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DETONATION TUBE CONDITIONS FOR SIMULATING: RP-1/LOX AND VARIOUS AMINE/ N_2O_4 ROCKET ENGINE PLUMES

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This memorandum documents the running conditions necessary to simulate RP-1/LOX and various Amine/N_2O_4 rocket engine plumes using the Grumman Detonation Tube Facility to reproduce the chemical and thermodynamic state properties of the rocket engine combustion chamber. Absolute measurements of shortwave infrared (SWIR) radiation from a variety of plumes are being obtained under contract to the Defense Advanced Research Projects Agency (DARPA). The propellant combinations being investigated are UDMH/N_2O_4 , A-50/N_2O_4, RP-1/LOX, and H_2/O_2

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DETONATION TUBE CONDITIONS FOR SIMULATING RP-1/LOX AND VARIOUS AMINE/N_2O_4 ROCKET ENGINE PLUMES†

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November 1973

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LIST OF SYMBOLS

a	speed of sound
A	area
H	enthalpy
LM	NASA/Grumman Lunar Module
mw	molecular weight
M	Mach number
O/F	oxidizer to fuel weight ratio
psia	pounds per square inch absolute
P	pressure
T	temperature
U	velocity
γ	ratio of specific heats
ρ	density

<u>Subscripts</u>

1	undetonated gas in driven tube
2	driven tube gas behind incident detonation wave after reaction is completed
5	stagnation conditions behind reflected detonation wave
c	rocket engine simulated chamber condition (usually = shock tube region 5)
D	refers to detonation wave
e	nozzle exit plane
R	refers to reflected shock wave
*	sonic condition

Propellant Terminology

A-50	50% blend by weight of hydrazine and UDMH
LOX	liquid oxygen
RP-1	kerosene-type rocket fuel
UDMH	unsymmetrical dimethyl hydrazine

INTRODUCTION

The Rocket Plume Simulation Facility of the Grumman Research Department employs a detonation tube to reproduce the chemical and state properties of a rocket combustion chamber (Ref. 1). High temperature, high pressure species generated in this manner expand through contoured nozzles into a large chamber, evacuated to simulate a specific altitude. The facility was originally used to simulate the Grumman Lunar Module ascent, descent, and RCS engine plumes (Refs. 1-3), and then for a NASA Space Shuttle proposal investigation (Ref. 4) and a NASA-funded simulation of high pressure hydrogen/oxygen rocket engine plumes (Ref. 5).

Absolute measurements of SWIR radiation (2 to 5 microns) from a variety of plumes are currently being conducted in the Rocket Plume Simulation Facility, under contract to the Defense Advanced Research Projects Agency (Ref. 6). The propellant combinations under investigation include UDMH/N_2O_4, A-50/N_2O_4, RP-1/LOX, and H_2/O_2. Only A-50/N_2O_4 (O/F = 2.0) and H_2/O_2 plumes had previously been simulated, and therefore computations of the detonation tube conditions for the other propellant combinations were required.

This memorandum documents the detonation tube running conditions necessary to simulate an RP-1/LOX plume and various Amine/N_2O_4 plumes. Note that the detonation tube technique simulates a somewhat ideal combustion chamber since it is devoid of O/F gradients resulting from imperfect mixing or film cooling.

DETONATION TUBE TEST CONDITIONS

Actual rocket engine combustion chamber properties for the RP-1/LOX and Amine/N_2O_4 propellant combinations that we simulated are listed in Table 1. The corresponding detonation tube test conditions were computed, following the procedure given in Ref. 1, and are presented in Tables 2 through 9. The computer program of Ref. 7 was used for all these calculations. For several of the propellant combinations, two different initial gas mixtures were determined, both of which would produce the same required combustion chamber properties (compare Tables 3a and 3b, 4a and 4b, 5a and 5b, and 9a and 9b). In all cases except one (Table 8) the chamber pressures to be simulated were chosen to be 200. psia.

DISCUSSION

The theoretical accuracy of the simulated combustion chamber properties can be assessed by comparing Table 1 with Tables 2 through 9. Exact simulation was achieved for the RP-1/LOX and UDMH/N_2O_4 propellant combinations and also for A-50/N_2O_4 at an O/F ratio of 1.7.

For O/F ratios of 2.0 and 2.3, however, the A-50/N_2O_4 simulation (Tables 6 through 8) was imperfect because of thermodynamic constraints (Ref. 1). This resulted in theoretical temperatures between 2 and 5 percent higher than the actual engine theoretical combustion chamber temperatures and also in minor perturbation in the gaseous species concentrations. The nonidealities will be transmitted to the exit plane of a test nozzle, and we therefore compared the equilibrium exit plane properties produced by an engine with those produced by the detonation tube. The results of this comparison are presented in Table 10 and show that the differences in the mole fractions of the major chemical species (H_2O, CO_2, N_2) are negligible and the equilibrium exit plane static temperatures agree to within 5 percent or better. The close agreement between equilibrium static temperature for an ideal engine and the detonation tube simulation is shown in Fig. 1 where both temperatures are displayed against nozzle area ratio for the case of A-50/N_2O_4 at an O/F = 2.0. For the three cases where simulation was imperfect, the difference from the ideal rocket combustion chamber can either be neglected or corrected for in the reduction of experimental data. Alternatively, these three cases may be treated as unique, independent combustion chamber conditions in an investigation to determine the dependence of plume observables upon temperature, species concentration, etc.

