

Modeling of Radiation Heat Transfer in Liquid Rocket Engines

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Motivation

- Design of cooling circuits of regeneratively cooled rocket engines both a good physical insight on the workings of the engine and a method of calculating the effects of design changes on the heat transfer via conjugated convection/conduction/radiation and cooling requirements of LRE's
- Conjugated convection and conduction models for liquid rocket engines are well established (e.g., TDK-RTE model)
- Combustion gases in liquid rocket engines consists of gases at very high temperatures (up to 7000R) with radiatively participating gases, e.g. water vapor, CO, CO₂ and soot.

Previous Works

- Hammad, K.J., and Naraghi, M.H.N., “Exchange Factor Model for Radiative Heat Transfer Analysis in Rocket Engines,” AIAA Journal of Thermophysics and Heat Transfer, Vol. 5, No. 3, pp. 327-334, 1991.
- Liu, J., and Tiwari, S.N., “Radiative Heat Transfer Effects in Chemically Reacting Nozzle Flows,” AIAA Journal of Thermophysics and Heat Transfer, Vol. 10, No. 3, 1996.
- Badinand, T. and Fransson, T.H., “Radiative Heat Transfer in Film Cooled LH/LO Rocket Engine Thrust Chamber”, AIAA Journal of Thermophysics and Heat Transfer, Vol. 17, No. 2, pp. 29-34, 2003.
- Wang, Tee-See, “Multidimensional Unstructured-Grid Liquid Rocket Engine Nozzle Performance and Heat Transfer Analysis,” AIAA paper 2004-4016 presented at the 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit July 11-14, 2004, Fort Lauderdale, Florida.

Radiation Heat Transfer from Hot-Gases

- Combustion Gases consist of several radiatively participating species
- These species are: soot, CO, CO₂, and water vapor
- HITRAN and HITEMP database is used to evaluate absorption coefficients
- Properties of the radiatively participating species are spectral, consisting of a large number of bands
- A Plank-mean approach is be used to evaluate absorption factors

Exchange Factors between gas and surface elements

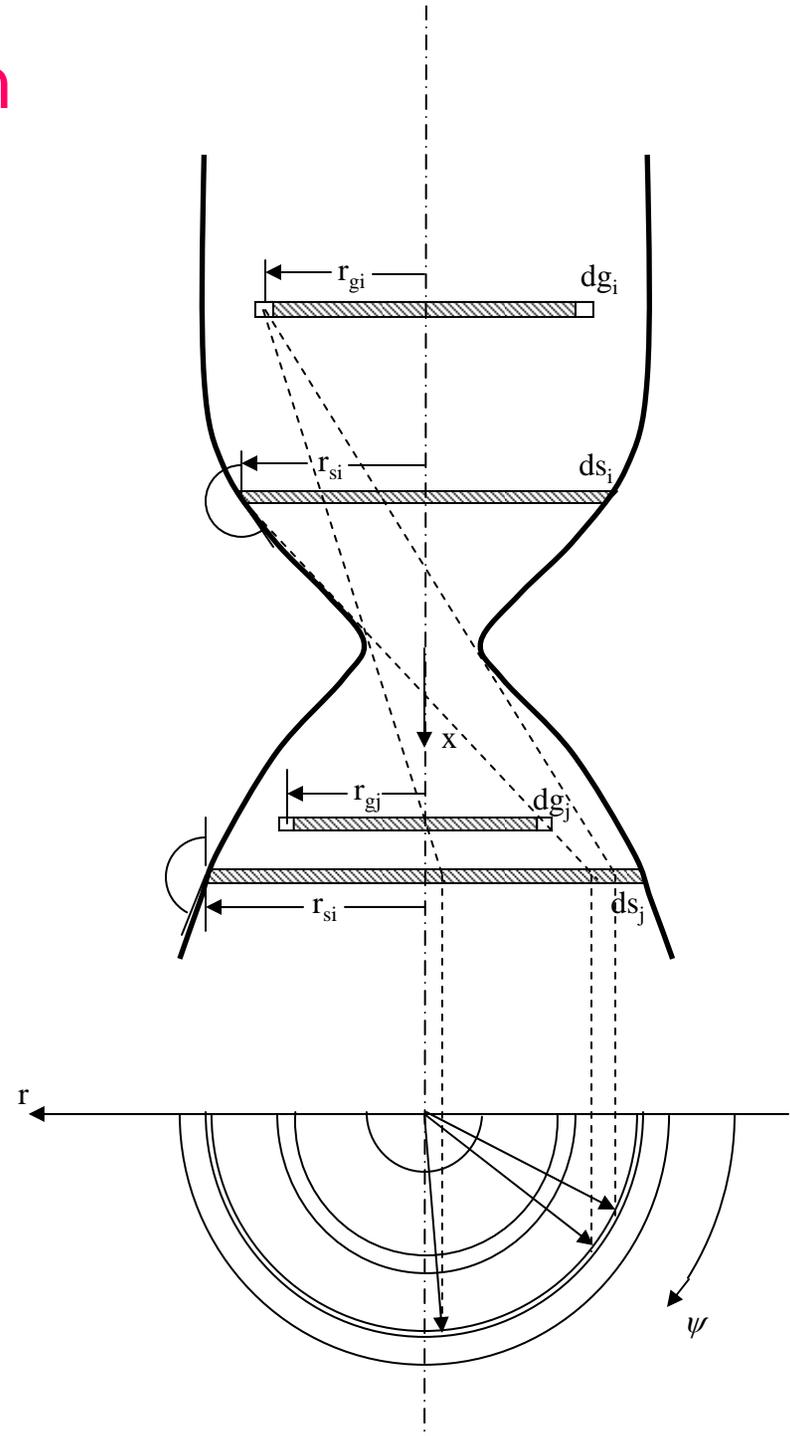
$$\overline{dss}(\mathbf{r}_i, \mathbf{r}_j) = \frac{2r_j ds_j}{\pi} \int_{\psi_{\min}}^{\psi_{\max}} \frac{\cos \beta_i \cos \beta_j \tau(\mathbf{r}_i - \mathbf{r}_j)}{|\mathbf{r}_i - \mathbf{r}_j|^2} d\psi_j$$

$$\overline{dsg}(\mathbf{r}_i, \mathbf{r}_j) = \frac{2k_{t_j} r_j dr_j dx_j}{\pi} \int_{\psi_{\min}}^{\psi_{\max}} \frac{\cos \beta_i \tau(\mathbf{r}_i - \mathbf{r}_j)}{|\mathbf{r}_i - \mathbf{r}_j|^2} d\psi_j$$

