

AD-771 067

**DETONATION TUBE CONDITIONS FOR SIMU-
LATING: RP-1/LOX AND VARIOUS AMINE/
N₂O₄ ROCKET ENGINE PLUMES**

J. Leng, et al

Grumman Aerospace Corporation

Prepared for:

Defense Advanced Research Projects Agency

November 1973

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Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Grumman Aerospace Corporation		2a. REPORT SECURITY CLASSIFICATION Unclassified	
		2b. GROUP N/A	
3. REPORT TITLE Detonation tube conditions for Simulating RP-1/LOX and Various Amine/ N_2O_4 Rocket Engine Plumes			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Research Memorandum			
5. AUTHOR(S) (First name, middle initial, last name) J. Leng and M. W. Slack			
6. REPORT DATE November 1973	7a. TOTAL NO. OF PAGES 20	7b. NO. OF REFS 7	
8a. CONTRACT OR GRANT NO.	8b. ORIGINATOR'S REPORT NUMBER(S) RM 581		
b. PROJECT NO. N/A	8c. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) None		
c.			
d.			
10. DISTRIBUTION STATEMENT Approved for Public release; distribution unlimited.			
11. SUPPLEMENTARY NOTES None		12. SPONSORING MILITARY ACTIVITY None	
13. ABSTRACT 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[†]

by

J. Leng

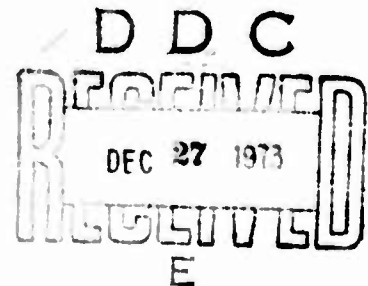
Fluid Dynamics

and

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Aerophysics

November 1973



[†]This investigation was partially supported by the Defense Advanced Research Project Agency under Contract No. DAAH04-72-C-0728, "Measurement of IR and VUV Radiation Emitted by Simulated Rocket Exhaust 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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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

Subscripts

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/N₂O₄ propellant combinations and also for A-50/N₂O₄ at an O/F ratio of 1.7.

