RTE

A COMPUTER CODE FOR THREE-DIMENSIONAL ROCKET THERMAL EVALUATION

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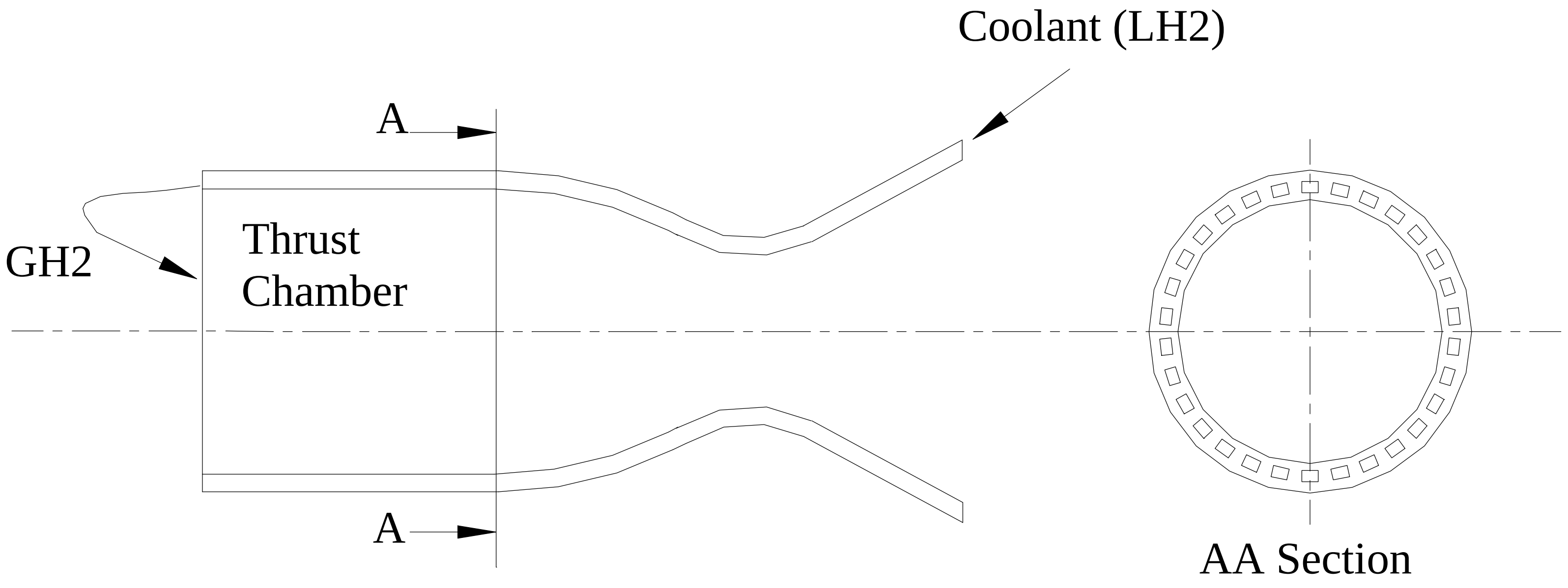
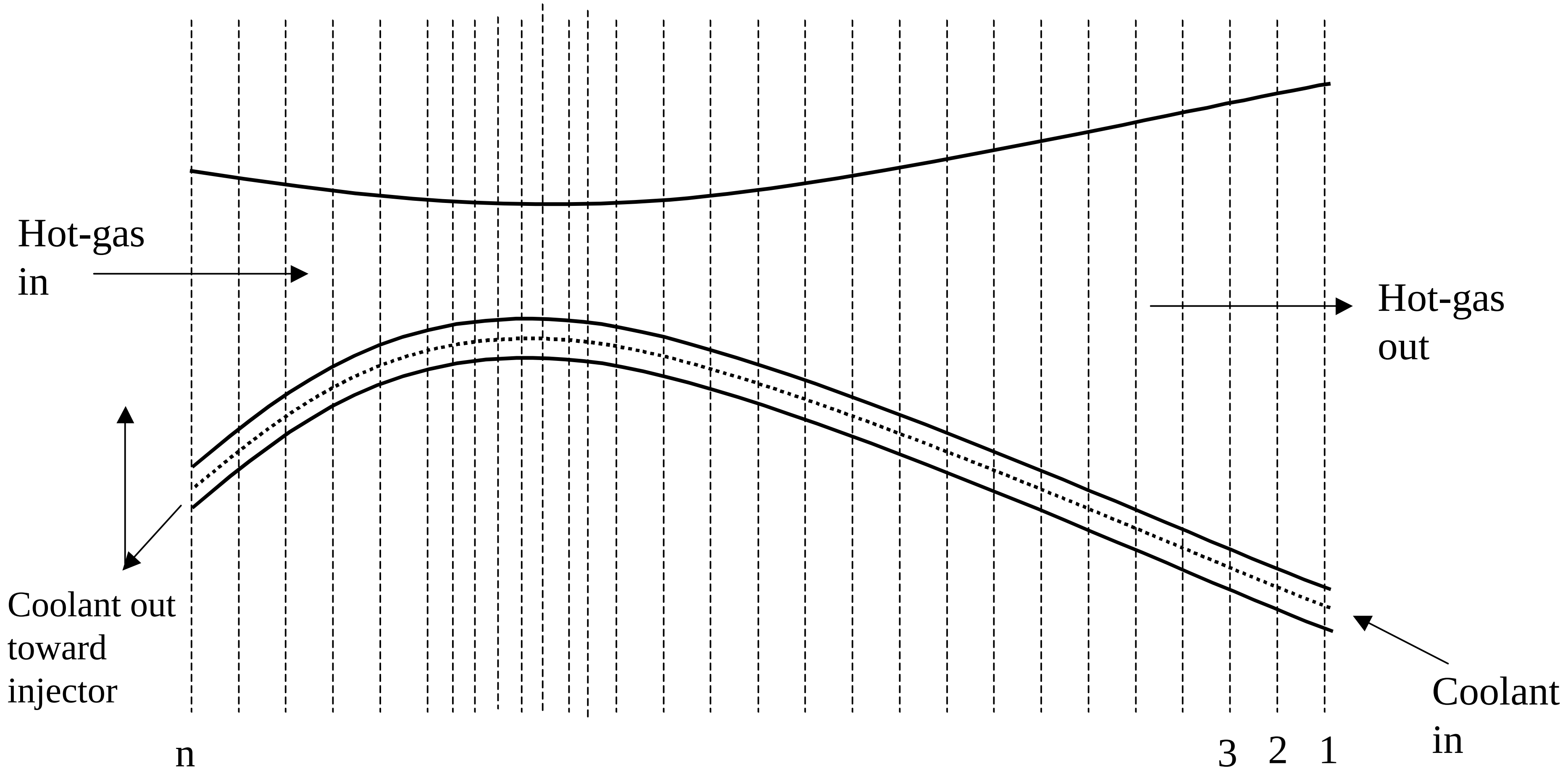
Regeneratively Cooled Rocket Engines



Modes of Heat Transfer Incorporated in RTE

- Convection and radiation from combustion gases (hot-gases).
- Three-dimensional conduction within the wall.
- Convection to the coolant.
- Conjugating all these mode of heat transfer.

Typical Nozzle Broken into a Number of Stations



Hot-gas in

Hot-gas out

Coolant out toward injector

Coolant in

Convection from Hot-Gases

- RTE uses the Chemical Equilibrium program by Gordon & McBride for hot-gas side thermodynamics and transport properties.
- Uses adiabatic wall temperature (enthalpy) along with convective heat transfer correlation for calculating heat flux from hot-gases.
- Can be linked to TDK’s Boundary Layer Modules for hot-gas-side heat flux calculations.
- Heat fluxes can be input using a matrix of heat fluxes.

Hot-Gas-Side Heat flux Using Adiabatic Wall Temperature (Enthalpy)

The reference enthalpy of the gas side, is given by (Eckert):

$$i_{GX_n} = 0.5(i_{GW_n} + i_{GS_n}) + 0.180(i_{G0_n} - i_{GS_n})$$

The adiabatic wall enthalpy (Bartz and Eckert)

$$i_{GAW_n} = i_{GS_n} + (\Pr_{GX_n})^{1/3}(i_{G0_n} - i_{GS_n})$$

Hot-Gas Side Convective Heat Transfer

$$q_n = h_{G_n}\left(T_{GAW_n} - T_{GW_n}\right)$$

Or

$$q_n = \frac{h_{G_n}}{C_{p_{GX\,n}}}\left(i_{GAW_n} - i_{GW_n}\right)$$

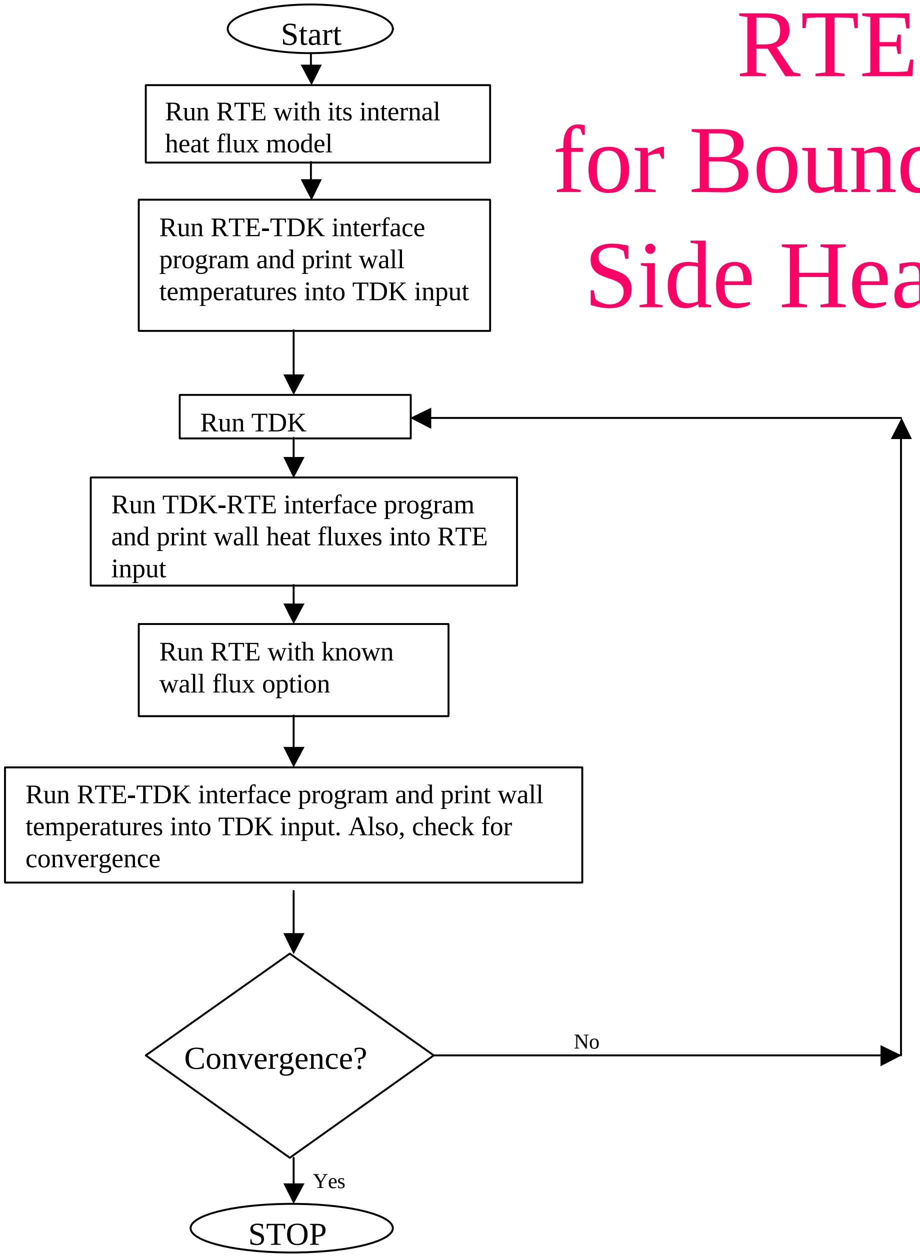
Hot-Gas Side Convective Heat Transfer

$$h_{G_n} = \frac{C_{G_n} k_{GX_n}}{d_{G_n}} \mathrm{Re}_{GX_n}{}^{0.8} \, \mathrm{Pr}_{GX_n}{}^{0.3}$$

$$\mathrm{Re}_{GX_n} = \frac{4\dot{W}_G}{p \, d_{G_n} m_{GX_n}} \frac{T_{GS_n}}{T_{GX_n}}$$

$$\mathrm{Pr}_{GX_n} = \frac{C_{p_{CX_n}} m_{GX_n}}{k_{GX_n}}$$

RTE-TDK Interface for Boundary Layer Hot-Gas-Side Heat Flux Calculations



Start

Run RTE with its internal heat flux model

Run RTE-TDK interface program and print wall temperatures into TDK input

Run TDK

Run TDK-RTE interface program and print wall heat fluxes into RTE input

Run RTE with known wall flux option

Run RTE-TDK interface program and print wall temperatures into TDK input. Also, check for convergence

Convergence?