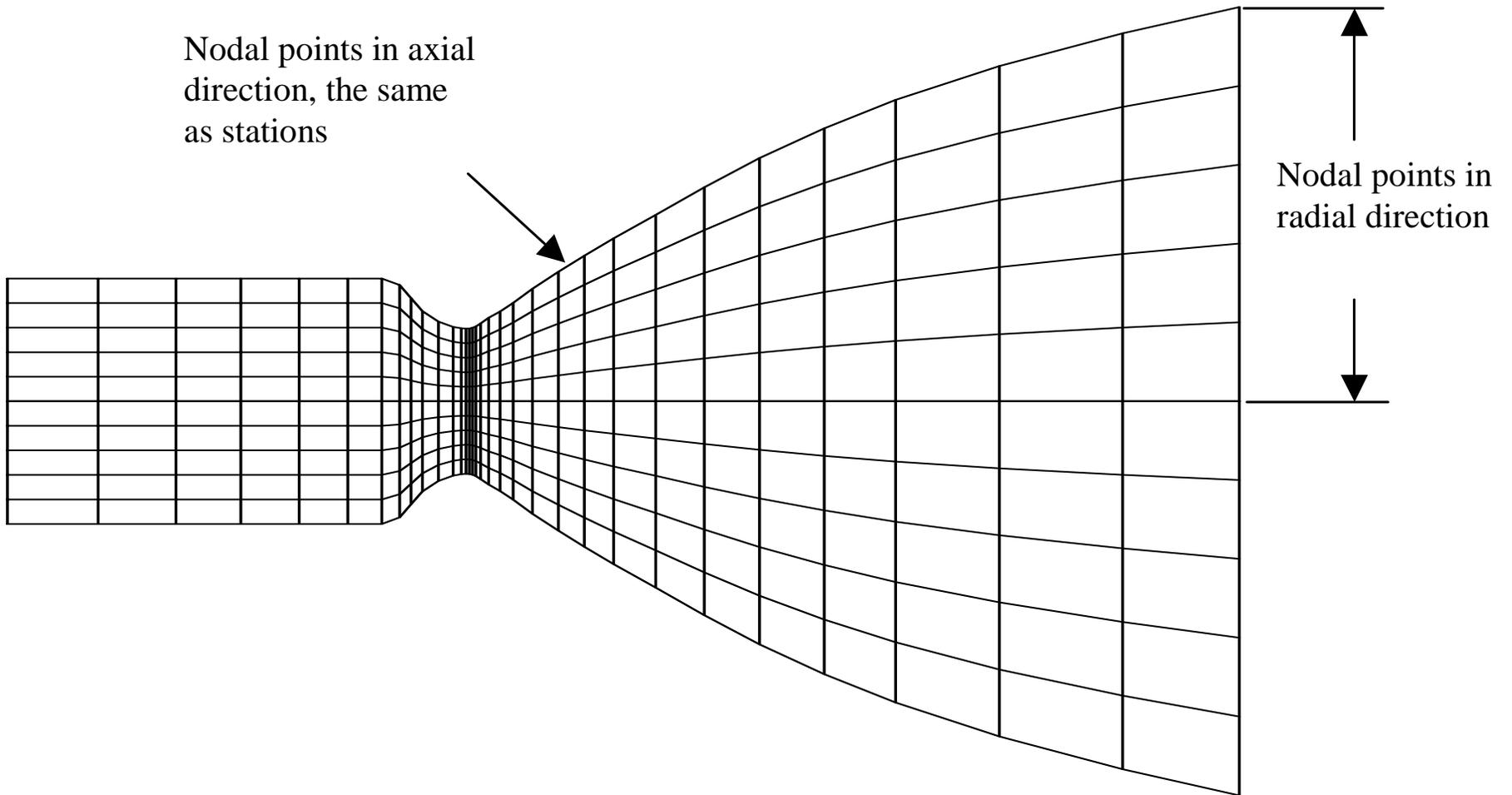
$$\overline{dgs}(\mathbf{r}_i, \mathbf{r}_j) = \frac{r_j ds_j}{2\pi} \int_{\psi_{\min}}^{\psi_{\max}} \frac{\cos \beta_j \tau(\mathbf{r}_i - \mathbf{r}_j)}{|\mathbf{r}_i - \mathbf{r}_j|^2} d\psi_j$$

$$\overline{dgg}(\mathbf{r}_i, \mathbf{r}_j) = \frac{k_{t_j} r_j dr_j dx_j}{2\pi} \int_{\psi_{\min}}^{\psi_{\max}} \frac{\tau(\mathbf{r}_i - \mathbf{r}_j)}{|\mathbf{r}_i - \mathbf{r}_j|^2} d\psi_j$$

$$\tau(\mathbf{r}_i - \mathbf{r}_j) = e^{-k_t |\mathbf{r}_i - \mathbf{r}_j|}$$



Radiative Nodal Points



Total Exchange Factors

Account for wall reflection and gas scattering

$$\overline{\mathbf{DSS}} = \left[\mathbf{I} - \left\{ \overline{\mathbf{dss}} + \overline{\mathbf{dsg}}\omega_0 \mathbf{W}_g \left[\mathbf{I} - \overline{\mathbf{dgg}}\omega_0 \mathbf{W}_g \right]^{-1} \overline{\mathbf{dgs}} \right\} \rho \mathbf{W}_s \right]^{-1} \left\{ \overline{\mathbf{dss}} + \overline{\mathbf{dsg}}\omega_0 \mathbf{W}_g \left[\mathbf{I} - \overline{\mathbf{dss}}\omega_0 \mathbf{W}_g \right]^{-1} \overline{\mathbf{dgs}} \right\} \alpha$$

$$\overline{\mathbf{DGS}} = \left[\mathbf{I} - \overline{\mathbf{dgg}}\omega_0 \mathbf{W}_g \right]^{-1} \overline{\mathbf{dgs}} \left[\mathbf{I} - \rho \mathbf{W}_s \left\{ \overline{\mathbf{dss}} + \overline{\mathbf{dsg}}\omega_0 \mathbf{W}_g \left[\mathbf{I} - \overline{\mathbf{dgg}}\omega_0 \mathbf{W}_g \right]^{-1} \overline{\mathbf{dgs}} \right\} \right]^{-1} \alpha$$

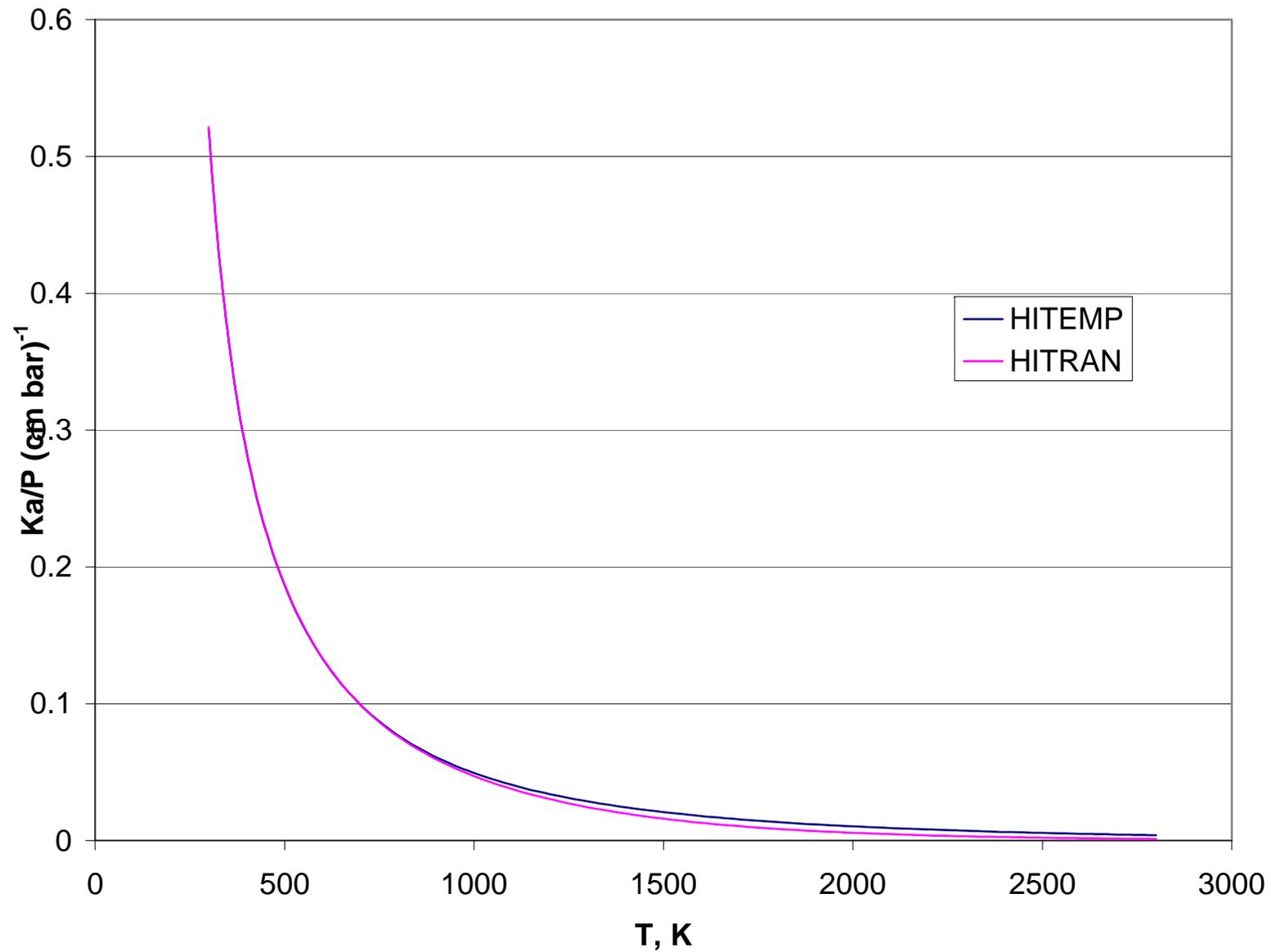
Wall heat flux at station n

$$q_{r,n} = \sum_{j=1}^{2n_r+m} w_{s,j} \overline{DS_j S_n} E_{s,j} + \sum_{j=1}^{m \cdot n_r} w_{g,j} \overline{DG_j S_n} E_{g,j} - E_{s,n}$$

