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FINAL REPORT

ROCKET ENGINE THRUST CHAMBER WALL TEMPERATURE DISTRIBUTION CALCULATION AND ANALYSIS

MAY 1976

Principal Investigator:

Hrishikesh Saha

Prepared For

National Aeronautics and Space Administration

George C. Marshall Space Flight Center

Grant No. NSG-8022

Technical Monitor: Klaus Gross

ALABAMA AGRICULTURAL AND MECHANICAL UNIVERSITY
SCHOOL OF TECHNOLOGY
HUNTSVILLE, ALABAMA

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FOREWORD

This report describes a procedure to predict wall temperature profile of a rocket thrust chamber with a regenerative wall cooling system.

This investigation, entitled ROCKET ENGINE THRUST CHAMBER WALL TEMPERATURE DISTRIBUTION CALCULATION AND ANALYSIS, was conducted for the propulsion Division of MSFC, National Aeronautical and Space Administration under the grant No. NSG-8022 with Klaus W. Gross as technical monitor. Hrishikesh Saha of Alabama Agricultural and Mechanical University was the principal investigator.

This research program contributed extensively to improve faculty and student-research capability at the Alabama A&M University and this support by NASA-MSFC is greatly appreciated.

The author wishes to acknowledge the helpful assistance and advice received from Mr. Klaus W. Gross and Alfred Krebsbach, NASA-MSFC. The author would also like to express his appreciaiton to Mr. Marion I. Kent, Assistant Director, University Affairs, NASA-MSFC, for his effort in making this grant possible.

ROCKET ENGINE THRUST CHAMBER WALL TEMPERATURE DISTRIBUTION CALCULATION AND ANALYSIS

ABSTRACT

An analytical computational concept is presented which predicts the temperature profiles along a regeneratively cooled thrust chamber wall on the hot gas-side and on the coolant-side, and also the coolant bulk temperature profile. The computational model is based upon a coupling of the boundary layer heat transfer process with the heat transfer process through the chamber wall and the coolant flow heat absorption. The calculation is started with approximate temperature distributions for the hot gas-side wall and the coolant flow. The iteration process of the computer program is terminated when the total heat transfer rates from the hot gas boundary layer to the wall and from the wall to the coolant are equal. The computer program for the integration of regenerative cooling process to a thrust chamber is kept general such that this program can be used with any boundary layer analysis computer program for temperature profile and heat transfer studies. A sample application of this concept is shown by using a boundary layer analysis program BLIMP [12] for the RL10 rocket engine thrust chamber. This example also shows the importance of an appropriate enhancement factor distribution to incorporate the effects of coolant channel curvature, associated turbulance, surface roughness, asymmetric heating, entrance region, and coolant bulk temperature correction.

DEFINITION OF SYMBOLS

Symbol	Definition
A_{tube}	Cross-sectional area of each cooling tube or channel, ft^2
C_f	Skin friction coefficient
C_H	Stanton number
D_{tube}	Equivalent tube diameter, ft
H	Enthalpy, ft^2/s^2
J	Conversion factor between thermal and work units (778.2), ft-lbf/Btu
M_∞	Mach number at boundary layer edge
$\mathfrak{M}$	Mean molecular weight at boundary layer edge, lbm/mole
P_∞	Static pressure at boundary layer edge, lbf/ft^2
$\dot{Q}_w$	Total heat transfer rate, Btu/s
P_r	Prandtl number
R_e	Reynolds number
$\mathcal{R}$	Universal gas constant
T	Temperature, °R
U_∞	Velocity at boundary layer edge, ft/s
C_p	Specific heat at constant pressure, Btu/lbm °R
g	Acceleration of gravity (32.174), ft-lbm/lbf s^2
h_0	Total enthalpy, ft^2/s^2

DEFINITION OF SYMBOLS (Continued)

Symbol	Definition
h_g	Heat transfer coefficient on the gas side, Btu/ft^2 s°R
h_ℓ	Heat transfer coefficient on the coolant side, Btu/ft^2 s°R
m_ℓ	Coolant mass flow rate, lbm/s
$\dot{q}_w$	Specific heat transfer rate, Btu/ft^2 s
N	**Total number of x-stations**
r	Nozzle radius, ft
t	Chamber wall thickness, ft
u	Velocity within boundary layer, ft/s
x	Axial coordinate, ft or -
y	Distance normal to wall, ft or -
α	Angle between wall and nozzle axis
δ	Velocity thickness, ft
δ_r'	Distance from nth streamline to real wall, ft
δ^*	Displacement thickness, ft
Δ	Temperature thickness, ft
θ	Momentum thickness, ft
ϕ	Energy thickness, ft
μ	Dynamic viscosity, lbm/ft s

DEFINITION OF SYMBOLS (Continued)

Symbol	Definition
ρ	Density, lbm/ft^3
λ	Thermal conductivity, Btu/ft s°R
τ_W	Shear stress, lbm/s^2
η_1	Cooling coefficient for geometry effects
η_E	Efficiency (enhancement)factor for the effects of coolant channel geometry and coolant flow characteristics.

Subscripts

a	Adiabatic wall
c	Calculated value or convection
i	Section
j	Overall iteration number
ℓ	Coolant
N	Newly computed value
r	Radiation
w	Wall or wall material
wg	Gas side wall
$w\ell$	Coolant side wall
∞	Free stream or boundary layer edge

INTRODUCTION

NASA-MSFC Propulsion Division, at present, uses the computer program BLIMP (Boundary Layer Integral Matrix Procedure [12] to evaluate laminar and turbulent boundary layer flow properties over a rocket nozzle contour, and to compute the heat transfer rate and performance loss in a rocket thrust chamber. Computer programs to solve boundary layer equations need a wall temperature profile as a boundary condition. This temperature profile depends on the thrust chamber contour, wall thickness and material, type of wall cooling process, and the cooling cycle involved. Aerospace industries, involved in manufacturing rocket engines, predict the wall temperature distribution from in house heat transfer calculations and, if available, from scaled test data.

The primary purpose of this report is to provide MSFC with a rigorous computational capability to predict the necessary temperature profile to initiate rocket thrust chamber performance computation. The computer program BLIMP for the boundary layer analysis was extended with an option to predict a thrust chamber wall temperature profile by coupling the boundary layer analysis with the regenerative cooling process. Both up and down path cooling flow for the regenerative process were considered. The computational method and the resulting computer programs were kept general such that these could be used with any available boundary layer computer program and not be restricted to BLIMP program only.

The calculation of the temperatures of the gas-side wall, the regenerative coolant-side wall, and the coolant fluid along the thrust chamber contour is made by considering the heat exchange between the combustion product flow in the thrust chamber and the coolant flow in the cooling jacket. The steady-state conditions that are considered require the temperatures of the combustion products, the chamber walls, and also the heat flux through the walls to remain constant at any point in time. It is assumed that heat transfer occurs only by convection and conduction from the hot gas to the thrust chamber wall, neglecting the radiation. The regenerative fluid flows through the tubes or channels in the opposite or same direction to the combustion products, receiving heat by convection and conduction.

The necessary inputs to the numerical solution method are the cooling system arrangement layout and configuration, anticipated coolant flow rate, wall material and fluid properties. The iterative solution is initiated with an initial guess of the gas-side wall temperature profile which then is improved through iterations until the heat flux to the wall predicted by the boundary layer analysis matches the heat flux from the wall, to the coolant flow, or to the environment through radiation.

FUNDAMENTAL EQUATIONS FOR THE REGENERATIVE COOLING CYCLE

The coolant enters downstream with a lower temperature [Fig. 1 & 2] and a higher pressure than at the injector head. Regenerative cooling consists of the steady flow of heat from combustion products through the solid chamber wall to the coolant. For the steady-state conditions the gas and wall temperatures and the specific heat flux through the wall remain constant with time at any given point.

1. The convective specific heat transfer rate on the hot gas-side is written

$$q_{wg} = h_g \, (T_{wa} - T_{wg}) \tag{1}$$

where q_{wg} = convective heat transfer rate per unit area,

T_{wg} = hot gas-side wall temperature,

h_g = hot gas heat transfer (film) coefficient,

T_{wa} = adiabatic wall temperature is that which would be attained by the surface of an adiabatic or insulating (q_{wg} = 0) wall

$$T_{wa} = r{*}U^2_{gE} / \, (2{*}Cp_{gE}{*}778.16{*}32.17) + T_{gE} \tag{2}$$

r = recovery factor

U_{gE} = hot gas flow velocity at the boundary layer edge,

Cp_{gE} = hot gas specific heat at the boundary layer edge,

T_{gE} = hot gas temperature at the boundary layer edge.

2. One dimensional specific heat transfer rate through the solid wall is described by

$$q_\omega = -\lambda_\omega \frac{dT\omega}{dr} = \frac{\lambda\omega}{t} \, (T_{\omega g} - T_{\omega \ell}) \tag{3}$$

where $\lambda\omega$ = thermal conductivity of the wall material,

t = wall thickness,

$T_{\omega\ell}$ = coolant-surface wall temperature.

3. Specific heat transfer rate from the wall to the liquid coolant film is

$$q_{\omega\ell} = h_\ell \, (T_{\omega\ell} - T_\ell) \tag{4}$$

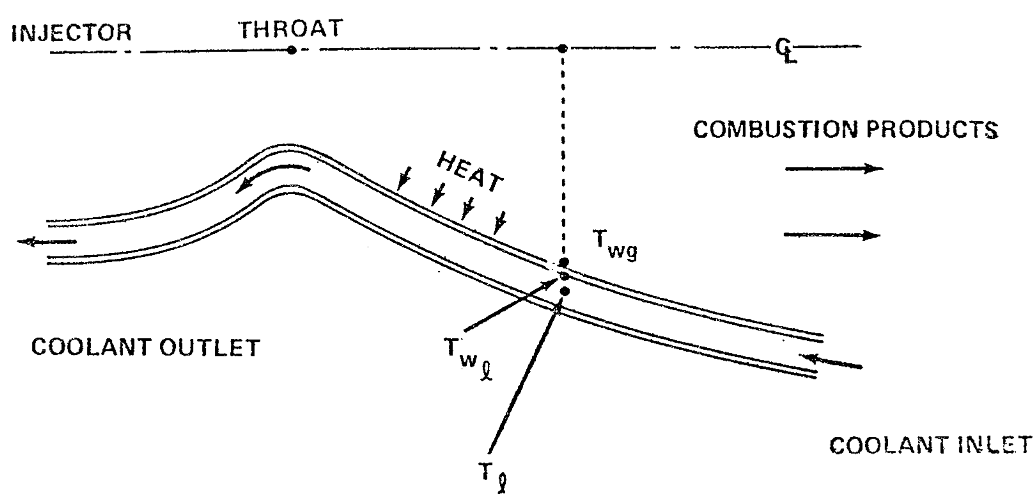


Figure 1. Regeneratively cooled combustor flow model.