No

Yes

STOP

Inputting Hot-Gas-Side Heat Fluxes Using a Matrix of Fluxes

- Hot-gas-side heat fluxes can be input using a matrix of heat fluxes.
- Rows of this matrix represent axial positions and its columns represent wall temperatures.
- This option can be used if other programs are available for hot-gas-side heat flux calculations.

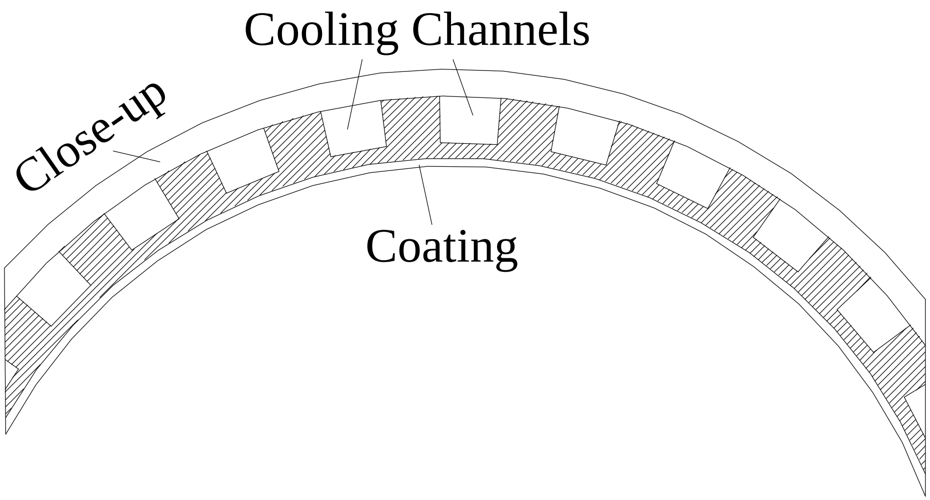
Radiation Heat Transfer from Hot-Gases

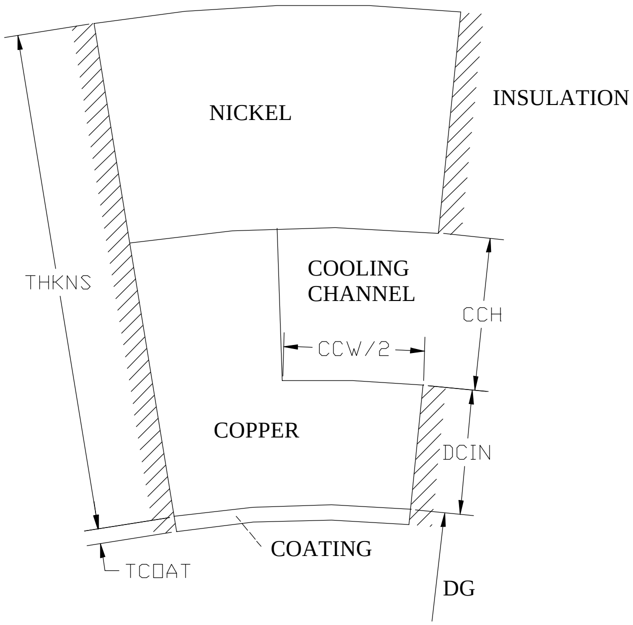
Radiation heat transfer is calculated using the Discrete Exchange Factor (DEF) method

$$q''_r = \left(\sum_{l=1}^{m+2} w_{s_l} E_{s_l} \overline{DS_l S_n} + \sum_{l=1}^{m} w_{g_l} E_{g_l} \overline{DG_l S_n} - E_{s_n} \right)$$

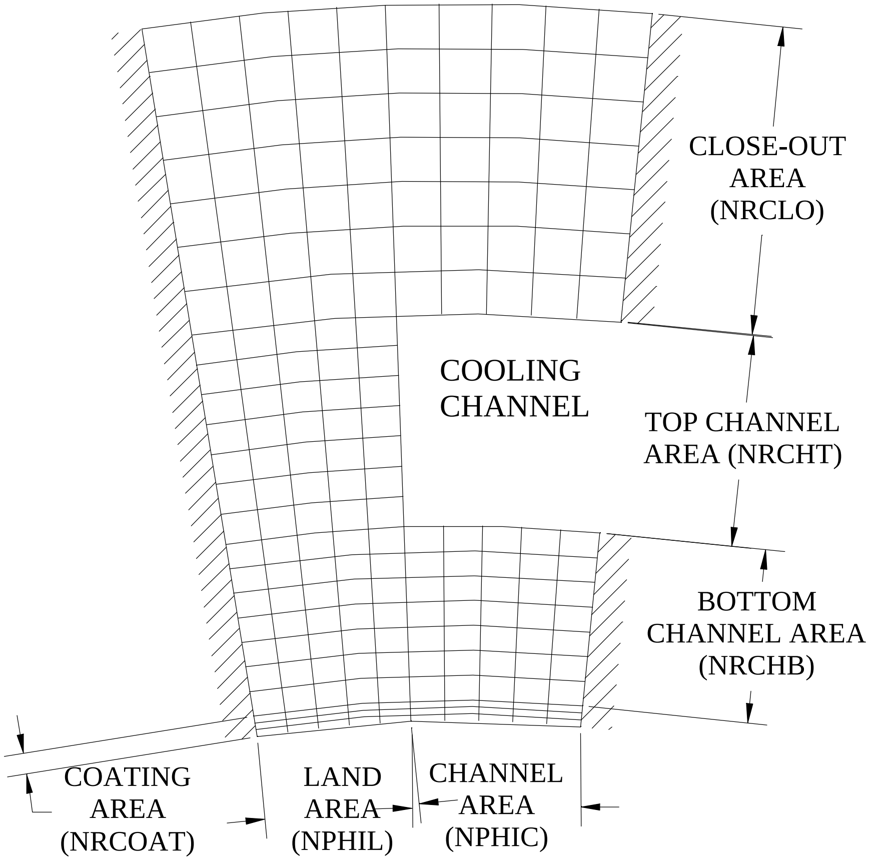
$$E_{s_n} = es\, T_{s_n}^4 \qquad\qquad E_{g_l} = 4K_{t_l}(1 - w_0)sp\, r^2 T_{g_l}^4$$

Cross-Section at Each Station





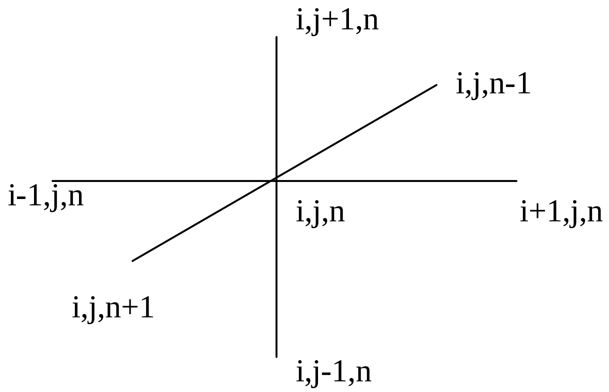
3-D Finite Difference Method for Wall Heat Conduction



Each node at this station (station n) is linked to the two corresponding nodes at stations before (n-1) and after (n+1) for three dimensional heat conduction analysis.

3-D Finite Difference Model for Wall Heat Conduction

Typical middle node



$$T^{l}_{i,j,n} = \frac{T^{l-1}_{i+1,j,n}/R_1 + T^{l-1}_{i,j-1,n}/R_2 + T^{l-1}_{i-1,j,n}/R_3 + T^{l-1}_{i,j+1,n}/R_4 + T_{i,j,n+1}/R_5 + T_{i,j,n-1}/R_6}{1/R_1 + 1/R_2 + 1/R_3 + 1/R_4 + 1/R_5 + 1/R_6}$$

$$R_1 = \frac{r\Delta f}{\Delta r\left(\Delta S^{n-1,n}_{i,j} + \Delta S^{n,n+1}_{i,j}\right)}\left(\frac{1}{k^{l-1}_{i,j,n}} + \frac{1}{k^{l-1}_{i+1,j,n}}\right)$$

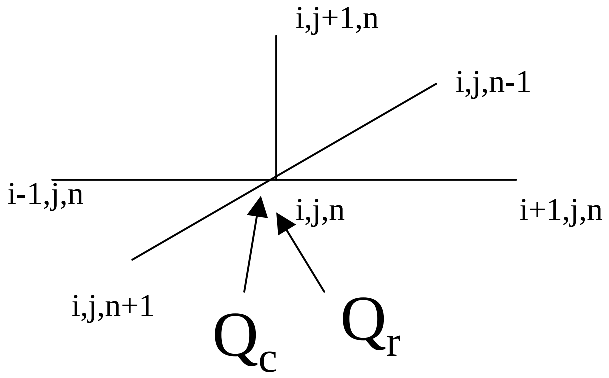
$$R_2 = \frac{\Delta r}{\left(r + \frac{\Delta r}{2}\right)\Delta f\left(\Delta S^{n-1,n}_{i,j} + \Delta S^{n,n+1}_{i,j}\right)}\left(\frac{1}{k^{l-1}_{i,j,n}} + \frac{1}{k^{l-1}_{i,j-1,n}}\right)$$

$$R_3 = \frac{r\Delta f}{\Delta r\left(\Delta S^{n-1,n}_{i,j} + \Delta S^{n,n+1}_{i,j}\right)}\left(\frac{1}{k^{l-1}_{i,j,n}} + \frac{1}{k^{l-1}_{i-1,j,n}}\right)$$

$$R_4 = \frac{\Delta r}{\left(r - \frac{\Delta r}{2}\right)\Delta f\left(\Delta S^{n-1,n}_{i,j} + \Delta S^{n,n+1}_{i,j}\right)}\left(\frac{1}{k^{l-1}_{i,j,n}} + \frac{1}{k^{l-1}_{i,j+1,n}}\right)$$

3-D Finite Difference Method for Wall Heat Conduction

Typical surface node



$$T_{i,j,n}^{l} = [T_{i+1,j,n}^{l-1}/R_1 + T_{i,j-1,n}^{l-1}/R_2 + T_{i-1,j,n}^{l-1}/R_3 + T_{i,j+1,n}^{l-1}/R_4 + T_{i,j,n+1}/R_5 + T_{i,j,n-1}/R_6 + Q_c + Q_r]/(1/R_1 + 1/R_2 + 1/R_3 + 1/R_4 + 1/R_5 + 1/R_6)$$

$$Q_r = \frac{\Delta f\,(\Delta S_{i,j}^{n-1,n} + \Delta S_{i,j}^{n,n+1})\sin b_n}{4p}\left(\sum_{l=1}^{m+2} w_{s_l} E_{s_l}\,\overline{DS_l S_n} + \sum_{l=1}^{m} w_{g_l} E_{g_l}\,\overline{DG_l S_n} - E_{s_n}\right)$$

Wall Materials Incorporated in RTE

- Copper
- Nickel
- Soot
- NARloy-Z
- Columbium
- Zirconia

- SS-347
- Amzirc
- Platinum
- Glidcop
- Inconel718
- Nicraly

Coolant Flow Convection

- GASP (Gas Properties) and WASP (Water and Steam Properties) are used for evaluating coolant properties.
- A one-dimensional approach is used for coolant heat transfer and pressure drop calculations.

