PROPELLANT CHEMISTRY FOR CFD APPLICATIONS

R.C. Farmer, P.G. Anderson, Gary C. Cheng

SECA, Inc.
Huntsville, AL

ABSTRACT

Current concepts for Reusable Launch Vehicle design have created renewed interest in the use of RP-1 fuels for high pressure and tri-propellant propulsion systems. Such designs require the use of analytical methodology which accurately accounts for the effects of real fluid properties, combustion of large hydrocarbon fuel molecules, and the possibility of soot formation. These effects are inadequately treated in current computational fluid dynamics (CFD) codes which are used for propulsion system analyses.

The objective of this investigation is to provide an accurate analytical description of hydrocarbon combustion thermodynamics and kinetics which is sufficiently computationally efficient to be practical design tool when used with CFD codes such as the FDNS code.

A rigorous description of real fluid properties for RP-1 and its combustion products will be derived from the literature and from experiments conducted in this investigation. Upon the establishment of such a description, the fluid description will be simplified by using the minimum of empiricism necessary to maintain accurate combustion analyses and including such empirical models into an appropriate CFD code. An additional benefit from this approach is that the real fluid properties analysis simplifies the introduction of the effects of droplet sprays into the combustion model.

Typical species compositions of RP-1 have been identified, surrogate fuels have been established for analyses, and combustion and sooting reaction kinetics models have been developed. Methods for predicting the necessary real fluid properties have been developed and essential experiments have have been designed. Verification studies are in progress, and preliminary results from these studies will be presented. The approach has been determined to be feasible, and upon its completion the required methodology for accurate performance and heat transfer CFD analyses for high pressure, tripropellant propulsion systems will be available.

1995 CFD Workshop
NASA/MSFC

PROPELLANT CHEMISTRY FOR CFD APPLICATIONS

R.C. Farmer, P.G. Anderson, Gary C. Cheng

SECA, Inc.
Huntsville, AL

RP-1 COMBUSTION CHEMISTRY

- RP-1 combustion model w/soot formation

- Verify model w/data from literature

- Verify model w/new test data

- Describe real fluid thermodynamic properties

- Add real fluid HC properties to CICM

- Real fluid single element model

    Real fluid HC, H_2, and O_2

    Real fluid tri-propellant

    Additional turbulence models

- Account for radiation

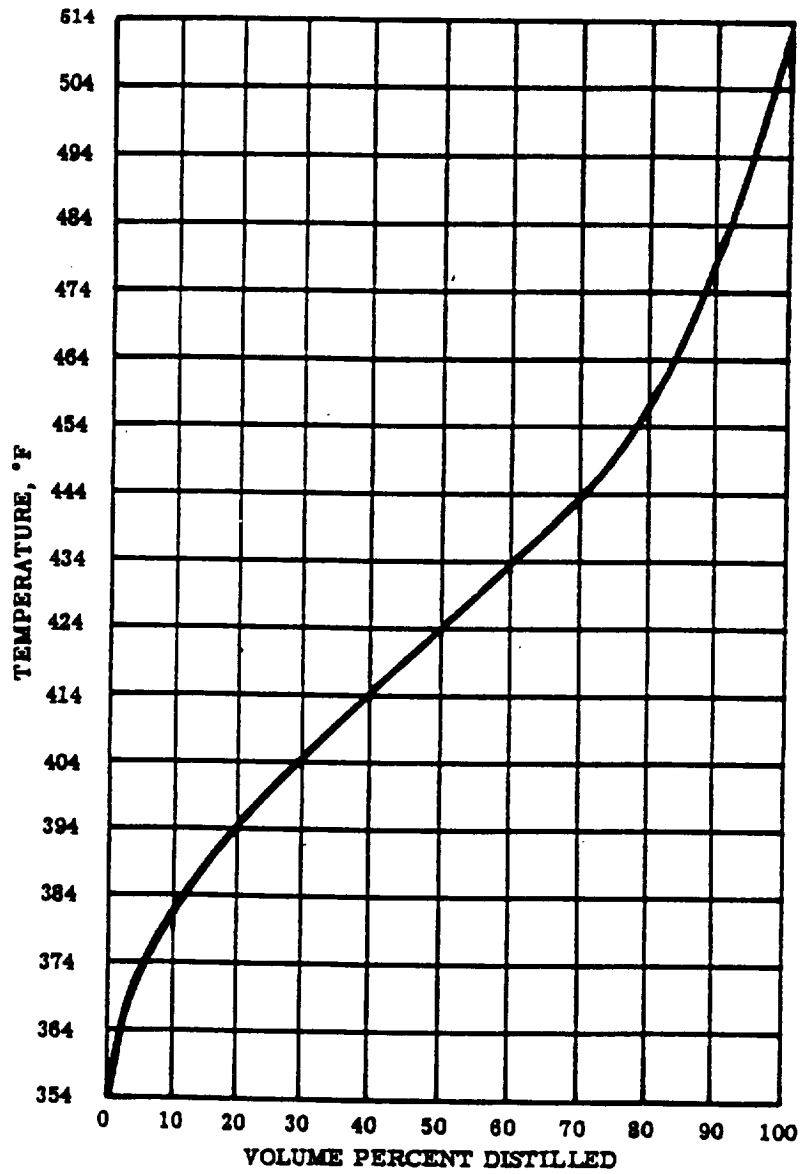- Assemble elements to make injector model

RP-1

RP-1 is a straight run kerosene fraction which is subjected to acid washing and sulfur dioxide extraction. The mean molecular weight is about 174, and the H/C ratio is about 1.9. This implies that RP-1 is a multicomponent hydrocarbon fuel without a specified species distribution.

Composition by Hydrocarbon Type	
Composition	**Volume %**
dinuclear aromatics	2.3
mononuclear aromatics	15.1
dicyclo-paraffins	11.6
monocycyclo-paraffins	33.8
branched-paraffins	15.1
normal paraffins	22.1
	100.0

or

Composition	Volume %
aromatics	17.4
cyclo-paraffins	45.4
paraffins	37.2
	100.0

Distillation Curve for RP-1

HYDROCARBONS ISOLATED FROM ONE REFERENCE PETROLEUM

Molecular Formula	Name	Type	Normal Boiling Point
$C_{10}H_{14}$	1.3-Diethylbenzene	Benzene	181.10
$C_{10}H_{14}$	1-Methyl-3-propylbenzene	Benzene	181.80
$C_{10}H_{14}$	n-Bulylbenzene	Benzene	183.27
$C_{10}H_{18}$	Bicycloparaffin	Bicycloparaffin	183.4
$C_{10}H_{18}$	Bicycloparaffin	Bicycloparaffin	183.7
$C_{10}H_{14}$	1-Methyl-4-propylbenzene	Benzene	183.30
$C_{10}H_{14}$	1, 2-Diethylbenzene	Benzene	183.42
$C_{10}H_{14}$	1,3-Dimethyl-5-ethylbenzene	Benzene	183.58
$C_{10}H_{14}$	1, 4-Diethylbenzene	Benzene	183.78
$C_{10}H_{14}$	1, Methyl-2-propylbenzene	Benzene	184.80
$C_{10}H_{14}$	1, 4-Dimethyl-2-ethylbenzene	Benzene	186.83
$C_{10}H_{18}$	trans-Decahydro-naphthalene	Bicycloparaffin	187.25
$C_{10}H_{14}$	1, 3-Dimethyl-4-ethylbenzene	Benzene	188.20
$C_{10}H_{14}$	1, 2-Dimethyl-4-ethylbenzene	Benzene	189.48
$C_{10}H_{16}$	Tricyclo (3.3.1.1)- decane	Tricycloparaffin	190
$C_{10}H_{14}$	1, 3-Dimethyl-2-ethylbenzene	Benzene	190.01
$C_{10}H_{12}$	1-Methylindan	Aromatic-cycloparaffin	190.6
$C_{10}H_{12}$	2-Methylindan	Aromatic-cycloparaffin	191.4
$C_{10}H_{14}$	1, 2-Dimethyl-3 ethylbenzene	Benzene	193.91
$C_{10}H_{18}$	cis-Decahydro-naphthalene	Bicycloparaffin	195.69
$C_{11}H_{24}$	n-Undecane	Normal paraffin	195.89
$C_{10}H_{14}$	1,2,4,5-Tetramethyl-benzene	Benzene	196.80
$C_{10}H_{14}$	1,2,3,5-Tetramethyl-benzene	Benzene	198.00
$C_{11}H_{20}$	Bicycloparaffin	Bicycloparaffin	202.5
$C_{11}H_{16}$	1-Methyl-3-n-butylbenzene	Benzene	204.1
$C_{10}H_{14}$	1,2,3,4-Tetramethyl-benzene	Benzene	205.04
$C_{10}H_{12}$	4-Methylindan	Aromatic-cycloparaffin	205.5

834

HYDROCARBONS ISOLATED FROM ONE REFERENCE PETROLEUM (Continued)