For O/F ratios of 2.0 and 2.3, however, the A-50/N₂O₄ 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 (H₂O, CO₂, N₂) 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/N₂O₄ 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 ₂ O ₄					A-50/N ₂ O ₄				
		2.7	2.7	2.35	2.0	2.0	2.3	2.0	2.0	2.0	1.7
O/F (ratio)	2.7	2.7	2.35	2.0	2.0	2.3	2.0	2.0	2.0	2.0	1.7
Press. (psia)	200.	200.	200.	200.	200.	200.	200.	200.	200.	1000.	200.
Enthalpy ($\frac{\text{cal}}{\text{gm}}$)	-175.8	+20.2	+27.6	+36.8	+36.8	+53.7	+64.1	+64.1	+64.1	+64.1	+76.9
Temp (°R)	6226.	5861.	5819.	5627.	5627.	5740.	5764.	5764.	5764.	6064.	5679.
γ	1.1269	1.1299	1.1370	1.1569	1.1569	1.1308	1.1331	1.1331	1.1331	1.1428	1.1439
mole. wt	23.287	23.484	22.451	21.154	21.154	23.159	22.239	22.239	22.239	22.570	21.090
Mole Fractions (all gaseous)											
CO	0.30304	0.12273	0.15181	0.18367	0.18367	0.05530	0.07194	0.07194	0.07194	0.06896	0.09118
CO ₂	0.14747	0.08848	0.07119	0.05095	0.05095	0.06146	0.05139	0.05139	0.05139	0.05620	0.03877
H	0.04059	0.02147	0.02496	0.02363	0.02363	0.01556	0.02012	0.02012	0.02012	0.01308	0.02269
HCO	0.00005	0.00002	0.00002	0.00003	0.00003	0.00001	0.00001	0.00001	0.00001	0.00002	0.00001
HO ₂	0.00004	0.00003	0.00001	-	-	0.00003	0.00002	0.00002	0.00002	0.00003	0.00001
H ₂	0.07845	0.05956	0.09106	0.14651	0.14651	0.04475	0.06983	0.06983	0.06983	0.06254	0.11451
H ₂ O	0.30276	0.32814	0.32472	0.30193	0.30193	0.37475	0.37689	0.37689	0.37689	0.39789	0.36419
N	-	0.00001	0.00001	-	-	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
NH	-	0.00001	0.00001	-	-	-	0.00001	0.00001	0.00001	0.00001	0.00001
NO	-	0.01307	0.00763	0.00280	0.00280	0.01648	0.01115	0.01115	0.01115	0.01122	0.00540
N ₂	-	0.28531	0.27885	0.26919	0.26919	0.33505	0.33288	0.33288	0.33288	0.33788	0.32848
O	0.02192	0.01036	0.00584	0.00177	0.00177	0.01057	0.00736	0.00736	0.00736	0.00449	0.00327
OH	0.07201	0.04795	0.03551	0.01804	0.01804	0.05043	0.04242	0.04242	0.04242	0.03623	0.02729
O ₂	0.03365	0.02286	0.00836	0.00147	0.00147	0.03556	0.01595	0.01595	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 ($\frac{\text{cal}}{\text{gm}}$)	ρ_1 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_1	mw_1	U_D ($\frac{\text{ft}}{\text{sec}}$)	a_1 ($\frac{\text{ft}}{\text{sec}}$)
	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 ($\frac{\text{cal}}{\text{gm}}$)	ρ_2 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_2	mw_2	U_2 ($\frac{\text{ft}}{\text{sec}}$)	a_2 ($\frac{\text{ft}}{\text{sec}}$)
	80.8	5753.	-459.6	0.000973	1.1204	23.984	3117.4	3654.5
	Mole Fractions (all gaseous)							
	HCO 0.00002 OH 0.05614	CO 0.29069 HO ₂ 0.00002	CO ₂ 0.17333 H ₂ 0.07392 O 0.01468	H 0.03206 H ₂ O 0.33262 O ₂ 0.02652				
Region ③	P_5 (psia)	T_5 (°R)	H_5 ($\frac{\text{cal}}{\text{gm}}$)	ρ_5 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_5	mw_5	U_R ($\frac{\text{ft}}{\text{sec}}$)	a_5 ($\frac{\text{ft}}{\text{sec}}$)
	200.	6226.	-175.4	0.002164	1.1269	23.287	2546.8	3869.4
	Mole Fractions (all gaseous)							
	HCO 0.00065 OH 0.07201	CO 0.30304 HO ₂ 0.00005 H ₂ O ₂ 0.00001	CO ₂ 0.14747 H ₂ 0.07845 O 0.02192	H 0.04059 H ₂ O 0.30276 O ₂ 0.03365				

TABLE 3a CHEMICAL AND STATE PROPERTIES IN THE REFLECTED DETONATION SHOCK TUBE FOR SIMULATING A UDMH/N₂O₄ ROCKET ENGINE PLUME AT O/F = 2.70

Region ①	P_1 (psia)	T_1 (°R)	H_1 ($\frac{\text{cal}}{\text{gm}}$)	ρ_1 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_1	mw_1	U_D ($\frac{\text{ft}}{\text{sec}}$)	a_1 ($\frac{\text{ft}}{\text{sec}}$)		
	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 ($\frac{\text{cal}}{\text{gm}}$)	ρ_2 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_2	mw_2	U_2 ($\frac{\text{ft}}{\text{sec}}$)	a_2 ($\frac{\text{ft}}{\text{sec}}$)		
	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 ₂ O	0.35788		
	NO	0.00849	N ₂	0.29492	O	0.00594	O ₂	0.01691		
Region ③	P_5 (psia)	T_5 (°R)	H_5 ($\frac{\text{cal}}{\text{gm}}$)	ρ_5 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_5	mw_5	U_R ($\frac{\text{ft}}{\text{sec}}$)	a_5 ($\frac{\text{ft}}{\text{sec}}$)		
	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 ₂ O	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/N₂O₄ ROCKET ENGINE PLUME AT O/F = 2.70

