Aluminized Propellants and a Method Defining Low-Altitude Exhaust Plumes

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A semiempirical method defining the low-altitude plume properties of temperature, pressure, and velocity is updated to explicitly include the aluminum content of the propellant. The analytical results are compared to centerline total temperature distribution data for nine rocket motors, liquid and solid propellants, with an aluminum content ranging from 0 to 22%, and over three orders of magnitudes of thrust level. For two highly aluminized rockets, the paper results and the SPF-1(KW) results are compared to axial and radial total temperature data and pitot pressure data.

Nomenclature

Al%	= percent aluminum by weight
D	= diameter
M	= Mach number
P	= pressure
R	= gas constant
T	= temperature
X	= axial distance from nozzle exit
γ	= specific heat ratio
c	= chamber
cl	= centerline
opt	= optimum (after isentropic change to ambient conditions)
ss	= sonic tip
t	= total
∞	= ambient

Introduction

A METHOD to describe the low-altitude plume parameters of pressure, temperature, and velocity for rocket exhausts at discrete axial locations was presented[1] in 1969 and published[2] in 1970 and has been in continuous use since. The method required only the combustion chamber pressure and temperature, the nozzle throat diameter, nozzle exit plane exhaust gas constant (or molecular weight) and specific heat ratio, the ambient pressure and temperature, and now the aluminum content of the propellant.

The purpose of this paper is to update the centerline temperature equation to explicitly consider the aluminum content in the propellant. First the empirical equations describing the plume centerline parameters will be given, and then comparisons of analytical results with static test data from nine rocket motors will be presented. The rocket motor propellants are both liquid and solid with aluminum content ranging from 0 to 22% and thrust levels ranging to near 100,000 lb.

Finally, the centerline and radial total temperature and pitot pressure data distributions for the MK56 Dual Thrust Rocket Motor (DTRM) and MK104 DTRM (both 22% aluminum) are compared to the SPF-1(KW)[3] results, as well as the results from this paper.

The primary concern for the work reported here is to determine the effects of exhaust plume heating and loading on adjacent structures during missile firings. The most critical element for predicting exhaust plume heating or loading is an accurate model of the flowfield plume.

Discussion

The basic equations for defining the low-altitude exhaust plume characteristics of this paper are found in Ref. 2. The method is a semiempirical description of the exhaust centerline distributions of pressure and temperature with Gaussian radial distributions. The basic assumptions are:

1) The momentum of the exhaust after expansion or compression to ambient pressure is conserved.

2) Metal oxides in the exhaust species are considered to be in the gaseous state at all temperatures.

3) After the exhaust has expanded or compressed to ambient pressure, the static pressure in the plume is considered to be the ambient value.

4) No shock structure is considered in the supersonic portion of the plume.

5) The supersonic flow of the plume decays smoothly as an exponential function[2]:

$$M_{cl} = M_{opt} \exp - X/X_{ss} \ln M_{opt} \tag{1}$$

where the length of the supersonic region[2] is defined by

$$X_{ss} = \frac{D_{opt}150}{\left[\dfrac{1000\{[(1+\gamma)/2]^{\gamma/(\gamma-1)}-1\}}{P_{t_{opt}}/P_\infty - 1}\right]^{1/(0.235M_{opt}+2.03)}} \tag{2}$$

The 1970 equation for the centerline temperature distribution assumed that the inviscid centerline region existed up to the sonic location in the plume. In other words, the supersonic centerline temperature was assumed to be equal to the combustion chamber temperature, T_c. The subsonic centerline temperature[2] was defined by

$$T_{cl} = 0.1\,[X/(150D_{opt})]^{1/\log_{10}[X_{ss}/(150D_{opt})]}\,(T_c - T_\infty) + T_\infty \tag{3}$$

Centerline temperature data from aluminized propellants have been available since 1970. These data have dictated a modification to Eq. (3) to explicitly consider the percent by weight of aluminum in the propellant. The centerline temperature beyond the inviscid region is now defined by

$$T_{cl} = 0.1\,[X/(C_1 D_{opt})]^{1/\log_{10}[X_{cl}/(C_1 D_{opt})]}\,(T_c - T_\infty) + T_\infty \tag{4}$$

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The constant C_1 is defined as

$$C_1 = 130 - 30\text{Al\%}/22 \quad (5)$$

The centerline length of the inviscid region is now defined as

$$X_{ct} = X_{ss} - 0.33X_{ss}\text{Al\%}/22 \quad (6)$$

As a result of this modification, the inviscid centerline length decreases as the aluminum content in the propellant increases.

