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FROM: O. J. Demuth

SUBJECT: Transmittal of Users Manual for Program E25107 and
ANSC Report N8110R:72-030 for Project 141

DISTRIBUTION: R. G. Ackerman, R. H. Coppo, K. Sato, J. L. Watkins,
J. J. Williams

ENCLOSURES: (1) Technical and Users Manual for Program E25107 Nozzle Heat
Transfer (Revision of Program E25104), dated February 1972

(2) Correlation of NRX-A5 and NRX-A6 Technology Nozzle Test
Data With Calculated Performance, ANSC Report No.
N8110R:72-030, dated February 1972

Attached hereto as Enclosures are (1) the description of computer code E25107 which is used to calculate the thermal performance of tubular regeneratively cooled rocket nozzles, and (2) the results of using this program to correlate NRX-A5 and NRX-A6 test data. This work was conducted for Project 141, Work Statement 9c.

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O. J. Demuth
O. J. Demuth, Supervisor
Thermophysics Section
Engineering Staff Department

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TECHNICAL AND USERS MANUAL FOR
PROGRAM E25107
NOZZLE HEAT TRANSFER
(Revision of Program E25104)

February 1972

J. J. WILLIAMS

J. J. Williams

NOZZLE HEAT TRANSFER

PROGRAM E25107

I. INTRODUCTION

A. PROBLEM TO BE SOLVED

This program computes heat transfer parameters of tubular regeneratively-cooled rocket engines.

Allowance is made for variations of various geometric and fluid parameters permitting comparisons as well as design calculations.

This program is a modification of E25106 and E25104 which were written by T. M. Sheehy.

B. METHOD OF APPROACH

The bulk temperature and pressure, gas-side wall temperature and liquid-side wall temperatures are guessed. The program then iterates on these four values until the computed values are equal to the assumed values within a prescribed tolerance. This procedure is followed at various increments along the nozzle beginning at the point where the coolant exists and terminating at the point where coolant is discharged.

The station data describing the nozzle contour may be input directly or may be generated by the program.

C. MATHEMATICAL MODEL

See Appendix A.

D. NUMERICAL METHODS USED

1. For a description of the iteration scheme, see Appendix B.
2. Interpolations performed on the station data are linear.
3. Interpolation is performed on the coolant properties by using a third degree interpolating polynomial which is continuous and has a continuous 1st derivative.

II. INPUT DATA

A. DISCUSSION

This program utilizes the NAMELIST feature of Fortran IV for loading in data. A complete description of how it is used will be found in the "Namelist Usage Report, Program E61214", Computing Sciences Division, by N. Cull.

B. DATA

This section provides a list, by variable name, of all the data used by the program together with a brief description or definition.

	<u>ITEM</u>	<u>DESCRIPTION</u>	<u>DEFAULT VALUE</u>
1.	REYEXP	Exponent on Reynolds number when HGC = 4	0.
2.	PRLEXP	Exponent on Prandtl number when HGC = 4.	0.
3.	ITRFL...	The maximum number of iterations to convergence. When this parameter is not input.	10.
4.	LW...	Land width for U-tube with/and or groove configuration.	
5.	FRIC...	Friction factor flag. If FRIC is zero the friction factor equation is modified. If FRIC = -1., M. F. Taylor Equation is used. If FRIC = 1., friction factor is computed from equation shown in section VII.L.2., (2) Appendix A.	-1.
6.	SUM...	Output flag SUM = 1, short output SUM = 2, long output SUM = 3, both long and short output	
7.	WGSTA...	The gas flow rate, WGSTAR, is computed whenever WGSTA equals Zero. When WGSTA is non-zero then WGSTAR is input.	0.

	<u>ITEM</u>	<u>DESCRIPTION</u>	<u>DEFAULT VALUE</u>
8.	HLC...	Liquid-side heat transfer coefficient flag. HLC assumes values 1 through 11 depending upon which h_2 relationship is desired. (See Section VI.A of Appendix A.) HLC = 9 requires that TANH table be input	0.
9.	HGC...	Gas-side heat transfer coefficient flag. HGC takes on the value 1, 2, 3, or 4 depending on which h equation is desired. (See Section VI.B of Appendix Z.) HGC = 3 requires that TANG tables be input.	0.
10	WALL...	Wall-type flag used only for the non-cryogenic case. If equal to zero a cylindrical wall is assumed. If non-zero, a flat surface is assumed. (See Sections VI.E.2 and VI.G.2 of Appendix A.)	
11.	MERCR...	= 0 if cryogenic case = 1 if non-cryogenic	0.
12.	PC...	Chamber pressure	0.
13.	TC...	Chamber temperature	0.
14.	MR...	Mixture ratio	0.
15.	WGSTAR...	The gas flow rate through the throat	0.
16.	WGCORE...	The gas flow rate from the core	0.
17.	ZW...	The axial coordinate at which the flow rate $\dot{W}$ changes. (See Section VI.B of Appendix A.)	0.
18.	PIN...	Coolant inlet pressure.	0.
19.	TIN...	Coolant inlet temperature	0.
19a.	COEF(4,5)...	Constants to the 4th degree polynomial used to describe temperature dependent properties.	0.
20.	E...	Surface roughness of coolant passage.	0.

	<u>ITEM</u>	<u>DESCRIPTION</u>	<u>DEFAULT VALUE</u>
21.	XPLOT(10)...	Array of flags used to indicate which variables to plot versus length. The individual flags are: XPLOT(1) = 1., coolant pressure XPLOT(2) = 1., coolant bulk temperature XPLOT(3) = 1., nozzle radius XPLOT(4) = 1., coolant side heat transfer coefficient XPLOT(5) = 1., gas side heat transfer coefficient XPLOT(6) = 1., tube wall thickness XPLOT(7) = 1., gas side wall temperature XPLOT(8) = 1., coolant channel flow area XPLOT(9) = 1., coolant channel leg height XPLOT(10) = 1., gas side Cg coefficient The short output option or the combination output option (SUM = 1. or SUM = 3.) must be used if plots are to be obtained.	0.
22.	K1...	Constant used in momentum loss equation. (See Section VI.L.1.b of Appendix A.)	1.
22a.	K2...	Constant used in the pressure drop equation.	0.
23.	K3...	Constant used in computing outlet pressure. (See Section VI.L.4 of Appendix A.)	1.
24.	K4...	Same as above.	0.
24a.	K5S...	Flag set to 1. if Ito curved tube friction factor correction is to be applied.	1.
25.	CC2...	Same as above	0.
26.	CC1...	Same as No. 22	0.
27.	AL...	Area of inlet passage	1.0
28.	A0	Area of outlet passage	1.0
29.	CB1...	Constant used in h ₂ equation. (See Appendix A, Section VI.A.)	1.
30.	CB2...	Same as above	1.
31.	AASTAR...	Exit area/throat area ratio (see Section C for description of when this is needed).	

	<u>ITEM</u>	<u>DESCRIPTION</u>	<u>DEFAULT VALUE</u>
32.	RC...	Radius of barrel section	
33.	RD...	Radius of curvature downstream of throat (required input when K5S = 1.)	
34.	RU...	Radius of curvature upstream of throat (required input when K5S = 1.)	
35.	RB...	Convergent radius	
36.	RSTAR...	Throat Radius	
37.	ZB...	Barrel length	
38.	ZOL...	Over-all length of nozzle	
39.	ALPHA...	Divergence angle	
40.	BETAA...	Convergence angle	
41.	N1P...	Number of points desired in Section 1.	
42.	N2P...	Number of points desired in Section 2.	
43.	N3P...	Number of points desired in Section 3.	
44.	N4P...	Number of points desired in Section 4.	
45.	N5P...	Number of points desired in Section 5.	
46.	N6P...	Number of points desired in Section 6.	
47.	GAMMA...	Ratio of specific heats when TMACH(Ito) table is used to obtain local values of gas side pressure, temperature and velocity	
48.	EPOGEØ...	Emissivity of core face, ϵ_0 . (See Section VI.C.2.a of Appendix A.)	
49.	EP1GEØ...	Emissivity of tube wall, ϵ_1 . (See Section VI.C.2.a of Appendix A.)	
50.	TO...	Temperature of core face	
50a.	TB...	Temperature of coolant, °R.	
51.	WBC...	Bolt coolant flow	
52.	HBC...	Enthalpy change of bolt coolant	

	<u>ITEM</u>	<u>DESCRIPTION</u>
53.	WF...	Film coolant flow
54.	XJ...	Developed length for initial rise in TFI.
55.	TCF...	Reference temperature of coolant
56.	VF...	Velocity of injected film coolant.
57.	TWL...	Temperature of coolant wall at 1st station
58.	TWG...	Temperature of gas wall at 1st station
59.	ZSTAR...	Axial distance to the nozzle throat
60.	ASTAR...	Throat area
61.	COOL...	Designates type of coolant used. = 1, NBS equilibrium hydrogen = 2, Aerozine-50 = 3, Water = 4, NBS para hydrogen
62.	MW...	Molecular weight
63.	ZETA...	Combustion efficiency used in computing β .
64.	CONTR...	Contour subprogram bypass flag. If CONTR=2, the program checks the Material Curve Data Flag (TMKM) to obtain the nozzle contour data. Nozzle contour station data will be generated whenever CONTR=0. If CONTR=1, station data is input directly.
64a.	ZD	Z to downstream point of tangency, in. (required input if K5S is input at 1.0)
64b.	ZU	Z to upstream point of tangency, in. (required input if K5S is input as 1.0)
65.	NTOT...	Total number of stations input
65a.	SMALTC...	Coating thickness, tc, in.
66.	DUMPEM...	Dump flag. If non-zero, intermediate values will be printed after each iteration.
66a.	SMALTS...	Space thickness, ts, in.
67.	TITLE...	Title. (Limited to 80 characters.) This information appears at the top of each page of output (must be enclosed in quotes). For UNIVAC usage the title is read from card preceding DATUM by A format.

	<u>ITEM</u>	<u>DESCRIPTION</u>
68.	NDL...	Number of points in the table of discontinuities TAZ1.
69.	DZ...	Applicable only if contour subroutine is used. Stations will be spaced DZ inches apart.
70.	NC...	Nozzle contour flag: = -1, input all stations = 0, conical nozzle = 1, contoured nozzle
71.	RBO...	"Burn-Out" equations flag (see Section IX of Appendix A)
72.	TATWM(25)...	Values of temperature for the yield stress table (TASTRY). (See Section VI.N.2 of Appendix A.)
73.	TASTRY(25)...	Yield stress
74.	TTATMR(20)...	Values of temperature for the thermal conductivity table (TAKMR). (See Section VI.D of Appendix A.)
75.	TTAKMR(20)...	Thermal conductivity of tube wall.
76.	TAZ(100)...	Z values for the following curves: (must be in numerical order)
76.a	TASMTM(100)...	Tube metal thickness, t_m
76.b	TACC(100)...	Factor in gas side heat transfer coefficient, C_g
76.c	TACL(100)...	Factor in coolant-side heat transfer coefficient, C_c . (If TACL is negative then C_c will be calculated from a curve Ref. AGC Report RN-S-0274.)
76.d	TAKC(100)...	Thermal conductivity of tube coating, k_c
76.e	TATC(100)...	Coating thickness, t_c
76.f	TASMD(100)...	Undeformed coolant tube diameter, d
76.g	TASML(100)...	Tube leg height, L for U-tube but for the rectangular slots it is the land width.
76.h	TASMIS(100)...	Space thickness, t_s
76.i	TASMDS(100)...	Slotted passage height
76.j	TABETA(100)...	Factor defining temperature recovery, β .

	<u>ITEM</u>	<u>DESCRIPTION</u>
76.k	TAAF(100)...	Cross sectional area of single tube, A_f . If leg height iteration is being made TAAF must input as an initial guess to avoid a divide by zero.
76.l	PXM(100)...	Table of constants from which K_6 is determined in the friction loss equation. (See Section VI.M.2.c of Appendix A.)
76.m	PDM(100)...	Table of constants from which K_5 is determined in the dynamic pressure drop equation. (See Section VI.M.1.c of Appendix A.) (not used at present)
76.n	TATWG(100)...	Temp. of gas wall if LHITE=1 or if CGITE=1
76.o	TAHL(100)...	Liquid side heat transfer coefficient if HLC=9
76.p	TANG(100)...	Gas side heat transfer coefficient if HGC=3
76.q	CGITE(100)...	Table from which CGITE is determined. CGITE is the C iteration flag. Iteration is performed on C_g if and only if CGITE=0. (See Section VII of Appendix A.)
76.r	PPFM(100)...	Table from which to obtain PFM used in friction factor (default to zero)
76.s	EEPGEO(100)...	Table from which EPGEOM is determined. This is the heated area factor, ϵ .
76.t	LHITE(100)...	Table from which the leg height iteration flag is determined. If LHITE=0, the leg height iteration is performed. (See Section VII of Appendix A.) This option may be used only with HLG set to 1, 10 or 11 and may not be used with the land and groove configuration. An error will result if the computed height is negative so results computed with this option should be checked by running with LHITE=0.
76.u	LH(100)...	Table from which UW, the central land width, for U-tube configurations is determined. See the U-tube figure.
76.v	TMKM(100)...	Material curve data flag. = 0 Stainless steel curve data is used. = -1 Hastelloy X curve data is used = +1 Material curve data is being input. (See Section VI.D of Appendix A.)

<u>ITEM</u>	<u>DESCRIPTION</u>
76.v TULI(100)...	Signifies type of coolant tubes used as follows: - 1, Port or Star - 2, Tube - 3, Tube - 4, Tube
77. TAZI(100)...	Z values for the following step functions. This table also determines the flow path in that the 1st point of the table is the location at which the coolant enters the nozzle and the next point would then be downstream with respect to the direction of flow. Whenever a discontinuity occurs in any of the following tables the location at which it occurs must be input twice.
77.a TAFEV(100)...	Radiation factor (not used in present version)
77.b TANMB(100)...	Number of coolant tubes through which the coolant is flowing.
77.c TANT(100)...	Total number of tubes
77.d TAWDOT(100)...	Coolant flow rate.

The next four items provide for input of all nozzle station data. These are omitted when the contour flag CONTR = 0.

78. ZZZZZZ(200)...	Axial coordinate Z, measured from the injector face.
79. RRRRRR(200)...	Radius corresponding to Z
80. SSSSSS(200)...	Developed length
81. AAAAAA(200)...	Area ratio at the point Z. (Input should be negative upstream of the throat.)

The next five tables are used to input the gas-side transport properties as a function of temperature. These are ignored when using hydrogen since the gas-side properties are obtained from hydrogen subroutine.

82. GAST(50)...	Temperature
82a. GASK(50)...	Thermal Conductivity

	<u>ITEM</u>	<u>DESCRIPTION</u>
83.	GASCP(50)...	Specific heat at constant pressure
84.	GASRHO(50)...	Density
85.	GASMU(50)...	Viscosity
85.a	GASMUT(50)...	Molecular weight of gas
85.b	GAS...	Flag to determine gas side properties
		GAS = 1, NBS equilibrium hydrogen
		GAS = 2, NBS para-hydrogen
		GAS = 3, above tables must be input

The next four tables provide the program with a means of determining velocity, pressure and temperature of the gas as a function of area ratio:

86.	TAAST(100)...	Area ratio
87.	TVK(100)...	Gas velocity
87.a	TRHOK(100)...	Gas density
88.	TTINK(100)...	Gas temperature
89.	TPK(100)...	Gas pressure
89.a	TMACH(100)...	Used with GAMMA to generate TVK, TPK and TTINK if input.

The following 14 items are constants used in the computation of the burnout heat flux ratio: (see Section IX of Appendix A)

90.	VDTC...	VDTC
90.a	QOABO...	Coolant burnout heat flux.
91.	RBOFP...	F_p
92.	RBOFT...	F_T
93.	RBOA1...	A_1
94.	RBOA2...	A_2

	<u>ITEM</u>	<u>DESCRIPTION</u>
95.	RBOB1...	B_1
96.	RBOB2...	B_2
97.	RBON1...	N_1
98.	RBON2...	N_2
99.	RBOM1...	M_1
100.	RBOM2...	M_2
101.	RBOK1...	K_1
102.	RBOC1...	C_1

The following 5 items are used if PFM and EPGEOM are to be determined from experimental data.

103.	DPI...	Required pressure drop, psi
104.	DTI...	Required temperature increase, °R
105.	FLAG...	Flag set to 1. if PFM option is used
106.	ZCHAN...	Iteration flag, see code
107.	CONLHB...	Flag. See Code.
108.	FILMC...	} not used at present.
109.	MMAT...	
110.	PREXP...	
111.	RBOFLG...	
112.	RN...	
113.	TF...	
114.	THK...	
115.	TSAT...	

C. USAGE OF THE NOZZLE STATION DATA GENERATING SUBPROGRAM (CONTUR)

The program will compute the station coordinates of a nozzle by dividing the nozzle into segments of circular arcs connected by straight lines as shown:

By input of certain critical dimensions such as throat radius, convergent angle, etc., coordinates of the tangent points 0, 1, 2, ---6 are computed. Definition of a contoured divergent section by means of length and radial coordinates is required if the nozzle is of this type.

Once the coordinates of the tangent points are determined, two methods are available for automatically locating stations. In the first, the number of equal length station intervals between two tangent points can be specified for any segment; e.g., for three station intervals between Points 1 and 2, input $N2P = 3$. If intervals are not specified or are input zero, each segment will be divided into approximate 3 in. intervals between stations. For a contoured nozzle, stations in the divergent section aft of the downstream point of tangency (Point 5) are located by input. Stations are always placed at the tangent points.

The second method for locating stations is by even interval. This is done merely by input of the desired print interval DZ, and a non-zero number here calls this method. This interval is held throughout the nozzle regardless of whether it is conical or contoured. Again, stations are always placed at the tangent points.

Because the program works progressively in the direction of coolant flow, it is necessary to input the points of entry and exit of the coolant as axial distances in the TAZ1 table. In case of a discontinuity such as a tube split, change in direction of coolant flow or change in coolant flow rate, a double station must be input in the TAZ1 table. If a station is desired at a certain location, include a single point defining the location in the TAZ1 table. Always input TAZ1 data in direction of coolant flow.

Certain dimensions are required to be input for any case in which Subroutine CONFUR is used. These are:

Chamber radius	(RC)
Throat radius	(RSTAR)
URAD	(RU)
DRAD	(RD)
Convergent radius	(RB)
Convergent angle	(β)
Divergent angle at DPT	(α)

Other dimensions are required to define the relative location of the nozzle forward end, throat, and exit. To accomplish this, any pair of the following may be used:

AASTAR, ZOL
AASTAR, ZB
AASTAR, ZSTAR
ZOL, ZB
ZOL, ZSTAR

If more than one pair is input, the pair nearest the top of the list is used; i.e., if AASTAR, ZB, and ZSTAR are all input, the contour will be computed using AASTAR and ZB.

In the case of a contoured nozzle, input of AASTAR is automatic as it is computed from the last point defining the contour; therefore, only a length dimension (ZOL, ZB, or ZSTAR) is required. The contour is input by defining points aft of the downstream point of tangency (Point 5) by axial distance from the throat and radius. Values are input in pairs of axial distance and radius, one pair per card, with Z in columns 1 - 10 and R in columns 11 - 20. After the last pair, include one card with a -1. between columns 1 and 10 to signify end of table.

The following examples are included to demonstrate input.
(See Figure A)

1. Given: Conical nozzle, coolant enters at pt. (6) and exits at pt. (0). Overall length and barrel length known. A print interval of 2 in. is desired. There is a tube split at axial distance 15 in.
Input: NC = 0., RC = 14., RSTAR = 5., RU = 3.5, RD = 2., RB = 4.5, ALPHAA = 17.5, BETAA = 45., ZOL = 43.5, ZB = 9., DZ = 2., NDL = 4., TAZ1 = 43.5, 15., 15., 0.,
2. Given: Conical nozzle, coolant enters at forward end, flows aft and reverses direction at aft end, and exits at forward end. Area ratio at exit and length to throat are known. Stations are desired at axial distance 5, 14, 17, 19, 20, 25, 35 and 43.5 in.
Input: NC = 0., RC = 14., RSTAR = 5., RU = 3.5, RD = 2., RB = 4.5, ALPHAA = 17.5, BETAA = 45., AASTAR = 9., ZSTAR = 21., DZ = 0., NDL = 18., N1P = 1., N2P = 1., N4P = 1., N5P = 1., N6P = 1., TAZ1 = 0., 5., 14., 17., 19., 20., 25., 35., 43.5, 43.5, 35., 25., 20., 19., 17., 14., 5., 0.,

CONICAL NOZZLE

CONTOURED NOZZLE

MATHEMATICAL MODEL

APPENDIX A

I. GAS CONDITIONS

At the present time gas pressure and temperature as functions of nozzle area ratio must be input in tabular form. In addition when the coolant is not hydrogen, the properties (density, thermal conductivity, viscosity and specific heat at constant pressure) must be input as functions of temperature.

II. NOZZLE GAS-SIDE CONTOUR AND STATION LOCATION

In the case of a conical nozzle, the Z-R coordinates and developed lengths X can be computed when pertinent nozzle dimensions are known. In the case of a contoured nozzle, only the stations forward of the throat can be calculated; aft of the throat the coordinates must be input as axial length measured from the throat, and radius. The developed length X will be computed by the program. For unconventional nozzles the data must be input in tabular form at each station.

The program merely breaks the nozzle into circular arcs and connecting straight lines, and computes coordinates and developed lengths at each tangent point. It then breaks each segment down into the number of intervals input as, N'_1 , N'_2 , etc. If any N' is not input, an approximate length of 3 inches between stations is used. Exceptions to this are in the arc described by R_d which is usually small and is therefore taken as a single segment, and the arcs described by R_u and R_g which are presently divided in half. In any case, no intervals are greater than 3 inches long.

In cases where discontinuities in the data exists such as coolant flow rates, number of coolant tubes, or where the coolant flow changes direction nozzle data at these discontinuities are inserted into the contour

data generated by the program. A table of axial coordinates called TAZ1 is used to locate all discontinuities and also to determine the flow direction at each point in the nozzle.

III. GEOMETRIC PARAMETERS OF COOLANT TUBES

Four basic coolant tube configurations are being considered: U-Tubes (Figure 2), Truncated Tubes (Figure 3), Round or Flattened Tubes (Figure 4), and Rectangular Slots (Figure 5).

A. Round or Flattened Tubes. The gas-side radius, circumference, ambient-side radius, and side length are computed as follows:

1. $r_g = \pi R / (N_t - \pi)$
2. $s = \pi d$
3. $r_a = \pi(2R + 2r_g + s - \pi r_g) / (2N_t + \pi^2)$
4. $l = .5 [s - \pi(r_g + r_a)]$

If $l \leq 0$, a round tube condition exists, and diameter, circumference, ambient-side radius and side length are re-computed as follows:

5. $d = 2r_g$
6. $s = \pi d$
7. $r_a = r_g$
8. $l = 0$

Calculation of flow area and equivalent diameter:

9. $A_f = \frac{\pi}{2} [(r_g - t_m)^2 + (r_a - t_m)^2] + l(r_g + r_a - 2t_m)$
10. $d_e = 4 A_f / [\pi(r_g + r_a - 2t_m) + 2l]$

B. U-Tubes. The gas-side radius, back-side tube width, flow area and equivalent diameter are computed as follows:

$$1. \quad r_g = (\pi R - .5 N_t t_s) / (N_t - \pi)$$

When A_f is input, ℓ is solved from the following equation:

$$2. \quad \frac{2\pi}{N_t} \ell^2 + [2(r_g - t_m) + \frac{2\pi}{N_t} (R + r_g) - t_s - 2t_m] \ell + \pi(r_g - t_m)^2 - 2 A_f = 0$$

$$3. \quad b = [2\pi(R + r_g + \ell) / N_t] - t_s$$

$$4. \quad A_f = .5 \{ \pi(r_g - t_m)^2 + \ell [2(r_g - t_m) + b - 2t_m] \} - UW * UL$$

$$5. \quad d_e = 4 A_f / [\pi(r_g - t_m) + (b - 2t_m)] + 2|UW|$$

C. Truncated Tubes. Calculations of flow area and equivalent diameter are as follows:

$$1. \quad r_g = \pi R / (N_t - \pi)$$

$$2. \quad d_{\min} = \frac{2r_g}{\pi} \left[\pi - \cos^{-1} \left(\frac{t_m}{r_g} \right) \right] + \frac{2r_g}{\pi} \sin \left[\cos^{-1} \left(\frac{t_m}{r_g} \right) \right]$$

$$3. \quad \text{if } d > d_{\min} \text{ and } d < 2r_g \text{ then}$$

a. θ is computed from the following equation:

$$\pi d = 2r_g (\pi - \theta) + 2r_g \sin \theta$$

$$b. \quad \ell = r_g \cos \theta$$

$$c. \quad \alpha = \sin^{-1} \left(\frac{\ell - t_m}{r_g - t_m} \right)$$

4. If $d \leq d_{\min}$ then

a. $l = t_m$

b. $\alpha = 0.$

c. $0 = \cos^{-1} \left(\frac{t_m}{r_g} \right)$

5. $A_f = (r_g - t_m)^2 \left(\frac{\pi}{2} + \alpha \right) + (l - t_m) (r_g - t_m) \cos \alpha$

6. $d_e = 4 A_f / [2 \left(\frac{\pi}{2} + \alpha \right) (r_g - t_m) + 2 (r_g - t_m) \cos \alpha]$

Whenever $d > d_{\min}$ and $d \geq 2r_g$ then the flow area and equivalent diameter are computed as follows:

7. $r_a = \pi(2R + 2r_g + \pi d - \pi r_g) / (2N_t + \pi^2)$

8. $l = .5 [\pi d - \pi(r_g - r_a)]$

If $l \leq 0$ then

$d = 2r_g$

$r_a = r_g$

$s = \pi d$

$l = 0.$

9. $A_f = \frac{\pi}{2} [(r_g - t_m)^2 + (r_a - t_m)^2] + l(r_g + r_a - 2t_m)$

10. $d_e = 4 A_f / [\pi(r_g + r_a - 2t_m) + 2l]$

D. Rectangular Slots. Flow area and equivalent diameter are computed as follows:

1. $W = \frac{2\pi}{N_t} (R + t_m) - l$

2. $A_f = W d_s$

3. $d_e = \frac{2A_f}{W + d_s}$

IV. GAS PRESSURE AND TEMPERATURE AT STATIONS

After stations have been located, area ratio is calculated at each station by:

$$A/A^* = (R/R^*)^2$$

P_∞ and T_∞ are obtained by interpolation as a function of area ratio.

V. BETA FACTOR AT STATIONS

β will either be input as a function of axial length or computed by the program.

A. If input, interpolation may be made at each station.

B. If β is to be computed, it will be input as a negative value. Having obtained gas properties at a specific station, the Prandtl number is computed by:

$$P_r = \mu C_p / k$$

Using T_∞ at the station being considered, β is computed as follows:

$$\beta = \eta^2 [P_r^{1/3} T_c + T_\infty (1 - P_r^{1/3})] / T_c$$

VI. CALCULATION OF DESIRED PARAMETERS

Because T_{WG} , T_{WL} , T_b and P are all interrelated, an iterative procedure is used for solution. The normal procedure involves assuming initial values of these four parameters, then using previous values in subsequent iterations. At the first station, guesses of $T_{WG} = T_{WL} = 1500^\circ R$ are used and T_b and P are input.

A. CALCULATION OF THE LIQUID SIDE HEAT TRANSFER COEFFICIENT h_l

At the present time there are ten different equations and one table look up option which can be used to calculate h_l . The method utilized depends on the value of the input parameter HLC.

$$\text{HLC} = 1., \quad h_l = \frac{C_L K_{cf}}{d_e} \left[\frac{\rho_{cf} d_e v}{\mu_{cf}} \right]^{.8} \left[1 + \frac{.01457 \mu_{WL} \rho_b}{\mu_b \rho_{WL}} \right] \left[\frac{P}{P_{r_{cf}}} \right]^{.4}$$

$$\text{HLC} = 2., \quad h_l = \frac{C_L K_{cf}}{d_e} \left[\frac{d_e v \rho_b}{\mu_{cf}} \right]^{.8} \left[\frac{\mu_{cf} C_{p_{cf}}}{K_{cf}} \right]^{.4}$$

$$\text{HLC} = 3., \quad h_l = \frac{C_L K_b}{d_e} \left[\frac{d_e v \rho_b}{\mu_b} \right]^{.8} \left[\frac{\mu_b C_{p_b}}{K_b} \right]^{.4} \left[\frac{T_b}{T_{WL}} \right]^{.34}$$

$$\text{HLC} = 4., \quad h_l = \frac{C_L K_{cf}}{d_e} \left[\frac{d_e v \rho_b}{\mu_{cf}} \right]^{.8} \left[\frac{\mu_{cf} C_{p_{cf}}}{K_{cf}} \right]^{.4} \left[\frac{\rho_{WL}}{\rho_b} \right]^{.8}$$

$$\text{HLC} = 5., \quad h_l = \frac{C_L K_b}{d_e} \left[\frac{d_e v \rho_b}{\mu_b} \right]^{.8} \left[\frac{\mu_b C_{p_b}}{K_b} \right]^{.4}$$

$$\text{HLC} = 6., \quad h_l = \frac{C_L K_b}{d_e} \left[\frac{d_e v \rho_b}{\mu_b} \right]^{.8} \left[\frac{\mu_b C_{p_b}}{K_b} \right]^{.4} \left[\frac{\mu_b}{\mu_{WL}} \right]^{.14}$$

$$\text{HLC} = 7., \quad h_l = \frac{C_L K_{cf}}{d_e} \left[\frac{d_e v \rho_{cf}}{\mu_{cf}} \right]^{.8} \left[\frac{\mu_{cf} C_{p_{cf}}}{K_{cf}} \right]^{.4}$$

$$\text{HLC} = 8., \quad h_l = \frac{C_L K_b}{d_e} \left[\frac{d_e v \rho_b}{\mu_b} \right]^{.95} \left[\frac{\mu_b C_{p_b}}{K_b} \right]^{.4}$$

$$\begin{aligned} \text{HLC} = 9., \quad h_l &= \text{table look up from TAHL vs. TAZ input table.} \\ \text{HLC} = 10., \quad h_l &= 0.00704 \frac{K}{d_e} \text{Re}^{.879} \text{Pr}^{.4} \end{aligned}$$

where all fluid properties are determined from:

$$\text{Property} = \frac{\int_{T_{\text{bulk}}}^{T_{\text{wall}}} (\text{Property}) dT}{T_{\text{wall}} - T_{\text{bulk}}}$$

The coefficient is multiplied by the following terms when K5S = 1.

1. $\left[1 + \frac{4.0}{x/d_e} \right]^{.856}$
2. and the lowest value of a., b. or c.
 - a. $(1 + 1.107 \emptyset)$ for the entrance to the throat region,
 - b. $.876 \left[\text{Re}_b \left(\frac{d_e}{2R_c} \right)^2 \right]^{.0666}$ for fully developed curve tube flow
 - c. $(3.033 - 1.649 \emptyset)$ to represent decay of the curvature effect

HLC = 11. Recent analysis of 2230 points of hydrogen heat transfer data in the specific operating range of the NERVA has led to the following coolant-side correlation for hydrogen.

$$h_l = 0.00821 \frac{K_{\text{film}}}{d_e} \text{Re}_{\text{film}}^{.874} \text{Pr}_{\text{film}}^{.4} \left(1 + .0146 \frac{\mu_w \rho_b}{\mu_b \rho_w} \right)^{.622}$$

The subscript "film" refers to properties based on the average temperature between bulk and wall.

When K5S = 1., a factor that accounts for entrance effects is multiplied times this expression and takes the following forms:

$$\text{for } 0 \leq x/d_e < 5.198$$

$$\text{Entrance factor} = 1.8$$

$$\text{for } 5.198 < x/d_e \leq 120$$

$$\text{Entrance factor} = \left(1 + \frac{4.0}{x/d_e} \right)^{1.030}$$

for $x/d_e \leq 120$ the entrance factor has attenuated to unity

Also when $K5S = 1.$, a factor that accounts for coolant channel curvature, for the case in which heat transfer exists over the convex surface of the curve (the nozzle throat), is multiplied times the straight tube correlation and takes the following forms:

$$\text{curved tube factor} = \left\{ \begin{array}{l} 1 + 1.128 \phi \\ .797 \left[Re_b \left(\frac{d_e}{2r_c} \right)^2 \right]^{.0785} \\ 2.502 - 1.16 \phi \end{array} \right.$$

in which ϕ is the angle of curvature in radians.

For the particular value of ϕ , Re_b , and $\frac{d_e}{r_c}$ at a location on a curved tube, the expression above that yields the lowest curved tube factor is utilized.