Region ①	P ₁ (psia)	T ₁ (°R)	H ₁ ($\frac{\text{cal}}{\text{gm}}$)	ρ_1 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_1	mw ₁	U _D ($\frac{\text{ft}}{\text{sec}}$)	a ₁ ($\frac{\text{ft}}{\text{sec}}$)		
	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 ₂ O	0.31306
Region ②	P ₂ (psia)	T ₂ (°R)	H ₂ ($\frac{\text{cal}}{\text{gm}}$)	ρ_2 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_2	mw ₂	U ₂ ($\frac{\text{ft}}{\text{sec}}$)	a ₂ ($\frac{\text{ft}}{\text{sec}}$)		
	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 ₂ O	0.35807		
	NO	0.00846	N ₂	0.29498	O	0.00592	O ₂	0.01687		
Region ③	P ₅ (psia)	T ₅ (°R)	H ₅ ($\frac{\text{cal}}{\text{gm}}$)	ρ_5 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_5	mw ₅	U _R ($\frac{\text{ft}}{\text{sec}}$)	a ₅ ($\frac{\text{ft}}{\text{sec}}$)		
	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 ₂ O	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/N₂O₄ ROCKET ENGINE PLUME AT O/F = 2.35

Region ①	P_1 (psia)	T_1 (°R)	H_1 ($\frac{\text{cal}}{\text{gm}}$)	ρ_1 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_1	mw_1	U_D ($\frac{\text{ft}}{\text{sec}}$)	a_1 ($\frac{\text{ft}}{\text{sec}}$)		
	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 ($\frac{\text{cal}}{\text{gm}}$)	ρ_2 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_2	mw_2	U_2 ($\frac{\text{ft}}{\text{sec}}$)	a_2 ($\frac{\text{ft}}{\text{sec}}$)		
	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 ₂ O	0.35249		
	NO	0.00385	N ₂	0.28711	O	0.00242	O ₂	0.00407		
Region ③	P_5 (psia)	T_5 (°R)	H_5 ($\frac{\text{cal}}{\text{gm}}$)	ρ_5 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_5	mw_5	U_R ($\frac{\text{ft}}{\text{sec}}$)	a_5 ($\frac{\text{ft}}{\text{sec}}$)		
	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 ₂ O	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/N₂O₄ ROCKET ENGINE PLUME AT O/F = 2.35

Region ①	P_1 (psia)	T_1 (°R)	H_1 ($\frac{\text{cal}}{\text{gm}}$)	ρ_1 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_1	mw_1	U_D ($\frac{\text{ft}}{\text{sec}}$)	a_1 ($\frac{\text{ft}}{\text{sec}}$)		
	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 ₂ O	0.31428
Region ②	P_2 (psia)	T_2 (°R)	H_2 ($\frac{\text{cal}}{\text{gm}}$)	ρ_2 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_2	mw_2	U_2 ($\frac{\text{ft}}{\text{sec}}$)	a_2 ($\frac{\text{ft}}{\text{sec}}$)		
	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 ₂ O	0.35265			
NO	0.00383	N ₂	0.28716	O	0.00240	O ₂	0.00405			
Region ③	P_5 (psia)	T_5 (°R)	H_5 ($\frac{\text{cal}}{\text{gm}}$)	ρ_5 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_5	mw_5	U_R ($\frac{\text{ft}}{\text{sec}}$)	a_5 ($\frac{\text{ft}}{\text{sec}}$)		
	200.0	5819.	+27.6	0.002223	1.1370	22.451	2562.5	3826.8		
	Mole Fractions (all gaseous)									
Region ④	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 ₂ O	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/N₂O₄ ROCKET ENGINE PLUME AT O/F = 2.00