Convection Options

- Surface roughness
- Entrance effect
- Curvature effect
- Swiler option for enhancing coolant convection
- Cooling channel contraction and expansion
- Pass-and-a-half cooling channel option
- Pressure drop
- Blocked channel option to study a worst case scenario

Cooling Channel Heat Transfer Coefficient

$$\frac{Nu}{Nu_r} = C_{C_n} Re^{0.8} Pr^{0.4}$$

Where $Nu_r = y^{-0.55}$ $y = 1 + g\,(T_W - T_S)$

$$g = \left|\frac{1}{r}\frac{\partial r}{\partial T}\right|_P = \frac{1}{r}\frac{\left(\frac{\partial P}{\partial T}\right)_r}{\left(\frac{\partial P}{\partial r}\right)_T}$$

Heat Transfer Coefficient for Oxygen

$$Nu = C_{C_n} Re_{CS} Pr_{CS}^{0.4} \left(\frac{\bar{c}_p}{c_{p_{CS}}} \right) \left(\frac{P_{Cri}}{P_{CS}} \right)^{0.2} \sqrt{ \left(\frac{k_{CS}}{k_{CW}} \right) \left(\frac{r_{CW}}{r_{CS}} \right) }$$

Where $P_{Cri} = 731.4$ psia

$$\bar{c}_p = \frac{i_{CW} - i_{CS}}{T_{CW} - T_{CS}}$$

Entrance Effect Correlation Options

$$f_{Ent.} = 2.88\left(\frac{\sum_{i=1}^{n}\Delta S_{i,i+1}}{d_{C_n}}\right)^{-0.325}$$

$$f_{Ent.} = \left[1+\left(\frac{\sum_{i=1}^{n}\Delta S_{i,i+1}}{d_{C_n}}\right)^{-0.7}\left(\frac{T_W}{T_b}\right)^{0.1}\right]$$

$$f_{Ent.} = \left(\frac{T_W}{T_b}\right)^{\left[1.59/\left(\sum_{i=1}^{n}\Delta S_{i,i+1}/d_{C_n}\right)\right]}$$

Curvature Effect

$$f_{Cur.} = \left[\mathrm{Re}_{CX_{Avg.}} \left(\frac{r_{C_n}}{R_{Cur._n}} \right)^2 \right]^{\pm 1/20}$$

where r_{C_n} is the hydraulic radius of cooling channel, $R_{Cur._n}$ is the radius of curvature, the sign (+) denotes the concave curvature and the sign (-) denotes the convex one

Swilers for Enhancing Heat Transfer

$$\frac{Gr}{Re^2} = \frac{2d_{C_n} b_T \left| T_{C_W} - T_{CS} \right| \tan a}{d_i}$$

$$f_{\text{swiler}} = F\left(1 + 0.25\sqrt{\frac{Gr}{Re}}\right)$$

$$F = 1 + 0.004872\frac{\tan^2 a}{d_i\left(1 + \tan^2 a\right)}$$

Surface Roughness

$$\frac{Nu}{Nu_{smooth}} = \left(\frac{f}{f_{smooth}} \right)^{n}$$

$$n = 0.68 Pr^{0.215}$$

$$\frac{1}{\sqrt{f}} = -2.0 \log\left[\frac{e}{3.7065D} - \frac{5.0452}{\mathrm{Re}_{CX_{Avg.}}} \log\left(\frac{1}{2..8257} \left(\frac{e}{D} \right)^{1.1098} + \frac{5.8506}{\mathrm{Re}_{CX_{Avg.}}^{\;0.8981}} \right) \right]$$

Pressure Drop

$$P_{CS_n} = P_{CS_{n-1}} - \left[\left(\Delta P_{CS_{n-1,n}}\right)_f + \left(\Delta P_{CS_{n-1,n}}\right)_M\right]$$

$$\left(\Delta P_{CS_{n-1,n}}\right)_f = \frac{f_n}{8g_c}\left(\frac{r_{CS_n} + r_{CS_{n-1}}}{d_{C_n} + d_{C_{n-1}}}\right)\left(V_{CS_n} + V_{CS_{n-1}}\right)^2 \Delta S_{n-1,n}$$

$$\left(\Delta P_{CS_{n-1,n}}\right)_M = \left(\frac{2}{(A_C N)_{n-1} + (A_C N)_n}\right)\frac{W_C{}^2}{g_c}\left(\frac{1}{(r_{CS} A_C N)_n} - \frac{1}{(r_{CS} A_C N)_{n-1}}\right)$$

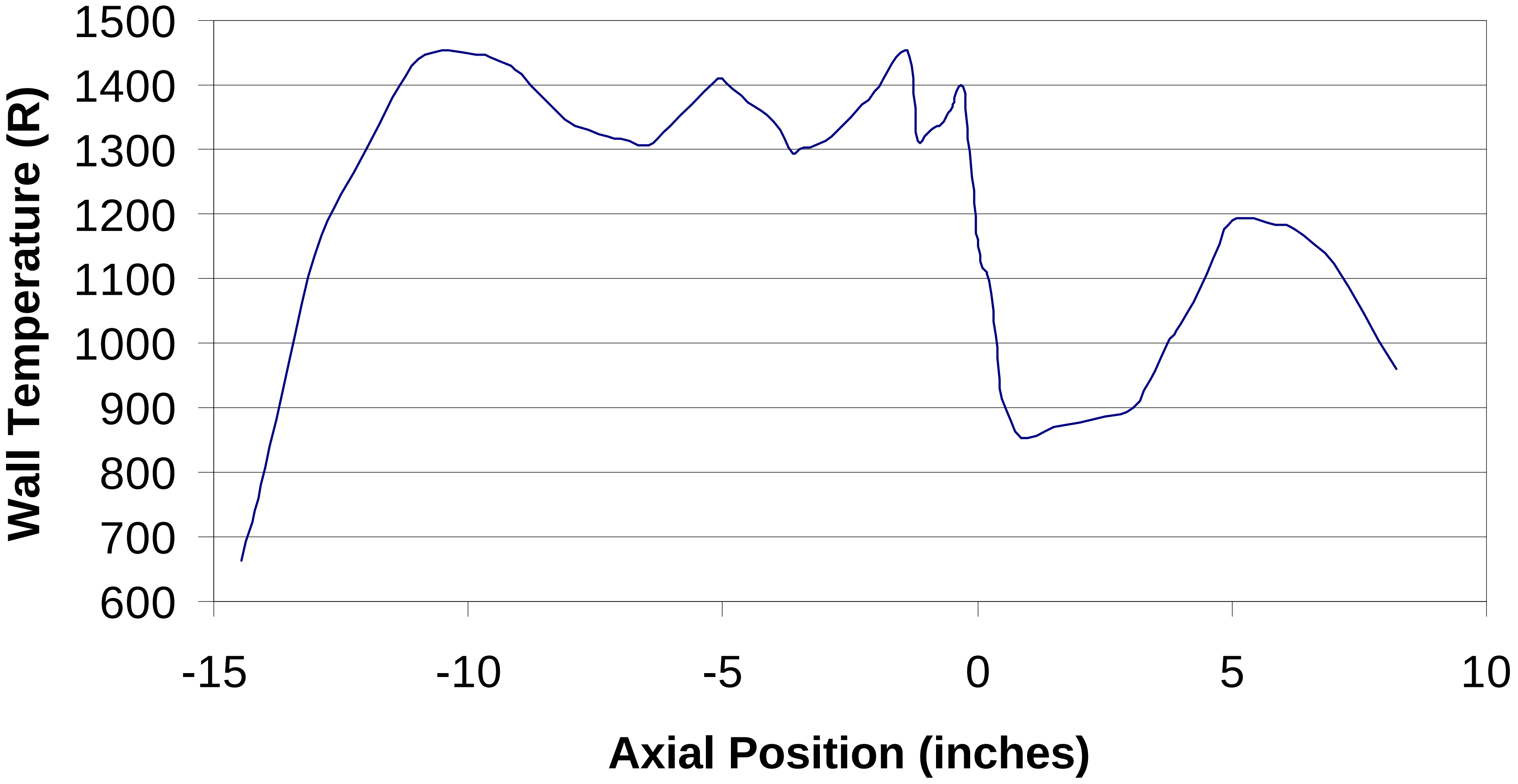
Typical RTE Results

- Space Shuttle Main Engine (SSME)
- Low-pressure chamber
- High pressure chamber with 200 cooling channels
- High pressure chamber with 150 cooling channels

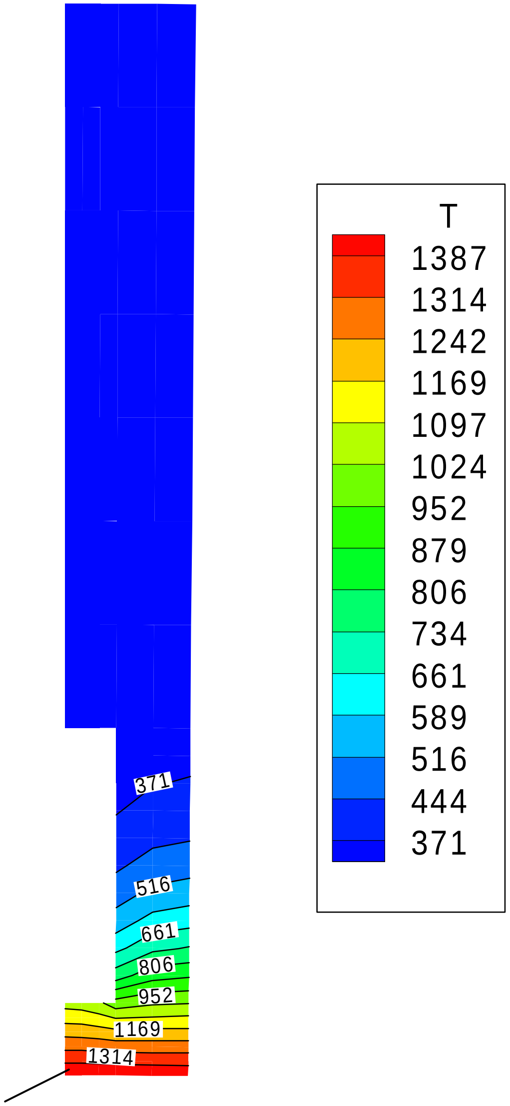
Results for SSME

Chamber pressure	**3027 psia**
O/F	**6.05**
Contraction ratio	**2.66**
Expansion ratio	**4.08**
Throat diameter	**10.88 inches**
Propellant	**GH2-LO2**
Coolant	**LH2**
Coolant inlet temperature	**95.03R**
Coolant inlet stagnation pressure	**6084 psia**
Total coolant flow rate	**29.06 lb/sec**
Approximate throat heat flux	**80 Btu/in^2-sec**
Number of cooling channels	**430**
Throat region channel aspect ratio	**5**

Wall Temperature Distribution for SSME

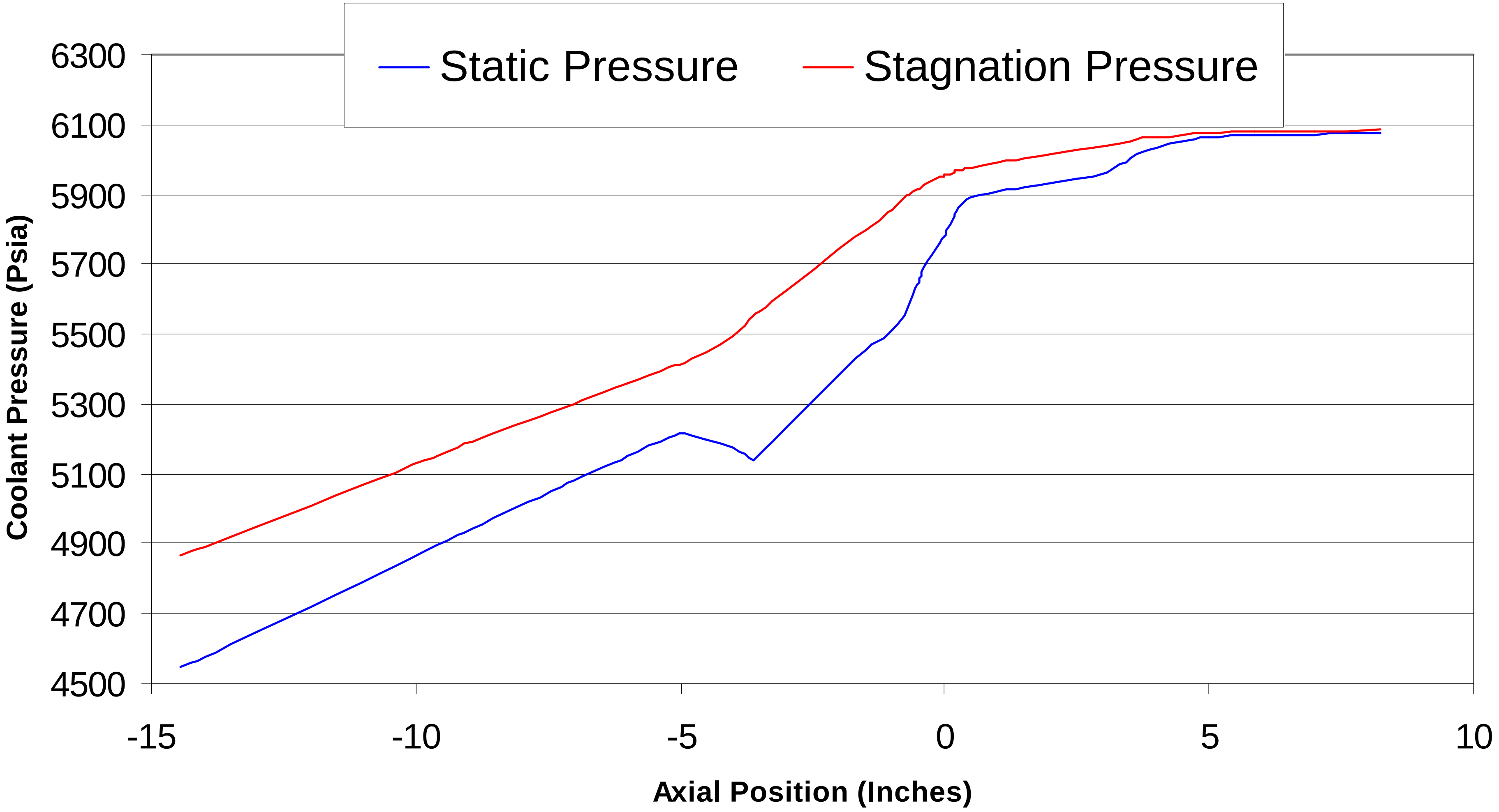


Temperature Profile (X=-1.4 Inches)



