the cooler is characteristic of nearly all runs. The initial rise in pressure is due primarily to the subsonic compression of the exhaust gas with very little acceleration of the cooling water except on the outer edges of flow. The abrupt decrease in pressure that follows occurs in the constant diameter section of the cooler where the wagon-wheel sprays are located. The drop in pressure in this section is caused by acceleration of the cooling water from the initial wagon-wheel spray bank and the loss in momentum of the previously injected liquid water as it strikes the piping and is then reaccelerated. This later loss in momentum is taken in account by the averaging of the liquid properties and the resultant use of Eqs. (34), (35), and (36). Although the area occupied by the internal water piping at each spray station is small (approximately 12 percent), it is sufficient to cause a drastic change in the pressure characteristics. The magnitude of the change caused by inclusion of this piping is best illustrated by assuming that in the constant diameter section the piping is removed but the water is still introduced uniformily over the cross section of the cooler at the various spray banks. Figure 5 shows the calculated cooler pressure for several blockages as well as the standard 12 percent used for the calculation of all data from the cooler in test cell T-1. All calculated pressures show good agreement initially, but then the pressure begins to increase for the case of zero blockage while decreasing rapidly for the remaining cases. This increase in static pressure is caused by the decrease in dynamic pressure while the total pressure of the exhaust stream remains essentially constant. The decrease in dynamic pressure is due primarily to the cooling of the exhaust gas stream. The decrease in pressure for the conditions with various amounts of blockage is due to the interference caused by the piping. The effect of blockage in a flow stream is well known and the above example illustrates its importance in a two-phase stream. The percentages in Fig. 5 cover the range of normal and extreme blockage conditions and indicate not only the importance of including the blockage in the analytical model but also the importance of minimizing it wherever possible in cooler design.

The measured and predicted liquid temperatures for the data points in Table I are shown in Fig. 4. Three of the four measured values show good agreement with the predicted values, while the remaining value (the initial measurement) is always high. It is significant to note that the predicted liquid temperature for the first wagon-wheel spray bank at 9.2 ft rises approximately 70°R in approximately 6 in. and then levels off at an almost constant value even when additional spray banks are used. This rapid rise in temperature is due to the fact that initially the liquid water temperature is low (536°R) and its vapor pressure at the drop surface is also low. The low vapor pressure of the drop combined with the low vapor partial pressure in the gas stream results in a low mass transfer rate, while the large difference in gas and liquid temperatures gives a high heat transfer rate and a rapid rise in the temperature of the liquid with little evaporation. As the liquid temperature begins to rise, the difference between the partial pressure of the drop and gas stream increases, and the mass transfer (or evaporation from the drop) increases. This increase in mass transfer continues until a liquid temperature is approached where heat transfer to the drop is almost completely used for the evaporation of water. The final temperature approached by the liquid is its adiabatic or wet bulb saturation temperature. As additional cooling water is added through the use of additional spray banks this process is repeated, but the rate of liquid temperature rise will decrease because of the smaller temperature difference between gas and liquid and also because the hotter liquid must also be cooled. The cooling of the liquid does not become important until there is a very large amount of "hot" liquid present. The fact that the cooler liquid temperature does rise very rapidly keeps the overall cooling process from becoming extremely inefficient due to alternately heating and cooling the liquid in the stream.

The previously mentioned thermocouple located at 9.2 ft always reads high. The high reading is believed to be caused by the location of the thermocouple at the edge of the diverging section where the fan-type spray will leave a liquid deficient region near the thermocouple. Since the smaller liquid quantity is surrounded by a large amount of hot exhaust gas, the heat transfer to the liquid will be abnormally high and thus cause the liquid temperature to rise to a value higher than is predicted by the computer model which assumes a uniform liquid distribution over the cross section of the cooler.

The validity of the computer model is best determined by comparing the predicted and measured values of static pressure, gas temperature, and specific humidity. A comparison using the static pressure has already been made, but measurements of the later two quantities have not been made because of the difficulties inherent in a two-phase stream. The exhaust gas temperature is important because of the effect on pumping machinery capabilities. As the temperature of the exhaust gas entering the machines is increased, the maximum mass flow rate that can be pumped at a constant pressure decreases; or, stated another way, for a given mass flow rate of exhaust gas, the minimum upstream pressure increases as the temperature of the exhaust gas entering the machinery increases. Therefore, it is desirable to cool the exhaust gas as much as possible. The specific humidity, like the gas temperature, places a lower limit on the pressure capabilities of the exhaust machinery. As the specific humidity increases, the minimum upstream pressure at the test cell also increases because this additional vapor is additional mass that must be removed. Therefore, the optimum condition would appear to consist of the lowest exhaust gas temperature and specific humidity. The problem is that the temperature normally decreases at the expense of an increase in humidity for spray coolers like those in ETF unless very large quantities of water are injected. Since the overall process of reducing the temperature is normally by evaporation of cooling water, the specific humidity for the process increases as the temperature decreases.

The predicted gas temperatures along the length of the cooler is shown in Fig. 6 for the three data points under discussion. The decrease in temperature follows the same path for the three runs as long as the same spray banks are used. As expected the lowest gas temperature occurs for the data point using the most cooling water (Run No. 36-13), while the highest temperature is predicted with the least amount of cooling water (Run No. 36-18). The temperature curve shows a distinct change occurring at approximately 9 ft. Although the data indicated that the pressure change at this point could be treated as a subsonic compression of a gas with no mass transfer, this is not the case with the predicted cooling curve. If the gas temperature followed a subsonic compression process with no mass transfer, the predicted temperature should be at some value greater than the cooler inlet value of approximately 3570°R. If this were a subsonic compression the wall-type sprays would probably be spraying directly along the wall and the thermocouple at 9.2 ft should be reading approximately gas temperature and the first wagon-wheel spray bank should be surrounded by the high temperature gas flow. As noted earlier, the thermocouple at the end of the divergent section indicates a measured temperature higher than the predicted liquid but certainly not an exhaust gas temperature. Since the thermocouple is measuring a liquid temperature (Refs. 8 and 10), there has obviously been heating of the water indicating that the temperature characteristics cannot be described by an isentropic compression. Therefore, some cooling and mass transfer has taken place in the divergent section of the cooler, and the predicted curve probably has the correct shape, but it is not possible to know if the temperature is absolutely correct. The remainder of the predicted exhaust gas temperature curve is typical—a rapid decrease in temperature while there is a large temperature difference between gas and liquid followed by a decreasing rate of cooling near the exit as the temperature difference decreases. The point where the cooling curves separate is the location of the next spray bank being used. The differences noted at the exit indicate the magnitude of temperature change that can be expected by using additional spray banks for the conditions of these tests.

Since one of the objects of the cooling process is to get the lowest value of exhaust gas temperature at the lowest specific humidity, the temperature as a function of the specific humidity is presented for the three data points in Fig. 7 to show how the cooling takes place. The two points immediately obvious and important to the model description are:

1. The overall process is one of humidification and not two separate processes, i.e., one of humidification followed by dehumidification, and
2. There are short periods of dehumidification downstream of each active injection station but quickly followed by a resumption of the evaporative process.

The normal method of visualizing the cooling process in an exhaust gas spray cooler is to picture first a short section of cooler in which sufficient water is present to provide saturation conditions. This water is injected into the stream and is immediately vaporized because of the large temperature difference between liquid and exhaust gas. This process involves transferring sufficient heat from the gas stream to vaporize the water. After the gas stream becomes saturated with respect to the cooling water that has been injected, any further cooling water serves to dehumidify the gas stream. This dehumidification process is generally imagined to take place very slowly when compared with the vaporization process. As shown in Fig. 7, the cooling process does not appear to follow the model described above; instead the process appears to be one of almost continuous evaporation with a few periods of slight dehumidification. Which process is correct becomes very important in the understanding and design of spray coolers. The first process actually describes what takes place in an infinitely long cooler where only small amounts of water are injected, and this water is allowed to reach temperature and velocity equilibrium before any more water is injected. In this way, saturation may be achieved but with no excess liquid water present. The second process describes a nonequilibrium process in terms of liquid and vapor temperatures, velocity, and concentrations but is the actual process in an exhaust gas cooler.

When liquid water is injected into the gas stream, initially the liquid is at a low temperature and partial pressure, whereas the gas stream has a relatively high temperature but low vapor pressure due to the small amount of vapor in the stream (generally only the water formed during the combustion process). Since the evaporation process is controlled by the vapor concentration difference (see Eq. (16)), the mass transfer will initially be very low, but because of the large temperature differences (on the order of 3000°R), the heat transfer rate will be very high. With the high heat transfer rate, the liquid temperature rises very rapidly, and the partial pressure difference between the liquid and gas stream increases, causing a rise in the mass transfer rate. This process of rising liquid temperature and mass transfer rate continues until a liquid temperature is approached where the heat transferred into the liquid is used almost completely for vaporization. The temperature that is approached by the liquid is the adiabatic or wet-bulb saturation temperature, but although this temperature is nearly achieved, the evaporation of the liquid continues because there still exists a partial pressure difference between the droplet surface and gas stream to provide the mass transfer driving force and a temperature difference to supply heat for vaporization. This process will continue until the partial pressure and temperature difference disappears.

This process discussed above is basically for one spray bank, whereas the normal cooler operation uses several banks. What happens when fresh cooling water (from a downstream spray bank) is injected into the gas stream can be divided into two processes. These occur:

1. When the vapor pressure of the fresh liquid is greater than the vapor pressure of the exhaust stream, and
2. When the vapor pressure of the fresh liquid is less than the vapor pressure of the gas stream.

Both of these conditions are shown in Fig. 7c. The first condition occurs at the entrance to the cooler when the exhaust gas contains very little vapor (the partial pressure is almost negligible) and water is injected with a partial pressure of approximately 64 psf. In this instance, evaporation begins immediately and continues the length of the cooler. The second case occurs when the gas temperature has reached 2500°R (at spray bank No. 4). The partial pressure of the gas stream is now 215 psf which is above that of the incoming water and should result in the gas stream being dehumidified. This is in fact what happens, but because the dehumidification takes place over such a short distance, the decrease in specific humidity does not show up. The dehumidification process is much clearer at spray bank No. 5 when the gas temperature has reached 1600°R, and the specific humidity decreases from 0.43 to 0.41 before beginning to increase again. Another way of picturing the process is shown in Fig. 8 where the partial pressure difference between the liquid and vapor is shown as a function of the specific humidity. When the pressure difference is positive, evaporation takes place, and when it is negative, dehumidification takes place. In this figure, the liquid from spray bank No. 1 is shown to be evaporating from the start, whereas the liquid from spray bank No. 4 initially causes dehumidification until the pressure difference reaches zero. Then the process for spray bank No. 4 becomes evaporative, and the specific humidity begins to increase again. The same thing will happen to the spray banks downstream as shown in Fig. 8 where dehumidification takes place immediately downstream of the injection station. The specific humidity has a greater decrease for each succeeding spray bank because the partial pressure difference is initially greater.

Three additional runs are included in this discussion to show the agreement between the model and the experimental data and also to point out some possible effects of the two wall spray banks in the diverging section which are normally omitted from the calculation procedure. The measured engine inlet parameters and the calculated cooler inlet parameters are shown in Table II, and the pressure as a function of distance data is shown in Fig. 9. These data show good agreement between theory and experiment at the cooler exit, but for Run 36-16, the agreement at the exit from the diverging section (9.2 ft) is not good. Comparing the measured and predicted pressure for the three runs shows that the agreement is good for Run 36-14, but becomes progressively poorer for Runs 36-15 and 36-16. From Table II, the test parameters, including the cooling water, are seen to be the same with only the engine fuel flow rate changing. Thus, there is poorer agreement between the model and data as the fuel flow rate decreases.

A possible explanation for this lies in the interaction between wall spray banks 2 and 3 and the relatively low velocity gas stream. At the interface between the liquid and gas streams, a portion of the hot exhaust gas is cooled by flowing radially through the wall sprays to the area betweer the interface and the duct wall while the remainder undergoes essentially an isentropic compression as it flows down the duct. As the Mach numbers of the two streams decrease, their static pressure increases, and for the gas flowing through the sprays, the total pressure will also increase because of the evaporation of water. The resultant effect is to increase the static pressure above that predicted by the model because of the cooling of the radially flowing gas.

To show the effect of the wall spray banks on the agreement between measured and predicted pressure, a run (35-44, Table II) was chosen with similar cooler inlet conditions but without spray banks 2 and 3 operating. The predicted and measured pressure for the first 9.2 ft is shown in Fig. 10 for Runs 35-44 and 36-16. The agreement between predicted and measured pressure for Run 35-44 is good, indicating that the wall sprays are at least part of the problem.

A second interesting point about Run 36-16 is that the measured pressure is higher than the total pressure calculated by assuming either an isentropic expansion or a two-phase cooling process, as shown in Fig. 11. To achieve this measured pressure, mass must be added to the stream but under conditions where there is not significant loss in momentum due to the added mass being accelerated. This condition could probably be achieved by the gases flowing radially through the water stream and adding vapor to the gas stream.

The condition of abnormally high static pressure is not usually encountered because the wall sprays are not used for conditions such as encountered in Run 36-16 where the cooler inlet velocity and temperature are low. For those runs where the sprays are used, such as 36-14, the total energy level of the stream masks any influence of the wall sprays.

If this radial mass flow through the wall sprays is the reason for the extremely high static pressure at the end of the diverging section, this technique might be a useful way of supplementing the exhaust pumping machinery to achieve a lower test cell pressure.

SECTION V
CONCLUDING REMARKS

An analytical model was developed to describe the process carried on by an exhaust gas spray cooler. The model consisted of the computer solution to the equations of conservation of species, momentum, and energy and the exchange of these quantities between the gas and liquid phase.

The model was compared with data from turbojet tests conducted in Propulsion Development Test Cell (T-1). The range of spray cooler inlet conditions was as follows:

$$\dot{m}_{nc} = 148 \text{ to } 155 \text{ lbm/sec}$$

$$T_{nc} = 1066 \text{ to } 2568°\text{R}$$

$$P_1 = 711 \text{ to } 909 \text{ psf}$$

$$V_{nc} = 402 \text{ to } 1147 \text{ ft/sec}$$

$$f_{\ell} = 2.5 \text{ to } 3.8$$

$$T_s = 536°\text{R}$$

The static pressure and liquid temperature were measured at six positions along the length of the cooler, and these pressures and temperatures were compared with similar values predicted by the model. The measured static pressure at the cooler exit agreed with the predicted value within 4 percent or less, and the measured liquid temperature agreed within 1 percent of the predicted value. With the exception of the pressure at the entrance to the cylindrical section, the agreement between model and measurement for the other data was at least this good. The predicted values of gas temperature and specific humidity are discussed, but measured values of these quantities were not available for comparison because of the lack of adequate instrumentation. Successful instrumentation was not available for making this type of measurements in a typical exhaust gas cooler stream with liquid-to-gas mass ratios on the order of 2 to 1 or greater.

Static pressure measurements at the exit to the diverging section of the cooler gave abnormally high results for one run based on the predicted value from the model. A possible explanation for these data based on a separated recirculating flow in this area was postulated. Additional data for verifying this were not available. A possible method for improving spray cooler performance based on this postulate was also mentioned.

REFERENCES

1. Nitsch, J. "The Heat and Material Transfer in Drops at High Vapor Partial Pressures and Vapor Partial Pressure Differences on the Example of a Direct Continuous Flow Spray Cooler." Dissertation TH Aachen, 1971.

2. Pelton, J. M. and Willbanks, C. E. "Analytical Model of an Exhaust Gas Cooling System Employing Liquid Injection." AEDC-TR-71-60 (AD724687), June 1971.

3. Pelton, J. M. "An Analytical Model for Predicting the Performance of an Exhaust Gas Cooling System." AEDC-TR-71-194 (AD731140), October 1971.

4. Shapiro, A. H., Wadleigh, K. R., Garvil, B. D., and Fowle, A. A. "The Aerothermopressor—A Device for Improving the Performance of a Gas Turbine Power Plant." Transactions, ASME, Vol. 78, No. 3, April 1956.

5. McBride, Bonnie J. and Gordon, Sanford. "Fortran IV Program for Calculation of Thermodynamic Data." NASA TND-4097, August 1967.

6. Wallis, G. B. One-Dimensional Two-Phase Flow. McGraw-Hill, New York, 1969.

7. Bird, R. B., Stewart, W. E., and Lightfoot, E. N. Transport Phenomena. John Wiley & Sons, Inc., New York, 1960.

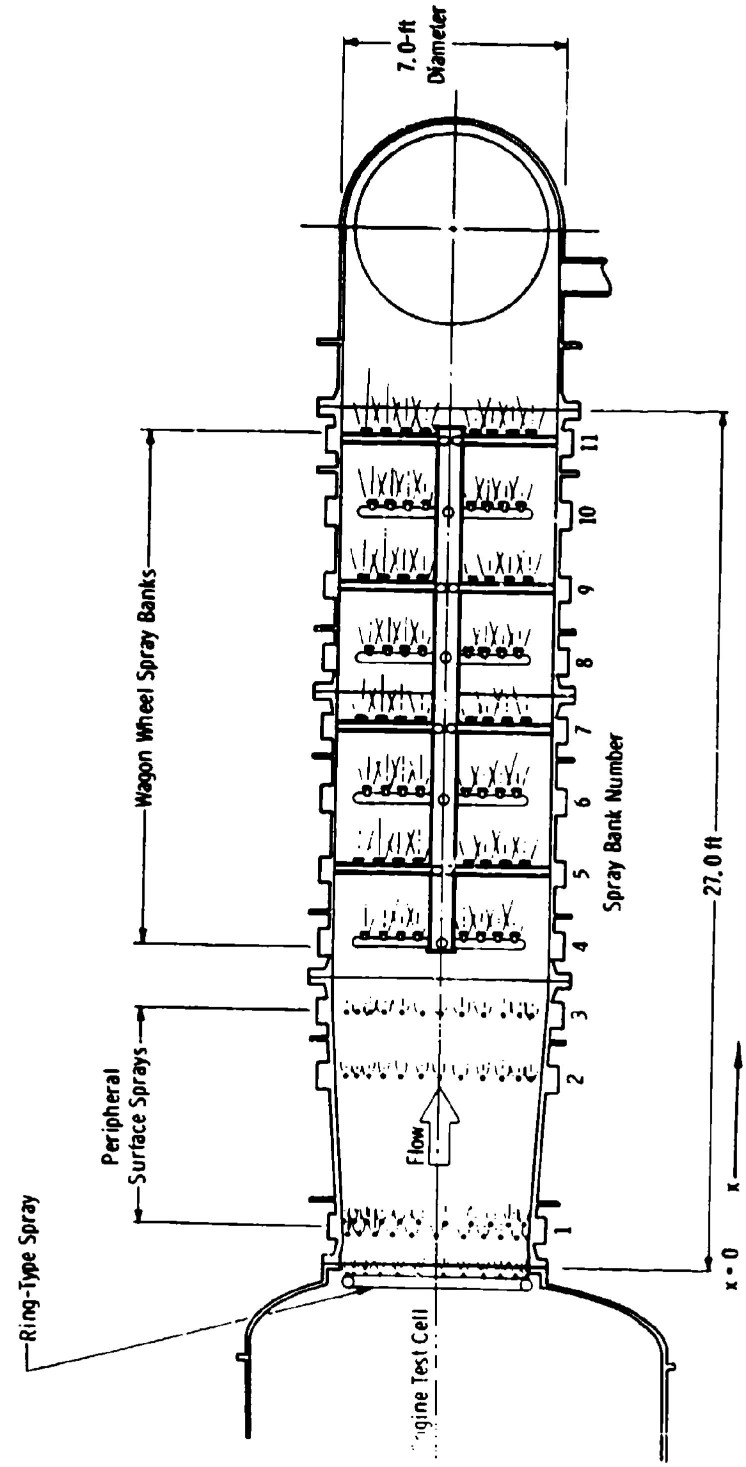
8. Pelton, John M., Clark, H. K., and Paulk, R. A. "The Development of a Temperature Measuring Probe for Use in a Two-Phase (Gas-Liquid) Environment." AEDC-TR-72-19, June 1972.

9. Carlson, D. J. and Hoglund, R. F. "Particle Drag and Heat Transfer in Rocket Nozzles." AIAA Journal, Vol. 2, 1964, p. 1980.