Molecular Formula	Name	Type	Normal Boiling Point
$C_{11}H_{16}$	1,3-Dimethyl-4-n propylbenzene	Benzene	206.6
$C_{10}H_{12}$	1,2,3,4-Tetra-hydronaphthalene	Aromatic-cycloparaffin	207.57
$C_{11}H_{16}$	1,2-Dimethyl-4-n-propylbenzene	Benzene	208.5
$C_{11}H_{16}$	Trimethylethylbenzene	Benzene	212.3
$C_{12}H_{26}$	n-Dodecane	Normal paraffin	216.28
$C_{10}H_8$	Naphthalene	Dinuclear aromatic	217.96
$C_{11}H_{14}$	2-Methyl-(1,2,3,4-tetra-hydronaphthalene)	Aromatic-cycloparaffin	220.7
$C_{11}H_{14}$	6-Methyl-(1,2,3,4-tetra-hydronaphthalene)	Aromatic-cycloparaffin	229.03
$C_{14}H_{30}$	2,6,10-Trimethylundecane	Branched paraffin	231
$C_{11}H_{14}$	5-Methyl-(1,2,3,4-tetra-hydronaphthalene)	Aromatic-cycloparaffin	234.35
$C_{13}H_{28}$	n-Tridecane	Normal paraffin	235.43
$C_{11}H_{10}$	2-Methylnaphthalene	Dinuclear aromatic	241.05
$C_{11}H_{10}$	1-Methylnaphthalene	Dinuclear aromatic	244.64
$C_{15}H_{32}$	2,6,10-Trimethyldodecane	Branched paraffin	249
$C_{14}H_{30}$	n-Tetradecane	Normal paraffin	253.52
$C_{12}H_{10}$	Biphenyl	Dinuclear aromatic	255.0
$C_{13}H_{12}$	2-Methylbiphenyl	Dinuclear aromatic	255.3
$C_{12}H_{12}$	2-Ethylnaphthalene	Dinuclear aromatic	257.9
$C_{12}H_{12}$	1-Ethylnaphthalene	Dinuclear aromatic	258.7
$C_{12}H_{12}$	2,6-Dimethylnaphthalene	Dinuclear aromatic	262
$C_{12}H_{12}$	2,7-Dimethylnaphthalene	Dinuclear aromatic	263
$C_{12}H_{12}$	1,7-Dimethylnaphthalene	Dinuclear aromatic	263
$C_{12}H_{12}$	1,6-Dimethylnaphthalene	Dinuclear aromatic	263
$C_{12}H_{12}$	1,3-Dimethylnaphthalene	Dinuclear aromatic	265
$C_{12}H_{12}$	1,5-Dimethylnaphthalene	Dinuclear aromatic	265
$C_{14}H_{14}$	2,5-Dimethylbiphenyl	Dinuclear aromatic	267
$C_{15}H_{16}$	Trimethylbiphenyl	Dinuclear aromatic	267
$C_{16}H_{18}$	Tetramethylbiphenyl	Dinuclear aromatic	267

RP-1 SURROGATE FUELS			
Formula	Species	Mol %	NBP(°C)
$C_{13}H_{12}$	methylbiphenyl	17.4	255
$C_{12}H_{24}$	n-heptylcyclopentane	45.4	224
$C_{12}H_{28}$	n-tridecane	37.2	235
		100.0	

$$M_{wt} = 173.9$$
$$H/C = 1.922$$

Note: Critical pressure for RP-1 is 340 psia, and critical temperature is 679°K.

RP-1 COMBUSTION PROPERTIES

HEAT OF COMBUSTION

$$HOC = -18640 \ (Btu/lbm) = -10.346 \ (kcal/gm)$$

HEAT OF VAPORIZATION

$$HOV = 106 \ (Btu/lbm)$$

HEAT OF FORMATION (HOF)

To determine a HOF for mixtures, an effective molecular formula must be specified **and** used to evaluate the HOF. Frequently, an arbitrary molecular weight of 100 gms is assumed for a basis for thermodynamic calculations.

H/C	HOF(kcal/100gm)	Source	Implied HOC (kcal/gm)
1.8624	-36.01	Lockheed	-10.287
1.90	-41.6	SAIC	-10.305
2.0	-44.36	Aerojet '78	-10.403
1.9063	-42.0	TMX - 1783	-10.305
1.9423	-33.068(v)	SP-273	-10.441(v)
1.9423	-38.946(l)	SP-273	-10.382(l)
1.922	-39.915	Surrogate Fuel	-10.346

SPECTROSCOPIC ANALYSIS OF H-1 GAS GENERATOR EXHAUST GASES			
Compound	Sample #1	Sample #3	Sample #4
CO	26.15*	36.82	37.93
CO_2	8.44	8.86	9.96
H_2O	2.66	1.14	0.85
H_2	1.97	2.22	2.34
CH_4	2.92	4.20	4.40
C_2H_2	4.16	5.62	4.27
C_2H_4	5.93	6.93	7.70
C_2H_6	0.72	...	...
Propyne	0.69	0.30	0.41
Propene	2.84	3.15	3.95
Diacetylene	0.12	0.08	0.21
1,3 Butadiene	1.30	1.32	1.52
2 Butene	1.57	0.80	1.16
- Butene	...	1.76	0.54
1.5 Hexadyne	1.98	1.58	1.73
3 Methyl Pentene -1	...	0.71	0.57
Cyclopentene	...	0.74	0.99
1,2,3 trimethylcyclopantane	...	1.14	0.97
Benzene	...	1.05	1.20
Ethyl Benzene	...	0.99	0.36
Carbon	...	5.22	2.06
RP-1	38.51	17.58	17.14

* Weight percentage composition of combustion products

Generalized Combustion Kinetics Model

I. **PURE PYROLYSIS**	$\begin{bmatrix} ALIPHATICS \\ AROMATICS \end{bmatrix} \rightarrow \begin{bmatrix} C_2H_2 \\ CH_4 \\ C_2H_4 \\ H_2 \end{bmatrix} \equiv INTERMEDIATES$	**V.** **SOOT FORMATION** — $\begin{bmatrix} ALIPHATICS \\ AROMATICS \\ INTERMEDIATES \end{bmatrix} \rightarrow SOOT$
II. **OXIDATIVE PYROLYSIS**	$\begin{bmatrix} ALIPHATICS \\ AROMATICS \end{bmatrix} + \begin{bmatrix} OH \\ O_2 \end{bmatrix} \rightarrow \begin{bmatrix} CH_4 \\ C_2H_2 \\ C_2H_4 \end{bmatrix} + \begin{bmatrix} H_2 \\ C_xH_yO_z \end{bmatrix}$	**VI.** **SOOT GASIFICATION** — $SOOT + \begin{bmatrix} O_2 \\ CO \\ CO_2 \\ H_2O \\ H_2 \\ OH \end{bmatrix} \rightarrow \begin{bmatrix} CO \\ CO_2 \\ CH_4 \end{bmatrix}$
III. **PARTIAL OXIDATION**	$\begin{bmatrix} ALIPHATICS \\ AROMATICS \\ CH_4 \\ C_2H_2 \\ C_2H_4 \end{bmatrix} + \begin{bmatrix} O_2 \\ OH \end{bmatrix} \rightarrow \begin{bmatrix} H_2 \\ CO \\ C_xH_yO_z \\ CO_2 \\ H_2O \end{bmatrix}$	**VII.** **NO$_x$ FORMATION** — BOUND NITROGEN AND/OR FUEL RICH NITROGEN CONVERSION: $FUEL + \begin{bmatrix} FBN \\ N_2 \end{bmatrix} \rightarrow \begin{bmatrix} HCN \\ NH_i \end{bmatrix}$; $\begin{bmatrix} HCN \\ NH_i \end{bmatrix} + \begin{bmatrix} O_2 \\ OH \end{bmatrix} \rightleftharpoons \begin{bmatrix} NO \\ NO_2 \end{bmatrix}$ — THERMAL FIXATION: $\begin{bmatrix} N_2 \\ O_2 \\ N \end{bmatrix} + \begin{bmatrix} O \\ N \\ OH \end{bmatrix} \rightarrow NO + \begin{bmatrix} N \\ O \\ H \end{bmatrix}$
IV. **ELEMENTARY STEPS TO COMPLETION**	$\begin{bmatrix} CO \\ H_2 \\ C_xH_yO_z \\ H_2O_2 \end{bmatrix} + \begin{bmatrix} O \\ H \\ OH \\ CHO \\ HO_2 \end{bmatrix} \rightleftharpoons \begin{bmatrix} H_2O \\ CO_2 \end{bmatrix}$	

Soot Model

Initial Polycyclic Aromatic Hydrocarbon (PAH) Formation

- Pyrolysis and combustion of fuel to form benzene and acetylene
- Implicit finite-rate chemistry

Planar PAH Growth

- HACA
  - Hydrogen abstraction, carbon addition (through reactions with acetylene)
- Oxidation
  - Implicit finite-rate chemistry using reactions from Frenklach, et al
- Properties for PAH compounds
  - Benson's group contribution method to obtain C_p for ideal gases
  - Benson data in tabular form for $300K < T < 1500K$
  - Used CEC data for selected species to generate group contributions as functions of temperature for $300K < T < 5000K$
  - Generated needed C_p data in CEC format
  - $S°_{298}$ corrected for symmetry and optical isomers using Benson's data.

840

Soot Model (Cont.)