T_{max}=1460R

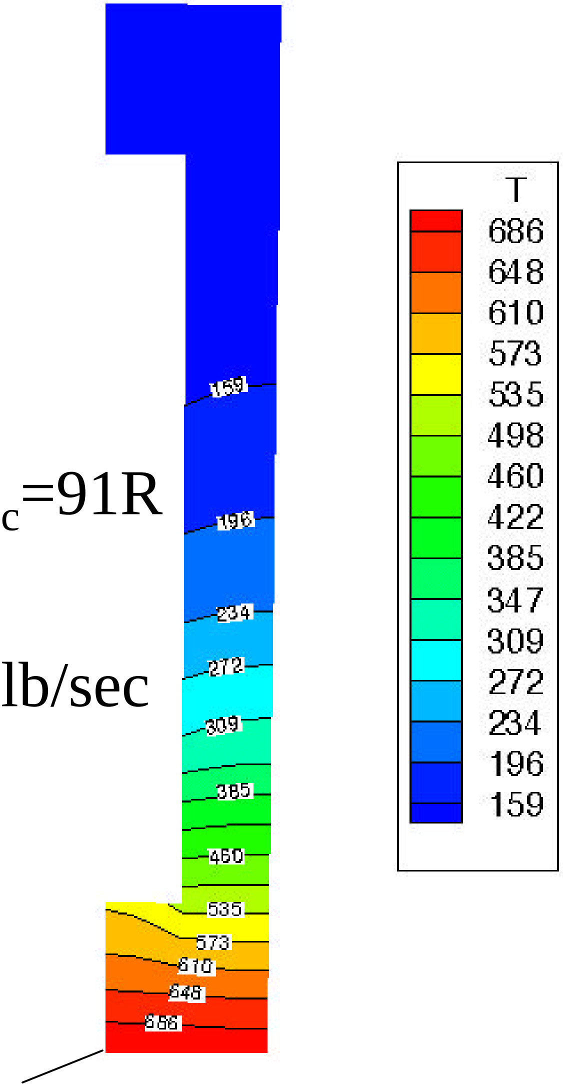
Coolant Pressure



Results for Low Pressure Chamber

Chamber pressure	450 psia
O/F	5.8
Contraction ratio	3.07
Expansion ratio	5.3
Throat diameter	8.0 inches
Propellant	GH2-LO2
Coolant	LH2
Coolant inlet temperature	50R
Coolant inlet stagnation pressure	700 psia
Total coolant flow rate	15 lb/sec
Approximate throat heat flux	19 Btu/in^2-sec
Number of cooling channels	240
Throat region channel aspect ratio	5
Channel width step changes at	X=3.039 inches X=-4.158 inches

Low Pressure Chamber (unblocked)