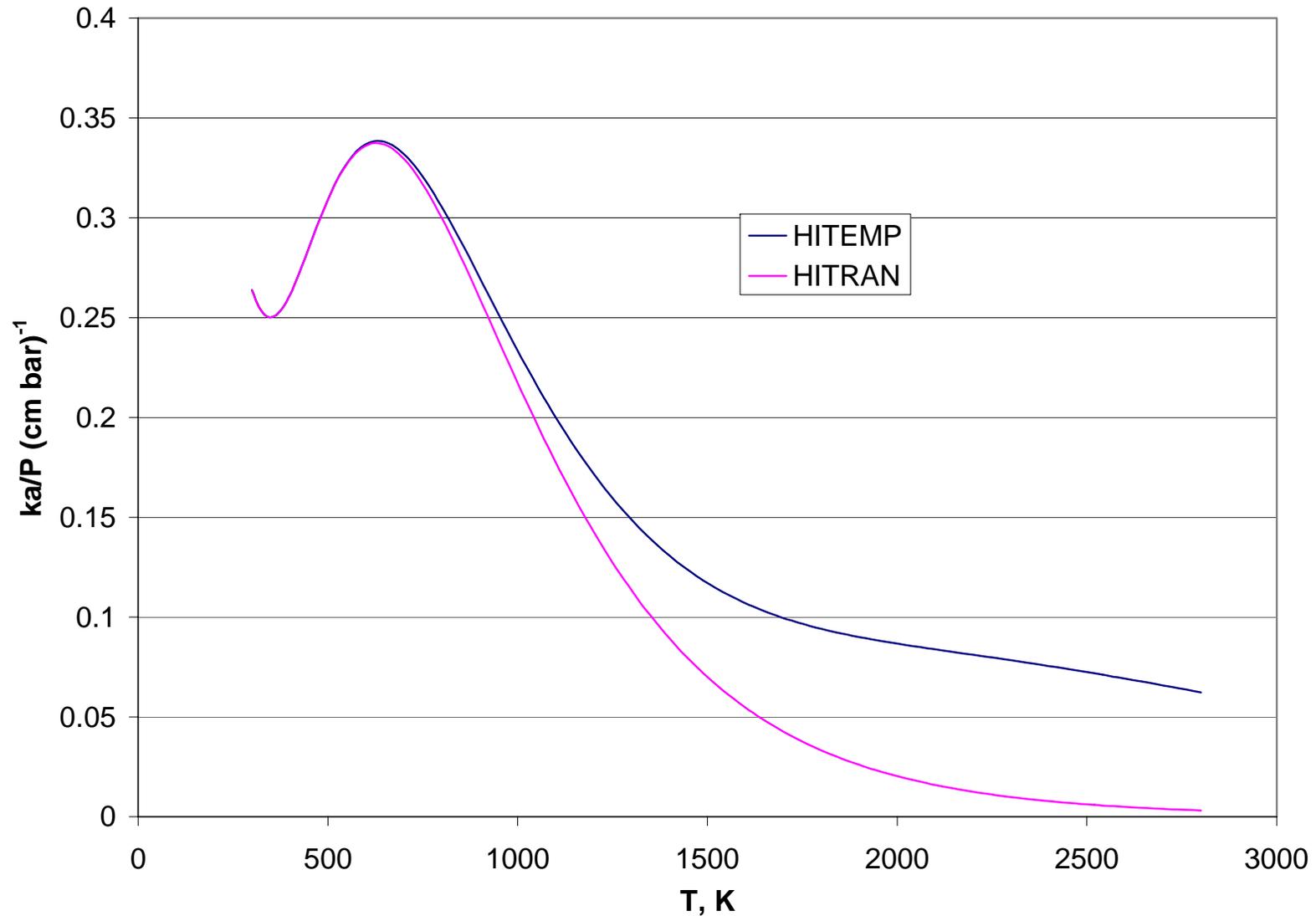
$$E_{s_n} = \varepsilon \sigma T_{s_n}^4 \quad E_{g_j} = 4K_{t_l} (1 - \omega_0) \sigma T_{g_j}^4$$

This model is built in the TDK's radiation module (RAD2005)

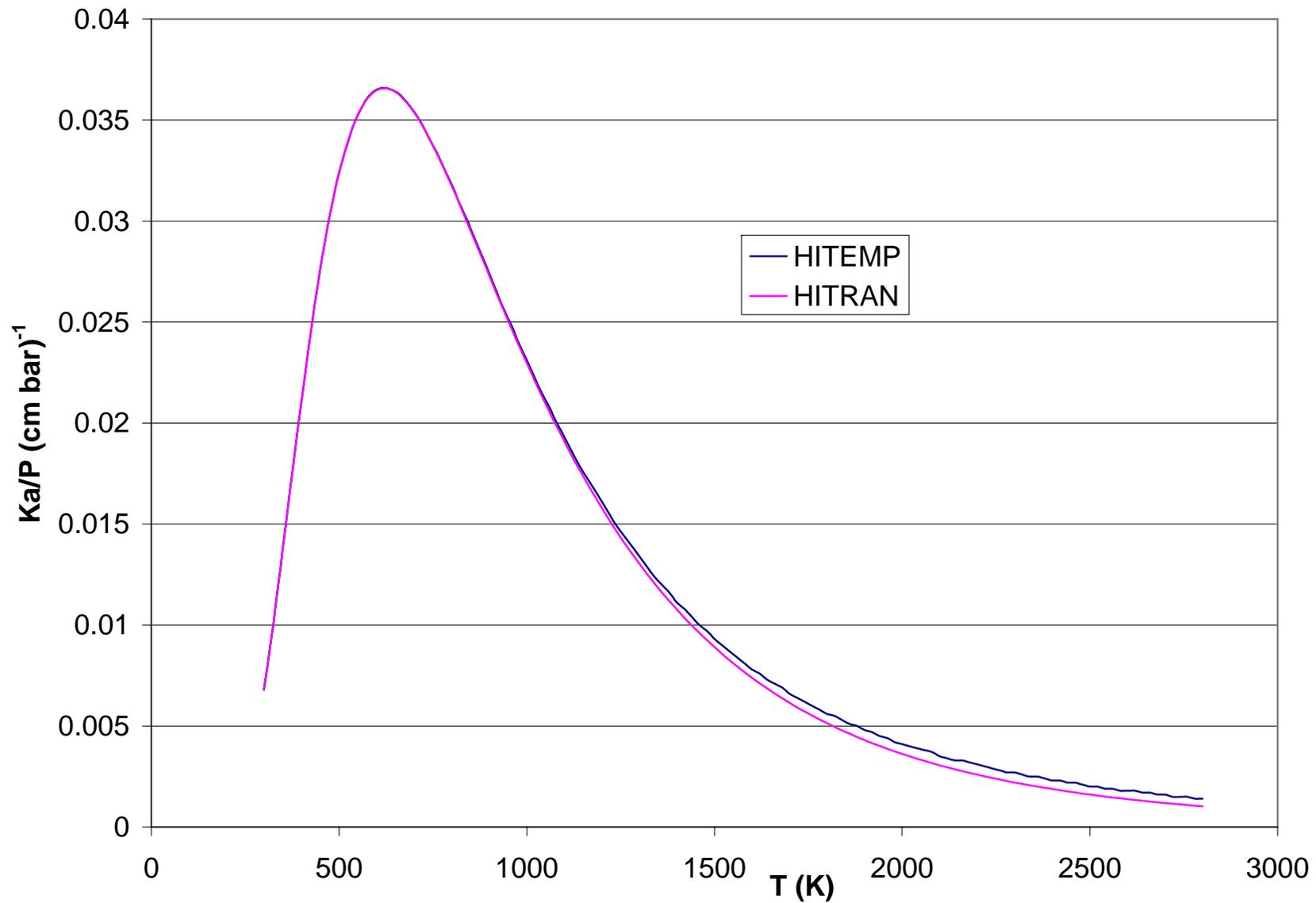
Plank-Mean Properties for Water-Vapor



Plank-Mean Properties for CO₂



Plank-Mean Properties for CO



Absorption Coefficient of Soot

When engines running with rich hydrocarbon fuels soot is present in the combustion gases.