10. Ranz, W. E. and Marshall, W. R., Jr. "Evaporation from Drops." Chemical Engineering Progress, Vol. 48, 1952, Part I pp. 141-146, Part II pp. 173-180.

APPENDIXES

I. ILLUSTRATIONS
II. TABLES
III. A LISTING OF THE COMPUTER PROGRAM AND THE REQUIRED AUXILIARY EQUATIONS FOR AN EXHAUST GAS COOLER
IV. A LISTING OF A VARIATION OF THE COMPUTER PROGRAM FOR HARDWARE BLOCKAGE OF THE DUCT



a. Section View Showing Internal Configuration
Fig. 1 Arrangement of Spray Banks in T-1 Cooler

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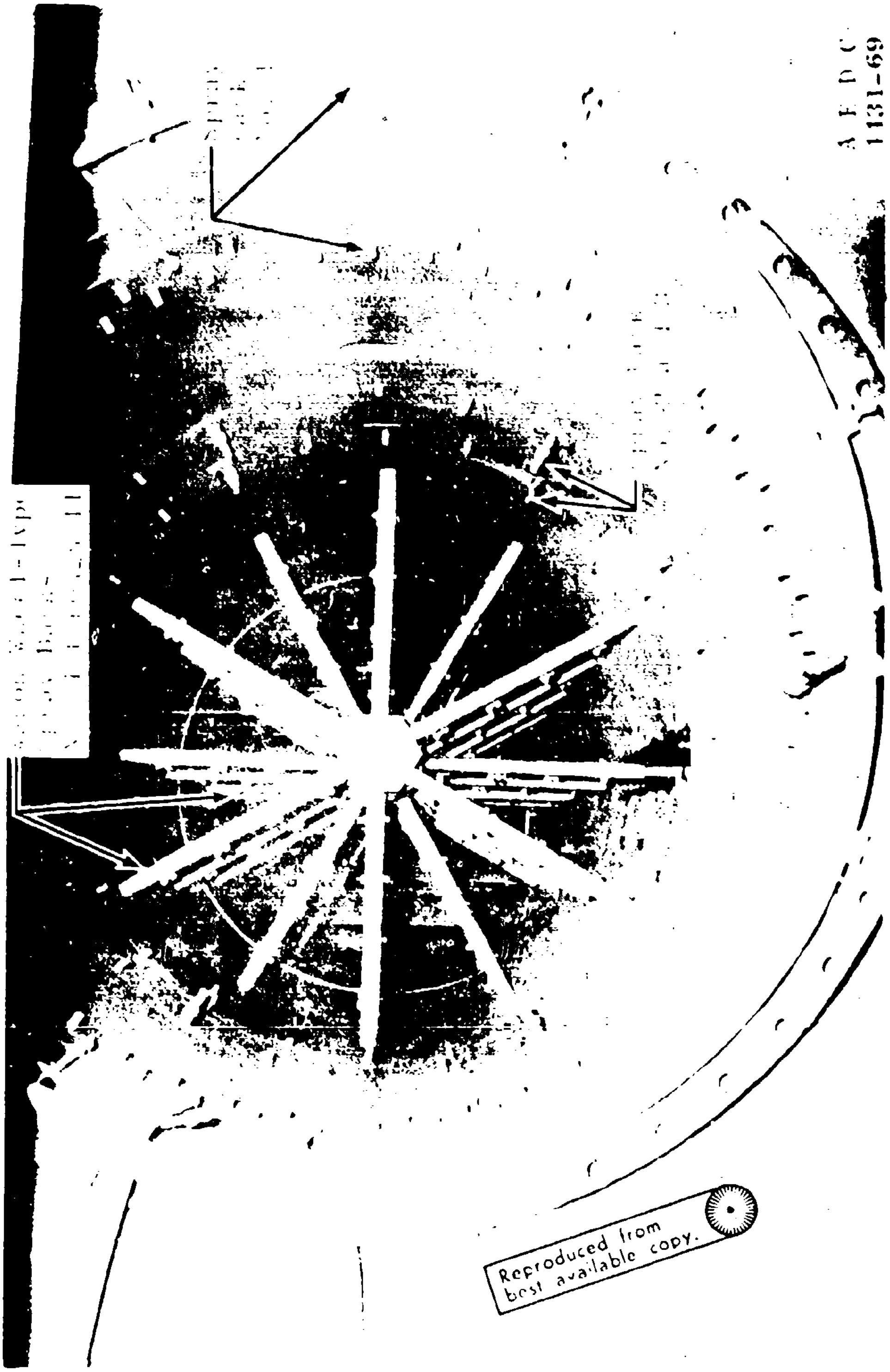
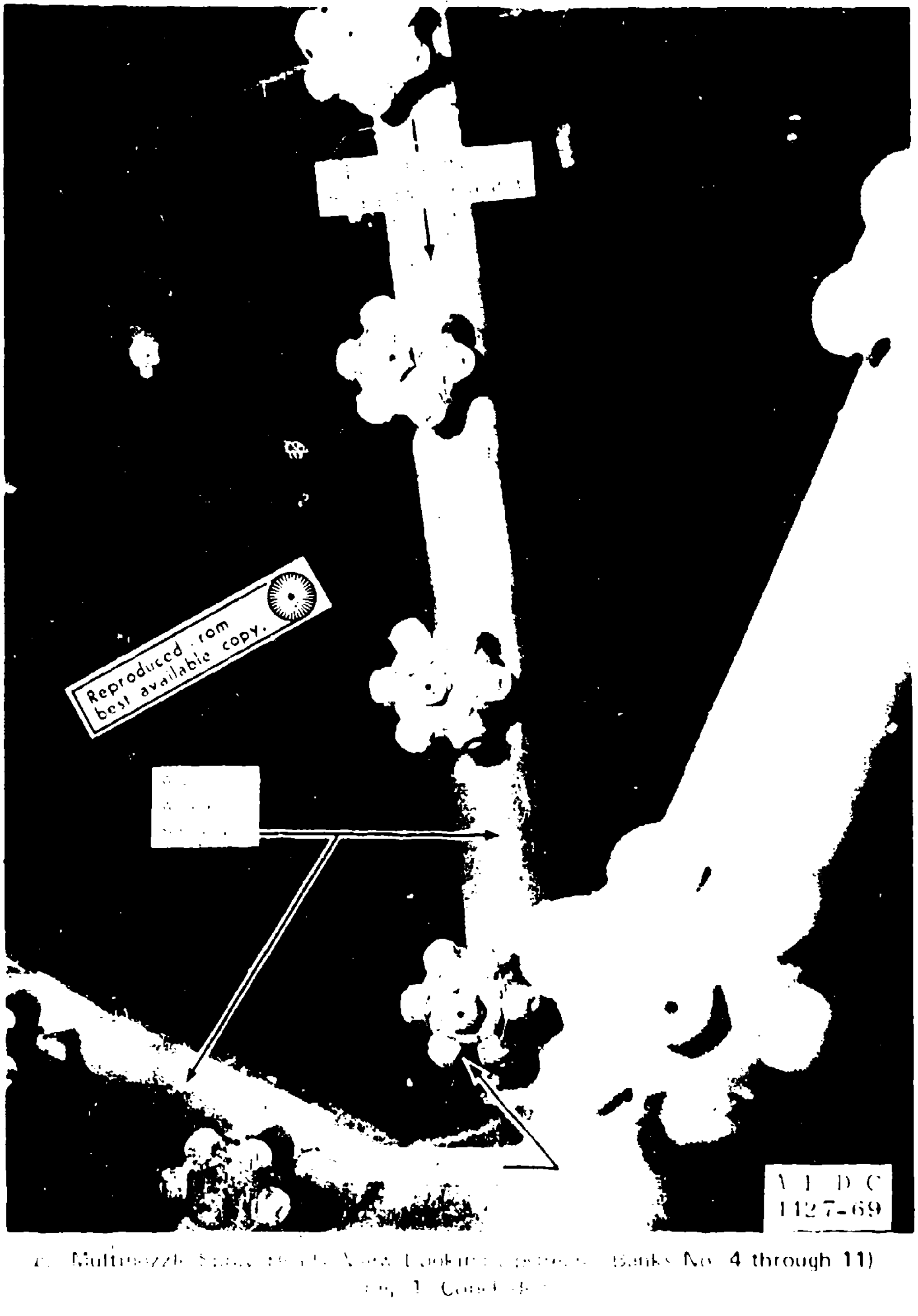


b. Internal View Showing Bank Configuration
Fig. 1 Continued



c. Multinozzle Stator (... View Looking ... Banks No. 4 through 11)

Fig. 1 Concluded

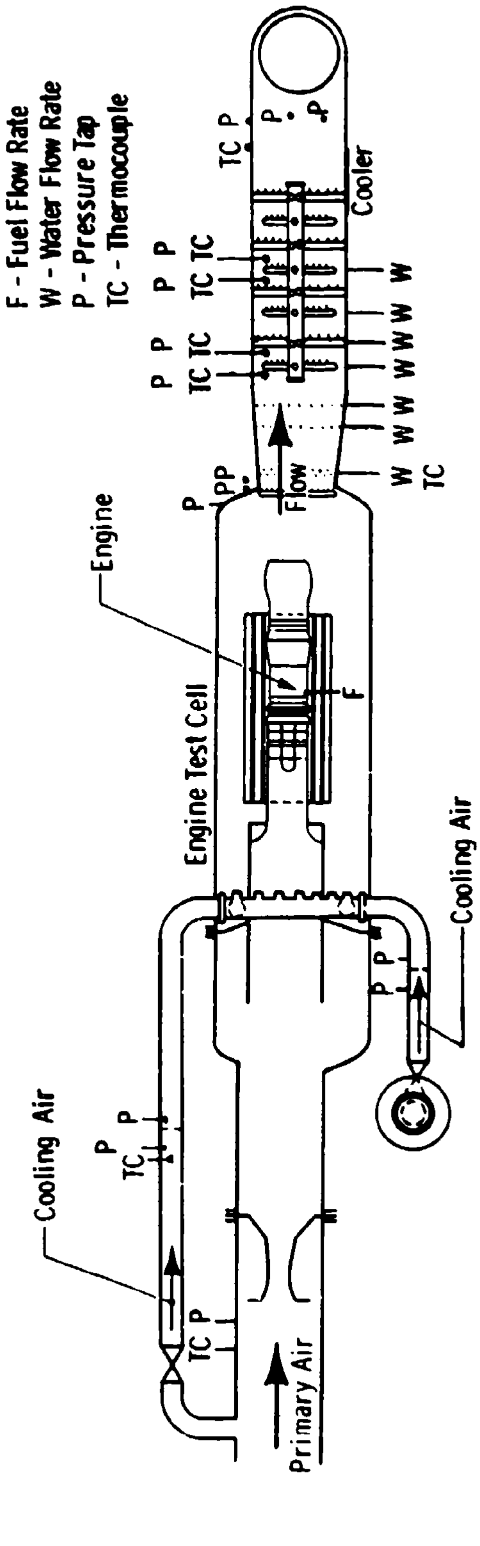
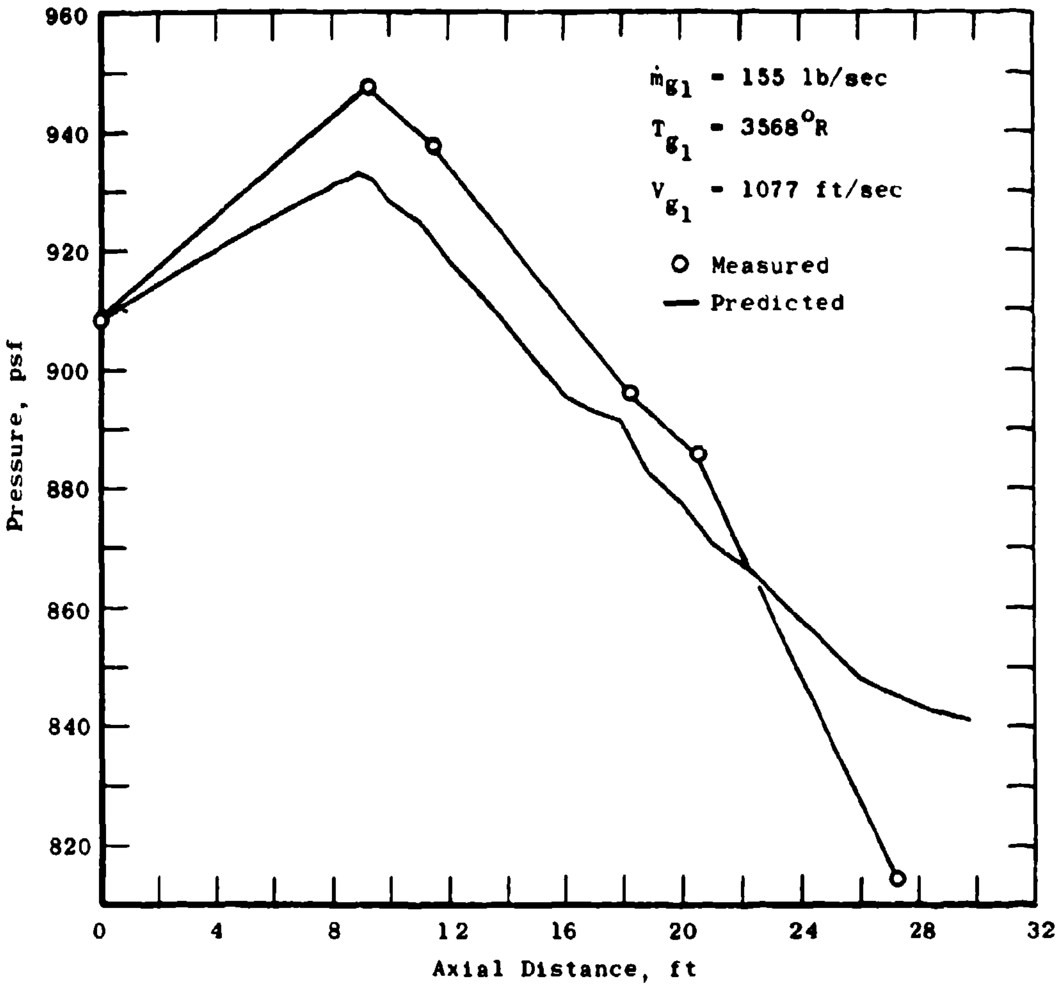
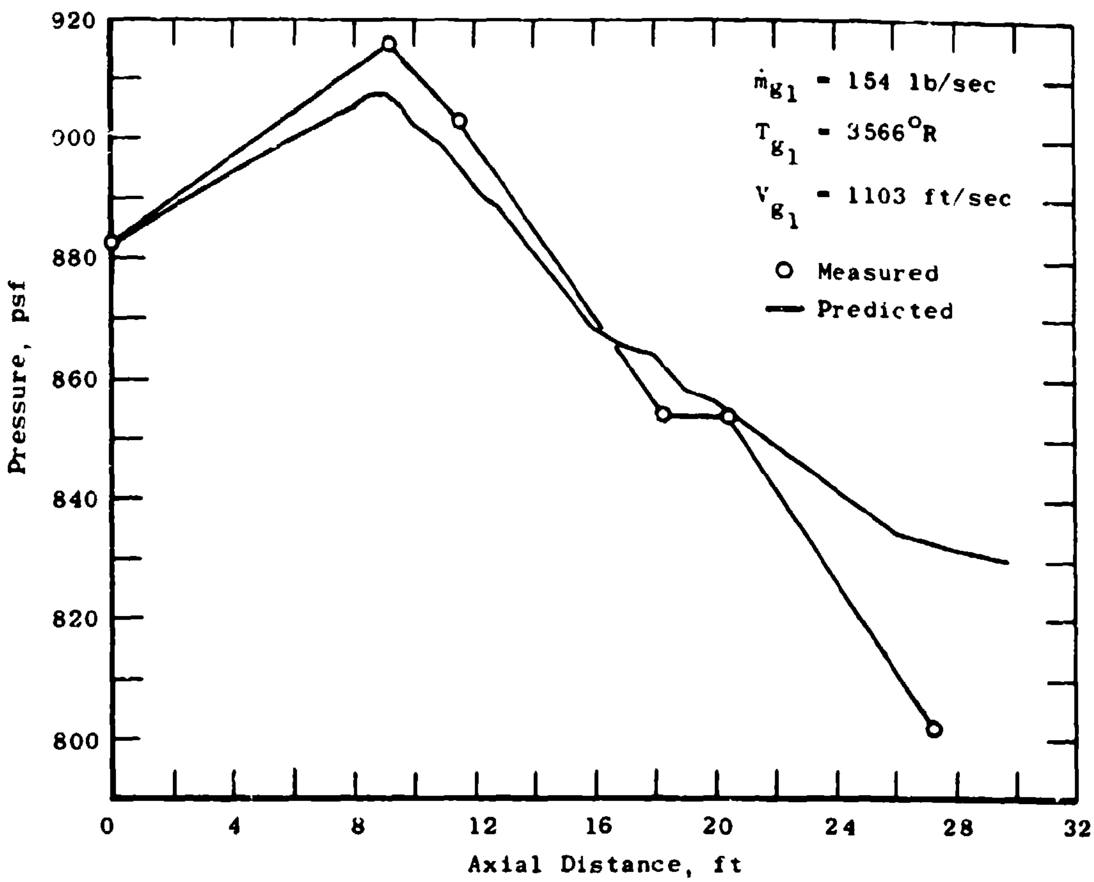