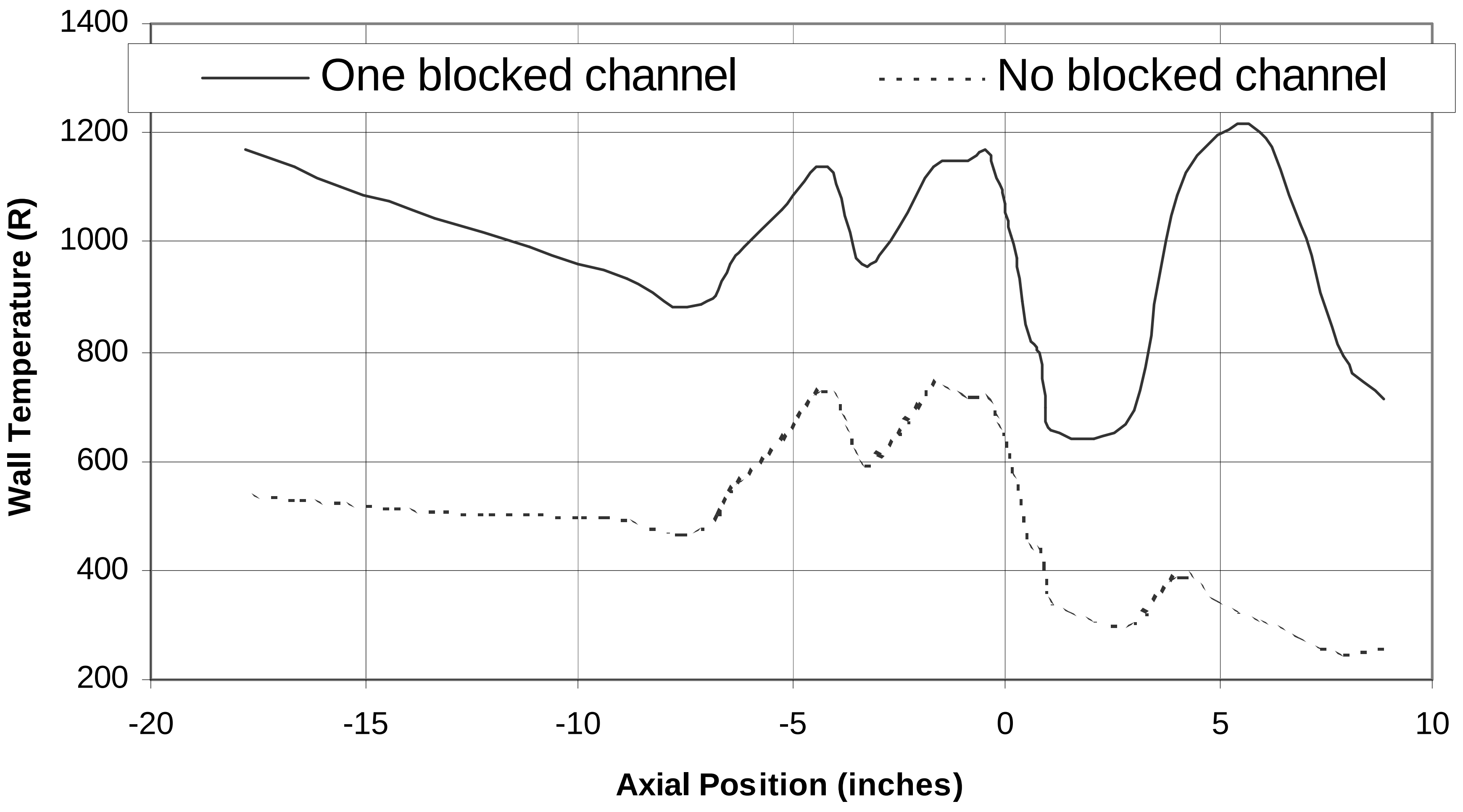
X=-0.618 inch

T_c=91R

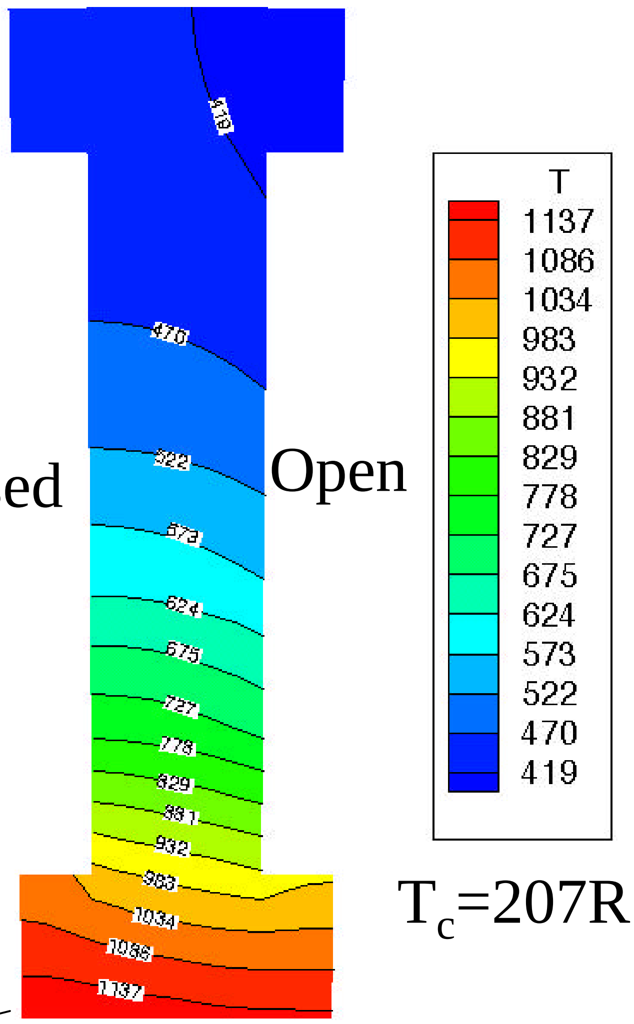
$\dot{m}_c$=0.0625 lb/sec

T_{max}=723R

Temperature Distribution



Temperature Profile



Closed

Open

T_c=207R

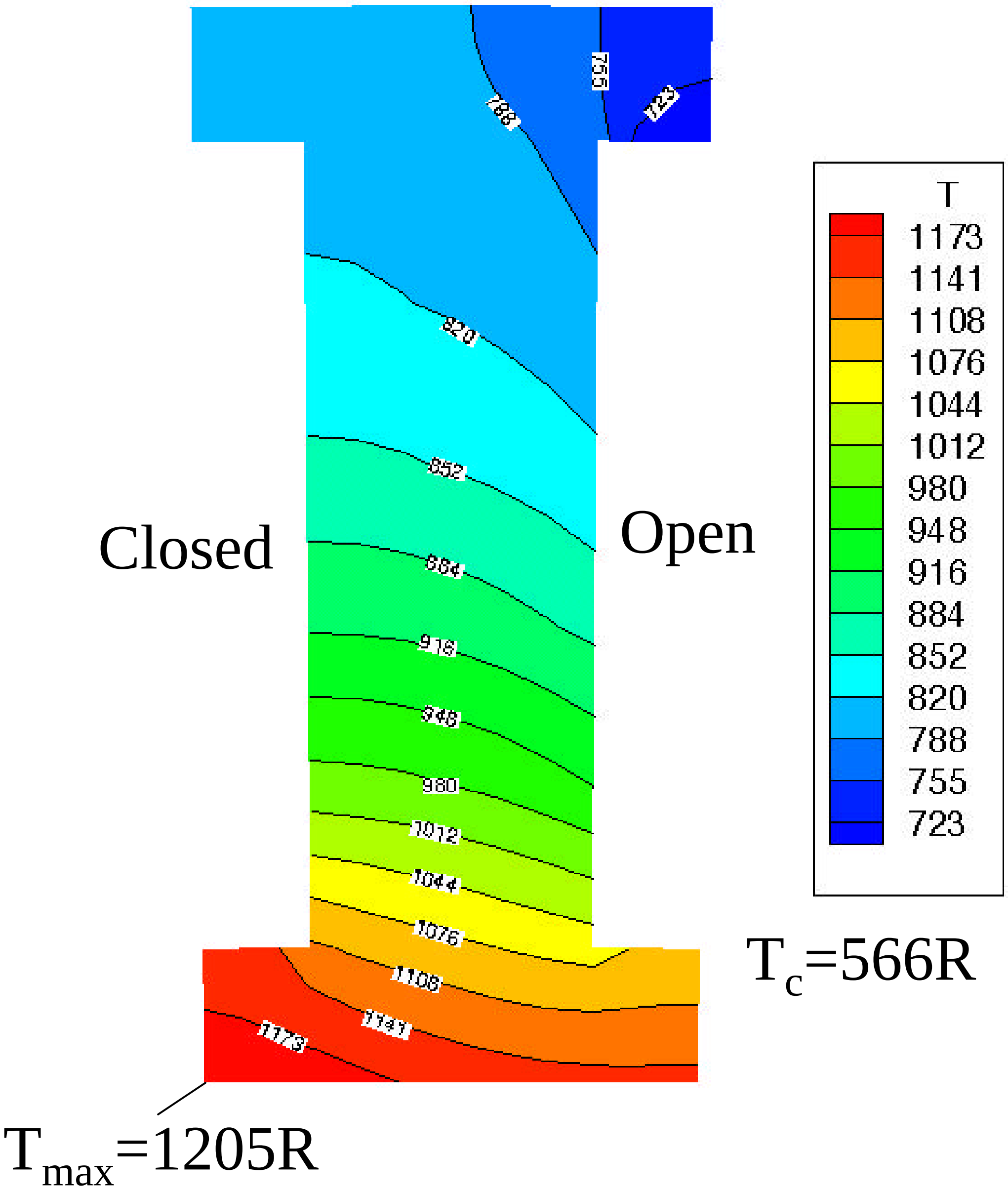
T_{max}=1188R

X=-0.618 inch

$\dot{m}_c$=0.036 lb/sec

42% reduction in coolant flow rate

Temperature Profile



X=-17.781 Inch

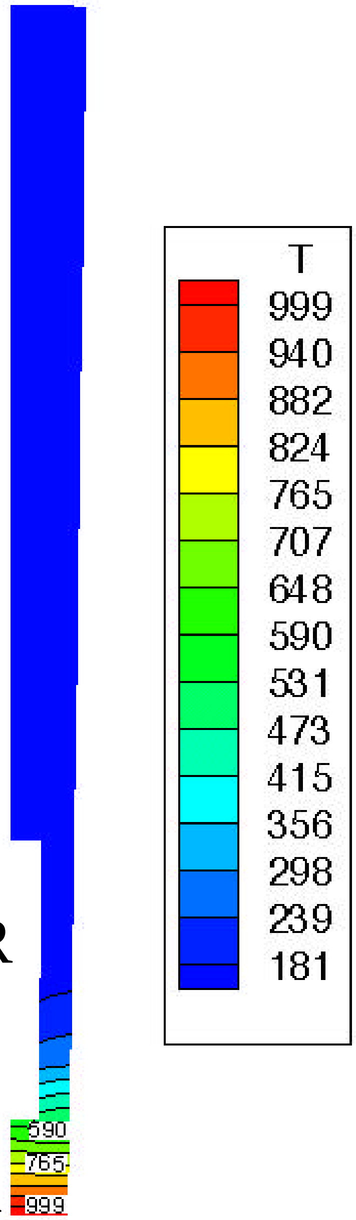
$\dot{m}_c$=0.036 lb/sec
42% reduction in coolant flow rate

Results for High Pressure Chamber

Chamber pressure	**2000 psia**
O/F	**5.8**
Contraction ratio	**3.41**
Expansion ratio	**6.63**
Throat diameter	**2.6 inches**
Propellant	**GH2-LO2**
Coolant	**LH2**
Total coolant flow rate	**6.45 lb/sec**
Coolant inlet temperature	**50 R**
Coolant inlet stagnation pressure	**3200 psia**
Approximate throat heat flux	**77 Btu/in^2-sec**
Number of cooling channels	**200**
Throat region channel aspect ratio	**5-7.8**
Channel width step changes at	**X=0.947 inches** **X=-3.906 inches**

High Pressure Chamber (unblocked)