Region ①	P_1 (psia)	T_1 (°R)	H_1 ($\frac{\text{cal}}{\text{gm}}$)	ρ_1 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_1	mw_1	U_D ($\frac{\text{ft}}{\text{sec}}$)	a_1 ($\frac{\text{ft}}{\text{sec}}$)		
	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 ($\frac{\text{cal}}{\text{gm}}$)	ρ_2 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_2	mw_2	U_2 ($\frac{\text{ft}}{\text{sec}}$)	a_2 ($\frac{\text{ft}}{\text{sec}}$)		
	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 ₂ O	0.31831		
	NO	0.00080	N ₂	0.27441	O	0.00034	O ₂	0.00029		
Region ③	P_5 (psia)	T_5 (°R)	H_5 ($\frac{\text{cal}}{\text{gm}}$)	ρ_5 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_5	mw_5	U_R ($\frac{\text{ft}}{\text{sec}}$)	a_5 ($\frac{\text{ft}}{\text{sec}}$)		
	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 ₂ O	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/N₂O₄ ROCKET ENGINE PLUME AT O/F = 2.00

Region ①	P_1 (psia)	T_1 (°R)	H_1 ($\frac{\text{cal}}{\text{gm}}$)	ρ_1 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_1	mw_1	U_D ($\frac{\text{ft}}{\text{sec}}$)	a_1 ($\frac{\text{ft}}{\text{sec}}$)		
	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 ₂ O	0.31260
Region ②	P_2 (psia)	T_2 (°R)	H_2 ($\frac{\text{cal}}{\text{gm}}$)	ρ_2 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_2	mw_2	U_2 ($\frac{\text{ft}}{\text{sec}}$)	a_2 ($\frac{\text{ft}}{\text{sec}}$)		
	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 ₂ O	0.31838			
NO	0.00080	N ₂	0.27444	O	0.00033	O ₂	0.00029			
Region ③	P_5 (psia)	T_5 (°R)	H_5 ($\frac{\text{cal}}{\text{gm}}$)	ρ_5 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_5	mw_5	U_R ($\frac{\text{ft}}{\text{sec}}$)	a_5 ($\frac{\text{ft}}{\text{sec}}$)		
	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 ₂ O	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/N₂O₄ ROCKET ENGINE PLUME AT O/F = 2.30

Region 1	P_1 (psia)	T_1 (°R)	H_1 ($\frac{\text{cal}}{\text{gm}}$)	ρ_1 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_1	mw_1	U_D ($\frac{\text{ft}}{\text{sec}}$)	a_1 ($\frac{\text{ft}}{\text{sec}}$)
	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 ($\frac{\text{cal}}{\text{gm}}$)	ρ_2 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_2	mw_2	U_2 ($\frac{\text{ft}}{\text{sec}}$)	a_2 ($\frac{\text{ft}}{\text{sec}}$)
	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 ₂ O 0.39675		
	NO 0.01245	N ₂ 0.34257		O 0.00765		O ₂ 0.03311		
Region 3	P_5 (psia)	T_5 (°R)	H_5 ($\frac{\text{cal}}{\text{gm}}$)	ρ_5 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_5	mw_5	U_R ($\frac{\text{ft}}{\text{sec}}$)	a_5 ($\frac{\text{ft}}{\text{sec}}$)
	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 ₂ O 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/N₂O₄ ROCKET ENGINE PLUME AT O/F = 2.00

Region ①	P_1 (psia)	T_1 (°R)	H_1 ($\frac{\text{cal}}{\text{gm}}$)	ρ_1 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_1	mw_1	U_D ($\frac{\text{ft}}{\text{sec}}$)	a_1 ($\frac{\text{ft}}{\text{sec}}$)
	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 ($\frac{\text{cal}}{\text{gm}}$)	ρ_2 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_2	mw_2	U_2 ($\frac{\text{ft}}{\text{sec}}$)	a_2 ($\frac{\text{ft}}{\text{sec}}$)
	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 ₂ O 0.40642				
NO	0.00713	N ₂ 0.34187	O 0.00416	O ₂ 0.01149				
Region ③	P_5 (psia)	T_5 (°R)	H_5 ($\frac{\text{cal}}{\text{gm}}$)	ρ_5 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_5	mw_5	U_R ($\frac{\text{ft}}{\text{sec}}$)	a_5 ($\frac{\text{ft}}{\text{sec}}$)
	200.0	5794.	+89.0	0.002208	1.1330	22.175	2562.5	3835.3
	Mole Fractions (all gaseous)							
Region ④	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 ₂ O 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/N₂O₄ ROCKET ENGINE PLUME AT O/F = 2.00 AND CHAMBER PRESSURE = 1000. PSIA