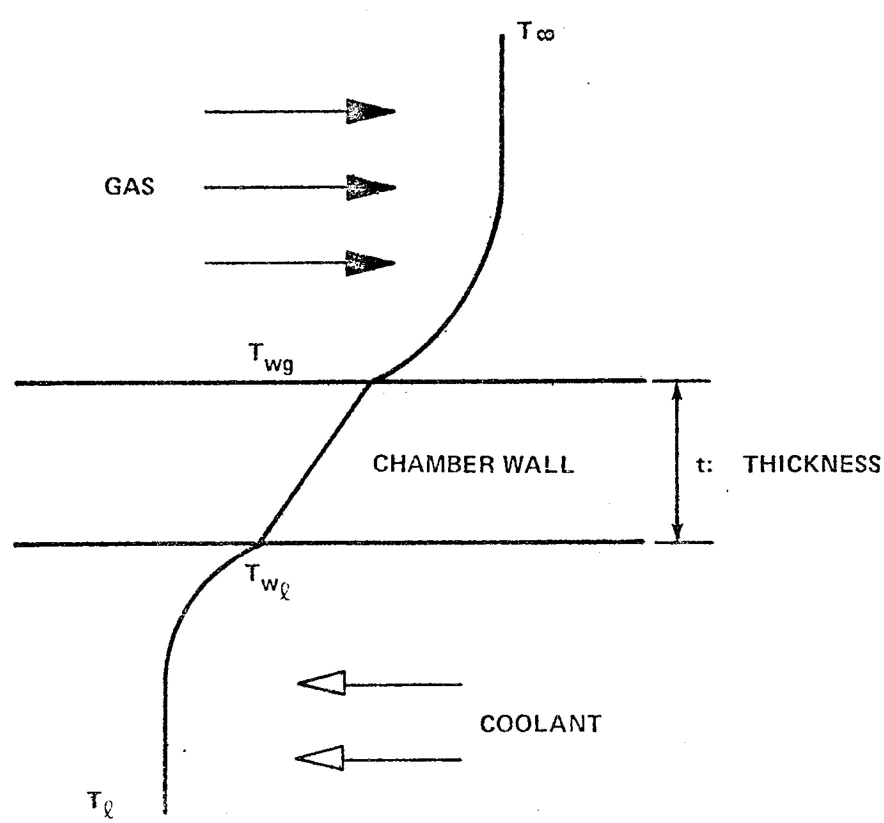


Figure 2. Model of temperature profile.

Where h_ℓ = heat transfer coefficient of the coolant,

T_ℓ = coolant free-stream temperature,

An empirical relation of the heat transfer coefficient for the hydrogen coolant flow is given by the modified Colburn equation [13]:

$$h_\ell = 0.025 \frac{\lambda_\ell}{D_{tube}} Re_\ell^{0.8} \, Pr_\ell^{0.4} \left(\frac{T_\ell}{T_{w\ell}}\right)^{0.55} \cdot \eta_E \tag{5}$$

Where Reynolds number, $Re_\ell = (\rho_\ell U_\ell D_{tube})/\mu_\ell$,

equivalent tube diameter, $D_{tube} = 2\,(A_{tube}/\pi)^{1/2}$

coolant bulk viscosity, $\mu_\ell = \mu_\ell(T_\ell, P_\ell)$,

coolant bulk specific heat, $Cp_\ell = Cp_\ell\,(T_\ell, P_\ell)$,

coolant bulk thermal conductivity, $\lambda_\ell = \lambda_\ell(T_\ell, P_\ell)$,

mass flow density, $\rho_\ell U_\ell = \rho_\ell(x)\,U_\ell\,(x)$

$= m_\ell / (\eta_\ell \cdot A_{tube})$,

total coolant mass flow rate = m_ℓ,

number of cooling tubes = η_ℓ,

axial distance from the throat = x,

η_E = enhancement factor for associatedturbulence, surface roughness of the tube, and curvature effects [13]. The accuracy of the enhancement factor significantly affects the heat transfer calculation and the resulting wall temperatures.

For steady-state conditions the heat flow from the hot gas (including radiation heat transfer $\dot{q}_r$) may be written.

$$\dot{q} = \dot{q}_{wg} + \dot{q}_r = \dot{q}_w = \dot{q}_{w\ell} \tag{6}$$

The (usually small) radient heat transfer rate $\dot{q}_r$ to the hot wall surface will be neglected for this study. Equations (1), (2), (3), (4), & (6) can be combined to solve for Twg & Twℓ:

$$T_{wg} = T_{wa} - (T_{wa} - T_\ell)/\,(1 + h_g\,(t_w/\lambda_w + 1/h_\ell)), \tag{7}$$

$$T_{w\ell} = T_\ell + (T_{wa} - T_\ell)/\,(1 + h_\ell(t_w/\lambda_w + 1/h_g)), \tag{8}$$

The solution to the unknown $\dot{q}$, T_{wg}, $T_{w\ell}$, T_ℓ, and also h_g and h_ℓ, can be obtained by considering the equations (1), (3), (4), (6), (7), and (8) together with the boundary layer analysis program.

4. Coolant bulk temperature calculation.

The coolant fluid flows through the tubes or channels in the opposite or same direction to the combustion products and receives heat by conduction and convection along the contour of the thrust chamber. This heat exchange causes the temperature variation of the regenerative coolant flow. The essential features of regenerative cooling within a rocket can be studied without geometric complications by considering a one-dimensional model, i.e. assuming that the inner wall of the thrust chamber consists of a single wall and not of tubes, and ignoring the heat transfer through the walls which separate the coolant passage.

The cooled surface area A_i in contact with the hot gases of an arbitrary section Δx_i between the stations x_i and x_{i+1}, where x is the distance along the nozzle axis, can be determined from the given geometry of the nozzle contour [Fig. 3],

$$A_i = 2\pi r_i \Delta x_i / \cos\alpha_i \tag{9}$$

Where $r_i = r(x_i)$ = wall radius,

$\alpha_i = \alpha(x_i)$ = angle between the chamber wall and the nozzle axis at x_i, $\Delta x_i = x_{i+1} - x_i$

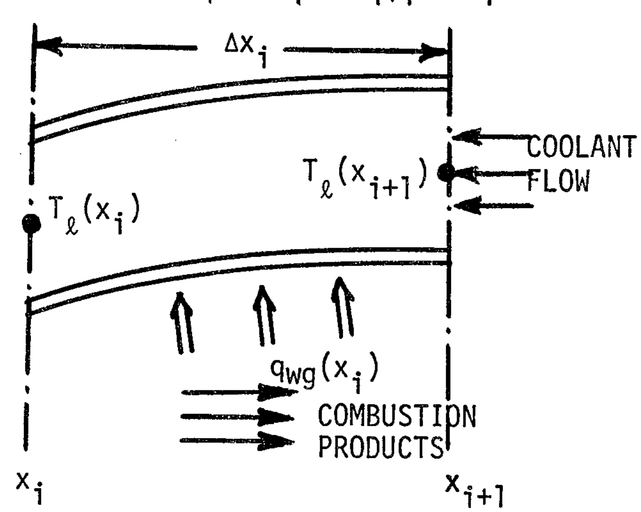


Figure 3. Up-pass coolant flow temperature analysis in a nozzle section

The up-pass outlet coolant temperature of the ith section is calculated by

$$T_{\ell i} = T_{\ell i+1} + \eta_1 \cdot \bar{\dot{q}}_{wgi} \bar{A}_i / (\dot{m}_\ell \bar{C}_{p\ell}) \tag{10}$$

Where $T_{\ell i} = T_\ell (xi)$ = the outlet temperature of the coolant,

$T_{\ell i+1} = T_\ell (x_{i+1})$ = the inlet temperature of the coolant,

$\dot{m}_\ell$ = coolant flow rate,

$\bar{C}_{p_\ell} = (C_{p\ell}(T_{\ell i}) + C_{p\ell}(T_{\ell i+1})/2$ = the mean specific heat of the coolant between $T_{\ell i}$ and $T_{\ell i+1}$,

$\bar{A}_i = 2\pi \bar{r}_i \Delta x_i / \overline{COS\alpha}_i$, the mean area,

$\bar{r}_i = (r_i + r_{i+1})/2$ = the mean radius,

$\overline{COS\alpha}_i = (COS\alpha_i + COS\alpha_{i+1})/2$ = the mean cosine angle,

$\bar{\dot{q}}_{wgi} = (\dot{q}_{wgi} + \dot{q}_{wgi+1})/2$ = the mean heat flux,

$\dot{q}_{wgi} = \dot{q}_{wgi} (xi)$ = the heat flux at a station x_i.

η_1 = cooling efficiency to account for surface area geometry effects.

Similarly, the down-pass outlet coolant temperature of the ith section of a nozzle is calculate by

$$T_{\ell i+1} = T_{\ell i} + \eta_1 \bar{\dot{q}}_{wgi} \bar{A}_i / (\dot{m}_\ell \bar{C}_{p\ell}) \tag{11}$$

Where $T_{\ell i+1} = T_\ell (x_{i+1})$ = the outlet temperature of the coolant, and

$T_{\ell i} = T_\ell (x_i)$ = the inlet temperature of the coolant.

The other variables remain the same as described in equation (9).

5. Total heat transfer rate calculation.

The heat transfer rate through the cylindrical surface area of section i, between x_i and x_{i+1} in Figure 3, is

$$\dot{Q}_W (x_i) = \bar{A}_i \bar{\dot{q}}_{wgi} / (\dot{m}_\ell \overline{C_{p\ell i}}) \tag{12}$$

Where the variables on the right hand side were described in equations (9) & (10).