High pressure chamber
200 cooling channels



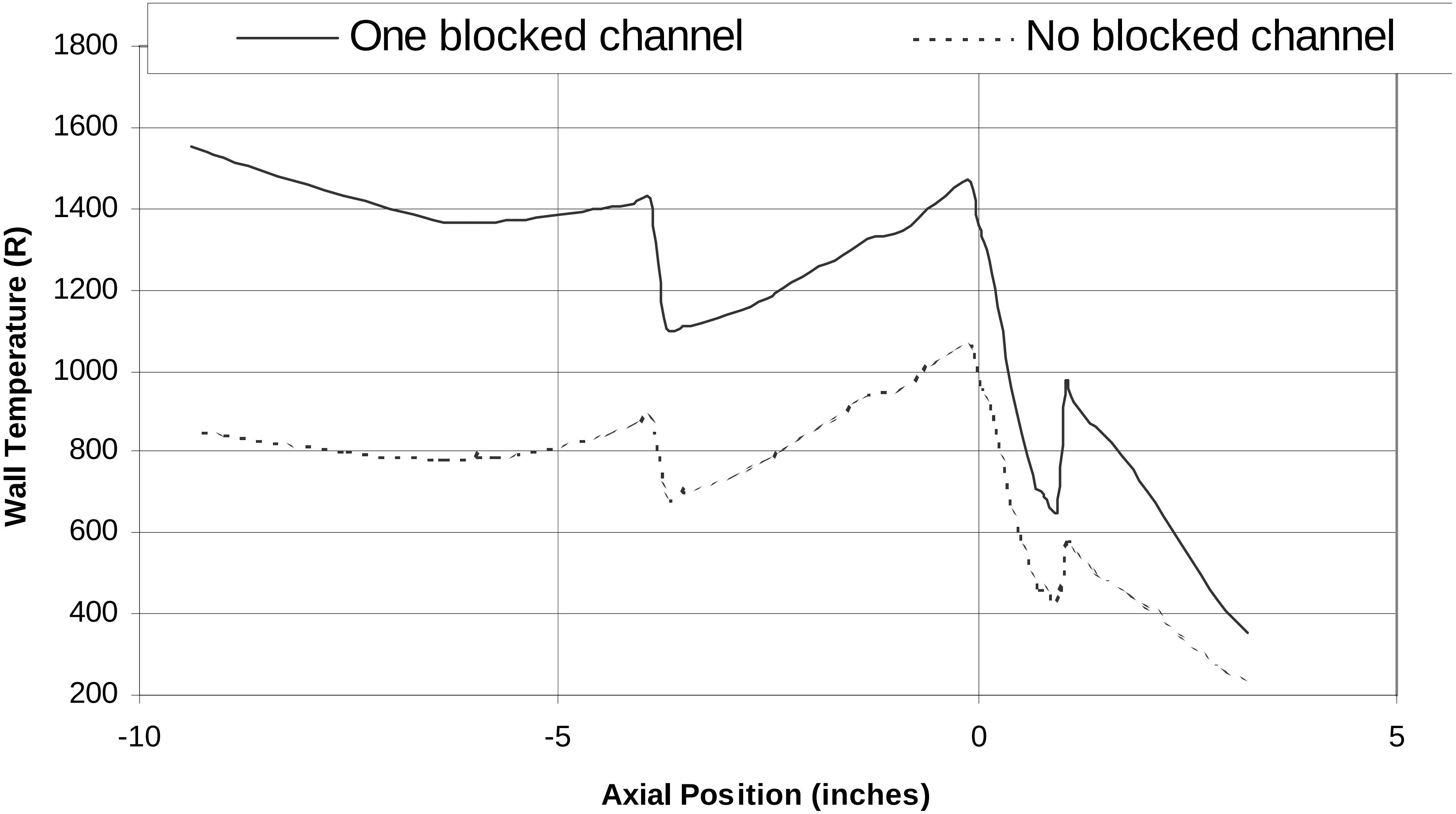
X=-0.1 inch

T_c=122R

$\dot{m}_c$=0.032 lb/sec

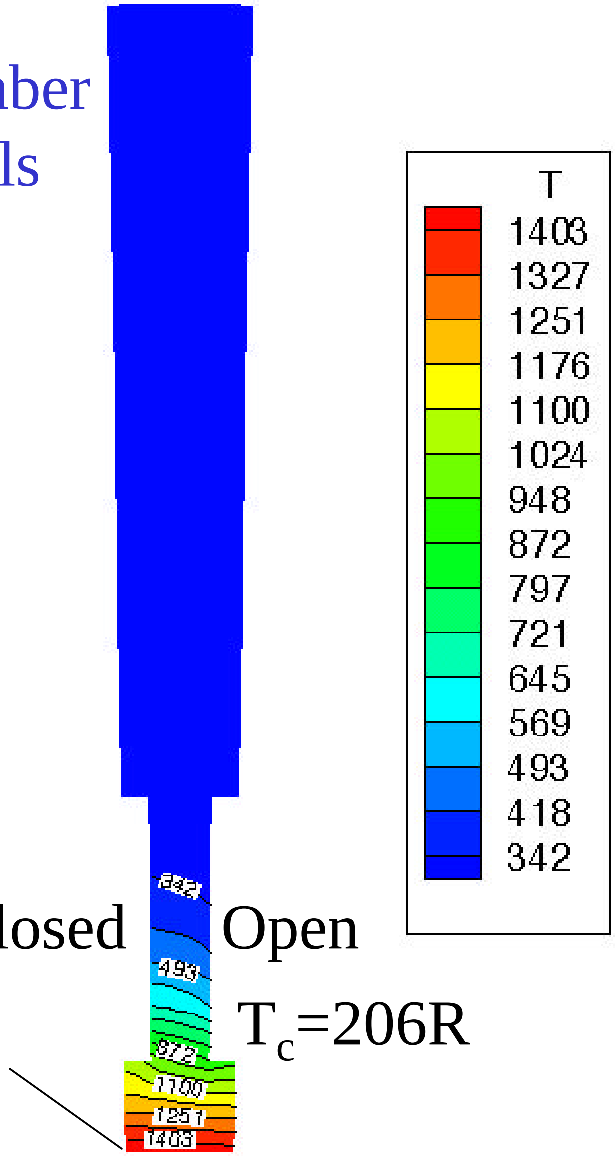
T_{max}=1058R

Temperature Distribution
High Pressure, 200 Channels



Temperature Profile

High pressure chamber
200 cooling channels



Closed

Open

T_{max}=1479R

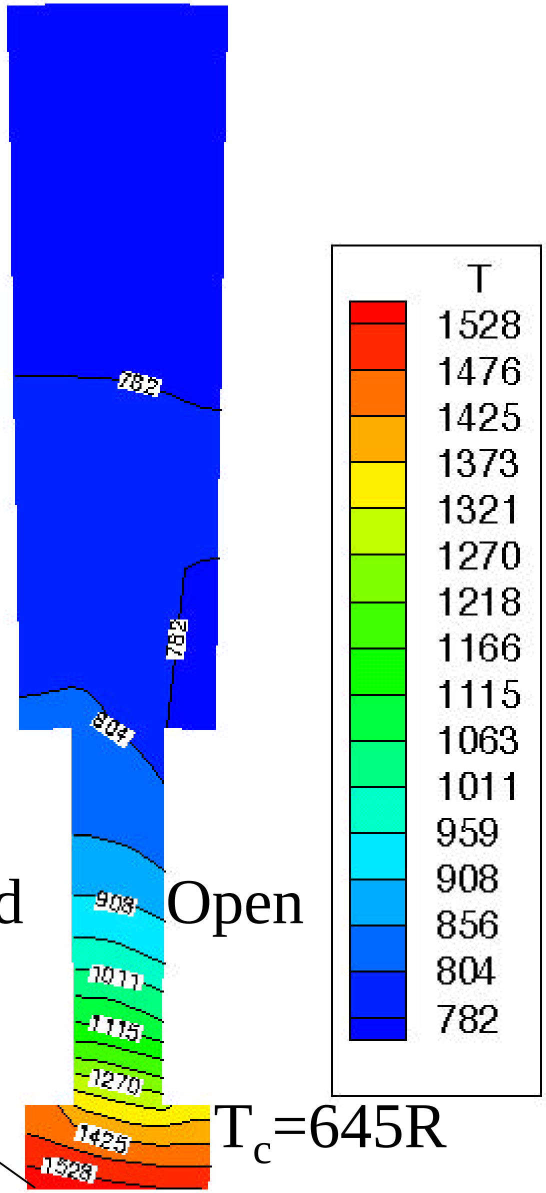
T_c=206R

X=-0.1 inch

$\dot{m}_c$=0.024 lb/sec
25% reduction in
coolant flow rate

Temperature Profile

High pressure chamber
200 cooling channels



Closed

Open

T_{max}=1580R

T_c=645R

X=-9.38 inch

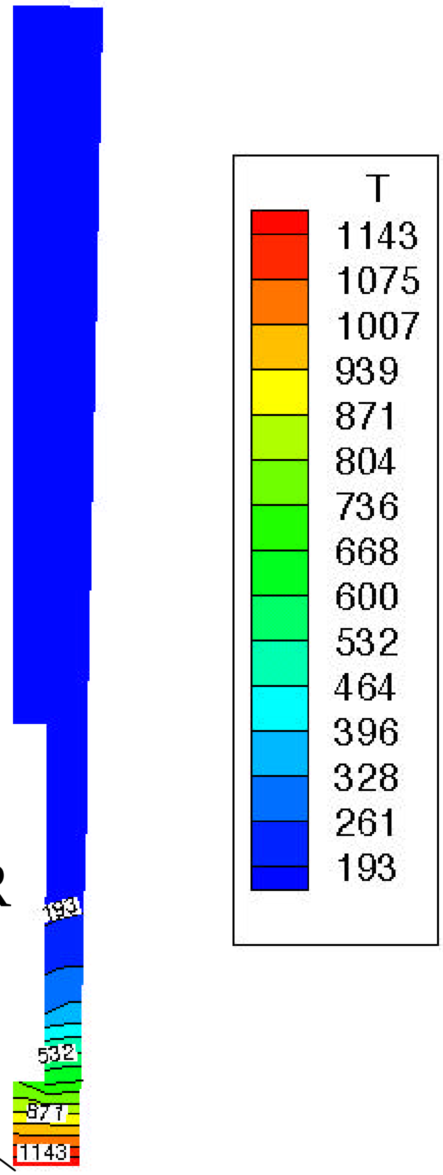
$\dot{m}_c$=0.024 lb/sec
25% reduction in
coolant flow rate

Results for High Pressure Chamber

Chamber pressure	2000 psia
O/F	5.8
Contraction ratio	3.41
Expansion ratio	6.63
Throat diameter	2.6 inches
Propellant	GH2-LO2
Coolant	LH2
Total coolant flow rate	6.45 lb/sec
Coolant inlet temperature	50 R
Coolant inlet stagnation pressure	2900 psia
Approximate throat heat flux	75 Btu/in^2-sec
Number of cooling channels	150
Throat region channel aspect ratio	5-7.8
Channel width step changes at	X=0.947 inches X=-3.906 inches

High Pressure Chamber (unblocked)

