N95- 23414

RADIATION/CONVECTION COUPLING IN ROCKET MOTORS AND PLUMES

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1995116994

R. C. Farmer
A. J. Saladino

SECA, Inc.
Huntsville, AL

Abstract

The three commonly used propellant systems; H2/O2, RP-1/O2, and solid propellants; primarily radiate as: molecular emitters, non-scattering small particles, and scattering larger particles, respectively. Present technology has accepted the uncoupling of the radiation analysis from that of the flowfield. This approximation becomes increasingly inaccurate as one considers plumes, interior rocket chambers, and nuclear rocket propulsion devices. This study will develop a hierarchy of methods which will address radiation/convection coupling in all of the aforementioned propulsion systems.

The nature of the radiation/convection coupled problem is that the divergence of the radiative heat flux must be included in the energy equation and that the local, volume-averaged intensity of the radiation must be determined by a solution of the radiative transfer equation (RTE). The intensity is approximated by solving the RTE along several lines of sight (LOS) for each point in the flowfield. Such a procedure is extremely costly; therefore, further approximations are needed. Modified differential approximations are being developed for this purpose. It is not obvious which order of approximations are required for a given rocket motor analysis. Therefore, LOS calculations have been made for typical rocket motor operating conditions in order to select the type approximations required. The results of these radiation calculations, and the interpretation of these intensity predictions are presented herein.

The study is still in progress. The inclusion of the selected radiation model into a coupled CFD solution will be reported at a later date.

RADIATION/CONVECTION COUPLING IN ROCKET MOTORS & PLUMES

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SECA, INC.

Presentation for:

Workshop for CFD Applications in Rocket Propulsion

April 20-22, 1993

NASA/MSFC, MSFC, AL

OBJECTIVE:

Develop a radiation/convection coupled analysis of rocket motors & plumes

Tasks:

1 - Characterize radiation for various type motors

2 - Develop radiation/convection coupling methodology

PARAMETERS AFFECTING RADIATION

H_2/O_2 Propellant System

- Radiator H_2O vapor
- Requires spectral integration

HC/O_2 Propellant System

- Radiators soot, H_2O, CO_2
- Requires soot concentration prediction

SRM

- Radiators Al_2O_3 particles, H_2O, CO_2, HCl
- Requires
  - Predicting particle size distributions
  - Predicting particle temperatures
  - Specifying optical property data

Internal Surface Characteristics

- Not well known
- Assume reflectivity of 0.2

Radiation Analyses

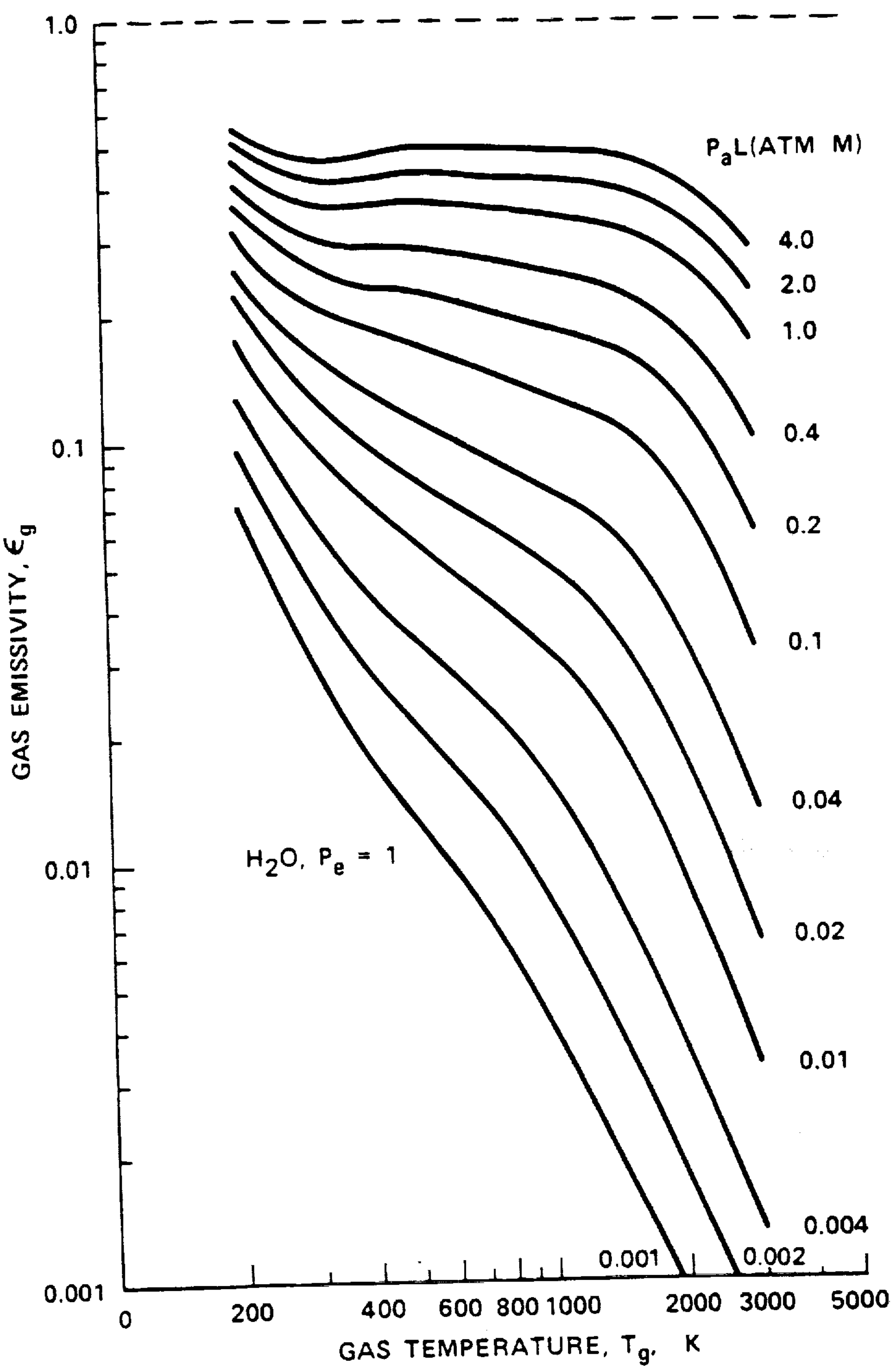
Molecular Radiators

- Narrow Band Models
- Wide Band Models
- Mean of all Bands

Particle Radiators

- Small particles - like soot emit & absorb but do not scatter
- large particles - like Al_2O_3 emit, absorb, & scatter non-isotropically.