In summary, the combustion chamber conditions for RP-1/LOX and a variety of Amine/N_2O_4 propellant combinations may be simulated with the detonation tube. The simulation is either precise or sufficiently close to the actual rocket combustion chamber conditions for the differences to be negligible or easily corrected for.

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TABLE 1 THEORETICAL EQUILIBRIUM CHEMICAL AND STATE COMBUSTION CHAMBER PROPERTIES FOR SEVERAL PROPELLANT COMBINATIONS

Chamber Properties	Propellants							
	RP-1/LOX	$UDMH/N_2O_4$			$A\text{-}50/N_2O_4$			
O/F (wt ratio)	2.7	2.7	2.35	2.0	2.3	2.0	2.0	1.7
Press. (psia)	200.	200.	200.	200.	200.	200.	1000.	200.
Enthalpy $\left(\frac{cal}{gm}\right)$	-175.8	+20.2	+27.6	+36.8	+53.7	+64.1	+64.1	+76.9
Temp (°R)	6226.	5861.	5819.	5627.	5740.	5764.	6064.	5679.
γ	1.1269	1.1299	1.1370	1.1569	1.1308	1.1331	1.1428	1.1439
mole. wt	23.287	23.484	22.451	21.154	23.159	22.239	22.570	21.090
Mole Fractions (all gaseous)								
CO	0.30304	0.12273	0.15181	0.18367	0.05530	0.07194	0.06896	0.09118
CO_2	0.14747	0.08848	0.07119	0.05095	0.06146	0.05139	0.05620	0.03877
H	0.04059	0.02147	0.02496	0.02363	0.01556	0.02012	0.01308	0.02269
HCO	0.00005	0.00002	0.00002	0.00003	0.00001	0.00001	0.00002	0.00001
HO_2	0.00004	0.00003	0.00001	-	0.00003	0.00002	0.00003	0.00001
H_2	0.07845	0.05956	0.09106	0.14651	0.04475	0.06983	0.06254	0.11451
H_2O	0.30276	0.32814	0.32472	0.30193	0.37475	0.37689	0.39789	0.36419
N	-	0.00001	0.00001	-	0.00001	0.00001	0.00001	0.00001
NH	-	0.00001	0.00001	-	-	0.00001	0.00001	0.00001
NO	-	0.01307	0.00763	0.00280	0.01648	0.01115	0.01122	0.00540
N_2	-	0.28531	0.27885	0.26919	0.33505	0.33288	0.33788	0.32848
O	0.02192	0.01036	0.00584	0.00177	0.01057	0.00736	0.00449	0.00327
OH	0.07201	0.04795	0.03551	0.01804	0.05043	0.04242	0.03623	0.02729
O_2	0.03365	0.02286	0.00836	0.00147	0.03556	0.01595	0.01140	0.00419

TABLE 2 CHEMICAL AND STATE PROPERTIES IN THE REFLECTED DETONATION SHOCK TUBE FOR SIMULATING AN RP-1/LOX ROCKET ENGINE PLUME AT O/F = 2.70

Region 1

P_1(psia)	T_1(°R)	$H_1\left(\frac{cal}{gm}\right)$	$\rho_1\left(\frac{slugs}{ft^3}\right)$	γ_1	mw_1	$U_D\left(\frac{ft}{sec}\right)$	$a_1\left(\frac{ft}{sec}\right)$
3.57	536.6	-820.6	0.000525	1.3358	27.311	6771.8	1142.0

Mole Fractions (all gaseous)

O_2 0.36635	H_2 0.24124	C_2H_4 0.13597	CO_2 0.25644

Region 2

P_2(psia)	T_2(°R)	$H_2\left(\frac{cal}{gm}\right)$	$\rho_2\left(\frac{slugs}{ft^3}\right)$	γ_2	mw_2	$U_2\left(\frac{ft}{sec}\right)$	$a_2\left(\frac{ft}{sec}\right)$
80.8	5753.	-459.6	0.000973	1.1204	23.984	3117.4	3654.5

Mole Fractions (all gaseous)

HCO 0.00002	CO 0.29069	CO_2 0.17333	H 0.03206
OH 0.05614	HO_2 0.00002	H_2 0.07392	H_2O 0.33262
		O 0.01468	O_2 0.02652

Region 5

P_5(psia)	T_5(°R)	$H_5\left(\frac{cal}{gm}\right)$	$\rho_5\left(\frac{slugs}{ft^3}\right)$	γ_5	mw_5	$U_R\left(\frac{ft}{sec}\right)$	$a_5\left(\frac{ft}{sec}\right)$
200.	6226.	-175.4	0.002164	1.1269	23.287	2546.8	3869.4

Mole Fractions (all gaseous)

HCO 0.00005	CO 0.30304	CO_2 0.14747	H 0.04059
OH 0.07201	HO_2 0.00005	H_2 0.07845	H_2O 0.30276
	H_2O_2 0.00001	O 0.02192	O_2 0.03365