In all cases:

$$v = \frac{\dot{W}_c}{N_{mb} A_f \rho_b}$$

K_b , μ_b , ρ_b , Cp_b are evaluated at P and T_b . K_{cf} , μ_{cf} , ρ_{cf} , Cp_{cf} evaluated at P and $T_{cf} = (T_B + T_{WL})/2$. K_{WL} , μ_{WL} , ρ_{WL} , Cp_{WL} are evaluated at P and T_{WL} .

For h_ℓ calculations for $HLC = 2$ through 9 the following modification to h_ℓ is performed whenever T_{WL} is greater than the saturation temperature T_{SAT} :

$$h_\ell = h_\ell C_{B1} \left(\frac{T_{WL}}{T_{SAT}} \right)^{C_{B2}}$$

B. CALCULATION OF GAS SIDE HEAT TRANSFER COEFFICIENT, h_g

The gas side heat transfer coefficient is calculated by one of four different computational schemes depending on the input parameter HGC. In addition, the gas properties used for three of the methods may be either (1) NBS equilibrium hydrogen, (2) values from input tables or (3) NBS para-hydrogen. This second option is controlled by the input parameter GAS.

The following relationships are available for determining gas side heat transfer coefficient.

$$(1) \quad h_g = C_G \left[\frac{4 \dot{W} \rho_{gf}}{\pi D^{2.25} \rho} \right]^{.8} \frac{\mu_{gf}^{.2} GU_{gf}}{P_r^{.6}}$$

$$(2) \quad h_g = C_G \left[\frac{4 \dot{W} T_\infty}{\pi D^{2.25} T_{gf}} \right]^{.8} \frac{\mu_{gf}^{.2} C_{p_{gf}}}{P_r^{.6}}$$

$$(3) \quad h_g = C_G \left[\frac{4 \dot{W} MW_{gf} T_\infty}{\pi D^{2.25} MW_\infty T_{gf}} \right]^{.8} \frac{\mu_{gf}^{.2} C_{p_{gf}}}{P_r^{.6}}$$

where: $T_{gf} = 1/2 (\beta T_c + T_{WG})$

ρ_{gf} , μ_{gf} , $C_{p_{gf}}$, $P_{r_{gf}}$ are evaluated at P_∞ and T_{gf} .

ρ is evaluated at P_∞ , T_∞ .

$$(4) \quad h_g = C_G \frac{K_f}{X} \left[\frac{\rho_f V X}{\mu_f} \right]^{\text{REYEXP}} \left[\frac{\mu_f C_{p_f}}{K_f} \right]^{\text{PRLEXP}}$$

evaluated at the Eckert reference temperature

$$T_f = .5 (T_{wg} + T_{fs}) + .22 \text{Pr}_f^{1/3} (T_o - T_{fs})$$

in which: X = Nozzle contour distance from core

T_{fs} = free-stream temperature

T_o = chamber temperature

(5) h_g = Direct table look up as a function of station location from the TANG input array.

If flow rate $\dot{W}$ changes, the axial length Z_w at which the change occurs will be input. If $Z_w = 0$ then $\dot{W} = \dot{W}_{g_{\text{core}}} = \dot{W}_{g^*}$.

a. If $Z < Z_w$, $\dot{W} = \dot{W}_{g_{\text{core}}}$

b. If $Z \geq Z_w$, $\dot{W} = \dot{W}_{g^*}$

The following table summarizes the options used for the various combinations of HGC and GAS. (Note that internally these are changed to IHGC and IGAS).

VALUE FOR HGC	VALUE FOR GAS	RELATIONSHIP FOR hg	GAS PROPERTIES
1	1	No. 1	NBS equilibrium hydrogen
	2	No. 3	from input tables*
	3	No. 1	NBS parahydrogen
2	1	No. 2	NBS equilibrium hydrogen
	2	"	from input tables*
	3	"	NBS parahydrogen
3	1	Table look up**	Not applicable
	2	"	"
	3	"	"
4	1	No. 4	NBS equilibrium hydrogen
	2	No. 4	from input tables*
	3	No. 4	NBS parahydrogen

* The gas properties input tables are GASMWT, GASRHO, GASMU, GASK and GASCP vs. GAST.

** The heat transfer coefficient table is TAHG vs. TAZ.

C. CALCULATION OF h_r

The coefficient h_r is a function of FEFV which may either be input as a function of axial length or computed by the program.

1. If FEFV is input, linear interpolation is performed to obtain the value at each station.

2. If FEFV is to be computed, it will be input as a negative value. Having already determined station coordinates computation is as follows: (Subscript P refers to previous station)

a. If $Z = 0$, then $F = 1$; if $Z \neq 0$, then

$$E_1 = (R/Z)^2$$

$$E_2 = (Z/R_c)^2$$

$$E_3 = 1 + (1 + E_1)E_2$$

$$F = .5 (E_3 - \sqrt{E_3^2 - 4 E_1 E_2})$$

$$\bar{F} = F - F_p$$

$$\bar{A} = \pi(R + R_p) \sqrt{(Z - Z_p)^2 + (R - R_p)^2}$$

b. Set $\epsilon_0 = .55$ and $\epsilon_1 = 1$ if not input

$$G_o = \left[\frac{1}{\bar{F}} + \left(\frac{1}{\epsilon_0} - 1 \right) + (\pi R_c^2 \sqrt{\bar{A}}) \left(\frac{1}{\epsilon_1} - 1 \right) \right]^{-1}$$

$$G_1 = G_o \pi R_c^2 / \bar{A}$$

$$FEFV = G_1 (T_o^4 - T_{WG}^4) / (\beta^4 T_c^4 - T_{WG}^4)$$

3. Compute h_r

$$h_r = (3.3 \times 10^{-15}) FEFV (\beta^4 T_c^4 - T_{WG}^4) / (\beta T_c - T_{WG})$$

D. THERMAL CONDUCTIVITY OF TUBE WALL

Various materials may be used for tube construction, each of which has its own curve of conductivity as a function of temperature. Tables for two materials, stainless steel and Hastelloy X, are built into the program (values are listed in Appendix D); however, provision has been made to input tables representing any other material. Interpolation for the conductivity is made at the mean temperature T_M :

$$T_M = .5[(h_g + h_r)(T_{WG} - \beta T_c) \frac{t_c}{k_c} (r_g + t_c)/(r_g + .5 t_c) + T_{WG} + T_{WL}]$$

E. OVERALL HEAT TRANSFER COEFFICIENT

1. Cryogenic

The coefficient U based on inside wall surface area is given by:

$$U = \{ [1/(h_g + h_r)](r_g - t_m)/(r_g + t_c) + (t_c/k_c)(r_g - t_m)/(r_g + .5 t_c) + (t_m/k_m)(r_g - t_m)/(r_g - .5 t_m) + 1/h_l \}^{-1}$$

2. Non-Cryogenic

For cylindrical wall type:

$$U = \left\{ \frac{(r_g - t_m)}{k_c} \ln \frac{r_g + t_c}{r_g} + \frac{1}{h_g + h_r} \frac{r_g - t_m}{r_g + t_c} + \frac{r_g - t_m}{k_m} \ln \frac{r_g}{r_g - t_m} + \frac{1}{h_l} \right\}^{-1}$$

For flat wall type:

$$U = \left\{ \frac{1}{h_g + h_r} + \frac{t_m}{K_m} + \frac{t_c}{K_c} + \frac{1}{h_l} \right\}^{-1}$$

F. HEAT FLUX, INSIDE

The heat flux based on inside surface area is:

$$q/A = U(\beta t_c - T_b)$$

G. COMPUTATION OF WALL TEMPERATURES

1. Cryogenic

$$T_{WGC} = q/A \left\{ (t_c/K_c)(r_g - t_m)/(r_g + .5 t_c) + (t_m/K_m)(r_g - t_m)/(r_g - .5 t_m) + \frac{1}{h_l} \right\} + T_b$$

$$T_{WLC} = q/A(1/h_l) + T_b$$

$$T_{WM} = q/A \left\{ (t_m/K_m)(r_g - t_m)/(r_g - .5 t_m) + 1/h_l \right\} + T_b$$

2. Non-Cryogenic

For cylindrical wall type:

$$T_{WGC} = q/A \left\{ \frac{(r_g - t_m)}{K_m} \ln \left(\frac{r_g}{r_g - t_m} \right) + \frac{(r_g - t_m)}{K_c} \ln \left(\frac{r_g + t_c}{r_g} \right) + \frac{1}{h_l} \right\} + T_b$$

$$T_{WLC} = q/A(1/h_l) + T_b$$

$$T_{WMC} = q/A \left\{ \frac{(r_g - t_m)}{K_m} \ln \left(\frac{r_g}{r_g - t_m} \right) + \frac{1}{h_l} \right\} + T_b$$

For flat wall type:

$$T_{WGC} = q/A \left\{ \frac{t_m}{K_m} + \frac{t_c}{K_c} + \frac{1}{h_l} \right\} + T_b$$

$$T_{WLC} = q/A(1/h_l) + T_b$$

$$T_{WMC} = q/A \left\{ \frac{t_m}{K_m} + \frac{1}{h_l} \right\} + T_b$$

In the non-cryogenic case, whenever $T_{WLC} > T_{SAT} + K$, then T_{WLC} is set equal to $T_{SAT} + K$ and the overall heat transfer coefficient and the above temperatures are recomputed as follows:

For cylindrical wall type:

$$U = \left\{ \frac{(r_g - t_m)}{K_c} \ln \left(\frac{r_g + t_c}{r_g} \right) + \frac{(r_g - t_m)}{K_m} \ln \left(\frac{r_g}{r_g - t_m} \right) + \frac{1}{h_g + h_r} \left(\frac{r_g - t_m}{r_g + t_c} \right) \right\}^{-1}$$

$$q/A = U(\beta t_c - T_{WLC})$$

$$T_{WGC} = q/A \left(\frac{r_g - t_m}{K_m} \right) \ln \left(\frac{r_g}{r_g - t_m} \right) + T_{WLC}$$

$$T_{WMC} = q/A \left(\frac{r_g - t_m}{K_m} \right) \ln \left(\frac{r_g}{r_g - t_m} \right) + T_{WLC}$$

For flat wall type:

$$U = \left\{ \frac{t_c}{K_c} + \frac{t_m}{K_m} + \frac{1}{h_g + h_r} \right\}^{-1}$$

$$q/A = U(\beta t_c - T_{WLC})$$

$$T_{WGC} = q/A \left(\frac{t_m}{K_m} \right) + T_{WLC}$$

$$T_{WMC} = q/A \left(\frac{t_m}{K_m} \right) + T_{WLC}$$

H. HEAT FLUX, OUTSIDE

The heat flux based on outside surface area is:

$$q/A_o = (h_g + h_r)(\beta T_c - T_{WGC})$$

I. SURFACE AREA BETWEEN STATIONS

1. c is set equal to .8 unless input.
2. Compute area (subscript P refers to value at previous station) by:

$$A_s = \frac{\pi}{2} \epsilon [(r_g^* t_c) + (r_g^* t_c)_P] |X - X_P|$$

J. HEAT INPUT TO COOLANT BETWEEN STATIONS

$$q = \left[1/2(q/A_o + q/A_{oP}) \right] A_s N_{MB}$$

K. COOLANT BULK TEMPERATURE

1. Obtain C_p at P, T_b

2. Compute average temperature, density, and specific heat between stations (subscript P refers to value at previous station).

$$\bar{T}_b = .5(T_b + T_{bP})$$

$$\bar{\rho} = .5(\rho_b + \rho_{bP})$$

$$\bar{C}_p = .5(C_p + C_{pP})$$

3. Obtain ρ' at P, T_{bP}

4. Compute T_{bc}

a. At Station No. 1:

$$T_{bc} = T_{b_{in}} - v^2 / (2gJ\bar{C}_p)$$

b. At other Stations:

$$T_{bc} = T_{bP} + q / (\dot{w} \bar{C}_p) - (v^2 - v_P^2) / (2gJ \bar{C}_p)$$

$$- \left[1/\rho' - \bar{T}_b \left(\frac{1}{\rho} - \frac{1}{\rho_P} \right) / (T_b - T_{bP}) \right] (P - P_P) / (\bar{C}_p J)$$

c. When $T_b = T_{bP}$, then

$$T_{bc} = T_{bP} + q/(\dot{w} \bar{C}_p) - (v^2 - v_p^2)/(2g J \bar{C}_p)$$

L. Compute new value of coolant pressure in subroutine CALCTP. Pressure loss is composed of friction losses and momentum losses. (Cryogenic Case)

1. At Station No. 1

a. Friction loss: $p_f = 0$.

b. Momentum loss. Set $K_1 = 1.0$ and $C_1 = 0.0$
unless input.

$$p_v = \{K_1 + C_1 [1.895 (A_f/A_1) - 4 (A_f/A_1)^{1/2} + 2.105] 1/(A_f/A_1)^2\} \\ (\rho_b v^2/2g)$$

2. Intermediate Stations

a. Friction loss. A friction factor is computed by one of the relationships shown in (1) (2) or (3) depending on the value of the input flag, FRIC, and is modified depending upon the value of the input flag K5S.

(1) If e is input:

$$f = 0.001375 [1 + 2 \times 10^4 e/d_e + \mu_b \times 10^6/v d_e \rho_b)^{1/3}]$$

(2) If e is not input and $FRIC = 1$

$$f = 0.5 [2.54 \log_{10} (v d_e \rho_b/\mu_b) - 2.17]^{-2}$$

(3) If e is not input and $FRIC = -1$ the M.F. Taylor equation is used

$$f = 2 \left[.0007 + \frac{.0625}{Re_{WL}^{.32}} \right] \left[\frac{T_b}{T_{WL}} \right]^{0.5}$$

where the subscript WL refers to properties evaluated at the liquid (coolant) side wall temperature.

This correlation was developed for surface Reynolds numbers (properties based on coolant-side wall temperature T_{w1}) of 3000 and greater and for the wall temperature-to-bulk temperature ratio between .35 and 7.35. Taylor has matched NRX-A6 full power pressure drop measurements. By employing his friction factor correlation over the heated surface of the coolant tube (semi-circular portion of U-tube) and employing a standard coolant bulk temperature-referenced friction factor over the unheated tube surface (legs and base of U-tube). This procedure is implemented by means of an effective friction factor, which is defined as:

$$f_{\text{eff}} = f_b \left(\frac{S_b}{S_b + S_c} \right) + f_c \left(\frac{S_c}{S_b + S_c} \right)$$

where:

f_{eff} = effective friction factor

f_b = friction factor referenced at coolant bulk temperature

f_c = Taylor's friction factor correlation referenced at tube temperature

S_b = surface area at coolant bulk temperature (legs and base of U-tube)

S_c = surface area at tube crown temperature (semi-circular portion of U-tube)

4. Any of the three expressions for straight tube friction factor may be modified to account for the effect of curvature by applying Ito's correction factor.

$$(f_{\text{eff}})_{\text{curved tube}} = (f_{\text{eff}})_{\text{straight tube}} \left[Re_b \left(\frac{d_E}{2R_c} \right)^2 \right]^{0.5}$$

If Z_d and Z_u are downstream and upstream tangent points, for $Z_u \leq Z < Z_d$ the friction factor is modified. When $Z^* \leq Z < Z_d$, $R_c = R_d$; when $Z_u \leq Z < Z^*$, $R_c = R_u$. This correction is made whenever $K5S = 1$.

5. Compute p_f

$$p_f = \frac{\rho_b v_p^2}{2g} \left[\left(\frac{M}{A_f} \right)_{eff} \frac{x - x_p}{\bar{d}_e} + 2K6 \frac{T_b - T_{bp}}{\bar{T}_b} \right]$$

b. Momentum loss

(1) Compute momentum loss by:

$$p_v = \rho_b (v^2 - v_p^2) / (2g)$$

$$p_v = [\rho_b A_f v^2 - (\rho_b A_f v_p^2)] / [0.5 (A_f + A_{fp}) g]$$

(2) If a discontinuity occurs in N_{mb} , momentum loss is computed as follows.

(a) For $N_{mb} < N_{mbp}$

$$p_v = (1 - A_{fp}/A_f)^2 (\rho_b v_p^2) / (2g)$$

(b) For $N_{mb} > N_{mbp}$

$$p_v = [1.895 (A_f/A_{fp}) - 4 (A_f/A_{fp})^{1/2} + 2.105] (\rho_b v_p^2) / (2g)$$

3. The computed pressure is given by:

$$p_{rc} = p_p - p_f - p_v$$

4. After the last station, the coolant has an additional loss through the discharge passage. If not input, set $K_3 = 1.0$, $K_4 = 1.0$ and Compute outlet pressure in subroutine out by:

$$p_{out} = p_{ns} - \left\{ K_3 + C_2 \left[\frac{K_4 + 1.895 \frac{A_2}{A_f} - 4 \frac{A_2}{A_f}^{1/2} + 2.105}{(A_2/A_f)^2} \right] \right\} \frac{\rho_b v_{ns}^2}{2g}$$

M. COMPUTATION OF COOLANT PRESSURE FOR THE NON-CRYOGENIC CASE

All calculations are done the same as for the cryogenic case.

N. STRESS CALCULATION

After convergence, values of hoop stress and safety factor in the tube wall at each station are computed.

1. Stress is computed by:

$$\sigma = Pr_g / t_m$$

2. Tables of yield stress for stainless steel and Hastelloy X are listed in Appendix E and are built into the program. Provision for card input of stress vs temperature has been made in the event other materials are used. Interpolation for yield stress is made as a function of T_{WM} . A safety factor is computed as follows:

$$F.S. = (\sigma_{yp}) / \sigma$$

VII. OPTIONAL LEG HEIGHT ITERATION

For design cases, leg height of the tube is unknown. However, a profile of T_{wg} as a function of axial length can be input and an altered sequence of computation followed.

- A. Compute FEFV, β , h_r , h_g , and q/A_o as normally
- B. Set T_{wgc} equal to T_{wg}

C. Compute:

$$q/A = (q/A_o) (r_g / (r_g - t_m))$$

$$q/A_m = (q/A_o) (r_g / (r_g - 0.5 t_m))$$

$$k' = t_m (q/A_m)$$

D. Interpolate for k_{wg} at T_{wg}

E. Compute

$$k_m = 0.5 (\sqrt{k_{wg}^2 - 2.4 \times 10^{-7} k' + k_{wg}})$$

$$T_{wlc} = T_{wg} - (q/A) (t_m / k_m) (r_g - t_m) / (r_g - 0.5 t_m)$$

$$h_1 = (q/A) / (T_{wlc} - T_b)$$

$$T_{w1} = T_{wlc}$$

$$C = [h_1 / (C_L k_{cf}) (1 + 0.01457 \mu_w \rho_b / \mu_b \rho_w)]^{1.25}$$

$$(\rho_{cf} / \mu_{cf})^{-1} Pr_{cf}^{-0.5}$$

F. Solve the following equation for ℓ :

$$C = \frac{\dot{w}}{N_{mb} \rho_b} \frac{[0.25 (\pi + 2) (r_g - t_m) + 0.5 \ell]^{0.25}}{[0.5 \pi (r_g - t_m)^2 + 2 (r_g - t_m) \ell]^{1.25}}$$

G. ℓ must be positive. If negative, set $\ell = 0$.

H. Compute: $A_f = 0.5 \pi (r_g - t_m)^2 + 2 (r_g - t_m) \ell$

$$d_e = 4 A_f / [(\pi + 2) (r_g - t_m) + 2 \ell]$$

I. Compute v , M , U , T_{wm} , q , T_{bc} , and p_{rc} as normally.

J. If convergence is not attained, increment T_{wg} by 100° and reiterate.

VIII. OPTIONAL C_g CALCULATION

For analysis of data, it is desirable to have the capability to compute the C_g that results in a given T_{wg} . In this instance T_{wg} is input as a function of axial length and calculation proceeds normally for FEFV, β , h_r and h_l . Alternate calculations are then made as follows.

A. Compute T_m : $T_m = 0.5 (T_{wg} + T_{wl})$

B. Interpolate for $k_m = f(T_m)$.

C. Compute:

$$q/A = (T_{wg} - T_b) / [(t_m/k_m)(r_g - t_m)/(r_g - 0.5 t_m) + 1/h_l]$$

$$q/A_o = (q/A)(r_g - t_m)/(r_g)$$

D. Compute T_{wlc} : $T_{wlc} = T_b + (q/A)(1/h_l)$

E. Set $T_{wgc} = T_{wg}$ and compute T_{wm} , q , T_{bc} , and p_{rc} as normally, and iterate on T_{wl} , T_b , and p . In case of non-convergence, stop.

F. When converged, compute h_g : $h_g = (q/A_o) / (\beta T_c - T_{wg})$

G. Compute U as normally and solve the Bartz equation for C_g :

$$C_g = h_g (\pi D^{2.25} \rho / 4 \dot{W} \rho_{gf}) (Pr^{0.6} / \mu^{0.2} C_p)_{gf}$$

IX. COMPUTATION OF BURNOUT HEAT FLUX RATIO

A. Burnout value of heat flux.

1. If $P > P_{crit}$

$$Q_{Bo} = h_l (T_{crit} - T_b)$$

2. If $P \leq P_{crit}$ and $IRBO = 1$

$$Q_{Bo} = C_1 v^{K1}$$

3. If $P \leq P_{crit}$ and $IRBO = 2$ and $VDT > VDTC$ where
 $VDT = V(T_{SAT} - T_b)$, then:

$$Q_{Bo} = [A_2 + B_2 v^{N_2} \frac{(T_{SAT} - T_b)}{B_3}^{M_2}] F_T F_P$$

4. If $P \leq P_{crit}$, $IRBO = 2$ and $VDT \leq VDTC$, then:

$$Q_{Bo} = [A_1 + B_1 v^{N_1} (T_{SAT} - T_b)^{M_1}] F_T F_P$$

- B. Burnout heat flux ratio:

$$R_{Bo} = \frac{|q/A_i|}{Q_{Bo}}$$

X. The following data is computed after completion of a run. These are printed after the output from the last station.

- A. Outlet pressure, See Paragraph VIII,L,4.

- B. Outlet (mix) temperature.

1. Look up H_{out} at p_{out} , T_{bns} and H_{in} at p_{in} , T_{in} .

2. Compute H_{mix} by:

$$H_{mix} = [\dot{w} H_{out} + \dot{w}_{bc} (H_{bc} + H_{in})] / (\dot{w} + \dot{w}_{bc})$$

3. Look up T_{mix} at p_{out} , H_{mix}

- C. Pressure drop. Compute Δp by: $\Delta p = p_{in} - p_{out}$

- D. Temperature rise. Compute ΔT by: $\Delta T = T_{mix} - T_{in}$

NOMENCLATURE

<u>Engineering Symbol</u>	<u>Definition</u>	<u>Program Symbol</u>
A	Cross-sectional area of nozzle, in. ²	AA
$\bar{A}$	Total surface area between stations, in. ²	ABAR
A _e	Cross-sectional area of nozzle, exit, in. ²	AE
A _f	Cross-sectional area of single tube, in. ²	AF, AFP
A _s	Surface area of single tube, in. ²	AS
A ₁	Area of inlet passage, in. ²	AL
A ₂	Area of outlet passage, in. ²	AO
A*	Throat area, in. ²	ASTAR
a	Sonic velocity of coolant, in./sec	AV
b	Spread of U-tube legs, in.	B
C	Constant used in solution for leg height	CL
C _g	Coefficient in gas-side heat transfer coefficient equation	CG
C _L	Coefficient in coolant-side heat transfer coefficient equation	CL
C ₁ , C ₂	Constants used in computing pressure drop	CC1, CC2
C _p	Specific heat at constant pressure, Btu/lb-°R	CP
$\bar{C}_p$	Mean value of C _p between stations, Btu/lb-°R	CPBAR
C _p gf	C _p evaluated at T _{gf} , Btu/lb-°R	CPGF
D	Nozzle diameter, in.	D
d	Undeformed tube diameter, in.	SMALD
d _e	Equivalent diameter of coolant tube, in.	DE
d _s	Slotted passage height	DS
E ₁ , E ₂ , E ₃	Factors used in computing FEFV	E1, E2, E3
e	Surface roughness of coolant passage, in.	E
F	Shape factor	F, FP
$\bar{F}$	Shape factor	FBAR
FEFV	Radiation factor	FEFV
F.S.	Factor of safety	FS
f	Friction coefficient	FC
G ₀ , G ₁	Gray-body shape factor	GO, G1

Engineering Symbol	Definition	Program Symbol
g	Acceleration due to gravity, 386.088 in./sec ²	G
H	Enthalpy, Btu/lb	H
H_{bc}	Enthalpy of bolt coolant, Btu/lb	HBC
H_c	Enthalpy at P_c , T_c , Btu/lb	HC
H_{in}	Enthalpy at P_{in} , T_{in} , Btu/lb	HIN
H_{mix}	Enthalpy at P_{out} , T_{mix} , Btu/lb	HMIX
H_{out}	Enthalpy at P_{out} , T_{out} , Btu/lb	HOUT
h_g	Gas-side heat-transfer coefficient, Btu/in. ² -sec-°R	HG
h_l	Coolant-side heat-transfer coefficient, Btu/in. ² -sec-°R	HL, HL1
h_r	Radiation heat-transfer coefficient, Btu/in. ² -sec-°R	HR
J	Mechanical equivalent of heat, 9339.12 in.-lb/Btu	J
K_1, K_3, K_4, K_5, K_6	Constants used in computing pressure drop	K_1, K_3, K_4, K_5, K_6
k	Thermal conductivity, Btu/in.-sec-°R	
k_c	k of tube coating, Btu/in.-sec-°R	KC
k_{cf}	k evaluated at T_{cf} , Btu/in.-sec-°R	KCF
k_m	k of tube wall, Btu/in.-sec-°R	KM, KMP
k_{wg}	k evaluated at T_{wg} , Btu/in.-sec-°R	KWG
k'	Factor defined in Paragraph IX,C.	KFAC
$\underline{l}$	Tube leg-height, in.	L
M	Mach number of coolant	MC
MR	Mixture ratio	MR
N_{mb}	Number of tubes through which coolant flows	NMB
N_t	Total number of tubes	NT
N'_6	Number of station segments between nozzle exit and downstream point of tangency	N6P
N'_5	Number of station segments between downstream point of tangency and throat	N5P
N'_4	Number of station segments between throat and upstream point of tangency	N4P
N'_3	Number of station segments between upstream point of tangency and covergency point of tangency	N3P

<u>Engineering Symbol</u>	<u>Definition</u>	<u>Program Symbol</u>
N'_2	Number of station segments in knuckle	N2P
N_i	Number of station segments in barrel section	N1P
P	Static pressure of combustion gases, psia	PSC
P_c	Chamber pressure, psia	PC
P_∞	Gas pressure at location defined by Z	PG
PFM	Pressure multiplier	PFM
Pr	Prandtl number = $\frac{\mu c_p}{k}$	
Pr_{cf}	Pr evaluated at T_{cf}	PRCF
Pr_{gf}	Pr evaluated at T_{gf}	PRGF
p	Static pressure of coolant, psia	P, PP
P_D	Dynamic pressure change	PD
P_f	Pressure loss due to friction, psi	PF
P_{in}	Inlet pressure, psia	PIN
P_{ns}	p at last station, psia	PLS
P_{out}	p at discharge plenum, psia	POUT
P_{rc}	Computed value of p, psia	PRC
P_v	Pressure loss due to momentum, psi	PV
q	Heat transferred to coolant between stations, Btu/sec	Q
q/A	Heat flux based on inside surface area, Btu/in. ² /sec	QOA
q/A _m	Heat flux based on mean metal area, Btu/in. ² -sec	QOAM
q/A _o	Heat flux based on outside surface area, Btu/in. ² -sec	QOAO
R	Radius of nozzle, in.	R
R_c	Radius of barrel section, in.	RC
R_d	Downstream radius of curvature, in.	RD
R_n	Radius at point in divergent section, in.	RN
R_u	Upstream radius of curvature, in.	RU
R_β	Convergent radius, in.	RB
R^*	Throat radius, in.	RSTAR

<u>Engineering Symbol</u>	<u>Definition</u>	<u>Program Symbol</u>
R'	Radius of curvature, in.	RCV
r_a	Ambient-side tube radius, in.	SMALRA
r_g	Gas-side tube radius, in.	SMALRG, SMALRGP
S	Entropy, Btu/lb	
S_c	S at P_c , T_c , Btu/lb	SC
s	Tube circumference, in.	S
T_b	Temperature of coolant, °R	TB, TBP
T_{bc}	TB calculated	TBC
T_c	Chamber temperature, °R	TC
T_{cf}	Reference temperature of coolant, °R	TRCF
T_{fi}	Temperature of film coolant, °R	TCF
T_{gf}	Reference temperature of gas, °R	TGF
T_{in}	Coolant inlet temperature, °R	TIN
T_m	Mean wall temperature, °R	TM
T_{mix}	Temperature of nozzle and bolt coolant mixture, °R	TMIX
T_{wg}	Temperature of gas wall, °R	TWG
T_{wgc}	Computed value of T_{wg} , °R	TWGC
T_{wl}	Temperature of coolant wall, °R	TWL
T_{wlc}	Computed value of T_{wl} , °R	TWLC
T_{wm}	Temperature of metal-coating interface, °R	TWM
T_o	Temperature of core face, °R	TO
T_∞	Gas temperature at location specified by Z , °R	TINFIN
T_b	Mean coolant temperature between stations, °R	TBAR
t_c	Coating thickness, in.	SMALTC
t_m	Metal thickness, in.	SMALTM
t_s	Space thickness, in.	SMALTS
UW	Dimension in land and groove U tube configuration	UW
UL	Dimension in land and groove U tube configuration	UL
U	Overall heat-transfer coefficient, Btu/in. ² -sec-°R	U
V	Gas velocity, in./sec	V
V_f	Velocity of injected film coolant, in./sec	VF
v	Coolant velocity, in./sec	VC, VP

Engineering Symbol	Definition	Program Symbol
v_{ns}	Coolant velocity at last station, in./sec	VNS
W	Slotted passage width	W, WP
$\dot{W}$	Gas flow rate, lb/sec	WG
$\dot{W}_{gcore}$	Gas flow from core, lb/sec	WGCORE
$\dot{W}_g^*$	Gas flow through throat, lb/sec	WGSTAR
$\dot{w}$	Coolant flow rate, lb/sec	WC
$\dot{w}_{bc}$	Bolt-coolant flow, lb/sec	WBC
$\dot{w}_f$	Film coolant flow, lb/sec	WF
X	Developed length, in.	X, XP
X'	Developed length for initial rise in T_{fi} , in.	XI
Z	Axial length, in.	Z, EP
Z_b	Barrel length, in.	ZB
Z_d	Z to downstream point of tangency, in.	ZD
Z_g	Overall length, in.	ZOL
Z_n	Axial length from throat of point in divergent section, in.	ZN
Z_u	Z to upstream point of tangency, in.	ZU
Z_w	Z to location of change in $\dot{W}$, in.	ZW
Z^*	Axial length to throat, in.	ZSTAR
α	Angle in truncated tube description	ALPHA
α_a	Divergence angle, degrees	ALPHA A
β	Factor defining temperature recovery and/or film cooling	BETA
β_a	Convergence angle, degrees	BETA A
γ_c	Ratio of specific heats at chamber conditions	
ϵ	Heated area factor	EPGEOM
ϵ_0	Emissivity of core face	EPO
ϵ_1	Emissivity of tube wall	EPL
μ	Absolute viscosity, lb/in.-sec	
μ_b	μ evaluated at T_b , lb/in.-sec	MUB
μ_{cf}	μ evaluated at T_{cf} , lb/in.-sec	MUCF

<u>Engineering Symbol</u>	<u>Definition</u>	<u>Program Symbol</u>
μ_{gf}	μ evaluated at T_{gf} , lb/in.-sec	MUGF
μ_w	μ evaluated at T_{w1} , lb/in.-sec	MUW
ρ	Density, lb/in. ³ $A_T T_\infty P_\infty$	RHO
ρ_b	ρ evaluated at T_b , lb/in. ³	RHOB, RHOBP
ρ_{cf}	ρ evaluated at T_{cf} , lb/in. ³	RHO CF
ρ_{gf}	ρ evaluated at T_{gf} , lb/in. ³	RHO GF
ρ_w	ρ evaluated at T_{w1} , lb/in. ³	RHO W
$\bar{\rho}$	Mean value of ρ between stations, lb/in. ³	RHOBAR
ρ'	ρ at previous station, lb/in. ³	RHOP
σ	Stress, lb/in. ²	STR
σ_{yp}	Yield stress, lb/in. ²	STRY
θ	Angle in truncated tube description	THETA

FIGURE 1
NOZZLE SYMBOLS

2. U-TUBE

FIGURE 2

3. TRUNCATED

FIGURE 3

4. ROUND OR FLATTENED

FIGURE 4

5. SLOTS

FIGURE 5

HEAT TRANSFER (NON-CRYOGENIC & CRYOGENIC)

Iteration Technique

To obtain new guesses for the variables, a set of simultaneous equations is solved for $\epsilon_1, \epsilon_2, \dots, \epsilon_n$. These are then added to the old guesses to form the new guesses.