The total heat transfer rate then is given by the summation of the heat transferred through all the sections of the nozzle wall, i.e.

$$\sum_{i=1}^{N-1} \dot{Q}_w (x_i) \tag{13}$$

Where N = the total number of x - stations for numerical computation.

6. Averaging of temperature profiles T_{wg} and T_ℓ.

For a smooth convergence towards the solution temperature profiles are averaged to be used as initial values for the next iteration as follows:

$$T_\ell (x_i)_m = (T_\ell (x_i)_m + T_\ell (x_i)_{m-1})/2 \tag{14}$$

$$T_{wg} (x_i)_m = (T_{wg} (x_i)_m + T_{wg} (x_i)_{m-1})/2 \tag{15}$$

Where m = number of iterations.

7. Convergence criteria for the iteration loop.

A solution is obtained when the absolute value of the relative difference between the two total heat fluxes [Eqn. 13] is less than a small value as shown:

$$\left| \frac{\sum_{i=1}^{N-1} \dot{Q}w - \sum_{i=1}^{N-1} \dot{Q}w_N}{\sum_{i=1}^{N-1} \dot{Q}w_N} \right| \leq \delta \tag{16}$$

Where $\dot{Q}_w$ = total heat flux computed by the boundary layer analysis computer program & equation (13).

$\dot{Q}_{wN}$ = total heat flux computed by the regenerative cooling cycle computer program (see computational Algorithm).

δ = convergence tolerance.

COMPUTATIONAL ALGORITHM

A step by step computational sequence is given below.

Step 1: Assume the gas-side wall temperature Twg distribution and coolant bulk temperature T_ℓ distribution, along the wall contour, i.e. The initial temperature profiles Twg and T_ℓ at each x-station are available.

Step 2: Compute heat flux $\dot{q}_{wg}$ at each x-station using the boundary layer analysis computer program (BLIMP in this case) with initial T_{wg} or previous iteration T_{wg} as input.

Step 3: Compute the total heat flux using equations (12) & (13).

Step 4: Compute hot gas heat transfer coefficient hg at every x-station using equations (1) and (2).

Step 5: Compute the coolant-side wall temperature Tw_ℓ and the coolant heat transfer coefficient h_ℓ by solving the equations (5) and (8) iteratively at every x-station.

Step 6: Compute the new gas-side wall temperature Twg_N at every x-station using equation (7).

Step 7: Compute the new heat flux $\dot{q}_{wgN}$ for every x-station using equation (1) and the Twg_N.

Step 8: Compute the new coolant bulk temperature $T_{\ell N}$ at every x-station except at the inlet (where coolant temperature remained constant) using equations (9) & (10) (or (11)) depending upon the coolant flow direction.

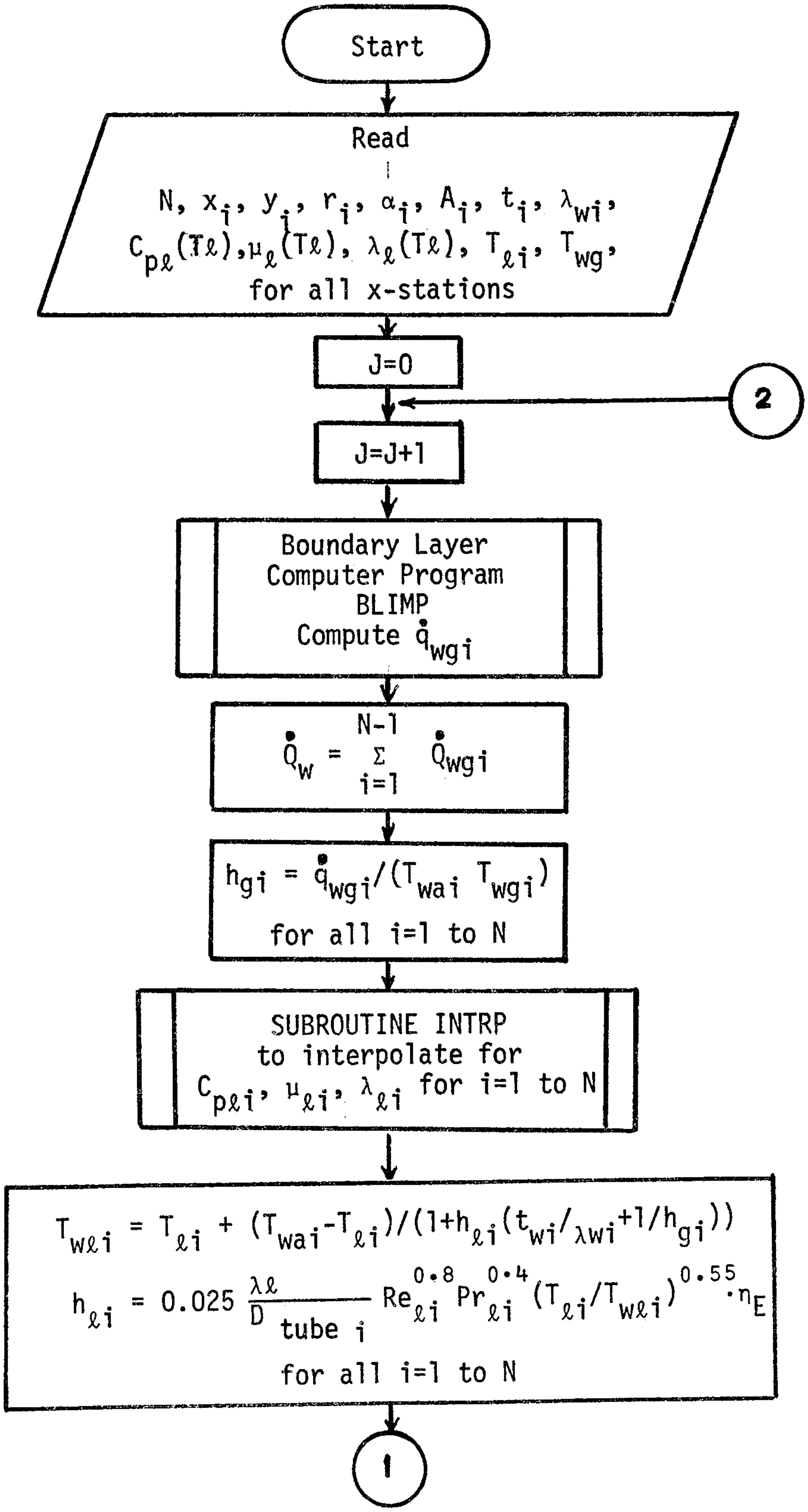
Step 9: Compute the total heat flux with $\dot{q}_{wgN}$ using equations (12) & (13).

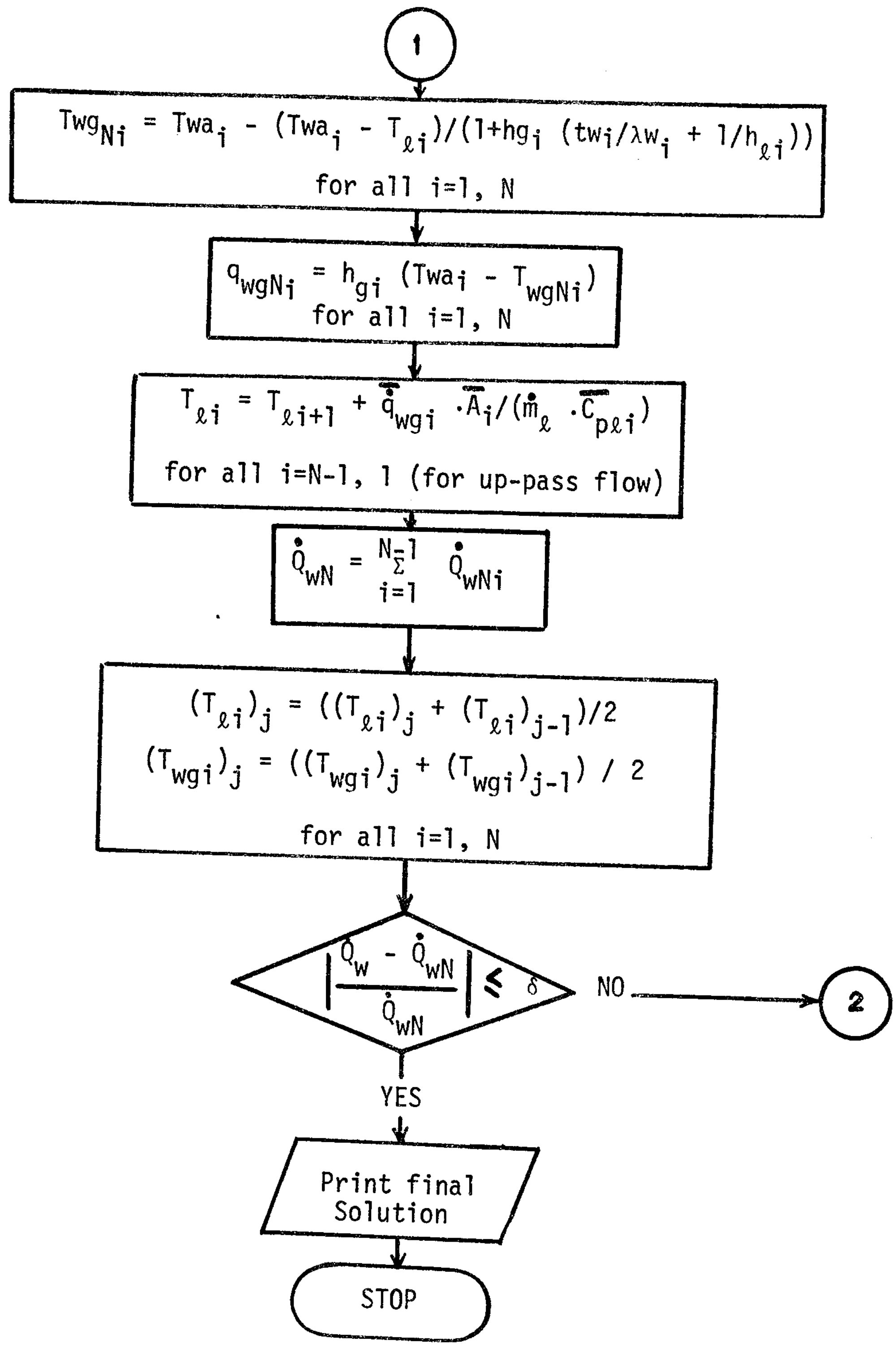
Step 10: Compute average values of T_ℓ and Twg to be used as initial values for next iteration using equations (14) and (15).