TABLE 3a CHEMICAL AND STATE PROPERTIES IN THE REFLECTED DETONATION SHOCK TUBE FOR SIMULATING A UDMH/N_2O_4 ROCKET ENGINE PLUME AT O/F = 2.70

Region 1

P_1 (psia)	T_1 (°R)	$H_1\left(\frac{cal}{gm}\right)$	$\rho_1\left(\frac{slugs}{ft^3}\right)$	γ_1	mw_1	$U_D\left(\frac{ft}{sec}\right)$	$a_1\left(\frac{ft}{sec}\right)$
4.54	536.6	-571.2	0.000574	1.3719	23.435	6500.3	1249.3

Mole Fractions (all gaseous)

O_2	0.24546	H_2	0.25251	N_2	0.29125	CO_2	0.12626	CH_4	0.08452

Region 2

P_2 (psia)	T_2 (°R)	$H_2\left(\frac{cal}{gm}\right)$	$\rho_2\left(\frac{slugs}{ft^3}\right)$	γ_2	mw_2	$U_2\left(\frac{ft}{sec}\right)$	$a_2\left(\frac{ft}{sec}\right)$
81.56	5378.4	-240.7	0.001055	1.1261	24.072	2963.9	3535.8

Mole Fractions (all gaseous)

HCO	0.00001	CO	0.10943	CO_2	0.10707	H	0.01448
OH	0.03391	HO_2	0.00001	H_2	0.05094	H_2O	0.35788
NO	0.00849	N_2	0.29492	O	0.00594	O_2	0.01691

Region 5

P_5 (psia)	T_5 (°R)	$H_5\left(\frac{cal}{gm}\right)$	$\rho_5\left(\frac{slugs}{ft^3}\right)$	γ_5	mw_5	$U_R\left(\frac{ft}{sec}\right)$	$a_5\left(\frac{ft}{sec}\right)$
200.	5860.8	+20.2	0.002314	1.1299	23.484	2484.3	3743.5

Mole Fractions (all gaseous)

HCO	0.00002	CO	0.12273	CO_2	0.08848	H	0.02147
OH	0.04795	HO_2	0.00003	H_2	0.05956	H_2O	0.32814
NO	0.01307	N_2	0.28531	O	0.01036	O_2	0.02286
NH	0.00001	N	0.00001	NO_2	0.00001		

TABLE 3b CHEMICAL AND STATE PROPERTIES IN THE REFLECTED DETONATION SHOCK TUBE FOR SIMULATING A $UDMH/N_2O_4$ ROCKET ENGINE PLUME AT O/F = 2.70

Region ①

P_1 (psia)	T_1 (°R)	$H_1\left(\frac{cal}{gm}\right)$	$\rho_1\left(\frac{slugs}{ft^3}\right)$	γ_1	mw_1	$U_D\left(\frac{ft}{sec}\right)$	$a_1\left(\frac{ft}{sec}\right)$
4.21	536.6	-574.3	0.000571	1.3262	25.190	6510.7	1185.0

Mole Fractions (all gaseous)

O_2	0.02569	H_2	0.43469	CH_4	0.00922	CO_2	0.21734	N_2O	0.31306

Region ②

P_2 (psia)	T_2 (°R)	$H_2\left(\frac{cal}{gm}\right)$	$\rho_2\left(\frac{slugs}{ft^3}\right)$	γ_2	mw_2	$U_2\left(\frac{ft}{sec}\right)$	$a_2\left(\frac{ft}{sec}\right)$
81.26	5374.8	-242.2	0.001052	1.1261	24.076	2976.2	3534.5

Mole Fractions (all gaseous)

HCO	0.00001	CO	0.10934	CO_2	0.10720	H	0.01443
OH	0.03382	HO_2	0.00001	H_2	0.05088	H_2O	0.35807
NO	0.00846	N_2	0.29498	O	0.00592	O_2	0.01687

Region ⑤

P_5 (psia)	T_5 (°R)	$H_5\left(\frac{cal}{gm}\right)$	$\rho_5\left(\frac{slugs}{ft^3}\right)$	γ_5	mw_5	$U_R\left(\frac{ft}{sec}\right)$	$a_5\left(\frac{ft}{sec}\right)$
200.0	5860.8	+20.2	0.002312	1.1299	23.484	2484.3	3743.5

Mole Fractions (all gaseous)

HCO	0.00002	CO	0.12273	CO_2	0.08848	H	0.02147
OH	0.04795	HO_2	0.00003	H_2	0.05956	H_2O	0.32814
NO	0.01307	N_2	0.28531	O	0.01036	O_2	0.02286
NH	0.00001	N	0.00001	NO_2	0.00001		

TABLE 4a CHEMICAL AND STATE PROPERTIES IN THE REFLECTED DETONATION SHOCK TUBE FOR SIMULATING A UDMH/N_2O_4 ROCKET ENGINE PLUME AT O/F = 2.35

Region 1

P_1 (psia)	T_1 (°R)	$H_1\left(\frac{cal}{gm}\right)$	$\rho_1\left(\frac{slugs}{ft^3}\right)$	γ_1	mw_1	$U_D\left(\frac{ft}{sec}\right)$	$a_1\left(\frac{ft}{sec}\right)$
4.48	536.6	-581.5	0.000560	1.3699	23.215	6604.2	1254.6