As of today little is known about the nature of the production, Destruction, shape and size distribution. An approximate value of soot absorption coefficient can be obtained via:

$$k_a = 3.72 f_v C_0 T / C_2$$

Where f_v is volume fraction of soot

$$C_0 = \frac{36\pi n k}{(n^2 - k^2 + 2)^2 + 4n^2 k^2}$$

$C_2 = 1.4388 \text{ cm K}$, n and k are real and imaginary part of index of refraction

Computer Model

The properties and computational models (RAD2005) discussed were incorporated in the TDK-RTE.

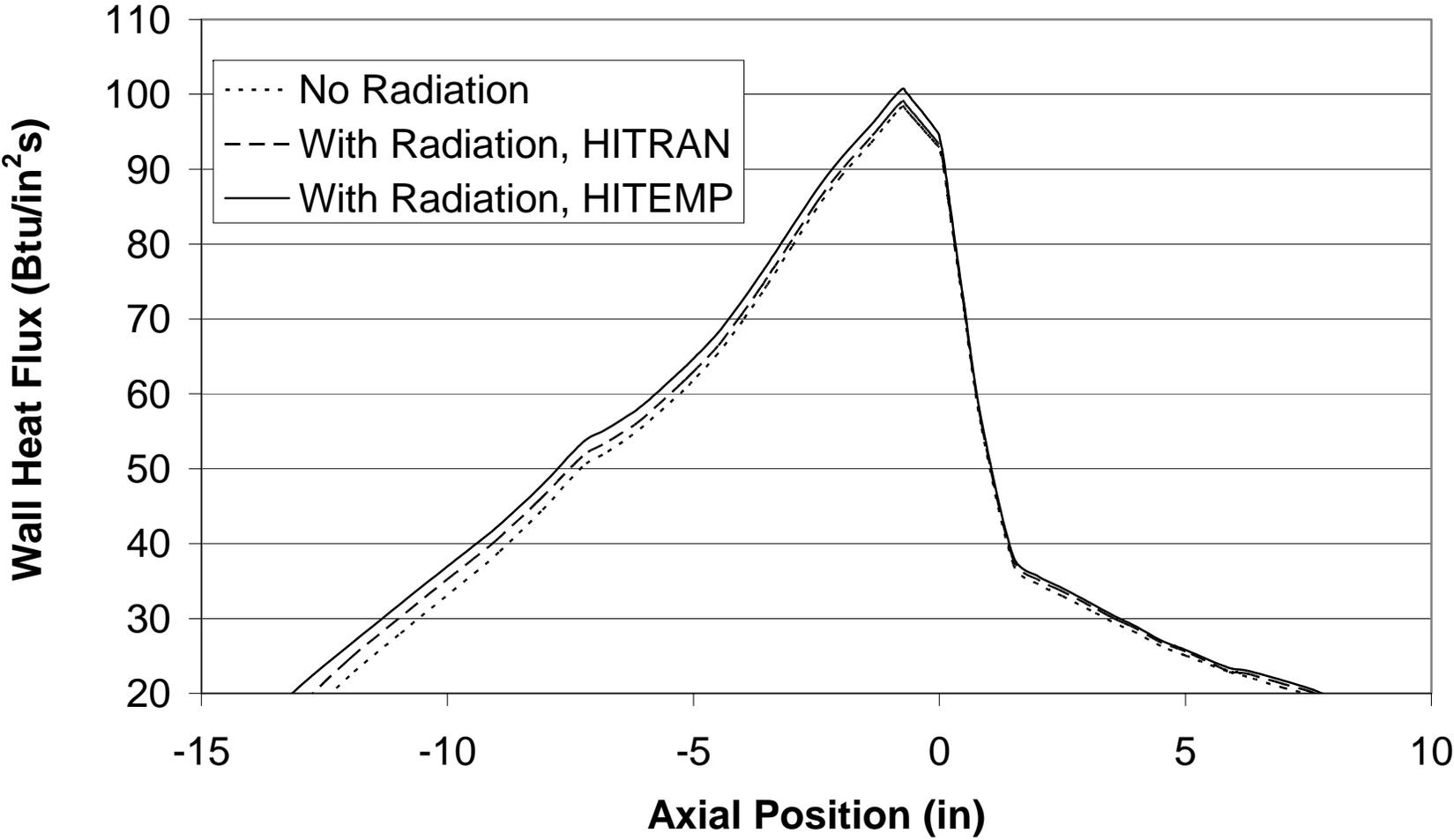
Naraghi, M.H.N., Dunn, S., and Coats, D., "A Model for Design and Analysis of Regeneratively Cooled Rocket Engines," AIAA paper 2005-3852, present at the Joint Propulsion Conference, Fort Lauderdale, July 2004.

Results for a LH2-LO2 Engine (SSME)

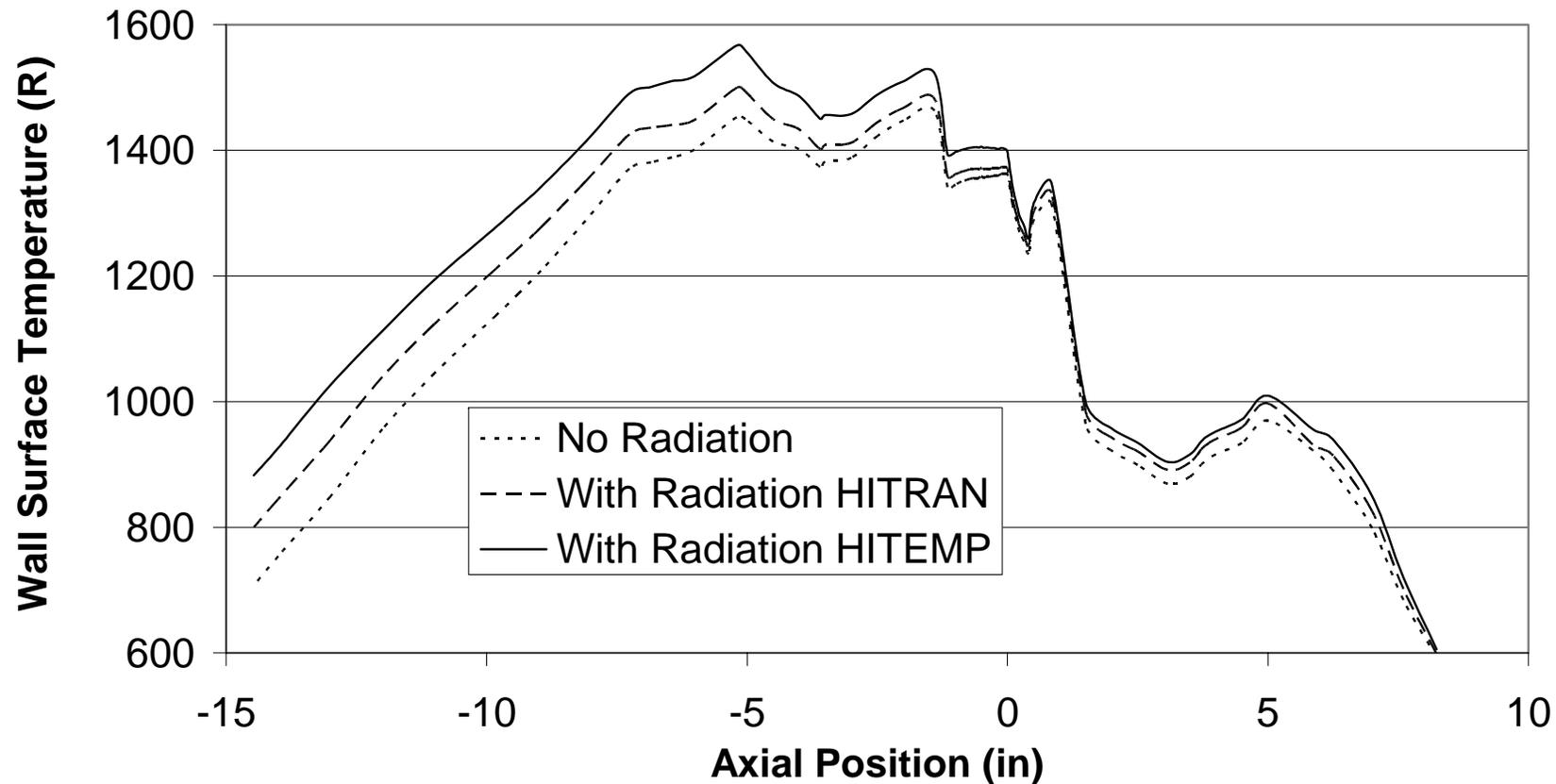
The specifications of this engine are:

Chamber pressure	3027 psia
O/F	6.0
Contraction ratio	3.0
Expansion ratio	77.5
Throat diameter	10.3 inches
Propellant	LH2-LO2
Coolant	LH2
Total coolant flow rate	29.06 lb/s
Coolant inlet temperature	95R
Coolant inlet stagnation pressure	6452 psia
Number of cooling channels	430

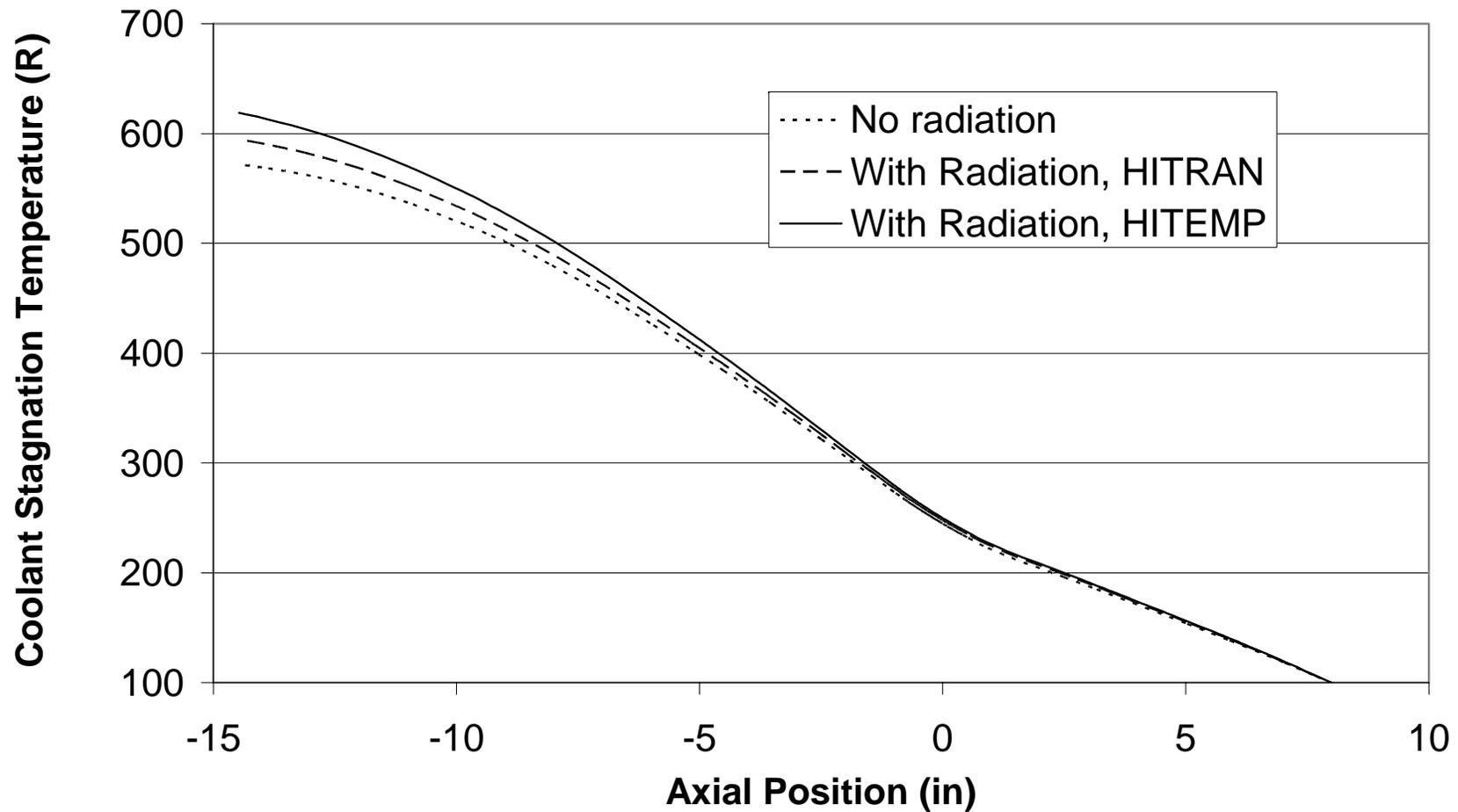
Effects of radiation on the wall heat flux of the SSME



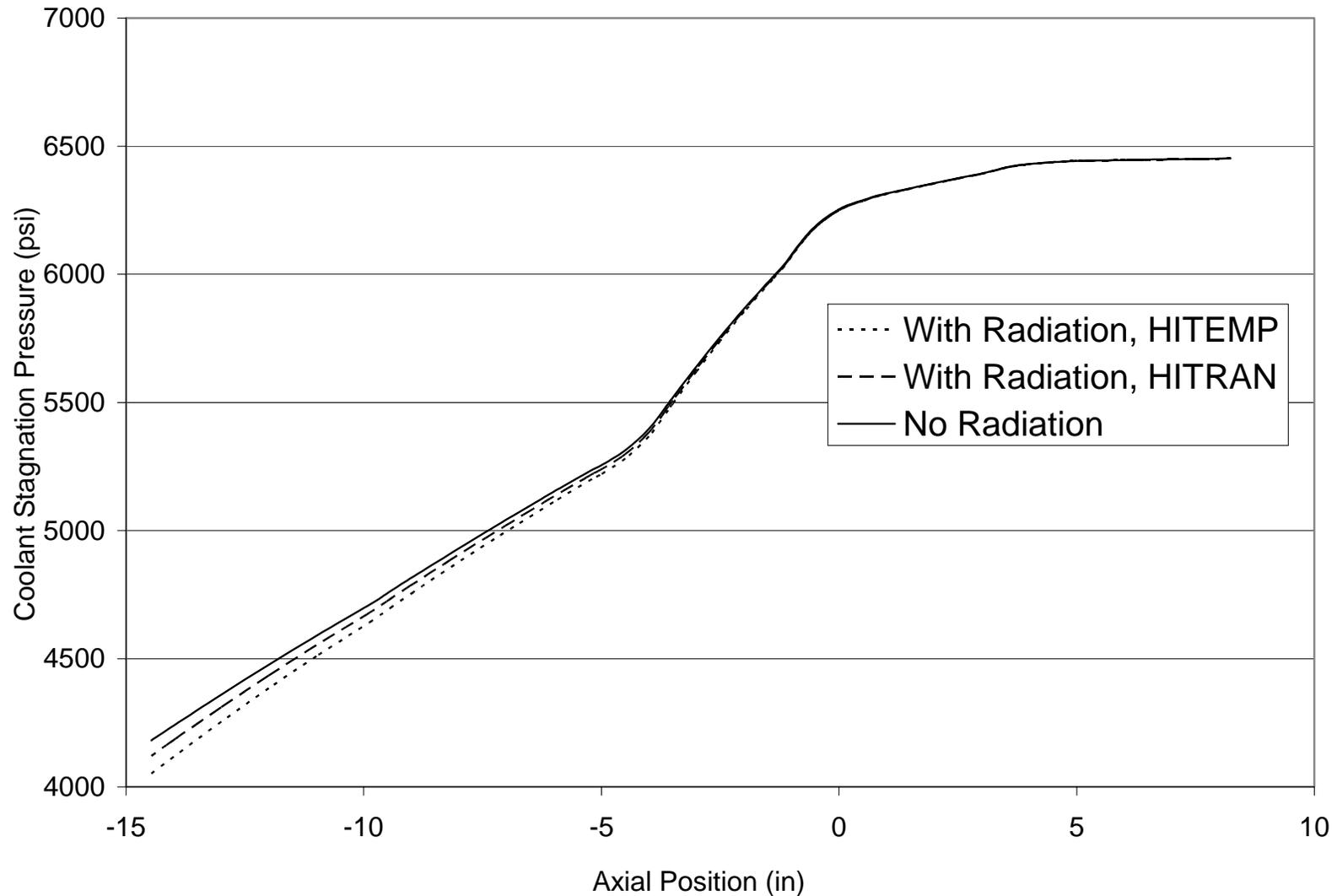
Effects of radiation on the wall temperature of the SSME