Fig. 2 Schematic Showing Instrumentation Location

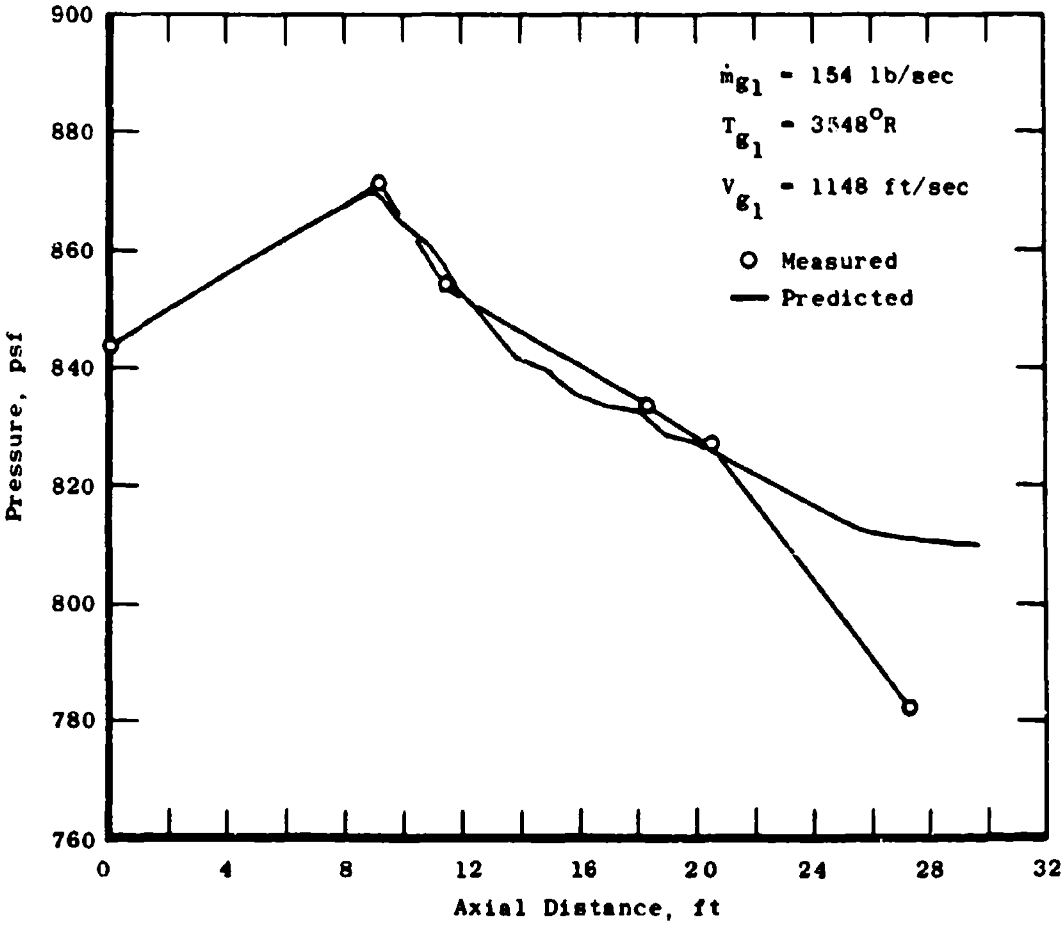


a. Run No. 36-13

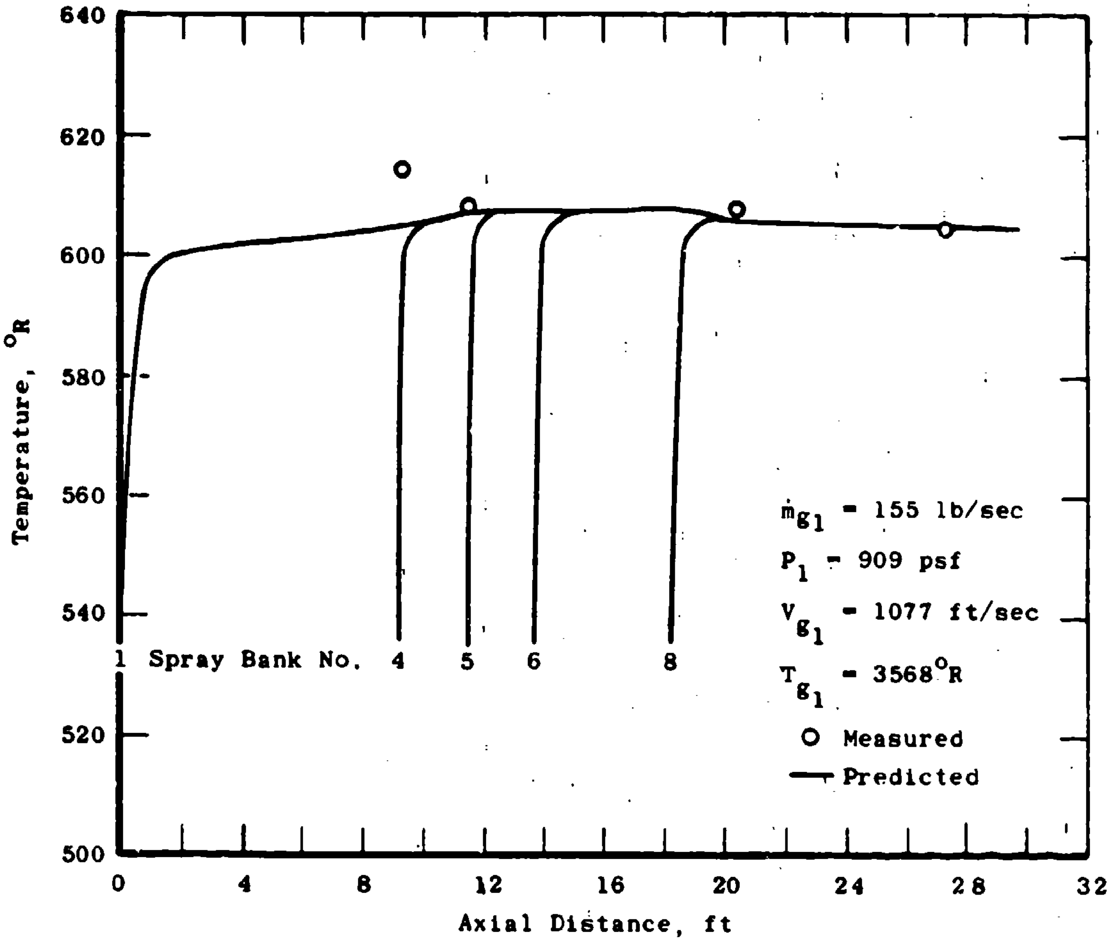
Fig. 3 Predicted and Measured Exhaust Gas Cooler Pressure as a Function of Axial Location



b. Run No. 36-14
Fig. 3 Continued

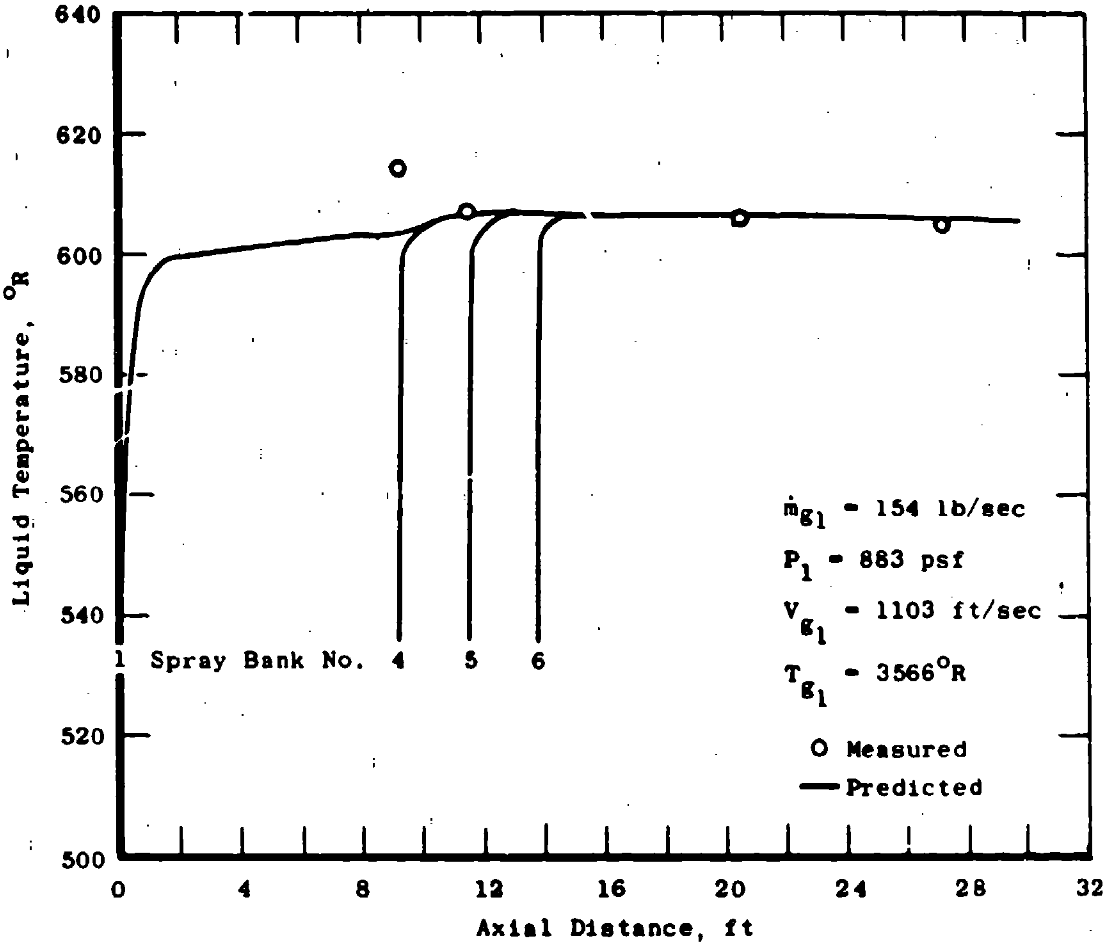


c. Run No. 36-18
Fig. 3 Concluded

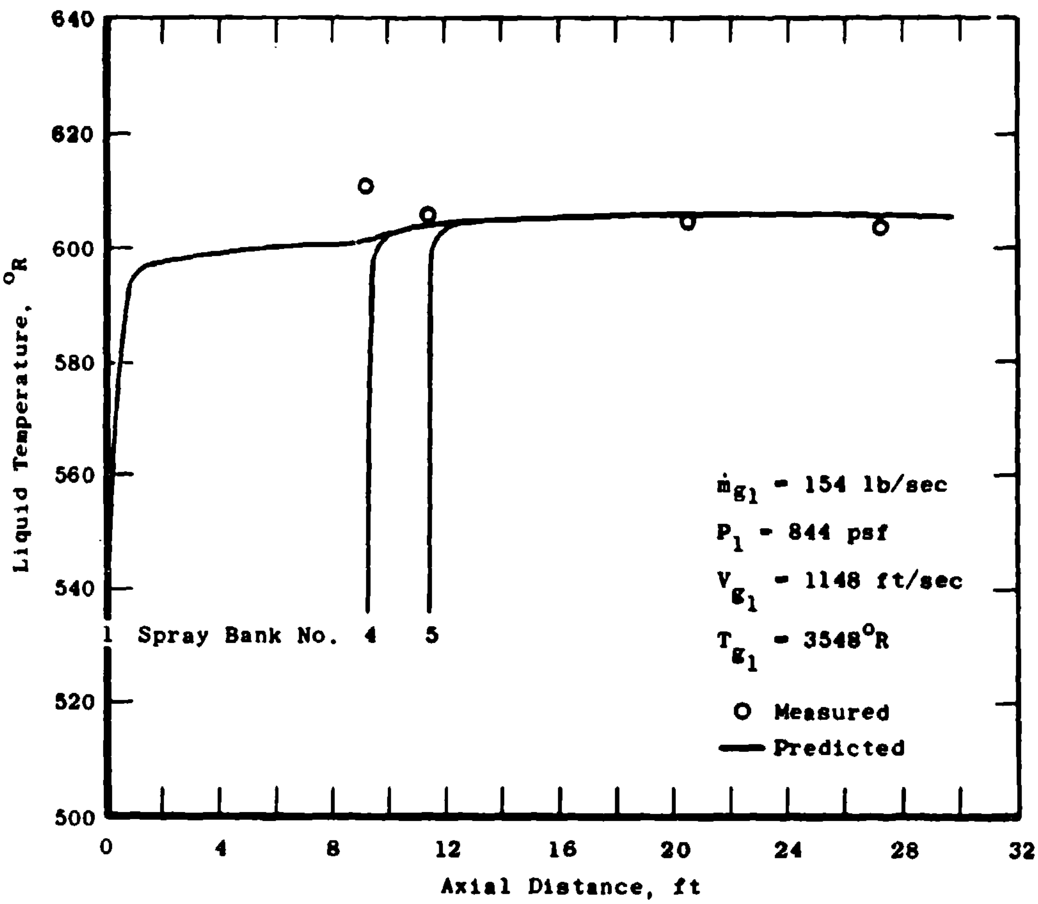


a. Run No. 36-13

Fig. 4 Predicted and Measured Liquid Temperature as a Function of Axial Location



b. Run No. 36-14
Fig. 4 Continued



c. Run No. 36-18
Fig. 4 Concluded

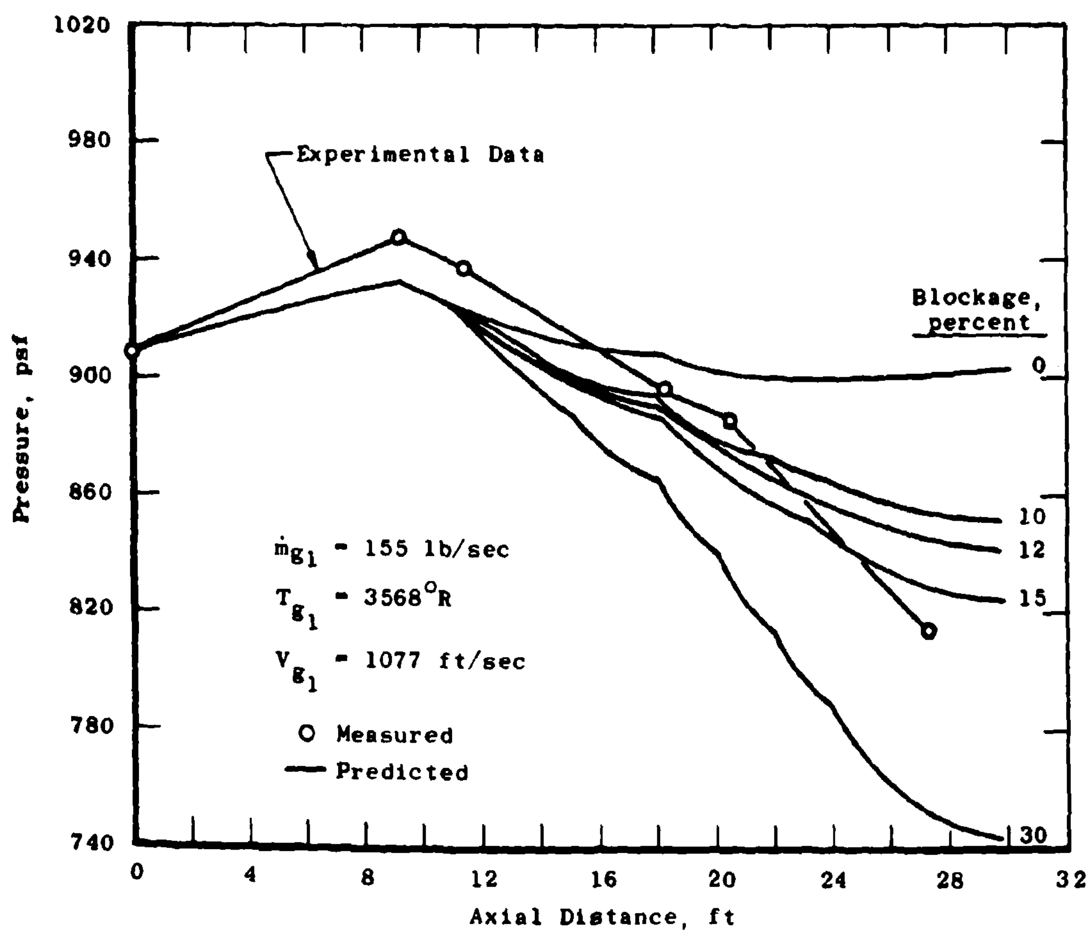


Fig. 5 Effect of Blockage on the Predicted Pressure in an Exhaust Gas Cooler

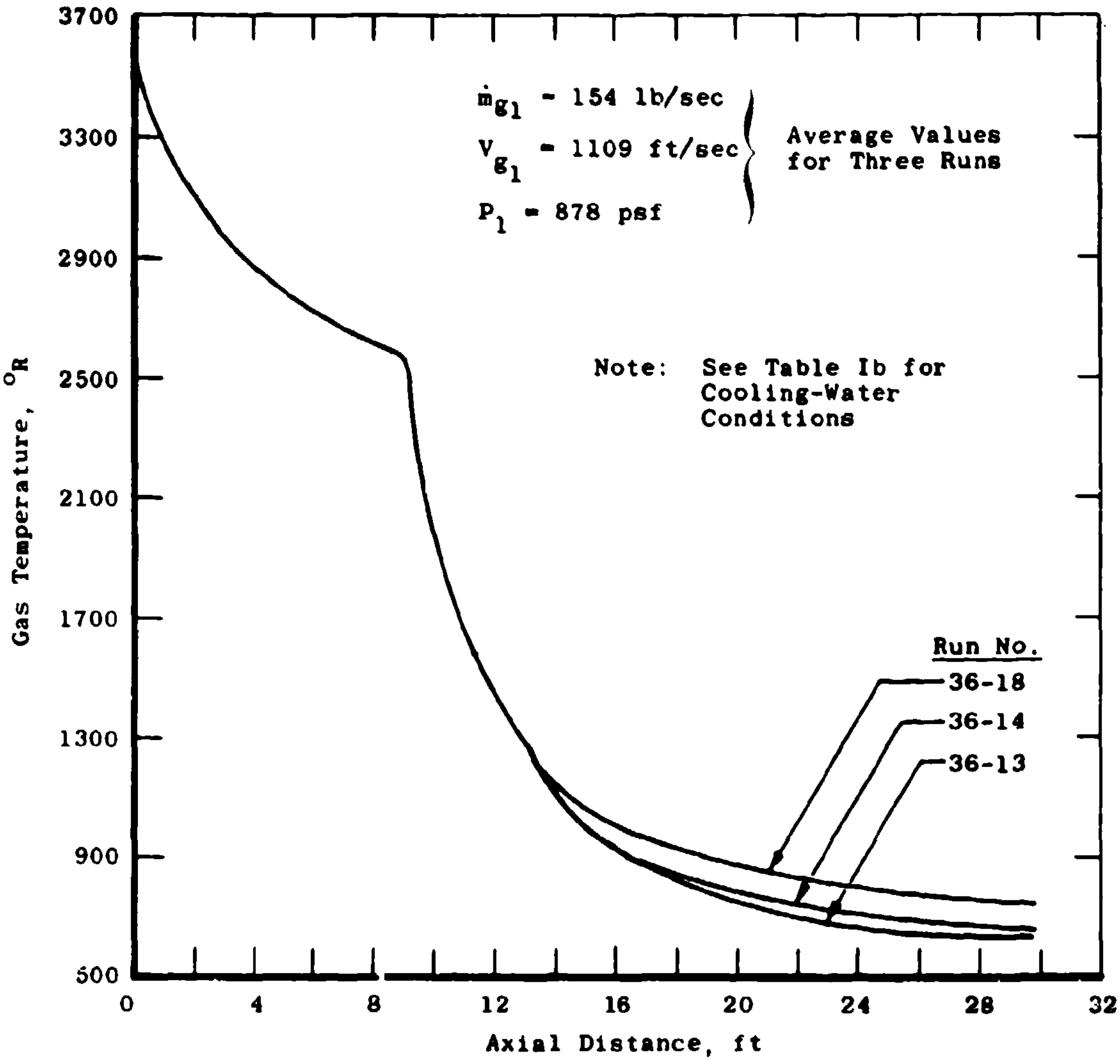
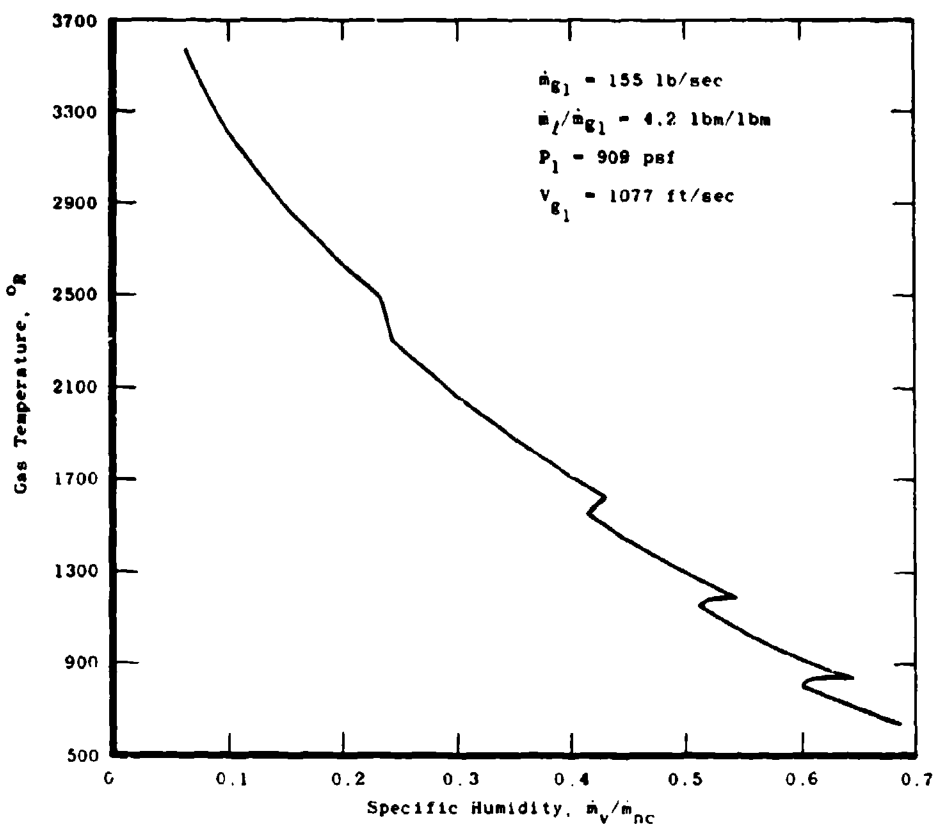
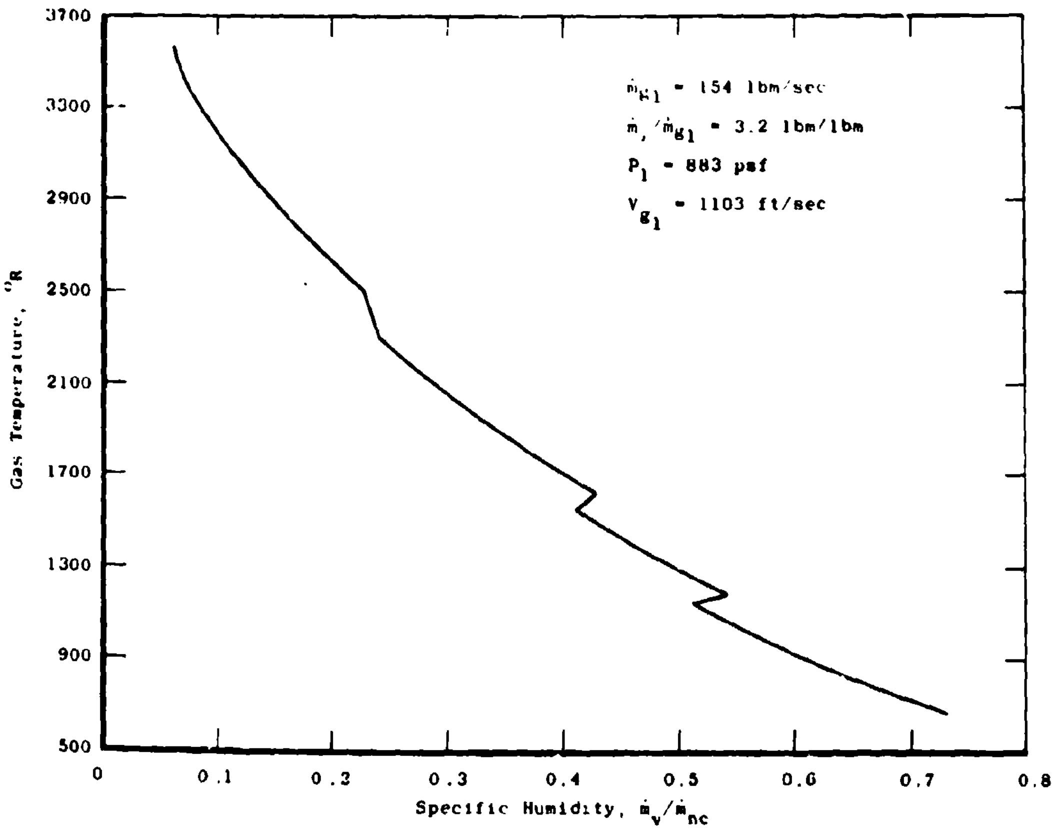