Additional centerline pitot pressure data have also become available since 1970 and have dictated a minor modification to the centerline pressure equation for the subsonic region ($X > X_{ss}$). The 1970 equation[2] is

$$P_{t2} = 0.001(150D_{\text{opt}}/X)^{0.235M_{\text{opt}}+2.03}(P_{t\text{opt}} - P_\infty) + P_\infty \quad (7)$$

The modified equation is

$$P_{t2} = 0.001(150D_{\text{opt}}/C_2)^{0.235M_{\text{opt}}+2.03}(P_{t\text{opt}} - P_\infty) + P_\infty \quad (8)$$

where the constant C_2 is defined as

$$C_2 = (X - X_{ss})30D_{\text{opt}}/(150D_{\text{opt}} - X_{ss}) + X \quad (9)$$

The centerline pressure is affected most far downstream and least near the sonic tip.

The overall method is uncomplicated in its mathematical description and effective in its predictive capability. Direct comparison with available data is a persuasive argument for the usefulness of this semiempirical method.

Data Comparison

Table 1 lists the pertinent conditions and geometry of the rocket motor for each set of plume data; nozzle exit geometry is given but is not pertinent in the methodology.

Figures 1-9 are the graphical centerline total temperature comparisons. Statistics for the individual data sets are also given.

Overall, and considering the data scatter, the comparison is excellent. The mean of the calculated values compared to the 70 data points is 1.01 with a standard deviation of 0.31.

Comparison: Standard Plume Flowfield (SPF-1)[3]

The MK56 DTRM rocket exhaust was extensively probed by the Naval Surface Weapons Center (NSWC), Dahlgren, VA,[6] both axially and radially. These data were compared[10] to the results from SPF-1. In addition, the MK104 DTRM rocket exhaust was probed by NSWC and also compared to the results from SPF-1.[7] In both cases, the "KW" mixing model was utilized and,

"All calculations were made with the interim version of the SPF which utilizes the heavy gas approach. However, the code was modified to implement the equilibrated mixture approach. The inviscid/shock calculations were

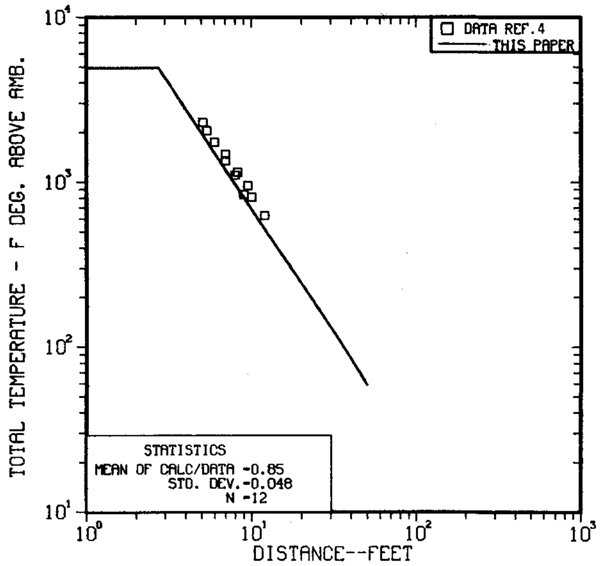

Fig. 1 H_2/OX rocket, total temperature comparison, centerline, 0% aluminum.

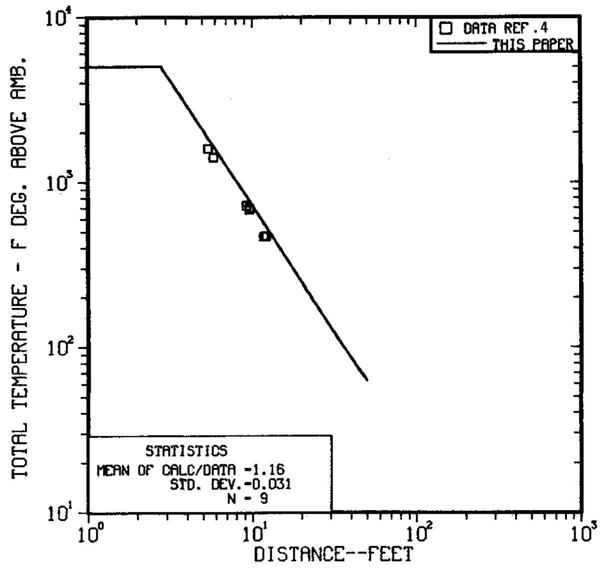

Fig. 2 RP-1/OX rocket, total temperature comparison, centerline, 0% aluminum.