Given variables $y_1, y_2, \dots, y_n$ as functions of $x_1, x_2, \dots, x_n$, set up the set of simultaneous equations

$$\frac{\partial y_1}{\partial x_1} \epsilon_1 + \frac{\partial y_1}{\partial x_2} \epsilon_2 + \frac{\partial y_1}{\partial x_3} \epsilon_3 + \dots + \frac{\partial y_1}{\partial x_n} \epsilon_n = y_1 - y_1^0$$

$$\frac{\partial y_2}{\partial x_1} \epsilon_1 + \frac{\partial y_2}{\partial x_2} \epsilon_2 + \frac{\partial y_2}{\partial x_3} \epsilon_3 + \dots + \frac{\partial y_2}{\partial x_n} \epsilon_n = y_2 - y_2^0$$

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$$\frac{\partial y_n}{\partial x_1} \epsilon_1 + \frac{\partial y_n}{\partial x_2} \epsilon_2 + \frac{\partial y_n}{\partial x_3} \epsilon_3 + \dots + \frac{\partial y_n}{\partial x_n} \epsilon_n = y_n - y_n^0$$

In our special case $y_1 = x_1 - x_{1c}$, $y_2 = x_2 - x_{2c}$, $\dots$, $y_n = x_n - x_{nc}$ where the subscript c denotes the computed value. Since we want the guessed values (i.e., $x_1, x_2, \dots, x_n$) to equal the computed values ($x_{1c}, x_{2c}, \dots, x_{nc}$) the y_i are set to zero.

The partials are approximated by the following method:

$$\frac{\partial y_1}{\partial x_1} = \frac{y_1 \Delta x_1 - y_1^0}{\Delta x_1}$$

$$\frac{\partial y_1}{\partial x_2} = \frac{y_1 \Delta x_2 - y_1^0}{\Delta x_2}$$

$$\frac{\partial y_1}{\partial x_n} = \frac{y_1 \Delta x_n - y_1^0}{\Delta x_n}$$

where the Δx_i are all an arbitrary small percentage of the x_i , and

$$y_1 \Delta x_1 = y_1(x_1 + \Delta x_1, x_2, x_3, \dots, x_n)$$

$$y_1 \Delta x_2 = y_1(x_1, x_2 + \Delta x_2, x_3, \dots, x_n)$$

$$y_1 \Delta x_n = y_1(x_1, x_2, x_3, \dots, x_n + \Delta x_n)$$

The program works in the following manner: Set up the equations (1) by columns. The first time through the program gives the values of y_0 for the constant terms. The second time through the program, change x_1 to $x_1 + \Delta x_1$ which results in the values for column one of the equations. The third time through change $x_1 + \Delta x_1$ back to x_1 and change x_2 to $x_2 + \Delta x_2$ to set up column two. This repeats until the equations are set up. Then the system is solved, the ϵ_i are added to the x_i to give new guesses, and the whole procedure is repeated until the y_1^0 are equal to zero (plus or minus a set limit of convergence).

APPENDIX C

Tables of Pressure Ratio

Fixed values of P_c/P to be used in setting up tables of T_∞ , P are:

1.0	20.0	500.0
1.1	30.0	750.0
1.2	50.0	1000.0
1.3	75.0	1500.0
1.4	100.0	2000.0
1.6	150.0	2500.0
2.0	200.0	3000.0
5.0	300.0	3500.0
10.0	400.0	4000.0

APPENDIX D

Conductivity Tables

Values of thermal conductivity as a function of temperature are:

<u>Material</u>	<u>Temperature, °R</u>	<u>Conductivity (Btu/in.-sec-°R)</u>
Hastelloy X	530	0.000130
	660	0.000147
	960	0.000189
	1060	0.000193
	1460	0.000263
	1560	0.000277
	1760	0.000306
	1960	0.000335
	2160	0.000364
Stainless Steel	210	0.000165
	260	0.000169
	360	0.000178
	528	0.000195
	660	0.000209
	860	0.000227
	1060	0.000248
	1260	0.000267
	1460	0.000287
	1660	0.000306
	1860	0.000327
	2060	0.000345
	2100	0.000348
	2250	0.000361
	2450	0.000380
	2625	0.000394
	2775	0.000408

APPENDIX E

Yield Stress Tables

Values of yield stress as a function of temperature are:

<u>Material</u>	<u>Temperature, °R</u>	<u>Yield Stress</u> <u>psi</u>
Hastelloy X	260	63000
	460	48000
	560	44000
	760	39000
	960	36000
	1160	34000
	1660	32000
	1860	29000
	2160	16000
	2360	10000
Stainless Steel	2560	5000
	60	57000
	160	46000
	260	38000
	360	34000
	460	31000
	660	28000
	1060	23000
	1460	19000
	1760	18000
	1960	14000
	2210	6000
	2460	3000

ENCLOSURE (2)

N8110R:72-030

ENGINEERING OPERATIONS REPORT

CORRELATION OF NRX-A5 AND NRX-A6
TECHNOLOGY NOZZLE TEST DATA WITH
CALCULATED PERFORMANCE

PROJECT 141, WORK STATEMENT 9c

FEBRUARY 1972

J. J. WILLIAMS

JJ Williams

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CLASSIFYING OFFICER	DATE

K. Sato
K. SATO, MANAGER
ENGINEERING STAFF DEPARTMENT

CORRELATION OF NRX-A5 AND NRX-A6
TECHNOLOGY NOZZLE TEST DATA WITH
CALCULATED PERFORMANCE

I. INTRODUCTION/SUMMARY

Calculations were made to determine factors to use with the Nozzle Heat Transfer Program (E25107) in order to model the NERVA 75K engine. The approach taken was to correlate NERVA Technology Nozzle data to the selected theoretical models and determine the appropriate correlation factors. This is an extension of the work reported in Reference (a) and sections of that report will be repeated here, in order to consolidate final major results in one report.

Early scale model heat transfer tests of the Technology Nozzle configuration are reported in References (b), (c), (d), (e) and (f). Data from these tests indicated that the heat transfer coefficients in the barrel and convergent section of the nozzle were much higher than predicted by conventional methods of calculation for chemical rocket nozzles such as References (g) and (h). This effect has also been observed in scale model tests of other nuclear nozzle configurations (References (i), (j), (k), and (l)). It is due to the fact that a conventional boundary layer does not begin to develop just aft of the reactor core, but rather there is a deceleration and coalescing of the many discrete jets of gas issuing from the core into the nozzle chamber. This effect necessitates recourse to empiricism in characterizing the nozzle gas-side heat transfer.

Also, advances have been made in the fields of fluid mechanics and heat transfer that pertain to the method employed in developing the models for liquid side heat transfer and pressure drop. As a consequence of these developments it was appropriate to update the previous model and this was done as part of the work reported in Reference (a). Since that time, however, some additional modifications have been made to the analytical model for liquid side pressure drop and additional test points from technology nozzles NRX-A5 and NRX-A6 were analyzed to determine pressure factor multiplier and heat transfer surface area multipliers. In addition, some minor changes were made in the computer code itself. This report describes the additional work and presents an example calculation for the NERVA 75K engine using the recommended model parameters.

II. TECHNICAL DISCUSSION

A. COMPUTER PROGRAMS EMPLOYED IN DEVELOPMENT OF GAS-SIDE THERMAL MODEL

Two technology nozzles (NRX-A5 and NRX-A6) were modeled on the E25107 regeneratively-cooled nozzle computer program (Reference (m)) by inputting the nozzle geometries (nozzle contours and coolant channel flow areas). This program solves the energy and momentum equations for a fluid flowing through a channel subjected to convective and radiative heat transfer. The major options employed in the model are summarized below.

1. Coolant-side Heat Transfer Coefficient

J. O. Sane and D. W. Lunsford, previously of ANSC, examined 2230 points of hydrogen heat transfer data in the specific operating range of the NERVA nozzle and derived a new coolant-side correlation (Reference (n)). This correlation has been utilized in the new model:

$$\text{Nu}_{\text{straight tube}} = .00821 \text{ Re}_f^{.874} \text{ Pr}_f^{.4} \left(1 + .0146 \frac{\mu_w \rho_b}{\mu_b \rho_w}\right)^{.622}$$

A factor that accounts for entrance effects is multiplied times this expression and takes the following forms:

$$\text{for } 0 \leq X/D_E < 5.198$$

$$\text{Entrance factor} = 1.8$$

$$\text{for } 5.198 < X/D_E \leq 120$$

$$\text{Entrance factor} = \left(1 + \frac{4.0}{X/D_E}\right)^{1.030}$$

$$\text{for } X/D_E \geq 120 \text{ the entrance factor has attenuated to unity.}$$

A factor that accounts for coolant channel curvature, for the case in which heat transfer exists over the convex surface of the curve (the nozzle throat), is multiplied times the straight tube correlation and takes the following forms:

$$\text{curved tube factor} = \begin{cases} 1 + 1.128 \phi \\ .797 \left[\text{Re}_b \left(\frac{D_E}{2R_c} \right)^2 \right]^{.0785} \\ 2.502 - 1.16 \phi \end{cases}$$

in which ϕ is the angle of curvature in radians.

For the particular value of ϕ , Re_b , and $\frac{D_E}{R_c}$ at a location on a curved tube, the expression above that yields the lowest curved tube factor is utilized.*

2. Friction Factor Correlation

M. F. Taylor (Reference (o)) has correlated frictional pressure drop measurements for helium, hydrogen, nitrogen, air, and carbon dioxide gases flowing through heated tubes by means of the following expression for the diabatic friction factor

$$f = 2 \left(.0007 + \frac{.0625}{\text{Re}_{WL}^{.32}} \right) \left(\frac{T_b}{T_{WL}} \right)^{0.5}$$

This correlation was developed for surface Reynolds numbers (properties based on coolant-side wall temperature T_{WL}) of 3000 and greater and for the wall temperature-to-bulk temperature ratio between .35 and 7.35. Taylor has matched NRX-A6 full power pressure drop measurements (Reference (p)) by employing his friction factor correlation over the heated surface of the coolant tube (semi-circular portion of U-tube) and employing a standard coolant bulk temperature-referenced friction factor over the unheated tube surface (legs and base of U-tube). This procedure is implemented by means of an effective friction factor, which is defined as:

$$f_{\text{eff}} = f_b \frac{S_b}{S_b + S_c} + f_c \frac{S_c}{S_b + S_c}$$

*Nomenclature used in this report is consistent with that used in Reference (m).

in which:

- f_{eff} = effective friction factor
- f_b = friction factor referenced at coolant bulk temperature
- f_c = Taylor's friction factor correlation referenced at tube temperature
- S_b = surface area at coolant bulk temperature (legs and base of U-tube)
- S_c = surface area at tube crown temperature (semi-circular portion of U-tube)

This expression and Taylor's friction factor correlation were added to the E25107 program, which already has a coolant bulk temperature-referenced friction factor correlation:

$$f_b = 0.5 \left[2.54 \log_{10} \left(\frac{V D_E \rho_b}{\mu_b} \right) - 2.17 \right]^2$$

which represents adiabatic flow pressure drop data.

The effect of curvature on the straight tube friction factor was accounted for by applying Ito's correction factor (Reference (q)):

$$(f_{eff})_{\text{curved tube}} = (f_{eff})_{\text{straight tube}} \left[Re_b \left(\frac{D_E}{2R_c} \right)^2 \right]^{0.5}$$

3. Frictional Pressure Drop Calculation

The effect of temperature gradient on pressure drop has been included by modifying the previously used relationship to the following:

$$P_f = \frac{\rho V^2}{2g} \left[(PFM) 4 f_{eff} \frac{|x - x_p|}{d_e} + 2K6 \frac{T_b - T_{b,p}}{\bar{T}_b} \right]$$

where normally $K_6 = 1$ and $PFM = 1$. The inclusion of the temperature term has caused the value of PFM required to match technology nozzle data to decrease from values previously obtained.

4. Entrance and Exit Pressure Drop

The pressure drop resulting from the flow of hydrogen coolant from the inlet manifold through the coolant tube inlet holes and into the coolant tubes and out of the outlet holes was calculated by means of a loss factor for incompressible flow. The equations defining these factors are shown in Reference (m).

The entrance and exit pressure loss factors used for the Technology Nozzles are summarized below:

	K_1 , Entrance Factor	K_3 , Exit Factor
NRX-A5	2.0	1.1
NRX-A6	2.0	1.1

5. Coolant Temperature and Pressure Drop Iteration

The coolant pressure and temperature drop can be input to the nozzle program and it will iterate on the value of a friction factor multiplier PFM and a heat transfer surface area multiplier $EPGEOM$ to match the input values of ΔP and ΔT . This option was employed for the technology nozzle runs by inputting the measured ΔP 's and ΔT 's shown in Table I. The mean value for the pressure multiplier (PFM) was 0.618 and the mean value for the heated area factor ($EPGEOM$) was 0.887. These values were used for the analysis shown in Table 1. The assumed gas side wall temperature distributions for the technology nozzles are those shown in Figures 1 and 2.

6. Hydrogen Properties

Per direction of the Space Nuclear Systems Office the December, 1969, NBS hydrogen properties were incorporated into the nozzle computer program. Para-hydrogen properties were utilized on the coolant-side and equilibrium

hydrogen properties were employed on the gas-side. The question of para to ortho conversion within the NERVA nozzle coolant channels has yet to be resolved at the date of this writing.

B. GAS-SIDE HEAT TRANSFER COEFFICIENT

All theoretical gas side heat transfer coefficients were calculated by the integral boundary layer method described in Reference (r). The option utilized for determination of skin friction coefficient was the method of Coles and the value used for the boundary layer interaction exponent was 0.25.

Another input to the boundary layer code is the value for the ratio of utilized to theoretical skin friction coefficient. This value effects the calculated heat transfer coefficient because the relationship used to obtain Stanton number is a modified Reynolds' analogy.

The appropriate value for the ratio of required to calculated skin friction coefficient was obtained in three steps.

1. The actual total heat transfer coefficient was estimated from NRX-A5 and NRX-A6 test data using the wall temperature distributions shown in Figures 1 and 2 and the heated area factor and pressure multiplier previously determined.

2. A modified version of the integral boundary layer program was used to determine the required values for the ratio. The calculated values are shown on Figure 3.

3. An approximate envelope curve was drawn on Figure 3 and the ratio of actual to theoretical friction coefficient was taken from this curve for all subsequent boundary layer analyses. It is estimated that the high ratio values near the core face result from effects of the discrete jets issuing from the core into the chamber and that these effects are damped by the contraction ahead of the throat. Since the distance from the core face to the start of the contraction is approximately the same for the technology nozzles and the NERVA 75K nozzle, the utilized ratio was taken as a function of length in the initial zone.

In the high Mach number region where the theory is less reliable, the ratio is assumed to be a function of Mach number only. The technology

nozzle Mach number distribution is shown on Figure 4. This profile was calculated as described in Reference (a). The friction coefficient ratio curve shown on Figure 3 is recommended for NERVA 75K engine analyses until more appropriate calculation techniques are developed.

C. EXAMPLE CASE

In order to illustrate use of the developed factors an example case was calculated for the 75K engine using the E25107 computer code.

The first step in the analysis was to calculate the gas side heat transfer coefficient distribution using integral boundary layer code with the factors shown on Figure 3, appropriate chamber conditions, surface Mach number distribution and estimated wall temperatures. The resulting heat transfer coefficient distribution is shown on Figure 5.

This distribution along with the other necessary data were specified for typical 75K engine conditions and the resulting output is shown as Table 2. The calculations predict lower gas-side wall temperatures than previously calculated for similar conditions in the barrel and initial portions of the convergent section. The maximum temperature is approximately 30 degrees lower than previously calculated for similar conditions. The over-all coolant temperature rise and pressure drop is approximately the same as previously calculated.

III. REFERENCES

- ✓ (a) Memorandum N4320:M1648 to J. L. Watkins from R. V. Lundin/J. O. Sane, Subject: "Updated NERVA Gas-Side Heat Transfer Model", dated 4 March 1971
- (b) Scale Model Heat Transfer Tests of the NERVA Nozzle, Aerojet-General Report No. 2221, July 1962 (Confidential/Restricted Data)
- (c) Scale Model Heat Transfer Tests of the NERVA Nozzle, CY 1962, Aerojet-General Report No. 2493, April 1963 (Confidential/Restricted Data)
- (d) Scale Model Heat Transfer Tests of the NERVA Nozzle, CY 1963, Aerojet-General Report No. RN-S-0059, March 1964

(e) Phase I, Experimental Investigation of Heat Transfer to Nuclear Rocket Nozzles Using Shock Tube Techniques, Cornell Aeronautical Laboratory Report No. HM-1650-Y-1, December 1963

(f) Phase II, Experimental Investigation of Heat Transfer to Nuclear Rocket Nozzles Using Shock Tube Techniques, Cornell Aeronautical Laboratory Report No. HM-1650-Y-2, December 1963

(g) D. R. Bartz, "A Simple Equation for Rapid Estimation of Rocket Nozzle Convective Heat Transfer Coefficients", Jet Propulsion, 49, January 1957

(h) D. G. Elliott, D. R. Bartz, and S. Silver, Calculation of Turbulent Boundary Layer - Growth and Heat Transfer in Axi-Symmetric Nozzles, Jet Propulsion Laboratory Technical Report No. 32-387, 15 February 1963

(i) A. Fortini and R. C. Ehlers, Comparison of Experimental to Predicted Heat Transfer in a Bell-Shaped Nozzle with Upstream Flow Disturbances, NASA TN D-1743, August 1963

(j) Aerojet Report RP-TR-0009

(k) J. F. Schmidt, D. R. Boldman, R. C. Ehlers, and J. W. Coats, "Experimental Study of Effect of Simulated Reactor Core Position on Nozzle Heat Transfer", NASA TM X-1208, March 1966

(l) D. R. Boldman, H. E. Neumann, and J. F. Schmidt, "Heat Transfer in 30° and 60° Half-Angle of Convergence Nozzles with Various Diameter Uncooled Pipe Inlets", NASA TN D-4177, September 1967

(m) Technical and Users Manual for Program E25107 Nozzle Heat Transfer, J. J. Williams, dated February 1972

✓ (n) Memorandum 4320:M1616, J. L. Watkins from J. O. Sane, Subject: "NERVA Nozzle Coolant-Side Heat Transfer Correlation", dtd 22 January 1971

(o) Taylor, Maynard F., "A Method of Correlating Local and Average Friction Coefficients for Both Laminar and Turbulent Flow of Gases Through a Smooth Tube with Surface to Fluid Bulk Temperature Ratios From .35 to 7.35", International Journal of Heat and Mass Transfer, Vol. 10, pp 1123-1128

(p) Taylor, Maynard F., "Applications of Variable Property Heat-Transfer and Friction Equations to Rocket Nozzle Coolant Passages and Comparison With Nuclear Rocket Test Results", AIAA Paper No. 70-661, presented at the AIAA 6th Propulsion Joint Specialist Conference, San Diego, California, June 15-19, 1970

(q) Ito, H., "Friction Factors for Turbulent Flow in Curved Pipes", Journal of Basic Engineering, Vol. 81, No. 2, June 1959, pp 123-124

(r) "Computer Program E95213, A Computer Code for Solution of the Integral Boundary Layer Equations", J. J. Williams, December 1969

FIGURE 1

FIGURE 2

CALCULATED GAS SIDE HEAT TRANSFER
COEFFICIENT FOR NUKA 75K ENGINE

FIGURE 5

NUK-75K-72-030

Ratio of Required to Calculated Friction Coefficient

FIGURE 3 - CALCULATED FRICTION COEFFICIENT RATIO

Surface Mach Number

FIGURE 4 - UTILIZED MACH NUMBER DISTRIBUTION FOR NRX-A5 AND A6

TABLE 1

SUMMARY OF DATA USED TO DETERMINE VALUES
FOR HEATED AREA AND PRESSURE DROP FACTORS

NRX A-5 EP-III

Correlation Run	Time Sec	PIN PSIA	TIN °R	WGSTAR lb/sec	WGCORE lb/sec	TAWDOT lb/sec	DPI PSI	DTI °R	Pc PSIA	Tc °R	EPGEOM -	PFM -	Reactor Power M.W.
1	25245-250	257.9	45.0	33.1	33.1	31.9	26.4	29.1	180.9	1919	.5644	.5385	229.7 (1)
2	25395-400	875.2	52.0	71.0	71.0	68.5	140.6	102.9	571.2	4095	.8802	.5708	1116
3	25475-480	857.0	52.2	70.9	70.9	68.4	136.1	97.6	557.5	3939	.8579	.5977	1063
4	25680-685	854.1	52.0	70.7	70.7	68.2	135.7	98.3	554.6	3912	.8625	.5828	1049
5	25900-905	870.7	52.5	71.0	71.0	68.5	140.7	102.4	563.5	4003	.8771	.5579	1084
6	26045-050	870.5	52.7	70.9	70.9	68.4	141.5	102.5	562.5	4004	.8766	.5722	1083
7	26175-180	868.5	52.8	70.8	70.8	68.3	140.5	102.7	561.5	4005	.8776	.5454	1081
8	26247-252	868.6	52.8	70.7	70.7	68.2	140.7	103.4	560.6	4003	.8812	.5368	1079

NRX A-5 EP-IV

9	12935-940	757.5	51.3	70.4	70.4	67.9	115.8	71.5	498.5	3245	.7393	.7522	847.4 (1)
10	12970-975	880.3	52.7	70.2	70.2	67.7	144.8	103.0	569.6	4168	.8730	.7188	1125
11	13000-005	874.7	52.4	70.2	70.2	67.7	143.4	102.2	565.6	4122	.8714	.7103	1111
12	13190-210	875.7	52.2	70.6	70.6	68.1	145.5	103.4	564.1	4048	.8805	.6857	1091
13	13270-275	876.3	52.2	70.5	70.5	68.0	146.1	104.2	563.5	4056	.8844	.6834	1093
14	13540-545	878.2	52.4	70.2	70.2	67.7	150.2	106.2	562.0	4079	.8932	.7318	1099
15	13810-815	876.5	52.0	69.6	69.6	67.1	151.0	109.1	557.9	4118	.9082	.7269	1096

NRX A-6 EP III B

16	14250	790	47.9	67.1	67.1	64.3	112.0	86.7	533.0	3982	.8843	.5854	1022
17	14400	876	49.0	72.5	72.5	69.5	134.0	92.8	580.0	4050	.9074	.6484	1122
18	16200	890	50.0	73.3	73.3	70.3	139.0	97.2	587.0	4060	.9264	.5614	1135
19	17700	901	51.4	73.1	73.1	70.1	141.0	100.3	594.0	4156	.9356	.4880	1170
19a	Repeat of Run 19 except wall temperature increased by 100°R.										.8819	.5169	1170

For 17 Samples $\frac{\text{Mean EPGEOM}}{\text{PFM}} = \frac{.887}{.618}$

(1) Low power runs - neglect.
Wall temperature profile will not match these runs.

PIN Nozzle Inlet Pressure

TIN Nozzle Inlet Temperature

WGSTAR Gas Flow Rate through the Throat

WGCORE Gas Flow Rate from the Core

TAWDOT Coolant Flow Rate

DPI Required Pressure Drop

DTI Required Coolant Bulk Temperature Increase

Pc Chamber Pressure

Tc Chamber Temperature

EPGEOM Heated area factor = ϵ , for calculating surface area between stations,

$$A_s = \frac{\pi}{2} \epsilon [(r_g - t_c) + (r_g - t_c)_p] |x - x_p|$$

PFM Pressure multiplier, for calculating pressure loss due to friction,

$$P_f = \frac{\bar{\rho} \bar{v}^2}{2g} [(PFM) 4 f_{eff} \frac{|x - x_p|}{d_p} + 2K6 \frac{T_b - T_{bp}}{T_b}]$$

J. J. Williams
February 1972

N8110R:72-030

TABLE 2

SAMPLE COMPUTER CODE OUTPUT

NERVA 75K ENGINE -- NOMINAL CASE -- FEB 1972

\$DATU:

SUM = 3.0,
 ITRFL = 50.0 ,FRIC = -1.0 ,WGSTA = 1.0 ,PLC = 11.0 ,
 HGC = 3.000 ,ALL = 0.0 ,MERCRCR = 0.0 ,PC = 450.0 ,
 TC = 4252. ,MR = 0.0 ,WGSTAR = 91.80 ,WGCORE = 91.80 ,
 PIN = 1375.0 ,TIN = 60.70 ,ASTAR = 98.696 ,ZSTAR = 28.528 ,
 TWL = 800. ,TVG = 800. ,COOL = 4.0 ,AASAR = 24.0 ,
 ZETA = 1.0 ,CONTR = 1.0 ,NDL = 5.0 ,NTOT = 40.0 ,
 NC = 1.0 ,Zk = 0.0 ,K1 = 1.00 ,K3 = 1.80 ,
 ZU=24.558,ZD=29.906,RU=5.605,RO=2.802,K5S=1.,
 K4 = 0.0 ,CC2 = 0.0 ,CC1 = 0.0 ,MW = 0.0 ,
 LW = .100 ,
 LHITE (1) = 40*0. ,
 CGITE (1) = 40* 0.0 ,
 TUJE (1) = 40* 4.0 ,
 TVKM (1) = 40* 0.0 ,
 PPFM (1) = 40* 0.618 ,
 EEPGE0(1) = 40* .887 ,
 TASMTS(1)= 40* .010 ,
 LH (1)= 6*.102 , .0937, .0673, .0158, .0040,
 18*.0000, 10*-.100, 2*.0000,
 TAHG=.00313,.00265,.00232,.00210,.00194,.00182,.00177,.00173,.00171,.00171,
 .00173,.00178,.00180,.00203,.00238,.00297,.00415,.00530,.00609,.00624,.00515,
 .00350,.00283,.00215,.00164,.00153,.00100,.00081,.00068,.00060,.00059,.00058,
 .00055,.00051,.00049,.00046,.00043,.00040,.00039,.00035,
 TASMTW(1) = .022, .022, .022, .022, .022,
 .022, .018, .018, .018, .017, .017,
 .017, .016, .016, .015, .015, .014,
 .014, .013, .013, .013, .013, .014,
 .015, .016, .017, .018, .019, .020,
 .021, .022, .023, .024, .025, .026,
 .027, .028, .028, .028, .028,
 TAZ (1) = 00.000, 01.685, 03.370, 05.055, 06.740,
 08.425, 09.875, 11.227, 12.388, 14.408, 15.859,
 17.310, 18.761, 20.212, 21.663, 23.114, 24.565,
 26.415, 28.385, 27.435, 28.528, 29.306, 30.023,
 31.345, 32.758, 33.066, 35.878, 37.933, 40.488,
 42.552, 44.528, 46.418, 50.040, 53.503, 56.846,
 60.123, 63.353, 66.528, 69.677, 72.813,
 TAAF (1) = .0910, .0910, .0910, .0910, .0910,
 .0910, .0929, .1000, .1160, .1320, .1393,
 .1351, .1297, .1164, .1010, .0847, .0672,
 .0467, .0360, .0363, .0534, .0637, .0692,
 .0787, .0894, .0909, .1128, .1305, .1561,
 .1727, .1677, .2017, .2271, .2497, .2696,
 .2875, .3040, .3199, .2851, .2965,
 TABETA(1) = .2700, .8480, .9335, .9680, .9850,
 .9940, .9980, 1.00 , 1.00 , 1.00 , 1.00 ,
 1.00 , 1.00 , 1.00 , 1.00 , 1.00 , 1.00 ,
 1.00 , .99 , .99 , .99 , .98 , .97 ,
 .96 , .95 , .95 , .94 , .93 , .93 ,
 .93 , .92 , .92 , .92 , .91 , .91 , .91 ,
 .91 , 3*.91,
 TAZ1 (1) = 72.813, 09.875, 09.875, 08.425, 0.0 ,
 TANT (1) = 216. , 216. , 216. , 216. , 216. ,
 TANNB (1) = 216. , 216. , 216. , 216. , 216. ,
 TADOT=77.8+77.8,3*74.69,
 ZZZZZZ(1) = 00.000, 01.685, 03.370, 05.055, 06.740,

08.425, 09.875, 11.227, 12.388, 14.408, 15.859,
 17.310, 18.761, 20.212, 21.663, 23.114, 24.565,
 25.415, 26.385, 27.435, 28.528, 29.306, 30.023,
 31.345, 32.758, 33.066, 35.878, 37.933, 40.488,
 42.552, 44.528, 46.413, 50.040, 53.503, 56.846,
 60.123, 63.353, 66.528, 69.678, 72.813,
 RRRRRR(1) = 21.065, 21.065, 21.065, 21.065, 21.065, 21.065,
 21.065, 20.874, 20.314, 19.423, 17.403, 15.952,
 14.501, 13.050, 11.599, 10.148, 8.697, 7.247,
 6.549, 6.032, 5.713, 5.605, 5.715, 6.037,
 6.842, 7.726, 7.927, 9.708, 11.210, 12.533,
 13.729, 14.829, 15.853, 17.725, 19.416, 20.972,
 22.420, 23.780, 25.066, 26.290, 27.459,
 AAAAAA(1) = -14.12, -14.12, -14.12, -14.12, -14.12,
 -14.12, -13.87, -13.14, -12.01, -09.64, -08.10,
 -6.69, -5.42, -4.28, -3.28, -2.41, -1.67,
 -1.37, -1.16, -1.04, -1.00, -1.04, -1.16,
 1.49, 1.9, 2.00, 3.00, 4.00, 5.00,
 6.00, 7.00, 8.00, 10.00, 12.00, 14.00,
 16.00, 18.00, 20.00, 22.00, 24.00,
 SSSSSS(1) = 83.996, 82.313, 80.628, 78.943, 77.258,
 75.573, 74.106, 72.638, 71.171, 68.314, 66.262,
 64.210, 62.158, 60.106, 58.054, 56.002, 53.950,
 52.850, 51.749, 50.648, 49.548, 48.760, 47.972,
 46.422, 44.752, 44.392, 41.060, 38.220, 35.655,
 33.265, 31.004, 28.852, 24.772, 20.922, 17.237,
 13.652, 10.145, 06.725, 03.345, 00.000,
 TAAAT(1) = - 20.0000, - 5.0000, - 1.6536, - 1.2853, - 1.1450,
 - 1.0750, - 1.0156, - 1.0044, 1.0000,
 1.3837, 2.0083, 3.0406, 3.9218, 5.4515,
 7.1210, 8.6260, 11.3326, 13.7738,
 16.1590, 22.1097, 25.7635, 34.0256, 41.4487,
 54.7178, 66.6046, 77.5459, 87.7815,
 97.4607, 106.6846, 197.4253,
 TPK(1) = 450.0000, 450.0000, 409.0909, 375.0000, 346.1538,
 321.4286, 281.2500, 225.0000, 244.5430,
 90.0000, 45.0000, 22.5000, 15.0000, 9.0000,
 6.0000, 4.5000, 3.0000, 2.2500,
 1.5000, 1.1250, 0.9000, 0.6000, 0.4500,
 0.3000, 0.2250, 0.1800, 0.1500,
 0.1286, 0.1125, 0.0450,
 TTINK(1) = 4250.0000, 4250.0000, 4161.6508, 4081.6236, 4008.5859,
 3941.4851, 3821.9220, 3626.2093, 3698.0607,
 2887.7922, 2407.8729, 1998.1818, 1789.4076, 1555.9597,
 1392.4403, 1286.3422, 1150.1874, 1062.0403,
 948.4737, 874.8162, 821.2947, 731.4761, 673.1272,
 597.7618, 548.7998, 5 3.2067, 485.5930,
 463.2340, 444.5725, 332.8209,

TAFEFV=40*0.,

SEND

NERVA 75K ENGINE NOMINAL CASE FEB 1972

40

***** SUMMARY *****

COOLANT = NBS PARA-HYDROGEN

PIN = 1375.0

TIN = 60.7

TC = 4252.

PC = 450.

WG = 91.8

WC = 77.8

MR = .00

NT = 216.