High pressure chamber
150 cooling channels



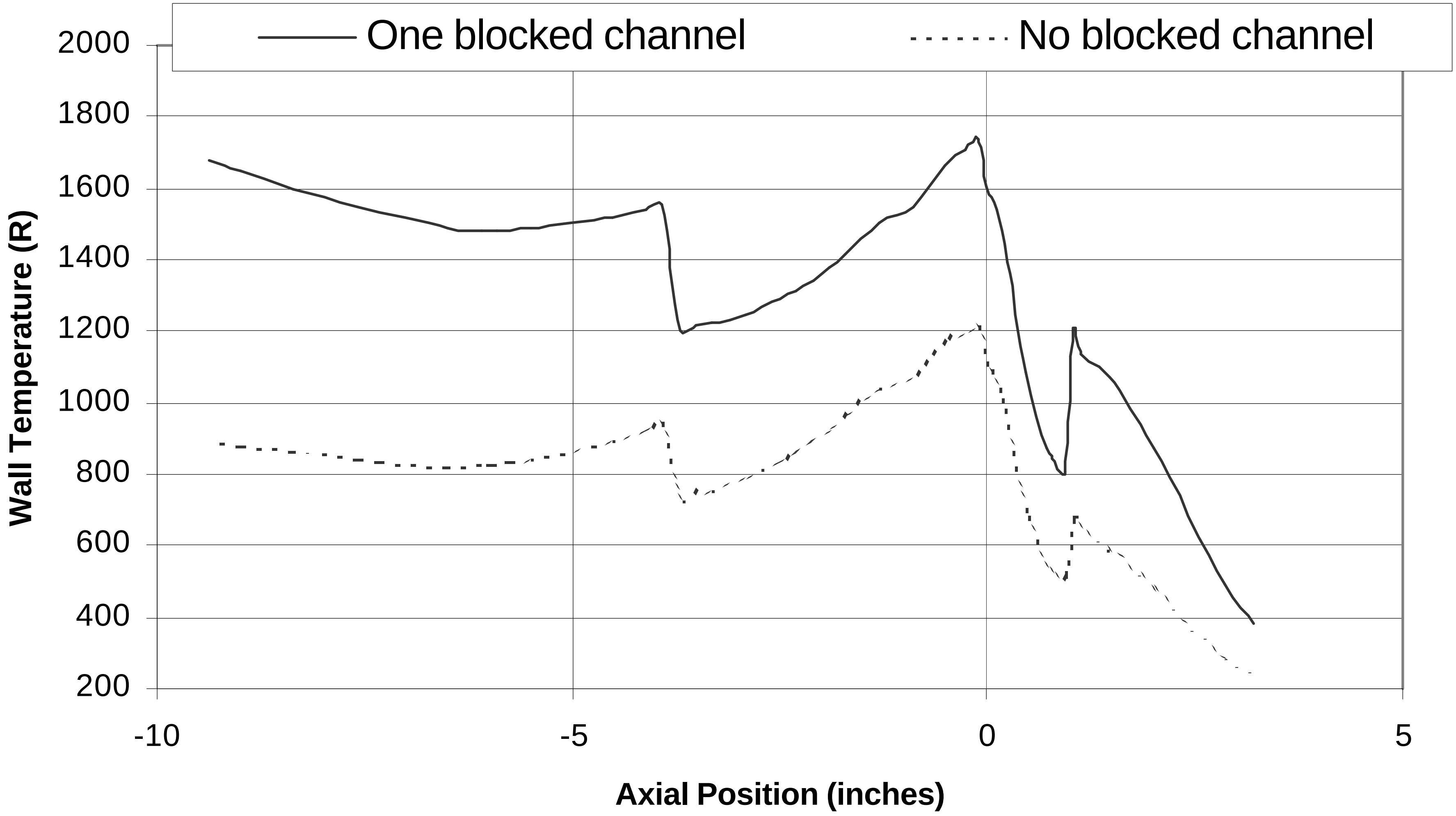
X=-0.1 inch

T_c=119R

$\dot{m}_c$=0.043 lb/sec

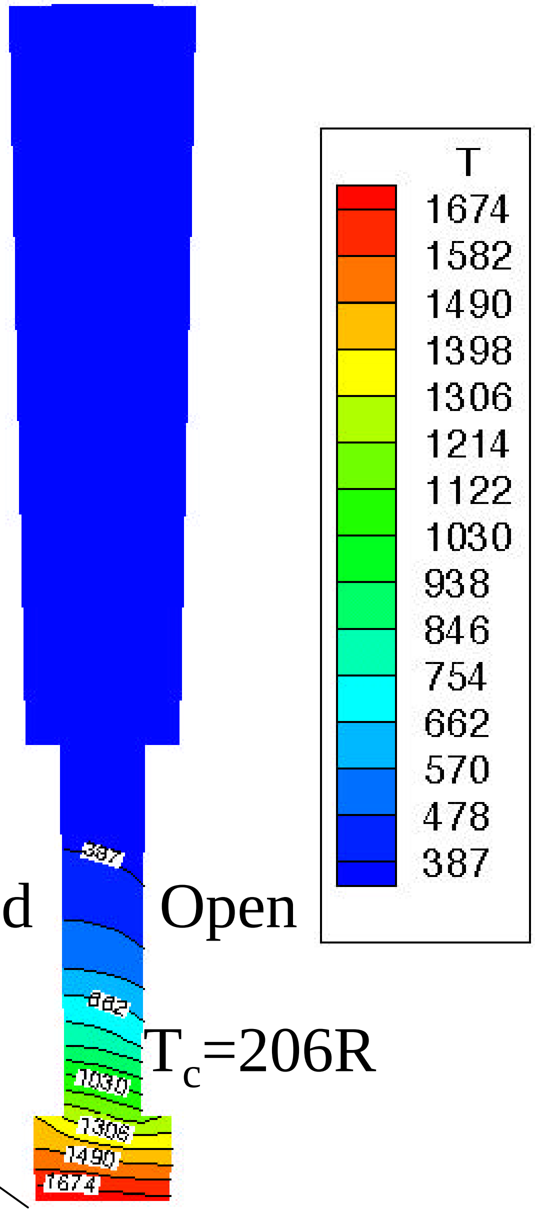
T_{max}=1211R

Temperature Distribution
High Pressure, 200 Channels



Temperature Profile

High pressure chamber
150 cooling channels



Closed

Open

T_c=206R

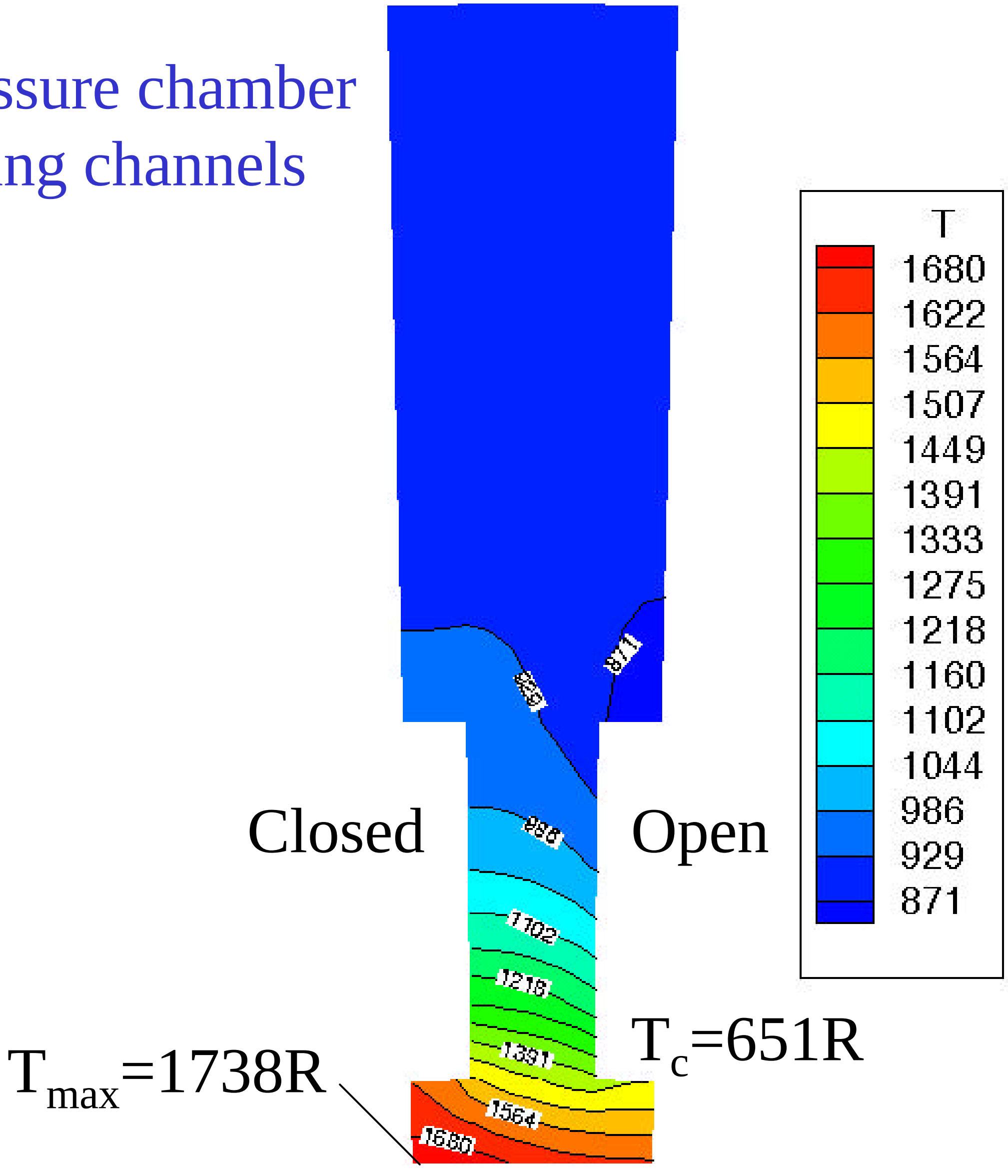
T_{max}=1766R

X=-0.1 inch

$\dot{m}_c$=0.031 lb/sec
28% reduction in
coolant flow rate

Temperature Profile

High pressure chamber
150 cooling channels



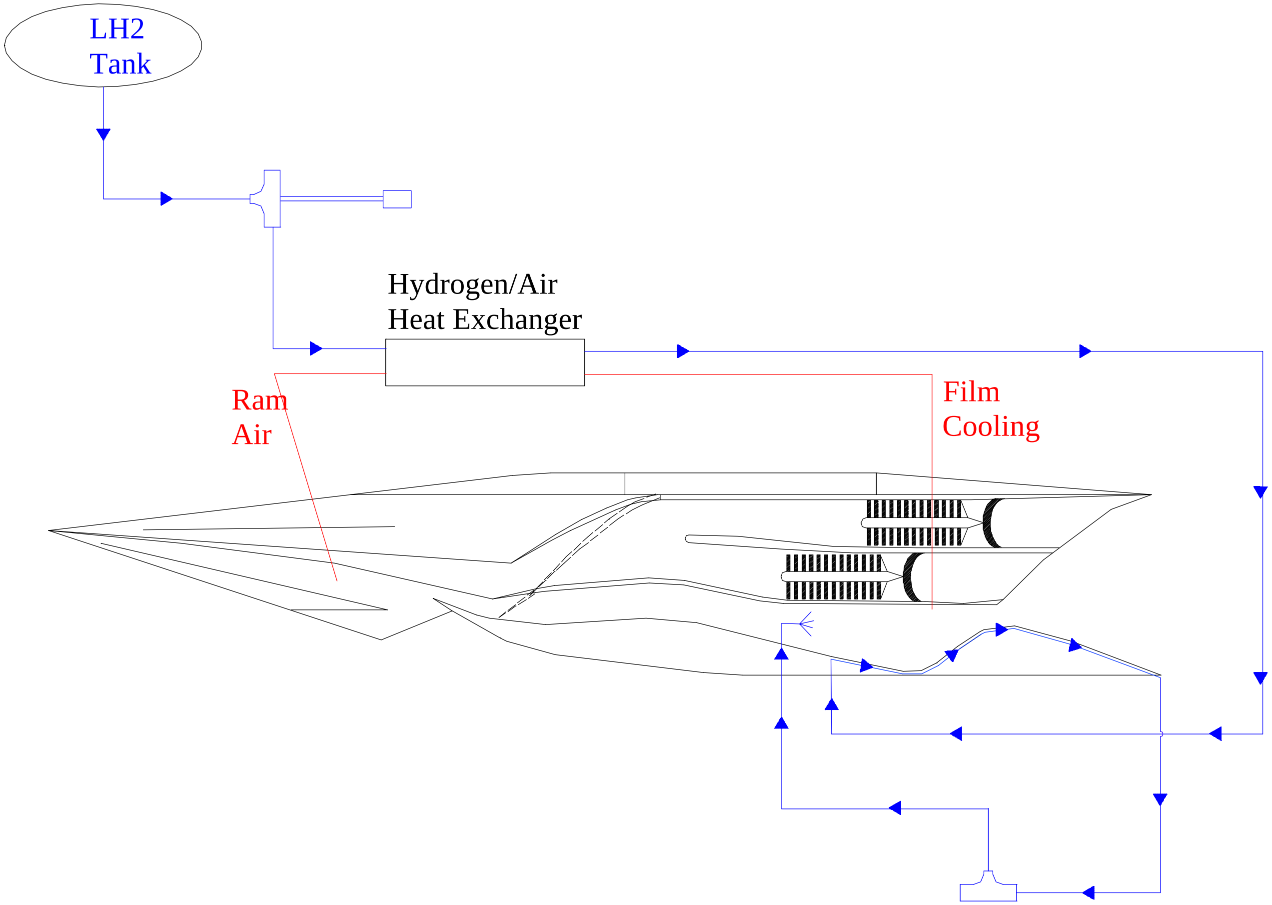
X=-9.38 inch

$\dot{m}_c$=0.031 lb/sec
28% reduction in
coolant flow rate

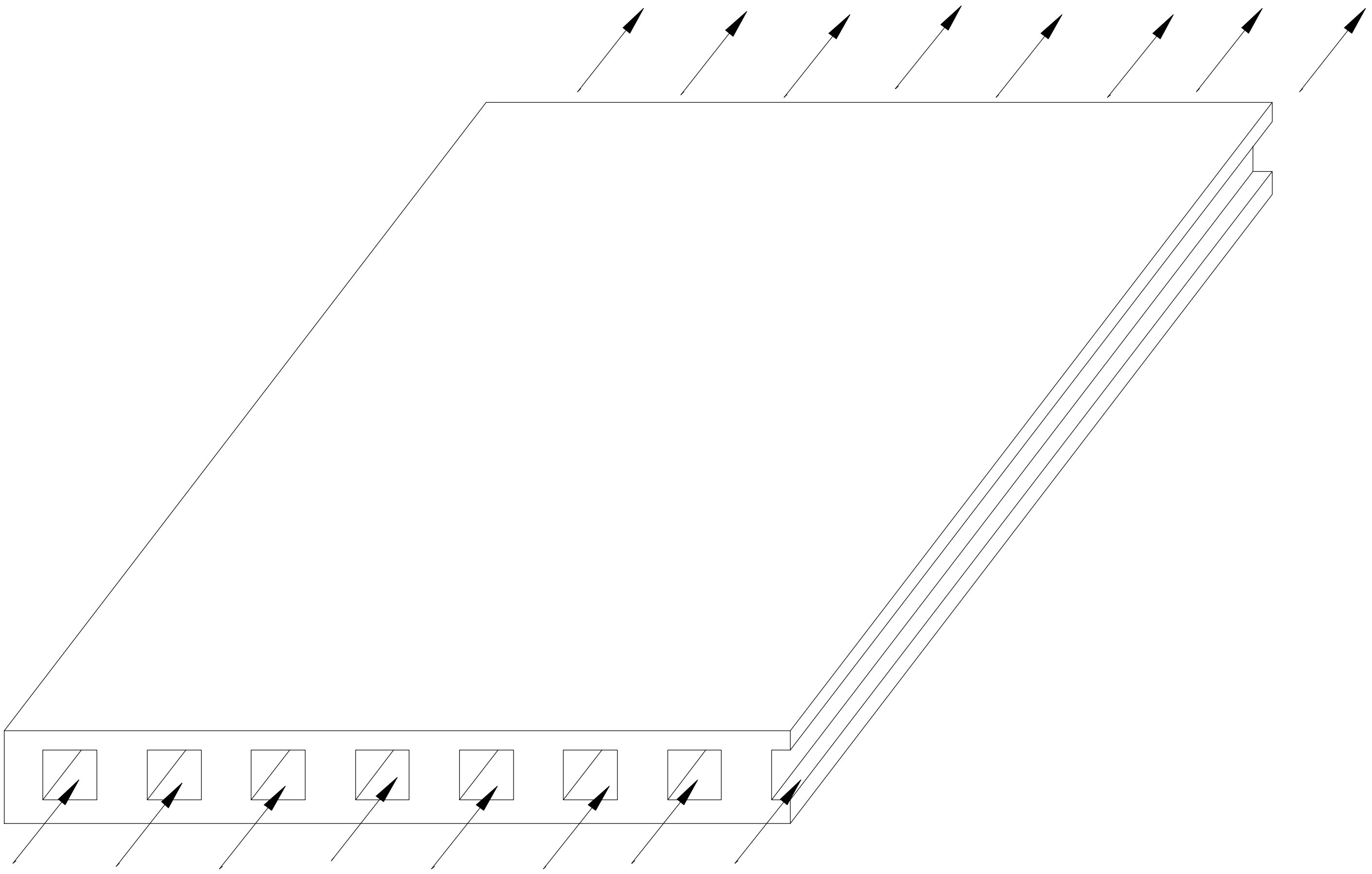
Future Work for Expanding Capabilities of RTE

- Modeling hypersonic air breathing engines.
- Incorporating other cooling channel shapes.
- Developing a CFD model for coolant flow analysis.
- Converting the code to a design tool.

Hypersonic Engines (Scramjets)



A Typical Cooling Panel for Scramjet

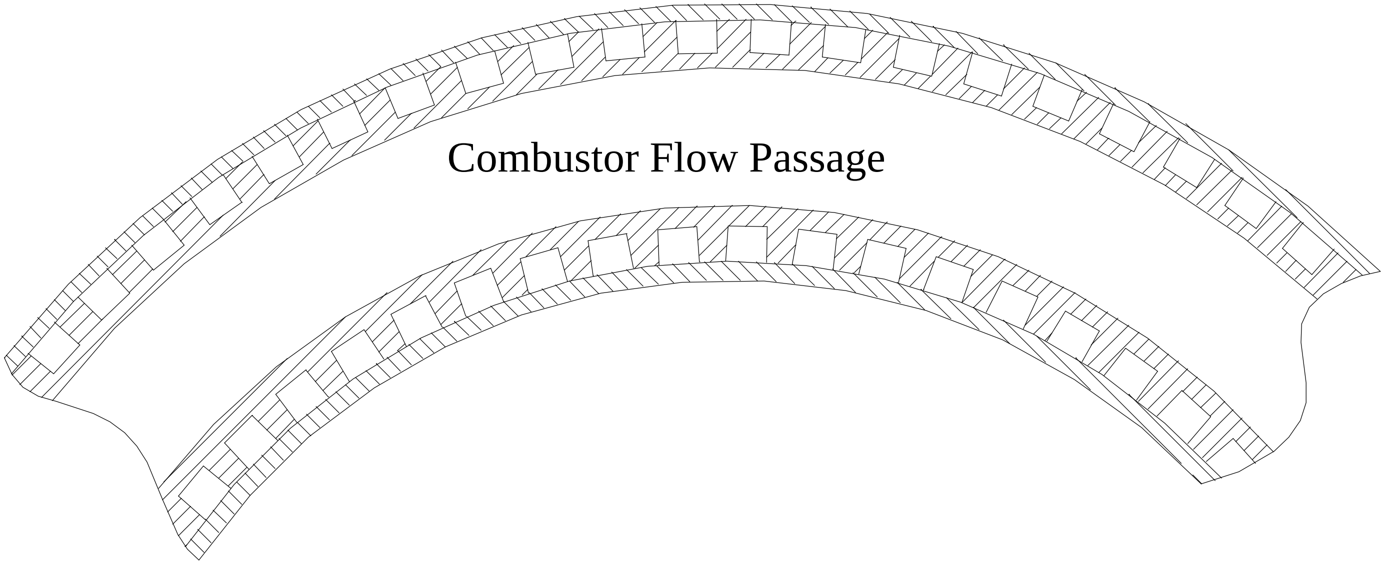


Coolant Flow (e.g., LH2)