Fig. 6 Predicted Exhaust Gas Temperature for Various Amounts of Injected Cooling Water

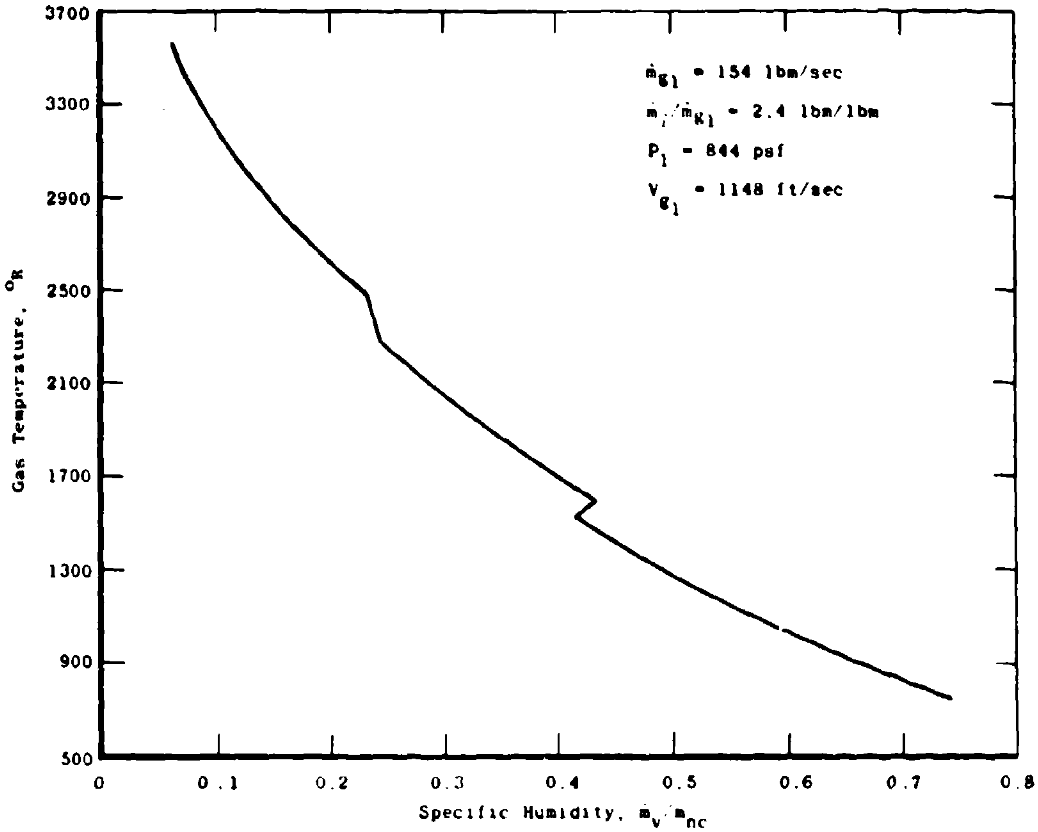


a. Run No. 36-13

Fig. 7 Predicted Relation between Exhaust Temperature and Specific Humidity for Three Cooling Water Flow Rates



b. Run No. 36-14
Fig. 7 Continued



c. Run No. 36-18
Fig. 7 Concluded

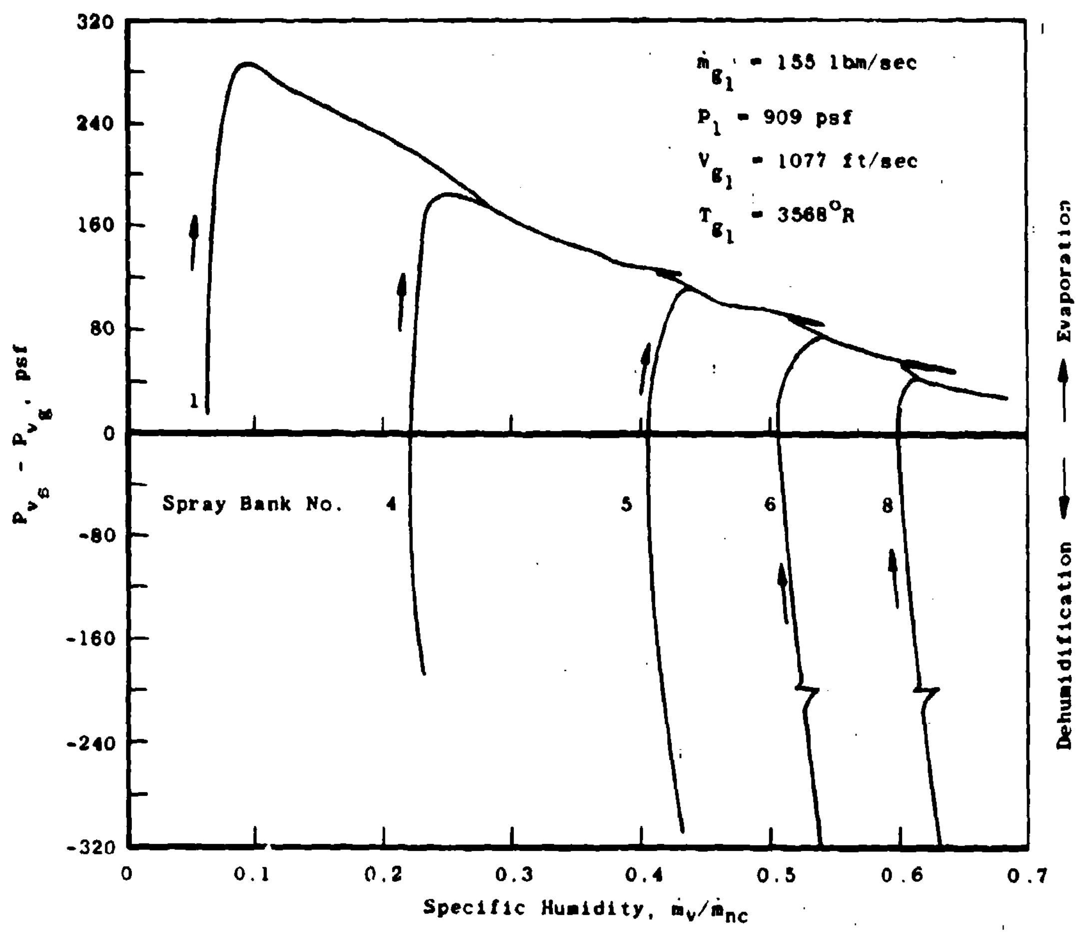


Fig. 8 Effect of the Difference in the Partial Pressures of the Liquid and Exhaust Gas Streams on the Specific Humidity for Run No. 36-13

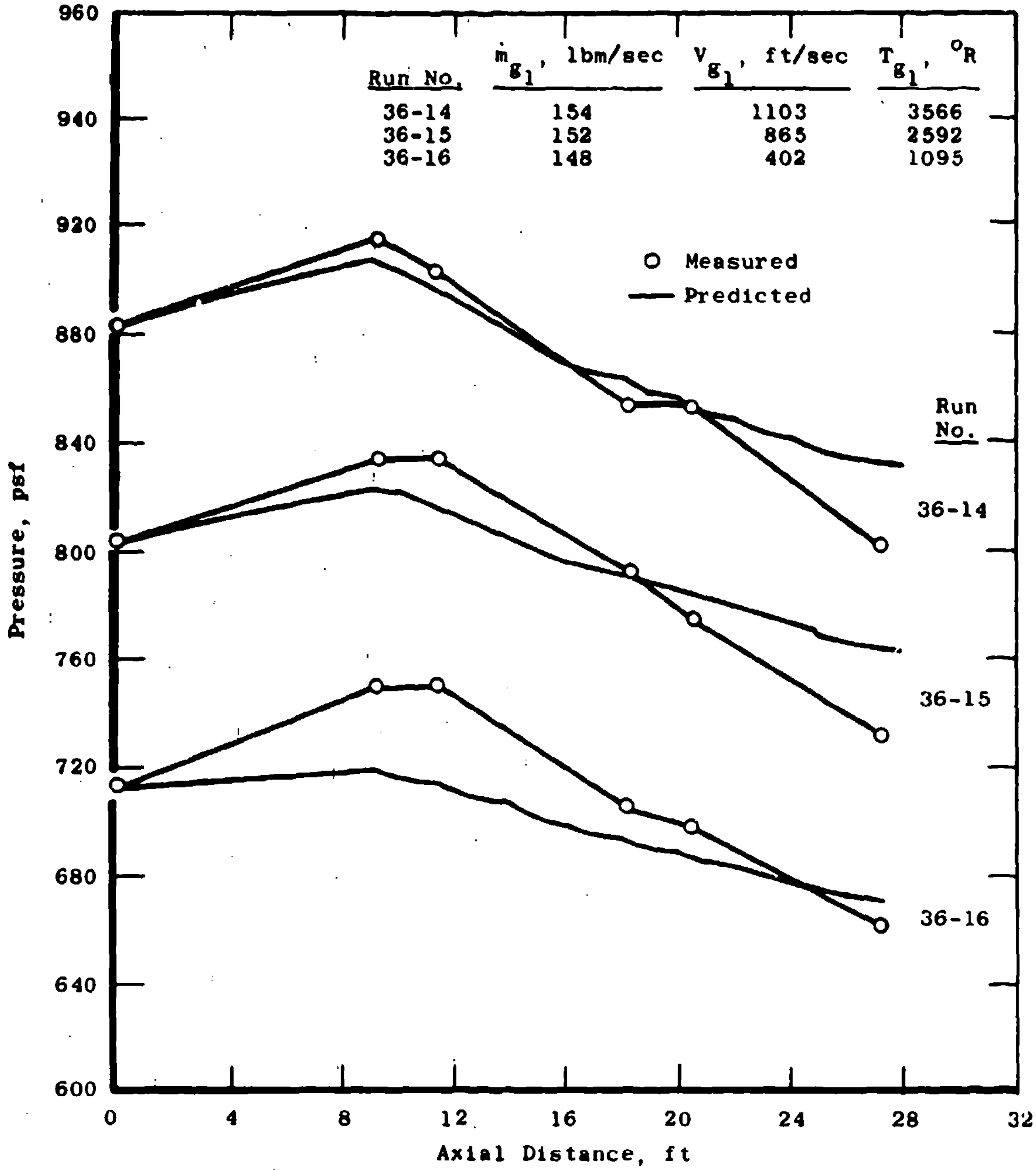


Fig. 9 Measured and Predicted Exhaust Gas Cooler Pressures for Approximately Constant Inlet Mass Flow Rate and Various Total Energy Levels

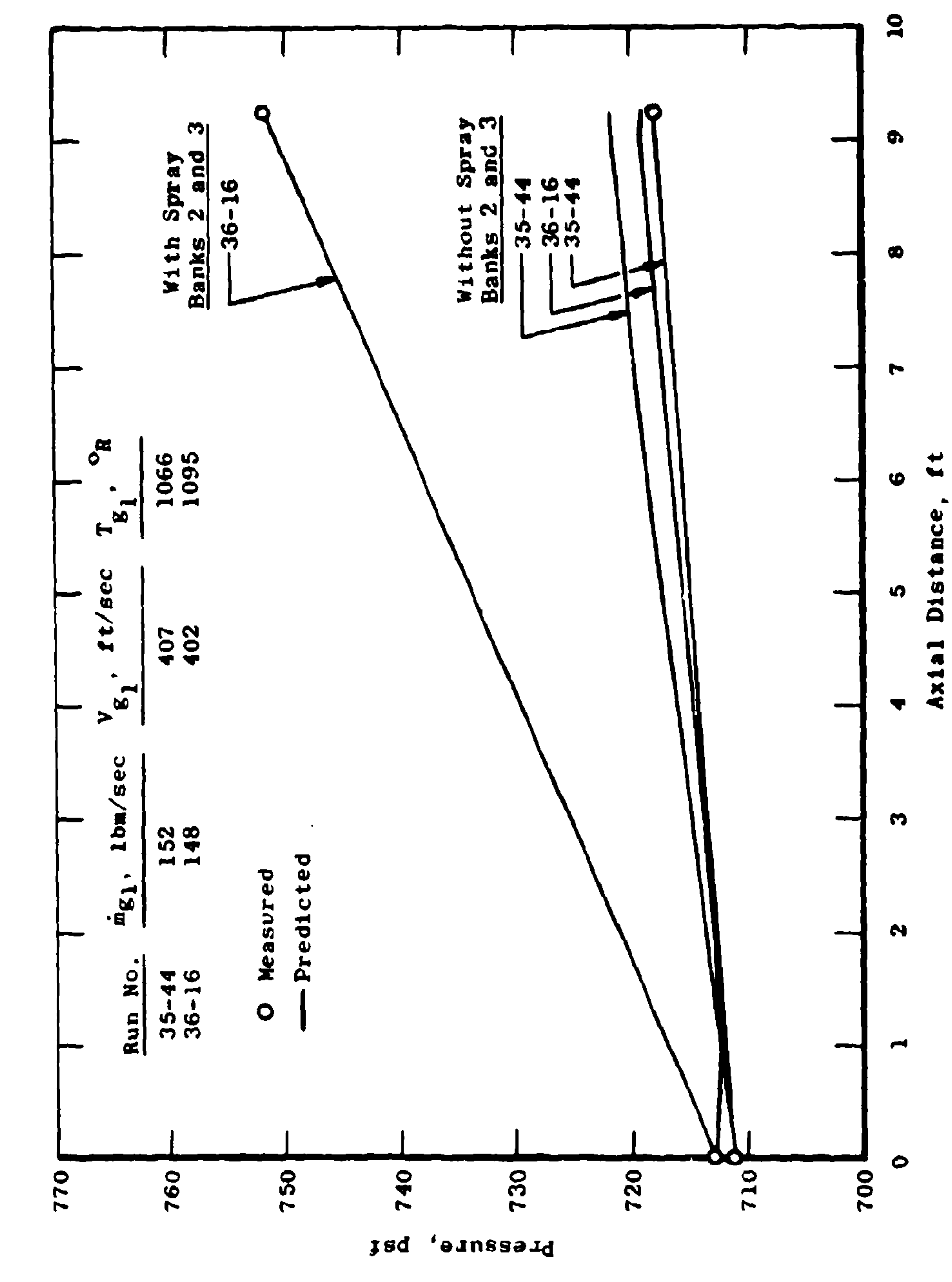


Fig. 10 A Comparison of Two Runs to Evaluate the Influence of the Wall Spray Banks on the Predicted and Measured Cooler Pressure

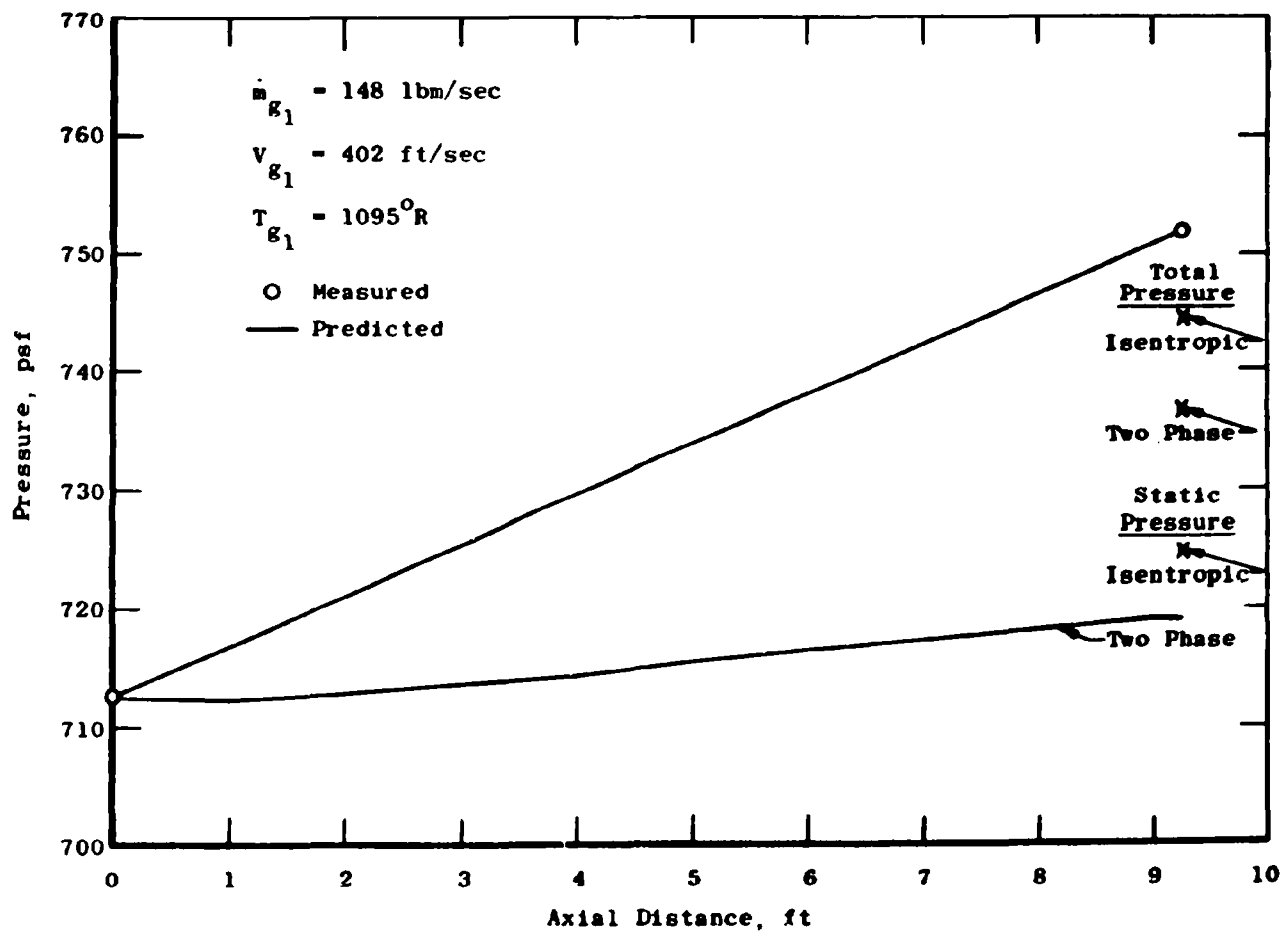


Fig. 11 A Comparison of the Measured Cooler Pressure with Several Values of Calculated Pressure for Run 36-16