Table 1 Rocket motor parameters[a]

Rocket motor	Chamber pressure, psia	Combustion temperature, °F	Throat diameter, in.	Gas constant, ft/°R	Specific heat ratio	Aluminum, wt.%	Exit diameter, in.
H_2/O_2	500	5000	0.53	88.8	1.28	0	1.50
RP-1/O_2	500	5100	0.53	69.3	1.25	0	1.50
MARC 16Al	2450	5520	0.30	55.0	1.20	21	1.16
MARC 81	2280	5780	0.49	53.8	1.20	18	2.17
MK27 DTRM	2150	5770	0.49	57.1	1.20	15	5.51
MK104 DTRM	2950	6500	2.07	46.8	1.13	22	6.58
MK56 DTRM	2550	6120	2.67	55.0	1.20	22	7.21
MK12	1230	4040	6.68	61.0	1.22	2.5	17.75
MK70	1200	5870	6.40	52.2	1.15	17	17.36

[a]Ambient pressure = 14.7 psia; except MK104 DTRM, 12.0 psia. Ambient temperature = 70°F. Gas constant includes Al_2O_3.

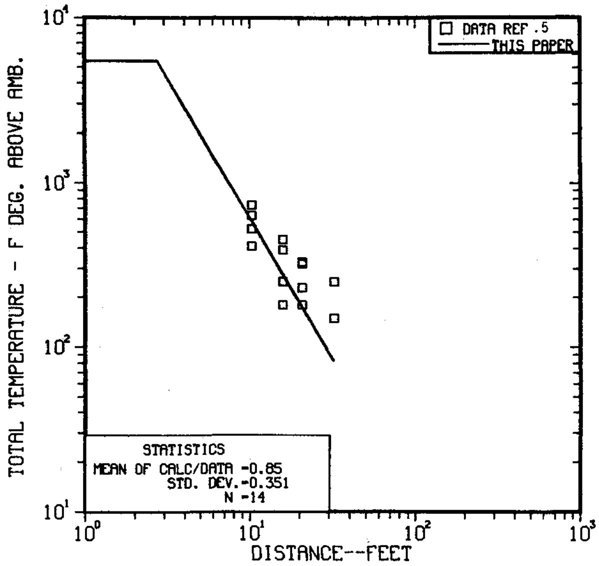

Fig. 3 MARC 16Al, total temperature comparison, centerline, 21% aluminum.

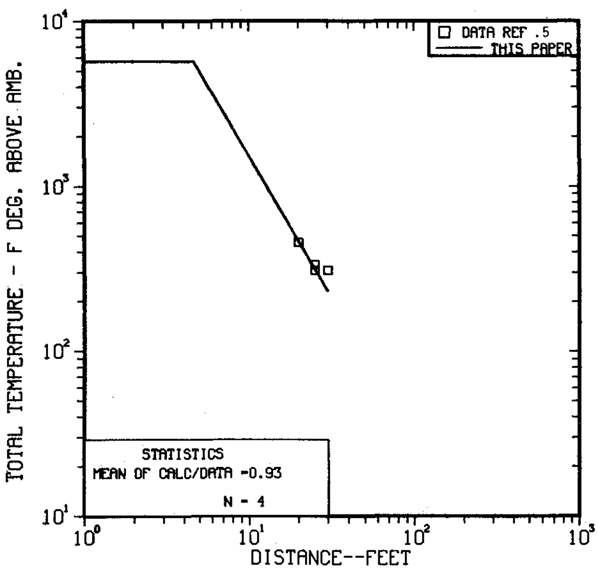

Fig. 4 MARC 81, total temperature comparison, centerline, 18% aluminum.