STA	A/AT Z	CL CG	SUM VC	TM Q/AI	HL HG	P PRC	TB DE	RG L	AF NMR	TWL TWG	RE MUR	WDOT/A MACH
1	24.00 72.81	.0304 .0260	0. 491.	.0280 1.3	.00451 .00035	27.46 1374.23	60.7 .557	.400 .1058	.296 216.	340. 523.	.6514+06 .6005-06	1.2 .0101

TUBE TYPE = U-TUBE

MATERIAL = STAINLESS STEEL

2	22.00 69.68	.0262 .0260	966. 529.	.0280 1.4	.00422 .00039	26.29 1373.97	64.9 .550	.383 .1225	.285 216.	392. 587.	.5591+06 .5466-06	1.3 .0112
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3	20.00 66.53	.0229 .0260	1921. 487.	.0280 1.3	.00241 .00040	25.07 1373.98	68.9 .578	.365 .1395	.320 216.	623. 791.	.2886+06 .5069-06	1.1 .0107
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4	18.00 63.35	.0207 .0260	2837. 529.	.0280 1.4	.00207 .00043	23.78 1373.75	72.6 .564	.346 .1593	.304 216.	743. 909.	.2392+06 .4719-06	1.2 .0120
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5	16.00 60.12	.0190 .0260	3763. 579.	.0270 1.5	.00203 .00046	22.42 1373.48	76.1 .549	.326 .1790	.288 216.	706. 961.	.2305+06 .4443-06	1.3 .0135
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6	14.00 56.85	.0181 .0260	4700. 640.	.0260 1.5	.00212 .00049	20.97 1373.15	79.6 .530	.304 .2003	.270 216.	811. 978.	.2382+06 .4185-06	1.3 .0154
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7	12.00 53.50	.0178 .0260	5644. 717.	.0250 1.6	.00236 .00051	19.42 1372.73	83.0 .508	.281 .2229	.250 216.	776. 948.	.2699+06 .3069-06	1.4 .0176
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8	10.00 50.04	.0177 .0260	6666. 819.	.0240 1.8	.00262 .00055	17.72 1372.15	86.4 .481	.257 .2468	.228 216.	771. 952.	.2921+06 .3784-06	1.6 .0206
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9	8.00 46.42	.0177 .0260	7623. 959.	.0230 1.9	.00318 .00058	15.05 1371.30	89.8 .446	.229 .2740	.202 216.	701. 893.	.3568+06 .3597-06	1.8 .0248
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10	7.00 44.53	.0177 .0260	8134. 1051.	.0220 2.0	.00364 .00059	14.93 1370.71	91.5 .426	.214 .2877	.189 216.	647. 841.	.4161+06 .3529-06	1.9 .0275
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11	6.00 42.55	.0177 .0260	8652. 1164.	.0210 2.1	.00420 .00060	13.73 1369.97	93.2 .403	.198 .3033	.174 216.	598. 796.	.4811+06 .3464-06	2.1 .0308
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12	5.00 40.49	.0177 .0260	9178. 1315.	.0200 2.4	.00454 .00068	12.53 1368.83	95.0 .376	.180 .3204	.157 216.	622. 831.	.4789+06 .3396-06	2.3 .0352
13	4.00 37.93	.0177 .0260	9807. 1622.	.0190 2.8	.00542 .00081	11.21 1366.45	97.0 .366	.160 .3444	.130 216.	622. 856.	.5719+06 .3320-06	2.8 .0440
14	3.00 35.68	.0177 .0260	10511. 1932.	.0180 3.5	.00548 .00100	9.71 1363.41	99.2 .331	.138 .3666	.113 216.	731. 987.	.4956+06 .3235-06	3.2 .0532
15	2.00 33.07	.0176 .0260	11421. 2490.	.0170 5.0	.00585 .00153	7.93 1357.03	102.1 .283	.112 .3925	.091 216.	957. 1265.	.3767+06 .3151-06	4.0 .0694
16	1.90 32.76	.0176 .0260	11525. 2543.	.0160 5.3	.00585 .00164	7.73 1356.29	102.4 .279	.109 .3956	.089 216.	1002. 1303.	.3567+06 .3141-06	4.0 .0710
17	1.49 31.35	.0176 .0260	12043. 2954.	.0150 6.6	.00627 .00215	6.84 1350.65	104.0 .253	.096 .4079	.079 216.	1157. 1489.	.3047+06 .3093-06	4.6 .0830
18	1.16 30.02	.0176 .0260	12570. 3441.	.0140 8.4	.00683 .00288	6.04 1343.08	105.5 .228	.084 .4207	.069 216.	1333. 1698.	.2587+06 .3043-06	5.2 .0972
19	1.04 29.31	.0176 .0260	12876. 3676.	.0130 10.5	.00952 .00350	5.71 1338.56	106.4 .219	.079 .4239	.066 216.	1212. 1651.	.3036+06 .3014-06	5.5 .1043
20	1.00 28.53	.0176 .0260	13276. 4616.	.0130 15.2	.01493 .00515	5.61 1322.08	107.3 .205	.078 .3485	.053 216.	1124. 1754.	.3921+06 .2970-06	6.7 .1320
21	-1.04 27.43	.0176 .0260	14024. 7090.	.0130 19.3	.03066 .00624	5.71 1267.43	108.3 .186	.079 .2168	.036 216.	738. 1620.	.9269+06 .2882-06	9.9 .2070
22	-1.16 26.38	.0176 .0260	14875. 7414.	.0130 18.1	.02334 .00608	6.03 1251.09	110.8 .190	.084 .1941	.036 216.	888. 1688.	.7569+06 .2831-06	10.0 .2191
23	-1.37 25.41	.0176 .0260	1526. 5867.	.0140 14.8	.01316 .00530	6.55 1278.63	114.4 .213	.092 .2349	.047 216.	1241. 1882.	.4330+06 .2818-06	7.7 .1729
24	-1.67 24.57	.0176 .0260	16407. 4171.	.0140 11.5	.00931 .00415	7.25 1302.85	117.5 .251	.102 .3056	.067 216.	1356. 1853.	.3229+06 .2806-06	5.4 .1228
25	-2.41 23.11	.0176 .0260	17599. 3456.	.0150 8.2	.00613 .00297	8.70 1308.88	121.8 .291	.123 .3000	.085 216.	1456. 1833.	.2789+06 .2777-06	4.3 .1020
26	-3.28 21.66	.0176 .0260	18697. 3026.	.0150 6.8	.00546 .00238	10.15 1311.53	125.6 .326	.145 .2830	.101 216.	1369. 1696.	.2994+06 .2746-06	3.6 .0892

27	-4.28 20.21	.0176 .0260	19791. 2721.	.0160 5.9	.00494 .00203	11.60 1312.97	129.4 .355	.166 .2664	.116 216.	1321. 1631.	.3077+06 .2737-06	3.1 .0801
28	-5.42 -18.76	.0176 .0260	20914. -2534.	.0160 5.4	.00456 .00188	13.05 1313.47	133.3 .378	.188 .2409	.130 216.	1323. 1611.	.3041+06 .2729-06	2.8 .0745
29	-6.69 17.31	.0176 .0260	22105. 2531.	.0170 5.2	.00455 .00178	14.50 1312.68	137.4 .388	.209 .1997	.135 216.	1277. 1575.	.3251+06 .2720-06	2.7 .0744
30	-8.10 15.86	.0176 .0260	23388. 2562.	.0170 5.1	.00460 .00173	15.95 1311.67	141.9 .393	.230 .1580	.139 216.	1244. 1540.	.3436+06 .2710-06	2.6 .0752
31	-9.64 14.41	.0176 .0260	24801. 2827.	.0170 5.1	.00521 .00171	17.40 1308.95	146.7 .373	.252 .0987	.132 216.	1134. 1447.	.4075+06 .2709-06	2.7 .0830
32	-12.01 12.39	.0176 .0260	27053. 3440.	.0180 5.4	.00676 .00171	19.42 1302.59	154.4 .324	.282 .0228	.116 216.	948. 1314.	.5397+06 .2720-06	3.1 .1006
33	-13.14 11.23	.0175 .0260	28362. 4146.	.0180 5.6	.00881 .00173	20.31 1295.14	158.8 .255	.295 .0063	.100 216.	797. 1201.	.6169+06 .2725-06	3.6 .1208
34	-13.87 9.87	.0175 .0260	29783. 4644.	.0180 5.8	.01077 .00177	20.87 1288.39	163.5 .225	.303 .0000	.093 216.	706. 1141.	.7174+06 .2734-06	3.0 .1348
35	-14.12 8.42	.0175 .0260	31253. 4722.	.0220 5.9	.01079 .00182	21.07 1287.24	168.8 .218	.306 .0035	.091 216.	713. 1233.	.6917+06 .2758-06	3.8 .1363
36	-14.12 6.74	.0175 .0260	32975. 4939.	.0220 6.1	.01080 .00194	21.07 1282.47	175.0 .218	.306 .0035	.091 216.	739. 1272.	.6818+06 .2783-06	3.8 .1417
37	-14.12 5.06	.0175 .0260	34763. 5116.	.0220 6.3	.01064 .00210	21.07 1277.97	181.4 .218	.306 .0035	.091 216.	776. 1319.	.6560+06 .2812-06	3.8 .1459
38	-14.12 3.37	.0175 .0260	366.3 5325.	.0220 6.5	.01052 .00232	21.07 1273.07	188.0 .218	.306 .0035	.091 216.	808. 1360.	.6363+06 .2859-06	3.8 .1507
39	-14.12 1.69	.0175 .0260	38484. 5551.	.0220 6.5	.01093 .00265	21.07 1267.96	194.5 .218	.306 .0035	.091 216.	787. 1339.	.6742+06 .2905-06	3.8 .1560
4	-14.12 .09	.0175 .0260	39710. 5709.	.0220 2.1	.01938 .00313	21.07 1264.04	198.7 .218	.306 .0035	.091 216.	304. 540.	.1922+07 .2935-06	3.8 .1507

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AEROJET NUCLEAR SYSTEMS COMPANY
SACRAMENTO, CALIFORNIA

TO: J. L. Watkins 4 March 1971
FROM: R. V. Lundin/J. O. Sane RVL/JOS:rbk:N4320:M1648
Project 141, W.S. 2e
SUBJECT: Updated NERVA Nozzle Gas-Side Heat Transfer Model
DISTRIBUTION: D. W. Lunsford, K. Sato, L. A. Shurley, E. A. Thomas, W. R. Thompson
REFERENCES: See Attachment A
ENCLOSURES: See Attachment B

I. INTRODUCTION

The approach to predicting the gas-side thermal environment in the NERVA nozzle has been to relate scale model and full scale NERVA Technology Nozzle data to theoretical models representing boundary layer growth and film cooling effects. Early scale model heat transfer tests of the Technology Nozzle configuration are reported in References (a), (b), (c), (d) and (e). Data from these tests indicated that the heat transfer coefficients in the barrel and convergent section of the nozzle were much higher than predicted by conventional methods of calculation for chemical rocket nozzles such as References (f) and (g). This effect has also been observed in scale model tests of other nuclear nozzle configurations (References (h), (i), (j) and (k)). It is due to the fact that a conventional boundary layer does not begin to develop just aft of the reactor core, but rather there is a deceleration and coalescing of the many discrete jets of gas issuing from the core into the nozzle chamber. This effect necessitates recourse to empiricism in characterizing the nozzle gas-side heat transfer.

The practice of placing braze alloy patches, that melt within specific temperature ranges, on the gas-side wall of Technology Nozzle coolant channels has yielded nozzle wall temperature distributions which were utilized to formulate the previous NERVA gas-side heat transfer model (Reference (1)), which is based upon braze alloy patch data from tests NRX-A3, NRX/EST, and NRX-A5. Since the formulation of this model, two technology nozzles have been fired, NRX-A6 and XE-Prime, providing additional braze patch data. Also, advances have been made in the fields of fluid mechanics and heat transfer that pertain to the method employed in developing the current model. As a consequence of these developments it was appropriate to update the previous model.

II. SUMMARY

The NERVA 75K gas-side thermal model has been updated based on the braze alloy patch temperature data of Technology Nozzles NRX-A5, NRX-A6, and XE-Prime. The theoretical heat transfer coefficient profiles were calculated by the ANSC boundary layer

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growth program (Reference (m)) employing the skin friction correlation of Coles with a boundary layer interaction exponent equal to 0.25. An empirical correlation factor was applied to the skin friction coefficient within the boundary layer model through the barrel and convergent section of the nozzle to account for turbulence-induced skin friction and heat transfer enhancement.

Two methods of accounting for the film cooling effect of the core peripheral flow were examined, the method of Hatch and Papell (Reference (n)) and the method of Ewen (Reference (o)). Given the gas-side heat transfer coefficients and film cooling factors as input, the Technology Nozzle coolant channel wall temperature profiles were computed using the E25104 regeneratively-cooled nozzle computer program (Reference (p)) which has been modified to include the coolant-side heat transfer correlation reported in Reference (q), the December 1969 NBS parahydrogen and equilibrium hydrogen properties, the friction factor model of Taylor (Reference (r)), the curvature enhancement factor of Ito (Reference (s)) in the coolant pressure drop calculation, an improved method of calculating entrance and exit losses for the nozzle coolant channels, a coolant bulk-temperature-rise calculation based on an enthalpy balance, and recognition of variable thermal conductivity across the coolant channel crown per Reference (t).

The gas-side wall temperature profiles for the NRX-A5, -A6 and XE-Prime nozzles computed with the new model using Ewen's film cooling model are shown in Enclosures (1), (2) and (3). The three corresponding profiles using the Hatch and Papell model are shown in Enclosures (4), (5) and (6). The new model has been applied to the NERVA 75K nozzle geometry and operating conditions corresponding to the LOBE 215A reference design case corrected for the film cooling conditions of Reference (u). Enclosure (7) illustrates the comparison of the gas-side wall temperatures predicted by the new model and the previous model. The new model predicts temperatures lower than the previous model in the barrel section, a portion of the convergent section, and in the divergent section. Higher temperatures are predicted by the new model immediately upstream of the geometric throat.

III. METHOD OF ANALYSIS

The philosophy by which the updated as well as the previous NERVA gas-side heat transfer model was formulated is that the hydrogen coolant heat transfer mechanism was known from resistance-heated tube data, the hot-gas recovery temperature profile was known from a film cooling calculation, and, thus, the gas-side heat transfer coefficient profile, could be inferred from the nozzle gas-side wall temperature measurements from Technology Nozzle braze alloy patches.

The details of each facet of this development are presented herein.

A. Braze Alloy Patch Data

Braze alloy patches were applied to the gas-side coolant channel crowns of Technology Nozzles NRX-A3, NRX/EST, NRX-A5, NRX-A6, and XE-Prime. These data were

reviewed to establish the best sources from which to calibrate the new model. The criterion for the selection of tests is the degree to which the braze patch data can be related to known engine operating conditions. The braze patch data represent nozzle tube wall temperatures attained during the most severe operating conditions. At best, the most severe operating condition corresponds to a full power, steady-state hold in which no unusual gas boundary layer events occur, such as off-design core peripheral flow. A comparison between the Technology Nozzle tests with braze patch data can be made on the basis of this criterion as follows:

<u>Test</u>	<u>Characteristics of Test</u>
NRX-A3	An emergency flow shut-down occurred during the test, such that the braze patch data do not represent full power steady-state operation. In addition, the difference in melt temperatures for the braze alloys used were so large that temperature uncertainties of 400°F were attained.
NRX/EST	Significant core erosion occurred such that the film coolant flowed into the core rather than along the surface of the coolant tubes. This effect resulted in excessive wall temperatures (>1600°F) in the nozzle barrel.
NRX-A5	Some core erosion occurred, but not to the extent of the EST test.
NRX-A6	No deleterious events were reported.
XE-Prime	No deleterious events were reported.

It was concluded that tests NRX-A5, NRX-A6, and XE-Prime provide the best sources for formulating the new NERVA 75K hot-gas side heat transfer model. The measured engine operating parameters corresponding to the most severe nozzle conditions (and, therefore, to the braze patch data) are summarized in Table I with their respective references. The sources of the braze alloy patch data for NRX-A5, NRX-A6, and XE-Prime are References (v), (w), and (x), respectively.

The braze alloy patch temperature data are illustrated in Enclosure (1), (2), (3), (14) and (15) for the NRX-A5, NRX-A6, XE-Prime, NRX-A3 and NRX-EST technology nozzles, respectively. The temperature spread at each braze alloy patch location represents the temperature difference between the liquidus temperature of the patch with the highest melting point that has melted and the solidus temperature of the patch with the next highest melting point that has not melted.

B. Computer Programs Employed in Development of Gas-Side Thermal Model1. Regeneratively-Cooled Nozzle Computer Program

Each technology nozzle (NRX-A5, NRX-A6, and XE-Prime) was modeled on the E25104 regeneratively-cooled nozzle computer program (Reference (p)) by inputting the nozzle geometries (nozzle contours and coolant channel flow areas). This program solves the energy and momentum equations for a fluid flowing through a channel subjected to convective and radiative heat transfer. The particular options employed in the model are summarized below.

a. Coolant-side heat transfer coefficient

Recently J. O. Sane and D. W. Lunsford of ANSC have examined 2230 points of hydrogen heat transfer data in the specific operating range of the NERVA nozzle and have derived a new coolant-side correlation (Reference (q)). This correlation has been utilized in the new model:

$$Nu_{\text{straight tube}} = .00821 Re_f^{.874} Pr_f^{.4} \left(1 + .0146 \frac{\mu_w \rho_b}{\mu_b \rho_w} \right)^{.622}$$

A factor that accounts for entrance effects is multiplied times this expression and takes the following forms:

$$\text{for } 0 \leq X/D_E < 5.198$$

$$\text{Entrance factor} = 1.8$$

$$\text{for } 5.198 < X/D_E \leq 120$$

$$\text{Entrance factor} = \left(1 + \frac{4.0}{X/D_E} \right)^{1.030}$$

$$\text{for } X/D_E \geq 120 \text{ the entrance factor has attenuated to unity.}$$

A factor that accounts for coolant channel curvature, for the case in which heat transfer exists over the convex surface of the curve (the nozzle throat), is multiplied times the straight tube correlation and takes the following forms:

$$\text{curved tube factor} = \begin{cases} 1 + 1.128 \phi \\ .797 \left[\text{Re}_b \left(\frac{D_E}{2R_c} \right)^2 \right]^{.0785} \\ 2.502 - 1.16 \phi \end{cases}$$

in which ϕ is the angle of curvature in radians.

For the particular value of ϕ , Re_b , and $\frac{D_E}{R_c}$ at a location on a curved tube, the expression above that yields the lowest curved tube factor is utilized.

b. Friction Factor Correlation

M. F. Taylor (Reference (r)) has correlated frictional pressure drop measurements for helium, hydrogen, nitrogen, air, and carbon dioxide gases flowing through heated tubes by means of the following expression for the diabatic friction factor

$$f = 2 \left(.0007 + \frac{.0625}{\text{Re}_{WL}^{.32}} \right) \left(\frac{T_b}{T_{WL}} \right)^{0.5}$$

This correlation was developed for surface Reynolds numbers (properties based on coolant-side wall temperature T_{WL}) of 3000 and greater and for the wall temperature-to-bulk temperature ratio between .35 and 7.35. Taylor has matched NRX-A6 full power pressure drop measurements (Reference (y)) by employing his friction factor correlation over the heated surface of the coolant tube (semi-circular portion of U-tube) and employing a standard coolant bulk temperature-referenced friction factor over the unheated tube surface (legs and base of U-tube). This procedure is implemented by means of an effective friction factor, which is defined as:

$$f_{\text{eff}} = f_b \left(\frac{S_b}{S_b + S_c} \right) + f_c \left(\frac{S_c}{S_b + S_c} \right)$$

in which:

f_{eff} = effective friction factor

f_b = friction factor referenced at coolant bulk temperature

f_c = Taylor's friction factor correlation referenced at tube temperature

S_b = surface area at coolant bulk temperature (legs and base of U-tube)

S_c = surface area at tube crown temperature (semi-circular portion of U-tube)

This expression and Taylor's friction factor correlation were added to the E25104 program, which already has a coolant bulk temperature-referenced friction factor correlation:

$$f_b = 0.5 \left[2.54 \log_{10} \left(\frac{VD_E \rho_b}{\mu_b} \right) - 2.17 \right]^2$$

which represents adiabatic flow pressure drop data.

The effect of curvature on the straight tube friction factor was accounted for by applying Ito's correction factor (Reference (s)):

$$(f_{eff})_{\text{curved tube}} = (f_{eff})_{\text{straight tube}} \left[Re_b \left(\frac{D_E}{2R_c} \right)^2 \right]^{0.5}$$

c. Entrance and Exit Pressure Drop

The pressure drop resulting from the flow of hydrogen coolant from the inlet manifold through the coolant tube inlet holes and into the coolant tubes (turning 90 degrees) was calculated by means of a loss factor for incompressible flow.

$$\Delta P_{\text{inlet}} = K_1 \frac{\rho_b V_i^2}{2g} = K_1 \frac{\rho_b V_1^2}{2g} \left(\frac{A_1}{A_i} \right)^2$$

in which : $K_1 = 1.6$ = the loss factor equal to the sum of the loss factors due to flow from the inlet manifold into the inlet holes ($K = .5$) and due to flow through a 90 degree angle ($K = 1.1$)

ρ_b = coolant bulk density

V_i = coolant velocity in inlet holes

V_1 = coolant velocity at inlet to coolant tubes

A_i = area of inlet holes

A_1 = coolant tube area at tube entrance

The pressure drop resulting from the flow of hydrogen coolant from the coolant tubes into the outlet holes (turning 90 degrees) and from the outlet holes into the reflector inlet plenum was calculated by means of loss factors for incompressible flow

$$\Delta P_{\text{exit}} = K_t \rho_b \frac{V_e^2}{2g} + K_c \rho_b \frac{V_o^2}{2g} + K_e \rho_b \frac{V_o^2}{2g}$$

$$\text{or } \Delta P_{\text{exit}} = K_3 \rho_b \frac{V_e^2}{2g}$$

$$K_3 = K_t + (K_c + K_e) \left(\frac{A_e}{A_o} \right)^2$$

in which:

K_3 = effective exit loss factor

K_t = 90 degree turning loss factor = 1.1

K_c = loss factor due to area contraction from coolant tube cross-sectional area to exit hole cross-sectional area

K_e = loss factor due to flow from the exit holes into the reflector inlet plenum = 1.0

V_e = coolant velocity at exit of coolant tube

V_o = coolant velocity in outlet holes

A_e = coolant tube cross-sectional area at exit (last station)

A_o = outlet hole cross-sectional area

The entrance and exit pressure loss factors for the Technology Nozzles are summarized below:

	K_1 , Entrance Factor	K_3 , Exit Factor
NRX-A5	1.27	2.04
NRX-A6	1.203	2.10
XE-Prime	1.28	3.35

d. Coolant Temperature and Pressure Drop Iteration

The coolant pressure and temperature drop can be input to the nozzle program and it will iterate on the value of a friction factor multiplier PFM and a heat transfer surface area multiplier EPGEOM to match the input values of ΔP and ΔT . This option was employed for the technology nozzle runs by inputting the measured ΔP 's and ΔT 's shown in Table I.

e. Hydrogen Properties

Per direction of the Space Nuclear Systems Office the December, 1969 NBS hydrogen properties were incorporated into the nozzle computer program. Para-hydrogen properties were utilized on the coolant-side and equilibrium hydrogen properties were employed on the gas-side. The question of para to ortho conversion within the NERVA nozzle coolant channels has yet to be resolved at the date of this writing.

f. Core Thermal Radiation

Thermal radiation from the core face to the gas-side surface of the coolant channels is accounted for in the program by the calculation of gray body view factors from the expression for radiation exchange between gray surfaces in an enclosure:

$$\bar{F}_{o-i} = \left[\frac{1}{F_{o-i}} + \frac{1}{\epsilon_o} - 1 + \frac{\pi R_c^2}{A_i} \left(\frac{1}{\epsilon_i} - 1 \right) \right]^{-1}$$

in which:

$\tilde{F}_{o-i}$ = the gray body view factor from the core to the coolant channel surface

F_{o-i} = the black body view factor from the core to the coolant channel surface

ϵ_o = emissivity of the core

ϵ_i = emissivity of the coolant channel

R_c = radius of core surface

A_i = area of coolant channel section

Thermal radiation heat transfer from the core to the coolant channel is calculated from

$$q_{o-i} = \sigma \tilde{F}_{o-i} (T_o^4 - T_{WG}^4)$$

in which:

q_{o-i} = thermal radiation flux from the core to the coolant channel

σ = Stefan-Boltzmann constant

T_o = core temperature

T_{WG} = gas-side wall temperature

g. Gas-side Heat Transfer Coefficient

The most desirable computational scheme envisioned for an overall NERVA nozzle heat transfer model is for the E25104 regeneratively cooled nozzle program to be combined with the E25213 boundary layer growth computer program (described below), the latter program being employed as a subroutine to predict gas-side heat transfer coefficients. Unfortunately, the run time for the boundary layer program is an order of magnitude longer than that of the E25104 program. Thus, it was economically expedient to program a closed-form equation for the gas-side heat transfer coefficient in the same manner as the simplified Bartz equation was used in the E25104 program for the current NERVA nozzle thermal model. The equation that was programmed is:

$$hg = C_g \frac{K_f}{X} \left(\frac{\rho V X}{\mu} \right)_f^{.8} \left(\frac{\mu C_p}{K} \right)_f^{.3}$$

evaluated at the Eckert reference temperature

$$T_f = .5 (T_{WG} + T_{fs}) + .22 Pr_f^{1/3} (T_o - T_{fs})$$

in which: X = nozzle contour distance from core
 T_{fs} = free-stream temperature
 T_o = chamber temperature

C_g is a coefficient which is a function of nozzle station and chamber conditions. This expression is reported to correlate hot gas-side heat transfer data from a hydrogen-oxygen rocket nozzle firing (Reference (z)) better than conventional correlations with Reynolds' number based on nozzle diameter.

h. Static Pressure and Temperature Distribution

A wall Mach number profile is required input to the program, which calculates the static pressure and temperature distribution based on γ evaluated at stagnation conditions.

2. Gas-Side Heat Transfer Coefficient Computer Program

The gas-side heat transfer coefficients that were input to the E25104 nozzle computer program were generated by the E25213 boundary layer growth computer program (Reference (m)). This program solves the integral boundary layer equations to determine the heat transfer coefficients along the walls of an axisymmetric nozzle by means of the von Karman form of the Reynold's analogy between heat transfer and fluid friction:

$$C_h = \frac{hg}{UC_p} = \frac{C_f (R_\phi)}{2} \left(\frac{\phi}{\theta} \right)^n$$

$$1 - 5 \left(\frac{C_f (R_\phi)}{2} \right)^{1/2} \left[1 - Pr + \ln \left(\frac{6}{5 Pr + 1} \right) \right]$$

in which:

C_h	=	Stanton number
$C_f (R_\phi)$	=	skin friction coefficient based on energy thickness-Reynolds number
ϕ	=	energy thickness
θ	=	momentum thickness
Pr	=	Prandtl number
n	=	boundary layer interaction exponent
h_g	=	gas-side heat transfer coefficient
C_p	=	specific heat of gas
ρ	=	density of gas
U	=	free stream velocity of gas

Three options were available in the program for the calculation of the turbulent skin friction coefficient, the method of Coles (Reference (aa)), the method of Eckert, and the method of Spalding and Chi. The boundary layer interaction exponent is a variable that determines the influence of the ratio of energy thickness to momentum thickness on the calculation of heat transfer coefficients. It can have a value ranging from 0 to .25. Included in the program is the option to input a station-varying multiplicative factor to be applied to the calculated skin friction coefficient, a feature that was utilized in this analysis. The wall Mach number profile is required input as well as an assumed gas-side wall temperature distribution.

3. Nozzle Wall Mach Number Computer Programs

The nozzle wall Mach number profile was calculated in three segments: a one-dimensional flow calculation from the core to the upstream tangent point, a transonic flow calculation from the upstream tangent point to the geometric throat, and a two-dimensional flow calculation from the throat to the exit plane.

A subroutine in the E25213 boundary layer growth program calculates the one-dimensional Mach number distribution based on the ratio of specific heats γ evaluated at stagnation conditions.

The transonic Mach number profile was determined from a computer program that employs the method of Hopkins and Hill (Reference (bb)) to solve the transonic flow equations based on the throat geometry and the value of γ evaluated at the geometric throat conditions.

The two-dimensional wall Mach number profile downstream of the throat was predicted from the E21201 nozzle performance program (Reference (cc)) which employs the method of characteristics to solve the axisymmetric supersonic compressible flow equations. A Mach profile from the centerline of the nozzle to the wall of the geometric throat is required to initiate the method of characteristics. The program has three options available to determine this start line: the method of Sauer, the method of Hill-Kliegel, and the method of Hall. The method of Sauer was selected because it predicts a value of the geometric throat Mach number very close to that of the more rigorous Hopkins-Hill method. The value of γ required for this program was evaluated at the geometric throat.

4. Film Cooling Computer Program

The film cooling model employed in the current as well as previous gas-side models was based on the Hatch and Papell correlation (Reference (n)), modified to account for rocket engine geometry, since it correlates data that are most representative of rocket engine operating conditions (high free-stream temperature-to-film coolant temperature ratio). The Hatch and Papell film cooling correlation, however, is based on a model that is not entirely representative of the mixing process of the film coolant with the hot gas main flow. A film cooling model has been recently formulated (Reference (o)) which represents explicitly the mixing of the film coolant and mainstream through the use of an entrainment parameter which prescribes the entrainment of mainstream gas into the mixing layer. This model, developed specifically for nozzle application, matches the Hatch and Papell data better than the Hatch and Papell model (Reference (dd)) and was also applied in this analysis. Both models predict the adiabatic wall temperature distribution along the film-cooled walls, which is subsequently input to the E25104 regeneratively cooled nozzle program as the driving potential to the coolant channels.

G. Technology Nozzle Description

Each of the Technology Nozzles had, within fabricability limits, the same contour (Enclosure (8)) which can be divided into six regions: (1) a constant diameter barrel region 9.18 inches long, (2) a curved "knuckle" region of radius 4.36 inches which turns the flow by 45 degrees, (3) a conical convergent section 11.12 inches in length, with a half-angle of convergence of 45 degrees, (4) a curved upstream transition region of radius 4.36 inches between the convergent cone and the geometrical throat, which has a radius of 4.36 inches, (5) a curved downstream transition region of radius .872 inches between the geometrical throat and the exit cone, and (6) a 29.77 inch long exit cone that extends to area ratio 10 with a half-angle of divergence of 17.5 degrees.

Each nozzle consisted of 186 CRES 347 U-tubes brazed into a CRES 347 jacket. The measured coolant channel flow areas for the NRX-A5, NRX-A6, and XE-Prime nozzles are given in References (ee), (ff) and (gg), respectively.

The reactor core consists of a matrix of fueled and unfueled graphite blocks with many small channels for the flow of hydrogen. Near the core exit plane an annulus exists between the walls of the nozzle and the periphery of the core, allowing relatively cool hydrogen gas to flow along the walls of the nozzle downstream of the core. This core peripheral flow provides a film cooling effect in the barrel section and a portion of the convergent section.

The width of the annulus for each technology nozzle was determined from interface drawings and represents a cold dimension.

<u>Nozzle</u>	<u>Annulus Thickness</u>	<u>Reference</u>
NRX-A5	.482 inches	Dwg No. 1010045
XE-Prime	.482 inches	Dwg No. 1010045
NRX-A6	.493 inches	Dwg No. 1115780

D. Approach to Updating Current NERVA Gas-side Heat Transfer Model

The steps that were taken to formulate a new gas-side thermal model utilizing the computer programs and test data described above are summarized below:

1. The E23102 Thermocal Computer Program was run for the Technology Nozzle maximum power, steady-state operating conditions given in Table I for NRX-A5, NRX-A6, and XE-Prime to provide values of γ in the throat. Values of γ in the chamber were provided by NBS equilibrium hydrogen tables.

2. The E21201 nozzle performance computer program was run for each of the Technology Nozzles operating at the conditions of Table I to predict the wall Mach number profile from the geometric throat to the exit plane. The throat values of γ predicted from Step 1 were input to the program.

3. The transonic flow computer program employing the method of Hopkins and Hill was utilized to determine the wall Mach number profile from the upstream tangent point to the geometric throat. The throat values of γ predicted from Step 1 were input to the program.

4. The nozzle wall Mach number profile was input for each Technology Nozzle to the E25213 boundary layer growth computer program for the conditions of Table I. Each of the options for the skin friction correlation was tried with various values for the interaction exponent.

5. The Ewen film cooling program and the Hatch-Papell film cooling program were run for each Technology Nozzle for the conditions of Table I, yielding beta (ratio of the recovery temperature to the chamber temperature) distributions along the gas-side wall from the core to some point in the convergent section where the film cooling effect dissipated.

6. The gas-side heat transfer coefficients predicted from Step 4 for each Technology Nozzle were input to the E25104 nozzle computer program along with the film cooling beta's, the wall Mach number profiles, and the measured pressure and temperature drops and operating conditions of Table I. The resulting gas-side wall temperature distributions were compared with the braze alloy patch data.

7. Appropriate input changes to the E25213 boundary layer growth computer program were made to bring the gas-side wall temperature predictions in closer agreement with the measurements (repetition of Steps 4 and 6).

8. The problem converged when the gas-side wall temperatures input to the E25213 computer program agreed with the temperatures output from the E25104 computer program.

IV. RESULTS

A. Formulation of Updated Gas-Side Thermal Model

The γ 's obtained from the E23102 thermocal computer program and the NBS equilibrium H_2 tables are shown in Table II. Enclosure (9) depicts the wall Mach number profile obtained for the XE-Prime nozzle. The NRX-A5 and NRX-A6 nozzles had similar profiles because the contour was the same, the γ 's were almost identical, and the operating conditions were very similar. Enclosure (10) is the wall Mach number profile in the transonic region for all three Technology Nozzles. The sonic point at the wall is predicted to be .77 inches upstream of the geometric throat or 25.73 inches downstream of the core.