Aerosol Dynamics Based on Frenklach and Harris's "Method II"
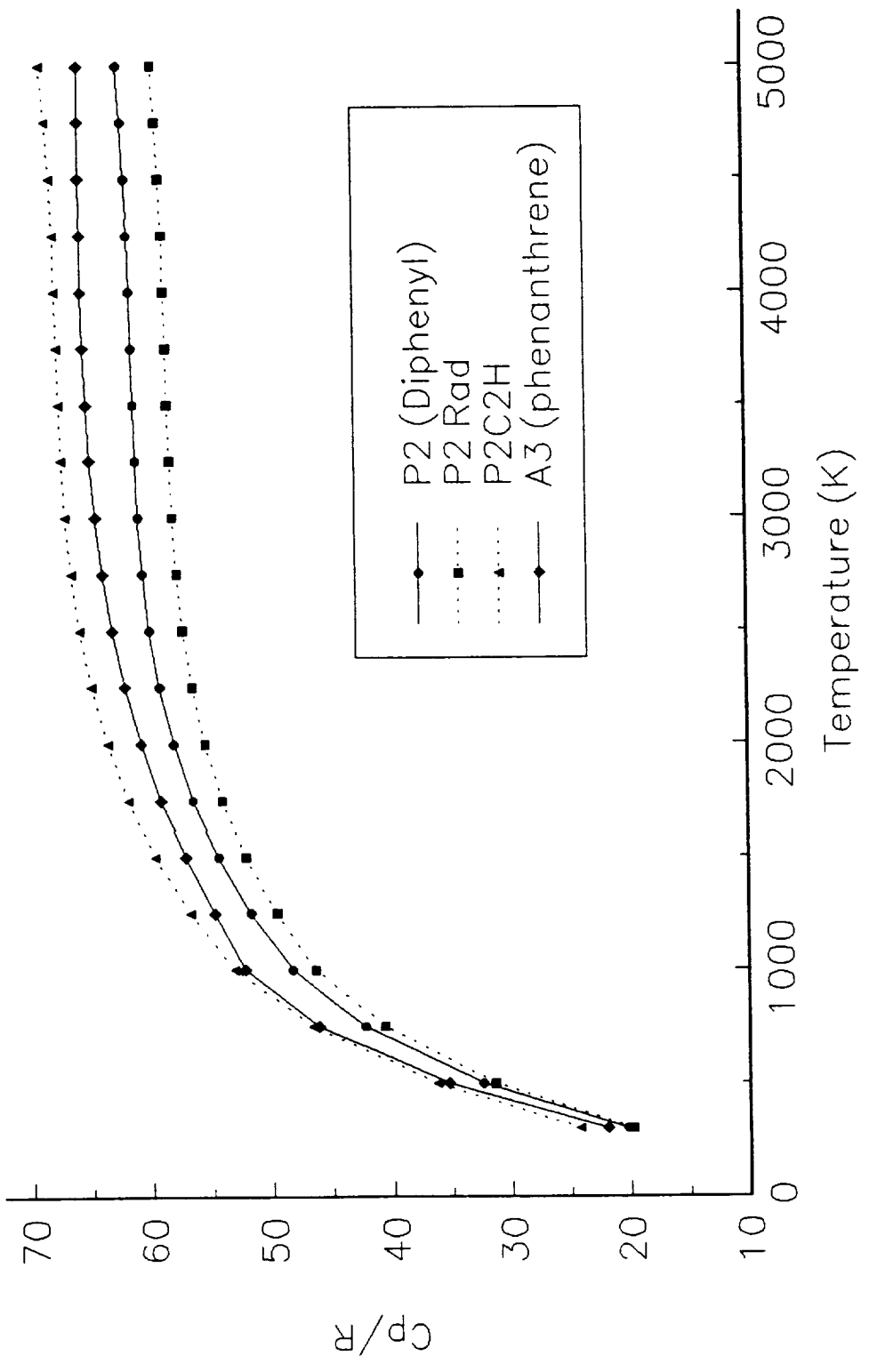
- Method of moments
- Nucleation
    - Collisions of planar PAH's to form 3-D particles
- Coagulation
    - Collisions of 3-D particles to form larger particles

Surface Growth on 3-D Particles

- Collisions with planar PAH's
- HACA
- Oxidation by reactions with O_2 and OH

Model provides soot formation and oxidation rates to be used to develop a quasiglobal reaction rate for soot production.

Cp's for Diphenyl Compounds
Dotted lines are synthesized data

842

Toluene and Iso-Octane Quasiglobal Kinetics Model

GLOBAL MECHANISM	A	B	E/R	POWER DEPENDENCIES
Toluene (aromatic)				
$C_7H_8 \rightarrow 3.5\ C_2H_2 + 0.5\ H_2$	1.7982 E10	0	3.5000 E4	$[C_7H_8]^{1.0}$
$C_7H_8 + 3.5\ O_2 \rightarrow 7\ CO + 4\ H_2$	4.4963 E9	1	2.6785 E4	$[C_7H_8]^{0.5}[O_2]^{1.0}$
$C_7H_8 + OH \rightarrow 3.25\ C_2H_2 + 0.5\ CO + 0.5\ H_2O + 0.75\ H_2$	1.4721 E17	0	1.4510 E4	$[C_7H_8]^{1.0}[OH]^{1.0}$
Iso-Octane (aliphatic)				
$C_8H_{18} \rightarrow 4\ C_2H_4 + H_2$	1.0473 E12	0	3.5229 E3	$[C_8H_{18}]^{1.0}$
$C_8H_{18} + 4\ O_2 \rightarrow 8\ CO + 9\ H_2$	1.2900 E9	1	2.5160 E4	$[C_8H_{18}]^{0.5}[O_2]^{1.0}$
$C_8H_{18} + OH \rightarrow 3.75\ C_2H_4 + 0.5\ CO + 0.5\ H_2O + 1.5\ H_2$	2.0000 E17	0	1.4919 E4	$[C_8H_{18}]^{1.0}[OH]^{1.0}$
Secondary Fuel				
$C_2H_2 + 6\ OH \rightarrow 4\ H_2O + 2\ CO$	4.7850 E15	0	1.3883 E4	$[C_2H_2]^{1.0}[OH]^{1.0}$
$C_2H_2 + 2\ OH \rightarrow 2\ CO + 2\ H_2$	2.8000 E16	0	0	$[C_2H_2]^{1.0}[OH]^{1.5}$
$C_2H_4 + 4\ OH \rightarrow 2\ CO + 2\ H_2O + 2\ H_2$	2.2020 E15	0	1.2079 E4	$[C_2H_4]^{1.0}[OH]^{1.0}$
$C_2H_4 + 2\ OH \rightarrow 2\ CO + 3\ H_2$	2.1129 E27	-3.0	6.3062 E3	$[C_2H_4]^{1.0}[OH]^{1.5}$
$C_2H_2 + O_2 = 2\ CHO$	4.0000 E12	0	1.4092 E4	$[C_2H_2]^{1.0}[O_2]^{1.0}$
$C_2H_4 + M = C_2H_2 + H_2 + M$	2.0893 E17	0	3.9810 E4	$[C_2H_4]^{1.0}[M]^{1.0}$
Soot Parameters				
C_7H_8 = $HC \rightarrow$ soot	4.0465 E14	-2.0	1.6110 E4	$[HC]^{1.45}[O_2]^{-0.5}$
i = A	2.000 E1	0	1.5090 E4	As indicated by the
B	4.4600 E-3	0	7.6490 E3	equation for [soot]
T	1.5100 E5	0	4.8820 E4	
Z	2.1300 E1	0	-2.0630 E3	

SOOT PARAMETERS

$$soot + O_2 \rightarrow CO_2$$

$$12 P_{O_2} A_t \left[\frac{K_A X}{1 + K_Z P_{O_2}} + K_B (1-X) \right]$$

$$X = \left[1 + K_T / (K_B P_{O_2}) \right]^{-1}$$

$$K_i = A_i \exp \{ -E_i / RT \}, \quad i = A, B, T, Z$$

where $A_t = 6 [C_s/(\rho_s \cdot D_s)]$ $(cm^2$ surface$/cm^3)$,

P_{O2} = partial pressure of O_2 (atm),

$C_s = (g \cdot$ soot$/cm^3$ of gas$)$, $\rho_s = (g \cdot$ soot$/cm^3$ of soot$)$,