TABLE I
INLET ENGINE AND COOLER CONDITIONS FOR RUNS NO. 36-13, 36-14, AND 36-18

a. Measured and Calculated Exhaust Gas Parameters

Run No.	Inlet Flow Rate		Inlet Air Temperature, °R	Cooler Inlet Pressure, P, psia	Inlet Area, ft²	Calculated Cooler Inlet Conditions		
	Fuel, lbm/sec	Air, lbm/sec				Moisture Mass Fraction, C_v	Velocity, V_g, ft/sec	Temperature, T_g, °R
36-13	7.40	147.57	778.0	6.31	30.275	0.05959	1077.0	3567.8
36-14	7.36	146.99	787.0	6.13	30.275	0.05950	1103.1	3566.4
36-18	7.33	146.97	782.0	5.87	30.275	0.05928	1147.7	3548.2

TABLE I (Concluded)
b. Cooling Water Flow Rate Conditions

Inlet Liquid						
Run No.	Station or Spray Bank	Distance from Entrance, x, ft	Liquid Ratio, f_ℓ, lbm/lbm	Velocity V_ℓ, ft/sec	Temperature, T_s, °R	Drop Size, D, ft
36-13	1	0	0.524	70.0	536	0.20×10^{-2}
	4	9.25	0.849	90.0	↓	0.59×10^{-3}
	5	11.50	0.890	90.0	↓	↓
	6	13.75	0.951	95.0	↓	↓
	7	16.00	0.0	90.0	↓	↓
	8	18.25	0.968	94.0	↓	↓
	9	20.50	0.0	90.0	↓	↓
	10	22.75	0.0	90.0	↓	↓
	11	25.00	0.0	90.0	↓	↓
36-14	1	0	0.520	69.5	↓	0.20×10^{-2}
	4	9.25	0.849	91.5	↓	0.59×10^{-3}
	5	11.50	0.908	91.0	↓	↓
	6	13.75	0.961	95.5	↓	↓
	7	16.00	0.0	↓	↓	↓
	8	18.25	↓	↓	↓	↓
	9	20.50	↓	↓	↓	↓
	10	22.75	↓	↓	↓	↓
	11	25.00	↓	↓	↓	↓
36-18	1	0	0.531	71.0	↓	0.194×10^{-2}
	4	9.25	0.887	92.0	↓	0.59×10^{-3}
	5	11.50	0.935	91.5	↓	↓
	6	13.75	0	↓	↓	↓
	7	16.00	↓	↓	↓	↓
	8	18.25	↓	↓	↓	↓
	9	20.50	↓	↓	↓	↓
	10	22.75	↓	↓	↓	↓
	11	25.00	↓	↓	↓	↓

TABLE II
INLET ENGINE AND COOLER CONDITIONS FOR RUNS NO. 36-14, 36-15, 36-16, AND 35-44

a. Measured and Calculated Exhaust Gas Parameters

Run No.	Inlet Flow Rate		Inlet Air Temperature, °R	Cooler Inlet Pressure, P, psia	Inlet Area, ft^2	Calculated Cooler Inlet Conditions		
	Fuel, lbm/sec	Air, lbm/sec				Moisture Mass Fraction, C_v	Velocity, V_g, ft/sec	Temperature, T_g, °R
36-14	7.36	146.99	787.0	6.13	30.275	0.05950	1103.4	3567.5
36-15	4.32	147.23	779.0	5.58	30.275	0.03584	864.9	2592.3
36-16	0.65	147.23	781.0	4.95	30.275	0.00552	402.0	1095.5
35-44	1.219	152.5	484.2	4.94	30.275	0.00997	407.6	1066.3

TABLE II (Concluded)
b. Cooling Water Flow Rate Conditions

Run No.	Station or Spray Bank	Distance from Entrance, x, ft	Inlet Liquid: Liquid Ratio, f_ℓ, lbm/lbm	Inlet Liquid: Velocity V_ℓ, ft/sec	Inlet Liquid: Temperature, T_s, °R	Inlet Liquid: Drop Size, D, ft
36-14	1	0.0	0.52	69.5	536	0.0020
	2	4.8	0.187	81.0	↓	0.0020
	3	6.9	0.176	76.6		0.0020
	4	9.25	0.849	91.5		0.00059
	5	11.5	0.908	91.0		↓
	6	13.75	0.961	95.5		
	7	16.00	0.0	↓		
	8	18.25	0.0			
	9	20.5	0.0			
36-15	1	0.0	0.534	71.0		0.00197
	2	4.8	0.191	81.0		0.00197
	3	6.9	0.179	76.0		0.00197
	4	9.25	0.873	87.0		0.00059
	5	11.5	0.921	89.0		↓
	6	13.75	0.979	90.0		
	7	16.00	0.0	↓		
	8	18.25	0.0			
	9	20.5	0.0			
36-16	1	0.0	0.547	72.0		0.00194
	2	4.8	0.195	81.0		0.00194
	3	6.9	0.186	77.0		0.00194
	4	9.25	0.910	88.0		0.00059
	5	11.5	0.959	91.0		↓
	6	13.75	1.01	↓		
	7	16.0	0.0			
	8	18.25	0.0			
	9	20.5	0.0			
35-44	1	0.0	0.175	60.0		0.0020
	2	4.8	0.0	60.0		0.0020
	3	6.9	0.0	60.0		0.0020
	4	9.25	1.020	104.0		0.00059
	5	11.5	1.341	98.5		↓
	6	13.75	0.0	93.0		
	7	16.00	↓	↓		
	8	18.25				
	9	20.5			↓	

APPENDIX III
A LISTING OF THE COMPUTER PROGRAM AND THE REQUIRED AUXILIARY EQUATIONS FOR AN EXHAUST GAS COOLER

A listing of the computer program for the solution of the equations developed in the text is given in this section. In addition, auxiliary equations necessary to define certain constants used for the computer solution are listed.

AUXILIARY EQUATIONS

These auxiliary equations are used to define certain dimensionless numbers which are in turn solved for certain coefficients used in the equations developed in the text. The properties of the system used in the equations are evaluated at the so-called "film temperature" which is defined as

$$T_{fi} = \frac{T_{si} + T_g}{2}$$

where the f indicates a film property and the i identifies the particular liquid stream being discussed. For this program, the noncondensable gas was assumed to be dry air, and the various constants were calculated using the properties of air. The desired constants and equations are given below:

$$C_{Di} = \frac{24}{Re_{fi}}\left[1 + 0.15\,(Re_{fi})^{0.687}\right] \quad \text{(Ref. 9)}$$

$$C_{p_{fi}} = \left(\bar{x}_{v_{fi}}\right)\left(M_v / M_{fi}\right)\left(C_{pv_{fi}}\right) + \left(1 - \bar{x}_{v_{fi}}\right)\left(M_{nc} / M_{fi}\right)\left(C_{p_{nc_{fi}}}\right)$$

$$D_i = \left(6M_{di} / \pi\rho_\ell\right)^{1/3}$$

$$h_i = \frac{\left(Nu_{fi}\right)\left(\mu_{fi}\right)\left(C_{p_{fi}}\right)}{\left(D_i\right)\left(Pr_{fi}\right)}$$

$$k_{fi} = \bar{x}_{v_{fi}}\, k_{v_{fi}} + \left(1 - \bar{x}_{v_{fi}}\right) k_{nc_{fi}}$$

$$k_{xi} = \frac{\left(Nu_{ab_{fi}}\right)\left(\mu_{fi}\right)}{\left(D_i\right)\left(Sc_{fi}\right)\left(M_{fi}\right)}$$

$$M_{fi} = \bar{x}_{v_{fi}} M_v + \left(1 - \bar{x}_{v_{fi}}\right) M_{nc}$$

$$\frac{\dot{m}_{nc}}{A_o} = \left[\frac{V_g \left(1 - C_v\right) P}{T_g R_U \left(\frac{1-C_v}{M_{nc}} + \frac{C_v}{M_v}\right)}\right]_{x = 0}$$

$$Nu_{ab_{fi}} = 2 + 0.6 \left(Re_{fi}\right)^{1/2} \left(Sc_{fi}\right)^{1/3} \quad \text{(Ref. 10)}$$

$$Nu_{fi} = 2 + 0.6 \left(Re_{fi}\right)^{1/2} \left(Pr_{fi}\right)^{1/3} \quad \text{(Ref. 10)}$$

$$Pr_{fi} = \frac{\left(C_{p_{fi}}\right)\left(\mu_{fi}\right)}{k_{fi}}$$

$$R = Ru / \left[\bar{x}_v M_v + \left(1 - \bar{x}_v\right) M_{nc}\right]$$

$$Re_{fi} = \frac{\left(V_g - V_{\ell i}\right)\left(\rho_{fi}\right)\left(D_i\right)}{\mu_{fi}}$$

$$Sc_{fi} = \frac{\mu_{fi}}{\left(\rho_{fi}\right)\left(D_{ab_{fi}}\right)}$$

$$V_g \rho_g \left(1 - C_v\right) = \frac{\dot{m}_{nc}}{A_o} \Big/ \frac{A}{A_o}$$

$$\bar{x}_{v_{fi}} = \frac{\bar{x}_{v_{si}} + \bar{x}_v}{2}$$

$$\bar{x}_v = \frac{C_v/M_v}{C_v/M_v + (1 - C_v)M_{nc}}$$

$$\bar{x}_{v_{si}} = \frac{P_{v_{si}}}{P}$$

$$\mu_{fi} = \left(\bar{x}_{v_{fi}}\right)\left(\mu_{v_{fi}}\right) + \left(1 - \bar{x}_{v_{fi}}\right)\left(\mu_{nc_{fi}}\right)$$

$$\rho_{fi} = \frac{(P)\left(M_{fi}\right)}{R_u T_{fi}}$$

COMPUTER LISTING

The following computer program was programmed for the IBM 360 computer and was used to obtain the calculated data of this program.

DETERMINATION OF EXHAUST GAS COOLER INLET CONDITIONS

```
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*4    T2TW(150)
      REAL*4 AREA,RAIR,RFUEL
      REAL*4 ARTM,ARPR,ARW1
      REAL*4 IRUN(2),WHAT(14)
      COMMON /GRP/ ARTM(150),ARPR(150),ARW1(150),NPLT
      COMMON / ENTH / T, TY, R, COA(7), H(6), CO2A(7), H2A(7), XN2A(7),
     1  O2A(7), H2OA(7), WT(6), COB(7), CO2B(7), H2B(7), XN2B(7),
     2  O2B(7), H2OB(7), C(6), A(6), P(212)
      CALL ERRSET(261,256,-1,1)
      WT(1) = 28.011
      WT(2) = 44.011
      WT(3) =  2.016
      WT(4) = 28.016
      WT(5) = 32.0
      WT(6) = 18.016
      P(201)= 11.766
      P(203)= 12.260
      P(205)= 12.770
      P(207)= 13.298
      P(209)= 13.844
      P(211)= 14.408
      R= 1.98726
C     PRESSURE DATA  32 F  TO  212 F
C
      READ (5,100)  (P(I),I=32,199)
      READ (5,100)  (P(I),I=200,212,2)
  100 FORMAT (8D10.0)
C
C     TEMPERATURE COEFFICIENTS
C
      READ (5,101) (COA(I),I=1,7), (COB(I),I=1,7), (CO2A(I),I=1,7),
     1 (CO2B(I),I=1,7), (H2A(I),I=1,7), (H2B(I),I=1,7), (XN2A(I),I=1,7),
     2 (XN2B(I),I=1,7), (O2A(I),I=1,7), (O2B(I),I=1,7), (H2OA(I),I=1,7),
     3 (H2OB(I),I=1,7)
  101 FORMAT (5D16.7/2D16.7)
C
C    INPUT CONDITIONS
  987 FORMAT (20A4)
C
C    MASS FRACTIONS
C
  105 FORMAT (6D12.5)
    1 READ (17,END=999) C,P1,T1,TW1,VG1,VW1,TGUESS,IRUN,WHAT
      READ (17) AREA,RAIR,RFUEL
      TGUESS=TW1+.01*(T1-TW1)
      T2MAX=TW1-.01
      T2MIN=TW1+.01

      IF (P1.EQ.0.AND.T1.EQ.0.) GO TO 999
      NPLT=0
C
      EM=0.
      DO 6 I = 1,6
      EM = EM  +  C(I)/ WT(I)
    6 CONTINUE
      EM = 1.0 / EM
      CV1 = C(6)
```

```
      CNC1 = 1.0 - CV1
      PV1 =(P1 * EM * CV1)/ 18.
      PNC1 = P1 - PV1
      EMNC =(P1 * EM * CNC1) / PNC1
      T=T1/ 1.8
      CALL ENTHAL
      SUM = 0.0
      DO 7 I = 1, 5
      SUM = SUM + C(I) * H(I)
    7 CONTINUE
      HNC1 = SUM / CNC1
C     ITERATE FOR TEMPERATURE AS A FUNCTION OF ENTHALPY
C
      DOTM=RAIR+RFUEL
      CONSTN=((1545.*DOTM)/(28.85*144.*P1*AREA))**2
      CONSTN=CONSTN/(2.*778.*32.2)
      TGS1=T1/1.8
      TGS2=(T1-0.5*T1)/1.8
      T=TGS1
      CALL ENTHAL
      CALL SUMIT (C,H,CNC1,ENT1)
      T=T*1.8
      FUNC1=ENT1+CONSTN*T*T-HNC1
      T=TGS2
      CALL ENTHAL
      CALL SUMIT (C,H,CNC1,ENT2)
      T=T*1.8
      FUNC2=ENT2+CONSTN*T*T-HNC1
  401 TGIF=(TGS1+TGS2)/2.
      IF (DABS((TGS2-TGS1)/TGS2).LT.0.1D-06) GO TO 410
      T=TGIF
      CALL ENTHAL
      CALL SUMIT(C,H,CNC1,ENT3)
      T=T*1.8
      FUNC3=ENT3+CONSTN*T*T-HNC1
      TSTA=FUNC1*FUNC3
      TSTB=FUNC2*FUNC3
      IF (TSTA) 404,404,402
  402 IF (TSTB) 405,405,403
  403 WRITE (6,411)
  411 FORMAT('0 NO ROOT FOR INITIAL ENTHALPH')
      GO TO 1
  404 FUNC2=FUNC3
      TGS2=TGIF
      GO TO 401
  405 FUNC1=FUNC3
      TGS1=TGIF
      GO TO 401
  410 ENTNU=ENT3
      T1=TGIF*1.8
C     END OF ITERATION
      VG1=(DOTM*1545.*T1)/(P1*AREA*144.)
      VG1=VG1/28.85
      WRITE (6,413) ENTNU,T1,VG1
      WRITE(9)C(6),VG1,T1,P1
  413 FORMAT ('0  ENTHALPY = ',E12.4,'   GAS TEMPERATURE = ',E12.4,
     *  '    GAS VELOCITY = ',E12.4)
      GO TO 1
  999 CONTINUE
```

```
      ENDFILE 9
      REWIND 9
      RETURN
      END

      SUBROUTINE ENTHAL
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON / ENTH / T, TT, R, COA(7), H(6), CO2A(7), H2A(7), XN2A(7),
     1 O2A(7), H2OA(7), WT(6), COB(7), CO2B(7), H2B(7), XN2B(7),
     2 O2B(7), H2OB(7), C(6), A(6), P(212)
    3 TT=R*T*1.8
      IF (T.LT.1000) GO TO 10
      DO 4  J=1,6
    4 A(J)=COA(J)
      CALL HTRT (T,A,H(1))
      H(1)=H(1)*TT/WT(1) +28488.3  *1.8/WT(1)
      DO 5  J=1,6
    5 A(J) = CO2A(J)
      CALL HTRT (T,A,H(2))
      H(2)=H(2)*TT/WT(2) +96290. *1.8/WT(2)
      DO 6 J=1,6
    6 A(J)=H2A(J)
      CALL HTRT (T,A,H(3))
      H(3)=H(3)*TT/WT(3) +2023.8 *1.8/WT(3)
      DO 7 J=1,6
    7 A(J)=XN2A(J)
      CALL HTRT (T,A,H(4))
      H(4)=H(4)*TT/WT(4)  +2072.3 *1.8/WT(4)
      DO 8 J=1,6
    8 A(J)=O2A(J)
      CALL HTRT (T,A,H(5))
      H(5)=H(5)*TT/WT(5) +2074.7 *1.8/WT(5)
      DO 9 J=1,6
    9 A(J)=H2OA(J)
      CALL HTRT (T,A,H(6))
      H(6)=H(6)*TT/WT(6) +60164.7 *1.8/WT(6)
      HV2=H(6)
      GO TO 17
   10 DO 11 J=1,6
   11 A(J)=COB(J)
      CALL HTRT (T,A,H(1))
      H(1)=H(1)*TT/WT(1) +28488.3  *1.8/WT(1)
      DO 12 J=1,6
   12 A(J)=CO2B(J)
      CALL HTRT (T,A,H(2))
      H(2)=H(2)*TT/WT(2) +96290. *1.8/WT(2)
      DO 13 J=1,6
   13 A(J)=H2B(J)
      CALL HTRT (T,A,H(3))
      H(3)=H(3)*TT/WT(3) +2023.8 *1.8/WT(3)
      DO 14 J=1,6
   14 A(J)=XN2B(J)
      CALL HTRT (T,A,H(4))
      H(4)=H(4)*TT/WT(4)  +2072.3 *1.8/WT(4)
      DO 15 J=1,6
   15 A(J)=O2B(J)
      CALL HTRT (T,A,H(5))
      H(5)=H(5)*TT/WT(5) +2074.7 *1.8/WT(5)
```

```
      DO 16 J=1,6
   16 A(J)=H2OB(J)
      CALL HTRT (T,A,H(6))
      H(6)=H(6)*T1/WT(6) +60164.7 *1.9/WT(6)
      HV2=H(6)
   17 CONTINUE
      HNC2 =0.0
      DO 18 I=1,5
   18 HNC2=HNC2 + C(I)*H(I)
      HNC2=HNC2/(1.0-C(6))
      RETURN
      END

      SUBROUTINE SUMIT(C,H,CN,ENTH)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION C(1),H(1)
      SUM=0.
      DO 1 I=1,5
    1 SUM=SUM+C(I)*H(I)
      ENTH=SUM/CN
      RETURN
      END
```