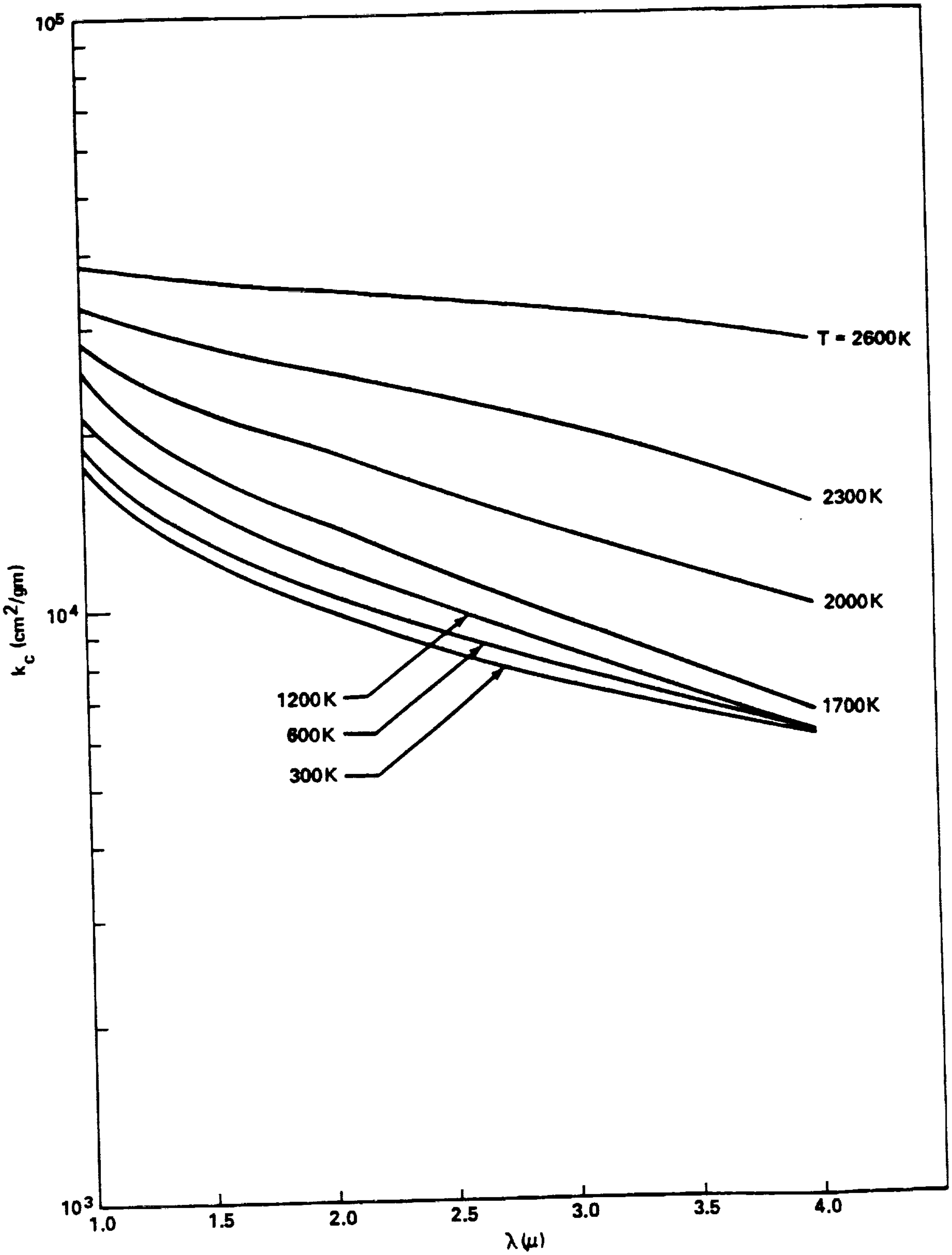
Evaluations made with line-of-sight (LOS) calculation for typical motors.



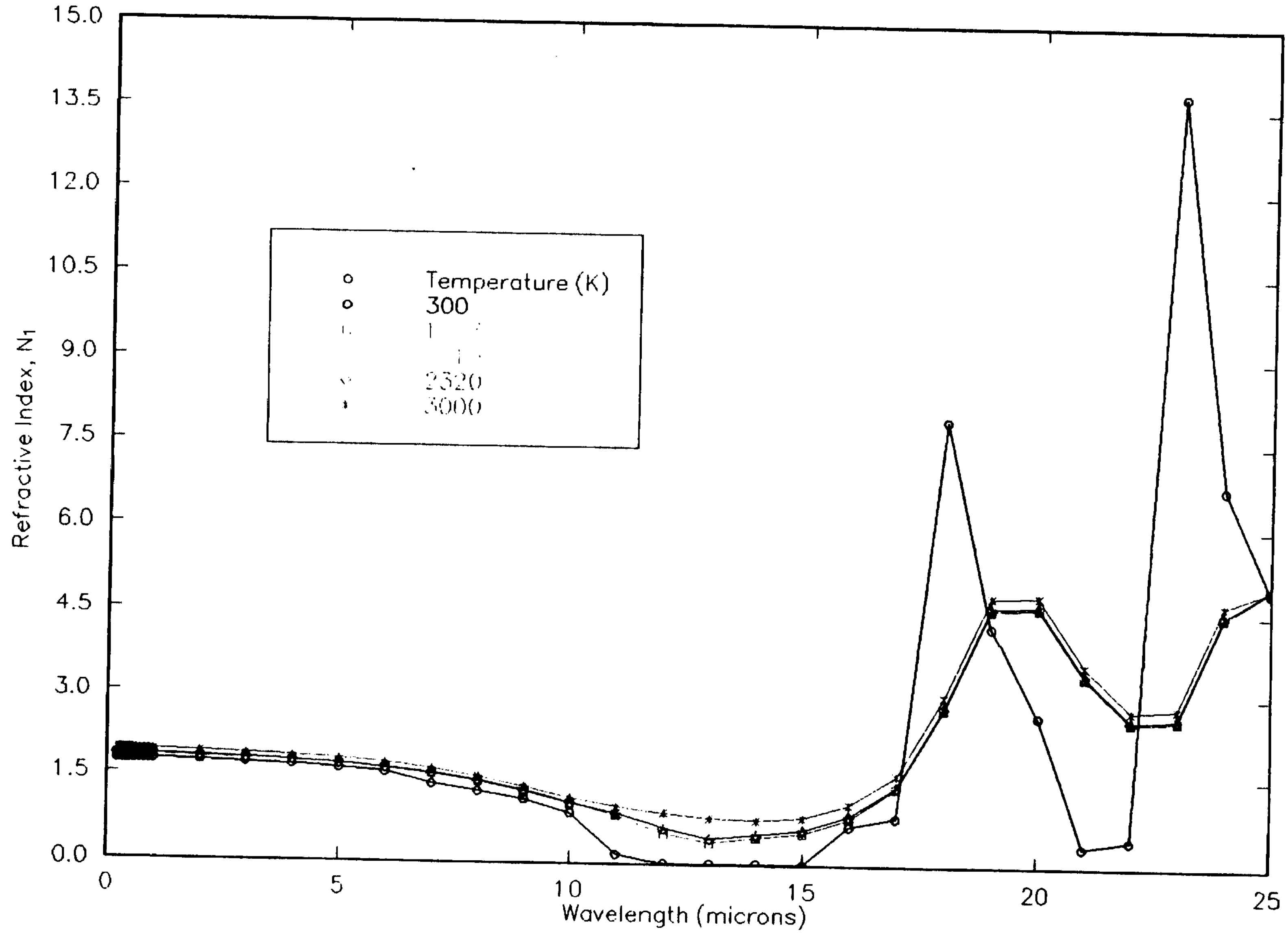
Total emissivity of H_2O.