D_s = diameter of soot (cm),
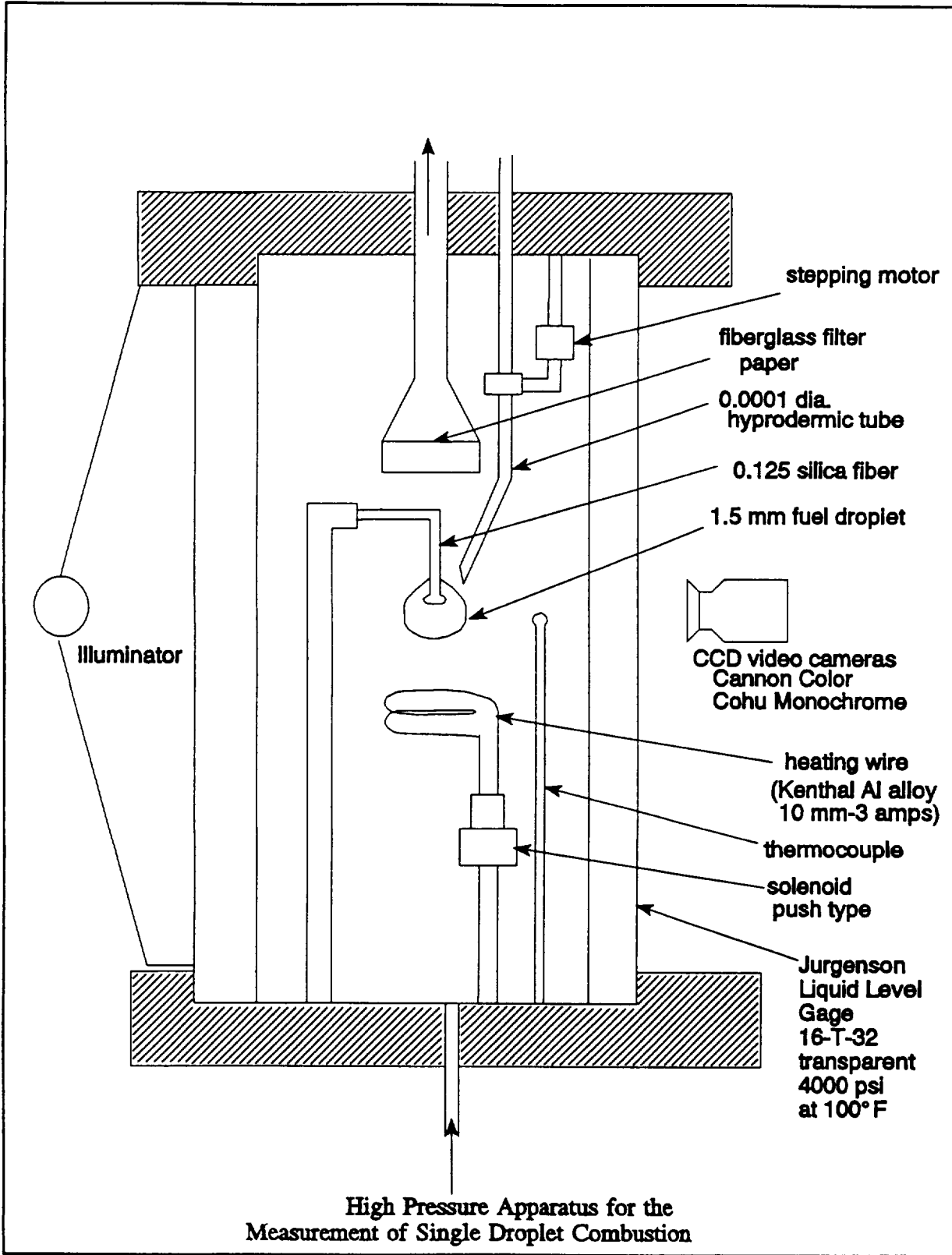
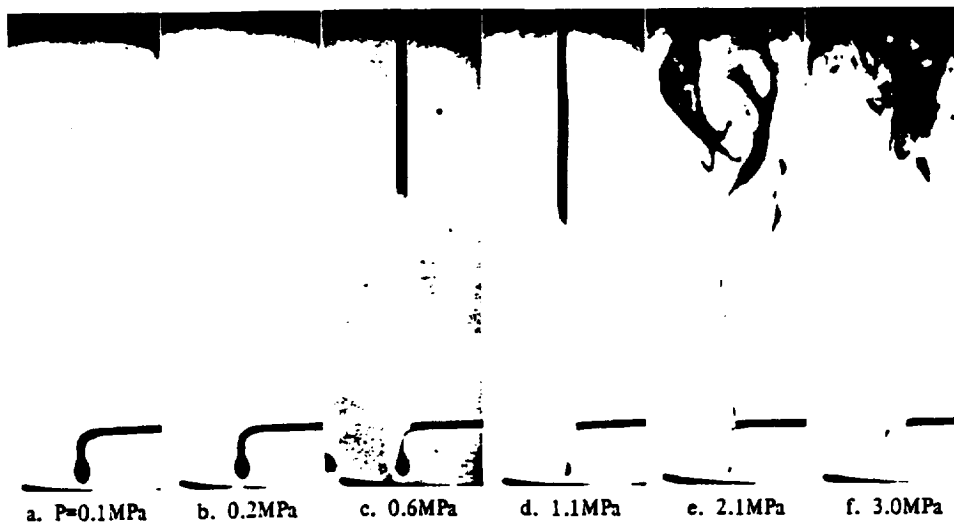[soot] = mass of soot/volume of gas (g/cm^3).

Elementary Reactions

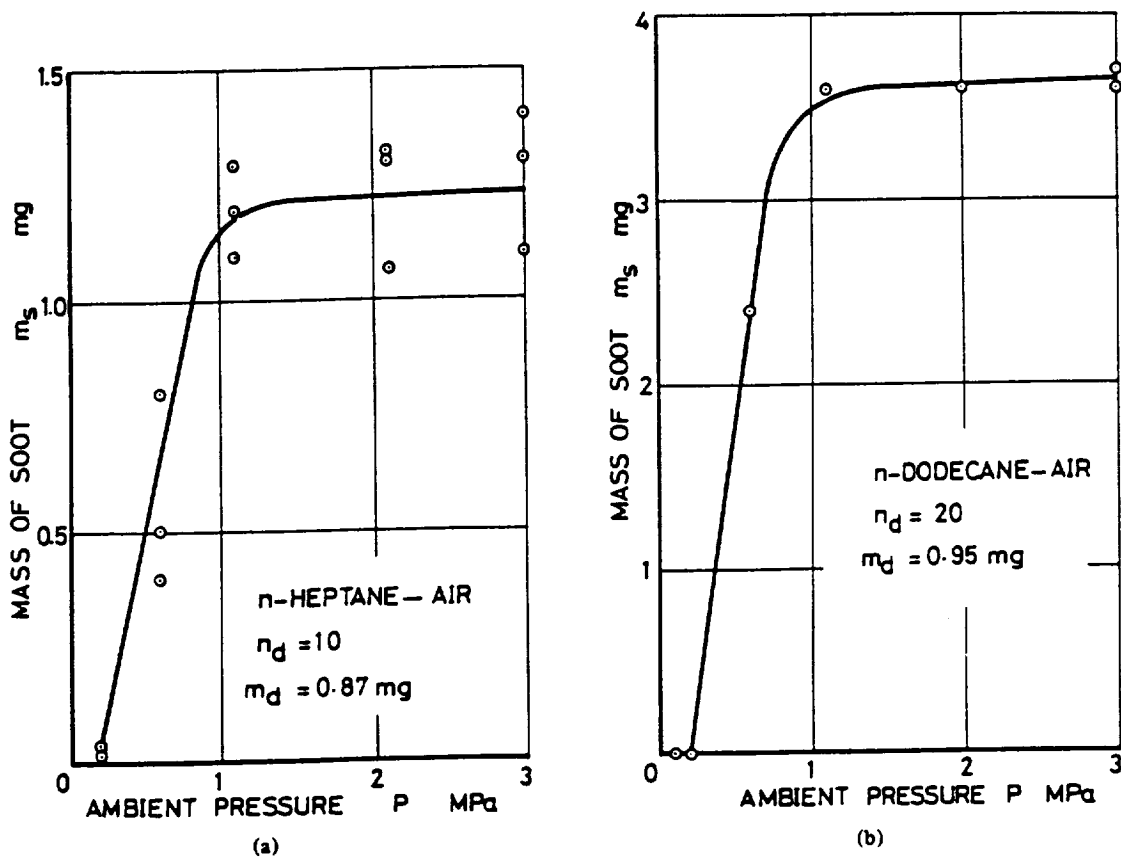| ELEMENTARY MECHANISM	A	B	E/R
Wet CO Mechanism			
$H_2 + O_2 = OH + OH$	1.7000 E13	0	2.4070 E4
$OH + H_2 = H_2O + H$	2.1900 E13	0	2.5900 E3
$OH + OH = O + H_2O$	6.0230 E12	0	5.5000 E2
$O + H_2 = H + OH$	1.8000 E10	1.0	4.4800 E3
$H + O_2 = O + OH$	1.2200 E17	-0.91	8.3690 E3
$M + O + H = OH + M$	1.0000 E16	0	0
$M + O + O = O_2 + M$	2.5500 E18	-1.0	5.9390 E4
$M + H + H = H_2 + M$	5.0000 E15	0	0
$M + H + OH = H_2O + M$	8.4000 E21	-2.0	0
$CO + OH = H + CO_2$	4.0000 E12	0	4.0300 E3
$CO + O_2 = CO_2 + O$	3.0000 E12	0	2.5000 E4
$CO + O + M = CO_2 + M$	6.0000 E13	0	0