A comparison of gas-side wall temperatures predicted by the E25104 nozzle program indicated that the skin friction correlation that resulted in the best match of the braze alloy patch data between the geometric throat and the exit plane was the Coles correlation. An interaction exponent of .25 was selected to match the high extremes of the XE-Prime and NRX-A6 wall temperature measurements in this region (the NRX-A5 Technology Nozzle braze alloy patch temperature measurements were erratic in this region). In support of this selection, a comparison of direct measurements of turbulent skin friction on nonadiabatic flat plates at Mach number 6.5 (Reference (hh)) with eight skin friction correlation schemes revealed that the best predictions (within 5 percent) were given by the Coles method.

Unfortunately, the melting temperature of the braze alloy patches 3 inches from the exit plane of the Technology Nozzles were such that none of patches melted, and all that is known of the gas-side wall temperatures in this region is that they are below 885°R.

The portion of the nozzle from the core to the geometric throat provided the greatest difficulty in formulating the gas-side heat transfer model because wall heat transfer was enhanced in this region due to turbulent mixing of the gases streaming from the core, whereas the core peripheral flow provided a film cooling effect. Both the Ewen and the Hatch and Papell film cooling models were applied in this region.

The application of the Ewen film cooling model provided two parameters to match the braze alloy patch data in this region: the skin friction coefficient multiplying factor and a film coolant entrainment rate multiplying factor. The latter factor is an input option to the Ewen film cooling program and it provides for entrainment rates of the mainstream gas into the film coolant stream greater than those calculated within the program. The procedure was to input various values of the entrainment rate multiplier factor to the film cooling program Step 5) to determine beta distributions for each Technology Nozzle. Corresponding to each value of the entrainment rate factors, skin friction coefficient multiplier factor distributions were determined to match braze alloy patch temperature data upstream of the throat. The best match of the data was obtained for an entrainment rate factor of 2.0. The skin friction correlation multiplier profile corresponding to this value is presented in Enclosure (11) as a function of nozzle axial distance from the core. The sharp decrease in the value of the factor at the core is required to maintain a constant value of the ratio of empirical to theoretical heat transfer coefficient over the first three inches of the barrel section (where no braze alloy patches existed). The effect of the skin friction coefficient multiplier on the heat transfer coefficient distribution is illustrated in Enclosure (12) for the XE-Prime nozzle. The enhancement effect is seen to extend to an axial distance of about 18 inches.

Enclosures (1), (2), and (3) illustrate the application of the new gas-side thermal model with Ewen's film cooling model to the NRX-A5, NRX-A6, and XE-Prime Technology Nozzles, respectively. The predicted gas-side wall temperature distributions follow the same trend for all nozzles. The wall temperature at the core is below the core peripheral flow temperature, it increases to a maximum between one and six inches from the core as the film cooling effect diminishes. The wall temperature then decreases due to a decreasing gas-side heat transfer coefficient (Enclosure (12)), reaching a minimum about 12-13 inches from the core. The wall temperature then increases with increasing distance and attains a maximum at 25.15 inches from the core, where the maximum heat transfer coefficient was predicted by the E25213 program. (This is .58 inches upstream of the sonic point or 1.35 inches upstream of the geometric throat.) A decrease in the wall temperature occurs until the downstream tangent point. Aft of this

point the gas-side heat transfer coefficient profile flattens for a short distance while the coolant-side heat transfer coefficient decreases with distance, resulting in a temperature increase with distance that attains a maximum about 29.5 inches from the core. Downstream of this location the wall temperature decreases attaining a value a few hundred degrees above the inlet temperature of the coolant at the exit plane.

The use of the Hatch and Papell film cooling model provided one parameter, the skin friction coefficient multiplier, to be varied to match the braze alloy patch data. Enclosure (11) illustrates the skin friction coefficient multiplier profile that best matches the data and Enclosure (12) illustrates the effect of this multiplier on the heat transfer coefficient distribution for the XE-Prime nozzle. Enclosures (4), (5), and (6) represent the gas-side wall temperature profiles predicted by the updated model using the Hatch and Papell film cooling model.

The greatest uncertainty in the model is in the first six inches downstream of the core. Due to the large temperature uncertainties at the 3 inch braze alloy patch location for the NRX-A5* and XE-Prime nozzles, and the fact that the film cooling conditions for NRX-A5 and XE-Prime were based on pre-test predictions presented in References (jj) and (kk), whereas the film coolant temperature was actually measured for the NRX-A6 test (Reference (ll)), the model in this region was based on the NRX-A6 data. Aft of this region to a point 19 inches downstream of the core the model was a compromise based on the braze data of all three nozzles. Comparing the Hatch and Papell model (Enclosure (5)) with Ewen's model (Enclosure (2)) for NRX-A6, it is seen that Ewen's model comes closer to the braze patch reading at distance nine inches. This reading has been verified in the post test braze patch photographs.

The values of the friction factor multiplier PFM and the heat transfer surface area multiplier EPGEOM required to match the measured values of coolant temperature and pressure drop are summarized below for each of the two film cooling models.

* The braze alloy patch temperatures reported originally in Reference (v) for NRX-A5 at this location demonstrated a temperature span from 1450-1585°R. However, post fire braze patch photographs indicate a temperature span between 1450°R and 1960°R, similar to the XE-Prime data.

<u>Nozzle</u>	Ewen's Film Cooling Model		Hatch and Papell Film Cooling Model	
	<u>PFM</u>	<u>EPGEOM</u>	<u>PFM</u>	<u>EPGEOM</u>
NRX-A5	1.521	.883	1.482	.897
NRX-A6	1.549	.948	1.582	.923
XE-Prime	1.825	.923	1.821	.972
Average	1.632	.918	1.628	.930

The large difference between the value of PFM for the XE-Prime nozzle and the values for the other two nozzles has not been resolved.

B. Comparison of Updated Gas-Side Model With Previous Model

The NERVA 75K reference nozzle design case LOBE 215A corrected for the film cooling conditions of Reference (u) per the method of Hatch and Papell was selected as the basis of comparison between the updated and the previous model. The updated model was applied to the 75K nozzle by enacting Steps 1 through 3 described in III.D. Both the film cooling model of Hatch and Papell and the film cooling model of Ewen were used. The skin friction coefficient (Coles, interaction exponent = .25) multiplier profiles of Enclosure (11) were input to the E25213 boundary layer growth program as a function of nozzle contour distance. The resulting gas-side heat transfer coefficient distributions were input to the nozzle program E25104. The resulting gas-side wall temperature distributions are illustrated in Enclosure (7) along with the temperature distribution predicted for the corrected version of run LOBE 215A. The new model predicts lower gas-side wall temperatures by as much as 600°R in the barrel and convergent section, higher temperatures immediately upstream of the throat by as much as 250°R and lower temperatures in the divergent section by as much as 600°R. The difference in the results are mostly attributed to differences in the gas-side heat transfer coefficients, the coolant-side coefficients having a secondary influence.

The updated Cg profiles for the 75K NERVA nozzle are shown in Enclosure (13). The solid curve represents the Cg for the equation quoted on page 10:

$$hg = C_g \frac{K_f}{X} \left(\frac{\rho V X}{\mu} \right)_f^{.8} \left(\frac{\mu C_p}{K} \right)_f^{.3}$$

where the characteristic dimension in the Reynolds number is the developed distance along the contour rather than the local chamber diameter as in the

simplified Bartz equation. It is seen that this equation does result in considerable flattening of the Cg profile relative to that for the simplified Bartz equation as was suggested in Reference (ii).

CONCLUSIONS

The upgraded model with either of the two film cooling models predicts lower temperatures in the forward portion of the nozzle than does the previous model. This is due both to a lower gas-side heat transfer coefficient (which is a result of including the NRX-A6 and XE-Prime data) and a higher coolant-side heat transfer coefficient in the forward portion of the nozzle (see Enclosure (4) of Reference (q)). Although the application of Ewen's film cooling model results in a wall temperature profile which fits the NRX-A6 data better than the profile predicted by the Hatch and Papell model, continued use of the Hatch and Papell model is recommended for the 75K NERVA nozzle since it results in a more conservative prediction as seen in Enclosure (7).

The updated model is seen to predict lower wall temperatures in the divergent section and this is consistent with the previous model derived from braze patch data (Reference (1)).

FUTURE WORK

The friction factor multiplier PFM and the heat transfer surface area multiplier EPGEOM that were calculated from the Technology Nozzle tests were based on the measured coolant temperature and pressure drops of one full-power, steady-state test for each nozzle. Many other tests were conducted for each nozzle under different operating conditions providing different measurements for coolant temperature and pressure drop. These data will be utilized to refine the values of PFM and EPGEOM in the updated model.

R. V. Lundin
Thermodynamics
Scientific Staff Department

J. O. Sane
Thermodynamics
Scientific Staff Department

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- ENCLOSURES:
- (1) Gas-side Wall Temperature Predictions and Braze Alloy Patch Data for Technology Nozzle NRX-A5 Using Ewen's Film Cooling Model
 - (2) Gas-side Wall Temperature Predictions and Braze Alloy Patch Data for Technology Nozzle NRX-A6 Using Ewen's Film Cooling Model
 - (3) Gas-side Wall Temperature Predictions and Braze Alloy Patch Data for Technology Nozzle XE-Prime Using Ewen's Film Cooling Model
 - (4) Gas-side Wall Temperature Predictions for Technology Nozzle NRX-A5 Using the Hatch and Papell Film Cooling Model
 - (5) Gas-side Wall Temperature Predictions for Technology Nozzle NRX-A6 Using the Hatch and Papell Film Cooling Model
 - (6) Gas-side Wall Temperature Predictions for Technology Nozzle XE-Prime Using the Hatch and Papell Film Cooling Model
 - (7) Comparison of Updated Gas-side Thermal Model and Current Gas-side Thermal Model for NERVA 75K Nozzle
 - (8) Technology Nozzle and NERVA 75K Nozzle Contour
 - (9) Wall Mach Number Profile for XE-Prime Nozzle
 - (10) Transonic Wall Mach Number Profile for Technology Nozzles
 - (11) Skin Friction Coefficient Multiplier Profile for Technology Nozzles
 - (12) Gas-side Heat Transfer Coefficient Profiles for the XE-Prime Nozzle
 - (13) C_G Distribution for NERVA 75K Nozzle
 - (14) Braze Alloy Patch Data for Technology Nozzle NRX-A3
 - (15) Braze Alloy Patch Data for Technology Nozzle NRX-EST

TABLE I

MAXIMUM POWER STEADY-STATE AS-RUN OPERATING CONDITIONS FOR
NRX-A5, NRX-A6, AND XE-PRIME NOZZLE FIRINGS

<u>Test</u>	<u>Parameter</u>	<u>Reference</u>
NRX-A5, S/N -024 EP-IV CRT 12970- 12975 Sec	$P_c = 569.6 \text{ psia}$	"Data Analysis Report of NRX-A5 Tests", NRO Report No. RN-S-0317, p. 20. ↓
	$T_c = 4168^\circ\text{R}$	
	$\dot{w}_{\text{gas}} = 70.2 \text{ lb/sec}$	
	$\dot{w}_{\text{coolant}} = 67.7 \text{ lb/sec}$	
	$P_{\text{nozzle in}} = 880.3 \text{ psia}$	
	$P_{\text{nozzle out}} = 735.5 \text{ psia}$	
	$\Delta P_{\text{nozzle}} = 144.8 \text{ psi}$	
	$T_{\text{nozzle in}} = 52.7^\circ\text{R}$	
	$T_{\text{nozzle out}} = 155.7^\circ\text{R}$	
	$\Delta T_{\text{nozzle}} = 103.0^\circ\text{R}$	
NRX-A6, S/N -031 EP III-A CRT 17700 sec	$P_c = 594 \pm 5.81 \text{ psia}$	"NRX-A6 and NRX Program Data Analysis Report (U)", NRO Report No. RN-S-0464, July 1968, p. 2. ↓ same, p. 18.
	$T_c = 4156 \pm 51.96^\circ\text{R}$	
	$\dot{w}_{\text{gas}} = 73.1 \pm 1.26 \text{ lb/sec}$	
	$\dot{w}_{\text{coolant}} = 70.1 \text{ lb/sec}$	
	$P_{\text{nozzle out}} = 750.6 \pm 11.0 \text{ psia}$	

TABLE I

MAXIMUM POWER STEADY-STATE AS-RUN OPERATING CONDITIONS FOR
NRX-A5, NRX-A6, AND XE-PRIME NOZZLE FIRINGS

<u>Test</u>	<u>Parameter</u>	<u>Reference</u>
NRX-A6, S/N -031 EP III-A CRT 17700 sec (Cont.)	$\Delta P_{\text{nozzle}} = 150.5 \text{ psia}$	"NRX-A6 and NRX Program Data Analysis Report (U)", NRO Report No. RN-S-0464, July 1968, p. 50.
	$\Delta T_{\text{nozzle}} = 98^{\circ}\text{R}$	
	$P_{\text{nozzle in}} = 901 \text{ psia}$	"NRX-A6 Nozzle Performance", L. A. Shurley, 7750:M0208, 15 January 1968, Table I.
	$T_{\text{nozzle in}} = 51.4^{\circ}\text{R}$	
	$P_c = 553 \text{ psia}$	"Analysis of Engine Tempera- ture, Pressure, and Flow Measure- ments", A. Anderson and A. Ottaviani, Spear Memo No. 21, <u>Spear Report XE-Prime EP-5C</u> , NT0-R-0171, June 1969.
	$T_c = 4100^{\circ}\text{R}$	
XE-Prime, S/N -028 EP-5C, CRT 38935- 38940 sec	$\dot{w}_{\text{coolant}} = 74.8 \text{ lb/sec}$?	
	$\dot{w}_{\text{core exit}} = 72.4 \text{ lb/sec}$	
	$\dot{w}_{\text{nozzle throat}} = 70.5 \text{ lb/sec}$	
	$P_{\text{nozzle in}} = 923 \text{ psia}$	
	$P_{\text{nozzle out}} = 742 \text{ psia}$	
	$\Delta P_{\text{nozzle}} = 181 \text{ psi}$	
	$T_{\text{nozzle in}} = 50.4^{\circ}\text{R}$	
	$T_{\text{nozzle out}} = 143^{\circ}\text{R}$	
	$\Delta T_{\text{nozzle}} = 92.6^{\circ}\text{R}$	

TABLE II
VALUES OF γ FOR TECHNOLOGY NOZZLES

Nozzle	Chamber	Geo. Throat
NRX-A5	1.296	1.316
NRX-A6	1.297	1.316
XE-Prime	1.298	1.319

COMPARISON OF UPDATED GAS-SIDE THERMAL MODEL AND
PREVIOUS GAS-SIDE THERMAL MODEL FOR NERVA 75 K NOZZLE

SKIN FRICTION COEFFICIENT MULTIPLIER PROFILE FOR TECHNOLOGY NOZZLES

GAS-SIDE HEAT TRANSFER COEFFICIENT PROFILES FOR THE XE-PRIME NOZZLE

AEROJET NUCLEAR SYSTEMS COMPANY
SACRAMENTO, CALIFORNIA

NS H7C
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16

TO: J. L. Watkins 22 January 1971
FROM: J. O. Sane DWL:jm:N4320:M1616
SUBJECT: NERVA Nozzle Coolant-Side Heat Transfer Correlation Project 141, s031
DISTRIBUTION: D. W. Lunsford, E. A. Thomas, P. P. Ventura Work Statement 2f.

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- ENCLOSURES:
- (1) Log of the Ratio of Measured to Calculated Heat Transfer Coefficient Based on New Correlation Equation A Divided by Reynolds Number Versus Log of Reynolds Number
 - (2) Log of the Ratio of Measured to Calculated Heat Transfer Coefficient Based on New Correlation Equation B Divided by Reynolds Number Versus Log of Reynolds Number

CLASSIFICATION CATEGORY	
<i>Unclassified</i>	
<i>WR Thompson</i>	<i>1-25-71</i>
CLASSIFYING OFFICER	DATE

ENCLOSURES:
(Cont.)

- (3) Log of the Ratio of Measured to Calculated Heat Transfer Coefficient Based on Hess and Kunz Correlation Equation Divided by Reynolds Number Versus Log of Reynolds Number
- (4) Comparison of Heat Transfer Coefficient for New Correlation and Hess and Kunz Correlation Versus Nozzle Axial Distance
- (5) Nozzle Heat Transfer Computer Program Output Based on New Coolant Side Correlation Equation A
- (6) Nozzle Heat Transfer Computer Program Output Based on Hess and Kunz Coolant Side Correlation

INTRODUCTION:

All forced convection heat transfer correlation equations are dependent on the fluid physical properties data used for their derivation. A change in these data requires at least a revalidation of the correlation equations. Such a situation presently exists for cryogenic hydrogen. The National Bureau of Standards has recently issued a new compilation of hydrogen physical properties data in the form of a computer program. This new set of data will, in a short time, supersede all older compilations; more specifically, the computer program used for heat transfer analysis of the NERVA nozzle contains hydrogen properties by O. A. Farmer of Los Alamos Scientific Laboratory and a coolant-side heat transfer correlation equation based on Farmer's properties. It is desired to incorporate the new NBS properties data into the program for NERVA nozzle design.

DISCUSSION:

All available resistance-heated tube data for heat transfer to cryogenic para hydrogen have been edited into the ranges of interest to the design of the NERVA nozzle coolant passages; i.e., pressures between 700 and 1800 psia, bulk temperatures less than 250°R , heat fluxes greater than $1.0 \text{ Btu/in}^2\text{-sec-}^{\circ}\text{R}$, and Reynolds numbers greater than 5000. The resulting 1718 straight tube points and 512 curved tube points were taken from References (a), (b), (c), (d), and (e), and have been correlated by a least-squares, multiple-regression technique against currently suggested equation forms.

Two equations for heat transfer coefficient have been chosen for incorporation into the steady state nozzle heat transfer program (E25104). One uses the

average between fluid bulk temperature and coolant side wall temperature to describe the coolant film while the other uses an integral method defined by:

$$\text{Property} = \frac{\int_{T_b}^{T_w} (\text{Property}) dT}{T_w - T_b}$$

Both equations were retained since the integral method, although correlating the data better, requires about four times as much computer time and causes some problems with the convergence of the nozzle heat transfer program.

The two equations are:

A. Film temperature based on average between bulk and wall temperature

$$\text{Nu} = 0.00821 \text{ Re}^{.874} \text{ Pr}^{.4} \left(1 + 0.01457 \frac{\mu_b \rho_w}{\mu_w \rho_b} \right)^{.622} \left(1 + \frac{4.0}{x/d_e} \right)^{1.03}$$

For curvature enhancement the following terms are to be appended:

$(1 + 1.128 \phi)$ for the entrance to the throat region,

$0.797 \left(\text{Re}_b \left(\frac{d_e}{2R_c} \right)^2 \right)^{.0785}$ for fully developed curve flow

and $(3.070 - 1.707 \phi)$ to represent decay of the curvature effect.

where ϕ represents the angle of curvature in radians.

B. Integral Method

$$\text{Nu} = 0.00704 \text{ Re}^{.879} \text{ Pr}^{.4} \left(1 + \frac{4.0}{x/d_e} \right)^{.856}$$

For curvature enhancement the following terms are to be appended:

$(1 + 1.107 \phi)$ for the entrance to the throat region,

$.876 \left(\text{Re}_b \left(\frac{d_e}{2R_c} \right)^2 \right)^{.0666}$ for fully developed curve tube flow

and $(3.033 - 1.649 \phi)$ to represent decay of the curvature effect.

For Equation A, 88.81% of the measured heat transfer coefficients lie within $\pm 25\%$ of the calculated value; and for Equation B, 91.24% of the measured values lie within $\pm 25\%$ of the calculated value. Enclosure (1) shows the correlation of Equation A graphically in the form of

$$\log \left(\frac{h_{\text{measured}}}{h_{\text{calculated (Eq. A)}} / \text{Re}} \right) \text{ vs } \log \text{ Re}$$

Enclosure (2) is a similar plot based on Equation B, and Enclosure (3) shows the currently used Hess and Kunz correlation. Comparison of these three plots reveals the improvement of the data correlation.

A further comparison was made by programing Equation A into the nozzle heat transfer program (E25104). Identical runs were then made with both new Equation A and the Hess and Kunz correlation. Enclosure (4) is a plot of the coolant side heat transfer coefficient versus axial distance for the two correlations. Enclosures (5) and (6) are copies of the computer runs.

CONCLUSIONS AND RECOMMENDATIONS:

Either of the two new correlations provides a better data fit than the currently used Hess and Kunz equation and satisfies the requirement of having a correlation equation based on the new NBS hydrogen physical properties compilation. For economy's sake, Equation A is recommended since the integral method of defining film temperature used in Equation B increases over-all run time of the nozzle heat transfer program by a factor of four. At the time when this equation is incorporated into production work, it will be balanced with a new gas side model and calibrated against technology braze alloy data so that essentially no change in predicted hot side wall temperature will result.

J. O. Sane
Thermodynamics
Scientific Staff Department

Enclosure (1)

Log Ratio of Measured to Calculated
Heat Transfer Coefficient Based on
Equation A Divided by Reynolds
Number Verses Log Reynolds
Number

$\text{Log} \left[\frac{h_{\text{measured}}}{h_{\text{calculated}} Re} \right]$

Enclosure (2)
 Log Ratio of Measured to Calculated
 Heat Transfer Coefficient Based on
 Equation B Divided by Reynolds
 Number

EQUATION 14 - HESS & KUNZ RATIO VS RE PLOT

LOG (RATIO)

$$\text{Log} \left[\frac{h_{e \text{ measured}}}{h_{e \text{ calculated}}} \right]$$

Enclosure (3)
 Log Ratio of Measured to Calculated
 Heat Transfer Coefficient Based on
 Hess and Kunz Correlation Divided
 by Reynolds Verses Log Reynolds
 Number

REGENERATIVE COOLING HEAT TRANSFER (NON-CRYOGENIC AND CRYOGENIC)

PROGRAM E25104

25 NOV 70

*** DERIVED CORRELATION EQUATION WITH FILM TEMPERATURE REFERENCE

PAGE 1

COOLANT = PARA-HYDROGEN (NBS)

TUBE TYPE = VARIABLE

MR = .00 PC = 456. TC = 4290. HC = 0. PIN = 1271.0 TIN = 60.2

UNITS USED IN THIS PROGRAM ARE AS FOLLOWS

PRESSURE	= LB./SQ.IN.	VELOCITY	= IN./SEC.
TEMPERATURE	= DEG.R.	HEAT TRANSFER COEFFICIENT	= BTU/SEC.-SQ.IN.-DEG.R.
ENTHALPY	= BTU/LB.	HEAT FLUX	= BTU/SEC.-SQ.IN.
ENTROPY	= BTU/LB.-DEG.R.	HEAT RATE	= BTU/SEC.
DENSITY	= LB./CU.IN.	LENGTH	= IN.
VISCOSITY	= LB./IN.-SEC.	AREA	= SQ.IN.
CONDUCTIVITY	= BTU/SEC.-IN.-DEG.R.	STRESS	= LB./SQ.IN.
SPECIFIC HEAT	= BTU/LB.-DEG.R.		

EFF SURF AREA	LEG SPREAD	EQUIV DIA	NMB	SMD	RA	RG	THC
THM	THS	GAMMA	ENTROPY	GAS VEL	FRIC FACT	PFM	PF
PV	SUM PF	COOL VEL	COOL MACH	DEV DIST	HG	HL	HR
SHAPE FACT	GRAY BODY	FCFV	CL	CG	U	Q/AO	0
STRESS	YLD STR	KC	KM	KWG	CP-CB	PR-CF	VISC-CB
VISC-CF	VISC-CW	RHO-CB	RHO-CF	RHO-CW	RHORAR	H-CB	CP-GF
PR-GF	VISC-GF	RHO-GB	RBO	QOABO	RHO-GF	KB	KCF
PPB-B	VDT	TSAT					

STA -1	Z = -72.46	TWG = 682.	PRC = 1270.3	WG = 93.3	PG = 1.0	NT = 216.
	R = 27.459	TWM = 583.	TB = 60.1	WC = 74.6	TG = 850.	AF = .296
ITR 5	A/AT = 24.00	TWL = 483.	Q/AI = 1.48	SUMQ = 0.	BETA = .910	L = .1058

.00000	.80377+00	.55725+00	.21600+03	.00000	.00000	.40020+00	.00000
.28000-01	.10000-01	.00000	.00000	.00000	.28005-02	.18003+01	.00000
.71587+00	.00000	.47456+03	.99535-02	.83610+02	.42803-03	.35032-02	.00000
.11704+00	.00000	.00000	.17680-01	.89200-01	.38569-03	.13789+01	.00000
.10886+05	.27719+05	.10000+11	.20081-03	.00000	.28690+01	.74642+00	.59022-06
.34635-06	.46920-06	.24545-02	.47591-03	.27067-03	.00000	-.16284+02	.37061+01
.67591+00	.13169-05	.12982-06	.00000	.00000	.48490-07	.16793-05	.19243-05
.00000	.00000	.00000					

TUBE TYPE = U-TUBE

MATERIAL = STAINLESS STEEL

STA -2	Z = 69.32	TWG = 736.	PRC = 1270.1	WG = 93.3	PG = 1.2	NT = 216.
	R = 26.290	TWM = 635.	TB = 64.5	WC = 74.6	TG = 888.	AF = .285
ITR 3	A/AT = 22.00	TWL = 534.	Q/AI = 1.55	SUMQ = 1005.	BETA = .910	L = .1225

.33114+01	.76945+00	.54996+00	.21600+03	.00000	.00000	.38294+00	.00000
.28000-01	.10000-01	.00000	.00000	.00000	.28194-02	.18003+01	.94204-01
.11503+00	.94204-01	.51222+03	.1160-01	.80265+02	.45215-03	.32880-02	.00000
.11742+00	.00000	.00000	.17680-01	.85100-01	.40247-03	.14324+01	.10054+04
.16100+05	.27010+05	.19000+11	.20637+03	.00000	.30588+01	.74049+00	.53257-06
.30304-06	.49590-06	.23650-02	.43121-03	.24600-03	.24090-02	-.30983+01	.37136+01
.67513+00	.13075-05	.14093-06	.00000	.00000	.53972-07	.16260-05	.20269-05
.00000	.00000	.00000					

STA 3	Z = 66.17	TWG = 909.	PRC = 1270.1	WG = 93.3	PG = 1.3	NT = 216.
	P = 25.066	TWM = 830.	TB = 68.4	WC = 74.6	TG = 925.	AF = .321
ITR 4	A/AT = 20.00.	TWL = 751.	Q/AI = 1.32	SUMQ = 1920.	BETA = .910	L = .1401

.31951+01	.73383+00	.57881+00	.21600+03	.00000	.00000	.36488+00	.00000
.28000-01	.10000-01	.00000	.00000	.00000	.28150-02	.18003+01	.88513-01
.11915+00	.13272+00	.47187+03	.10641+01	.76085+02	.40635-03	.19305-02	.00000
.11642+00	.00000	.00000	.17680-01	.69100-01	.34364-03	.12166+01	.91410+03
.15281+05	.24886+05	.10000+11	.22435-03	.00000	.32235+01	.70370+00	.49362-06
.42781-06	.60563-06	.22822-02	.31734-03	.17698-03	.23236-02	.90526+01	.37380+01
.67622+00	.13619-05	.15791-06	.00000	.00000	.60797-07	.15795-05	.23328-05
.00000	.00000	.00000					

STA 4	Z = 63.00	TWG = 966.	PRC = 1269.9	WG = 93.3	PG = 1.5	NT = 216.
	R = 23.780	TWM = 889.	TB = 71.7	WC = 74.6	TG = 964.	AF = .305
ITR 3	A/AT = 18.00	TWL = 812.	Q/AI = 1.32	SUMQ = 2727.	BETA = .910	L = .1601

.30728+01	.69645+00	.56491+00	.21600+03	.00000	.00000	.34590+00	.00000
.28000-01	.10000-01	.00000	.00000	.00000	.27714-02	.18003+01	.84699-01
.11431+00	.26742+00	.51185+03	.11893-01	.73465+02	.41433-03	.17898-02	.00000
.11433+00	.00000	.00000	.17680-01	.62400-01	.34560-03	.12172+01	.80770+03
.10413+05	.24174+05	.10000+11	.23003-03	.00000	.33620+01	.69983+00	.46088-06
.44586-06	.63614-06	.22125-02	.29513-03	.16383-03	.22474-02	.19999+02	.37459+01
.67635+00	.13730-05	.17471-06	.00000	.00000	.69231-07	.15386-05	.24018-05
.00000	.00000	.00000					

STA 5	Z = 59.77	TWG = 1031.	PRC = 1269.7	WG = 93.3	PG = 1.9	NT = 216.
	R = 22.420	TWM = 955.	TB = 74.8	WC = 74.6	TG = 1017.	AF = .289
ITR 3	A/AT = 16.00	TWL = 878.	Q/AI = 1.40	SUMQ = 3532.	BETA = .910	L = .1799

.29778+01	.65688+00	.54920+00	.21600+03	.00000	.00000	.32582+00	.00000
.27000-01	.10000-01	.00000	.00000	.00000	.27350-02	.18003+01	.10091+00
.14204+00	.36032+00	.55926+03	.13382-01	.69958+02	.44710-03	.17430-02	.00000
.11255+00	.00000	.00000	.17680-01	.58400-01	.36575-03	.12844+01	.80452+03
.14052+05	.23363+05	.10000+11	.23697-03	.00000	.34806+01	.69474+00	.43678-06
.46553-06	.66997-06	.21404-02	.27403-03	.15188-03	.21765-02	.30624+02	.37550+01
.67653+00	.13859-05	.20260-06	.00000	.00000	.83581-07	.14980-05	.24765-05
.00000	.00000	.00000					

STA 6	Z = 56.49	TWG = 1096.	PRC = 1269.4	WG = 93.3	PG = 2.2	NT = 216.
	R = 20.972	TWM = 1018.	TB = 77.9	WC = 74.6	TG = 1069.	AF = .271
ITR 3	A/AT = 14.00	TWL = 941.	Q/AI = 1.52	SUMQ = 4358.	BETA = .910	L = .2013

.28563+01	.61476+00	.53089+00	.21600+03	.00000	.00000	.30445+00	.00000
.26000-01	.10000-01	.00000	.00000	.00000	.26975-02	.18003+01	.12237+00
.18406+00	.49069+00	.61709+03	.15223-01	.66373+02	.49677-03	.17676-02	.00000
.10930+00	.00000	.00000	.17680-01	.55700-01	.39859-03	.13948+01	.82646+03
.13594+05	.22638+05	.10000+11	.24363-03	.00000	.35980+01	.69051+00	.41326-06
.48332-06	.70133-06	.20669-02	.25727-03	.14221-03	.21036-02	.41797+02	.37641+01
.67670+00	.13987-05	.22808-06	.00000	.00000	.97491-07	.14571-05	.25455-05
.00000	.00000	.00000					

COOLANT = PARA-HYDROGEN (NBS)

TUBE TYPE = VARIABLE

MR = .00 PC = 456. TC = 4290. HC = 0. PIN = 1271.0 TIN = 60.2

* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *
EFF SURF AREA	LEG SPREAD	EQUIV DIA	NMB	SMD	RA	RG	THC
TH	THS	GAMMA	ENTROPY	GAS VEL	FRIC FACT	PFM	PF
PV	SUM PF	COOL VEL	COOL MACH	DEV DIST	HG	HL	HR
SHAPE FACT	GRAY BODY	FCFV	CL	CG	U	Q/AO	Q
STRESS	YLO STR	KC	KM	KWG	CP-CB	PR-CF	VISC-CB
VISC-CF	VISC-CW	RHO-CB	RHO-CF	PHO-CW	RHOBAR	H-CB	CP-GF
PP-GF	VISC-GF	RHO-GB	RBO	QOABO	RHO-GF	KB	KCF
PPB-B	VD*	TSAT					
* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *

STA 7	Z = 53.15	TWG = 1149.	PRC = 1269.0	WG = 93.3	PG = 2.8	NT = 216.
	P = 19.416	TWM = 1068.	TB = 80.8	WC = 74.6	TG = 1140.	AF = .251
ITR 3	A/AT = 12.00	TWL = 987.	Q/AI = 1.69	SUMQ = 5224.	BETA = .910	L = .2241