Wide band model correlation parameters for various gases

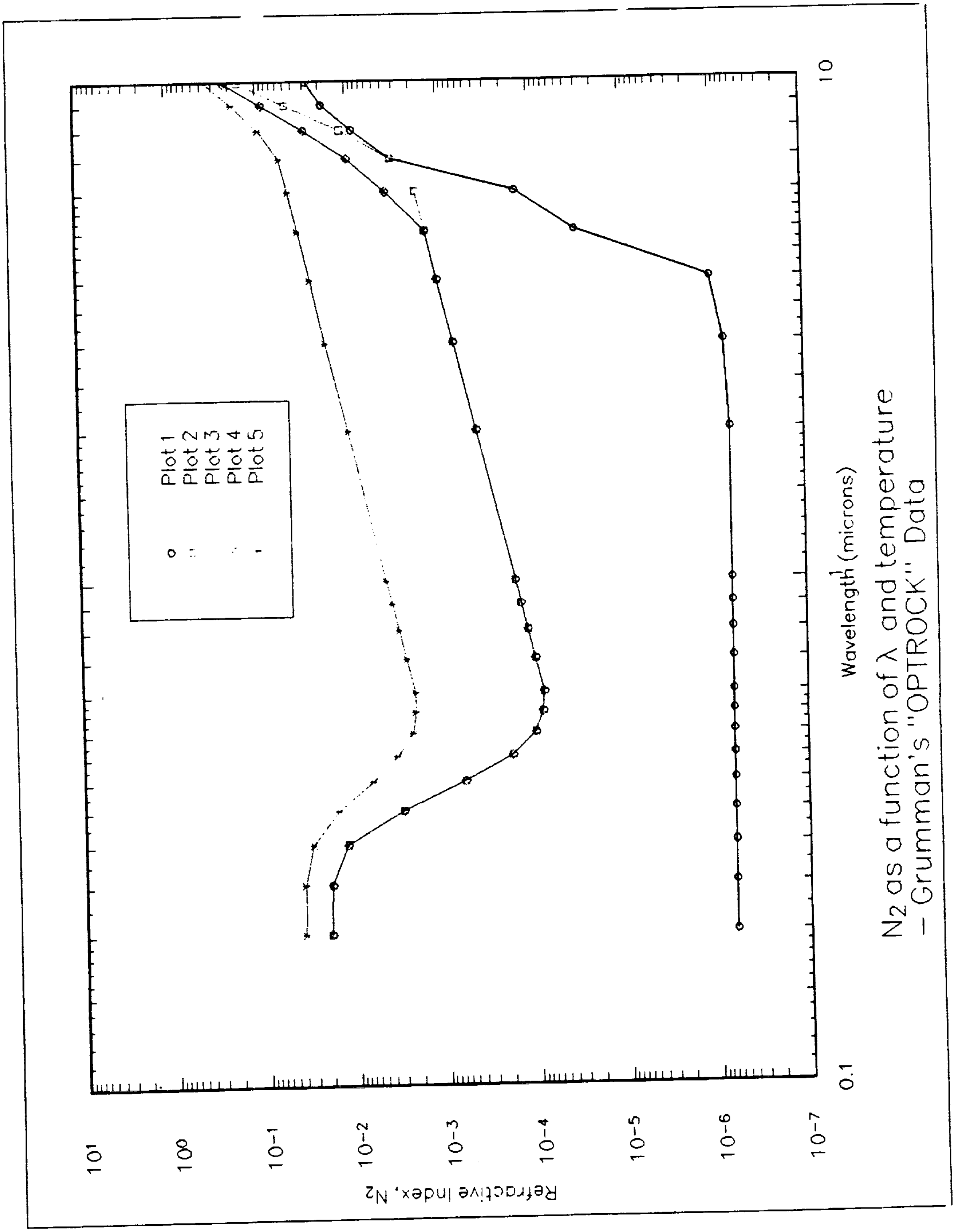
Band Location λ [μm]	(δ_k)	Pressure Parameters n	b	Correlation Parameters α_0 [$cm^{-1}/(g/m^2)$]	γ_0	ω_0 [cm^{-1}]
H_2O	$m = 3$, $\eta_1 = 3652\,cm^{-1}$, $\eta_2 = 1595\,cm^{-1}$, $\eta_3 = 3756\,cm^{-1}$, $g_k = (1, 1, 1)$					
71 μm[a]	$\eta_c = 140\,cm^{-1}$ (Rotational) (0,0,0)	1	$8.6\sqrt{T_0/T} + 0.5$	44,205	0.14311	69.3
6.3 μm	$\eta_c = 1600\,cm^{-1}$ (0,1,0)	1	$8.6\sqrt{T_0/T} + 0.5$	41.2	0.09427	56.4
2.7 μm	$\eta_c = 3760\,cm^{-1}$ (0,2,0)			0.2		
	(1,0,0)	1	$8.6\sqrt{T_0/T} + 0.5$	2.3	0.13219[b,c]	60.0[b]
	(0,0,1)			23.4		
1.87 μm	$\eta_c = 5350\,cm^{-1}$ (0,1,1)	1	$8.6\sqrt{T_0/T} + 1.5$	3.0	0.08169	43.1
1.38 μm	$\eta_c = 7250\,cm^{-1}$ (1,0,1)	1	$8.6\sqrt{T_0/T} + 1.5$	2.5	0.11628	32.0
CO_2	$m = 3$, $\eta_1 = 1351\,cm^{-1}$, $\eta_2 = 666\,cm^{-1}$, $\eta_3 = 2396\,cm^{-1}$, $g_k = (1, 2, 1)$					
15 μm	$\eta_c = 667\,cm^{-1}$ (0,1,0)	0.7	1.3	19.0	0.06157	12.7
10.4 μm	$\eta_c = 960\,cm^{-1}$ (−1,0,1)	0.8	1.3	2.47×10^{-9}	0.04017	13.4
9.4 μm	$\eta_c = 1060\,cm^{-1}$ (0,−2,1)	0.8	1.3	2.48×10^{-9}	0.11888	10.1
4.3 μm	$\eta_u = 2410\,cm^{-1}$ (0,0,1)	0.8	1.3	110.0	0.24723	11.2
2.7 μm	$\eta_c = 3660\,cm^{-1}$ (1,0,1)	0.65	1.3	4.0	0.13341	23.5
2.0 μm	$\eta_c = 5200\,cm^{-1}$ (2,0,1)	0.65	1.3	0.060	0.39305	34.5