MAIN PROGRAM FOR EXHAUST GAS SPRAY COOLER

```
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON BA,VLB,AA,RNC
      COMMON        ROL,VW,GW,GC,RV,CJ,WNCAO,B(4) ,ISTA
      COMMON ISET,KKK,KOUNT,KN,KKI
      COMMON DL,BL,CL,TSA
      COMMON FLN,VLA,DA,FLA
      COMMON GE1,GE2,GE3,GE4,GE5,GE6,GE7,GE8,GE9,GE10,GE11,GE12,GE13,GE1
     14,GE15,GE16,GE17,GE18
      COMMON PVTS,DAB,SCF,RE,ABN,FNU
      COMMON ROF
      COMMON/LDW/ MICH
      DIMENSION Y(99),YP(99),A5(10),A6(10),A7(10),A8(10),A10(10),XVS(10
     1),XHL(10),XHFG(10),BARH(10),DM(10),XK(10),CO(10)
     2,XHV(10)
      DIMENSION FL(10),VL(10),TS(10),D(10),STA(11)
  103 FORMAT(1H1,'BEGIN STATION',I4,12X,12HRUN NUMBER  ,8A8)
      M=0
  200 M=M+1
      XVF=0.0
      KI=1
      AA=.88
      VLB=1.0
      IKK=0
      BA=.25
      KN=1
      KI=1
      MICH=0
      READ(5,51015,END=222)ALP
51015 FORMAT(10A8)
      READ(5,102) NSTA
      NS1= NSTA+1
      READ(5,101)(STA(I),I=1,NS1)
      READ(9,END=222)CV,VG,TG,P
      P=P*144.0
      READ(5,101)(FL(I),I=1,NSTA)
      READ(5,101)(VL(I),I=1,NSTA)
      READ(5,101)(TS(I),I=1,NSTA)
      READ(5,101)(D(I),I=1,NSTA)
      READ(5,101)(B(I),I=1,4)
  100 FORMAT(4E10.2)
  101 FORMAT( 8F10.0)
  102 FORMAT( I2)
      CPL=1.0
      GE1=STA(2)-.25D0
      GE2=GE1+.1D0
      GE3=STA(3)-.25D0
      GE4=GE3+.1D0
      GE5=STA(4)-.25D0
      GE6=GE5+.1D0
      GE7=STA(5)-.25D0
      GE8=GE7+.1D0
      GE9=STA(6)-.25D0
      GE10=GE9+.1D0
      GE11=STA(7)-.25D0
      GE12=GE11+.1D0
      GE13=STA(8)-.25D0
      GE14=GE13+.1D0
```

```
      GE15=STA(9)-.25D0
      GE16=GE15+.1D0
      GE17=STA(10)-.25D0
      GE18=GE17+.1D0
      FLN=0.0
      VLA=0.0
      DA=0.0
      FLA=0.0
      CL=0.0
      DL=0.0
      TSA=0.0
      BL=0.0
      CJ=778.0
      GC= 32.2
      ISET = 9
      GW=29.0
      VW=18.0
      RV=1.986*778.0
      RVAP=RV/VW
      RNC=RV/GW
      ROL=62.4
      TREF = 540.0
      ISTA=1
      MSTA=ISTA
      NEQ=8
C     THE ARRAYS USED IN DIFFE ARE NOW SET UP
      Y(1)=CV
      Y(2)=VG
      Y(3)=TG
      Y(4)=P
      Y(5)=FL(1)
      Y(6)=VL(1)
      Y(7)=TS(1)
      Y(8)= D(1)
      WNCAO = Y(2) *(1.0-Y(1))*Y(4)/(Y(3)*RV*((1-Y(1))/GW+Y(1)/VW) )
      X=0.0
      WRITE(6,103)ISTA,ALP
3     CONTINUE
      DX=.0001
      KOUNT =0
      IF(ISTA .EQ. 1)J=8
      DO 1 II=1,9999999
      IF(ISTA .EQ. 1)KKI=8
      IF(ISTA .EQ. 2)KKI=16
      IF(ISTA .EQ. 3)KKI=24
      IF(ISTA .EQ. 4)KKI=32
      IF(ISTA .EQ. 5)KKI=40
      IF(ISTA .EQ. 6)KKI=48
      IF(ISTA .EQ. 7)KKI=56
      IF(ISTA .EQ. 8)KKI=64
      IF(ISTA .EQ. 9)KKI=72
      IF(X .GE. STA(2) .AND. X .LE. GE3)KKI=8
      IF(X .GE. GE3 .AND. X .LE. STA(3))KKI=16
      IF(X .GE. STA(3) .AND. X .LE. GE5)KKI=16
      IF(X .GE. GE5 .AND. X .LE. STA(4))KKI=24
      IF(X .GE. STA(4) .AND. X .LE. GE7)KKI=24
      IF(X.GE.STA(5).AND.X.LE.GE9)KKI=32
      IF(X .GE. STA(6) .AND. X .LE. GE11)KKI=40
      IF(X .GE. STA(7) .AND. X .LE. GE13)KKI=48
      IF(X .GE. STA(8) .AND. X .LE. GE15)KKI=56
      IF(X .GE. STA(9) .AND. X .LE. GE17)KKI=64
```

```
      IF(ISTA .EQ. 2 .AND. X .GE. STA(2))MSTA=3
      IF(X .GE. STA(2) .AND. X .LE. GE3)MSTA=3
      IF(ISTA .EQ. 3 .AND. X .GE. STA(3))MSTA=3
      IF(X .GE. STA(3) .AND. X .LE. GE5)MSTA=3
      IF(ISTA .EQ. 4 .AND. X  .GE. STA(4))MSTA=3
      IF(ISTA .EQ. 5 .AND. X .GE. STA(5))MSTA=3
      IF(ISTA .EQ. 6 .AND. X .GE. STA(6))MSTA=3
      IF(ISTA .EQ. 7 .AND. X .GE. STA(7))MSTA=3
      IF(ISTA .EQ. 8 .AND. X .GE. STA(8))MSTA=3
      IF(ISTA .EQ. 9 .AND. X .GE. STA(9))MSTA=3
      IF(X .GE. GE3 .AND. X .LE. GE4)MSTA=1
      IF(X .GE. GE5 .AND. X .LE. GE6)MSTA=1
      IF(X .GE. GE7 .AND. X .LE. GE8)MSTA=1
      IF(X .GE. GE9 .AND. X .LE. GE10)MSTA=1
      IF(X .GE. GE11 .AND. X .LE. GE12)MSTA=1
      IF(X .GE. GE13 .AND. X .LE. GE14)MSTA=1
      IF(X .GE. GE15 .AND. X .LE. GE16)MSTA=1
      IF(X .GE. GE17 .AND. X .LE. GE18)MSTA=1
      IF(X .GE. GE2 .AND. X .LE. STA(2))MSTA=2
      IF(X .GE. GE4 .AND. X .LE. STA(3))MSTA=2
      IF(X .GE. GE6 .AND. X .LE. STA(4))MSTA=2
      IF(X .GE. GE8 .AND. X .LE. STA(5))MSTA=2
      IF(X .GE. GE10 .AND. X .LE. STA(6))MSTA=2
      IF(X .GE. GE12 .AND. X .LE. STA(7))MSTA=2
      IF(X .GE. GE14 .AND. X .LE. STA(8))MSTA=2
      IF(X .GE. GE16 .AND. X .LE. STA(9))MSTA=2
      IF(X .GE. GE18)MSTA=2
      CALL DIFFE(X,Y,YP,DX,IKK,NEQ,KI,MSTA)
      KI=1
      IF(X .GE. GE1 .AND. X .LE. GE1+DX)GO TO 909
      IF(X .GE. GE3 .AND. X .LE. GE3+DX)GO TO 666
      IF(X .GE. GE5 .AND. X .LE. GE5+DX)GO TO 666
      IF(X .GE. GE7 .AND. X .LE. GE7+DX)GO TO 666
      IF(X .GE. GE9 .AND. X .LE. GE9+DX)GO TO 666
      IF(X .GE. GE11.AND. X .LE. GE11+DX)GO TO 666
      IF(X .GE. GE13 .AND. X .LE. GE13+DX)GO TO 666
      IF(X .GE. GE15 .AND. X .LE. GE15+DX)GO TO 666
      IF(X .GE. GE17 .AND. X .LE. GE17+DX)GO TO 666
      GO TO 669
  666 FLN=(Y(LA)+Y(LA-4)+Y(LA-8))
      VLA=(Y(LA+1)*Y(LA)+Y(LA-3)*Y(LA-4)+Y(LA-7)*Y(LA-8))/FLN
      DA=(Y(LA+3)*Y(LA)+Y(LA-1)*Y(LA-4)+Y(LA-5)*Y(LA-8))/FLN
      TSA=(Y(LA+2)*Y(LA)+Y(LA-2)*Y(LA-4)+Y(LA-6)*Y(LA-8))/FLN
      GO TO 669
  909 FLN=FLN+Y(J-3)
      VLA=VLA+(Y(J-3)*Y(J-2)/FLN)
      DA=DA+(Y(J-3)*Y(J)/FLN)
      TSA=TSA+Y(J-1)/ISTA
  669 CONTINUE
      IF(X .GE. GE1 .AND. X .LE. GE1+DX)GO TO 8000
      IF(X .GE. GE3 .AND. X .LE. GE3+DX)GO TO 8000
      IF(X .GE. GE5 .AND. X .LE. GE5+DX)GO TO 8000
      IF(X .GE. GE7 .AND. X .LE. GE7+DX)GO TO 8000
      IF(X .GE. GE9 .AND. X .LE. GE9+DX)GO TO 8000
      IF(X .GE. GE11.AND. X .LE. GE11+DX)GO TO 8000
      IF(X .GE. GE13 .AND. X .LE. GE13+DX)GO TO 8000
      IF(X .GE. GE15 .AND. X .LE. GE15+DX)GO TO 8000
      IF(X .GE. GE17 .AND. X .LE. GE17+DX)GO TO 8000
      IF(X .GE. GE2 .AND. X .LE. GE2+DX)GO TO 8001
      IF(X .GE. GE4 .AND. X .LE. GE4+DX)GO TO 8001
      IF(X .GE. GE6 .AND. X .LE. GE6+DX)GO TO 8001
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      IF(X .GE. GE8 .AND. X .LE. GE8+DX)GO TO 8001
      IF(X .GE. GE10 .AND. X .LE. GE10+DX)GO TO 8001
      IF(X .GE. GE12 .AND.X .LE. GE12+DX)GO TO 8001
      IF(X .GE. GE14 .AND. X .LE. GE14+DX)GO TO 8001
      IF(X .GE. GE16 .AND. X .LE. GE16+DX)GO TO 8001
      IF(X .GE. GE18 .AND. X .LE. GE18+DX)GO TO 8001
   99 IF(X.GE.STA(ISTA+1))GO TO 2
      GO TO 1
 8000 CONTINUE
      IF(ISTA .EQ. 1)LA=5
      IF(ISTA .EQ. 2)LA=13
      IF(ISTA .EQ. 3)LA=21
      IF(ISTA .EQ. 4)LA=29
      IF(ISTA .EQ. 5)LA=37
      IF(ISTA .EQ. 6)LA=45
      IF(ISTA .EQ. 7)LA=53
      IF(ISTA .EQ. 8)LA=61
      IF(ISTA .EQ. 9)LA=69
      Y(LA+1)=VLA
      FLA=AA*FLN
      Y(LA)=FLA
      RG=Y(1)*RVAP+(1.0-Y(1))*RNC
      ROG=Y(4)/(RG*Y(3))
      SIG=.004790
      Y(LA+2)=TSA
      Y(LA+3)=DA
      KI=0
      GO TO 1
 8001 CONTINUE
      IF(ISTA .EQ. 1)JJ=8
      IF(ISTA .EQ. 2)JJ=16
      IF(ISTA .EQ. 3)JJ=24
      IF(ISTA .EQ. 4)JJ=32
      IF(ISTA .EQ. 5)JJ=40
      IF(ISTA .EQ. 6)JJ=48
      IF(ISTA .EQ. 7)JJ=56
      IF(ISTA .EQ. 8)JJ=64
      IF(ISTA .EQ. 9)JJ=72
      PIE =3.1416
      DO 88 I=1,2
      J=JJ+4*(I-1)
      GO TO(20,21),I
   20 CONTINUE
      FLA=AA*FLN
      FLB=(1.0-AA)*FLN
      RG=Y(1)*RVAP+(1.0-Y(1))*RNC
      ROG=Y(4)/(RG*Y(3))
      SIG=.004790
      DB=(418.6*SIG)/(ROG*(Y(2)-VLB)**2)
      GO TO 22
   21 CONTINUE
      Y(J-2)=VLB
      Y(J-3)=FLB
      Y(J-1)=TSA
      Y(J)=DB
      IKK=IKK+8
      NEQ=NEQ+4
      KI=0
   22 CONTINUE
   88 CONTINUE
```

```
1       CONTINUE
        JJJ= JJJ+1
2       CONTINUE
        WRITE(6,12139)
12139   FORMAT(1H1)
C       WE WILL NOW PLOT THE STATION JUST FINISHED
        ISTA= ISTA+1
        IF(ISTA .EQ. 1)LA=5
        IF(ISTA .EQ. 2)LA=13
        IF(ISTA .EQ. 3)LA=21
        IF(ISTA .EQ. 4)LA=29
        IF(ISTA .EQ. 5)LA=37
        IF(ISTA .EQ. 6)LA=45
        IF(ISTA .EQ. 7)LA=53
        IF(ISTA .EQ. 8)LA=61
        IF(ISTA .EQ. 9)LA=69
        IF(ISTA .GT. NSTA)GO TO 5
        ISET = 9
        WRITE(6,103)ISTA,ALP
C       SET UP  ARRAYS  FOR DIFFE
        Y(NEQ+1)=FL(ISTA)
        Y(NEQ+2)=VL(ISTA)
        Y(NEQ+3)=TS(ISTA)
        Y(NEQ+4)=D(ISTA)
        NEQ =NEQ+4
        KOUNT = 0
        GO TO 3
    5   GO TO 200
  222   STOP
        END

        SUBROUTINE DIFFE(X,Y,YP,DX,IKK,NEQ,KI,MSTA)
        IMPLICIT REAL*8(A-H,O-Z)
        COMMON BA,VLB,AA,RNC
        COMMON        ROL,VW,GW,GC,RV,CJ,WNCAO,B(4) ,ISTA
        COMMON ISET,KKK,KOUNT,KN,KKI
        COMMON DL,BL,CL,TSA
        COMMON FLN,VLA,DA,FLA
        COMMON GE1,GE2,GE3,GE4,GE5,GE6,GE7,GE8,GE9,GE10,GE11,GE12,GE13,GE1
       14,GE15,GE16,GE17,GE18
        COMMON PVTS,DAB,SCF,RE,ABN,FNU
        COMMON ROF
        DIMENSION Y(99),YP(99),Z(99),ZP(99),ZN(99)
        DY=0.0
        CALL  YFUNC(X,Y,YP,KI,1,MSTA,IKK,DX,DY)
  120   CONTINUE
        DO 1  I=1,NEQ
        Z(I)=Y(I)+DX*YP(I)
    1   CONTINUE
        X=X+DX
        DX2=.5D+0*DX
        DO 5  J=2,999
        DY=DX
  666    CALL  YFUNC(X,Z,ZP,KI,J,MSTA,IKK,DX,DY)
        K=0
        DO 40  I=1,NEQ
        ZN(I)=Y(I)+DX2*(YP(I)+ZP(I))
        IF(DABS(ZN(I)-Z(I))-1.D-05*DABS(ZN(I)))4,4,3
    3   K=1
```

```
    4 KK=J
      Z(I)=ZN(I)
   40 CONTINUE
      IF(K)5,6,5
    5 CONTINUE
      WRITE(6,99)(ZN(I),I=1,NEQ)
      WRITE(6,90)KK
   90 FORMAT(I5)
   99 FORMAT(4E20.10)
      STOP
    6 DO 7 I=1,NEQ
    7 Y(I)=Z(I)
 1210 CONTINUE
      IF(J .GE. 3 .AND. J .LE. 5)GO TO 1212
      IF(J .LT. 3)GO TO 2020
      DX=.5*DX
      GO TO 1212
 2020 DX=2.0*DX
      IF(DX .GT. .01)DX=.01
 1212 CONTINUE
      RETURN
      END


      SUBROUTINE YFUNC(X,Y,YP,KI,K,MSTA,IKK,DX,DY)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON BA,VLB,AA,RNC
      COMMON         ROL,VW,GW,GC,RV,CJ,WNCAO,B(4),,ISTA
      COMMON ISET,KKK,KOUNT,KN,KKI
      COMMON DL,BL,CL,TSA
      COMMON FLN,VLA,DA,FLA
      COMMON GE1,GE2,GE3,GE4,GE5,GE6,GE7,GE8,GE9,GE10,GE11,GE12,GE13,GE1
     14,GE15,GE16,GE17,GE18
      COMMON PVTS,DAB,SCF,RE,ABN,FNU
      COMMON ROF
      DIMENSION Y(99),YP(99),A5(10),A6(10),A7(10),A8(10),A10(10),XVS(10
     1),XHL(10),XHFG(10),BARH(10),DM(10),XK(10),CD(10)
     2,XHV(10)
      RVAP=RV/VW
 9899 CONTINUE
      IF(ISTA .EQ. 1)J=8
      IF(ISTA .EQ. 2)J=16
      IF(ISTA .EQ. 3)J=24
      IF(ISTA .EQ. 4)J=32
      IF(ISTA .EQ. 5)J=40
      IF(ISTA .EQ. 6)J=48
      IF(ISTA .EQ. 7)J=56
      IF(ISTA .EQ. 8)J=64
      IF(ISTA .EQ. 9)J=72
      SIG=.00479
      PIE =3.1416
      SUM1=0.
      SUM2=0.
      SUM3=0.
      SUM4=0.
      SUM5=0.
      IF(X .GE. GE1-DX .AND. X .LE. GE1)GO TO 8001
      IF(X .GE. GE2-DX .AND. X .LE. GE2)GO TO 8001
      IF(X .GE. GE3-DX .AND. X .LE. GE3)GO TO 8001
      IF(X .GE. GE4-DX .AND. X .LE. GE4)GO TO 8001
```

```
      IF(X .GE. GE5-DX .AND. X .LE. GE5)GO TO 8001
      IF(X .GE. GE6-DX .AND. X .LE. GE6)GO TO 8001
      IF(X .GE. GE7-DX .AND. X .LE. GE7)GO TO 8001
      IF(X .GE. GE8-DX .AND. X .LE. GE8)GO TO 8001
      IF(X .GE. GE9-DX .AND. X .LE. GE9)GO TO 8001
      IF(X .GE. GE10-DX.AND.X.LE.GE10)GO TO 8001
      IF(X .GE. GE11-DX .AND. X .LE. GE11)GO TO 8001
      IF(X .GE. GE12-DX .AND. X .LE. GE12)GO TO 8001
      IF(X .GE. GE13-DX .AND. X .LE. GE13)GO TO 8001
      IF(X .GE. GE14-DX .AND. X .LE. GE14)GO TO 8001
      IF(X .GE. GE15-DX .AND. X .LE. GE15)GO TO 8001
      IF(X .GE. GE16-DX .AND. X .LE. GE16)GO TO 8001
      IF(X .GE. GE17-DX .AND. X .LE. GE17)GO TO 8001
      IF(X .GE. GE18-DX .AND. X .LE. GE18)GO TO 8001
      GO TO 8002
 9998 CONTINUE
 8001 CONTINUE
      RG=Y(1)*RVAP+(1.0-Y(1))*RNC
 8002 IF(KI .EQ. 0)GO TO 8003
      CALL ROGEE(ROG,Y(1),Y(2),X)
      GO TO 8009
 8003 ROG=Y(4)/(RG*Y(3))
 8009 CONTINUE
      DO 1 I=1,MSTA
      J=KKI+4*(I-1)
      A5(I) = PIE*ROL*Y(J)**2  /2.0
      CALL SUB1(Y(1),Y(3),Y(4),Y(J-1),XVS(I),XV,XK(I),Y(J),DM(I),CD(I),B
     1ARH(I),Y(J-2),Y(2))
      IF(XVF .GT. 1.0)RETURN
      YP(J)= XK(I)* PIE *Y(J)**2 *(XV-XVS(I))*VW/(A5(I)*Y(J-2)*(1-XVS(I)
     1))
      A6(I)= YP(J)
      YP(J-2)=((PIE/8.0)*ROG*(Y(J)**2    )*CD(I)*DABS(Y(2)-Y(J-2))*(Y(2)-
     1Y(J-2))-( Y(2)-Y(J-2))*Y(J-2)*A5(I)*A6(I))/(DM(I)*Y(J-2))
      A7(I)=YP(J-2)
      YP(J-3)= A5(I)*A6(I)*Y(J-3)/DM(I)
      A8(I)=YP(J-3)
      SUM1=SUM1+A5(I)*A6(I)*Y(J-3)/DM(I)
      CALL HLI(Y(J-1),XHL(I),XHFG(I),XHV(I))
      YP(J-1) =   BARH(I)* PIE * Y(J)**2 *(Y(3)-Y(J-1))/ (DM(I)*Y(J-2))-
     CXHL(I)*A5(I)*A6(I)/DM(I)+A5(I)*A6(I)*XHV(I)/DM(I)
      A10(I)= YP(J-1)
      SUM2 = SUM2 + Y(J-2)*A6(I)+ Y(J-3)*A7(I)
      SUM3 = SUM3 +A8(I)*(XHL(I)+Y(J-2)**2 /(2.0*GC*CJ))
      SUM4 = SUM4 +Y(J-3)* Y(J-2)*A7(I)/(GC*CJ)
      SUM5 = SUM5 + Y(J-3)*A10(I)
    1 CONTINUE
      YP(1) = -SUM1*(1-Y(1))**2
      A9=YP(1)
      CALL AAA3(X,Y(1),Y(2),A3,AA0,DAA0,ROG)
      CALL DERT( ROG,Y(1),Y(2),Y(3),Y(4),A9,SUM2,SUM3,SUM4,SUM5,A0,A3,A1
     C1,A12,A13,A14,R,CPV,CPA,A2,A4,AA0,A)
      YP(3) =(A11*A14-A12*A13)/(A11*(CPV*Y(1)/(1-Y(1))+CPA)-A12*A0*ROG*R
     C)
      A15= YP(3)
      YP(2) = (A13-A0*ROG*R*A15)/A11
      A16=YP(2)
      CALL DERP(ROG,Y(1),Y(2),Y(3),R,A2,A3,A4,A9,A15,A16,DP,A)
      YP(4) = DP
      IF(K.GT. 1) GO TO 3
```

```
      IF(X .EQ. 0.0)GO TO 9999
      IF(X .LT. BA)GO TO 3
      BA=BA+.25
 9999 WRITE(6,4)X
      WRITE(6,88888)ROF
      WW=Y(1)/(1.0-Y(1))
4     FORMAT(1H0,'X=',F16.10)
      WRITE(6,5) AAO,WW
5     FORMAT(1H0,'A/A0=',G16.6,5X,'WV/WNC=',G16.6)
      WRITE(6,6)Y(1),Y(2),Y(3),Y(4)
      IF(ISTA .EQ. 1)JJ=8
      IF(ISTA .EQ. 2)JJ=16
      IF(ISTA .EQ. 3)JJ=24
      IF(ISTA .EQ. 4)JJ=32
      IF(ISTA .EQ. 5)JJ=40
      IF(ISTA .EQ. 6)JJ=48
      IF(ISTA .EQ. 7)JJ=56
      IF(ISTA .EQ. 8)JJ=64
      IF(ISTA .EQ. 9)JJ=72
6     FORMAT(1H0,'CV=',G20.9,5X,'VG=',G20.9,5X,'TG=',G20.9,5X,'P=',G20.9
     1)
      IF(X .GE. GE2 .AND. X .LE. GE3-DX)GO TO 88
      IF(X .GE. GE4 .AND. X .LE. GE5-DX)GO TO 88
      IF(X .GE. GE6 .AND. X .LE. GE7-DX)GO TO 88
      IF(X .GE. GE8 .AND. X .LE. GE9-DX)GO TO 88
      IF(X .GE. GE10 .AND. X .LE. GE11-DX)GO TO 88
      IF(X .GE. GE12 .AND. X .LE. GE13-DX)GO TO 88
      IF(X .GE. GE14 .AND. X .LE. GE15-DX)GO TO 88
      IF(X .GE. GE16 .AND. X .LE. GE17-DX)GO TO 88
      IF(X .GE. GE18-DX)GO TO 88
      DO 10 I=1,1
      J=JJ+4*(I-1)
      WRITE(6,8) Y(J-3),Y(J-2),Y(J-1),Y(J)
      WRITE(6,9) YP(J-3),YP(J-2),YP(J-1),YP(J)
10    CONTINUE
      GO TO 1001
   88 DO 988 I=1,2
      J=IKK+4*(I-1)
      WRITE(6,8)Y(J-3),Y(J-2),Y(J-1),Y(J)
      WRITE(6,9)YP(J-3),YP(J-2),YP(J-1),YP(J)
  988 CONTINUE
      IF(X .GE. GE1+.2500-DX .AND. X .LE. GE3-DX)GO TO 1000
      IF(X .GE. GE3+.2500-DX .AND. X .LE. GE5-DX)GO TO 1000
      IF(X .GE. GE5+.2500-DX .AND. X .LE. GE7-DX)GO TO 1000
      IF(X.GE. GE7+.2500-DX.AND. X .LE. GE9-DX)GO TO 1000
      IF(X.GE. GE9+.25000-DX .AND. X .LE.GE11-DX)GO TO 1000
      IF(X .GE. GE11+.2500-DX .AND. X .LE. GE13-DX)GO TO 1000
      IF(X .GE. GE13+.2500-DX .AND. X .LE. GE15-DX)GO TO 1000
      IF(X .GE. GE15+.2500-DX .AND. X .LE. GE17-DX)GO TO 1000
      GO TO 1002
1000  CONTINUE
      IF(X .GE. GE1-DX+.2500)JJ=8
      IF(X .GE. GE3-DX+.2500)JJ=16
      IF(X .GE. GE5-DX+.2500)JJ=24
      IF(X .GE. GE7+.2500-DX)JJ=32
      IF(X .GE. GE9+.2500-DX)JJ=40
      IF(X .GE. GE11+.2500-DX)JJ=48
      IF(X .GE. GE13+.2500-DX)JJ=56
      IF(X .GE. GE15+.2500-DX)JJ=64
      IF(X .GE. GE18-DX)GO TO 1002
```

```
 1010 J=JJ+8
      WRITE(6,8) Y(J-3),Y(J-2),Y(J-1),Y(J)
      WRITE(6,9) YP(J-3),YP(J-2),YP(J-1),YP(J)
  199 CONTINUE
1001  CONTINUE
 1002 CONTINUE
      WRITE(6,7)YP(1),YP(2),YP(3),YP(4)
8     FORMAT(1H0,'FL=',G20.9,5X,'VL=',G20.9,5X,'TS=',G20.9,5X,'D=',G20.9
     1)
9     FORMAT(1H0,'FLP=',G16.6,5X,'VLP=',G16.6,5X,'TSP=',G16.6,5X,'DP=',G
     116.6)
7     FORMAT(1H0,'CVP=',G16.6,5X,'VGP=',G16.6,5X,'TGP=',G16.6,5X,'PP=',G
     116.6)
3     CONTINUE
2     FORMAT(1H ,7E16.6)
      RETURN
      END


      SUBROUTINE  SUB1( CV,TG,P,TS,XVS,XV,XK,D,DM,CD,BH,VL,VG)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON BA,VLB,AA,RNC
      COMMON        ROL,VW,GW,GC,RV,CJ,WNCAO,B(4) ,ISTA
      COMMON ISET,KKK,KOUNT,KN,KKI
      COMMON DL,BL,CL,TSA
      COMMON FLN,VLA,DA,FLA
      COMMON GE1,GE2,GE3,GE4,GE5,GE6,GE7,GE8,GE9,GE10,GE11,GE12,GE13,GE1
     14,GE15,GE16,GE17,GE18
      COMMON PVTS,DAB,SCF,RE,ABN,FNU
      COMMON ROF
 9899 CONTINUE
      XV=(CV/VW)/(CV/VW +(1-CV)/GW)
      X2=-9.06*((-.5696*TS+ .0839E-4 *TS**2 +.0927E-7 *TS**3+1352.3)/TS-
     C1.4425)
      X1= 672.0/TS
      PVTS = 2117.0 *X1**5.19*DEXP(X2)
      XVS = PVTS/P
      XVF =(XVS+XV)/2.0
      XM= XVF* VW +(1-XVF) *GW
      TFI =(TS+TG)/2.0
      FMV =(10.6E-7 *DSQRT(TFI))/(1+1538.0/TFI)
      FMNC= 7.5E-7*DSQRT(TFI)/(1+ 216.0/TFI)
      FM = XVF *FMV +(1-XVF)*FMNC
      DAB = (.5375/P)*(TFI/491.0)**2.334
      ROF = P* XM/(RV*TFI)
      SCF=FM/(ROF*DAB)
      RE =DABS(VG-VL)*ROF*D/FM
      IF(RE .LT. 0.0)GO TO 9999
      ABN= 2.0+0.6*DSQRT(RE) * SCF** 0.3333
      XK = ABN*FM/(D*SCF*XM)
      DM = D**3  *3.1416 *ROL/6.0
      CD = 24.0/RE*( 1.0+.15*RE**0.687)
      IF( TFI .GT.1700.0 .AND. TFI .LT.4500.0) GO TO 221
      IF(TFI .LT. 400.0 .OR. TFI .GT.4500)  GO  TO 222
      CPVF =.4304 +.1678E-4*TFI +0.2781E-7*TFI**2.0
      CPNCF = 0.2318 + 0.1040E-4 *TFI + 0.7166E-8 *TFI**2
      GO TO 102
221   CPVF = .3319 +0.1438E-3 *TFI -0.1312E-7 *TFI**2.0
      CPNCF= 0.2214 + 0.3521E-4*TFI- 0.3776E-8 *TFI**2
```

```
      GO TO 102
222   WRITE(6,101)
101   FORMAT(1H ,'TEMP-FI-IS OUT OF RANGE')
      WRITE(6,122) TG,TS
122   FORMAT(1H0,'TG=',E20.6, 5X,'TS=',E20.6)
9999  CONTINUE
      WRITE(6,9990)RE,VG,VL,ROF,D,FM
9990  FORMAT(6E18.10)
      STOP
102   CONTINUE
      FKV = 0.432*FMV
      FKNC = 0.257 *(0.115+ 5.17*CPNCF)* FMNC
      FK= XVF*FKV +(1-XVF)* FKNC
      CPF = XVF*(VW/XM )*CPVF +(1-XVF)*CPNCF*GW/XM
      PVF = CPF *FM/FK
      FNU = 2+.60 *DSQRT(RE) * PVF** 0.3333
      BH =FNU *FM *CPF/(D*PVF)
      RETURN
      END


      SUBROUTINE  ROGEE(ROG,CV,VG,X)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON BA,VLB,AA,RNC
      COMMON        ROL,VW,GW,GC,RV,CJ,WNCAO,B(4) ,ISTA
      AAO =B(1) +B(2)*X +B(3)*X**2.0+ B(4)*X**3.0
      ROG =WNCAO/((1-CV)*VG*AAO)
      RETURN
      END


      SUBROUTINE HLI(TS,XHL,XHFG,XHV)
      IMPLICIT REAL*8(A-H,O-Z)
      XHL =TS -540.0
      XHFG = -.5696*TS + .0839E-4 *TS**2 + 0.0927E-7 *TS**3.0+1352.3
      XHV=XHL+XHFG
      RETURN
      END


      SUBROUTINE AAA3(X,CV,VG,A3,AAO,DAAO,ROG)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON BA,VLB,AA,RNC
      COMMON        ROL,VW,GW,GC,RV,CJ,WNCAO,B(4) ,ISTA
      COMMON ISET,KKK,KOUNT,KN,KKI
      AAO = B(1) + B(2)*X +B(3)*X**2.0 +B(4)*X**3.0
      DAAO = B(2) +2.0* B(3)*X +3.0*B(4)*X**2.0
      A3 = VG *(1-CV)* DAAO/ (VG*(1-CV)*AAO)**2
      RETURN
      END


      SUBROUTINE  DERT( ROG,CV,VG,TG,P,A9,SUM2,SUM3,SUM4,SUM5,AO,A3,A11,
     1A12,A13,A14,R,CPV,CPA,A2,A4,AAO,A)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON BA,VLB,AA,RNC
      COMMON        ROL,VW,GW,GC,RV,CJ,WNCAO,B(4) ,ISTA
      COMMON ISET ,KKK
      IF(VG .LT. 0.0)GO TO 20
      R= P/(ROG* TG)
```

```
      A0 = GC*(1-CV)/ROG
      A4 = WNCAO/(VG**2*(1-CV) *AAO)
      A11 = (1.0-CV)*VG-TG*R*A0*A4
      A12= (1+CV/(1-CV))*VG/(GC*CJ )
      A1 = GW *CV +VW*(1-CV)
      A = WNCAO/(VG*(1-CV)**2*AAO)
      XV= GW *CV/A1
      A2 = RV*VW*GW*(GW-VW)/(A1**2*(XV*VW+(1-XV)*GW)**2)
      A13 = A0*WNCAO*TG*R*A3-A9*(VG**2+ROG*TG*A2*A0+TG*R*A *A0) -VG*(1-C
     CV)**2*SUM2
      CALL HEEV (TG,XHV,CPV,CPA      )
      A14 =-A9*(XHV+VG**2.0/(2*GC*CJ))/(1-CV)** 2   -SUM3-SUM4-SUM5
      RETURN
   20 WRITE(6,31)VG
   31 FORMAT(E20.10)
      STOP
      END


      SUBROUTINE  HEEV(TG,XHV,CPV,CPA)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON BA,VLB,AA,RNC
      COMMON        ROL,VW,GW,GC,RV,CJ,WNCAO,B(4) ,ISTA
      COMMON ISET ,KKK
      IF( TG .GE.1700.0 .AND. TG .LE.4500)GO TO 222
      IF( TG .LT.400.0 .OR. TG .GT.4500) GO TO 221
      XHV = .4304*TG +.0839E-4*TG**2.0+0.0927E-7*TG**3.0-236.3161+1042.9
      CPV = .4304 + .1678E-4*TG+.2781E-7*TG**2.0
      CPA = .2318+ .1040E-4*TG+.7166E-8 *TG**2.0
      GO TO 100
222   XHV = .3319 *TG + .0719E-3*TG**2.0-.04373E-7*TG**3-185.381+1042.9
      CPV = .3319 + .1438E-3*TG- 0.1312E-7*TG**2.0
      CPA = .2214 +0.3521E-4*TG -0.3776E-8*TG**2.0
      GO  TO  100
221   WRITE(6,99)
99    FORMAT(1H ,'TEMP-G IS OUT OF RANGE')
      WRITE(6,1) TG
1     FORMAT(1H0,'TG=',E16.6)
      STOP
100   CONTINUE
      RETURN
      END


      SUBROUTINE DERP(ROG,CV,VG,TG,R,A2,A3,A4,A9,A15,A16,DP,A)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON BA,VLB,AA,RNC
      COMMON        ROL,VW,GW,GC,RV,CJ,WNCAO,B(4) ,ISTA
      DP= ROG*R*A15 +(ROG*TG*A2+TG*R*A )*A9-TG*R*A4*A16-WNCAO*A3*TG*R
      RETURN
      END
```