Region ①	P_1 (psia)	T_1 (°R)	H_1 ($\frac{\text{cal}}{\text{gm}}$)	ρ_1 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_1	mw_1	U_D ($\frac{\text{ft}}{\text{sec}}$)	a_1 ($\frac{\text{ft}}{\text{sec}}$)
	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 ($\frac{\text{cal}}{\text{gm}}$)	ρ_2 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_2	mw_2	U_2 ($\frac{\text{ft}}{\text{sec}}$)	a_2 ($\frac{\text{ft}}{\text{sec}}$)
	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 ₂ O 0.42175					
NO 0.00703	N ₂ 0.34550	O 0.00251	O ₂ 0.00788					
Region ③	P_5 (psia)	T_5 (°R)	H_5 ($\frac{\text{cal}}{\text{gm}}$)	ρ_5 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_5	mw_5	U_R ($\frac{\text{ft}}{\text{sec}}$)	a_5 ($\frac{\text{ft}}{\text{sec}}$)
	1000.	6136.	+113.0	0.010568	1.1424	22.458	2636.7	3938.6
	Mole Fractions (all gaseous)							
Region ④	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 ₂ O 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/N₂O₄ ROCKET ENGINE PLUME AT O/F = 1.70

Region ①	P_1 (psia)	T_1 (°R)	H_1 ($\frac{\text{cal}}{\text{gm}}$)	ρ_1 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_1	mw_1	U_D ($\frac{\text{ft}}{\text{sec}}$)	a_1 ($\frac{\text{ft}}{\text{sec}}$)		
	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 ($\frac{\text{cal}}{\text{gm}}$)	ρ_2 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_2	mw_2	U_2 ($\frac{\text{ft}}{\text{sec}}$)	a_2 ($\frac{\text{ft}}{\text{sec}}$)		
	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 ₂ O	0.39078		
	NO	0.00221	N ₂	0.33637	O	0.00101	O ₂	0.00147		
Region ③	P_5 (psia)	T_5 (°R)	H_5 ($\frac{\text{cal}}{\text{gm}}$)	ρ_5 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_5	mw_5	U_R ($\frac{\text{ft}}{\text{sec}}$)	a_5 ($\frac{\text{ft}}{\text{sec}}$)		
	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 ₂ O	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/N₂O₄ ROCKET ENGINE PLUME AT O/F = 1.70

Region ①	P_1 (psia)	T_1 (°R)	H_1 ($\frac{\text{cal}}{\text{gm}}$)	ρ_1 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_1	mw_1	U_D ($\frac{\text{ft}}{\text{sec}}$)	a_1 ($\frac{\text{ft}}{\text{sec}}$)
	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 ₂ O 0.03601			
Region ②	P_2 (psia)	T_2 (°R)	H_2 ($\frac{\text{cal}}{\text{gm}}$)	ρ_2 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_2	mw_2	U_2 ($\frac{\text{ft}}{\text{sec}}$)	a_2 ($\frac{\text{ft}}{\text{sec}}$)
	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 ₂ O 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 ($\frac{\text{cal}}{\text{gm}}$)	ρ_5 ($\frac{\text{slugs}}{\text{ft}^3}$)	γ_5	mw_5	U_R ($\frac{\text{ft}}{\text{sec}}$)	a_5 ($\frac{\text{ft}}{\text{sec}}$)
	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 ₂ O 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/N₂O₄ 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 ₂ O	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.