Experimentally Determined Carbon Absorption Coefficients
(from Radiation Handbook)

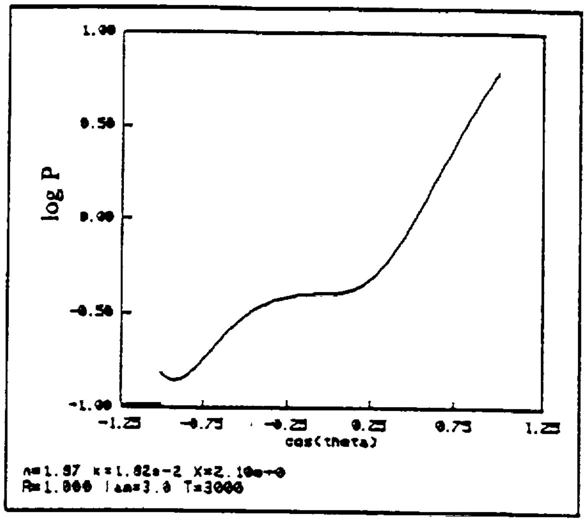


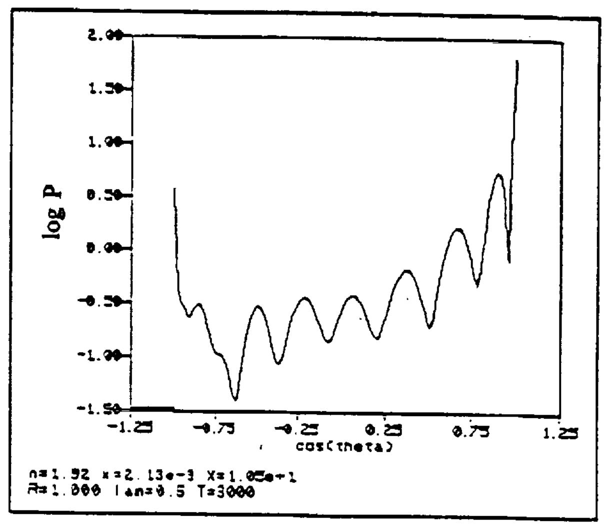
N_1 as a function of λ and temperature
– Grumman's "OPTROCK" Data

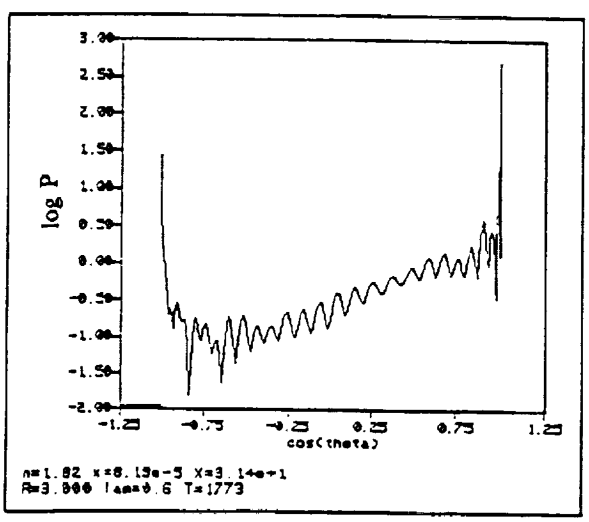


N_2 as a function of λ and temperature – Grumman's "OPTROCK" Data

PHASE FUNCTION AS DETERMINED BY MIE THEORY CALCULATION







Optical properties: n,κ
Particle Radius: R
Wavelength: lam
Temperature: T
Particle Size
Parameter: $X=2\pi R/\lambda$

Al_2O_3 RADIATION PROPERTIES

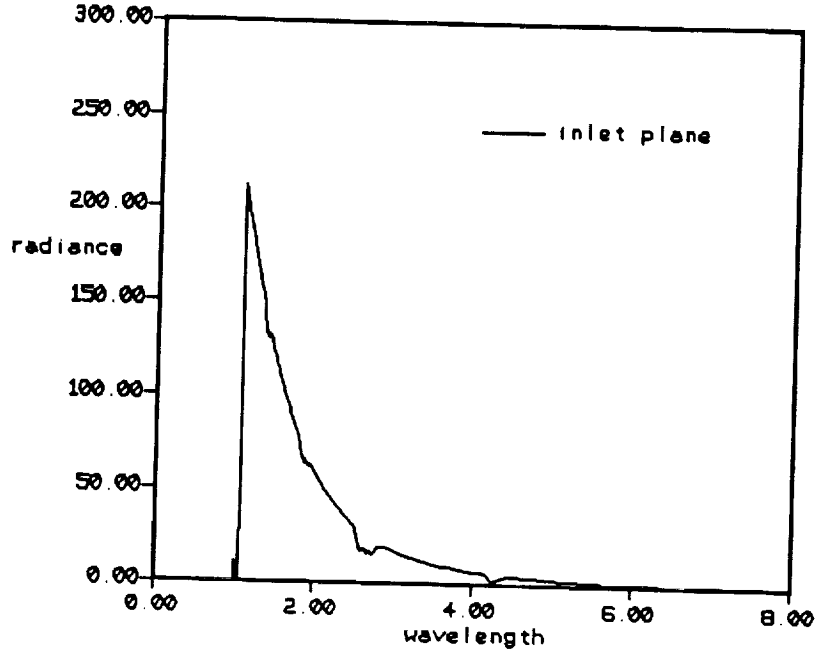
r, (μm)	Wave Number	σ_e, (cm^2)	Albedo	s_b	b_b	b_2	T(K)	
1.OE-3	400	6.181E-19	5.565E-10	.14352	.21295	.49999	3000	OS
		6.181E-19	5.565E-10	.1439	.2120	.5065		OM
3	5000	6.7430E-7	.98982	.073316	.061334	.087562	2320	RS
		5.956E-7	.9905	.07461	.06874	.14723		RM
3	10000	6.3054E-7	.99193	.059637	.053251	.070317	2320	RS
		6.618E-7	.9924	.05366	.05025	.10287		RM
3	3333	6.841E-7	.98754	.08270	.07050	.11115	2320	RS
		8.103E-7	.9831	.06509	.08108	.17645		RM
3	10000	6.723E-7	.98954	.07248	.060389	.085913	1773	RS
		6.752E-7	1.000	.05096	.05813	.11004		RM
3	10000	6.843E-7	.81057	.06522	.04385	.060442	3000	RS
		6.445E-7	.8666	.05318	.03896	.09529		RM