.27294+01	.56949+00	.50867+00	.21600+03	.00000	.00000	.28149+00	.00000
.25000-01	.10000-01	.00000	.00000	.00000	.26603-02	.18003+01	.15335+00
.24267+00	.64404+00	.68786+03	.17339-01	.62688+02	.55967-03	.18665-02	.00000
.10482+00	.00000	.00000	.17680-01	.52000-01	.41253-03	.15416+01	.86560+03
.13010+05	.22107+05	.10000+11	.24879-03	.00000	.37052+01	.68561+00	.39211-06
.40501-06	.72400-06	.20008-02	.24593-03	.3540-03	.20338-02	.52135+02	.37715+01
.67477+00	.14034-05	.27040-06	.00000	.00000	.12214-06	.14222-05	.26111-05
.00000	.00000	.00000					

STA 8	Z = 49.68	TWG = 1210.	PRC = 1268.4	WG = 93.3	PG = 3.8	NT = 216.
	P = 17.725	TWM = 1123.	TB = 84.0	WC = 74.6	TG = 1232.	AF = .229
ITR 3	A/AT = 10.00	TWL = 1037.	Q/AI = 1.93	SUMQ = 6154.	BETA = .920	L = .2483

.26184+01	.52028+00	.48126+00	.21600+03	.00000	.00000	.25653+00	.00000
.24000-01	.10000-01	.00000	.00000	.00000	.26242-02	.18003+01	.20415+00
.36324+00	.84220+00	.78574+03	.20317-01	.58838+02	.63623-03	.20226-02	.00000
.93791-01	.00000	.00000	.17680-01	.47500-01	.49686-03	.17469+01	.92996+03
.12289+05	.21501+05	.10000+11	.25399-03	.00000	.37956+01	.68040+00	.37410-06
.50908-06	.74737-06	.19234-02	.23491-03	.12930-03	.19621-02	.64411+02	.37860+01
.67126+00	.14273-05	.33466-06	.00000	.00000	.16055-06	.13874-05	.26807-05
.00000	.00000	.00000					

STA 9	Z = 46.06	TWG = 1281.	PRC = 1267.5	WG = 93.3	PG = 5.2	NT = 216.
	R = 15.853	TWM = 1186.	TB = 87.5	WC = 74.6	TG = 1346.	AF = .203
ITR 3	A/AT = 8.00	TWL = 1092.	Q/AI = 2.26	SUMQ = 7175.	BETA = .920	L = .2759

.25036+01	.46583+00	.44719+00	.21600+03	.00000	.00000	.22890+00	.00000
.23000-01	.10000-01	.00000	.00000	.00000	.25647-02	.18003+01	.29330+00
.36992+00	.11415+01	.92330+03	.24559-01	.54750+02	.76191-03	.22483-02	.00000
.90592-01	.00000	.00000	.17680-01	.43400-01	.58505-03	.20313+01	.10216+04
.11377+05	.20790+05	.10000+11	.25999-03	.00000	.38903+01	.67458+00	.35524-06
.52306-06	.77156-06	.18399-02	.22257-03	.12271-03	.18817-02	.78064+02	.38015+01

.67013+00	.14407-05	.42067-06	.00000	.00000	.21740-06	.13498-05	.27584-05
.00000	.00000	.00000					

STA 10	Z = 44.17	TWG = 1316.	PRC = 1266.9	WG = 93.3	PG = 6.3	NT = 216.
R = 14.829	TWM = 1218.	TB = 89.4	WC = 74.6	TG = 1421.	AF = .189	
ITR 2 A/AT = 7.00	TWL = 1120.	Q/AI = 2.48	SUMQ = 7729.	BETA = .920	L = .2898	

.12043+01	.43601+00	.42692+00	.21600+03	.00000	.00000	.21379+00	.00000
.22000-01	.10000-01	.00000	.00000	.00000	.25636-02	.18003+01	.20184+00
.41576+00	.13433+01	.10145+04	.27382-01	.52606+02	.84548-03	.24061-02	.00000
.85415-01	.00000	.00000	.17680-01	.41000-01	.64273-03	.22249+01	.55355+03
.11044+05	.20441+05	.10000+11	.26296-03	.00000	.39380+01	.67210+00	.34576-06

.53143-06	.78390-06	.17979-02	.21679-03	.11973-03	.18189-02	.84960+02	.38079+01
.66933+00	.14471-05	.48419-06	.00000	.00000	.26224-06	.13310-05	.27980-05
.00000	.00000	.00000					

STA 11	Z = 42.20	TWG = 1357.	PRC = 1266.1	WG = 93.3	PG = 8.1	NT = 216.
R = 13.729	TWM = 1254.	TB = 91.4	WC = 74.6	TG = 1520.	AF = .174	
ITR 3 A/AT = 6.00	TWL = 1150.	Q/AI = 2.77	SUMQ = 8326.	BETA = .930	L = .3058	

.11757+01	.40400+00	.40387+00	.21600+03	.00000	.00000	.19755+00	.00000
.21000-01	.10000-01	.00000	.00000	.00000	.25427-02	.18003+01	.26455+00
.57104+00	.16079+01	.11308+04	.30948-01	.50345+02	.94157-03	.26190-02	.00000
.78360-01	.00000	.00000	.17680-01	.37700-01	.71151-03	.24792+01	.59728+03
.10644+05	.20032+05	.10000+11	.26638-03	.00000	.39703+01	.67089+00	.33696-06

.53968-06	.79734-06	.17504-02	.21176-03	.11666-03	.17742-02	.93253+02	.38232+01
.66745+00	.14626-05	.58137-05	.00000	.00000	.33308-06	.13106-05	.28413-05
.00000	.00000	.00000					

STA 12	Z = 40.13	TWG = 1370.	PRC = 1264.9	WG = 93.3	PG = 10.9	NT = 216.
R = 12.533	TWM = 1260.	TB = 93.5	WC = 74.6	TG = 1644.	AF = .158	
ITR 3 A/AT = 5.00	TWL = 1151.	Q/AI = 3.10	SUMQ = 8970.	BETA = .930	L = .3231	

.11404+01	.36920+00	.37654+00	.21600+03	.00000	.00000	.17990+00	.00000
.20000-01	.10000-01	.00000	.00000	.00000	.25215-02	.18003+01	.36414+00
.82699+00	.19720+01	.12844+04	.35608-01	.47955+02	.10502-02	.29263-02	.00000
.72155-01	.00000	.00000	.17680-01	.33600-01	.79453-03	.27518+01	.64425+03
.10113+05	.19904+05	.10000+11	.26704-03	.00000	.39912+01	.67077+00	.32911-06

.54048-06	.79783-06	.17025-02	.21109-03	.11645-03	.17265-02	.10188+03	.38238+01
.66682+00	.14648-05	.72367-06	.00000	.00000	.44650-06	.12905-05	.28455-05
.00000	.00000	.00000					

STA 13	Z = 37.93	TWG = 1363.	PRC = 1262.3	WG = 93.3	PG = 14.9	NT = 216.
R = 11.210	TWM = 1240.	TB = 95.8	WC = 74.6	TG = 1799.	AF = .130	
ITR 3 A/AT = 4.00	TWL = 1117.	Q/AI = 3.65	SUMQ = 9682.	BETA = .930	L = .3444	

.11033+01	.33077+00	.36613+00	.21600+03	.00000	.00000	.16038+00	.00000
.19000-01	.10000-01	.00000	.00000	.00000	.24483-02	.18003+01	.55967+00
.10831+01	.25317+01	.16041+04	.45122-01	.45390+02	.12255-02	.35749-02	.00000
.63545-01	.00000	.00000	.17680-01	.29900-01	.93784-03	.32190+01	.71154+03
.93928+04	.19974+05	.10000+11	.26510-03	.00000	.40149+01	.67200+00	.32046-06

.53247-06	.73295-06	.16498-02	.21543-03	.11954-03	.16761-02	.11121+03	.38216+01
.66672+00	.14633-05	.90279-06	.00000	.00000	.60363-06	.12682-05	.28034-05
.00000	.00000	.00000					

COOLANT = PARA-HYDROGEN (NBS)

TUBE TYPE = VARIABLE

MR = .00 PC = 456. TC = 4290. HC = 0. PIN = 1271.0 TIN = 60.2

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EFF SURF AREA	LEG SPREAD	EQUIV DIA	NMB	SMD	RA	RG	THC
THM	THS	GAMMA	ENTROPY	GAS VEL	FRIC FACT	PFM	PF
PV	SUM PF	COOL VEL	COOL MACH	DEV DIST	HG	HL	HR
SHAPE FACT	GRAY BODY	FEFV	CL	CG	U	Q/AO	Q
STRESS	YLD STR	KC	KM	KWG	CP-CB	PR-CF	VISC-CB
VISC-CF	VISC-CW	RHO-CB	RHO-CF	RHO-CW	RHOBAR	H-CB	CP-GF
PR-GF	VISC-GF	RHO-GB	RBO	QOABO	RHO-GF	KB	KCF
PRB-B	VDT	TSAT					
* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *

STA 14	Z = 35.52	TWG = 1455.	PRC = 1259.0	WG = 93.3	PG = 23.7	NT = 216.
	R = 9.708	TWM = 1322.	TB = 98.4	WC = 74.6	TG = 2038.	AF = .113
ITR 3	A/AT = 3.00	TWL = 1189.	Q/AI = 4.34	SUMQ = 10492.	BETA = .940	L = .3666

.10719+01	.23708+00	.33127+00	.21600+03	.00000	.00000	.13821+00	.00000
.13000-01	.10000-01	.00000	.00000	.00000	.24195-02	.18003+01	.93285+00
.23060+01	.34645+01	.19259+04	.55088-01	.42550+02	.14663-02	.39836-02	.00000
.53135-01	.00000	.00000	.17680-01	.25200-01	.11042-02	.37794+01	.81025+03
.84081+04	.19048+05	.10000+11	.27319-03	.00000	.40417+01	.66912+00	.31064-06
.55119-06	.81440-06	.15898-02	.20386-03	.11227-03	.16198-02	.12177+03	.38433+01
.66335+00	.14879-05	.12670-05	.00000	.00000	.94326-06	.12429-05	.29015-05
.00000	.00000	.00000					

STA 15	Z = 32.71	TWG = 1573.	PRC = 1252.2	WG = 93.3	PG = 46.2	NT = 216.
	R = 7.927	TWM = 1420.	TB = 101.5	WC = 74.6	TG = 2442.	AF = .091
ITR 3	A/AT = 2.00	TWL = 1262.	Q/AI = 5.73	SUMQ = 11475.	BETA = .950	L = .3925

.10535+01	.23526+00	.28309+00	.21600+03	.00000	.00000	.11192+00	.00000
.17000-01	.10000-01	.00000	.00000	.00000	.23873-02	.18003+01	.18491+01
.50059+01	.53137+01	.24959+04	.72467-01	.39218+02	.19445-02	.49330-02	.00000
.40383-01	.00000	.00000	.17680-01	.20300-01	.14406-02	.48578+01	.98274+03
.69917+04	.10607+05	.10000+11	.28295-03	.00000	.40367+01	.66619+00	.30174-06
.57043-06	.84658-06	.15223-02	.19153-03	.10547-03	.15561-02	.13437+03	.38688+01
.65929+00	.15173-05	.20607-05	.00000	.00000	.17814-05	.12243-05	.30023-05
.00000	.00000	.00000					

STA 16	Z = 32.40	TWG = 1573.	PRC = 1251.4	WG = 93.3	PG = 53.5	NT = 216.
	R = 7.726	TWM = 1421.	TB = 101.9	WC = 74.6	TG = 2520.	AF = .089
ITR 2	A/AT = 1.90	TWL = 1263.	Q/AI = 5.85	SUMQ = 11582.	BETA = .950	L = .3956

.10051+00	.22942+00	.27922+00	.21600+03	.00000	.00000	.10895+00	.00000
.16000-01	.10000-01	.00000	.00000	.00000	.23852-02	.18003+01	.27540+00
.53237+00	.55891+01	.25495+04	.74092-01	.38358+02	.19961-02	.50186-02	.00000
.38925-01	.00000	.00000	.17680-01	.19300-01	.14731-02	.49950+01	.10696+03
.72701+04	.18624+05	.10000+11	.28305-03	.00000	.40352+01	.66594+00	.30087-06
.57207-06	.84930-06	.15153-02	.19046-03	.10490-03	.15188-02	.13571+03	.38673+01

.65910+00	.15161-05	.22976-05	.00000	.00000	.20642-05	.12226-05	.30109-05
.00000	.00000	.00000					

STA 17 Z = 30.99.	TWG = 1637.	PRC = 1245.4	WG = 93.3	PG = 83.4	NT = 216.
R = 6.842	TWM = 1473.	TB = 103.4	WC = 74.6	TG = 2838.	AF = .079
ITR 3 A/AT = 1.49	TWL = 1310.	Q/AI = 6.87	SUMQ = 12086.	BETA = .960	L = .4079

.43247+00	.20368+00	.25314+00	.21600+03	.00000	.00000	.95908-01	.00000
.15000-01	.10000-01	.00000	.00000	.00000	.23692-02	.18003+01	.15839+01
.44301+01	.71729+01	.29658+04	.86643-01	.37188+02	.23346-02	.56917-02	.00000
.32650-01	.00000	.00000	.17680-01	.16700-01	.17100-02	.57941+01	.50392+03
.67173+04	.18411+05	.10000+11	.28825-03	.00000	.40293+01	.66457+00	.29641-06

.58305-06	.86778-06	.14797-02	.18367-03	.10112-03	.14975-02	.14218+03	.38826+01
.65628+00	.15340-05	.32021-05	.00000	.00000	.31546-05	.12131-05	.30682-05
.00000	.00000	.00000					

STA 18 Z = 29.67	TWG = 1847.	PRC = 1237.3	WG = 93.3	PG = 182.6	NT = 216.
R = 6.037	TWM = 1656.	TB = 104.9	WC = 74.6	TG = 3396.	AF = .069
ITR 4 A/AT = 1.16	TWL = 1486.	Q/AI = 8.70	SUMQ = 12583.	BETA = .970	L = .4207

.35255+00	.18029+00	.22806+00	.21600+03	.00000	.00000	.84027-01	.00000
.14000-01	.10000-01	.00000	.00000	.00000	.23550-02	.18003+01	.21388+01
.59231+01	.93117+01	.34558+04	.10155+00	.35638+02	.31326-02	.62993-02	.00000
.27083-01	.00000	.00000	.17680-01	.16100-01	.21441-02	.72509+01	.49669+03
.61888+04	.16269+05	.10000+11	.30665-03	.00000	.40245+01	.66170+00	.29192-06

.62803-06	.94537-06	.14442-02	.16288-03	.88852-04	.14620-02	.14838+03	.39199+01
.67403+00	.15748-05	.50402-05	.00000	.00000	.65731-05	.12027-05	.33037-05
.00000	.00000	.00000					

STA 19 Z = 28.95	TWG = 1837.	PRC = 1232.7	WG = 93.3	PG = 231.6	NT = 216.
R = 5.715	TWM = 1611.	TB = 105.8	WC = 74.6	TG = 3651.	AF = .066
ITR 3 A/AT = 1.04	TWL = 1335.	Q/AI = 11.52	SUMQ = 12879.	BETA = .980	L = .4239

.16266+00	.17088+00	.21884+00	.21600+03	.00000	.00000	.79274-01	.00000
.13000-01	.10000-01	.00000	.00000	.00000	.23480-02	.18003+01	.14168+01
.31554+01	.10722+02	.36938+04	.10890+00	.34350+02	.40692-02	.90051-02	.00000
.23110-01	.00000	.00000	.27040-01	.17900-01	.28099-02	.96319+01	.29659+03
.62845+04	.16459+05	.10000+11	.30135-03	.00000	.40208+01	.66336+00	.28929-06

.60275-06	.90117-06	.14232-02	.17333-03	.95165-04	.14337-02	.15210+03	.39249+01
.67264+00	.15778-05	.68916-05	.00000	.00000	.82983-05	.11967-05	.31710-05
.00000	.00000	.00000					

STA 20 Z = 28.17	TWG = 1903.	PRC = 1216.5	WG = 93.3	PG = 248.0	NT = 216.
R = 5.605	TWM = 1591.	TB = 106.7	WC = 74.6	TG = 3736.	AF = .053
ITR 3 A/AT = 1.00	TWL = 1279.	Q/AI = 15.84	SUMQ = 13265.	BETA = .990	L = .3485

.15631+00	.16544+00	.20546+00	.21600+03	.00000	.00000	.77651-01	.00000
.13000-01	.10000-01	.00000	.00000	.00000	.22928-02	.18003+01	.19659+01
.14225+02	.12694+02	.46407+04	.13788+00	.34062+02	.56308-02	.13513-01	.00000
.25031-01	.00000	.00000	.28750-01	.23600-01	.38253-02	.13197+02	.38538+03
.60500+04	.15131+05	.10000+11	.29948-03	.00000	.40240+01	.66544+00	.28527-06

.57619-06	.85500-06	.13937-02	.18310-03	.10115-03	.14084-02	.15600+03	.39436+01
.67411+00	.15959-05	.72153-05	.00000	.00000	.87452-05	.11847-05	.30314-05
.00000	.00000	.00000					

**** DERIVED CORRELATION EQUATION WITH FILM TEMPERATURE REFERENCE

PAGE 4

COOLANT = PARA-HYDROGEN (NBS)

TUBE TYPE = VARIABLE

MR = .00 PC = 456. TC = 4290. HC = 0. PIN = 1271.0 TIN = 60.2

* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *
EFF SURF AREA	LEG SPREAD	EQUIV DIA	NMB	SMD	RA	R6	THC
THM	THS	GAMMA	ENTROPY	GAS VEL	FRIC FACT	PFM	PF
PV	SUM PF	COOL VEL	COOL MACH	DEV DIST	HG	HL	HR
SHAPE FACT	GRAY BODY	FEFV	CL	CG	U	Q/AO	Q
STRESS	YLD STR	KC	KM	KWG	CP-CB	PR-CF	VISC-CB
VISC-CF	VISC-CW	RHO-CB	RHO-CF	RHO-CW	RHORAR	H-CB	CP-GF
PP-GF	VISC-GF	RHO-GB	RBO	GOABO	RHO-GF	KB	KCF
PFGB-B	VDT	YSAT					
* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *

STA 21	Z = 27.08	TWG = 2088.	PRC = 1160.9	WG = 93.3	PG = 301.7	NT = 216.
	R = 5.713	TWM = 1692.	TB = 107.5	WC = 74.6	TG = 3910.	AF = .036
ITR 3	A/AT = -1.04	TWL = 1296.	Q/AI = 20.70	SUMQ = 13984.	BETA = .990	L = .2168

.21336+00	.16480+00	.18603+00	.21600+03	.00000	.00000	.79245-01	.00000
.13000-01	.10000-01	.00000	.00000	.00000	.21875-02	.18003+01	.55627+01
.50030+02	.18257+02	.71495+04	.21729+00	.32961+02	.79755-02	.17413-01	.46568-04
.27314-01	.21660-02	.00000	.29900-01	.33600-01	.49999-02	.17322+02	.71973+03
.59150+04	.93902+04	.10000+11	.30936-03	.00000	.40453+01	.66507+00	.27636-06
.55079-06	.86366-06	.13308-02	.17285-03	.95367-04	.13622-02	.16113+03	.39739+01
.66902+00	.16248-05	.83761-05	.00000	.00000	.10355-04	.11523-05	.30537-05
.00000	.00000	.00000					

STA 22	Z = 26.03	TWG = 1971.	PRC = 1142.8	WG = 93.3	PG = 353.9	NT = 216.
	R = 6.032	TWM = 1573.	TB = 110.0	WC = 74.6	TG = 4056.	AF = .036
ITR 3	A/AT = -1.16	TWL = 1175.	Q/AI = 19.92	SUMQ = 14822.	BETA = .990	L = .1941

.22692+00	.17355+00	.18901+00	.21600+03	.00000	.00000	.83953-01	.00000
.13000-01	.10000-01	.00000	.00000	.00000	.21722-02	.18003+01	.83566+01
.97270+01	.26614+02	.75426+04	.23158+00	.31861+02	.73214-02	.18711-01	.82328-04
.31392-01	.41430-02	.00000	.29180-01	.32800-01	.48150-02	.16840+02	.83740+03
.62376+04	.13638+05	.10000+11	.29777-03	.00000	.40108+01	.66941+00	.27095-06
.55051-06	.81048-06	.12719-02	.18638-03	.10346-03	.13013-02	.17160+03	.39529+01
.66847+00	.16013-05	.94592-05	.00000	.00000	.12356-04	.11349-05	.28953-05
.00000	.00000	.00000					

STA 23	Z = 25.06	TWG = 1972.	PRC = 1170.4	WG = 93.3	PG = 387.9	NT = 216.
	R = 6.549	TWM = 1656.	TB = 113.8	WC = 74.6	TG = 4140.	AF = .047
ITR 3	A/AT = -1.37	TWL = 1340.	Q/AI = 15.04	SUMQ = 15602.	BETA = 1.000	L = .2349

.24430+00	.19000+00	.21337+00	.21600+03	.00000	.00000	.91583-01	.00000
.14000-01	.10000-01	.00000	.00000	.00000	.22171-02	.18003+01	.64066+01
.33959+02	.33020+02	.59729+04	.18248+00	.30760+02	.53850-02	.12268-01	.11466-03
.39182-01	.53075-02	.00000	.26310-01	.27600-01	.36014-02	.12749+02	.78087+03
.64360+04	.13621+05	.10000+11	.30558-03	.00000	.39429+01	.66429+00	.27002-06
.59338-06	.88255-06	.12392-02	.16894-03	.93333-04	.12551-02	.18514+03	.39592+01

.66745+00	.16067-05	.10173-04	.00000	.00000	.13459-04	.11358-05	.31198-05
.00000	.00000	.00000					

STA 24	Z = 24.21	TWG = 1941.	PRC = 1194.1	WG = 93.3	PG = 414.7	NT = 216.
R	= 7.247	TWM = 1696.	TB = 117.0	WC = 74.6	TG = 4202.	AF = .067
ITR 3	A/AT = -1.67	TWL = 1452.	Q/AI = 11.69	SUMQ = 16266.	BETA = 1.000	L = .3056

.26902+00	.21266+00	.25077+00	.21600+03	.00000	.00000	.10189+00	.00000
.14000-01	.10000-01	.00000	.00000	.00000	.22832-02	.18003+01	.31826+01
-.26901+02	.36203+02	.42602+04	.12972+00	.29660+02	.41522-02	.87582-02	.14251-03
-.40652-01	.86955-02	.00000	.21630-01	.25200-01	.28015-02	.10087+02	.66348+03
.74961+04	.14379+05	.10000+11	.30983-03	.00000	.38883+01	.66230+00	.26901-06

.62269-06	.93153-06	.12064-02	.15980-03	.87998-04	.12223-02	.19690+03	.39537+01
.66702+00	.15998-05	.10719-04	.00000	.00000	.14454-04	.11354-05	.32739-05
.00000	.00000	.00000					

STA 25	Z = 22.76	TWG = 1932.	PRC = 1199.9	WG = 93.3	PG = 423.9	NT = 216.
R	= 8.697	TWM = 1747.	TB = 121.1	WC = 74.6	TG = 4221.	AF = .085
ITR 3	A/AT = -2.41	TWL = 1561.	Q/AI = 8.33	SUMQ = 17363.	BETA = 1.000	L = .3000

.50379+00	.25530+00	.29069+00	.21600+03	.00000	.00000	.12329+00	.00000
.15000-01	.10000-01	.00000	.00000	.00000	.23095-02	.18003+01	.29050+01
-.66055+01	.30108+02	.35262+04	.10761+00	.27609+02	.29432-02	.57807-02	.15881-03
.78500-01	.20952-01	.00000	.17680-01	.24700-01	.19971-02	.73135+01	.10971+04
.86019+04	.14559+05	.10000+11	.31512-03	.00000	.38336+01	.66219+00	.26709-06

.65160-06	.97720-06	.11564-02	.15019-03	.82290-04	.11814-02	.21279+03	.39521+01
.66637+00	.15977-05	.10906-04	.00000	.00000	.14793-04	.11270-05	.34253-05
.00000	.00000	.00000					

STA 26	Z = 21.31	TWG = 1821.	PRC = 1202.3	WG = 93.3	PG = 434.7	NT = 216.
R	= 10.148	TWM = 1660.	TB = 124.8	WC = 74.6	TG = 4244.	AF = .101
ITR 3	A/AT = -3.28	TWL = 1499.	Q/AI = 6.97	SUMQ = 10381.	BETA = 1.000	L = .2830

.69513+00	.29703+00	.32552+00	.21600+03	.00000	.00000	.14470+00	.00000
.15000-01	.10000-01	.00000	.00000	.00000	.23287-02	.18003+01	.17819+01
-.42667+01	.40890+02	.30833+04	.93816-01	.25557+02	.23699-02	.50769-02	.16163-03
.10837+00	.26190-01	.00000	.17680-01	.26000-01	.16738-02	.62495+01	.10182+04
.10396+05	.16776+05	.10000+11	.30597-03	.00000	.37851+01	.66185+00	.26503-06

.63642-06	.95174-06	.11090-02	.15554-03	.85610-04	.11327-02	.22717+03	.39339+01
.66726+00	.15778-05	.11123-04	.00000	.00000	.15416-04	.11307-05	.33460-05
.00000	.00000	.00000					

STA 27	Z = 19.86	TWG = 1729.	PRC = 1203.6	WG = 93.3	PG = 447.1	NT = 216.
R	= 11.599	TWM = 1577.	TB = 128.5	WC = 74.6	TG = 4271.	AF = .116
ITR 3	A/AT = -4.28	TWL = 1424.	Q/AI = 5.98	SUMQ = 19396.	BETA = 1.000	L = .2664

.80623+00	.33998+00	.35479+00	.21600+03	.00000	.00000	.16612+00	.00000
.16000-01	.10000-01	.00000	.00000	.00000	.23473-02	.18003+01	.12297+01
-.25125+01	.42120+02	.27780+04	.84313-01	.23505+02	.19458-02	.46142-02	.16469-03
.14877+00	.31792-01	.00000	.17680-01	.26900-01	.14370-02	.54042+01	.10147+04
.11293+05	.18103+05	.10000+11	.29811-03	.00000	.37560+01	.66254+00	.26421-06

.61865-06	.91930-06	.10681-02	.16271-03	.90433-04	.10885-02	.24080+03	.39189+01
.66755+00	.15611-05	.11368-04	.00000	.00000	.16066-04	.11332-05	.32531-05
.00000	.00000	.00000					

**** DERIVED CORRELATION EQUATION WITH FILM TEMPERATURE REFERENCE

PAGE 5

COOLANT = PARA-HYDROGEN (NBS)

TUBE TYPE = VARIABLE

MR = .00 PC = 456. TC = 4290. HC = 0. PIN = 1271.0 TIN = 60.2

* 2 * *	* * *	* * *	* * *	* * *	* * *	* * *	* * *
EFF SURF AREA	LEG SPREAD	EQUIV DIA	NMB	SMD	RA	RG	THC
THM	THS	GAMMA	ENTROPY	GAS VEL	FRIC FACT	PFM	PF
PV	SUM PF	COOL VEL	COOL MACH	DEV DIST	HG	HL	HR
SHAPE FACT	GRAY BODY	FCFV	CL	CG	U	Q/AO	Q
STRESS	YLD STR	KC	KM	KWG	CP-CB	PR-CF	VISC-CB
VISC-CF	VISC-CW	RHO-CB	RHO-CF	RHO-CW	RHOBAR	H-CB	CP-GF
PR-GF	VISC-GF	RHO-GF	RBO	QCABO	RHO-GF	KB	KCF
PPB-B	VDT	TSAT					

STA 28	Z	= 16.41	TWG	= 1716.	PRC	= 1204.1	WG	= 93.3	PG	= 456.0	NT	= 216.
	R	= 13.050	TWM	= 1574.	TB	= 132.2	WC	= 74.6	TG	= 4290.	AF	= .130
ITR 3	A/AT	= -5.42	TWL	= 1432.	Q/AI	= 5.53	SUMQ	= 20432.	BETA	= 1.000	L	= .2409

.91733+00	.30207+00	.37849+00	.21600+03	.00000	.00000	.18753+00	.00000
.16000-01	.10000-01	.00000	.00000	.00000	.23624-02	.18003+01	.92764+00
-.13023+01	.43047+02	.25879+04	.70361-01	.21453+02	.17922-02	.42494-02	.17146-03
.19729+00	.37685-01	.00000	.17680-01	.30500-01	.13289-02	.50543+01	.10361+04
.12909+05	.10147+05	.10000+11	.29705-03	.00000	.37351+01	.66235+00	.26393-06
.62110-06	.92276-06	.10290-02	.16152-03	.69950-04	.10485-02	.25454+03	.39167+01
.66742+00	.15583-05	.11543-04	.00000	.00000	.16417-04	.11354-05	.32686-05
.00000	.00000	.00000					

STA 29	Z	= 16.96	TWG	= 1720.	PRC	= 1203.3	WG	= 93.3	PG	= 456.0	NT	= 216.
	R	= 14.501	TWM	= 1572.	TB	= 136.3	WC	= 74.6	TG	= 4290.	AF	= .135
ITR 3	A/AT	= -6.69	TWL	= 1424.	Q/AI	= 5.41	SUMQ	= 21545.	BETA	= 1.000	L	= .1997

.10284+01	.42370+00	.38821+00	.21600+03	.00000	.00000	.20895+00	.00000
.17000-01	.10000-01	.00000	.00000	.00000	.23674-02	.18003+01	.79768+00
.17034-01	.43045+02	.25905+04	.78269-01	.19401+02	.17543-02	.42004-02	.17843-03
.25434+00	.43784-01	.00000	.17680-01	.36100-01	.13019-02	.49682+01	.11132+04
.13506+05	.10135+05	.10000+11	.29760-03	.00000	.37117+01	.66243+00	.26352-06
.62042-06	.91893-06	.98683-03	.16192-03	.90463-04	.10079-02	.26970+03	.39172+01
.66740+00	.15589-05	.11543-04	.00000	.00000	.16409-04	.11373-05	.32624-05
.00000	.00000	.00000					

STA 30	Z	= 15.51	TWG	= 1816.	PRC	= 1202.3	WG	= 93.3	PG	= 456.0	NT	= 216.
	R	= 15.952	TWM	= 1665.	TB	= 140.9	WC	= 74.6	TG	= 4290.	AF	= .139
ITR 3	A/AT	= -8.10	TWL	= 1515.	Q/AI	= 5.65	SUMQ	= 22800.	BETA	= 1.000	L	= .1580

.11395+01	.46532+00	.39305+00	.21600+03	.00000	.00000	.23036+00	.00000
.17000-01	.10000-01	.00000	.00000	.00000	.23733-02	.18003+01	.76246+00
.22036+00	.44607+02	.26243+04	.79095-01	.17349+02	.19234-02	.41090-02	.19040-03
.32015+00	.49965-01	.00000	.17680-01	.47200-01	.13608-02	.52290+01	.12550+04
.13090+05	.13680+05	.10000+11	.30650-03	.00000	.36654+01	.66203+00	.26305-06
.64482-06	.95050-06	.94475-03	.15273-03	.64742-04	.96579-03	.28690+03	.39329+01

.66681+00	.15756-05	.11543-04	.00000	.00000	.16184-04	.11432-05	.33900-05
.00000	.00000	.00000					

STA 31	Z = 14.05	TWG = 1754.	PRC = 1199.5	WG = 93.3	PG = 456.0	NT = 216.
R = 17.403	TWM = 1524.	TB = 146.2	WC = 74.6	TG = 4290.	AF = .132	
ITR 3 A/AT = -9.64	TWL = 1434.	Q/AI = 5.84	SUMQ = 24255.	BETA = 1.000	L = .0987	

.12616+01	.50643+00	.37300+00	.21600+03	.00000	.00000	.25178+00	.00000
.17000-01	.10000-01	.00000	.00000	.00000	.23730-02	.18003+01	.84452+00
.18090+01	.45452+02	.29103+04	.87508-01	.15279+02	.19566-02	.45348-02	.19076-03
.39478+00	.56206-02	.00000	.17680-01	.56000-01	.14094-02	.54463+01	.14546+04
.16566+05	.18021+05	.10000+11	.29972-03	.00000	.36548+01	.66213+00	.26323-06

.62562-06	.92362-06	.89896-03	.15925-03	.89521-04	.92186-03	.30642+03	.39228+01
.66718+00	.15648-05	.11543-04	.00000	.00000	.16329-04	.11660-05	.32894-05
.00000	.00000	.00000					

STA 32	Z = 12.10	TWG = 1686.	PRC = 1193.3	WG = 93.3	PG = 456.0	NT = 216.
R = 19.358	TWM = 1494.	TB = 154.5	WC = 74.6	TG = 4290.	AF = .116	
ITR 3 A/AT = -11.93	TWL = 1301.	Q/AI = 6.42	SUMQ = 26538.	BETA = 1.000	L = .0243	