APPENDIX IV
A LISTING OF A VARIATION OF THE COMPUTER PROGRAM FOR ZERO HARDWARE BLOCKAGE OF THE DUCT

The following computer program was programmed for the IBM 360 computer and has been used to calculate data for two-phase flow conditions with zero blockage of the ducting and also for cases where a drop-size distribution was to be simulated.

DETERMINATION OF EXHAUST GAS COOLER INLET CONDITIONS

```
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*4    T2TW(150)
      REAL*4 AREA,RAIR,RFUEL
      REAL*4 ARTM,ARPR,ARWI
      REAL*4 IRUN(2),WHAT(14)
      COMMON /GRP/ ARTM(150),ARPR(150),ARWI(150),NPLT
      COMMON / ENTH / T, TT, R, COA(7), H(6), CO2A(7), H2A(7), XN2A(7),
     1  O2A(7), H2OA(7), WT(6), COB(7), CO2B(7), H2B(7), XN2B(7),
     2  O2B(7), H2OB(7), C(6), A(6), P(212)
      CALL ERRSET(261,256,-1,1)
      WT(1) = 28.011
      WT(2) = 44.011
      WT(3) =  2.016
      WT(4) = 28.016
      WT(5) = 32.0
      WT(6) = 18.016
      P(201)= 11.766
      P(203)= 12.260
      P(205)= 12.770
      P(207)= 13.298
      P(209)= 13.844
      P(211)= 14.408
      R= 1.98726
C     PRESSURE DATA  32 F   TO   212 F
C
      READ (5,100)  (P(I),I=32,199)
      READ (5,100)  (P(I),I=200,212,2)
  100 FORMAT (8D10.0)
C
C     TEMPERATURE COEFFICIENTS
C
      READ (5,101) (COA(I),I=1,7), (COB(I),I=1,7), (CO2A(I),I=1,7),
     1 (CO2B(I),I=1,7), (H2A(I),I=1,7), (H2B(I),I=1,7), (XN2A(I),I=1,7),
     2 (XN2B(I),I=1,7), (O2A(I),I=1,7), (O2B(I),I=1,7), (H2OA(I),I=1,7),
     3 (H2OB(I),I=1,7)
  101 FORMAT (5D16.7/2D16.7)
C
C    INPUT CONDITIONS
  987 FORMAT (20A4)
C
C    MASS FRACTIONS
C
  105 FORMAT (6D12.5)
    1 READ (17,END=999) C,P1,T1,TW1,VG1,VW1,TGUESS,IRUN,WHAT
      READ (17) AREA,RAIR,RFUEL
      TGUESS=TW1+.01*(T1-TW1)
      T2MAX=TW1-.01
      T2MIN=TW1+.01
      IF (P1.EQ.0.AND.T1.EQ.0.) GO TO 999
      NPLT=0
C
      EM=0.
      DO 6 I = 1,6
      EM = EM  +  C(I)/ WT(I)
    6 CONTINUE
      EM = 1.0 / EM
      CV1 = C(6)
```

```
      CNC1 = 1.0 - CV1
      PV1 =(P1 * EM * CV1)/ 18.
      PNC1 = P1 - PV1
      EMNC =(P1 * EM * CNC1) / PNC1
      T=T1/ 1.8
      CALL ENTHAL
      SUM = 0.0
      DO 7 I = 1, 5
      SUM = SUM + C(I) * H(I)
    7 CONTINUE
      HNC1 = SUM / CNC1
C     ITERATE FOR TEMPERATURE AS A FUNCTION OF ENTHALPY
C
      DOTM=RAIR+RFUEL
      CONSTN=((1545.*DOTM)/(28.85*144.*P1*AREA))**2
      CONSTN=CONSTN/(2.*778.*32.2)
      TGS1=T1/1.8
      TGS2=(T1-0.5*T1)/1.8
      T=TGS1
      CALL ENTHAL
      CALL SUMIT (C,H,CNC1,ENT1)
      T=T*1.8
      FUNC1=ENT1+CONSTN*T*T-HNC1
      T=TGS2
      CALL ENTHAL
      CALL SUMIT (C,H,CNC1,ENT2)
      T=T*1.8
      FUNC2=ENT2+CONSTN*T*T-HNC1
  401 TGIF=(TGS1+TGS2)/2.
      IF (DABS((TGS2-TGS1)/TGS2).LT.0.1D-06) GO TO 410

      T=TGIF
      CALL ENTHAL
      CALL SUMIT(C,H,CNC1,ENT3)
      T=T*1.8
      FUNC3=ENT3+CONSTN*T*T-HNC1
      TSTA=FUNC1*FUNC3
      TSTB=FUNC2*FUNC3
      IF (TSTA) 404,404,402
  402 IF (TSTB) 405,405,403
  403 WRITE (6,411)
  411 FORMAT('0 NO ROOT FOR INITIAL ENTHALPH')
      GO TO 1
  404 FUNC2=FUNC3
      TGS2=TGIF
      GO TO 401
  405 FUNC1=FUNC3
      TGS1=TGIF
      GO TO 401
  410 ENTNU=ENT3
      T1=TGIF*1.8
C     END OF ITERATION
      VG1=(DOTM*1545.*T1)/(P1*AREA*144.)
      VG1=VG1/28.85
      WRITE (6,413) ENTNU,T1,VG1
      WRITE(9)C(6),VG1,T1,P1
  413 FORMAT ('0  ENTHALPY = ',E12.4,'    GAS TEMPERATURE = ',E12.4,
     *  '    GAS VELOCITY = ',E12.4)
      GO TO 1
  999 CONTINUE
```

```
      ENDFILE 9
      REWIND 9
      RETURN
      END

      SUBROUTINE ENTHAL
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON / ENTH / T, TT, R, COA(7), H(6), CO2A(7), H2A(7), XN2A(7),
     1 O2A(7), H2OA(7), WT(6), COB(7), CO2B(7), H2B(7), XN2B(7),
     2 O2B(7), H2OB(7), C(6), A(6), P(212)
    3 TT=R*T*1.8
      IF (T.LT.1000) GO TO 10
      DO 4  J=1,6
    4 A(J)=COA(J)
      CALL HTRT (T,A,H(1))
      H(1)=H(1)*TT/WT(1) +28488.3  *1.8/WT(1)
      DO 5  J=1,6
    5 A(J) = CO2A(J)
      CALL HTRT (T,A,H(2))
      H(2)=H(2)*TT/WT(2) +96290. *1.8/WT(2)
      DO 6 J=1,6
    6 A(J)=H2A(J)
      CALL HTRT (T,A,H(3))
      H(3)=H(3)*TT/WT(3) +2023.8 *1.8/WT(3)
      DO 7 J=1,6
    7 A(J)=XN2A(J)
      CALL HTRT (T,A,H(4))
      H(4)=H(4)*TT/WT(4)  +2072.3 *1.8/WT(4)
      DO 8 J=1,6
    8 A(J)=O2A(J)
      CALL HTRT (T,A,H(5))
      H(5)=H(5)*TT/WT(5) +2074.7 *1.8/WT(5)
      DO 9 J=1,6
    9 A(J)=H2OA(J)
      CALL HTRT (T,A,H(6))
      H(6)=H(6)*TT/WT(6) +60164.7 *1.8/WT(6)
      HV2=H(6)
      GO TO 17
   10 DO 11 J=1,6
   11 A(J)=COB(J)
      CALL HTRT (T,A,H(1))
      H(1)=H(1)*TT/WT(1) +28488.3  *1.8/WT(1)
      DO 12 J=1,6
   12 A(J)=CO2B(J)
      CALL HTRT (T,A,H(2))
      H(2)=H(2)*TT/WT(2) +96290. *1.8/WT(2)
      DO 13 J=1,6
   13 A(J)=H2B(J)
      CALL HTRT (T,A,H(3))
      H(3)=H(3)*TT/WT(3) +2023.8 *1.8/WT(3)
      DO 14 J=1,6
   14 A(J)=XN2B(J)
      CALL HTRT (T,A,H(4))
      H(4)=H(4)*TT/WT(4)  +2072.3 *1.8/WT(4)
      DO 15 J=1,6
   15 A(J)=O2B(J)
      CALL HTRT (T,A,H(5))
      H(5)=H(5)*TT/WT(5) +2074.7 *1.8/WT(5)
```

```
      DO 16 J=1,6
   16 A(J)=H2OB(J)
      CALL HTRT (T,A,H(6))
      H(6)=H(6)*1./WT(6) +60184.7 *1.87/WT(6)
      HV2=H(6)
   17 CONTINUE
      HNC2 =0.0
      DO 18 I=1,5
   18 HNC2=HNC2 + C(I)*H(I)
      HNC2=HNC2/(1.0-C(6))
      RETURN
      END

      SUBROUTINE SUMIT(C,H,CN,ENTH)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION C(1),H(1)
      SUM=0.
      DO 1 I=1,5
    1 SUM=SUM+C(I)*H(I)
      ENTH=SUM/CN
      RETURN
      END
```