OS Original Al_2O_3 Optical Properties in SIRRM

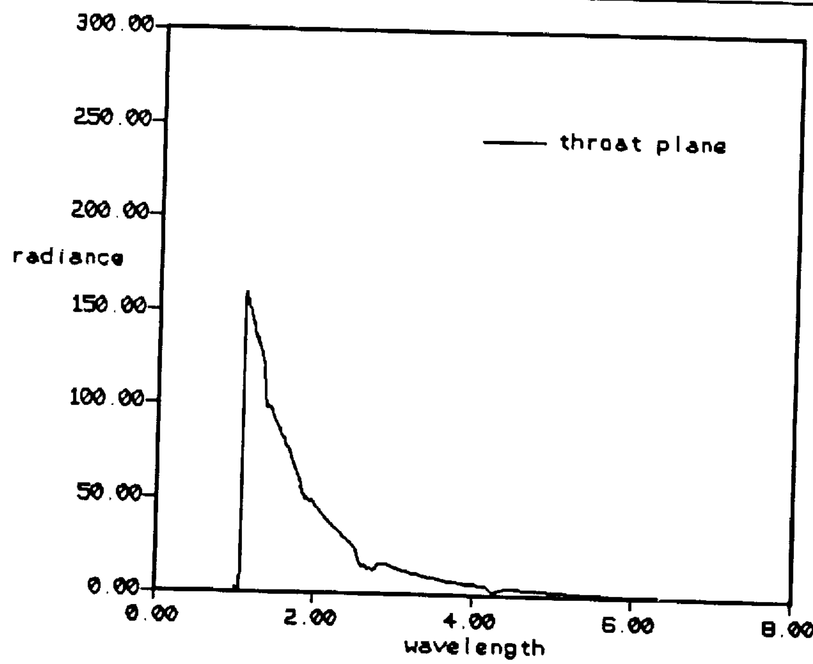
OM Original Al_2O_3 Optical Property Data With MIE Code

RS OPTROCK Properties in SIRRM

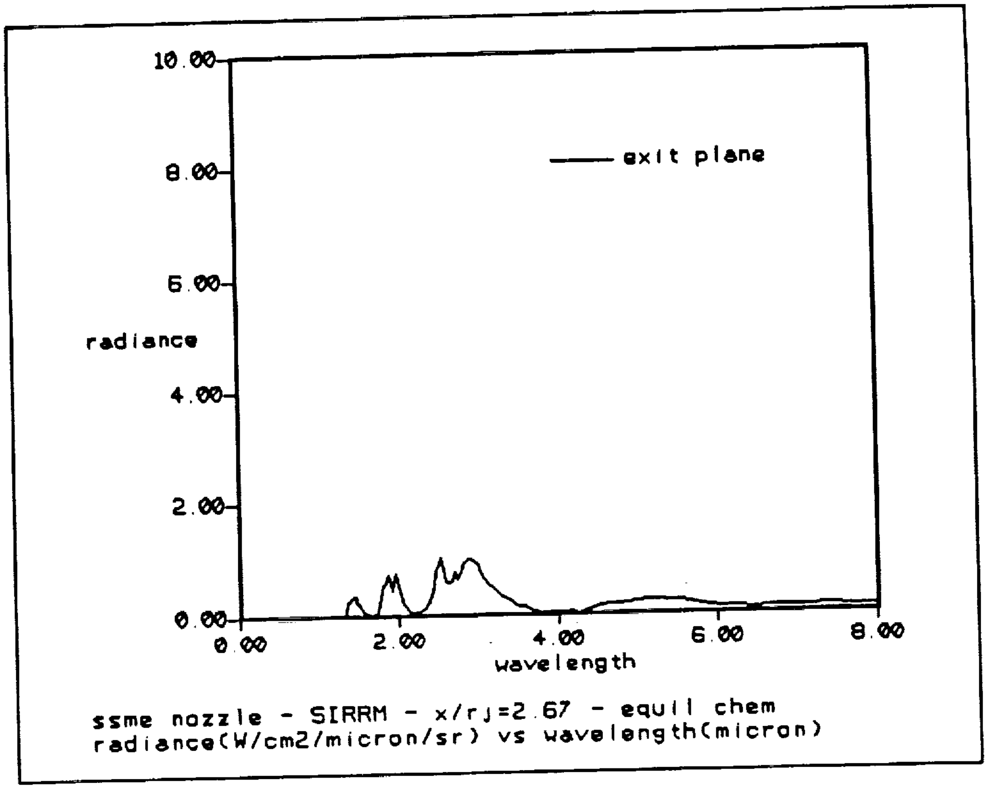
RM OPTROCK Properties Calculated With A MIE Code



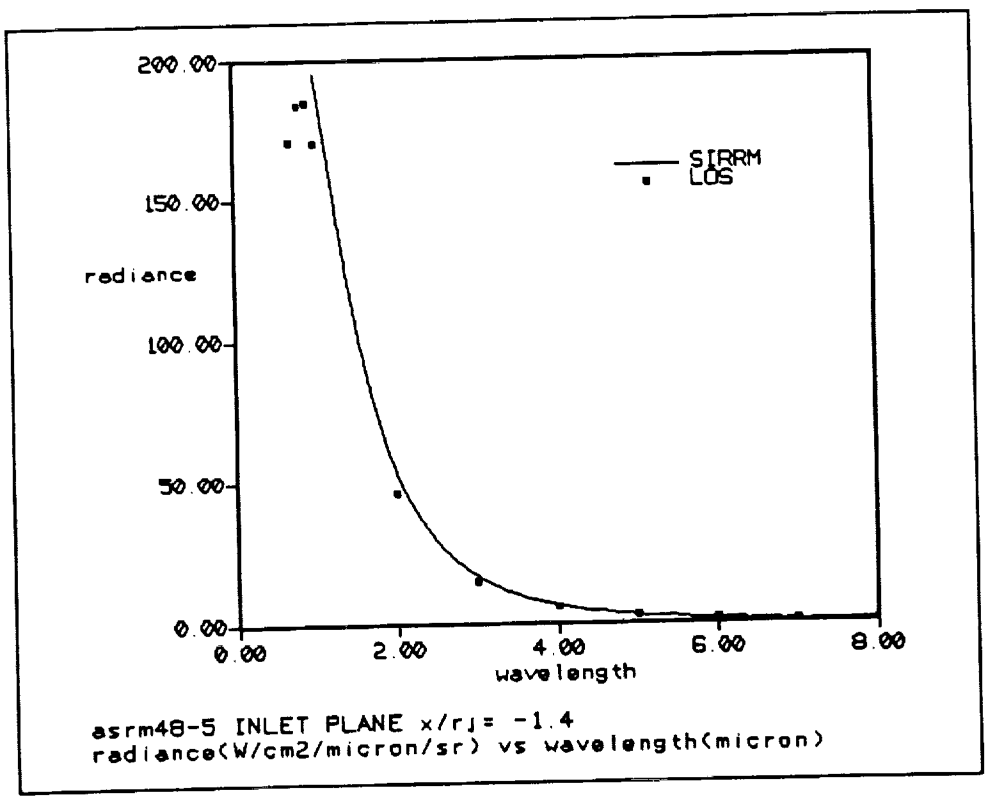
ssme nozzle - SIRRM - x/rj=-0.30 - equil chem
radiance(W/cm2/micron/sr) vs wavelength(micron)