Effects of radiation on the coolant stagnation temperature of the SSME



Effects of radiation on coolant stagnation pressure of SSME

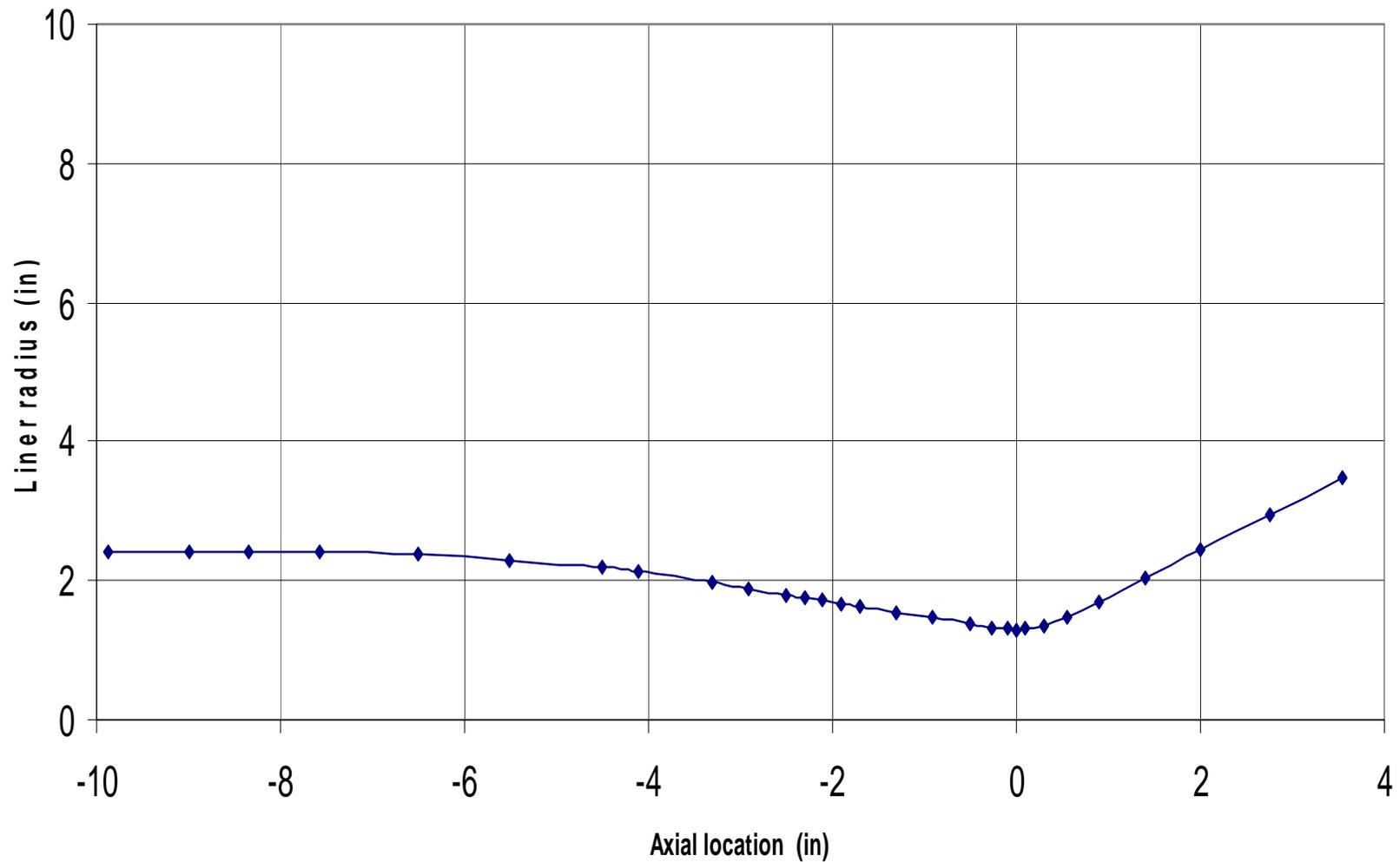


Results for a RP1-LO2 Engine

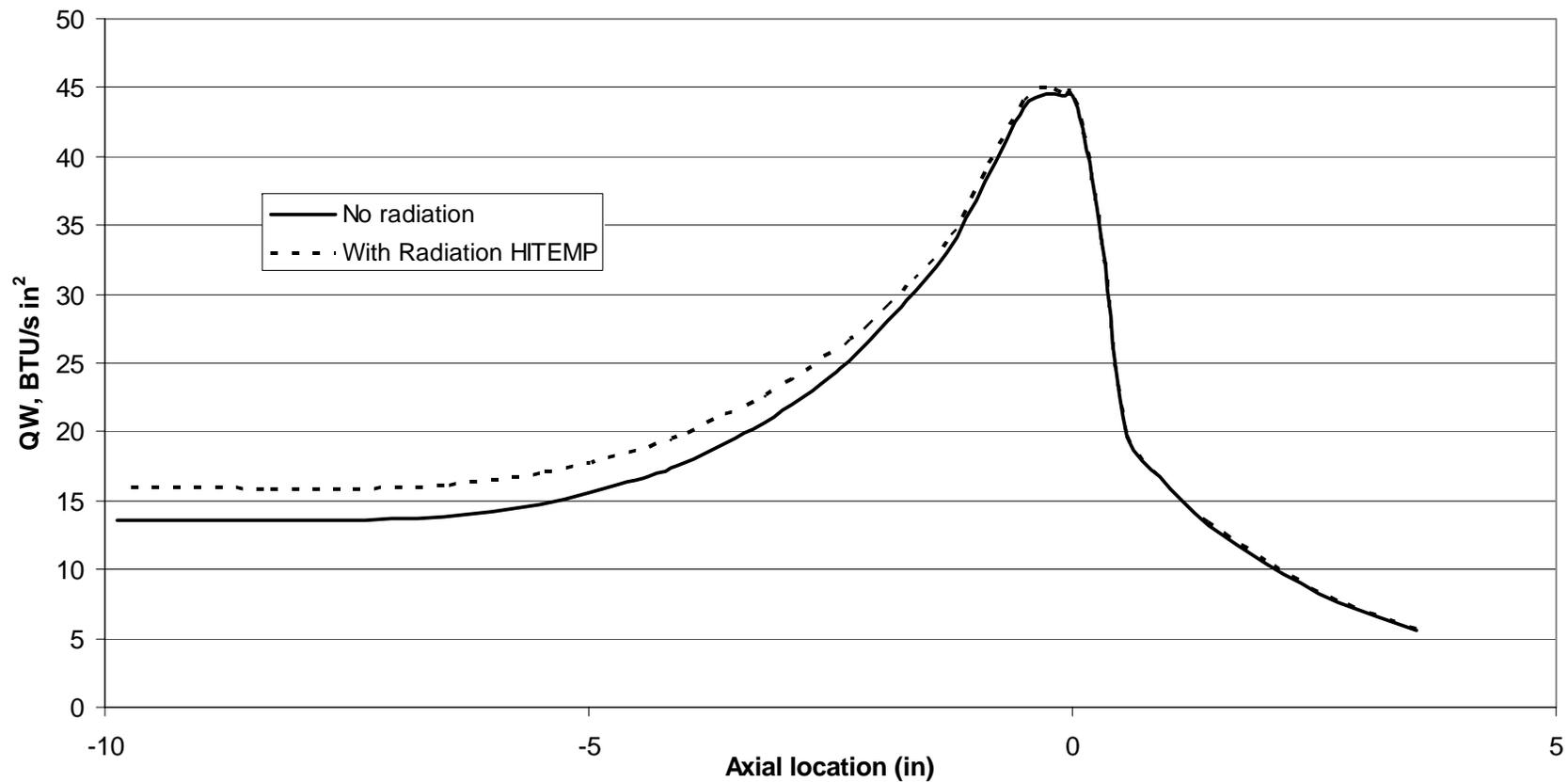
The specifications of this engine are:

Chamber pressure	2,000 psi
O/F (mixture ratio)	1.8
Contraction ratio	3.4
Expansion ratio	7.20
Throat diameter	2.6 inch
Propellant	RP1-LO2
Coolant	LO2
Total coolant flow rate	32.893 lb/s
Coolant inlet temperature	160°R
Coolant inlet pressure	3,000 psi
Number of cooling channels	100
Throat region channel aspect ratio	2.5