RP-1 COMBUSTION VERIFICATION EXPERIMENTS

Criteria: Minimize Effect of Turbulent Mixing

- Single Drop Combustion - LSU

- Well Stirred Reactor - Exxon

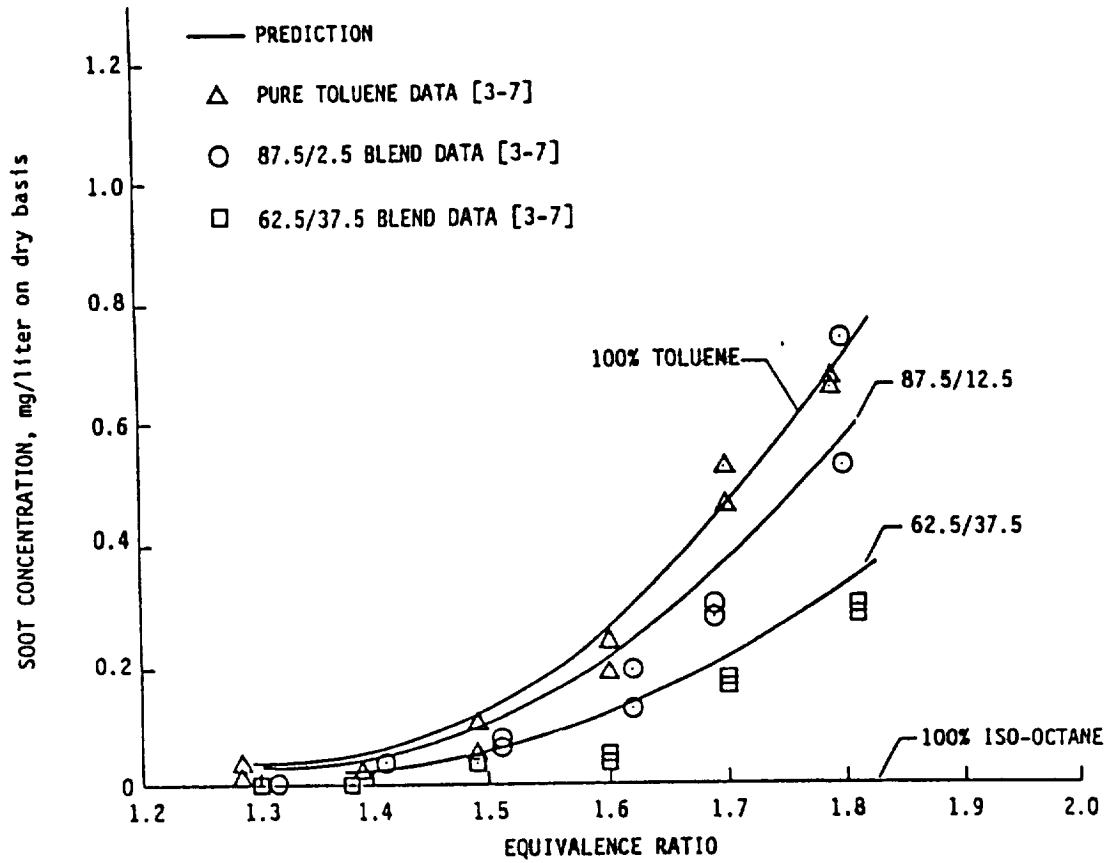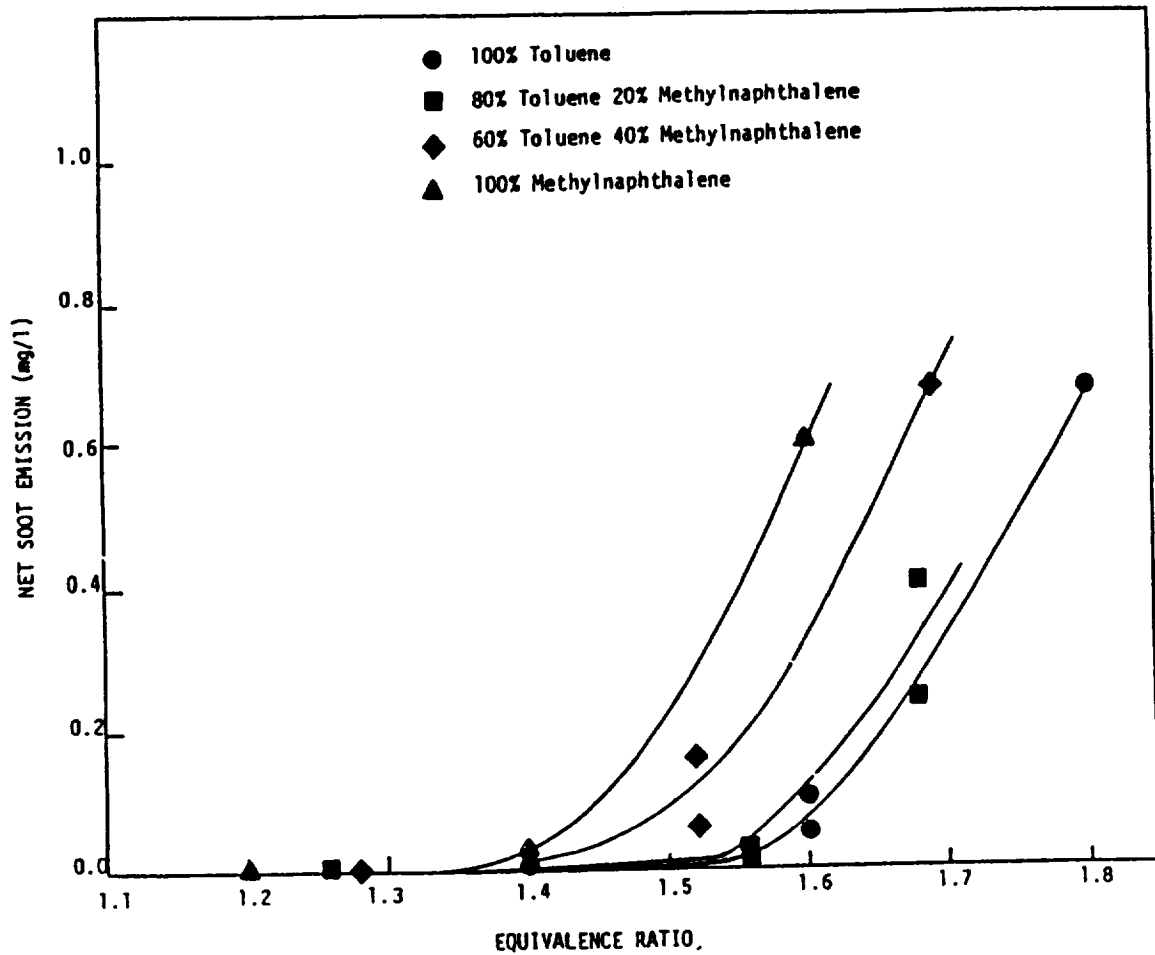- Rocket Test Motor - General Dynamics Corporation (GDC)

846

stepping motor

fiberglass filter
paper

0.0001 dia.
hyprodermic tube

0.125 silica fiber

1.5 mm fuel droplet

Illuminator

CCD video cameras
Cannon Color
Cohu Monochrome

heating wire
(Kenthal Al alloy
10 mm-3 amps)

thermocouple

solenoid
push type

Jurgenson
Liquid Level
Gage
16-T-32
transparent
4000 psi
at 100° F

High Pressure Apparatus for the
Measurement of Single Droplet Combustion

847

a. P=0.1MPa   b. 0.2MPa   c. 0.6MPa   d. 1.1MPa   e. 2.1MPa   f. 3.0MPa

Photograph of Burning Droplets (n-heptane in air).

(a)

n-HEPTANE — AIR

$n_d = 10$

$m_d = 0.87$ mg

(b)