Step 11: If the relative difference of the total heat fluxes, computed in steps 3 & 9, is not less than the convergence tolerance δ, then repeat step 2 through step 10, otherwise write the solutions together with the input values and stop.

The following flow chart shows the graphical representation of the computational sequence for a solution.

FLOW CHART OF THE CALCULATION PROCEDURE




1
$Twg_{Ni} = Twa_i - (Twa_i - T_{\ell i})/(1+hg_i\ (tw_i/\lambda w_i + 1/h_{\ell i}))$
for all i=1, N
$q_{wgNi} = h_{gi}\ (Twa_i - T_{wgNi})$
for all i=1, N
$T_{\ell i} = T_{\ell i+1} + \bar{\dot{q}}_{wgi} \cdot \bar{A}_i/(\dot{m}_\ell \cdot \bar{C}_{p\ell i})$
for all i=N-1, 1 (for up-pass flow)
$\dot{Q}_{wN} = \sum_{i=1}^{N-1} \dot{Q}_{wNi}$
$(T_{\ell i})_j = ((T_{\ell i})_j + (T_{\ell i})_{j-1})/2$
$(T_{wgi})_j = ((T_{wgi})_j + (T_{wgi})_{j-1}) / 2$
for all i=1, N
$\left| \frac{\dot{Q}_w - \dot{Q}_{wN}}{\dot{Q}_{wN}} \right| \leq \delta$
NO
2
YES
Print final Solution
STOP

APPLICATION OF THE MODEL, RESULTS AND DISCUSSION

In this section the regenerative cooling concept is applied to the following thrust chamber:

RL10 Rocket Engine

Characteristic parameters considered,

Nozzle Geometry -

area ratio, $\varepsilon = 12.87$
throat radius, $Rt = 0.21416$ [ft]

Stagnation Conditions -

temperature, $T_o = 5843$ [°R]
pressure, $P_o = 386.3$ [Psia]

Mixture ratio, MR = 4.839 for O_2/H_2 fuel system.

Coolant Cycle -

Number of Coolant Tubes, $n_\ell = 180$
Coolant Mass Flow Rate, $m_\ell = 5.546$ [lbm/s]
Coolant Tube wall thickness, $t_w = 1.0958.10^{-3}$ [ft]
Coolant Tube Area, $A_{tube} = A_{tube}(x)$, see Table 1,
Wall Heat Transfer Coefficient, $\lambda_w = \lambda_w(T_w)$, [Table 1]
Physical Properties $(C_{p\ell}, {}_\ell, \lambda_\ell)$ of coolant, [Table 2]

Computational Parameters -

Total number of x-stations, N = 22,
Convergence criteria, $\delta = 10^{-3}$,
Case 1: with Enhancement Factor, $\eta_E = 1.0$
Case 2: with Enhancement Factor, η_E as in Table 1.

Analysis of RL10 Rocket Engine

The RL10 engine thrust chamber expanding the reaction products to an area ration of ε = 12.87 is considered. The chamber wall is regeneratively cooled with liquid hydrogen which flows in an opposite direction to the combustion products. The input data for the computer program to predict gas-side wall temperature for the regenerative cooling process are given in Table 1 and 2. The cross-sectional area variation of an individual cooling tube, total number of tubes, wall thickness, heat conductivity of the wall material, coolant flow rate, recovery factor, enhancement factor, initial coolant temperature distribution along the wall, initial gas-side wall temperature distribution, etc. are given in Table 1; whereas, Table 2 lists the physical coolant properties as a function of temperature for an expected pressure range between 4500 psia and 6000 psia [13, 15] in order to determine the coolant flow heat transfer coefficient, the specific heat, thermal conductivity and viscosity at each x-station for a coolant temperature distribution.

In the thrust chamber of the RL10 engine, liquid hydrogen and oxygen react at a boundary layer mixture ratio of 4.839 at a pressure of 386.3 psia resulting in a stagnation temperature of 5843 °R. The free stream inviscid flow parameters serving as boundary layer edge conditions such as Mach number M_∞, static pressure P_∞, static temperature T_∞ and mean molecular weight , where obtained from the Two-Dimensional Kinetics (TDK) computer program [14]. The input data for the boundary layer analysis computer program, BLIMP [12], are shown in Table 3. The formate and description of these input data are given in reference 12.

The effects of curvature, associated turbulence, surface roughness, asymmetric heating, entrance region, and coolant bulk temperature [13] are expressed through a correction factor, called enhancement factor η_E. Since MSFC Propulsion Division recently acquired RL10 Rocket Engine thrust chamber gas-side wall temperature and coolant bulk temperature test data [16], two cases were considered; one without any enhancement factor ($\eta_E = 1.0$) and the other with a distribution of enhancement factors along the wall as shown in Table 1.

The calculated temperature distribution on the hot gas-side, coolant-side and the coolant are plotted in Figure 5 for $\eta_E = 1.0$ and the corresponding specific heat transfer rate through the chamber wall is shown in Figure 6. These results are also given in Table 5. The total heat flux through the wall for $\eta_E = 1.0$ is 4318.75 [Btu/Sec].

The computed temperature profiles for an enhancement factor distribution as given in Table 1, are shown in Figure 7. The enhancement factor distribution was chosen such that the computed gas-side wall temperature profile matches the test data [16]. The specific heat flux for this case is shown in Figure 8. The total heat flux through the wall is 4633.96 [Btu/Sec]. These computed values are also listed in Table 6.

The computation procedure converges within two to six eterations depending upon the input temperature profiles. The computed temperature profiles (T_{wg}, T_ℓ) for $\eta_E = 1.0$, shown in Figure 5, are higher than the test data [16]; whereas the total heat flux, $Q_W = 4318.75$ [Btu/Sec] through the wall is lower than the projected thest data, $Q_W = 4600$ [Btu/Sec] [16]. The computed coolant bulk temperature for the enhancement factor distribution (case 2) is higher than the test data; whereas the computed total heat flux through the wall for this case, $Q_W = 4633.96$ [Btu/Sec] in Figure 8 approximates the projected test data well.

CONCLUSION

A general computational method has been presented by which the hot gas-side wall temperature, coolant-side wall temperature, and the coolant bulk temperature profiles of a regeneratively cooled thrust chamber, can be determined. The analytical formulation is based upon a coupling of the boundary layer heat transfer with the heat transfer process through the chamber wall and the coolant flow heat absorption. This computational concept can be used with any boundary layer analysis program and is not restricted to a particular computer program to estimate regeneratively cooled thrust chamber temperature profiles mentioned above. As an application of this method, the boundary layer analysis computer program BLIMP was used to estimate the temperature profiles (T_{wg}, $T_{w\ell}$, T_{ℓ}) of the regeneratively cooled RL10 rocket engine; the RL10 thrust chamber was chosen because of recently acquired test data. Since an emperical equation for the coolant flow heat transfer coefficient was used and no adjustments for the coolant channel curvature, associated turbulence, surface roughness, asymmetric heating, entrance region, and coolant bulk temperature were made, the results of the first case with $\eta_E = 1.0$ are approximate; whereas the results of the second case with an η_E distribution can be made to approximate the test data well. Since the enhancement factor η_E distribution is not known a priori, more rigorous both experimental and analytical studies are required to properly estimate the influences of the coolant channel geometry and coolant fluid flow characteristics on the regeneratively cooled heat transfer process.

CONCLUSION (Cont'd)

There is an urgent need for enhancement factor distributions to determine the accumulative effects of all the parameters on the regeneratively cooled thrust chambers for various chamber pressures and propellant types. These enhancement factor distributions can be generated by matching the analytical predictions with existing test data of rocket engine thrust chambers. This method may establish a trend of enhancement factor variation with thrust chamber pressure level and propellant type, which could then be used to predict temperature profiles for similar rocket engine thrust chambers with regenerative cooling systems. The results of the analytical and experimental studies to compute the correction factors for a regeneratively cooled heat transfer process may vary with the boundary layer analysis program used, so showing the complexity of this type of analysis.