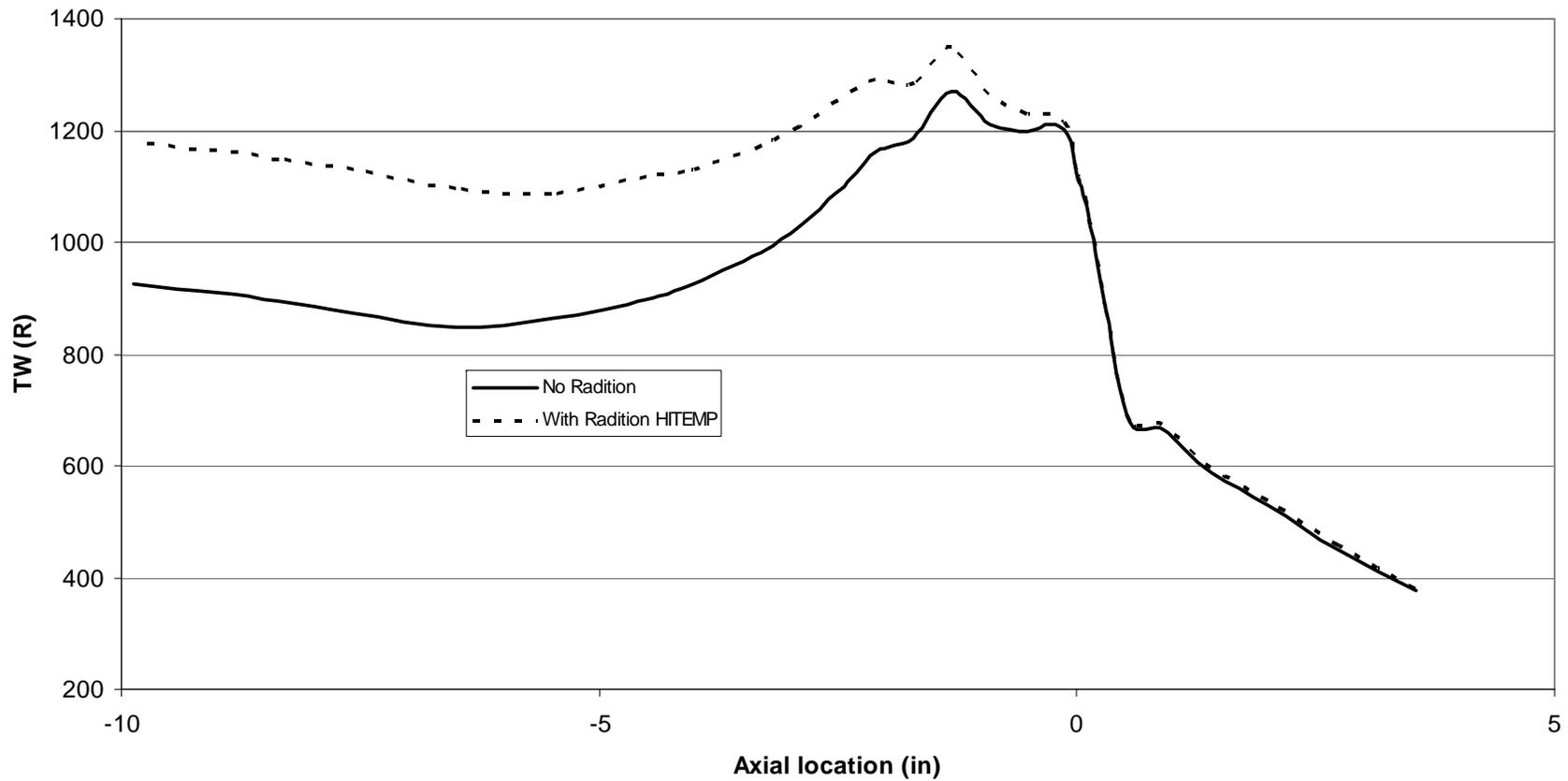
Contour of the RP1-LOX engine



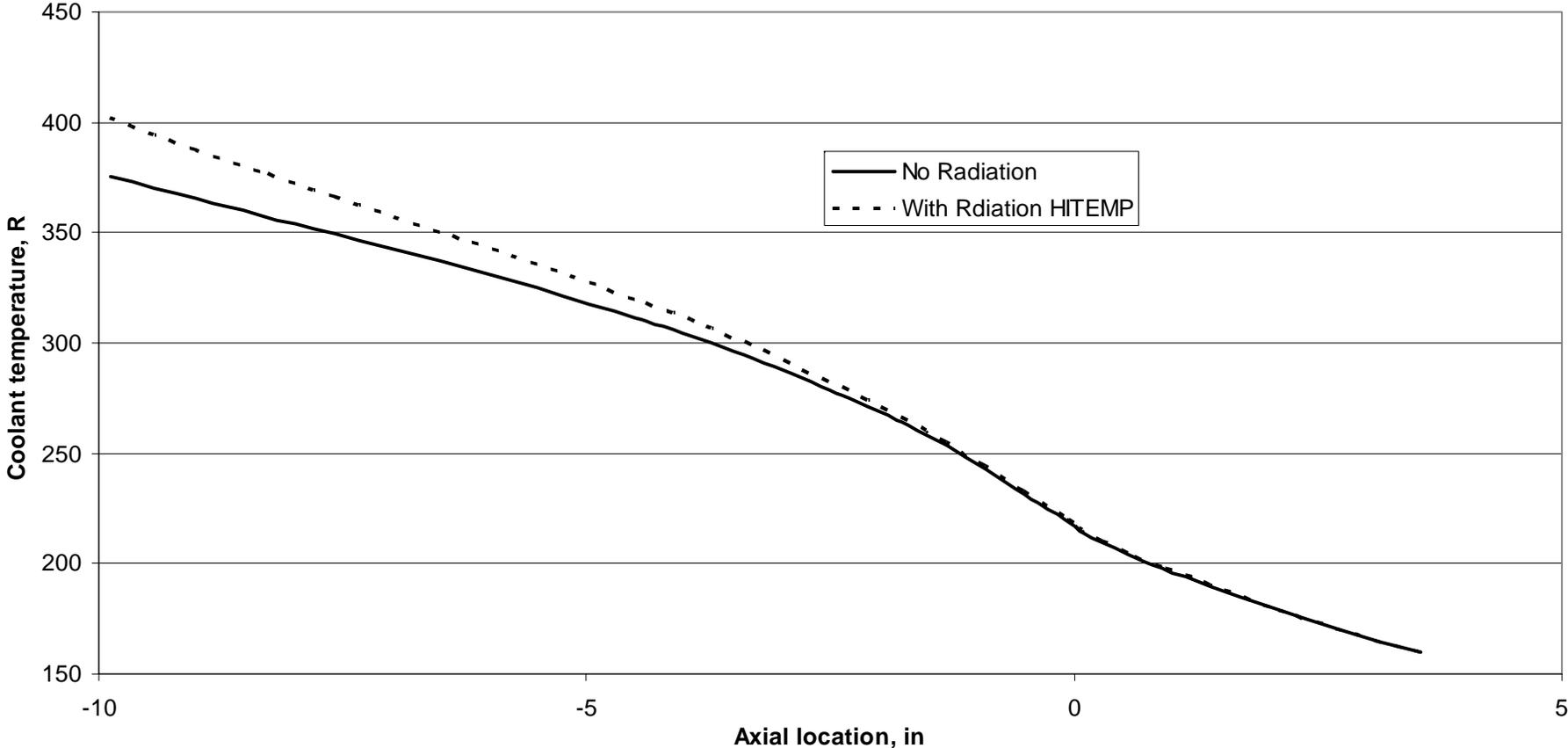
Effects of radiation on the wall heat flux of the RP1-LOX engine