Mole Fractions (all gaseous)

O_2	0.23090	H_2	0.24618	N_2	0.29230	CO_2	0.12309	CH_4	0.10753

Region 2

P_2 (psia)	T_2 (°R)	$H_2\left(\frac{cal}{gm}\right)$	$\rho_2\left(\frac{slugs}{ft^3}\right)$	γ_2	mw_2	$U_2\left(\frac{ft}{sec}\right)$	$a_2\left(\frac{ft}{sec}\right)$
81.64	5283.	-241.0	0.001025	1.1406	22.956	2992.6	3611.6

Mole Fractions (all gaseous)

HCO	0.00001	CO	0.14390	CO_2	0.08413	H	0.01586
OH	0.02097	HO_2	-	H_2	0.08517	H_2O	0.35249
NO	0.00385	N_2	0.28711	O	0.00242	O_2	0.00407

Region 5

P_5 (psia)	T_5 (°R)	$H_5\left(\frac{cal}{gm}\right)$	$\rho_5\left(\frac{slugs}{ft^3}\right)$	γ_5	mw_5	$U_R\left(\frac{ft}{sec}\right)$	$a_5\left(\frac{ft}{sec}\right)$
200.0	5819.	+27.6	0.002223	1.1370	22.451	2562.5	3826.8

Mole Fractions (all gaseous)

HCO	0.00002	CO	0.15181	CO_2	0.07119	H	0.02496
OH	0.03551	HO_2	0.00001	H_2	0.09106	H_2O	0.32472
NO	0.00763	N_2	0.27885	O	0.00584	O_2	0.00836
NH	0.00001	N	0.00001				

TABLE 4b CHEMICAL AND STATE PROPERTIES IN THE REFLECTED DETONATION SHOCK TUBE FOR SIMULATING A UDMH/N_2O_4 ROCKET ENGINE PLUME AT O/F = 2.35

Region 1

P_1 (psia)	T_1 (°R)	$H_1\left(\frac{cal}{gm}\right)$	$\rho_1\left(\frac{slugs}{ft^3}\right)$	γ_1	mw_1	$U_D\left(\frac{ft}{sec}\right)$	$a_1\left(\frac{ft}{sec}\right)$
4.15	536.6	-584.6	0.000558	1.3243	24.961	6614.4	1189.6

Mole Fractions (all gaseous)

O_2	0.00918	H_2	0.42858	CH_4	0.03367	CO_2	0.21429	N_2O	0.31428

Region 2

P_2 (psia)	T_2 (°R)	$H_2\left(\frac{cal}{gm}\right)$	$\rho_2\left(\frac{slugs}{ft^3}\right)$	γ_2	mw_2	$U_2\left(\frac{ft}{sec}\right)$	$a_2\left(\frac{ft}{sec}\right)$
81.34	5279.4	-243.5	0.001022	1.1407	22.959	3004.3	3610.6

Mole Fractions (all gaseous)

HCO	0.00001	CO	0.14386	CO_2	0.08421	H	0.01580
OH	0.02088	HO_2	-	H_2	0.08514	H_2O	0.35265
NO	0.00383	N_2	0.28716	O	0.00240	O_2	0.00405

Region 5

P_5 (psia)	T_5 (°R)	$H_5\left(\frac{cal}{gm}\right)$	$\rho_5\left(\frac{slugs}{ft^3}\right)$	γ_5	mw_5	$U_R\left(\frac{ft}{sec}\right)$	$a_5\left(\frac{ft}{sec}\right)$
200.0	5819.	+27.6	0.002223	1.1370	22.451	2562.5	3826.8

Mole Fractions (all gaseous)

HCO	0.00002	CO	0.15181	CO_2	0.07119	H	0.02496
OH	0.03551	HO_2	0.00001	H_2	0.09106	H_2O	0.32472
NO	0.00763	N_2	0.27885	O	0.00584	O_2	0.00836
NH	0.00001	N	0.00001				

TABLE 5a CHEMICAL AND STATE PROPERTIES IN THE REFLECTED DETONATION SHOCK TUBE FOR SIMULATING A UDMH/N_2O_4 ROCKET ENGINE PLUME AT O/F = 2.00

Region 1

P_1 (psia)	T_1 (°R)	$H_1\left(\frac{cal}{gm}\right)$	$\rho_1\left(\frac{slugs}{ft^3}\right)$	γ_1	mw_1	$U_D\left(\frac{ft}{sec}\right)$	$a_1\left(\frac{ft}{sec}\right)$
4.572	536.6	-572.7	0.000568	1.3674	23.100	6631.1	1256.5

Mole Fractions (all gaseous)

O_2	0.22122	H_2	0.22703	N_2	0.29550	CO_2	0.11352	CH_4	0.14273

Region 2

P_2 (psia)	T_2 (°R)	$H_2\left(\frac{cal}{gm}\right)$	$\rho_2\left(\frac{slugs}{ft^3}\right)$	γ_2	mw_2	$U_2\left(\frac{ft}{sec}\right)$	$a_2\left(\frac{ft}{sec}\right)$
82.02	4971.6	-234.8	0.001024	1.1778	21.484	2951.2	3680.4