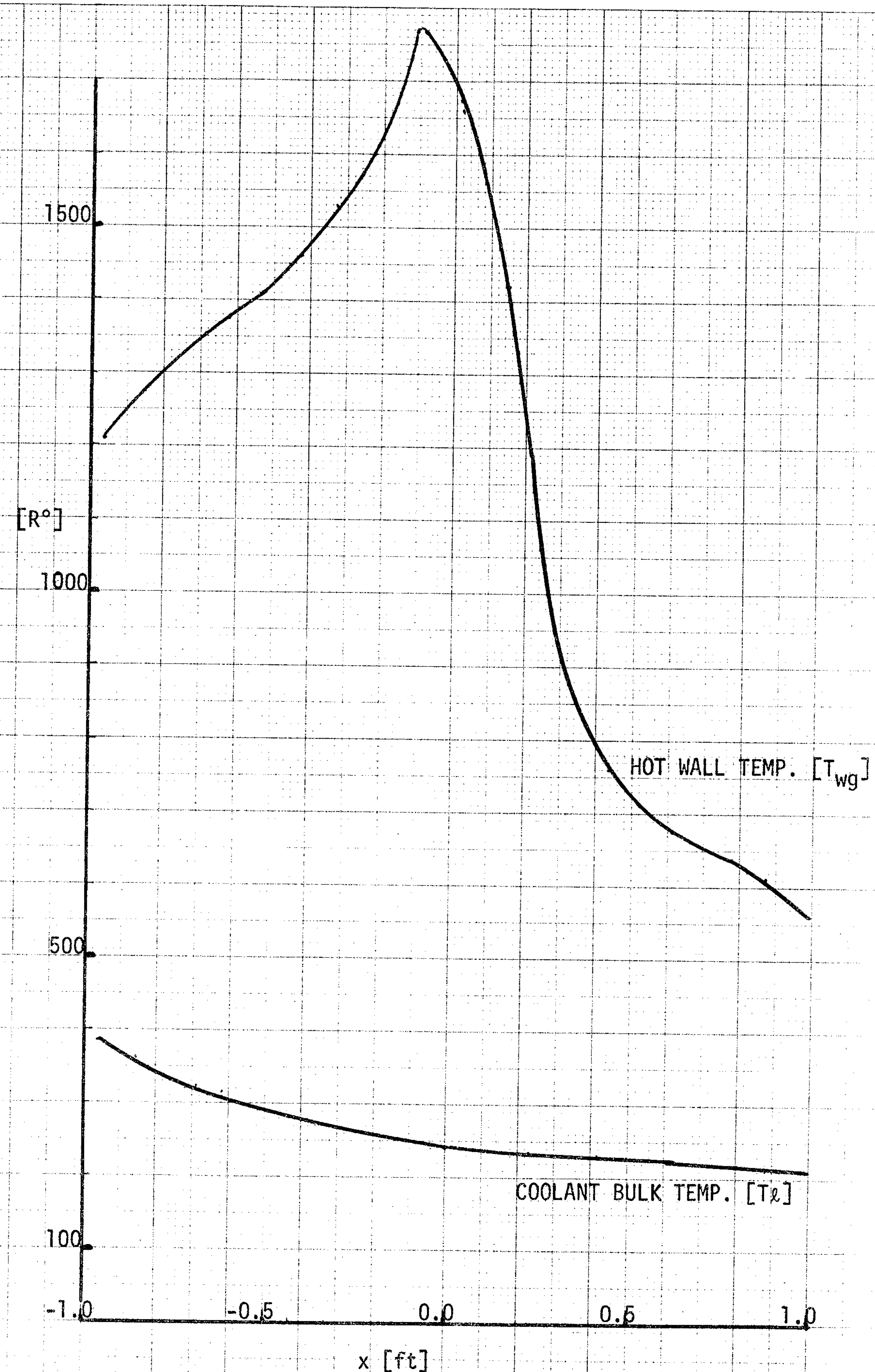


Figure 4. Initial Temperature Profiles for Regeneratively Cooled RL10 Thrust Chamber Calculation.

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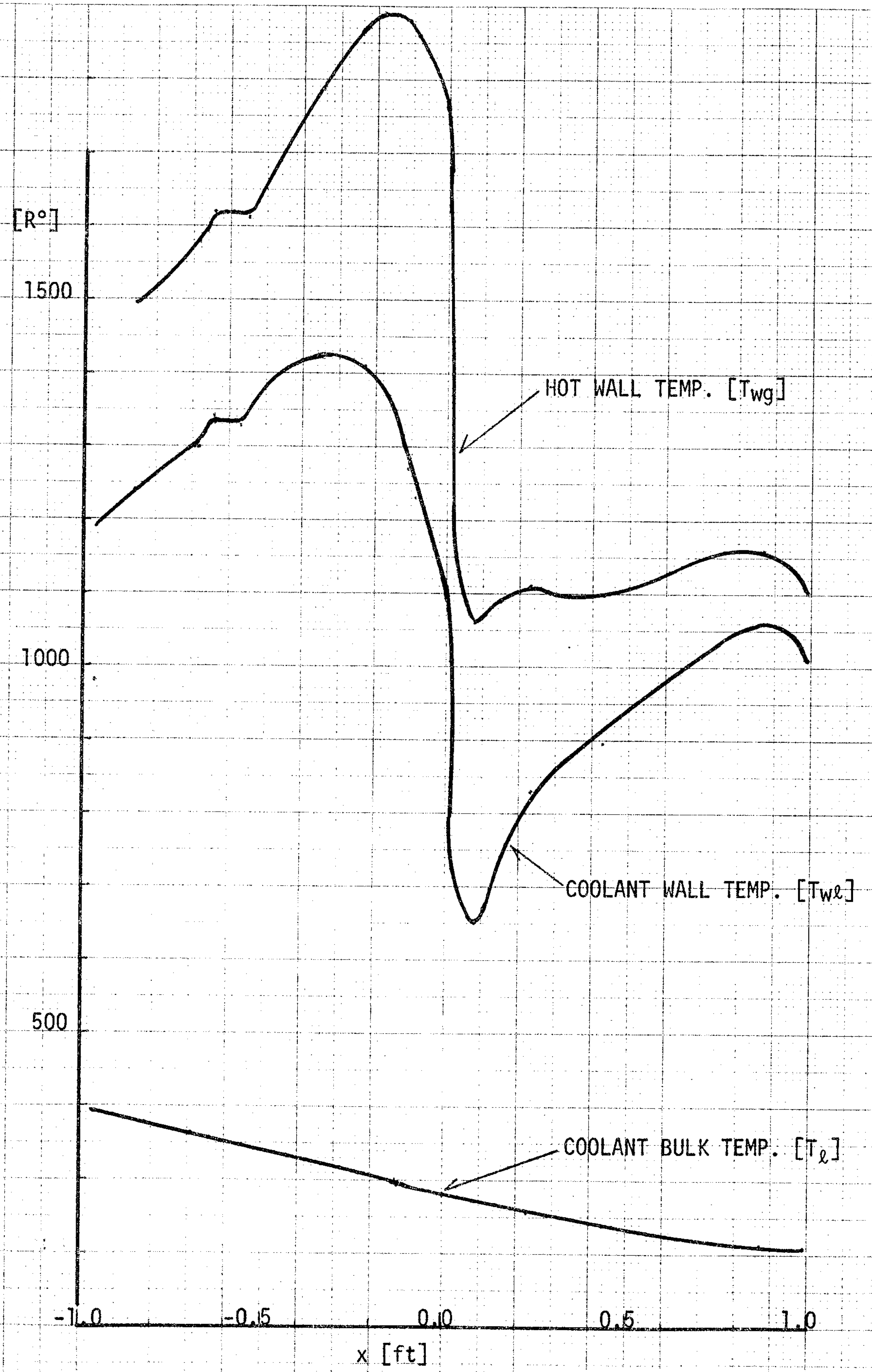

Figure 5. Calculated Temperature Profiles with $\eta_E = 1.0$ for Regeneratively Cooled RL10 Thrust Chamber.

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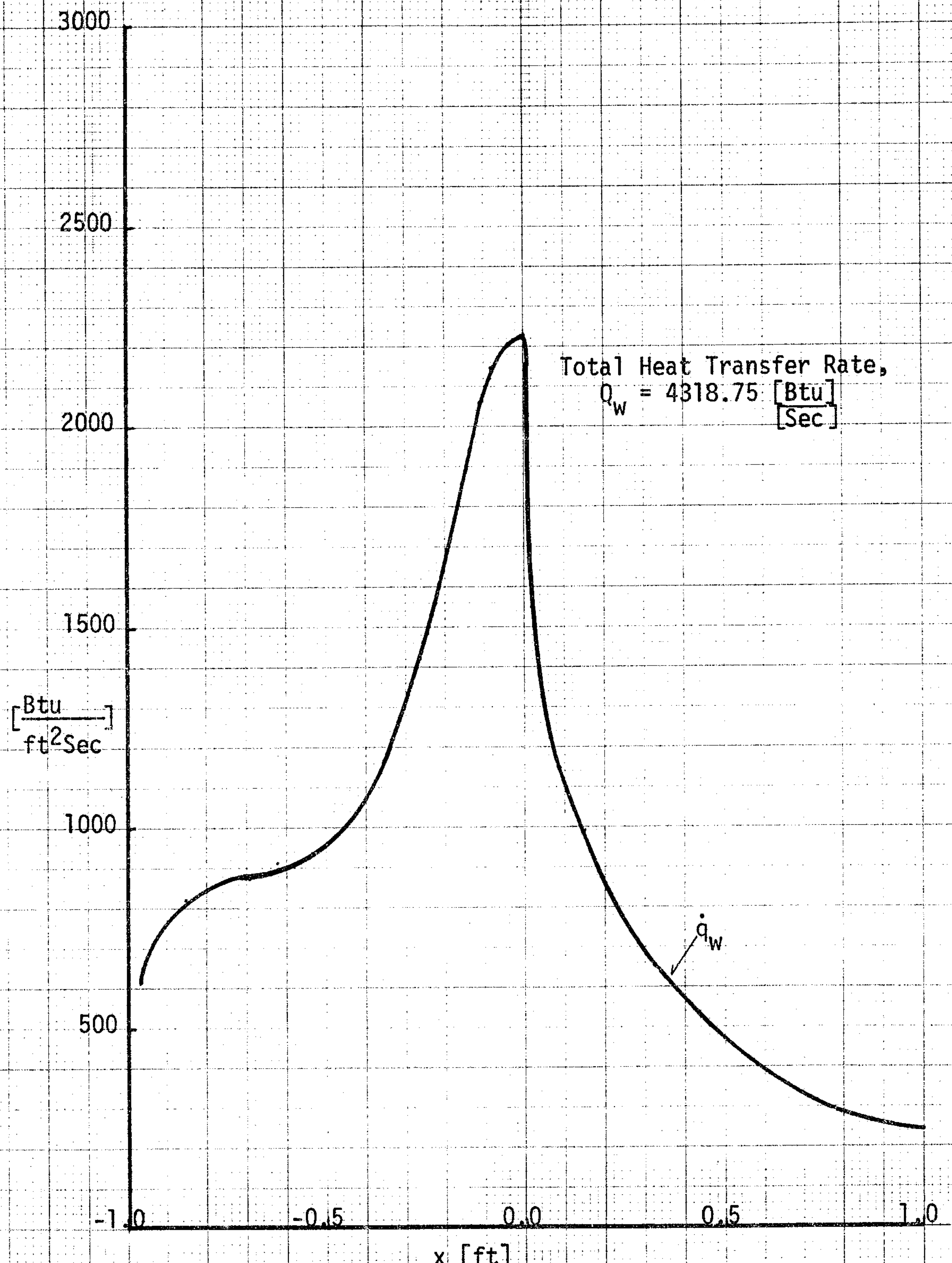

Figure 6. Specific Heat Transfer Rate with $\eta_E = 1.0$ for Regeneratively Cooled RL10 Thrust Chamber.