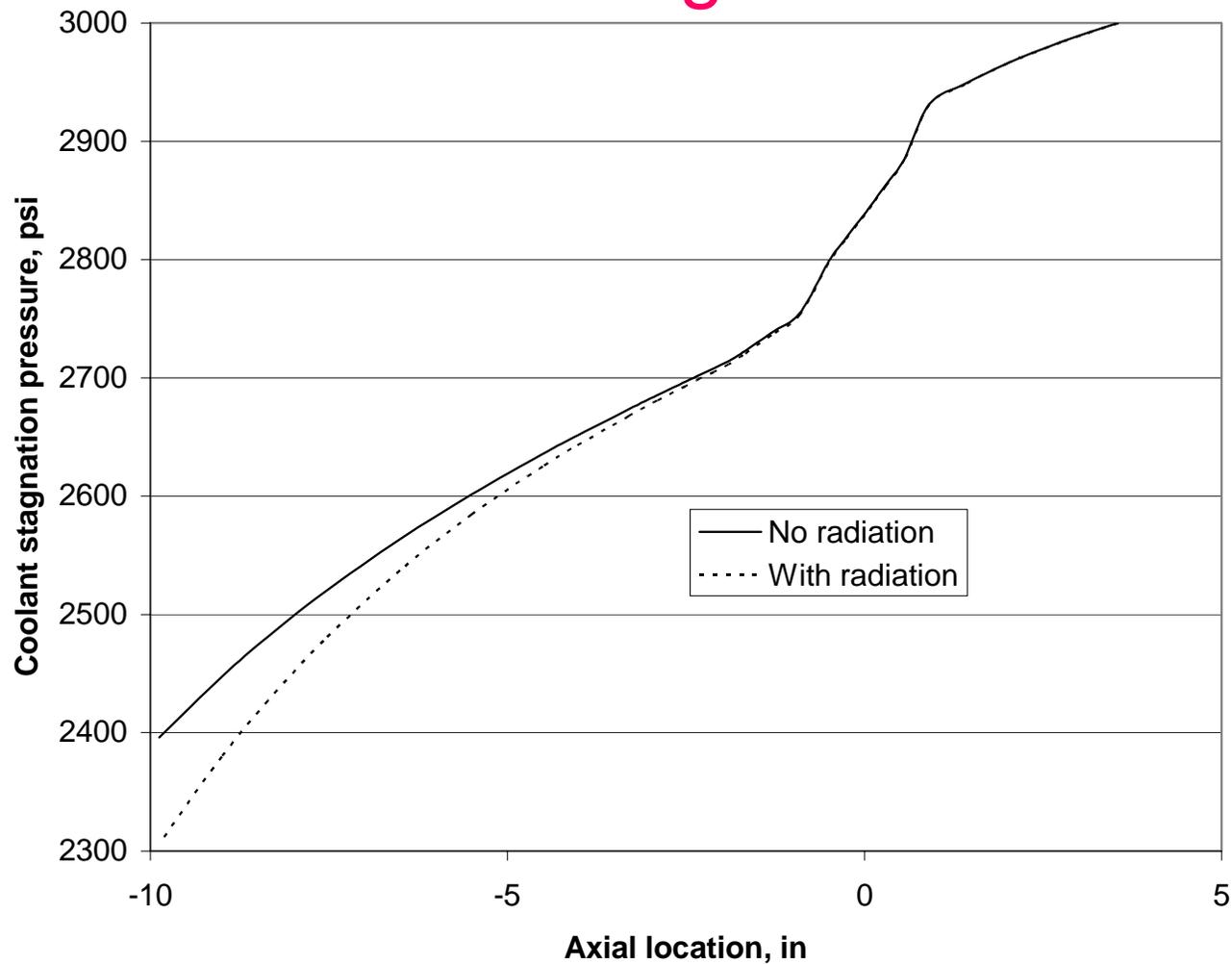
Effects of radiation on the wall temperature of the RP1-LOX engine



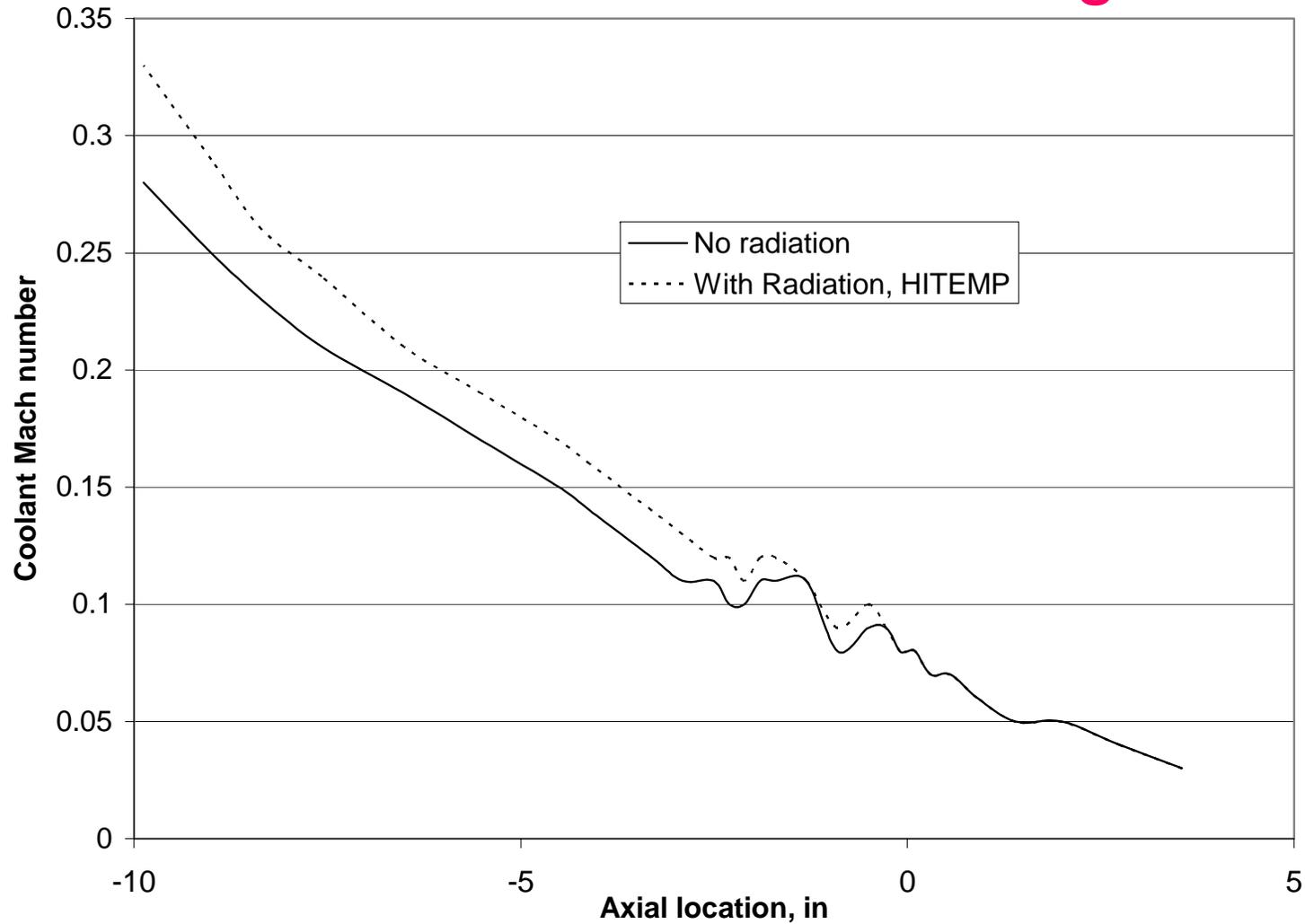
Effects of radiation on the coolant temperature of the RP1-LOX engine



Effects of radiation on the coolant stagnation pressure of the RP1-LOX engine



Effects of radiation on the coolant Mach number of the RP1-LOX engine



Concluding Remarks

- The effects of gas and surface radiation on the wall temperature, coolant pressure, temperature and Mach number were studied
- The results presented demonstrate that although the increase in heat flux due to radiation is small, it can have a significant effect on the wall temperature and coolant flow characteristics

Concluding Remarks

- For a LH2/LO2 engine it is shown that the radiation has a small effect on the wall temperature of the diverging section of the nozzle
- the radiation results in a substantial increase in the wall temperature of the thrust chamber and converging section of the nozzle, such that the local peak temperature is the same order of magnitude as the throat temperature

Concluding Remarks

- For the RP1/LO2 engine, radiative heat transfer resulted in a 30% increase in wall temperature. Additionally, it significantly increased the coolant pressure drop and Mach number
- neglecting radiation during the design phase may result in a faulty cooling system

Availability of the Radiation Code RAD2005

- The model presented is incorporated in a program (RAD2005) which can be linked to TDK and RTE
- TDK from Software Engineering Associates, Inc. (seainc.com)
- RTE from Tara Technologies, LLC (tara-technologies.com)