MAIN PROGRAM FOR EXHAUST GAS SPRAY COOLER WITH ZERO BLOCKAGE

```
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON BA
      COMMON        ROL,VW,GW,GC,RV,CJ,WNCAO,B(4) ,ISTA
      COMMON ISET,KKK,KOUNT
      COMMON/LOW/ MICH
      DIMENSION FL(10),VL(10),TS(10),D(10),Y(45), YP(45),STA(10)
  103 FORMAT(1H1,'BEGIN STATION',I4,12X,12HRUN NUMBER  ,2A9)
      M=0
  200 M=M+1
      BA=.25
      MICH=0
      READ(5,51015)ALP1,ALP2
51015 FORMAT(2A9)
      READ(5,102) NSTA
      KEN=0
      NS1= NSTA+1
      READ(5,101)(STA(I),I=1,NS1)
      READ(5,100) CV,VG,TG,P
      READ(5,101)(FL(I),I=1,NSTA)
      READ(5,101)(VL(I),I=1,NSTA)
      READ(5,101)(TS(I),I=1,NSTA)
      READ(5,101)(D(I),I=1,NSTA)
      READ(5,101)(B(I),I=1,4)
100   FORMAT(4E10.2)
101   FORMAT( 7E10.2)
102   FORMAT( I2)
      CPL=1.0
      CJ=778.0
      GC= 32.2
      ISET = 9
      GW=29.0
      VW=18.0
      RV= 1.986* 778.0
      ROL=62.4
      TREF = 540.0
      ISTA=1
      NEQ=8
C     THE ARRAYS USED IN DIFFE ARE NOW SET UP
      Y(1)=CV
      Y(2)=VG
      Y(3)=TG
      Y(4)=P
      Y(5)=FL(1)
      Y(6)=VL(1)
      Y(7)=TS(1)
      Y(8)= D(1)
      WNCAO = Y(2) *(1.0-Y(1))*Y(4)/(Y(3)*RV*((1-Y(1))/GW+Y(1)/VW) )
      X=0.0
      WRITE(6,103)ISTA,ALP1,ALP2
3     CONTINUE
      DX=.0001
      KOUNT =0
      DO 1 I= 1,999999
      CALL DIFFE(X,Y,YP,DX,KKK,NEQ,I,KEN)
      IF(X.GE.STA(ISTA+1))GO TO 2
1     CONTINUE
      JJJ= JJJ+1
```

```
2       CONTINUE
C       WE WILL NOW PLOT THE STATION JUST FINISHED
        ISTA= ISTA+1
        ISET = 9
        IF(ISTA .GT. NSTA)GO TO 5
        WRITE(6,103)ISTA,ALP1,ALP2
C       SET UP  ARRAYS  FOR DIFFE
        Y(NEQ+1)=FL(ISTA)
        Y(NEQ+2)=VL(ISTA)
        Y(NEQ+3)=TS(ISTA)
        Y(NEQ+4)=D(ISTA)
        NEQ =NEQ+4
        KOUNT = 0
        GO TO 3
      5 IF(M-1)200,222,222
    222 STOP
        END


        SUBROUTINE DIFFE(X,Y,YP,DX,KK,NEQ,I,KEN)
        IMPLICIT REAL*8(A-H,O-Z)
        DIMENSION Y(50),YP(50),Z(50),ZP(50),ZN(50)
        CALL YFUNC(X,Y,YP,1,KEN)
        DO 1 I=1,NEQ
      1 Z(I)=Y(I)+DX*YP(I)
        X=X+DX
        DX2=.5D+0*DX
        DO 5 J=2,9999
        CALL YFUNC(X,Z,ZP,J,KEN)
        K=0
        DO 40 I=1,NEQ
        ZN(I)=Y(I)+DX2*(YP(I)+ZP(I))
        IF(DABS(ZN(I)-Z(I))-1.D-05*DABS(ZN(I)))4,4,3
      3 K=1
      4 KK=J
        Z(I)=ZN(I)
     40 CONTINUE
        IF(K)5,6,5
      5 CONTINUE
        WRITE(6,99)(ZN(I),I=1,NEQ)
        WRITE(6,90)KK
     90 FORMAT(I5)
     99 FORMAT(4F20.10)
        STOP
      6 DO 7 I=1,NEQ
      7 Y(I)=Z(I)
        IF(J .GE. 3 .AND. J .LE. 5)GO TO 1212
        IF(J .LT. 3)GO TO 2020
        DX=.5*DX
        GO TO 1212
   2020 DX=2.0*DX
        IF(DX .GT..01)DX=.01
   1212 CONTINUE
        RETURN
        END
```

```
      SUBROUTINE YFUNC(X,Y,YP,K,KEN)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON BA
      COMMON       ROL,VW,GW,GC,RV,CJ,WNCA0,B(4) ,ISTA
      COMMON ISET,KKK,KOUNT
      DIMENSION  Y(50),YP(50),A5(10),A6(10),A7(10),A8(10),A10(10),XVS(10
     1),XHL(10),XHFG(10),BARH(10),DM(10),XK(10),CD(10)
     2,XHV(10),RE(10),SCF(10),ABN(10),PVF(10),FNU(10)
      PIE =3.1416
      SUM1=0.
      SUM2=0.
      SUM3=0.
      SUM4=0.
      SUM5=0.
      CALL ROGEE(ROG,Y(1),Y(2),X)
      DO 1 I=1,ISTA
      J= 8+4*(I-1)
      A5(I) = PIE*ROL*Y(J)**2  /2.0
      CALL SUB1(Y(1),Y(3),Y(4),Y(J-1),XVS(I),XV,XK(I),Y(J),DM(I),CD(I),B
     1ARH(I),Y(J-2),Y(2),RE(I),SCF(I),ABN(I),PVF(I),FNU(I))
      YP(J)= XK(I)* PIE *Y(J)**2 *(XV-XVS(I))*VW/(A5(I)*Y(J-2)*(1-XVS(I)
     1))
      A6(I)= YP(J)
      YP(J-2)=((PIE/8.0)*ROG*(Y(J)**2    )*CD(I)*DABS(Y(2)-Y(J-2))*(Y(2)-
     1Y(J-2))-( Y(J-2)-Y(2))*Y(J-2)*A5(I)*A6(I))/(DM(I)*Y(J-2))
      A7(I)=YP(J-2)
      YP(J-3)= A5(I)*A6(I)*Y(J-3)/DM(I)
      A8(I)=YP(J-3)
      SUM1=SUM1+A5(I)*A6(I)*Y(J-3)/DM(I)
      CALL HLI(Y(J-1),XHL(I),XHFG(I),XHV(I))
      YP(J-1) =    BARH(I)* PIE * Y(J)**2 *(Y(3)-Y(J-1))/ (DM(I)*Y(J-2))-
     CXHL(I)*A5(I)*A6(I)/DM(I)+A5(I)*A6(I)*XHV(I)/DM(I)
      A10(I)= YP(J-1)
      SUM2 = SUM2 + Y(J-2)*A8(I)+ Y(J-3)*A7(I)
      SUM3 = SUM3 +A8(I)*(XHL(I)+Y(J-2)**2 /(2.0*GC*CJ))
      SUM4 = SUM4 +Y(J-3)* Y(J-2)*A7(I)/(GC*CJ)
      SUM5 = SUM5 + Y(J-3)*A10(I)
1     CONTINUE
      YP(1) = -SUM1*(1-Y(1))**2
      A9=YP(1)
      CALL AAA3(X,Y(1),Y(2),A3,AA0,DAA0,ROG)
      CALL DERT( ROG,Y(1),Y(2),Y(3),Y(4),A9,SUM2,SUM3,SUM4,SUM5,A0,A3,A1
     C1,A12,A13,A14,R,CPV,CPA,A2,A4,AA0,A)
      YP(3) =(A11*A14-A12*A13)/(A11*(CPV*Y(1)/(1-Y(1))+CPA)-A12*A0*ROG*R
     C)
      A15= YP(3)
      YP(2) = (A13-A0*ROG*R*A15)/A11
      A16=YP(2)
      CALL DERP(ROG,Y(1),Y(2),Y(3),R,A2,A3,A4,A9,A15,A16,DP,A)
      YP(4) = DP
      IF(K.GT. 1) GO TO 3
      IF(X .EQ. 0.0)GO TO 9999
      IF(X .LT. BA)GO TO 3
      BA=BA+.25
 9999 WRITE(6,4)X
      WRITE(6,87654)KEN
87654 FORMAT(I30)
      WW= Y(1)/(1.0-Y(1))
4     FORMAT(1H0,'X=',F16.10)
      WRITE(6,5) AA0,WW
```

```
5     FORMAT(1H0,'A/A0=',G16.6,5X,'WV/WNC=',G16.6)
      WRITE(6,6) Y(1),Y(2),Y(3),Y(4)
6     FORMAT(1H0,'CV=',G20.9,5X,'VG=',G20.9,5X,'TG=',G20.9,5X,'P=',G20.9
     1)
      DO 10 I= 1,ISTA
      J=8+4*(I-1)
      WRITE(6,8) Y(J-3),Y(J-2),Y(J-1),Y(J)
8     FORMAT(1H0,'FL=',G20.9,5X,'VL=',G20.9,5X,'TS=',G20.9,5X,'D=',G20.9
     1)
      WRITE(6,9) YP(J-3),YP(J-2),YP(J-1),YP(J)
      WRITE(6,989)CD(I),BARH(I),RE(I),SCF(I)
  989 FORMAT(1H0,'CD=',G16.6,5X,'BARH=',G16.6,5X,'RE=',G16.6,5X,'SCF=',
     1G16.6)
      WRITE(6,899)ABN(I),PVF(I),FNU(I)
  899 FORMAT(1H0,'ABN=',G16.6,5X,'PVF=',G16.6,5X,'FNU=',G16.6)
10    CONTINUE
9     FORMAT(1H0,'FLP=',G16.6,5X,'VLP=',G16.6,5X,'TSP=',G16.6,5X,'DP=',G
     116.6)
      WRITE(6,7) YP(1),YP(2),YP(3),YP(4)
7     FORMAT(1H0,'CVP=',G16.6,5X,'VGP=',G16.6,5X,'TGP=',G16.6,5X,'PP=',G
     116.6)
1001  CONTINUE
1000  CONTINUE
3     CONTINUE
2     FORMAT(1H ,7E16.6)
      KEN=KEN+1
      RETURN
      END


      SUBROUTINE SUB1(CV,TG,P,TS,XVS,XV,XK,D,DM,CD,BH,VL,VG,RE,SCF,ABN,
     1PVF,FNU)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON BA
      COMMON        ROL,VW,GW,GC,RV,CJ,WNCAO,B(4) ,ISTA
      COMMON ISET,KKK
      XV=(CV/VW)/(CV/VW +(1-CV)/GW)
      X2=-9.06*((-.5696*TS+ .0839E-4 *TS**2 +.0927E-7 *TS**3+1352.3)/TS-
     C1.4525744)
      X1= 672.0/TS
      PVTS = 2117.0 *X1**5.19*DEXP(X2)
      XVS = PVTS/P
      XVF =(XVS+XV)/2.0
      XM= XVF* VW +(1-XVF) *GW
      TFI =(TS+TG)/2.0
      FMV =(10.6E-7 *DSQRT(TFI))/(1+1538.0/TFI)
      FMNC= 7.5E-7*DSQRT(TFI)/(1+ 216.0/TFI)
      FM = XVF *FMV +(1-XVF)*FMNC
      DAB = (.5375/P)*(TFI/491.0)**2.334
      ROF = P* XM/(RV*TFI)
      SCF=FM/(ROF*DAB)
      RE =DABS(VG-VL)*ROF*D/FM
      ABN= 2.0+0.6*DSQRT(RE) * SCF** 0.3333
      XK = ABN*FM/(D*SCF*XM)
      DM = D**3  *3.1416 *ROL/6.0
      CD = 24.0/RE*( 1.0+.15*RE**0.687)
      IF( TFI .GT.1700.0 .AND. TFI .LT.4500.0) GO TO 221
      IF(TFI .LT. 400.0 .OR. TFI .GT.4500)  GO  TO 222
      CPVF =.4304 +.1678E-4*TFI +0.2781E-7*TFI**2.0
      CPNCF = 0.2318 + 0.1040E-4 *TFI + 0.7166E-8 *TFI**2
```

```
      GO TO 102
221   CPVF = .3319 +0.1438E-3 *TFI -0.1312E-7 *TFI**2.0
      CPNCF= 0.2214 + 0.3521E-4*TFI- 0.3776E-8 *TFI**2
      GO TO 102
222   WRITE(6,101)
101   FORMAT(1H ,'TEMP-FI-TS OUT OF RANGE')
      WRITE(6,122) TG,TS
122   FORMAT(1HO,'TG=',E20.6, 5X,'TS=',E20.6)
      STOP
102   CONTINUE
      FKV = 0.432*FMV
      FKNC = 0.257 *(0.115+ 5.17*CPNCF)* FMNC
      FK= XVF*FKV +(1-XVF)* FKNC
      CPF = XVF*(VW/XM )*CPVF +(1-XVF)*CPNCF*GW/XM
      PVF = CPF *FM/FK
      FNU = 2+.60 *DSQRT(RE) * PVF** 0.3333
      BH =FNU *FM *CPF/(D*PVF)
      RETURN
      END


      SUBROUTINE  ROGFE(ROG,CV,VG,X)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON BA
      COMMON        ROL,VW,GW,GC,RV,CJ,WNCAO,B(4) ,ISTA
      AAO =B(1) +B(2)*X +B(3)*X**2.0+ B(4)*X**3.0
      ROG =WNCAO/((1-CV)*VG*AAO)
      RETURN
      END


      SUBROUTINE HLI(TS,XHL,XHFG,XHV)
      IMPLICIT REAL*8(A-H,O-Z)
      XHL =TS -540.0
      XHFG = -.5696*TS + .0839E-4 *TS**2 + 0.0927E-7 *TS**3.0+1352.3
      XHV=XHL+XHFG
      RETURN
      END


      SUBROUTINE AAA3(X,CV,VG,A3,AAO,DAAO,ROG)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON BA
      COMMON        ROL,VW,GW,GC,RV,CJ,WNCAO,B(4) ,ISTA
      AAO = B(1) + B(2)*X +B(3)*X**2.0 +B(4)*X**3.0
      DAAO = B(2) +2.0* B(3)*X +3.0*B(4)*X**2.0
      A3 = VG *(1-CV)* DAAO/ (VG*(1-CV)*AAO)**2
      RETURN
      END


      SUBROUTINE  DERT( ROG,CV,VG,TG,P,A9,SUM2,SUM3,SUM4,SUM5,AO,A3,A11,
     1A12,A13,A14,R,CPV,CPA,A2,A4,AAO,A)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON BA
      COMMON        ROL,VW,GW,GC,RV,CJ,WNCAO,B(4) ,ISTA
      COMMON ISET ,KKK
      IF(VG .LT. 0.0)GO TO 20
      R= P/(ROG* TG)
```

```
      A0 = GC*(1-CV)/ROG
      A4 = WNCAO/(VG**2*(1-CV) *AAO)
      A11 = (1.0-CV)*VG-TG*R*A0*A4
      A12= (1+CV/(1-CV))*VG/(GC*CJ )
      A1 = GW *CV +VW*(1-CV)
      A = WNCAO/(VG*(1-CV)**2*AAO)
      XV= GW *CV/A1
      A2 = RV*VW*GW*(GW-VW)/(A1**2*(XV*VW+(1-XV)*GW)**2)
      A13 = A0*WNCAO*TG*R*A3-A9*(VG**2+ROG*TG*A2*A0+TG*R*A *A0) -VG*(1-C
     CV)**2*SUM2
      CALL HEFV (TG,XHV,CPV,CPA      )
      A14 =-A9*(XHV+VG**2.0/(2*GC*CJ))/(1-CV)** 2   -SUM3-SUM4-SUM5
      RETURN
   20 WRITE(6,31)VG
   31 FORMAT(E20.10)
      STOP
      END


      SUBROUTINE  HEFV(TG,XHV,CPV,CPA)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON BA
      COMMON        ROL,VW,GW,GC,RV,CJ,WNCAO,B(4) ,ISTA
      COMMON ISET ,KKK
      IF( TG .GE.1700.0 .AND. TG .LE.4500)GO TO 222
      IF( TG .LT.400.0 .OR. TG .GT.4500) GO TO 221
      XHV = .4304*TG +.0839E-4*TG**2.0+0.0927E-7*TG**3.0-236.3161+1042.9
      CPV = .4304 + .1678E-4*TG+.2781E-7*TG**2.0
      CPA = .2318+ .1040E-4*TG+.7166E-8 *TG**2.0
      GO TO 100
222   XHV = .3319 *TG + .0719E-3*TG**2.0-.04373E-7*TG**3-185.381+1042.9
      CPV = .3319 + .1438E-3*TG- 0.1312E-7*TG**2.0
      CPA = .2214 +0.3521E-4*TG -0.3776E-8*TG**2.0
      GO  TO  100
221   WRITE(6,99)
99    FORMAT(1H ,'TEMP-G IS OUT OF RANGE')
      WRITE(6,1) TG
1     FORMAT(1H0,'TG=',E16.6)
      STOP
100   CONTINUE
      RETURN
      END


      SUBROUTINE DERP(ROG,CV,VG,TG,R,A2,A3,A4,A9,A15,A16,DP,A)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON BA
      COMMON        ROL,VW,GW,GC,RV,CJ,WNCAO,B(4) ,ISTA
      DP= ROG*R*A15 +(ROG*TG*A2+TG*R*A  )*A9-TG*R*A4*A16-WNCAO*A3*TG*R
      RETURN
      END
```