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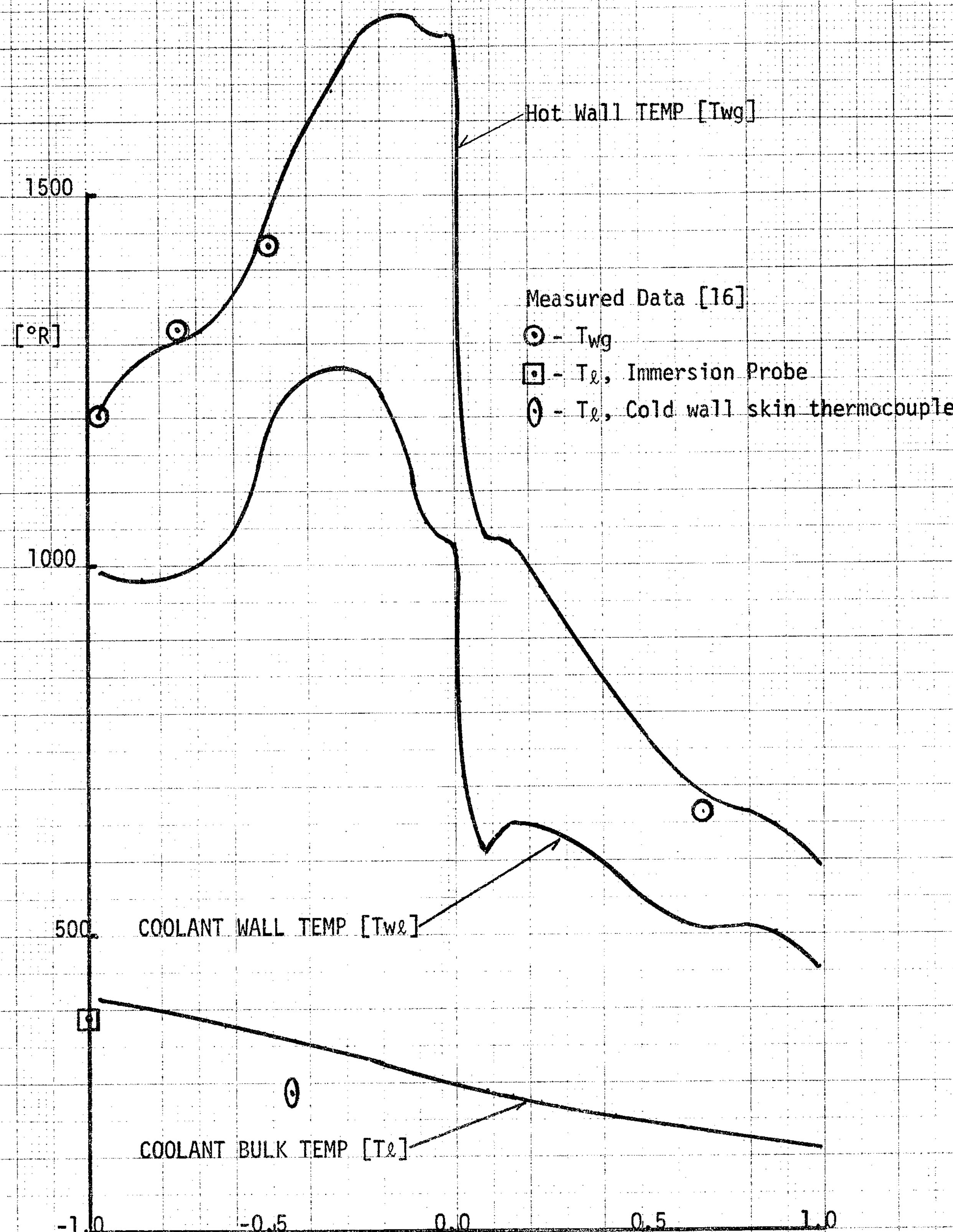

Figure 7. Calculated Temperature Profiles with η_E (Table 1) for Regeneratively Cooled RL10 Thrust Chamber.

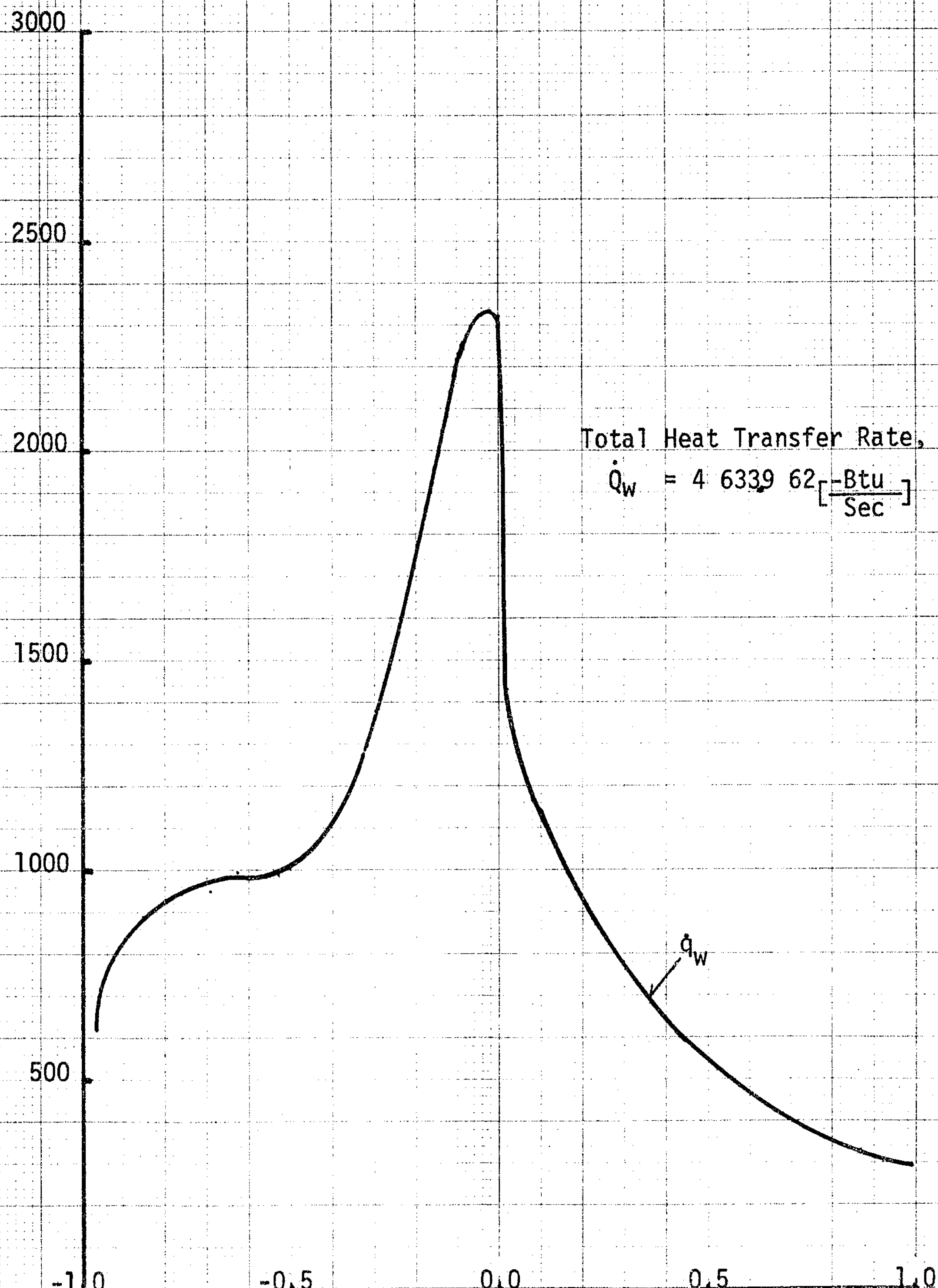

Figure 8. Specific Heat Transfer Rate with n_E (Table 1) for Regeneratively Cooled RL10 Thrust Chamber.

EUGENE DIETZGEN CO.
MADE IN U. S. A.
NO. 341-10 DIETZGEN GRAPH PAPER
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TABLE 1. INPUT DATA FOR REGENERATIVE COOLING COMPUTER PROGRAM (SATEMP)

ENHANCEMENT FACTOR

1.00000+00	1.40000+00	1.40000+00	1.40000+00	1.20000+00	1.20000+00	1.20000+00	1.20000+00
1.20000+00	1.20000+00	1.10000+00	1.00000+00	1.00000+00	1.00000+00	1.00000+00	1.10000+00
1.20000+00	1.40000+00	1.80000+00	2.40000+00	2.60000+00	2.80000+00		

INITIAL COOLANT TEMPERATURE

3.85000+02	3.63064+02	3.27966+02	3.15500+02	2.96905+02	2.83355+02	2.73339+02	2.63323+02
2.50833+02	2.48299+02	2.4[illegible]+02	2.39962+02	2.39875+02	2.39704+02	2.39607+02	2.38351+02
2.36979+02	2.35392+02	2.31226+02	2.25382+02	2.14853+02	2.10000+02		

WALL HEAT TRANSFER COEFFICIENTS

3.21493-03	3.29831-03	3.4[illegible]93-03	3.42658-03	3.47148-03	3.53561-03	3.62541-03	3.71520-03
3.71520-03	3.71520-03	3.71520-03	3.71520-03	3.71520-03	3.71520-03	3.71520-03	3.66646-03
3.48430-03	3.11872-03	2.63769-03	2.52866-03	2.44528-03	2.38114-03		

WALL THICKNESS

1.09580-03	1.09580-03	1.09580-03	1.09580-03	1.09580-03	1.09580-03	1.09580-03	1.09580-03
1.09580-03	1.09580-03	1.09580-03	1.09580-03	1.09580-03	1.09580-03	1.09580-03	1.09580-03
1.09580-03	1.09580-03	1.09580-03	1.09580-03	1.09580-03	1.09580-03		

COOLANT AREA

1.54597-04	1.49892-04	1.42228-04	1.38591-04	1.33166-04	1.26477-04	1.07338-04	8.29508-05
5.43743-05	5.[illegible]698-05	4.32[illegible]-05	4.33154-05	4.35842-05	4.41107-05	4.44072-05	5.05267-05
6.93138-05	9.79512-05	1.72037-04	2.67207-04	4.10298-04	4.33627-04		

WALL TEMPERATURE, TW IN DEGREES R

1.136826+03	1.423354+03	1.489079+03	1.475455+03	1.467344+03	1.578266+03	1.581965+03	1.661758+03
1.677369+03	1.666293+03	1.626483+03	1.567214+03	1.463649+03	1.257572+03	1.106709+03	9.756751+02
9.835097+02	9.700039+02	8.898803+02	8.899985+02	8.546963+02	8.089986+02	7.200000+02	5.450000+02
4.100000+02	3.650000+02	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