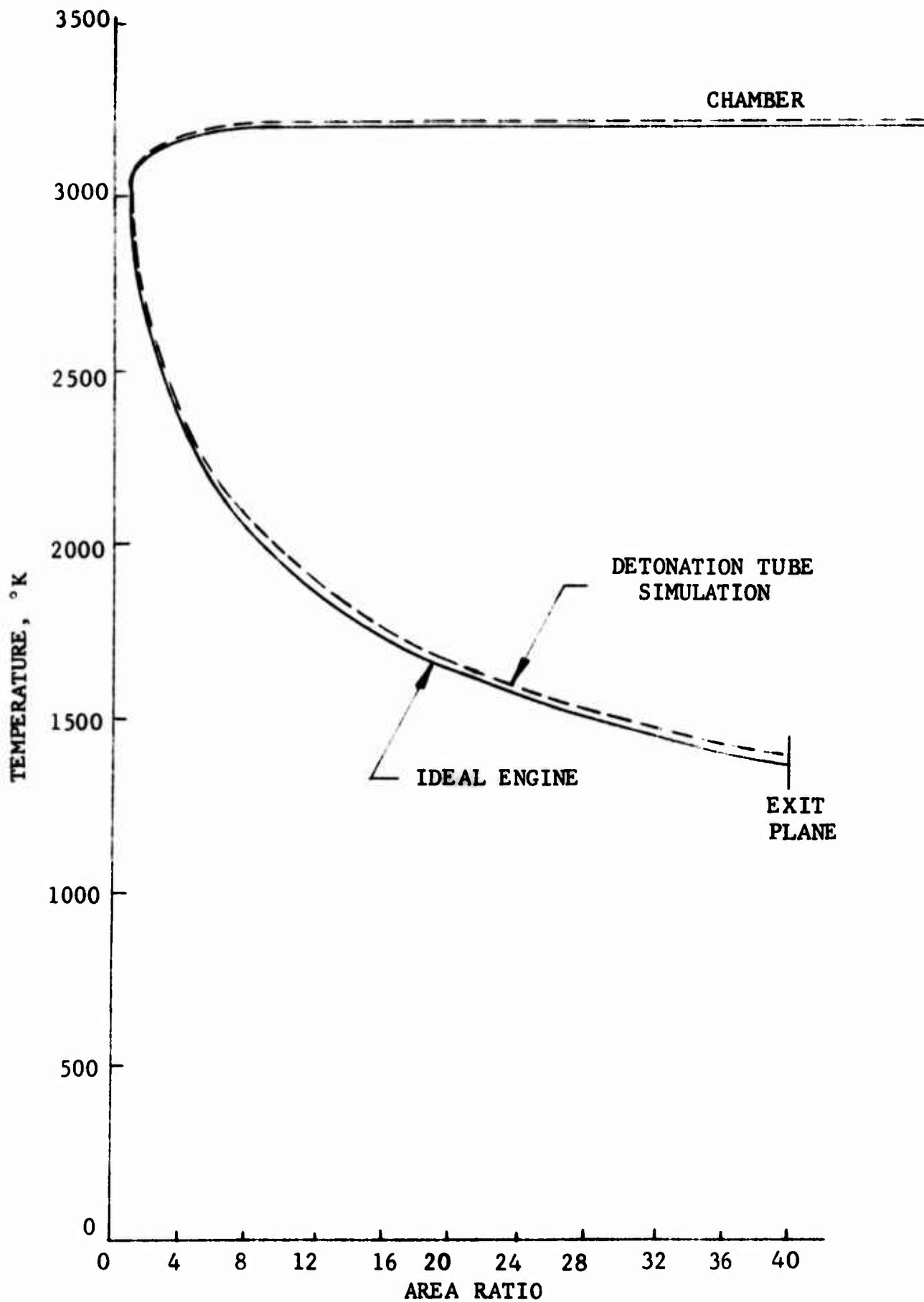


Fig. 1 Equilibrium Static Temperature versus Nozzle Area Ratio for A-50/N₂O₄ @ O/F = 2.0, P_c = 200. psia