.10454+01	.56197+00	.32414+00	.21600+03	.00000	.00000	.28063+00	.00000
.18000-01	.10000-01	.00000	.00000	.00000	.23797-02	.18003+01	.15843+01
.47083+01	.47033+02	.35634+04	.10643+00	.12537+02	.21190-02	.55985-02	.18888-03
.50730+00	.84247-01	.00000	.17690-01	.71700-01	.15525-02	.60110+01	.22835+04
.17410+03	.13245+05	.10000+11	.29014-03	.00000	.36386+01	.66414+00	.26514-06

.59382-06	.86497-06	.83562-03	.17187-03	.97580-04	.86729-03	.33647+03	.39119+01
.64566+00	.15328-05	.11543-04	.00000	.00000	.16511-04	.12010-05	.31229-05
.00000	.00000	.00000					

STA 33	Z = 10.94	TWG = 1647.	PRC = 1185.5	WG = 93.3	PG = 456.0	NT = 216.
R = 20.249	TWM = 1424.	TB = 159.6	WC = 74.6	TG = 4290.	AF = .100	
ITR 3 A/AT = -13.05	TWL = 1201.	Q/AI = 7.25	SUMQ = 28013.	BETA = 1.000	L = .0076	

.10652+01	.53779+00	.25507+00	.21600+03	.00000	.00000	.29378+00	.00000
.10000-01	.10000-01	.00000	.00000	.00000	.24145-02	.18003+01	.14397+01
.63107+01	.48476+02	.43263+04	.12856+00	.11070+02	.23922-02	.69631-02	.18300-03
.57008+00	.47196-01	.00000	.17680-01	.87500-01	.17554-02	.68065+01	.14745+04
.18163+05	.18377+05	.10000+11	.28340-03	.00000	.36446+01	.66650+00	.26615-06

.56982-06	.82120-06	.79843-03	.18223-03	.10479-03	.81703-03	.35543+03	.39059+01
.64614+00	.15438-05	.11543-04	.00000	.00000	.16636-04	.12221-05	.29972-05
.00000	.00000	.00000					

STA 34	Z = 9.59	TWG = 1592.	PRC = 1177.5	WG = 93.3	PG = 456.0	NT = 216.
R = 20.809	TWM = 1349.	TB = 165.5	WC = 74.6	TG = 4290.	AF = .092	
ITR 3 A/AT = -13.78	TWL = 1107.	Q/AI = 7.66	SUMQ = 29626.	BETA = .990	L = -.0004	

.11057+01	.60408+00	.22344+00	.21600+03	.00000	.00000	.30205+00	.00000
.10000-01	.10000-01	.00000	.00000	.00000	.24356-02	.18003+01	.23203+01
.57010+01	.50796+02	.49380+04	.14586+00	.96020+01	.25417-02	.81275-02	.16952-03
.52384+00	.45129-01	.00000	.17680-01	.96900-01	.18757-02	.72002+01	.16726+04
.10581+05	.13562+05	.10000+11	.27524-03	.00000	.36517+01	.66980+00	.26815-06

.54745-06	.77997-06	.76022-03	.19339-03	.11269-03	.77932-03	.37748+03	.38905+01
.64762+00	.15279-05	.11543-04	.00000	.00000	.16957-04	.12529-05	.28801-05
.00000	.00000	.00000					

COOLANT = PARA-HYDROGEN (MBS)

TUBE TYPE = VARIABLE

MR = .00 PC = 456. TC = 4290. HC = 0. PIN = 1271.0 TIN = 60.2

* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *
EFF SURF AREA	LEG SPREAD	EQUIV DIA	NMB	SMD	RA	RG	THC
THM	THS	GAMMA	ENTROPY	GAS VEL	FRIC FACT	PFM	PF
PV	SUM PF	COOL VEL	COOL MACH	DEV DIST	HG	HL	HR
SHAPE FACT	GRAY BODY	FEFV	CL	CG	U	Q/AO	Q
STRESS	YLD STR	KC	KM	KWG	CP-CB	PR-CF	VISC-CB
VISC-CF	VISC-CW	RHO-CB	RHO-CF	RHO-CW	RHOBAR	H-CB	CP-GF
PR-GF	VISC-GF	RHO-GB	RBO	QOABO	RHO-GF	KR	KCF
PFB-B	VDT	TSAT					
* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *

STA 35	Z = 8.13	TWG = 1668.	PRC = 1175.8	WG = 93.3	PG = 456.0	NT = 216.
	R = 21.000	TWM = 1381.	TB = 172.2	WC = 71.6	TG = 4290.	AF = .091
ITR 3	A/AT = -14.04	TWL = 1094.	Q/AI = 7.57	SUMQ = 31415.	BETA = .990	L = .0046

.11255+01	.60987+00	.21822+00	.21600+03	.00000	.00000	.30487+00	.00000
.22000-01	.10000-01	.00000	.00000	.00000	.24604-02	.18003+01	.27947+01
.11251+01	.53591+02	.50250+04	.14723+00	.61350+01	.25701-02	.82157-02	.15482-03
.60045+00	.41138-01	.00000	.17680-01	.10020+00	.18583-02	.70274+01	.17294+04
.15118+05	.10305+05	.10900+11	.27910-03	.00000	.36612+01	.67006+00	.27140-06
.54568-06	.77402-06	.72501-03	.19411-03	.11389-03	.74261-03	.40235+03	.39025+01
.64650+00	.15418-05	.11543-04	.00000	.00000	.16707-04	.12900-05	.28708-05
.00000	.00000	.00000					

STA 36	Z = 6.40	TWG = 1609.	PRC = 1169.7	WG = 93.3	PG = 456.0	NT = 216.
	R = 21.000	TWM = 1359.	TB = 179.6	WC = 71.6	TG = 4290.	AF = .091
ITR 3	A/AT = -14.04	TWL = 1063.	Q/AI = 7.60	SUMQ = 33449.	BETA = .980	L = .0046

.13373+01	.60987+00	.21822+00	.21600+03	.00000	.00000	.30487+00	.00000
.22000-01	.10000-01	.00000	.00000	.00000	.24652-02	.18003+01	.34381+01
.26279+01	.57029+02	.53035+04	.15409+00	.64000+01	.26132-02	.85588-02	.14861-03
.73816+00	.46568-01	.00000	.17680-01	.10140+00	.18893-02	.70541+01	.20337+04
.15040+05	.10369+05	.10000+11	.27694-03	.00000	.36705+01	.67072+00	.27487-06
.54118-06	.76305-06	.68694-03	.19564-03	.11607-03	.70597-03	.43028+03	.38930+01
.64733+00	.15308-05	.11543-04	.00000	.00000	.16906-04	.13305-05	.28472-05
.00000	.00000	.00000					

STA 37	Z = 4.80	TWG = 1642.	PRC = 1164.6	WG = 93.3	PG = 456.0	NT = 216.
	R = 21.000	TWM = 1350.	TB = 186.3	WC = 71.6	TG = 4290.	AF = .091
ITR 3	A/AT = -14.04	TWL = 1057.	Q/AI = 7.63	SUMQ = 35330.	BETA = .960	L = .0046

.12332+01	.60987+00	.21822+00	.21600+03	.00000	.00000	.30487+00	.00000
.22000-01	.10000-01	.00000	.00000	.00000	.24720-02	.18003+01	.33221+01
.13316+01	.60931+02	.54976+04	.15839+00	.48000+01	.26937-02	.87539-02	.16415-03
.75006+00	.5064-01	.00000	.17680-01	.10380+00	.19393-02	.70752+01	.18818+04
.15974+05	.10392+05	.10000+11	.27602-03	.00000	.37180+01	.67089+00	.27977-06
.54097-06	.75826-06	.68694-03	.19542-03	.11678-03	.67481-03	.45687+03	.38785+01

.14974+05 .18392+05 .10000+11 .27602-03 .00000 .37180+01 .67089+00 .27977-06

54007-06 .75826-06 .66269-03 .19542-03 .11678-03 .67481-03 .45687+03 .38785+01

.64882+00 .15139-05 .11543-04 .00000 .00000 .17209-04 .13744-05 .28413-05
.00000 .00000 .00000

STA 38 Z = 3.20 TWG = 1633. PRC = 1158.8 WG = 93.3 PG = 456.0 NT = 216.
R = 21.000 TWM = 1338. TB = 193.1 WC = 71.6 TG = 4290. AF = .091
ITR 3 A/AT = -14.04 TWL = 1042. Q/AI = 7.66 SUMQ = 37220. BETA = .930 L = .0046

.12332+01 .60987+00 .21822+00 .21600+03 .00000 .00000 .30487+00 .00000
.22000-01 .10000-01 .00000 .00000 .00000 .24786-02 .18003+01 .34662+01
.22871+01 .63817+02 .57400+04 .16400+00 .32000+01 .28323-02 .90204-02 .18371-03
.85379+00 .48950-01 .00000 .17680-01 .10810+00 .20177-02 .71087+01 .18891+04
.14900+05 .13424+05 .10000+11 .27475-03 .00000 .37682+01 .67121+00 .28463-06

.53785-06 .75154-06 .63470-03 .19571-03 .11789-03 .64869-03 .48354+03 .38569+01
.65116+00 .14887-05 .11543-04 .00000 .00000 .17660-04 .14178-05 .28296-05
.00000 .00000 .00000

STA 39 Z = 1.60 TWG = 1598. PRC = 1152.7 WG = 93.3 PG = 456.0 NT = 216.
R = 21.000 TWM = 1302. TB = 199.8 WC = 71.6 TG = 4290. AF = .091
ITR 3 A/AT = -14.04 TWL = 1006. Q/AI = 7.57 SUMQ = 39102. BETA = .840 L = .0046

.12332+01 .60987+00 .21822+00 .21600+03 .00000 .00000 .30487+00 .00000
.22000-01 .10000-01 .00000 .00000 .00000 .24851-02 .18003+01 .36318+01
.24791+01 .67449+02 .60027+04 .17010+00 .16000+01 .32745-02 .93925-02 .22977-03
.92666+00 .52028-01 .00000 .17680-01 .12200+00 .22254-02 .70289+01 .16829+04
.14321+05 .13541+05 .10000+11 .27120-03 .00000 .38181+01 .67228+00 .28947-06

.53036-06 .73570-06 .60692-03 .19878-03 .12119-03 .62081-03 .51008+03 .37912+01
.65989+00 .14123-05 .11543-04 .00000 .00000 .19030-04 .14610-05 .27904-05
.00000 .00000 .00000

STA 40 Z = .00 TWG = 1043. PRC = 1146.7 WG = 93.3 PG = 456.0 NT = 216.
R = 21.000 TWM = 806. TB = 205.3 WC = 71.6 TG = 4290. AF = .091
ITR 5 A/AT = -14.04 TWL = 569. Q/AI = 4.97 SUMQ = 40654. BETA = .270 L = .0046

.12332+01 .60987+00 .21822+00 .21600+03 .00000 .00000 .30487+00 .00000
.22000-01 .10000-01 .00000 .00000 .00000 .24903-02 .18003+01 .37953+01
.22497+01 .71244+02 .62411+04 .17567+00 .00000 .35726-01 .13686-01 .42879-02
.10000+01 .55186-01 .00000 .17680-01 .83710+00 .52183-02 .46213+01 .15517+04
.14744+05 .23215+05 .10000+11 .22214-03 .00000 .38591+01 .70601+00 .29343-06

.41261-06 .51302-06 .58374-03 .30448-03 .21039-03 .59533-03 .53197+03 .34836+01
.67656+00 .78995-06 .11543-04 .00000 .00000 .44501-04 .14965-05 .22708-05
.00000 .00000 .00000

FOR BOLT COOLANT OF .00 LB./SEC. ABSORBING .00 BTU/LB., OUTLET CONDITIONS ARE ---

ENTHALPY = 532.6 BTU/LB., TEMP. = 205.3 DEG.R., PRESS. = 1117.2 PSIA., RESULTING IN

DELTA T = 145.1 DEG.R., DELTA P = 153.8 PSI

REGENERATIVE COOLING HEAT TRANSFER (NON-CRYOGENIC AND CRYOGENIC)

PROGRAM E25104

30 NOV 70

*** HESS AND KUNZ CORRELATION EQUATION

PAGE 1

COOLANT = PARA-HYDROGEN (HBS)

TUBE TYPE = VARIABLE

MR = .00 PC = 456. TC = 4290. HC = 0. PIN = 1271.0 TIN = 60.2

UNITS USED IN THIS PROGRAM ARE AS FOLLOWS

PRESSURE	= LB./SQ.IN.	VELOCITY	= IN./SEC.
TEMPERATURE	= DEG.R.	HEAT TRANSFER COEFFICIENT	= BTU/SEC.-SQ.IN.-DEG.R.
ENTHALPY	= BTU/LB.	HEAT FLUX	= BTU/SEC.-SQ.IN.
ENTROPY	= BTU/LB.-DEG.R.	HEAT RATE	= BTU/SEC.
DENSITY	= LB./CU.IN.	LENGTH	= IN.
VISCOSITY	= LB./IN.-SEC.	AREA	= SQ.IN.
CONDUCTIVITY	= BTU/SEC.-IN.-DEG.R.	STRESS	= LB./SQ.IN.
SPECIFIC HEAT	= BTU/LB.-DEG.R.		

EFF	SURF AREA	LEG SPREAD	EQUIV DIA	NMR	SMD	RA	RG	THC
THM		THS	GAMMA	ENTROPY	GAS VFL	FRIC FACT	PFM	PF
PV		SUM PF	COOL VEL	COOL MACH	DEV DIST	HL	HL	HR
SHAPE FACT		GRAY BODY	FEFV	CL	CG	U	Q/AO	Q
STRESS		YLD STR	KC	KM	KWG	CP-CB	PR-CF	VISC-CB
VISC-CF		VISC-CW	RHO-CB	RHO-CF	RHO-CW	RHOBAR	H-CB	CP-GF
PF-GF		VISC-GF	RHO-CB	RBO	QOABO	RHO-GF	KB	KCF
PFB-B		VDT	TSAT					
STA 1 Z	= 72.46	TWG = 1206.	PRC = 1270.3	WG = 93.3	PG = 1.0	NT = 216.		
R	= 27.459	TWM = 1144.	TB = 60.1	WC = 74.6	TG = 850.	AF = .296		
ITR 5 A/AT	= 24.00	TWL = 1081.	Q/AI = 1.18	SUMQ = 0.	BETA = .910	L = .1058		

.00000	.80347+00	.55725+00	.21600+03	.00000	.00000	.40020+00	.00000
.20000-01	.10000-01	.00000	.00000	.00000	.28805-02	.18003+01	.00000
.71587+00	.00000	.47456+03	.99535-02	.83610+02	.40830-03	.11598-02	.00000
.11794+00	.00000	.00000	.17680-01	.89200-01	.30812-03	.11016+01	.00000
.16886+05	.21539+05	.10000+11	.25594-03	.00000	.28690+01	.67834+00	.59022-06
.51433-06	.76696-06	.24545-02	.23091-03	.12420-03	.00000	-.16284+02	.37794+01
.67209+00	.14191-05	.12982-06	.00000	.00000	.43640-07	.16793-05	.27083-05
.00000	.00000	.00000					

TUBE TYPE = U-TUBE

MATERIAL = STAINLESS STEEL

STA 2 Z	= 69.32	TWG = 1208.	PRC = 1270.1	WG = 93.3	PG = 1.2	NT = 216.	
R	= 26.290	TWM = 1141.	TB = 63.7	WC = 74.6	TG = 880.	AF = .285	
ITR 3 A/AT	= 22.00	TWL = 1075.	Q/AI = 1.26	SUMQ = 812.	BETA = .910	L = .1225	

.33114+01	.76945+00	.54996+00	.21600+03	.00000	.00000	.38294+00	.00000
.28000-01	.10000-01	.00000	.00000	.00000	.20268-02	.18003+01	.93937-01
.10391+00	.93937-01	.50834+03	.10904-01	.60265+02	.43364-03	.12472-02	.00000
.11742+00	.00000	.00000	.17680-01	.65100-01	.32845-03	.11692+01	.81209+03
.16100+05	.21522+05	.10000+11	.25573-03	.00000	.30229+01	.67861+00	.54106-06
.51365-06	.76410-06	.23831-02	.23144-03	.12492-03	.24180-02	-.57430+01	.37797+01
.67203+00	.14195-05	.14093-06	.00000	.00000	.49111-07	.16362-05	.27047-05
.00000	.00000	.00000					

STA 3	Z = 66.17	TWG = 1193.	PRC = 1270.1	WG = 93.3	PG = 1.3	NT = 216.
	R = 25.066	TWM = 1131.	TB = 67.1	WC = 74.6	TG = 925.	AF = .321
ITR 3	A/AT = 20.00.	TWL = 1070.	Q/AI = 1.16	SUMQ = 1587.	BETA = .910	L = .1401

.31951+01	.73383+00	.57881+00	.21600+03	.00000	.00000	.36488+00	.00000
.28000-01	.10000-01	.00000	.00000	.00000	.28277-02	.18003+01	.87952-01
.12513+00	.18189+00	.46597+03	.10381-01	.76385+02	.39671-03	.11614-02	.00000
.11642+00	.00000	.00000	.17680-01	.69100-01	.30359-03	.10755+01	.77457+03
.15281+05	.21671+05	.10000+11	.25478-03	.00000	.31660+01	.67877+00	.50722-06
.51324-06	.76201-06	.23111-02	.23178-03	.12552-03	.23471-02	.48093+01	.37776+01
.67342+00	.14167-05	.15791-06	.00000	.00000	.57475-07	.15958-05	.27026-05
.00000	.00000	.00000					

STA 4	Z = 63.00	TWG = 1162.	PRC = 1269.9	WG = 93.3	PG = 1.5	NT = 216.
	R = 23.780	TWM = 1097.	TB = 70.0	WC = 74.6	TG = 964.	AF = .305
ITR 3	A/AT = 18.00	TWL = 1033.	Q/AI = 1.22	SUMQ = 2314.	BETA = .910	L = .1601

.30728+01	.69645+00	.56491+00	.21600+03	.00000	.00000	.34590+00	.00000
.28000-01	.10000-01	.00000	.00000	.00000	.27878-02	.18003+01	.83918-01
.10798+00	.26581+00	.50373+03	.11525-01	.73465+02	.40739-03	.12624-02	.00000
.11483+00	.00000	.00000	.17680-01	.62400-01	.31698-03	.11169+01	.72757+03
.14418+05	.21977+05	.10000+11	.25156-03	.00000	.32911+01	.68217+00	.47764-06
.50458-06	.74568-06	.22482-02	.23888-03	.12990-03	.22797-02	.14390+02	.37733+01
.67445+00	.14110-05	.17471-06	.00000	.00000	.66572-07	.15604-05	.26571-05
.00000	.00000	.00000					

STA 5	Z = 59.77	TWG = 1173.	PRC = 1269.7	WG = 93.3	PG = 1.9	NT = 216.
	R = 22.420	TWM = 1105.	TB = 73.0	WC = 74.6	TG = 1017.	AF = .289
ITR 3	A/AT = 16.00	TWL = 1038.	Q/AI = 1.32	SUMQ = 3062.	BETA = .910	L = .1799

.29778+01	.65688+00	.54920+00	.21600+03	.00000	.00000	.32582+00	.00000
.27000-01	.10000-01	.00000	.00000	.00000	.27484-02	.18003+01	.99661-01
.13518+00	.36547+00	.54858+03	.12906-01	.69958+02	.44252-03	.13663-02	.00000
.11255+00	.00000	.00000	.17680-01	.58400-01	.34401-03	.12087+01	.74794+03
.14052+05	.21875+05	.10000+11	.25227-03	.00000	.34136+01	.68140+00	.45012-06
.50654-06	.74776-06	.21821-02	.23723-03	.12931-03	.22151-02	.24441+02	.37747+01
.67411+00	.14129-05	.20260-06	.00000	.00000	.81358-07	.15212-05	.26674-05
.00000	.00000	.00000					

STA 6	Z = 56.49	TWG = 1203.	PRC = 1269.4	WG = 93.3	PG = 2.2	NT = 216.
	R = 20.972	TWM = 1132.	TB = 76.0	WC = 74.6	TG = 1069.	AF = .271
ITR 3	A/AT = 14.00	TWL = 1061.	Q/AI = 1.46	SUMQ = 3847.	BETA = .910	L = .2013

.28563+01	.61476+00	.53089+00	.21600+03	.00000	.00000	.30445+00	.00000
.26000-01	.10000-01	.00000	.00000	.00000	.27126-02	.18003+01	.12050+00
.17673+00	.40597+00	.60383+03	.14617-01	.66373+02	.49464-03	.14824-02	.00000
.10930+00	.00000	.00000	.17680-01	.55700-01	.38152-03	.13358+01	.78492+03
.13595+05	.21565+05	.10000+11	.25486-03	.00000	.35258+01	.67876+00	.42778-06
.51325-06	.75812-06	.21123-02	.23164-03	.12650-03	.21472-02	.34885+02	.37791+01
.67305+00	.14186-05	.22808-06	.00000	.00000	.95758-07	.14824-05	.27026-05
.00000	.00000	.00000					

**** HESS AND KUNZ CORRELATION EQUATION

PAGE 2

COOLANT = PARA-HYDROGEN (NBS)

TUBE TYPE = VARIABLE

MR = .00 PC = 456. TC = 4290. HC = 0. PIN = 1271.0 TIN = 60.2

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EFF SURF AREA	LEG SPREAD	EQUIV DIA	NMB	SMD	RA	RG	THC
THM	THS	GAMMA	ENTROPY	GAS VEL	FRIC FACT	PFM	PF
PV	SUM PF	COOL VEL	COOL MACH	DEV DIST	HG	HL	HR
SHAPE FACT	GRAY BODY	FEFV	CL	CG	U	Q/AO	Q
STPESS	YLD STR	KC	KM	KWG	CP-CB	PR-CF	VISC-CB
VISC-CF	VISC-CW	RHO-CB	RHO-CF	RHO-CW	RHOBAR	H-CB	CP-GF
PP-GF	VISC-GF	RHO-CB	RBO	QOABO	RHO-GF	KB	KCF
PRB-B	VDT	TSAT					
* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *

STA	Z	TWG	PRC	WG	PG	NT
7	53.15	1234.	1269.0	93.3	2.8	216.
	R = 19.416	TWM = 1159.	TB = 78.8	WC = 74.6	TG = 1140.	AF = .251
ITR	3 A/AT = 12.00	TWL = 1082.	Q/AI = 1.63	SUMQ = 4680.	BETA = .910	L = .2241

.27294+01	.56949+00	.50867+00	.21600+03	.00000	.00000	.28149+00	.00000
.25000-01	.10000-01	.00000	.00000	.00000	.26758-02	.18003+01	.15088+00
.23647+00	.03685+00	.67279+03	.16748-01	.62688+02	.55770-03	.16287-02	.00000
.10482+00	.00000	.00000	.17680-01	.52000-01	.42725-03	.14892+01	.83275+03
.13019+05	.21263+05	.10000+11	.25730-03	.00000	.36332+01	.67639+00	.40645-06
.51930-06	.76740-06	.20456-02	.22659-03	.12397-03	.20789-02	.45011+02	.37833+01
.67199+00	.14240-05	.27040-06	.00000	.00000	.12042-06	.14453-05	.27344-05
.00000	.00000	.00000					

STA	Z	TWG	PRC	WG	PG	NT
8	49.68	1276.	1268.5	93.3	3.8	216.
	R = 17.725	TWM = 1194.	TB = 82.0	WC = 74.6	TG = 1232.	AF = .229
ITR	3 A/AT = 10.00	TWL = 1112.	Q/AI = 1.88	SUMQ = 5582.	BETA = .920	L = .2483

.26184+01	.52028+00	.48126+00	.21600+03	.00000	.00000	.25653+00	.00000
.24000-01	.10000-01	.00000	.00000	.00000	.26361-02	.18003+01	.20045+00
.35080+00	.83730+00	.76680+03	.19520-01	.58838+02	.63667-03	.18212-02	.00000
.98791-01	.00000	.00000	.17680-01	.47500-01	.48534-03	.17005+01	.90202+03
.12290+05	.20839+05	.10000+11	.26071-03	.00000	.37420+01	.67314+00	.38482-06
.52756-06	.78035-06	.19709-02	.21970-03	.12066-03	.20083-02	.56849+02	.38012+01
.67026+00	.14396-05	.33466-06	.00000	.00000	.15874-06	.14087-05	.27777-05
.00000	.00000	.00000					

STA	Z	TWG	PRC	WG	PG	NT
9	46.06	1325.	1267.6	93.3	5.2	216.
	R = 15.853	TWM = 1234.	TB = 85.5	WC = 74.6	TG = 1346.	AF = .203
ITR	3 A/AT = 8.00	TWL = 1143.	Q/AI = 2.22	SUMQ = 6581.	BETA = .920	L = .2759

.25036+01	.46583+00	.44719+00	.21600+03	.00000	.00000	.22890+00	.00000
.23000-01	.10000-01	.00000	.00000	.00000	.25970-02	.18003+01	.28735+00
.55148+00	.11246+01	.89991+03	.23552-01	.54753+02	.76048-03	.20964-02	.00000
.90592-01	.00000	.00000	.17680-01	.43400-01	.57396-03	.19937+01	.99887+03
.11348+05	.20348+05	.10000+11	.26452-03	.00000	.38364+01	.67141+00	.36603-06

.66928+00	.14489-05	.42067-06	.00000	.00000	.21573-06	.13713-05	.28235-05
.00000	.00000	.00000					

STA 10 Z = 44.17	TWG = 1349.	PRC = 1267.0	WG = 93.3	PG = 6.3	NT = 216.
R = 14.829	TWM = 1254.	TB = 87.4	WC = 74.6	TG = 1421.	AF = .189
ITR 3 A/AT = 7.00	TWL = 1158.	Q/AI = 2.44	SUMQ = 7125.	BETA = .920	L = .2898

.12043+01	.43601+00	.42692+00	.21600+03	.00000	.00000	.21379+00	.00000
.22000-01	.10000-01	.00000	.00000	.00000	.25755-02	.18003+01	.19771+00
.40769+00	.13224+01	.98939+03	.26287-01	.52606+02	.84422-03	.22023-02	.00000
.85415-01	.00000	.00000	.17680-01	.41000-01	.63332-03	.21930+01	.54452+03
.11045+05	.20108+05	.10000+11	.26640-03	.00000	.38665+01	.67074+00	.35607-06

.54068-06	.80083-06	.18436-02	.21132-03	.11596-03	.18657-02	.77402+02	.38147+01
.66868+00	.14533-05	.48419-06	.00000	.00000	.26070-06	.13514-05	.28466-05
.00000	.00000	.00000					

STA 11 Z = 42.20	TWG = 1382.	PRC = 1266.2	WG = 93.3	PG = 8.1	NT = 216.
R = 13.729	TWM = 1281.	TB = 89.3	WC = 74.6	TG = 1520.	AF = .174
ITR 3 A/AT = 6.00	TWL = 1180.	Q/AI = 2.74	SUMQ = 7715.	BETA = .930	L = .3058

.11757+01	.40400+00	.40387+00	.21600+03	.00000	.00000	.19755+00	.00000
.21000-01	.10000-01	.00000	.00000	.00000	.25527-02	.18003+01	.25896+00
.55215+00	.15813+01	.11017+04	.29751-01	.50345+02	.94041-03	.25140-02	.00000
.79360-01	.00000	.00000	.17680-01	.37700-01	.70337-03	.24521+01	.58978+03
.10645+05	.19776+05	.10000+11	.26912-03	.00000	.39399+01	.66980+00	.34547-06

.54673-06	.81049-06	.17967-02	.20760-03	.11373-03	.18201-02	.85092+02	.38282+01
.66677+00	.14673-05	.58137-06	.00000	.00000	.33158-06	.13303-05	.28783-05
.00000	.00000	.00000					

STA 12 Z = 40.13	TWG = 1393.	PRC = 1265.0	WG = 93.3	PG = 10.9	NT = 216.
R = 12.533	TWM = 1286.	TB = 91.5	WC = 74.6	TG = 1644.	AF = .158
ITR 3 A/AT = 5.00	TWL = 1179.	Q/AI = 3.06	SUMQ = 8353.	BETA = .930	L = .3231

.11404+01	.36920+00	.37654+00	.21600+03	.00000	.00000	.17990+00	.00000
.20000-01	.10000-01	.00000	.00000	.00000	.25304-02	.18003+01	.35601+00
.80302+00	.19373+01	.12509+04	.34266-01	.47955+02	.10490-02	.28177-02	.00000
.72155-01	.00000	.00000	.17680-01	.33600-01	.78610-03	.27241+01	.63749+03
.10114+05	.19670+05	.10000+11	.26959-03	.00000	.39724+01	.66977+00	.33654-06

.54693-06	.80993-06	.17481-02	.20730-03	.11376-03	.17724-02	.93550+02	.38282+01
.66636+00	.14691-05	.72367-06	.00000	.00000	.44465-06	.13095-05	.28793-05
.00000	.00000	.00000					

STA 13 Z = 37.93	TWG = 1398.	PRC = 1262.6	WG = 93.3	PG = 14.9	NT = 216.
R = 11.210	TWM = 1279.	TB = 93.8	WC = 74.6	TG = 1799.	AF = .130
ITR 3 A/AT = 4.00	TWL = 1160.	Q/AI = 3.60	SUMQ = 9055.	BETA = .930	L = .3444

.11033+01	.33077+00	.36613+00	.21600+03	.00000	.00000	.16038+00	.00000
.19000-01	.10000-01	.00000	.00000	.00000	.24570-02	.18003+01	.54667+00
.19226+01	.24840+01	.15608+04	.43375-01	.45390+02	.12233-02	.33718-02	.00000
.63545-01	.00000	.00000	.17680-01	.29900-01	.92296-03	.31703+01	.70236+03
.93946+04	.19618+05	.10000+11	.26892-03	.00000	.39962+01	.67041+00	.32789-06

.54278-06	.80176-06	.16956-02	.20937-03	.11537-03	.17219-02	.10288+03	.38281+01
.66578+00	.14690-05	.90279-06	.00000	.00000	.60480-06	.12873-05	.28575-05
.00000	.00000	.00000					

*** HESS AND KUNZ CORRELATION EQUATION

PAGE 3

COOLANT = PARA-HYDROGEN (NBS)

TUBE TYPE = VARIABLE

MR = .00 PC = 456. TC = 4290. HC = 0. PIN = 1271.0 TIN = 60.2

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EFF SURF AREA	LEG SPREAD	EQUIV DIA	NMB	SMD	RA	R6	THC
THM	THS	GAMMA	ENTROPY	GAS VEL	FRIC FACT	PFM	PF
PV	SUM PF	COOL VEL	COOL MACH	DEV DIST	HG	HL	HR
SHAPE FACT	GRAY BODY	FEFV	CL	CG	U	Q/AO	Q
STRESS	YLD STR	KC	KM	KWC	CP-CB	PR-CF	VISC-CB
VISC-CF	VISC-CW	RHO-CB	RHO-CF	RHO-CW	RHOBAR	H-CB	CP-GF
PP-GF	VISC-GF	RHO-GB	RBO	QCABO	RHO-GF	KB	KCF
PPB-B	VDT	TSAT					

STA 14	Z = 35.52	TWG = 1458.	PRC = 1259.4	WG = 93.3	PG = 23.7	NT = 216.
	R = 9.708	TWM = 1325.	TB = 96.4	WC = 74.6	TG = 2038.	AF = .113
ITR 3	A/AT = 3.00	TWL = 1193.	Q/AI = 4.34	SUMQ = 9859.	BETA = .940	L = .3660

.10719+01	.23708+00	.33127+00	.21600+03	.00000	.00000	.13821+00	.00000
.10000-01	.10000-01	.00000	.00000	.00000	.24284-02	.18003+01	.91026+00
.22049+01	.33943+01	.18716+04	.52876-01	.42550+02	.14660-02	.39579-02	.00000
.53135-01	.00000	.00000	.17680-01	.25200-01	.11022-02	.37744+01	.80396+03
.84104+04	.19018+05	.10000+11	.27352-03	.00000	.40231+01	.66900+00	.31811-06
.55158-06	.81598-06	.16359-02	.20368-03	.11194-03	.16658-02	.11339+03	.38438+01
.66329+00	.14885-05	.12670-05	.00000	.00000	.94276-06	.12621-05	.29036-05
.00000	.00000	.00000					

STA 15	Z = 32.71	TWG = 1570.	PRC = 1252.7	WG = 93.3	PG = 46.2	NT = 216.
	R = 7.927	TWM = 1412.	TB = 99.5	WC = 74.6	TG = 2442.	AF = .091
ITR 3	A/AT = 2.00	TWL = 1253.	Q/AI = 5.74	SUMQ = 10843.	BETA = .950	L = .3925

.10535+01	.23526+00	.28309+00	.21600+03	.00000	.00000	.11192+00	.00000
.17000-01	.10000-01	.00000	.00000	.00000	.23931-02	.18003+01	.18048+01
.49081+01	.51991+01	.24304+04	.70132-01	.39218+02	.19454-02	.49809-02	.00000
.40383-01	.00000	.00000	.17680-01	.20300-01	.14448-02	.48742+01	.98404+03
.69944+04	.18632+05	.10000+11	.28213-03	.00000	.40502+01	.66662+00	.30659-06
.56756-06	.84250-06	.15633-02	.19328-03	.10628-03	.15996-02	.12603+03	.38676+01
.65943+00	.15159-05	.20607-05	.00000	.00000	.17838-05	.12307-05	.29872-05
.00000	.00000	.00000					