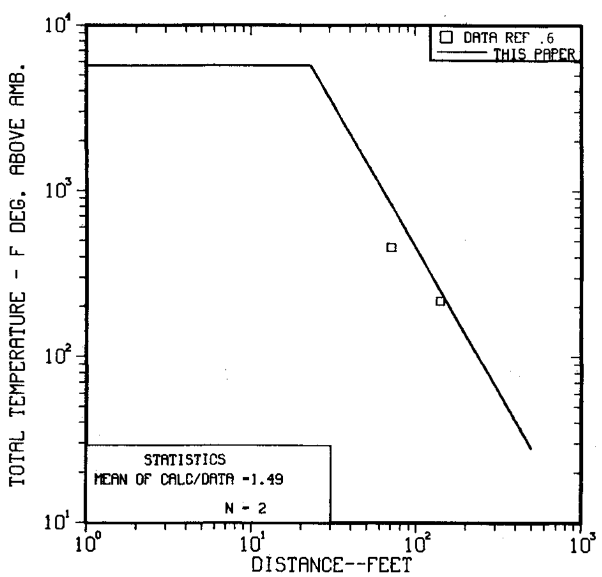

Fig. 5 MK27 DTRM, total temperature comparison, centerline, 15% aluminum.

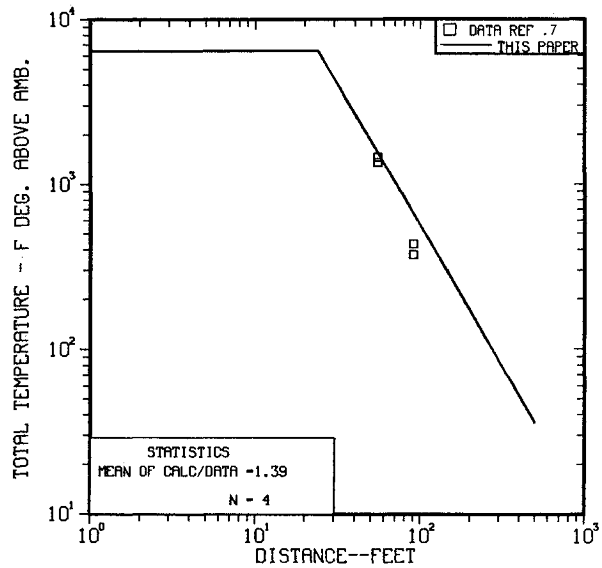

Fig. 6 MK104 DTRM, total temperature comparison, centerline, 22% aluminum.

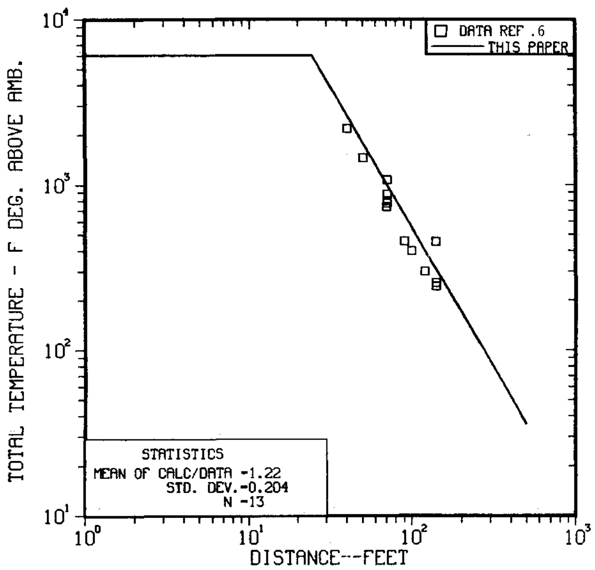

Fig. 7 MK56 DTRM, total temperature comparison, centerline, 22% aluminum.

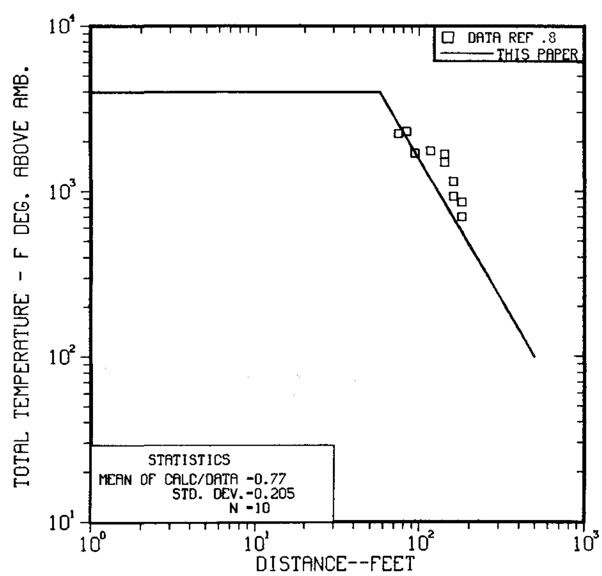

Fig. 8 MK12, total temperature comparison, centerline, 2.5% aluminum.