Mole Fractions (all gaseous)

HCO	0.00001	CO	0.18083	CO_2	0.05747	H	0.01163
OH	0.00681	HO_2	-	H_2	0.14909	H_2O	0.31831
NO	0.00080	N_2	0.27441	O	0.00034	O_2	0.00029

Region 5

P_5 (psia)	T_5 (°R)	$H_5\left(\frac{cal}{gm}\right)$	$\rho_5\left(\frac{slugs}{ft^3}\right)$	γ_5	mw_5	$U_R\left(\frac{ft}{sec}\right)$	$a_5\left(\frac{ft}{sec}\right)$
200.0	5626.8	+36.9	0.002156	1.1569	21.154	2671.8	3910.4

Mole Fractions (all gaseous)

HCO	0.00003	CO	0.18367	CO_2	0.05095	H	0.02363
OH	0.01804	HO_2	-	H_2	0.14651	H_2O	0.30193
NO	0.00280	N_2	0.26919	O	0.00177	O_2	0.00147

TABLE 5b CHEMICAL AND STATE PROPERTIES IN THE REFLECTED DETONATION SHOCK TUBE FOR SIMULATING A UDMH/N_2O_4 ROCKET ENGINE PLUME AT O/F = 2.00

Region ①

P_1 (psia)	T_1 (°R)	$H_1 \left(\frac{cal}{gm}\right)$	$\rho_1 \left(\frac{slugs}{ft^3}\right)$	γ_1	mw_1	$U_D \left(\frac{ft}{sec}\right)$	$a_1 \left(\frac{ft}{sec}\right)$
4.23	536.6	-575.7	0.000565	1.3225	24.829	6640.6	1191.9

Mole Fractions (all gaseous)

CH_4	0.07193	H_2	0.40698	N_2	0.00500	CO_2	0.20349	N_2O	0.31260

Region ②

P_2 (psia)	T_2 (°R)	$H_2 \left(\frac{cal}{gm}\right)$	$\rho_2 \left(\frac{slugs}{ft^3}\right)$	γ_2	mw_2	$U_2 \left(\frac{ft}{sec}\right)$	$a_2 \left(\frac{ft}{sec}\right)$
81.68	4968.	-236.3	0.001021	1.1779	21.485	2961.5	3679.1

Mole Fractions (all gaseous)

HCO	0.00001	CO	0.18081	CO_2	0.05751	H	0.01156
OH	0.00676	HO_2	-	H_2	0.14912	H_2O	0.31838
NO	0.00080	N_2	0.27444	O	0.00033	O_2	0.00029

Region ⑤

P_5 (psia)	T_5 (°R)	$H_5 \left(\frac{cal}{gm}\right)$	$\rho_5 \left(\frac{slugs}{ft^3}\right)$	γ_5	mw_5	$U_R \left(\frac{ft}{sec}\right)$	$a_5 \left(\frac{ft}{sec}\right)$
200.0	5626.8	+36.7	0.002153	1.1569	21.154	2671.8	3910.4

Mole Fractions (all gaseous)

HCO	0.00003	CO	0.18367	CO_2	0.05095	H	0.02363
OH	0.01804	HO_2	-	H_2	0.14651	H_2O	0.30193
NO	0.00280	N_2	0.26919	O	0.00177	O_2	0.00147

TABLE 6 CHEMICAL AND STATE PROPERTIES IN THE REFLECTED DETONATION SHOCK TUBE FOR SIMULATING AN A-50/N_2O_4 ROCKET ENGINE PLUME AT O/F = 2.30

Region ①	P_1(psia)	T_1(°R)	$H_1\left(\frac{cal}{gm}\right)$	$\rho_1\left(\frac{slugs}{ft^3}\right)$	γ_1	mw_1	$U_D\left(\frac{ft}{sec}\right)$	$a_1\left(\frac{ft}{sec}\right)$
	5.25	536.6	-474.2	0.000571	1.3854	20.196	6523.9	1352.6
	Mole Fractions (all gaseous)							
	O_2	0.20413	H_2	0.39465	N_2	0.29939	CO_2	0.10183
Region ②	P_2(psia)	T_2(°R)	$H_2\left(\frac{cal}{gm}\right)$	$\rho_2\left(\frac{slugs}{ft^3}\right)$	γ_2	mw_2	$U_2\left(\frac{ft}{sec}\right)$	$a_2\left(\frac{ft}{sec}\right)$
	82.14	5337.0	-142.5	0.001046	1.1271	23.529	2959.5	3564.3
	Mole Fractions (all gaseous)							
	HCO	-	CO	0.04757	CO_2	0.07106	H	0.01149
	OH	0.04010	HO_2	0.00002	H_2	0.03721	H_2O	0.39675
	NO	0.01245	N_2	0.34257	O	0.00765	O_2	0.03311
Region ⑤	P_5(psia)	T_5(°R)	$H_5\left(\frac{cal}{gm}\right)$	$\rho_5\left(\frac{slugs}{ft^3}\right)$	γ_5	mw_5	$U_R\left(\frac{ft}{sec}\right)$	$a_5\left(\frac{ft}{sec}\right)$
	200.0	5821.	+120.0	0.002278	1.1308	22.973	2515.6	3773.3
	Mole Fractions (all gaseous)							
	HCO	0.00001	CO	0.05834	CO_2	0.05748	H	0.01827
	OH	0.05466	HO_2	0.00004	H_2	0.04855	H_2O	0.36385
	NO	0.01755	N_2	0.33175	O	0.01235	O_2	0.03711
			N	0.00001	NO_2	0.00001		