TABLE 2. PHYSICAL PROPERTIES OF LIQUID HYDROGEN

Coolant Temperature (°R)	Coolant Specific Heat (Btu/lbm• °R)	Conductivity (Btu/ft s °R)	Viscosity (lbm/ft s)
50.000	1.950000	0.0000234000	0.0000648000
100.000	2.850000	0.0000235200	0.0000120000
150.000	3.550000	0.0000249000	0.0000062400
200.000	3.950000	0.0000276000	0.0000054000
250.000	4.200000	0.0000288000	0.0000051600
300.000	4.200000	0.0000300000	0.0000051600
350.000	4.050000	0.0000306000	0.0000062400
400.000	3.900000	0.0000318000	0.0000057600
450.000	3.800000	0.0000327600	0.0000061200
500.000	3.700000	0.0000342000	0.0000064800
550.000	3.600000	0.0000357600	0.0000067200
600.000	3.550000	0.0000375600	0.0000069600
650.000	3.530000	0.0000390000	0.0000073200
700.000	3.510000	0.0000410400	0.0000076800
750.000	3.500000	0.0000428400	0.0000079200
800.000	3.500000	0.0000444000	0.0000081600
850.000	3.480000	0.0000464400	0.0000084000
900.000	3.470000	0.0000482400	0.0000087600
950.000	3.460000	0.0000504000	0.0000090000
1000.000	3.460000	0.0000528000	0.0000093600

TABLE 3. INPUT DATA FOR BLIMP COMPUTER PROGRAM (RL10)

```
RL10 POST TEST PREDICTION CASE 1 PC = 386.3 E = 57 MR = 4.839 BLIMP APRIL 1976
 $DATA
 KAT = 2HH ,2HO , ATA = 4HHYDR,4H OXY, ATB = 4HOGEN,4HGEN , ATC = 2*4H    ,
 WAT = 1.0080,16.0,
 NETA = 12, KAPPA = 16, ETA = 0.0,2.0-3,6.0-3,1.0-2,2.5-2,6.0-2,.15,.40,.70,1.0,
 1.5,2.5,3*0.0, F2FIX = 0.0,5.0-2,.12,.25,.35,.45,.60,.75,.85,.95,.98,1.0,3*0.0,
 KR(8) = 1, NPLOT = 14*1, IU = 1, IP = 1, S = 0.4670, NSP = 2, IS = 2,
 IU = 0,
 KR = 1,0,2,0,0,6,2,3,2,1,0,2,1,1,3*0,1,0,0,
 RTM = .21416667, GE = -248.4, GW = -248.4, TKP = -1.0,-4.839, PTET = 26.286053,
 N = 292, NTH = 27, NS = 26, NSTAT = 1,9*0,1,14*0,1, NP = 1,2,3,4,5,9,13,17,22,
 23,27,30,36,46,51,100,133,169,252,259,265,-269,-271,275,283,292,
 TW = 1210.,1275.,1355.,1375.,1410.,1460.,1530.,1600.,2*1765.,1700.,1695.,1689.,
 1675.,1665.,1562.,1420.,1135.,760.,675.,610.,560.,720.,545.,410.,365.,
 N = 267, NP(22) = 267, NS = 22, ICOOL = 1,
 NP(15) = -51,-100,-133,-169,-252,-259,-265,-267,
 XITAB( 1) = -4.50,-4.0,-3.20,-2.9158548,
                                                            -2.4920231,-2.3751040,
 -2.2581849,-2.1412658,-2.0243467,-1.9074277,-1.7905086,-1.6735895,-1.5566704,
 -1.4397513,-1.3228322,-1.2059131,-1.0889941,-.9720750,-.8551559,-.7382368,
 -.6213177, -.5043986, -.3874795, -.2705604, -.1536413, -.0359914,
 XITAB(27) =    .0000000,  .0027664,  .0057013,  .0087689,  .0119526,  .0152327,
  .0186025,  .0222550,  .0255853,  .0291898,  .0328655,  .0366104,  .0404229,
  .0443019,  .0482975,  .0523102,  .0564422,  .0606458,  .0648893,  .0691963,
  .0735688,  .0780072,  .0825122,  .0870851,  .0917260,  .0964825,  .1012634,
  .1060036,  .1108005,  .1155637,  .1203560,  .1249964,  .1297456,  .1343580,
  .1390166,  .1436736,  .1482918,  .1529272,  .1575285,  .1621480,  .1667400,
  .1713477,  .1759389,  .1805374,  .1851381,  .1897409,  .1943477,  .1989656,
  .2035773,  .2082243,  .2128386,  .2175280,  .2222026,  .2268818,  .2316030,
  .2362968,  .2410600,  .2457714,  .2515385,  .2561789,  .2666467,  .2748255,
  .2830626,  .2913813,  .2997242,  .3080946,  .3165218,  .3249746,  .3334534,
  .3419712,  .3505128,  .3590821,  .3676739,  .3849153,  .3935435,  .4022011,
  .4108843,  .4195669,  .4370169,  .4545646,  .4633698,  .4722079,  .4810705,
  .4899635,  .4988881,  .5078432,  .5168313,  .5258542,  .5349145,  .5440061,
  .5531438,  .5623170,  .5715355,  .5807976,  .5900907,  .5994471,  .6088360,
  .6182805,  .6277637,  .6372951,  .6468725,  .6600786,  .6661136,  .6758354,
```

TABLE 3. (Continued)

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YITAB( 1) =  4*1.9949937,                                  1.9440902, 1.9113559,
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YITAB(27) =  1.0000000, 1.0000201, 1.0000855, 1.0002024, 1.0003763, 1.0006116,
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TABLE 3. (Continued)