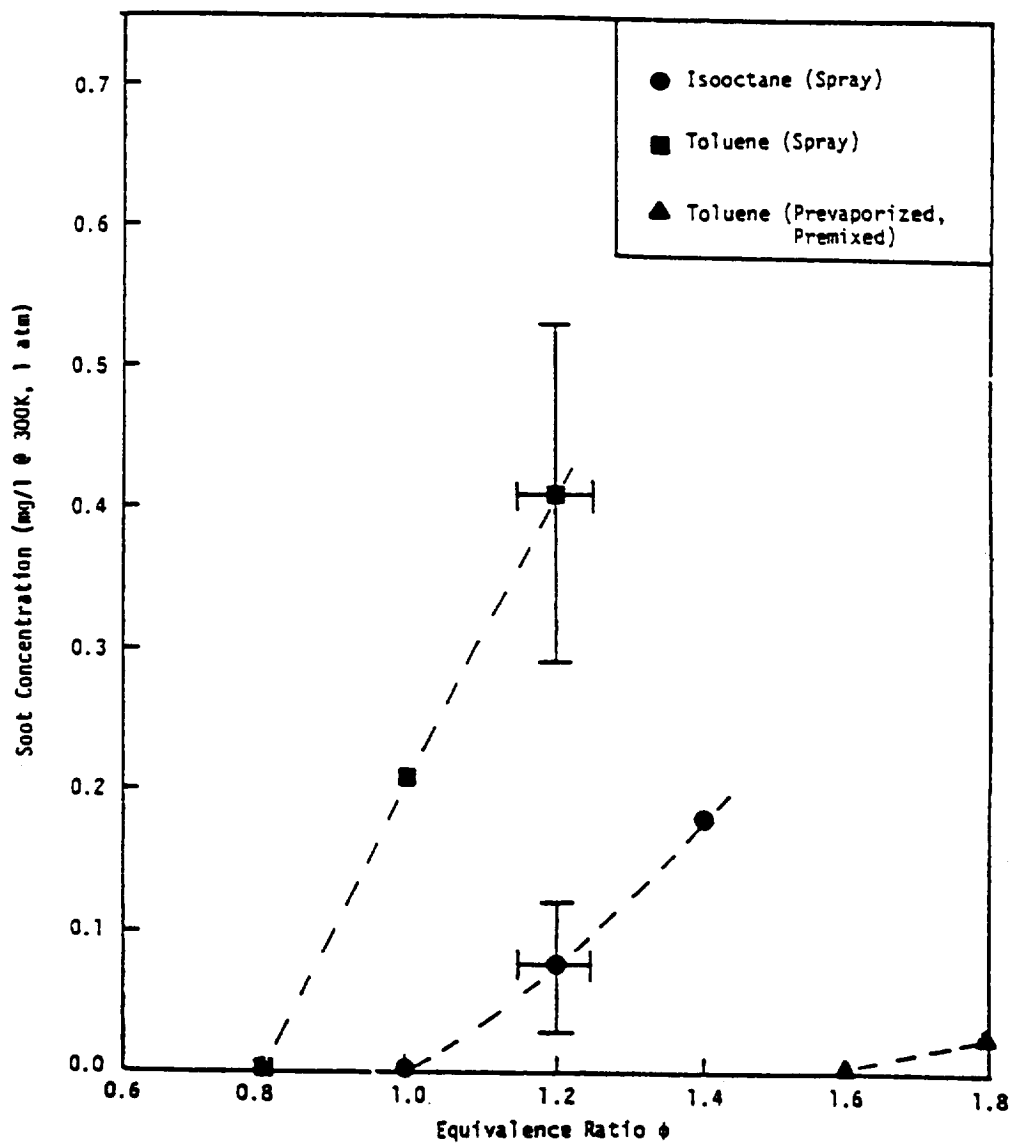n-DODECANE — AIR

$n_d = 20$

$m_d = 0.95$ mg

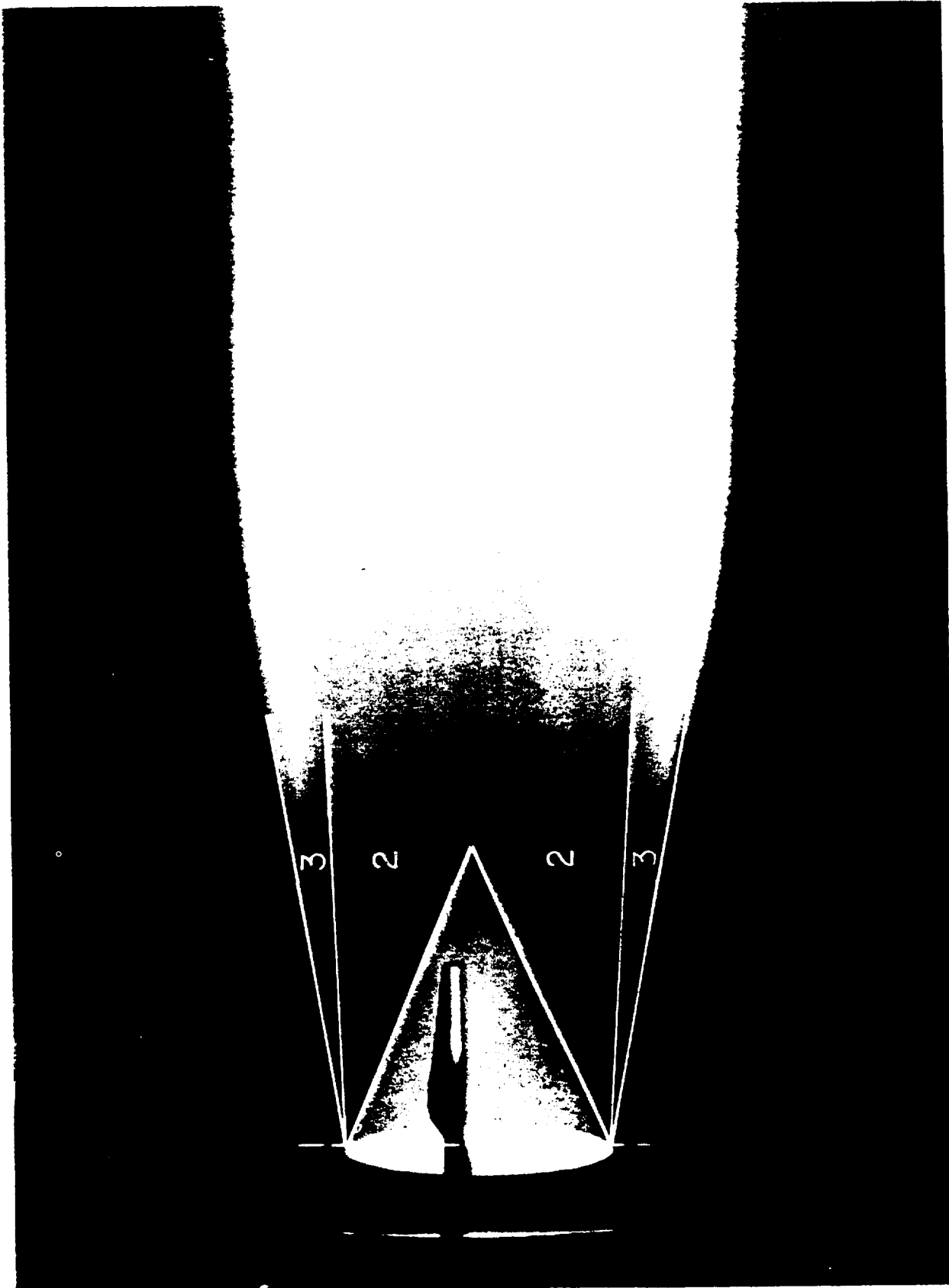Effect of Pressure: (a) n-heptane; (b) n-dodecane.

848

Comparison Of Quasiglobal Model Prediction Of Soot Emissions
With Experimental Data For Toluene And Toluene/Iso-Octane
Blends. Computation: Well-Stirred Reactor; Experiment:
Jet-Stired Combustor.

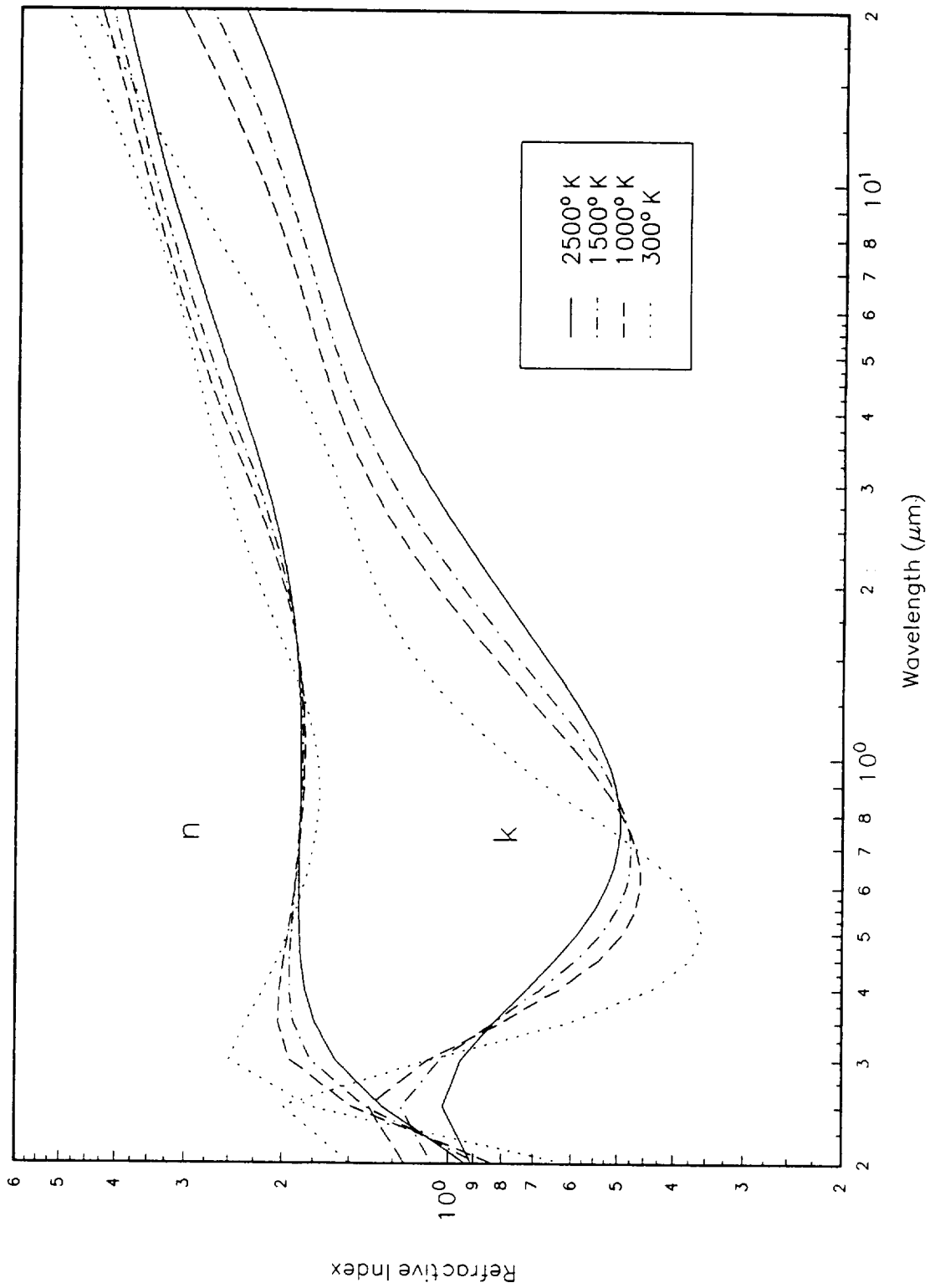JSC Soot Emissions For Toluene/Methylnaphthalene Blends;
T = 1900 K; τ = 3 ms.