STA 16	Z = 32.40	TWG = 1565.	PRC = 1251.9	WG = 93.3	PG = 53.5	NT = 216.
	R = 7.726	TWM = 1411.	TB = 99.8	WC = 74.6	TG = 2520.	AF = .089
ITR 2	A/AT = 1.90	TWL = 1258.	Q/AI = 5.88	SUMQ = 10950.	BETA = .950	L = .3956

.10051+00	.22942+00	.27922+00	.21600+03	.00000	.00000	.10895+00	.00000
.16000-01	.10000-01	.00000	.00000	.00000	.23910-02	.18003+01	.26882+00
.51585+00	.54679+01	.24824+04	.71795-01	.38858+02	.19971-02	.50729-02	.00000
.30925-01	.00000	.00000	.17680-01	.19300-01	.14779-02	.50137+01	.10734+03
.72730+04	.18630+05	.10000+11	.28214-03	.00000	.40487+01	.66641+00	.30572-06
.56375-06	.84479-06	.15562-02	.19235-03	.10579-03	.15590-02	.12737+03	.38659+01

.65925+00	.15146-05	.22976-05	.00000	.00000	.20673-05	.12273-05	.29946-05
.00000	.00000	.00000					

STA 17 Z = 30.99	TWG = 1625.	PRC = 1246.1	WG = 93.3	PG = 83.4	NT = 216.
R = 6.842	TWM = 1460.	TB = 101.4	WC = 74.6	TG = 2838.	AF = .079
ITR 3 A/AT = 1.49	TWL = 1295.	Q/AI = 6.90	SUMQ = 11457.	BETA = .960	L = .4079

.43247+00	.20368+00	.25314+00	.21600+03	.00000	.00000	.95908-01	.00000
.15000-01	.10000-01	.00000	.00000	.00000	.23750-02	.18003+01	.15451+01
.42850+01	.70130+01	.28850+04	.83948-01	.37188+02	.23365-02	.57861-02	.00000
.32650-01	.00000	.00000	.17680-01	.16700-01	.17187-02	.58268+01	.50632+03
.67210+04	.18450+05	.10000+11	.28695-03	.00000	.40435+01	.66495+00	.30128-06

.57864-06	.86104-06	.15211-02	.18586-03	.10228-03	.15387-02	.13377+03	.38807+01
.65649+00	.15318-05	.32021-05	.00000	.00000	.31617-05	.12219-05	.30452-03
.00000	.00000	.00000					

STA 18 Z = 29.67	TWG = 1825.	PRC = 1238.2	WG = 93.3	PG = 102.6	NT = 216.
R = 6.037	TWM = 1637.	TB = 102.9	WC = 74.6	TG = 3396.	AF = .069
ITR 3 A/AT = 1.16	TWL = 1449.	Q/AI = 8.98	SUMQ = 11964.	BETA = .970	L = .4207

.35255+00	.18029+00	.22806+00	.21600+03	.00000	.00000	.84027-01	.00000
.14070-01	.10000-01	.00000	.00000	.00000	.23608-02	.18003+01	.20852+01
.57507+01	.90982+01	.33604+04	.98356-01	.35638+02	.32061-02	.66755-02	.00000
.27083-01	.00000	.00000	.17680-01	.16100-01	.22136-02	.74016+01	.50710+03
.61935+04	.16699+05	.10000+11	.30377-03	.00000	.40392+01	.66234+00	.29671-06

.61808-06	.92890-06	.14852-02	.16735-03	.91378-04	.15032-02	.14007+03	.39163+01
.65032+00	.15709-05	.58402-05	.00000	.00000	.65988-05	.12113-05	.32516-05
.00000	.00000	.00000					

STA 19 Z = 23.95	TWG = 1745.	PRC = 1233.8	WG = 93.3	PG = 231.6	NT = 216.
R = 5.715	TWM = 1495.	TB = 103.8	WC = 74.6	TG = 3651.	AF = .066
ITR 3 A/AT = 1.04	TWL = 1244.	Q/AI = 12.29	SUMQ = 12276.	BETA = .980	L = .4239

.16266+00	.17088+00	.21884+00	.21600+03	.00000	.00000	.79274-01	.00000
.10000-01	.10000-01	.00000	.00000	.00000	.23536-02	.18003+01	.13814+01
.30357+01	.10480+02	.35931+04	.10553+00	.34850+02	.41820-02	.10784-01	.00000
.25110-01	.00000	.00000	.27040-01	.17900-01	.29981-02	.10280+02	.31231+03
.62897+04	.18049+05	.10000+11	.29025-03	.00000	.40356+01	.66685+00	.29393-06

.56643-06	.83908-06	.14630-02	.19114-03	.10543-03	.14741-02	.14402+03	.39096+01
.64925+00	.15611-05	.68916-05	.00000	.00000	.34320-05	.12051-05	.29811-05
.00000	.00000	.00000					

STA 20 Z = 28.17	TWG = 1890.	PRC = 1218.0	WG = 93.3	PG = 248.0	NT = 216.
R = 5.605	TWM = 1574.	TB = 104.8	WC = 74.6	TG = 3736.	AF = .053
ITR 4 A/AT = 1.00	TWL = 1258.	Q/AI = 15.94	SUMQ = 12674.	BETA = .990	L = .3485

.15631+00	.16544+00	.20546+00	.21600+03	.00000	.00000	.77651-01	.00000
.13000-01	.10000-01	.00000	.00000	.00000	.22981-02	.18003+01	.19170+01
.13847+02	.12397+02	.45149+04	.13364+00	.34062+02	.56341-02	.13812-01	.00000
.25031-01	.00000	.00000	.28750-01	.23600-01	.38470-02	.13279+02	.39781+03
.60572+04	.15391+05	.10000+11	.29786-03	.00000	.40398+01	.66631+00	.28972-06

.57041-06	.84579-06	.14325-02	.18660-03	.10295-03	.14478-02	.14810+03	.39413+01
.67150+00	.15936-05	.72153-05	.00000	.00000	.37619-05	.11927-05	.30012-05
.00000	.00000	.00000					

~~PAGE~~ 4

COOLANT = PARA-HYDROGEN (HDS)										TUBE TYPE = VARIABLE									
MR = .00 PC = 456. TC = 4290.										HC = 0. PIN = 1271.0 TIN = 60.2									
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EFF SURF AREA		LEG SPREAD		EQUIV DIA		NMB		SMD		RA		RG		THC					
THM		THS		GAMMA		ENTROPY		GAS VEL		FRIC FACT		PFM		PF					
PV		SUM PF		COOL VEL		COOL MACH		DEV DIST		HG		HL		HR					
SHAPE FACT		GRAY BODY		FEFV		CL		CG		U		Q/AO		Q					
STRESS		YLD STR		KC		KM		KWG		CP-CB		FR-CF		VISC-CB					
VISC-CF		VISC-CW		RHO-CB		PHO-CF		RHO-CW		RHOBAR		H-CB		CP-GF					
PP-GF		VISC-GF		RHO-CB		RBO		QOABO		RHO-GF		KB		KCF					
PFB-B		VDT		TSAT															
* * * * *										* * * * *									
STA 21	Z = 27.08	TWG = 2014.		PRC = 1164.0		WG = 93.3		PG = 301.7		NT = 216.									
	R = 5.713	TWM = 1589.		TB = 105.8		WC = 74.6		TG = 5910.		AF = .036									
ITR 3	A/AT = -1.04	TWL = 1164.		Q/AI = 21.49		SUMQ = 13411.		BETA = .990		L = .2168									
	.21836+00	.16480+00	.18603+00	.21600+03	.00000	.00000	.79245-01	.00000											
	.13000-01	.10900-01	.00000	.00000	.00000	.21922-02	.18003+01	.54216+01											
	.48598+02	.17818+02	.69515+04	.21052+00	.32961+02	.80048-02	.20311-01	.45309-04											
	.27314-01	.21660-02	.00000	.29900-01	.33600-01	.51881-02	.17982+02	.73722+03											
	.59313+04	.12282+05	.10000+11	.29921-03	.00000	.40653+01	.66995+00	.28044-06											
	.54559-06	.00513-06	.13687-02	.19179-03	.10633-03	.14006-02	.15369+03	.39612+01											
	.66944+00	.16118-05	.83761-05	.00000	.00000	.10470-04	.11599-05	.28753-05											
	.00000	.00000	.00000																
STA 22	Z = 26.03	TWG = 1931.		PRC = 1145.6		WG = 93.3		PG = 353.9		NT = 216.									
	R = 5.032	TWM = 1518.		TB = 108.2		WC = 74.6		TG = 4056.		AF = .036									
ITR 3	A/AT = -1.16	TWL = 1104.		Q/AI = 20.31		SUMQ = 14273.		BETA = .990		L = .1941									
	.22692+00	.17355+00	.18981+00	.21600+03	.00000	.00000	.83953-01	.00000											
	.13000-01	.10000-01	.00000	.00000	.00000	.21748-02	.18003+01	.81575+01											
	.10237+02	.25976+02	.73652+04	.22540+00	.31861+02	.73354-02	.20382-01	.81136-04											
	.31892-01	.41430-02	.00000	.29180-01	.32800-01	.49061-02	.17174+02	.86161+03											
	.62524+04	.14576+05	.10000+11	.29251-03	.00000	.40407+01	.67204+00	.27319-06											
	.53208-06	.77929-06	.13026-02	.19669-03	.10999-03	.13356-02	.16461+03	.39462+01											
	.66872+00	.15943-05	.94592-05	.00000	.00000	.12429-04	.11419-05	.27992-05											
	.00000	.00000	.00000																
STA 23	Z = 25.06	TWG = 1867.		PRC = 1172.5		WG = 93.3		PG = 387.9		NT = 216.									
	R = 6.549	TWM = 1521.		TB = 112.0		WC = 74.6		TG = 4140.		AF = .047									
ITR 3	A/AT = -1.37	TWL = 1175.		Q/AI = 15.79		SUMQ = 15079.		BETA = 1.000		L = .2349									
	.24430+00	.19000+00	.21337+00	.21600+03	.00000	.00000	.91583-01	.00000											

.66804+00	.15885-05	.10173-04	.00000	.00000	.13667-04	.11428-05	.28979-05
.00000	.00000	.00000					

STA 24 Z = 24.21	TWG = 1925.	FRC = 1195.6	WG = 93.3	PG = 414.7	NT = 216.
R = 7.247	TWM = 1676.	TB = 115.3	WC = 74.6	TG = 4202.	AF = .067
ITR 4 A/AT = -1.67	TWL = 1428.	Q/AI = 11.78	SUMQ = 15763.	BETA = 1.000	L = .3056

.26902+00	.21266+00	.25077+00	.21600+03	.00000	.00000	.10189+00	.00000
.14000-01	.10000-01	.00000	.00000	.00000	.22860-02	.18003+01	.31110+01
-.26219+02	.35349+02	.41611+04	.12630+00	.29660+02	.41556-02	.09712-02	.14168-03
.49652-01	.06955-02	.00000	.21630-01	.25200-01	.20216-02	.10165+02	.68411+03
.75055+04	.14707+05	.10000+11	.30772-03	.00000	.39141+01	.66274+00	.27120-06

.61627-06	.92112-06	.12351-02	.16271-03	.89613-04	.12518-02	.19018+03	.39510+01
.66711+00	.15969-05	.10719-04	.00000	.00000	.14489-04	.11424-05	.32403-05
.00000	.00000	.00000					

STA 25 Z = 22.76	TWG = 1895.	FRC = 1201.1	WG = 93.3	PG = 423.9	NT = 216.
R = 3.697	TWM = 1704.	TB = 119.4	WC = 74.6	TG = 4221.	AF = .085
ITR 3 A/AT = -2.41	TWL = 1512.	Q/AI = 8.47	SUMQ = 16873.	BETA = 1.000	L = .3000

.58379+00	.25530+00	.29069+00	.21600+03	.00000	.00000	.12329+00	.00000
.15000-01	.10000-01	.00000	.00000	.00000	.23110-02	.18003+01	.28442+01
-.83007+01	.30193+02	.34563+04	.10541+00	.27609+02	.29486-02	.60771-02	.15673-03
.75540-01	.20952-01	.00000	.17680-01	.24700-01	.20299-02	.74377+01	.11098+04
.86707+04	.15302+05	.10000+11	.31057-03	.00000	.38556+01	.66191+00	.26827-06

.63263-06	.95748-06	.11798-02	.15465-03	.84799-04	.12074-02	.20615+03	.39460+01
.66707+00	.15912-05	.10906-04	.00000	.00000	.14874-04	.11296-05	.33575-05
.00000	.00000	.00000					

STA 26 Z = 21.31	TWG = 1797.	FRC = 1203.5	WG = 93.3	PG = 434.7	NT = 216.
R = 10.148	TWM = 1633.	TB = 123.2	WC = 74.6	TG = 4244.	AF = .101
ITR 3 A/AT = -3.28	TWL = 1468.	Q/AI = 7.04	SUMQ = 17905.	BETA = 1.000	L = .2830

.69513+00	.29763+00	.32552+00	.21600+03	.00000	.00000	.14470+00	.00000
.15000-01	.10000-01	.00000	.00000	.00000	.23302-02	.18003+01	.17475+01
-.41905+01	.39941+02	.30213+04	.91987-01	.25557+02	.23725-02	.52376-02	.16031-03
.10837+00	.26190-01	.00000	.17680-01	.26000-01	.16903-02	.63133+01	.10323+04
.10407+05	.17258+05	.10000+11	.30341-03	.00000	.38065+01	.66193+00	.26618-06

.62837-06	.93849-06	.11318-02	.15857-03	.87622-04	.11558-02	.22071+03	.39300+01
.66740+00	.15736-05	.11123-04	.00000	.00000	.15469-04	.11303-05	.33040-05
.00000	.00000	.00000					

STA 27 Z = 19.86	TWG = 1718.	FRC = 1204.7	WG = 93.3	PG = 447.1	NT = 216.
R = 11.599	TWM = 1564.	TB = 126.9	WC = 74.6	TG = 4271.	AF = .116
ITR 3 A/AT = -4.28	TWL = 1410.	Q/AI = 6.01	SUMQ = 18928.	BETA = 1.000	L = .2664

.80623+00	.33998+00	.35479+00	.21600+03	.00000	.00000	.16612+00	.00000
.16000-01	.10000-01	.00000	.00000	.00000	.23476-02	.18003+01	.12074+01
-.23037+01	.41148+02	.27317+04	.82960-01	.23505+02	.19468-02	.46808-02	.16406-03
.14877+00	.31792-01	.00000	.17680-01	.26900-01	.14431-02	.54291+01	.10224+04
.11303+05	.18141+05	.10000+11	.29691-03	.00000	.37652+01	.66278+00	.26445-06

.61469-06	.91312-06	.10862-02	.16454-03	.91411-04	.11090-02	.23480+03	.39171+01
.68762+00	.15591-05	.11368-04	.00000	.00000	.16092-04	.11327-05	.32324-05
.00000	.00000	.00000					

~~PAGE 5~~

TUBE TYPE = VARIABLE

EFF	SURF	AREA	LEG	SPREAD	EQUIV	DIA	NMB	SMD	RA	RG	THC
THM	THS	GAMMA	ENTROPY	GAS	VFL	FRIC	FACT	PFM	PF		
PV	SUM	PF	COOL	VEL	COOL	MACH	DEV	DIST	HG	HL	HR
SHAPE	FACT	GRAY	BODY	FEFV	CL	CG	CP	CB	U	G/AO	G
STRESS	YLD	STR	KC	KM	KWG	CP	CB	PR	CF	VISC	CB

VISC-CF	VISC-CW	RHO-CB	RHO-CF	RHO-CW	RHO-RAR	H-CB	CP-GF
PF-CF	VISC-GF	RHO-GB	RBO	GOARO	RHO-GF	KP	KCF
POP-B	VDI	TSAT					

STA 26	L	=	10.41	TWG	=	1706.	PRC	=	1205.2	WG	=	93.3	PG	=	456.0	NT	=	216.	
	R	=	10.050	TWM	=	1503.	TF	=	130.6	WC	=	74.6	TG	=	4290.	AF	=	.130	
TR	26	WAT	=	-5.42	TWL	=	1421.	Q/AI	=	5.55	SUMQ	=	19966.	BETA	=	1.000	L	=	.2409

.91733+00	.38207+00	.37849+00	.21600+03	.00000	.00000	.18753+00	.00000
.16090-01	.10000-01	.00000	.00000	.00000	.23628-02	.18003+01	.91210+00
-.13674+01	.42060+02	.25436+04	.77070-01	.21453+02	.17923-02	.42987-02	.17138-03
.19729+00	.37685-01	.00000	.17680-01	.30500-01	.13336-02	.50569+01	.10389+04
.12920+05	.13180+05	.10000+11	.22759-03	.00000	.37442+01	.66244+00	.26416-06
.52012-06	.92090-06	.10469-02	.16228-03	.90306-04	.10665-02	.24850+03	.39165+01
.06743+00	.15581-05	.11543-04	.00000	.00000	.16420-04	.11349-05	.32609-05
.00000	.00000	.00000					

STA 29	Z	=	16.96	TWG	=	1717.	PRC	=	1204.3	WG	=	93.3	PG	=	456.0	NT	=	216.
	P	=	14.501	TWM	=	1568.	TR	=	134.6	WC	=	74.6	TG	=	4290.	AF	=	.135
ITR	3 A/AT	=	-6.69	TVL	=	1420.	Q/AI	=	5.41	SUMQ	=	21080.	BETA	=	1.000	L	=	.1997

.10287+01	.42370+00	.38821+00	.21600+03	.00000	.00000	.20895+00	.00000
.17000-01	.10000-01	.00000	.00000	.00000	.23677-02	.18003+01	.78433+00
.25991-01	.42845+02	.25474+04	.77023-01	.19401+02	.17545-02	.42109-02	.17826-03
.25434+00	.43784-01	.00000	.17680-01	.36100-01	.13020-02	.49730+01	.11141+04
.13508+05	.10144+05	.10000+11	.29731-03	.00000	.37214+01	.66250+00	.26375-06
.61914-06	.91743-06	.10035-02	.16260-03	.90756-04	.10252-02	.26344+03	.39168+01
.66742+00	.15584-05	.11543-04	.00000	.00000	.16415-04	.11368-05	.32557-05
.00000	.00000	.00000					

STA 30 Z	= 15.51	TWG = 1803.	PRC = 1203.4	WG = 93.3	PG = 456.0	NT = 216.
-----R	= 15.952	TWM = 1650.	---TB--= 139.2	---WC--= 74.6	---TG--= 4290.	---AF--= .139
ITR 3 A/AT	= -8.10	TWL = 1493.	Q/AI= 5.68	SUMQ = 22340.	BETA = 1.000	L = .1580

[illegible]

	.66689+00 .00000	.15732-05 .00000	.11543-04 .00000	.00000	.00000	.16216-04	.11390-05	.33654-05
STA 31 Z = 14.05. R = 17.403 ITR 3 A/AT = -9.64	TWG = 1760. TWM = 1601. TWL = 1442.	PRC = 1200.6 TB = 144.6 Q/AI = 5.82	WG = 93.3 WC = 74.6 SUMQ = 23796.	PG = 456.0 TG = 4290. BETA = 1.000	NT = 216. AF = .132 L = .0987			
	.12616+01 .17000-01 .18269+01 .39478+00 .16582+05	.50643+00 .10000-01 .44426+02 .56206-01 .17990+05	.37300+00 .00000 .28687+04 .00000 .10000+11	.21600+03 .00000 .86309-01 .17680-01 .30045-03	.00000 .00000 .15279+02 .56000-01 .00000	.00000 .23725-02 .19560-02 .14050-02 .36646+01	.25178+00 .18003+01 .44870-02 .54314+01 .66202+00	.00000 .83153+00 .19120-03 .14566+04 .26283-06
	.62733-06 .66714+00 .00000	.92731-06 .15660-05 .00000	.91214-03 .11543-04 .00000	.15866-03 .00000	.89060-04 .00000	.93636-03 .16313-03	.30029+03 .11588-05	.39239+01 .32984-05
STA 32 Z = 12.10 R = 19.358 ITR -18 A/AT = -11.95	TWG = 1704. TWM = 1519. TWL = 1333.	PRC = 1194.4 TB = 152.7 Q/AI = 6.25	WG = 93.3 WC = 74.6 SUMQ = 26041.	PG = 456.0 TG = 4290. BETA = 1.000	NT = 216. AF = .110 L = .0243			
	.18454+01 .18000-01 .46440+01 .50760+00 .17420+05	.56197+00 .10000-01 .45987+02 .64247-01 .13186+05	.32414+00 .00000 .35124+04 .00000 .10000+11	.21600+03 .00000 .10511+00 .17680-01 .29331-03	.00000 .00000 .12537+02 .71700-01 .00000	.00000 .23791-02 .20721-02 .15111-02 .36362+01	.28063+00 .18003+01 .52958-02 .58313+01 .66355+00	.00000 .15612+01 .19063-03 .22447+04 .26471-06
	.60333-06 .66744+00 .00000	.88220-06 .15577-05 .00000	.84774-03 .11543-04 .00000	.16002-03 .00000	.95171-04 .00000	.87994-03 .16424-04	.33007+03 .11935-05	.39162+01 .31726-05
STA 33 Z = 10.94 R = 20.249 ITR 3 A/AT = -13.05	TWG = 1696. TWM = 1482. TWL = 1268.	PRC = 1186.9 TB = 157.7 Q/AI = 7.10	WG = 93.3 WC = 74.6 SUMQ = 27479.	PG = 456.0 TG = 4290. BETA = 1.000	NT = 216. AF = .100 L = .0076			
	.10652+01 .10000-01 .61671+01 .57008+00 .18184+05	.58779+00 .10000-01 .47405+02 .47196-01 .13213+05	.25507+00 .00000 .42569+04 .00000 .10000+11	.21600+03 .00000 .12678+00 .17680-01 .28904-03	.00000 .00000 .11070+02 .87500-01 .00000	.00000 .24138-02 .23828-02 .17175-02 .36420+01	.29378+00 .18003+01 .63910-02 .66654+01 .66463+00	.00000 .14172+01 .18600-03 .14376+04 .26567-06
	.58624-06 .64553+00 .00000	.85051-03 .15546-05 .00000	.81144-03 .11543-04 .00000	.17418-03 .00000	.99669-04 .00000	.82959-03 .16479-04	.34034+03 .12137-05	.39134+01 .30831-05
STA 34 Z = 9.59 R = 20.809 ITR 3 A/AT = -13.78	TWG = 1653. TWM = 1423. TWL = 1194.	PRC = 1178.9 TB = 163.5 Q/AI = 7.46	WG = 93.3 WC = 74.6 SUMQ = 29112.	PG = 456.0 TG = 4290. BETA = .990	NT = 216. AF = .092 L = -.0004			
	.11057+01 .18000-01 .56421+01 .62608+00 .18604+05	.60408+00 .10000-01 .49688+02 .45429-01 .13358+05	.22344+00 .00000 .43623+04 .00000 .10000+11	.21600+03 .00000 .14397+00 .17680-01 .20334-03	.00000 .00000 .96020+01 .96900-01 .00000	.00000 .24342-02 .25297-02 .18258-02 .36489+01	.30205+00 .18003+01 .72373-02 .70110+01 .66660+00	.00000 .22831+01 .17309-03 .16332+04 .26719-06
	.56804-06 .64571+00 .00000	.81812-06 .15391-05 .00000	.77205-03 .11543-04 .00000	.13176-03 .00000	.10489-03 .00000	.79175-03 .16757-04	.36964+03 .12415-05	.39001+01 .29924-05

**** HESS AND KUNZ CORRELATION EQUATION

PAGE 6

COOLANT = PARA-HYDROGEN (MBS)

TUBE TYPE = VARIABLE

MR = .00 PC = 456. TC = 4290. HC = 0. PIN = 1271.0 TIN = 60.2

* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *
EFF SURF AREA	LEG SPREAD	EQUIV DIA	NMB	SMD	RA	RG	THC
THM	THS	GAMMA	ENTROPY	GAS VEL	FRIC FACT	PFM	PF
PV	SUM PF	COOL VEL	COOL MACH	DEV DIST	HG	HL	HR
SHAPE FACT	GRAY BODY	FEFV	CL	CG	U	Q/AO	Q
STRESS	YLD STR	KC	KM	KWG	CP-CB	PR-CF	VISC-CB
VISC-CF	VISC-CW	RHO-CB	RHO-CF	RHO-CW	RHOBAR	H-CB	CP-GF
PP-GF	VISC-GF	RHO-GF	RBO	QOABO	RHO-GF	KB	KCF
PPB-B	VDT	TSAT					
* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *	* * * * *

STA 35	Z = 8.13	TWG = 1730.	PRC = 1177.3	WG = 93.3	PG = 456.0	NT = 216.
	R = 21.000	TWM = 1458.	TB = 169.9	WC = 71.6	TG = 4290.	AF = .091
ITR 3	A/AT = -14.04	TWL = 1186.	Q/AI = 7.37	SUMQ = 30795.	BETA = .990	L = .0040

.11255+01	.60987+00	.21822+00	.21600+03	.00000	.00000	.30487+00	.00000
.22000-01	.10000-01	.00000	.00000	.00000	.24589-02	.18003+01	.27487+01
-.11598+01	.52436+02	.49425+04	.14519+00	.81350+01	.25573-02	.72454-02	.15816-03
.68045+00	.41138-01	.00000	.17680-01	.10020+00	.18064-02	.68350+01	.16831+04
.15138+05	.18099+05	.10000+11	.28682-03	.00000	.36582+01	.66670+00	.27034-00
.56870-06	.81482-06	.73712-03	.18166-03	.10543-03	.75459-03	.39384+03	.39122+01
.64564+00	.15531-05	.11543-04	.00000	.00000	.16506-04	.12770-05	.29911-05
.00000	.00000	.00000					

STA 36	Z = 6.40	TWG = 1717.	PRC = 1171.4	WG = 93.3	PG = 456.0	NT = 216.
	R = 21.000	TWM = 1444.	TB = 177.4	WC = 71.6	TG = 4290.	AF = .091
ITR 3	A/AT = -14.04	TWL = 1170.	Q/AI = 7.38	SUMQ = 32770.	BETA = .980	L = .0046

.13373+01	.60987+00	.21822+00	.21600+03	.00000	.00000	.30487+00	.00000
.22000-01	.10000-01	.00000	.00000	.00000	.24638-02	.18003+01	.33806+01
-.26109+01	.55817+02	.52192+04	.15202+00	.64000+01	.25996-02	.74308-02	.15214-03
.73816+00	.46568-01	.00000	.17680-01	.10140+00	.18315-02	.68436+01	.19755+04
.15061+05	.18143+05	.10000+11	.28535-03	.00000	.36677+01	.66700+00	.27383-00
.56637-06	.80766-06	.69804-03	.18207-03	.10642-03	.71758-03	.42201+03	.39035+01
.64641+00	.15430-05	.11543-04	.00000	.00000	.16687-04	.13184-05	.29788-05
.00000	.00000	.00000					

STA 37	Z = 4.80	TWG = 1713.	PRC = 1166.3	WG = 93.3	PG = 456.0	NT = 216.
	R = 21.000	TWM = 1438.	TB = 183.8	WC = 71.6	TG = 4290.	AF = .091
ITR 3	A/AT = -14.04	TWL = 1164.	Q/AI = 7.38	SUMQ = 34595.	BETA = .960	L = .0046

.12332+01	.60987+00	.21822+00	.21600+03	.00000	.00000	.30487+00	.00000
.22000-01	.10000-01	.00000	.00000	.00000	.24694-02	.18003+01	.32676+01
.18307+01	.59085+02	.54132+04	.15647+00	.48000+01	.26798-02	.75342-02	.16838-03
.79606+00	.45964-01	.00000	.17680-01	.10380+00	.18766-02	.68522+01	.18241+04
.14935+05	.18157+05	.10000+11	.28480-03	.00000	.36989+01	.66707+00	.27790-00
.56639-06	.80496-06	.67303-03	.18131-03	.10655-03	.68553-03	.44679+03	.38894+01

.18307+01	.59085+02	.54132+04	.13647+09	.48000+01	.26708-02	.75342-02	.16838-03
.79600+00	.45964-01	.00000	.17680-01	.10380+00	.18766-02	.68522+01	.18241+04
.14995+05	.13157+05	.10000+11	.28480-03	.00000	.36989+01	.66707+00	.27790-06
.56639-06	.80496-06	.67303-03	.18131-03	.10655-03	.68553-03	.44679+03	.38894+01

.64773+00	.15266-05	.11543-04	.00000	.00000	.16981-04	.13578-05	.29787-05
.00000	.00000	.00000					

STA 38	Z = 3.20	TWG = 1707.	PRC = 1160.7	WG = 93.3	PG = 456.0	NT = 216.
	R = 21.000	TWM = 1431.	TB = 190.3	WC = 71.6	TG = 4290.	AF = .091
ITR 3	A/AT = -14.04	TWL = 1156.	Q/AI = 7.40	SUMQ = 36421.	BETA = .930	L = .0046

.12332+01	.60987+00	.21822+00	.21600+03	.00000	.00000	.30487+00	.00000
.22000-01	.10000-01	.00000	.00000	.00000	.24758-02	.18003+01	.34057+01
.21450+01	.62490+02	.56405+04	.16172+00	.32000+01	.28181-02	.76620-02	.18904-03
.85079+00	.48950-01	.00000	.17680-01	.10810+00	.19469-02	.68642+01	.18268+04
.14924+05	.13177+05	.10000+11	.28414-03	.00000	.37474+01	.66713+00	.28261-06

.56607-06	.80162-06	.64590-03	.18067-03	.10676-03	.65946-03	.47260+03	.38684+01
.64987+00	.15022-05	.11543-04	.00000	.00000	.17418-04	.13999-05	.29769-05
.00000	.00000	.00000					

STA 39	Z = 1.60	TWG = 1673.	PRC = 1154.8	WG = 93.3	PG = 456.0	NT = 216.
	R = 21.000	TWM = 1399.	TB = 196.8	WC = 71.6	TG = 4290.	AF = .091
ITR 3	A/AT = -14.04	TWL = 1124.	Q/AI = 7.28	SUMQ = 38236.	BETA = .840	L = .0046

.12332+01	.60987+00	.21822+00	.21600+03	.00000	.00000	.30487+00	.00000
.22000-01	.10000-01	.00000	.00000	.00000	.24821-02	.18003+01	.35604+01
.23099+01	.66051+02	.58853+04	.16740+00	.16000+01	.32622-02	.78564-02	.23795-03
.92666+00	.52028-01	.00000	.17680-01	.12200+00	.21376-02	.67577+01	.18143+04
.14843+05	.18290+05	.10000+11	.28084-03	.00000	.37955+01	.66809+00	.28727-06

.55957-06	.78760-06	.61904-03	.18333-03	.10912-03	.63247-03	.49820+03	.38029+01
.65814+00	.14260-05	.11543-04	.00000	.00000	.18786-04	.14415-05	.29428-05
.00000	.00000	.00000					

STA 40	Z = .00	TWG = 1057.	PRC = 1149.1	WG = 93.3	PG = 456.0	NT = 216.
	R = 21.000	TWM = 849.	TB = 201.9	WC = 71.6	TG = 4290.	AF = .091
ITR 5	A/AT = -14.04	TWL = 641.	Q/AI = 4.43	SUMQ = 39685.	BETA = .270	L = .0046

.12332+01	.60987+00	.21822+00	.21600+03	.00000	.00000	.30487+00	.00000
.22000-01	.10000-01	.00000	.00000	.00000	.24871-02	.18003+01	.37103+01
.20286+01	.69761+02	.61003+04	.17244+00	.00000	.35602-01	.10078-01	.48533-02
.10000+01	.55186-01	.00000	.17680-01	.83710+00	.46315-02	.41274+01	.14497+04
.14775+05	.23044+05	.10000+11	.22600-03	.00000	.38338+01	.70115+00	.29096-06

.43302-06	.54998-06	.59722-03	.28074-03	.18763-03	.60813-03	.51867+03	.34841+01
.67649+00	.79305-06	.11543-04	.00000	.00000	.44255-04	.14746-05	.23503-05
.00000	.00000	.00000					

FOR BOLT COOLANT OF .00 LB./SEC. ABSORBING .00 BTU/LB., OUTLET CONDITIONS ARE ---

ENTHALPY = 519.4 BTU/LB., TEMP. = 201.9 DEG.R., PRESS. = 1120.3 PSIA., RESULTING IN

DELTA T = 141.7 DEG.R., DELTA P = 150.7 PSI