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```

TABLE 3. (Continued)

```
PITAB(27) =  4.990374-01, 4.783269-01, 4.589973-01, 4.405664-01, 4.228140-01,
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 3.102541-01, 2.954693-01, 2.809705-01, 2.665733-01, 2.526673-01, 2.389772-01,
 2.254910-01, 2.123799-01, 1.995748-01, 1.870694-01, 1.748673-01, 1.629743-01,
 1.513949-01, 1.401396-01, 1.311906-01, 1.309749-01, 1.251473-01, 1.249386-01,
 1.275773-01, 1.324817-01, 1.322323-01, 1.366383-01, 1.364089-01, 1.362402-01,
 1.399689-01, 1.397731-01, 1.426874-01, 1.424915-01, 1.444678-01, 1.442722-01,
 1.452047-01, 1.450087-01, 1.448142-01, 1.446187-01, 1.444191-01, 1.430379-01,
 1.428335-01, 1.402537-01, 1.400480-01, 1.362917-01, 1.360873-01, 1.358460-01,
 1.314741-01, 1.312416-01, 1.272249-01, 1.269886-01, 1.234089-01, 1.231073-01,
 1.228419-01, 1.193248-01, 1.163997-01, 1.138389-01, 1.133373-01, 1.111287-01,
 1.092949-01, 1.087542-01, 1.072777-01, 1.061741-01, 1.056059-01, 1.048711-01,
 1.045255-01, 1.039406-01, 1.042782-01, 1.036893-01, 1.039232-01, 1.040654-01,
 1.034803-01, 1.029484-01, 1.027420-01, 1.021569-01, 1.018905-01, 1.013045-01,
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 4.463719-02, 4.433523-02, 4.416019-02, 4.386112-02, 4.368529-02, 4.339152-02,
 4.309871-02, 4.293337-02, 4.264092-02, 4.247614-02, 4.218971-02, 4.190599-02,
 4.174613-02, 4.146541-02, 4.118708-02, 4.103221-02, 4.075692-02, 4.060555-02,
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TABLE 3. (Continued)

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4.033348-02, 4.006396-02, 3.922019-02, 3.742495-02, 3.567271-02, 3.392434-02,
3.229674-02, 3.055596-02, 2.892183-02, 2.725607-02, 2.553724-02, 2.387873-02,
2.222616-02, 2.062046-02, 1.917819-02, 1.769413-02, 1.636607-02, 1.518055-02,
1.401361-02, 1.286626-02, 1.174924-02, 1.073427-02, 9.800554-03, 8.880822-03,
8.004150-03, 7.272036-03, 6.581071-03, 5.920839-03, 5.343326-03, 4.765369-03,
4.498747-03, 4.239153-03, 3.987162-03, 3.742348-03, 3.523369-03, 3.308332-03,
3.116858-03, 2.920582-03, 2.752193-03, 2.609557-03, 2.462551-03, 2.339737-03,
2.209409-03, 2.133884-03, 2.086547-03,
$END
     300.      1000.      5000.                                              13100  N
H                    J 9/65H   100  000  000  0G   300.000  5000.000               1
 0.25000000E 01 0.              0.                0.                0.             2
 0.25471627E 05-0.46011763E 00 0.25000000E 01 0.                    0.             3
 0.             0.              0.25471627E 05-0.46011762E 00                      4
0                    J 6/620   100  000  000  0G   300.000  5000.000               1
 0.25420596E 01-0.27550619E-04-0.31028033E-08 0.45510674E-11-0.43680515E-15        2
 0.29230803E 05 0.49203080E 01 0.29464287E 01-0.16381665E-02 0.24210316E-05        3
-0.16028432E-08 0.38906964E-12 0.29147644E 05 0.29639949E 01                       4
02                   J 9/650   20   00   00   0G   300.000  5000.000               1
 0.36219535E 01 0.73618264E-03-0.19652228E-06 0.36201558E-10-0.28945627E-14        2
-0.12019825E 04 0.36150960E 01 0.36255985E 01-0.18782184E-02 0.70554544E-05        3
-0.67635137E-08 0.21555993E-11-0.10475226E 04 0.43052778E 01                       4
H2                   J 3/61H   20   00   00   0G   300.000  5000.000               1
 0.31001901E 01 0.51119464E-03 0.52644210E-07-0.34909973E-10 0.36945345E-14        2
-0.87738042E 03-0.19629421E 01 0.30574451E 01 0.26765200E-02-0.58099162E-05        3
 0.55210391E-08-0.18122739E-11-0.98890474E 03-0.22997056E 01                       4
OH                   J 3/660   1H   100  000  0G   300.000  5000.000               1
 0.29106427E 01 0.95931650E-03-0.19441702E-06 0.13756646E-10 0.14224542E-15        2
 0.39353815E 04 0.54423445E 01 0.38375943E 01-0.10778858E-02 0.96830378E-06        3
 0.18713972E-09-0.22571094E-12 0.36412823E 04 0.49370009E 00                       4
H20                  J 3/61H   20   100  000  0G   300.000  5000.000               1
 0.27167633E 01 0.29451374E-02-0.80224374E-06 0.10226682E-09-0.48472145E-14        2
-0.29905826E 05 0.66305671E 01 0.40701275E 01-0.11084499E-02 0.41521180E-05        3
-0.29637404E-08 0.80702103E-12-0.30279722E 05-0.32270046E 00                       4
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TABLE 4. RL10 THRUST CHAMBER SPECIFICATIONS AND FLOW PARAMETERS

GAS SPECIFIC HEAT, CPG IN BTU/LB-R

9.979573-01	9.978854-01	9.978130-01	9.977561-01	9.977283-01	9.975889-01	9.972494-01	9.964052-01
9.930069-01	9.918741-01	9.845738-01	9.819319-01	9.762147-01	9.630011-01	9.531510-01	9.441662-01
9.366704-01	9.276075-01	9.657809-01	8.893965-01	8.699543-01	8.626574-01	0.000000	0.000000
0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

COSINE OF WALL ANGLE, COSALF

1.000000+00	1.000000+00	1.000000+00	1.000000+00	9.928647-01	8.972141-01	8.968728-01	8.968727-01
9.620210-01	9.763213-01	9.969619-01	9.992747-01	9.895547-01	9.356657-01	8.823415-01	8.449200-01
8.447740-01	8.455357-01	8.608924-01	8.743788-01	8.945388-01	9.033066-01	0.000000	0.000000
0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

NOZZLE RADIUS, RDX IN FEET

4.272612-01	4.272612-01	4.272612-01	4.272612-01	4.163593-01	3.771824-01	3.277886-01	2.783948-01
2.275808-01	2.220326-01	2.141667-01	2.142100-01	2.146497-01	2.169612-01	2.192227-01	2.560120-01
2.986191-01	3.490739-01	4.762356-01	5.758685-01	7.110282-01	7.683454-01	0.000000	0.000000
0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

EDGE TEMPERATURE, TE IN DEGREES R

5.841737+03	5.839111+03	5.836475+03	5.834401+03	5.833390+03	5.828325+03	5.816019+03	5.785656+03
5.666669+03	5.628115+03	5.391924+03	5.311281+03	5.144618+03	4.794822+03	4.560576+03	4.363050+03
4.208391+03	4.032169+03	3.648153+03	3.390533+03	3.112031+03	3.014022+03	0.000000	0.000000
0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

EDGE VELOCITY, UE IN FT/SEC

3.196324+02	5.540772+02	7.159614+02	8.211082+02	8.677570+02	1.071335+03	1.450816+03	2.111687+03
3.684568+03	4.360887+03	5.821642+03	6.296151+03	7.155092+03	8.598703+03	9.382043+03	9.961226+03
1.037323+04	1.080613+04	1.164463+04	1.214649+04	1.264829+04	1.281641+04	0.000000	0.000000
0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

AXIAL DISTANCE, XST IN FEET

-9.637500-01	-8.566667-01	-6.853333-01	-6.244789-01	-5.337083-01	-4.335476-01	-3.333869-01	-2.332262-01
-1.080254-01	-8.298519-02	0.000000	1.878006-03	6.251482-03	1.481954-02	1.964465-02	8.243603-02
1.510602-01	2.304147-01	4.387014-01	6.133885-01	8.719065-01	9.910731-01	0.000000	0.000000
0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

TABLE 5. PARAMETERS COMPUTED FOR RL10 (η_E=1.0) BY REGENERATIVE COOLING PROGRAM

SN	TADWG	TWG	QWG	TWL	TL	HG	HL
1	5.84378+03	1.19391+03	6.19516+02	9.81806+02	3.92318+02	1.33233-01	1.05320+00
2	5.84525+03	1.49824+03	8.20814+02	1.24128+03	3.82753+02	1.88823-01	9.55690-01
3	5.84673+03	1.57057+03	8.75013+02	1.30388+03	3.64853+02	2.04626-01	9.29202-01
4	5.84789+03	1.62235+03	9.15608+02	1.34714+03	3.58206+02	2.16684-01	9.22647-01
5	5.84846+03	1.60945+03	9.35252+02	1.32767+03	3.48123+02	2.20630-01	9.50352-01
6	5.85130+03	1.72304+03	1.04616+03	1.41447+03	3.36394+02	2.53415-01	9.66041-01
7	5.85816+03	1.78931+03	1.23288+03	1.42567+03	3.23848+02	3.03005-01	1.11423+00
8	5.87502+03	1.87098+03	1.56104+03	1.41056+03	3.10730+02	3.89866-01	1.41366+00
9	5.93965+03	1.88365+03	2.06041+03	1.27593+03	2.93814+02	5.07990-01	2.08943+00
10	5.96009+03	1.86689+03	2.14935+03	1.23294+03	2.90485+02	5.25102-01	2.27119+00
11	6.07925+03	1.77295+03	2.23100+03	1.11492+03	2.79584+02	5.18080-01	2.65937+00
12	6.11738+03	1.71980+03	2.16564+03	1.08104+03	2.79344+02	4.92463-01	2.68937+00
13	6.19175+03	1.60919+03	2.02949+03	1.00979+03	2.78809+02	4.42872-01	2.76309+00
14	6.32787+03	1.37639+03	1.69043+03	8.35000+02	2.77843+02	3.41398-01	3.01555+00
15	6.40453+03	1.21650+03	1.45223+03	7.24275+02	2.77353+02	2.79919-01	3.22521+00
16	6.46148+03	1.06226+03	1.15203+03	6.52673+02	2.71311+02	2.13370-01	3.00043+00
17	6.50221+03	1.09163+03	9.92547+02	7.41676+02	2.64844+02	1.83446-01	2.07337+00
18	6.54575+03	1.11572+03	8.05978+02	8.31275+02	2.57500+02	1.48430-01	1.40161+00
19	6.63729+03	1.09815+03	5.38389+02	8.97778+02	2.38993+02	9.71972-02	8.16864-01
20	6.70279+03	1.13107+03	3.85774+02	9.86898+02	2.25215+02	6.92379-02	5.06456-01
21	6.78388+03	1.16584+03	2.69187+02	1.06490+03	2.07415+02	4.79148-02	3.13941-01
22	6.81602+03	1.10740+03	2.43878+02	1.01347+03	2.00000+02	4.27210-02	2.99801-01

TOTAL HEAT TO THE WALL, SUMQG IN BTU/SEC = 4.347468+03

TADWG = Adiabatic Gas-Side Wall Temperature [°R]

TWG = Gas-side Wall Temperature [°R]

QWG = Heat Transfer Rate to the Wall [BTU/Ft^2 SEC]

TWL = Coolant-side Wall Temperature [°R]

TL = Coolant Bulk Temperature [°R]

HG = Heat Transfer Coefficient on the Gas-side, [Btu/ft^2 Sec °R]

HL = Heat Transfer Coefficient on the Coolant side [Btu/ft^2 Sec °R]

TABLE 6. PARAMETERS COMPUTED FOR RL10 BY REGENERATIVE COOLING PROGRAM (η_E=Table 1)

SN	TADWG	TWG	QWG	TWL	TL	HG	HL
1	5.84378+03	1.20226+03	6.20145+02	9.90207+02	4.16245+02	1.33608-01	1.08040+00
2	5.84525+03	1.27755+03	8.88871+02	9.82512+02	4.06159+02	1.94599-01	1.54212+00
3	5.84673+03	1.31566+03	9.51971+02	1.00432+03	3.86656+02	2.10099-01	1.54112+00
4	5.84789+03	1.35320+03	9.97489+02	1.03159+03	3.79390+02	2.21926-01	1.52930+00
5	5.84846+03	1.43967+03	9.66555+02	1.13789+03	3.68644+02	2.19234-01	1.25641+00
6	5.85130+03	1.56434+03	1.07982+03	1.24189+03	3.56496+02	2.51884-01	1.21952+00
7	5.85816+03	1.64096+03	1.27067+03	1.26617+03	3.43556+02	3.01307-01	1.37717+00
8	5.87502+03	1.72818+03	1.61014+03	1.25327+03	3.30047+02	3.88281-01	1.74393+00
9	5.93965+03	1.74018+03	2.15892+03	1.10341+03	3.12453+02	5.14093-01	2.72929+00
10	5.96009+03	1.72345+03	2.25380+03	1.05869+03	3.08969+02	5.31977-01	3.00593+00
11	6.07925+03	1.71418+03	2.32245+03	1.02918+03	2.97626+02	5.32055-01	3.17445+00
12	6.11738+03	1.68916+03	2.15039+03	1.05490+03	2.97383+02	4.85611-01	2.83851+00
13	6.19175+03	1.57994+03	2.01046+03	9.82711+02	2.96854+02	4.35938-01	2.93107+00
14	6.32787+03	1.35513+03	1.66931+03	8.17209+02	2.95900+02	3.35692-01	3.20182+00
15	6.40453+03	1.20546+03	1.43610+03	7.14929+02	2.95415+02	2.76223-01	3.42281+00
16	6.46148+03	1.03913+03	1.16418+03	6.13251+02	2.89356+02	2.14701-01	3.59382+00
17	6.50221+03	1.03457+03	1.03954+03	6.53552+02	2.82661+02	1.90126-01	2.80254+00
18	6.54575+03	9.75232+02	8.76806+02	6.45470+02	2.74801+02	1.57401-01	2.36530+00
19	6.63729+03	8.24767+02	6.02780+02	5.81965+02	2.54698+02	1.03704-01	1.84180+00
20	6.70279+03	7.12958+02	4.63798+02	5.15751+02	2.39364+02	7.74308-02	1.67803+00
21	6.78388+03	6.49524+02	3.30637+02	5.04351+02	2.18696+02	5.38992-02	1.15746+00
22	6.81602+03	5.92410+02	2.98990+02	4.57162+02	2.10000+02	4.80412-02	1.20969+00

TOTAL HEAT TO THE WALL, SUMQG IN BTU/SEC = 4.633962+03

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