Dependence Of Soot Concentration On Equivalence Ratio; Ratio; Atomization Air = 15 g/min/nozzle; Indicated Temperature = 1900±35K.
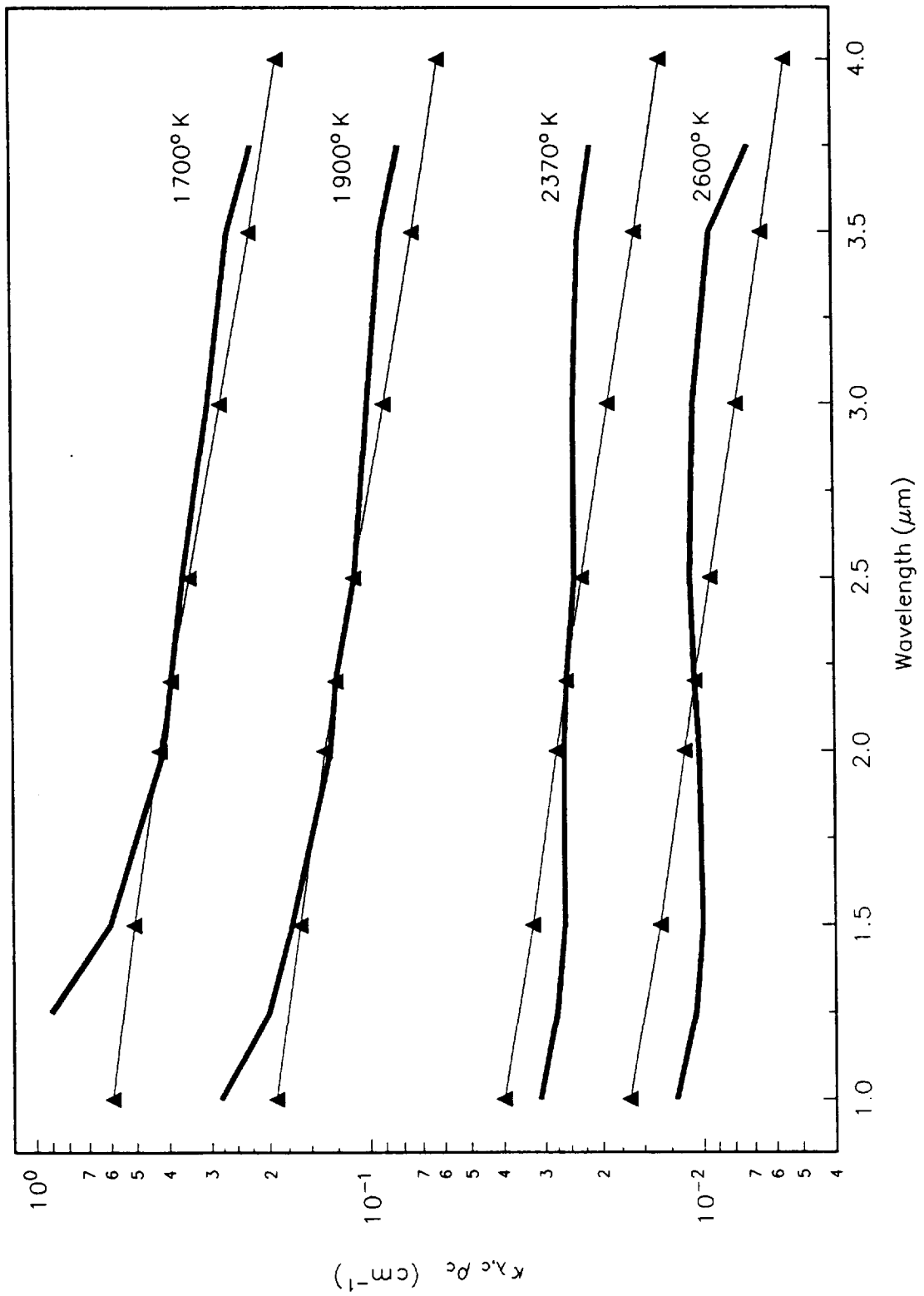
Photograph of the exit flow at an exit pressure of 2 atm. Region 1 is the undisturbed cone, region 2 is the Prandtl-Meyer expansion zone, and region 3 is the mixing zone. The spectrometer line of sight is indicated by a dotted line.
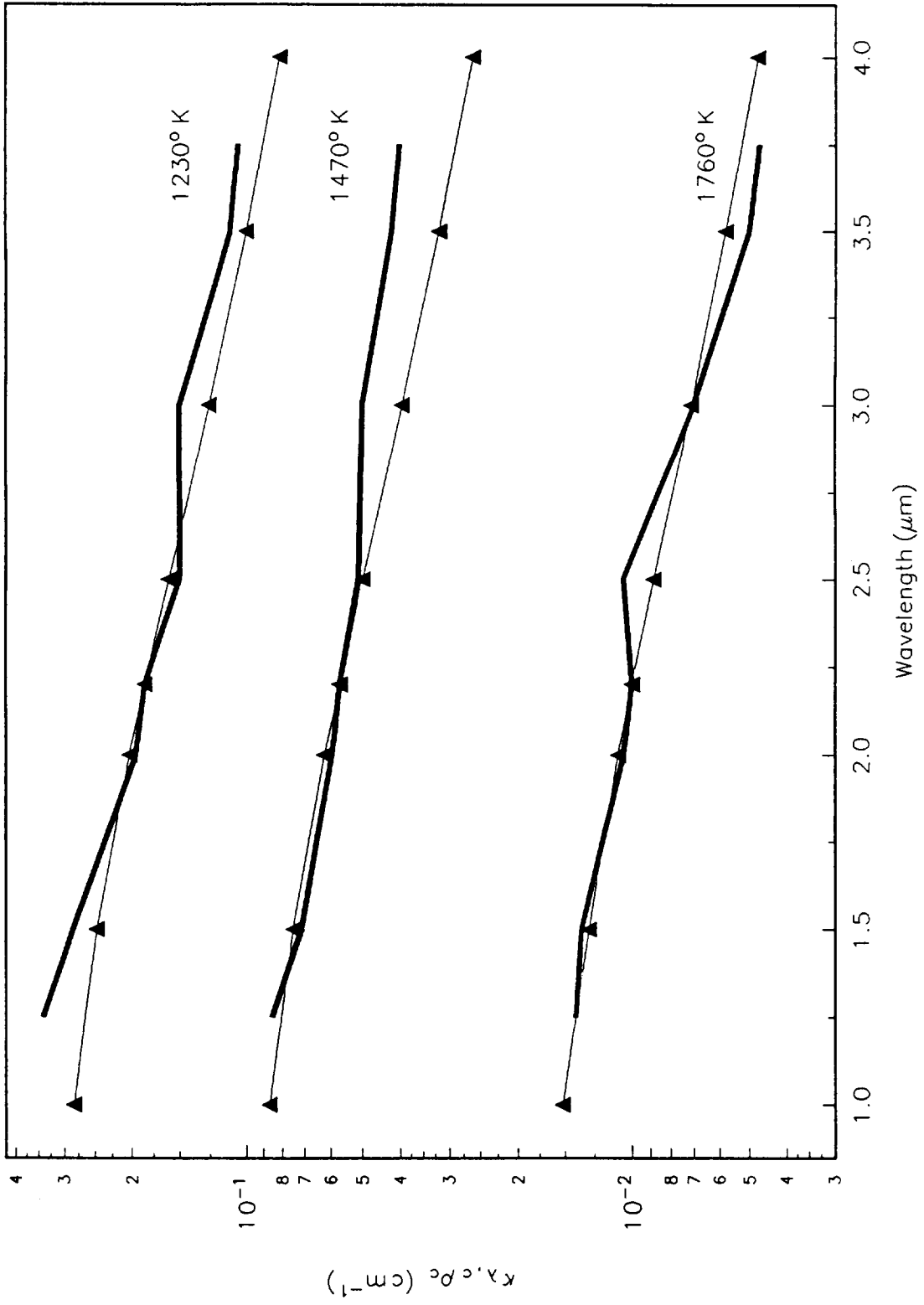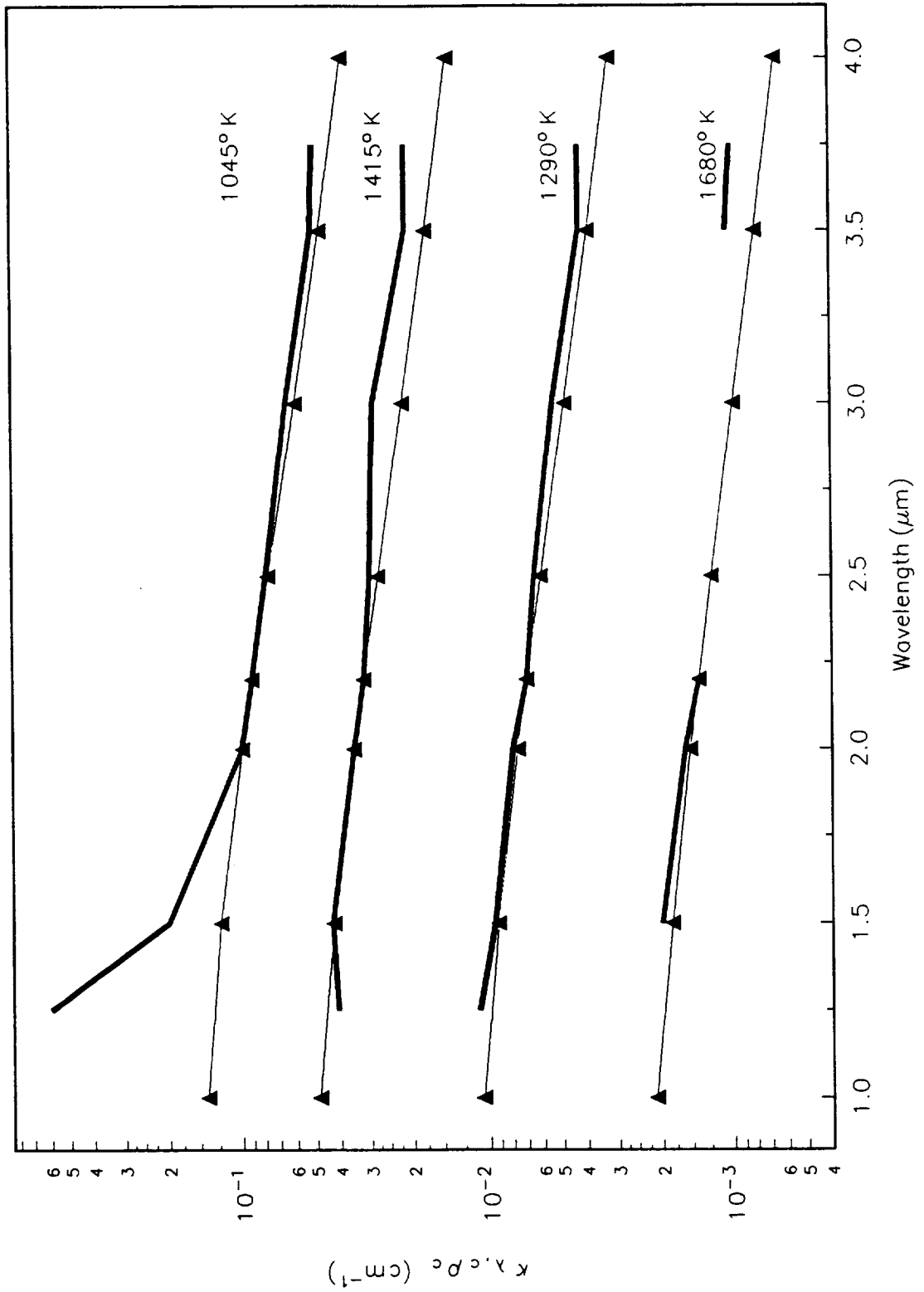
AREA RATIO= 1.50