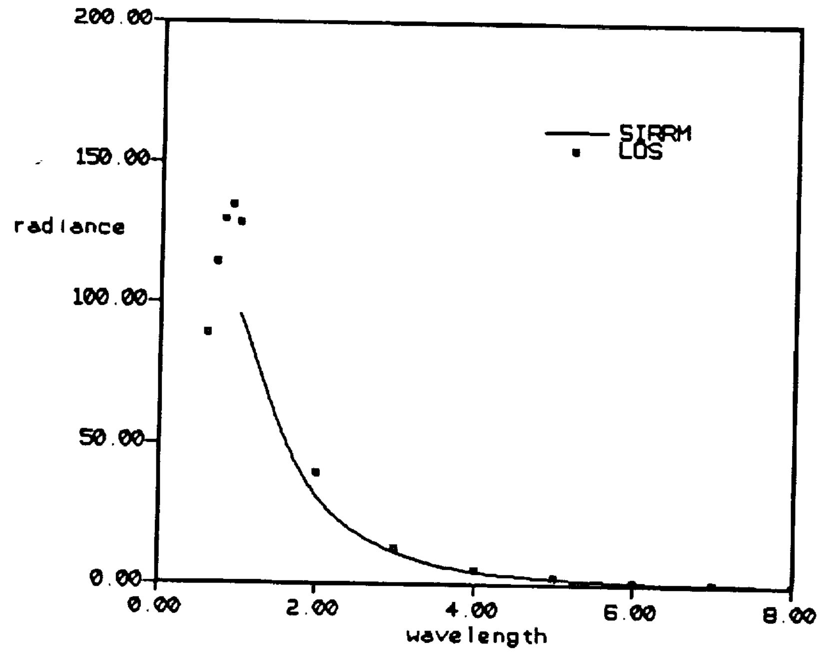
ssme nozzle - SIRRM - x/rj=0.0 - equil chem
radiance(W/cm2/micron/sr) vs wavelength(micron)



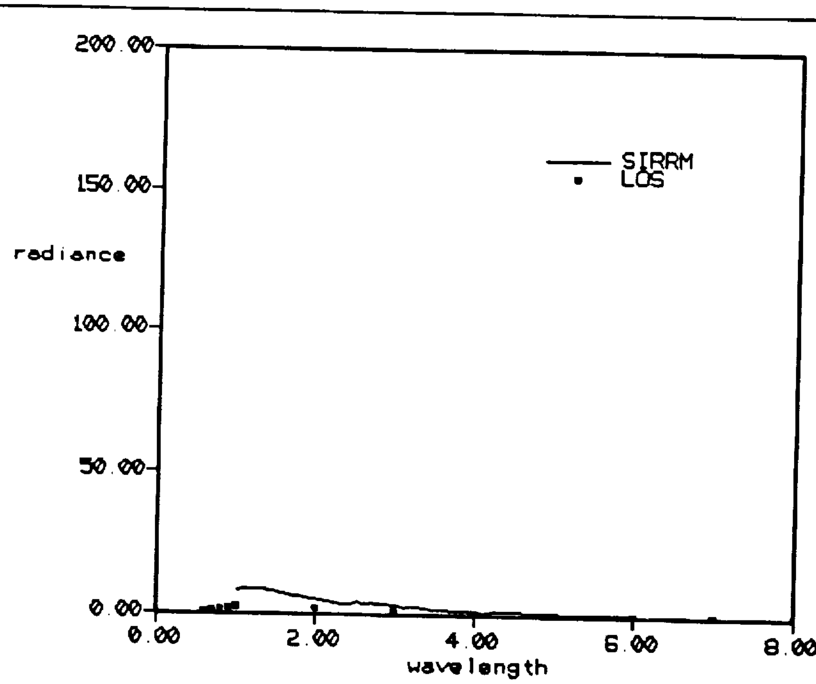
10.00
8.00
6.00
4.00
2.00
0.00
radiance
exit plane
0.00
2.00
4.00
6.00
8.00
wavelength
ssme nozzle - SIRRM - x/rj=2.67 - equil chem
radiance(W/cm2/micron/sr) vs wavelength(micron)



200.00
150.00
100.00
50.00
0.00
radiance
SIRRM
LOS
0.00
2.00
4.00
6.00
8.00
wavelength
asrm48-5 INLET PLANE x/rj= -1.4
radiance(W/cm2/micron/sr) vs wavelength(micron)



asrm48-5 THROAT PLANE x/rj= 0.04
radiance(W/cm2/micron/sr) vs wavelength(micron)



asrm48-5 EXIT PLANE x/rj= 2.25
radiance(W/cm2/micron/sr) vs wavelength(micron)