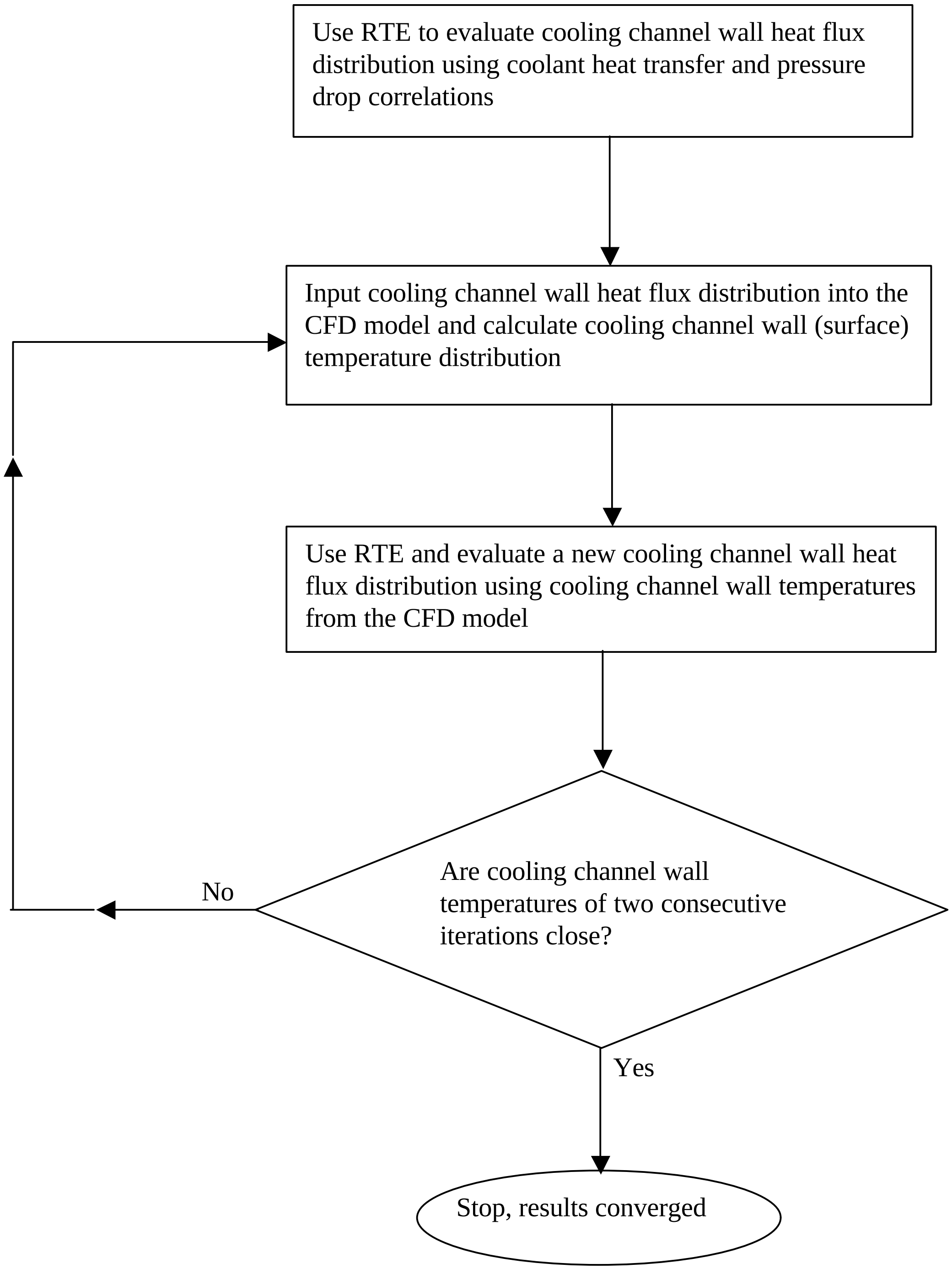
Combustor and Nozzle Flow Passage for Hypersonic Engines

Mostly rectangular cross-section

Some axisymmetric passages



A CFD Model for Cooling Channel Flow of RTE



Use RTE to evaluate cooling channel wall heat flux distribution using coolant heat transfer and pressure drop correlations

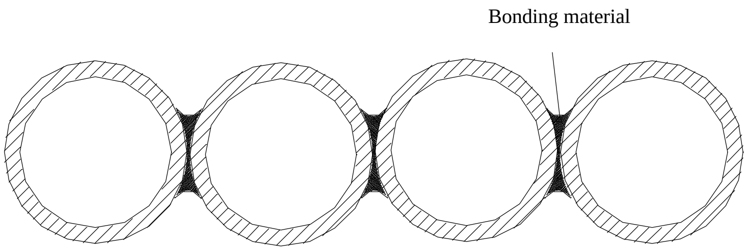
Input cooling channel wall heat flux distribution into the CFD model and calculate cooling channel wall (surface) temperature distribution

Use RTE and evaluate a new cooling channel wall heat flux distribution using cooling channel wall temperatures from the CFD model

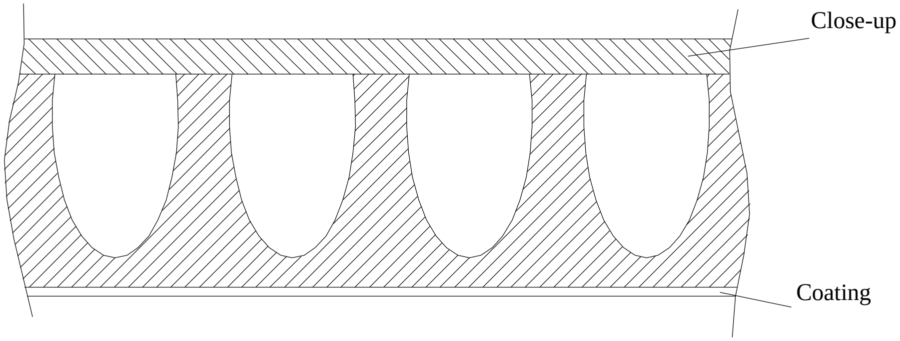
Are cooling channel wall temperatures of two consecutive iterations close?

Stop, results converged

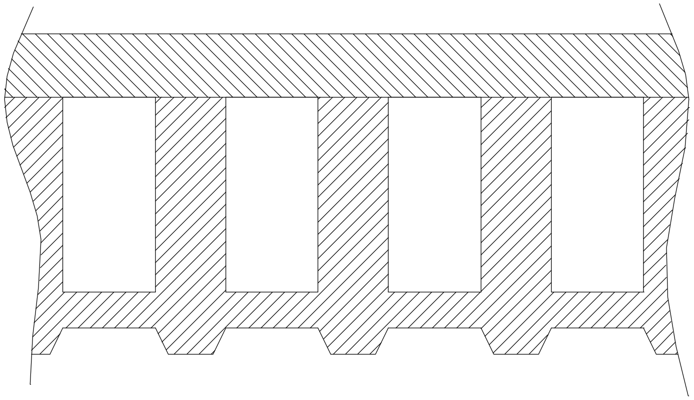
Different Cooling Channel Shapes



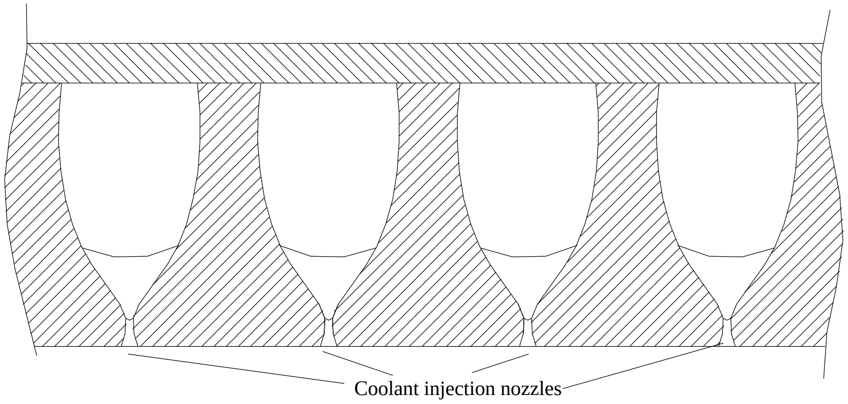
Tubular Channels



Truncated Oval Channels

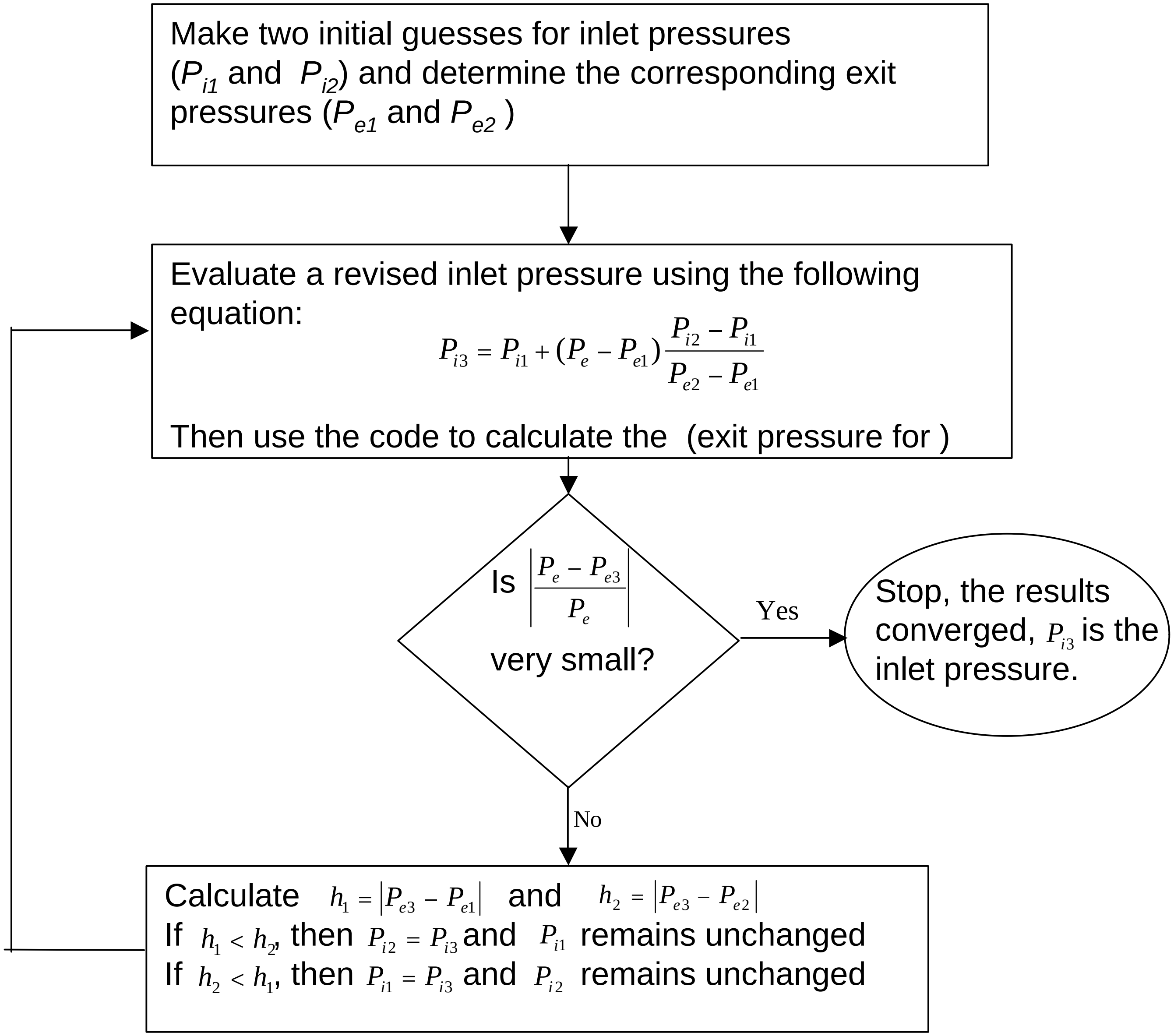


Increased hot-gas side surface area



Cooling channel with transpiration injection

Design for Inlet Pressure



Make two initial guesses for inlet pressures (P_{i1} and P_{i2}) and determine the corresponding exit pressures (P_{e1} and P_{e2})

Evaluate a revised inlet pressure using the following equation:

$$P_{i3} = P_{i1} + (P_e - P_{e1})\frac{P_{i2} - P_{i1}}{P_{e2} - P_{e1}}$$

Then use the code to calculate the (exit pressure for)

Is $\left|\frac{P_e - P_{e3}}{P_e}\right|$ very small?

Stop, the results converged, P_{i3} is the inlet pressure.

Calculate $h_1 = |P_{e3} - P_{e1}|$ and $h_2 = |P_{e3} - P_{e2}|$

If $h_1 < h_2$, then $P_{i2} = P_{i3}$ and P_{i1} remains unchanged

If $h_2 < h_1$, then $P_{i1} = P_{i3}$ and P_{i2} remains unchanged

Design for Aspect Ratio

Breaks the cooling channel width interval into a number of increments (i.e. $w_1, w_2, w_3, \ldots, w_n$, where w_1 is the minimum width and w_n is the maximum width).

For each width value a procedure similar to that shown before will be used to determine the corresponding cooling channel height that yields the desired surface temperature at the throat. The resulting output will be n possible solutions,(w_1,h_1) , (w_2,h_2), … (w_n,h_n), from which the most feasible design from manufacturing point can be selected.

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