Wavelength (μm)

$\kappa_{\lambda c}\, \rho_c$ (cm^{-1})

1700° K

1900° K

2370° K

2600° K

854

AREA RATIO = 3.0

1230° K

1470° K

1760° K

Wavelength (μm)

$K_{\lambda,c}\rho_c$ (cm^{-1})

AREA RATIO = 5.25

1045° K

1415° K

1290° K

1680° K

Wavelength (μm)

$\kappa_{\lambda,c}\,\rho_c$ (cm^{-1})

Soot Density from GDC Experiments				
$\kappa_\lambda \rho_c$ (cm⁻¹)	T(°K)	O/F	ρ_c(gm/cc)	κ_λ(cm²/gm)
0.1400E-02	1680.0000	1.8500	0.1087E-06	0.1288E+05
0.7000E-02	1415.0000	1.6000	0.5200E-06	0.1346E+05
0.3200E-01	1290.0000	1.5000	0.2343E-05	0.1366E+05
0.9000E-01	1045.0000	1.3300	0.6531E-05	0.1378E+05
0.1000E-01	1760.0000	1.6000	0.7886E-06	0.1268E+05
0.5700E-01	1470.0000	1.4500	0.4268E-05	0.1335E+05
0.1850E+00	1230.0000	1.2500	0.1348E-04	0.1373E+05
0.1050E-01	2600.0000	2.1000	0.9944E-06	0.1056E+05
0.2550E-01	2370.0000	1.8500	0.2295E-05	0.1111E+05
0.1250E+00	1900.0000	1.5000	0.1015E-04	0.1232E+05
0.3900E+00	1700.0000	1.4000	0.3040E-04	0.1283E+05

Rayleigh Theory for Small Particles
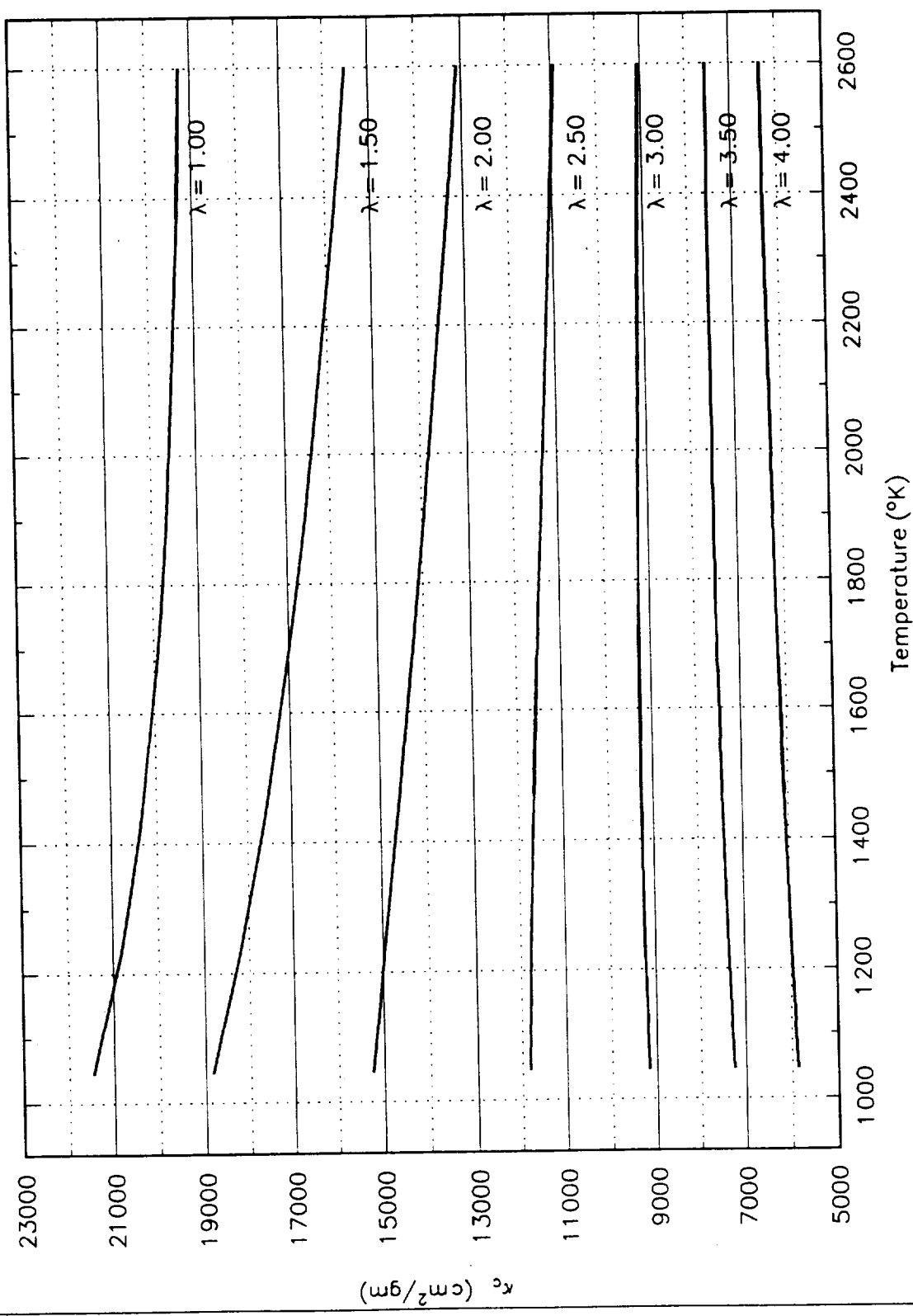
$$K_\lambda = \left(\frac{36\pi nk}{(n^2-k^2+2)^2 + 4n^2k^2} \right) \left(\frac{\rho_c}{\rho_o} \right) \left(\frac{1}{\lambda} \right)$$

K_λ(cm⁻¹) $= \kappa_\lambda \rho_c =$ linear absorption coefficient

κ_λ(cm²/gm) $=$ mass absorption coefficient

ρ_c (gm/cc of volume) $=$ soot density

ρ_o (gm/cc of soot) $=$ bulk soot density

858

CONCLUSIONS:

Real fluid RP-1 and H_2 combustion kinetics models will be incorporated into several element models and evaluated.

The element models will be assembled into an entire injector model and the motor performance evaluated.