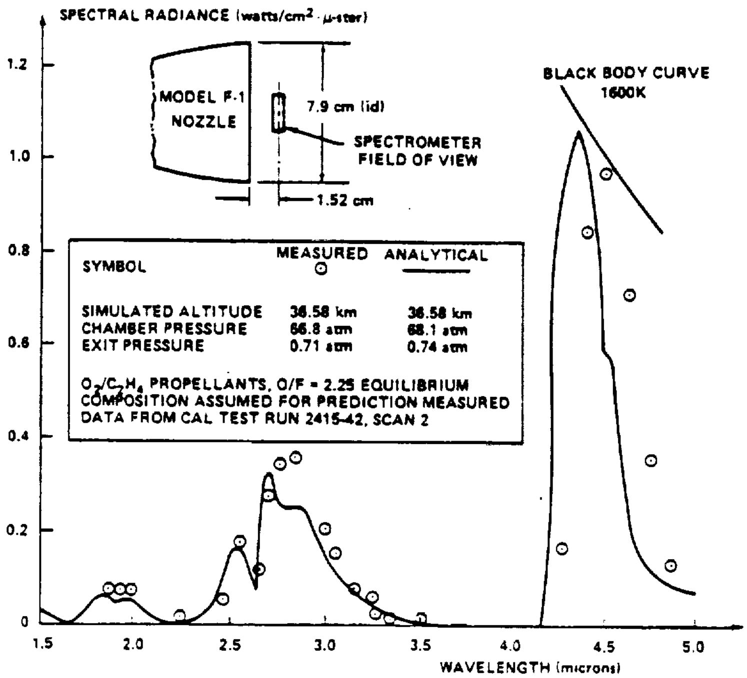
TOTAL GAS RADIATION - cal/cm^2-s

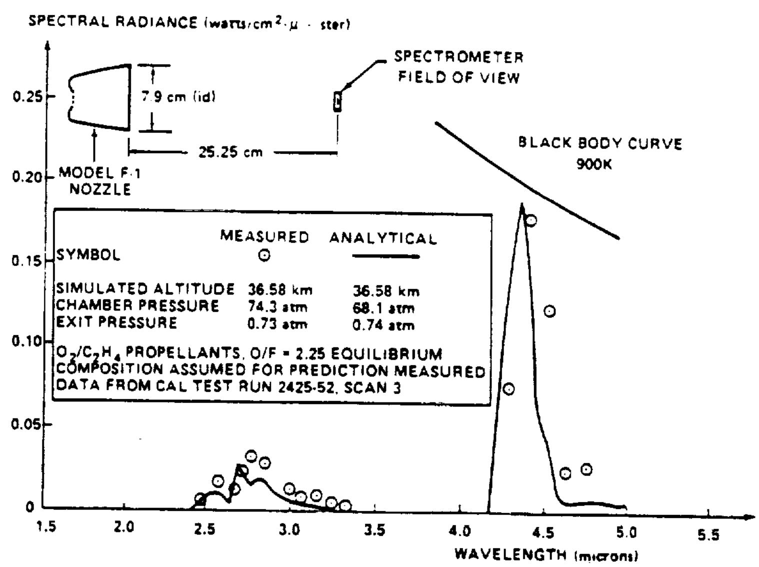
	SSME			
	Mean	Wide	Narrow	σT^4
CHAMBER $P=194.4$ atm $T=3626.02K$ $L=43.98$ cm $P_w= 134.5$ atm	234	90.7	124	234
THROAT $P=115$ atm $T=3450K$ $L=25.42$ cm $P_w= 81.1$ atm	192	65.8	98.4	192
EXIT $P=0.1943$ atm $T=1279K$ $L=230.436$ cm $P_w= 0.15$ atm	0.692	0.621	0.63	3.62

TOTAL GAS RADIATION - cal/cm^2-s

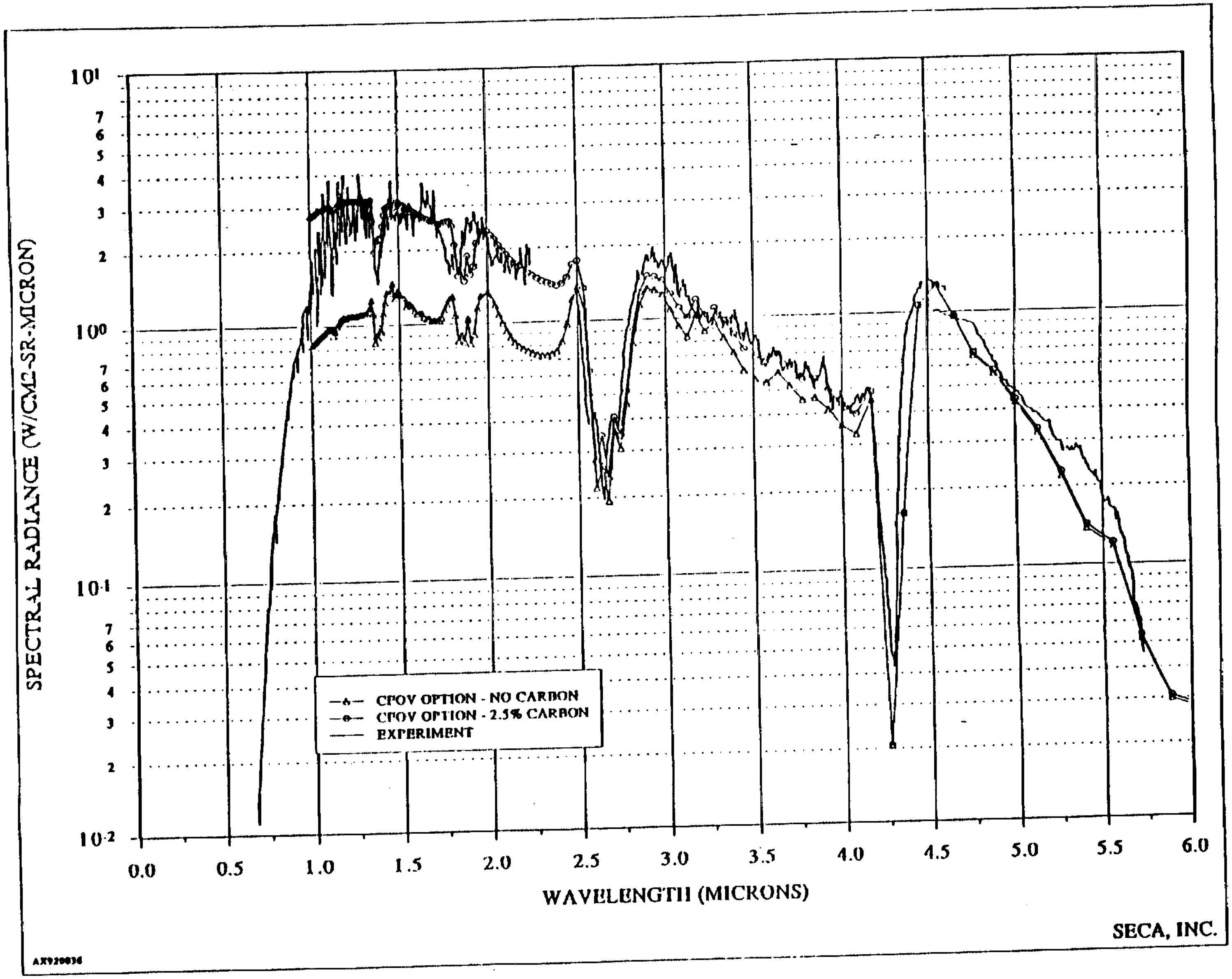
	ASRM 48-5		
	Mean	Wide	σT^4
CHAMBER P=43 atm T=3513K L=105.184 cm P_w= 5.76 atm P_c= 0.57 atm	91.1	51.4	206
THROAT P=25 atm T=3230K L=24.918 cm P_w= 3.40 atm P_c= 0.33 atm	21.6	22.1	147
EXIT P=1.04 atm T=2200 K L=67.95 cm P_w= 0.14 atm P_c= 0.014 atm	2.48	2.53	31.7

Al_2O_3 PARTICLE RADIATION - cal/cm^2-s		
	LOS	σT^4
CHAMBER	182	206.3
THROAT	95.0	156.8
EXIT	12.5	39.1





Plume Radiation from a Small Scale F-1 Engine
(Reardon, Radiation Handbook)



RSRM48-1 SIRRM-II Predicted Plume Radiance at $X/R_j = 2.24$

TRENDS IN Al_2O_3 PARTICLE SIZE FOR SRM

(from Netzer's experiments)

- Chamber near propellant surface - 130 μm
- Chamber at nozzle entrance - 4-17 μm
- Converging Nozzle Section - particles breakup
- Diverging Nozzle Section - particles agglomerate
- Plume Nearfield - multi-modal PSD w/large particles near centerline
- Plume Farfield - small particles

PRESENT PLUME RADIATION METHODOLOGY

- Flowfields - Standard Axisymmetric Models (RAMP2, SPF/2, SPF/3)
- Radiation - SIRRM, Reverse Monte Carlo
- Particle Size Based on MNASA 48" Measurements of Sambamurthi
- Improve Particle-Gas Heat Transfer Method of Moylan

RADIATION/CONVECTION COUPLING

Transport Equation Solver: the FDNS-EL Code

Energy Equation contains:

$$\nabla \cdot \vec{q}_r = \int_0^\infty \kappa_\lambda [4\pi I_{\lambda b}\{T\} - \int_{4\pi} I_\lambda \{\vec{r},\ \vec{\Omega}\} d\,\vec{\Omega}] d\lambda$$

The last term in this equation requires an evaluation of the intensity in all directions at each point in the flowfield.