TABLE 7 CHEMICAL AND STATE PROPERTIES IN THE REFLECTED DETONATION SHOCK TUBE FOR SIMULATING AN A-50/N_2O_4 ROCKET ENGINE PLUME AT O/F = 2.00

Region 1

P_1 (psia)	T_1 (°R)	$H_1\left(\frac{cal}{gm}\right)$	$\rho_1\left(\frac{slugs}{ft^3}\right)$	γ_1	mw_1	$U_D\left(\frac{ft}{sec}\right)$	$a_1\left(\frac{ft}{sec}\right)$
5.30	536.6	-521.63	0.000557	1.3847	19.529	6617.0	1374.9

Mole Fractions (all gaseous)

O_2 0.17468	H_2 0.41977	N_2 0.29723	CO_2 0.10832

Region 2

P_2 (psia)	T_2 (°R)	$H_2\left(\frac{cal}{gm}\right)$	$\rho_2\left(\frac{slugs}{ft^3}\right)$	γ_2	mw_2	$U_2\left(\frac{ft}{sec}\right)$	$a_2\left(\frac{ft}{sec}\right)$
82.23	5297.4	-180.9	0.001018	1.1312	22.697	2994.6	3622.1

Mole Fractions (all gaseous)

HCO	-	CO	0.06431	CO_2	0.06158	H	0.01357
OH	0.02963	HO_2	0.00001	H_2	0.05983	H_2O	0.40642
NO	0.00713	N_2	0.34187	O	0.00416	O_2	0.01149

Region 5

P_5 (psia)	T_5 (°R)	$H_5\left(\frac{cal}{gm}\right)$	$\rho_5\left(\frac{slugs}{ft^3}\right)$	γ_5	mw_5	$U_R\left(\frac{ft}{sec}\right)$	$a_5\left(\frac{ft}{sec}\right)$
200.0	5794.	+89.0	0.002208	1.1330	22.175	2562.5	3835.3

Mole Fractions (all gaseous)

HCO	0.00001	CO	0.07275	CO_2	0.05024	H	0.02125
OH	0.04397	HO_2	0.00002	H_2	0.07120	H_2O	0.37280
NO	0.01155	N_2	0.33170	O	0.00789	O_2	0.01658
NH	0.00001	N	0.00001	NO_2	0.00001		

TABLE 8 CHEMICAL AND STATE PROPERTIES IN THE REFLECTED DETONATION SHOCK TUBE FOR SIMULATING AN A-50/N_2O_4 ROCKET ENGINE PLUME AT O/F = 2.00 AND CHAMBER PRESSURE = 1000. PSIA

Region 1

P_1(psia)	T_1(°R)	$H_1\left(\frac{cal}{gm}\right)$	$\rho_1\left(\frac{slugs}{ft^3}\right)$	γ_1	mw_1	$U_D\left(\frac{ft}{sec}\right)$	$a_1\left(\frac{ft}{sec}\right)$
25.60	536.6	-521.63	0.002693	1.3847	19.529	6751.5	1374.9

Mole Fractions (all gaseous)

O_2 0.17468	H_2 0.41977	N_2 0.29723	CO_2 0.10832

Region 2

P_2(psia)	T_2(°R)	$H_2\left(\frac{cal}{gm}\right)$	$\rho_2\left(\frac{slugs}{ft^3}\right)$	γ_2	mw_2	$U_2\left(\frac{ft}{sec}\right)$	$a_2\left(\frac{ft}{sec}\right)$
411.01	5554.8	-168.0	0.004905	1.1418	22.932	3043.9	3707.0

Mole Fractions (all gaseous)

HCO 0.00001	CO 0.06182	CO_2 0.06537	H 0.00893
OH 0.02498	HO_2 0.00001	H_2 0.05420	H_2O 0.42175
NO 0.00703	N_2 0.34550	O 0.00251	O_2 0.00788

Region 5

P_5(psia)	T_5(°R)	$H_5\left(\frac{cal}{gm}\right)$	$\rho_5\left(\frac{slugs}{ft^3}\right)$	γ_5	mw_5	$U_R\left(\frac{ft}{sec}\right)$	$a_5\left(\frac{ft}{sec}\right)$
1000.	6136.	+113.0	0.010568	1.1424	22.458	2636.7	3938.6

Mole Fractions (all gaseous)

HCO 0.00002	CO 0.07067	CO_2 0.05386	H 0.01471
OH 0.03935	HO_2 0.00003	H_2 0.06515	H_2O 0.39048
NO 0.01218	N_2 0.33568	O 0.00525	O_2 0.01254
NH 0.00001	N 0.00001	NO_2 0.00001	

TABLE 9a CHEMICAL AND STATE PROPERTIES IN THE REFLECTED DETONATION SHOCK TUBE FOR SIMULATING AN A-50/N_2O_4 ROCKET ENGINE PLUME AT O/F = 1.70

Region 1

P_1 (psia)	T_1 (°R)	$H_1\left(\frac{cal}{gm}\right)$	$\rho_1\left(\frac{slugs}{ft^3}\right)$	γ_1	mw_1	$U_D\left(\frac{ft}{sec}\right)$	$a_1\left(\frac{ft}{sec}\right)$
5.44	536.6	-542.2	0.000555	1.3840	18.947	6679.7	1395.6

Mole Fractions (all gaseous)

O_2	0.15185	H_2	0.43386	N_2	0.29752	CO_2	0.10745	CH_4	0.00932

Region 2

P_2 (psia)	T_2 (°R)	$H_2\left(\frac{cal}{gm}\right)$	$\rho_2\left(\frac{slugs}{ft^3}\right)$	γ_2	mw_2	$U_2\left(\frac{ft}{sec}\right)$	$a_2\left(\frac{ft}{sec}\right)$
82.6	5106.6	-198.1	0.001004	1.1554	21.491	2986.1	3693.6

Mole Fractions (all gaseous)

HCO	0.00001	CO	0.08713	CO_2	0.04530	H	0.01291
OH	0.01357	HO_2		H_2	0.10924	H_2O	0.39078
NO	0.00221	N_2	0.33637	O	0.00101	O_2	0.00147

Region 5

P_5 (psia)	T_5 (°R)	$H_5\left(\frac{cal}{gm}\right)$	$\rho_5\left(\frac{slugs}{ft^3}\right)$	γ_5	mw_5	$U_R\left(\frac{ft}{sec}\right)$	$a_5\left(\frac{ft}{sec}\right)$
200.0	5679.	+76.9	0.002132	1.1439	21.090	2656.2	3912.7

Mole Fractions (all gaseous)

HCO	0.00001	CO	0.09118	CO_2	0.03877	H	0.02269
OH	0.02729	HO_2	0.00001	H_2	0.11451	H_2O	0.36419
NO	0.00540	N_2	0.32848	O	0.00327	O_2	0.00419
NH	0.00001	N	0.00001				

TABLE 9b CHEMICAL AND STATE PROPERTIES IN THE REFLECTED DETONATION SHOCK TUBE FOR SIMULATING AN A-50/N_2O_4 ROCKET ENGINE PLUME AT O/F = 1.70

Region ①

P_1 (psia)	T_1 (°R)	$H_1\left(\frac{cal}{gm}\right)$	$\rho_1\left(\frac{slugs}{ft^3}\right)$	γ_1	mw_1	$U_D\left(\frac{ft}{sec}\right)$	$a_1\left(\frac{ft}{sec}\right)$
5.39	536.6	-542.6	0.000554	1.3778	19.110	6681.3	1386.7

Mole Fractions (all gaseous)

O_2	0.12576	H_2	0.45639	N_2	0.26407	CO_2	0.11777	N_2O	0.03601

Region ②

P_2 (psia)	T_2 (°R)	$H_2\left(\frac{cal}{gm}\right)$	$\rho_2\left(\frac{slugs}{ft^3}\right)$	γ_2	mw_2	$U_2\left(\frac{ft}{sec}\right)$	$a_2\left(\frac{ft}{sec}\right)$
82.48	5106.6	-198.3	0.001003	1.1554	21.491	2987.4	3693.6

Mole Fractions (all gaseous)

HCO	0.00001	CO	0.08713	CO_2	0.04531	H	0.01290
OH	0.01355	HO_2	-	H_2	0.10924	H_2O	0.39080
NO	0.00220	N_2	0.33638	O	0.00101	O_2	0.00147

Region ⑤

P_5 (psia)	T_5 (°R)	$H_5\left(\frac{cal}{gm}\right)$	$\rho_5\left(\frac{slugs}{ft^3}\right)$	γ_5	mw_5	$U_R\left(\frac{ft}{sec}\right)$	$a_5\left(\frac{ft}{sec}\right)$
200.0	5679.	+76.9	0.002132	1.1439	21.090	2656.2	3912.7

Mole Fractions (all gaseous)

HCO	0.00001	CO	0.09118	CO_2	0.03877	H	0.02269
OH	0.02729	HO_2	0.00001	H_2	0.11451	H_2O	0.36419
NO	0.00540	N_2	0.32848	O	0.00327	O_2	0.00419
NH	0.00001	N	0.00001				

TABLE 10 COMPARISON OF EQUILIBRIUM EXIT PLANE PROPERTIES ($A_e/A_* = 40.$) BETWEEN IDEAL ENGINE AND IDEAL DETONATION TUBE FOR SLIGHTLY IMPERFECT SIMULATION OF A-50/N_2O_4 MIXTURES[†]