The intensity is obtained from the Radiative Transfer Equation (RTE):

$$\vec{\Omega} \cdot \nabla I_\lambda \{\vec{r},\ \vec{\Omega}\} = \kappa_\lambda\, I_{\lambda b}\{T\} - (\kappa_\lambda + \sigma_\lambda) I_\lambda \{\vec{r}, \vec{\Omega}\}$$

$$+ \frac{\sigma_\lambda}{4\pi} \int_{4\pi} P\{\vec{r},\ \vec{\Omega}' - \vec{\Omega}\} I_\lambda \{\vec{r},\ \vec{\Omega}'\}\, d\Omega'$$

FORMAL SOLUTION TO RTE

$$I\{\vec{r},\ \vec{\Omega}\} = I\{\vec{r}\,',\ \vec{\Omega}\}\ e^{-\tau}$$

$$+ \int_{o}^{\tau} e^{-\kappa t} \left[\kappa I_b\{\vec{r}\} + \frac{\sigma}{4\pi} \int_{4\pi} I\{\vec{r},\ \vec{\Omega}\}\ P\{\vec{r},\ \vec{\Omega}' - \vec{\Omega}\} d\vec{\Omega}' \right] dt$$

(Subscript λ is suppressed for clarity, but intensity is still monochromatic)

Solutions have been obtained by:

- **the PIM method** (Tan)
  - ●● numerical evaluation of the integral terms.
- **the YIX method** (Tan & Howell)
  - ●● uses piecewise-constant interpolation and stores intermediate integral evaluations to improve the PIM method.

SOLUTIONS TO THE RTE USING SPHERICAL HARMONICS

(P_N - Approximation)

The P_1 - Approximation (ODA) requires solutions of PDE's to evaluate the integrated form of the RTE rather than integral equations:

1. Express the intensity as a generalized Fourier Series using Legendre Polynomials.

2. Express the Phase Function with Legendre Polynominals

$$P\{\vec{r},\ \vec{\Omega}'-\vec{\Omega}\} = 1+A_1\,\vec{r}\cdot(\vec{\Omega}'-\vec{\Omega})$$

Requires solution to:

$$\nabla_\tau\cdot\left(\frac{1}{(1-A_1\omega/3)}\nabla_\tau G\right) = -3(1-\omega)(4\pi I_b - G)$$

If $A_1\omega$ is constant, this is an elliptic PDE. When solved,

$$\vec{q} = -\left(\frac{1}{3-A_1\omega}\right)\nabla_\tau G$$

G is incident radiation at a point

$$G\{r\} = \int_{4\pi} I\{\vec{r},\ \vec{\Omega}'\}\,d\Omega'$$

$$I\{\vec{r},\ \vec{\Omega}\} = \frac{1}{4\pi}[G\{\vec{r}\} + 3\vec{q}\{\vec{r}\}\cdot\vec{\Omega}]$$

Limitation: For N=1 or 3, accurate for only optically thick media.

THE MODIFIED DIFFERENTIAL APPROXIMATION

The MDA generalizes P_1 solution to treat arbitrary optical thickness.

Let surface & media contribute to intensity:

$$I\{\vec{r}, \vec{s}\} = I_w\{\vec{r}, \vec{s}\} + I_m\{\vec{r}, \vec{s}\}$$

Solution requires evolution of:

$$G_w\{\vec{r}\} = \frac{1}{\pi} \int_{4\pi} J_w\{\vec{r}_w\}\, e^{-\tau_s}\, d\Omega$$

$$\vec{q}_w\{\vec{r}\} = \frac{1}{\pi} \int_{4\pi} J_w\{\vec{r}_w\}\, e^{-\tau_s}\, \vec{s}\, d\Omega$$

$$J_i = \epsilon_i \pi I_{bi} + (1-\epsilon_i) \sum_{j=1}^{N} J_i e^{-\tau_{ij}} F_{i-j}$$

$$\nabla_\tau G_m = A_1 \omega (\vec{q}_w + \vec{q}_m) - 3\, \vec{q}_m$$

$$\nabla_\tau \cdot \vec{q}_m = (1-\omega) 4\pi I_b + \omega (G_w + G_m) - G_m$$

THE IMPROVED DIFFERENTIAL APPROXIMATION

The IDA has the same solution features as the MDA but is more computationally efficient.

Solution requires:

The ODA, i.e. the P_1 solution, and also:

$$J_w\{\vec{r}\} = \epsilon\pi I_{bw}\{\vec{r}\}$$

$$+ (1-\epsilon)\int_A \left[J_w\{\vec{r}'\}e^{-\tau_s} + \pi S^*\{\vec{r}-s_o\hat{s},\ \hat{s}\}(1-e^{\tau_s})\right]\frac{\cos\theta\cos\theta'}{\pi S^2}dA$$

$$G\{\vec{r}\} = \int_A [J_w\{\vec{r}'\}e^{-\tau_s} + \pi S^*\{\vec{r}-s_o\hat{s},\ \hat{s}\}(1-e^{-\tau_s})\frac{\cos\theta' dA}{\pi S^2}$$

$$q\{\vec{r}\} = \int_A [J_w\{\vec{r}'\}e^{-\tau_s} + \pi S^*\{\vec{r}-s_o\hat{s},\ \hat{s}\}(1-e^{-\tau_s})]\,\hat{s}\,\frac{\cos\theta' dA}{\pi S^2}$$

SOLUTIONS TO THE RTE
USING THE METHOD OF DISCRETE COORDINATES

Solves a number of LOS's to obtain:

$$G\{\vec{r}\} = \sum_{i=l}^{n} w_i I_i\{\vec{r}\}$$

$$\vec{q}\{\vec{r}\} = \sum_{i=l}^{n} w_i I_i\{\vec{r}\}\vec{s}_i$$

w_i's are weighting functions which must sum to the surface of a unit sphere.

Radiation/convection coupled solution has been reported for a 2-D sooty, ethylene flame in which 12 LOS's were used to evaluate each grid point (Kaplan, NRL)

CONCLUSIONS

1. For H_2/O_2 motors -
   - use narrow band models for H_2O
   - within chamber use $\epsilon = 0.95$ between 1-4μm

2. For SRM motors -
   - use narrow band models for CO_2 & H_2O
   - use linear anisotropic scattering model for Al_2O_3 particles
   - within chamber use $\epsilon = 0.97$ between 0.6-8μm

3. For HC/O_2 motors -
   - reasonable prediction of soot concentration is needed

4. Radiation/convection coupling
   - use FDNS (or FDNS-EL) for flowfield
   - use ODA in chamber & converging nozzle
   - use IDA in diverging nozzle & plume