O/F	2.0		2.0		2.3	
P_c (psia)	200.		1000.		200.	
	Engine	Det Tube	Engine	Det Tube	Engine	Det Tube
T_e(°K)	1369.	1397.	1333.	1383.	1597.	1681.
P_e(psia)	0.4395	0.4439	2.0918	2.1286	0.4998	0.5130
a_e(ft/sec)	2535.4	2559.7	2503.0	2547.6	2634.8	2691.9
mole. wt	23.663	23.663	23.663	23.663	25.154	25.145
γ_e	1.2420	1.2409	1.2435	1.2415	1.2222	1.2118
M_e	4.114	4.097	4.195	4.167	3.906	3.870
Mole. Fractions (all gaseous)						
CO	0.02720	0.02303	0.02606	0.02761	0.00014	0.00040
CO_2	0.10404	0.10321	0.10518	0.10363	0.12669	0.12639
H_2	0.05811	0.05728	0.05925	0.05770	0.00019	0.00047
H_2O	0.45051	0.45134	0.44937	0.45092	0.49114	0.49051
NO	-	-	-	-	0.00028	0.00040
N_2	0.36014	0.36014	0.36014	0.36014	0.37275	0.37255
O	-	-	-	-	0.00001	0.00002
OH	-	-	-	-	0.00040	0.00073
O_2	-	-	-	-	0.00840	0.00853

[†]See Tables 6 through 8.

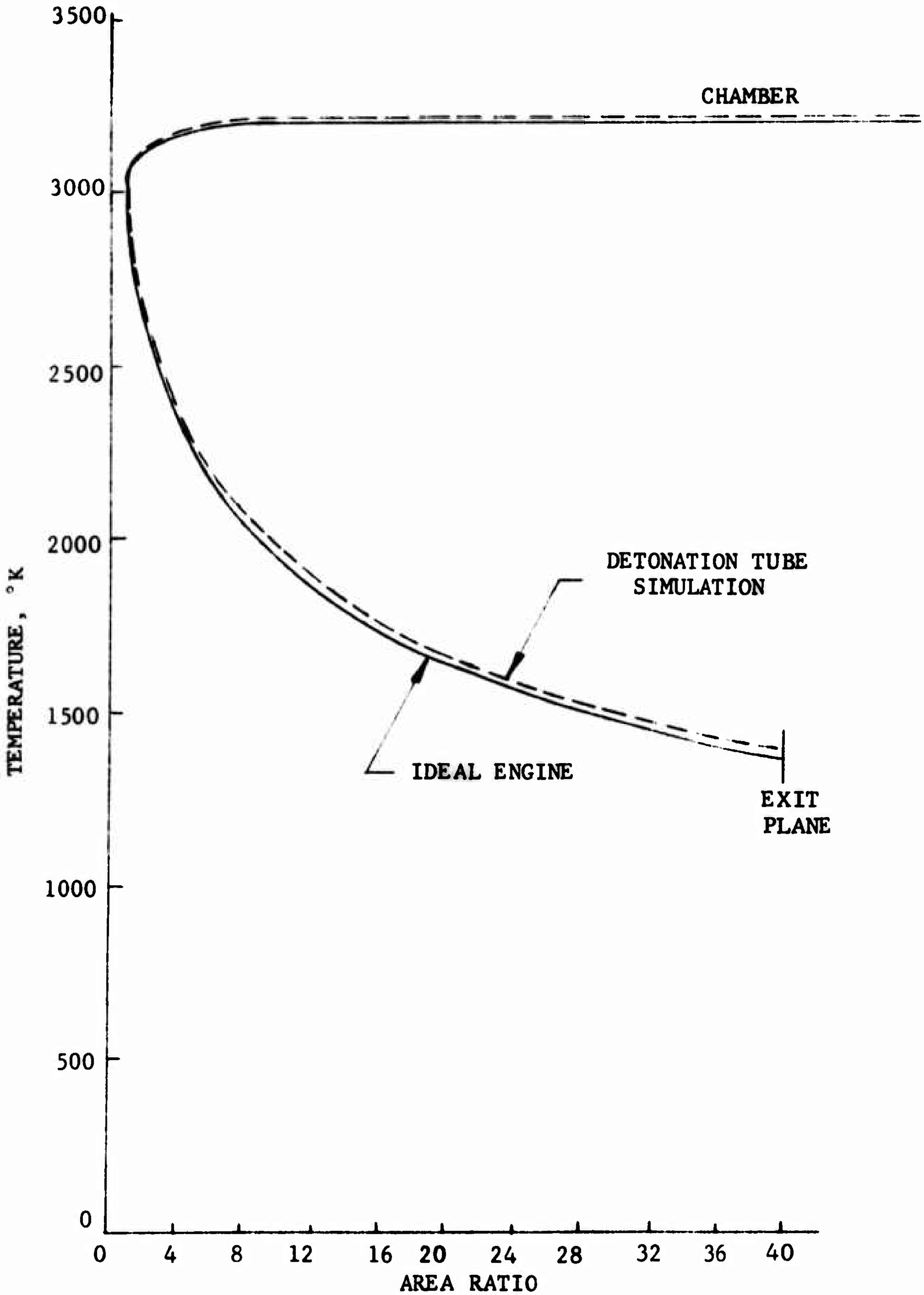

Fig. 1 Equilibrium Static Temperature versus Nozzle Area Ratio for A-50/N_2O_4 @ O/F = 2.0, P_c = 200. psia