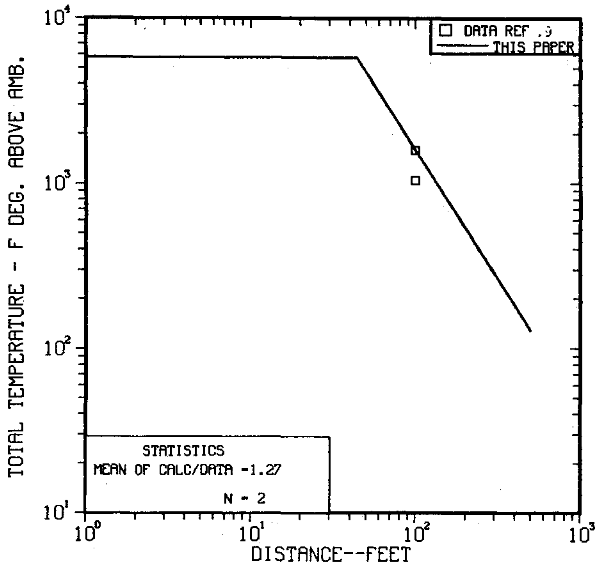

Fig. 9 MK70, total temperature comparison, centerline, 17% aluminum.

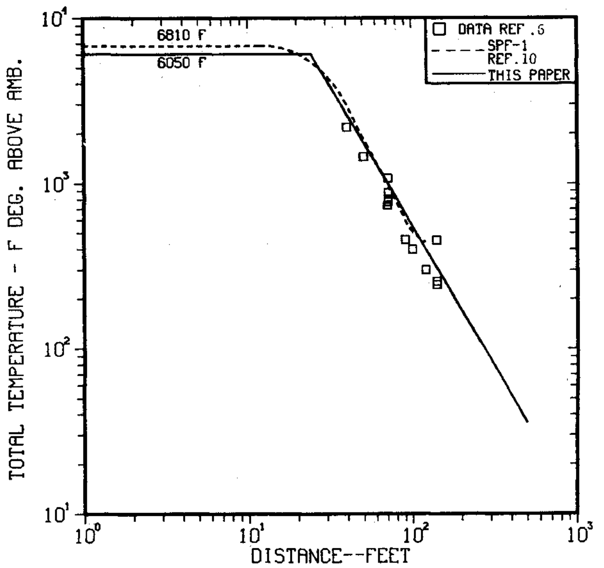

Fig. 10 MK56 DTRM, total temperature comparison, centerline, 22% aluminum.

repeated and used as an overlaid map for the mixing calculations employing the KW model. The results show that the heavy gas and equilibrated mixture calculations are not sufficiently different to influence the turbulence model evaluation. Thus, all results presented here constitute a valid comparison between gas/particle equilibrium plume calculations and the data."[10]

A further comparison with the results from the methods presented herein follow.

Table 2 is a list of the MK56 DTRM input for the SPF-1 and this paper.

Figures 10 and 11 compare the SPF-1(KW) and the results of the present paper with the centerline total temperature and pitot pressure data, respectively.

In the interest of conserving space and considering the strong agreement of the SPF-1 and the present paper along the centerline temperature, the radial temperature profile comparisons will not be presented; suffice it to say that agreement of the radial and axial comparisons is similar.

The pitot pressure radial comparisons are presented in Figs. 12-17.

Table 2 MK56 DTRM input parameters

	SPF-1	This paper
Chamber pressure, psia	2550	2550
Combustion temperature, °F	6220(3710 K)	6120
Throat radius, in.	—	1.335
Area ratio	7.27	—
Exit radius, ft	0.3	—
Specific heat ratio	—	1.2
Aluminum, wt.%	22	22
Molecular weight including Al_2O_3	—	28.05
Ambient pressure, psia	—	14.7
Ambient temperature, °F	—	70

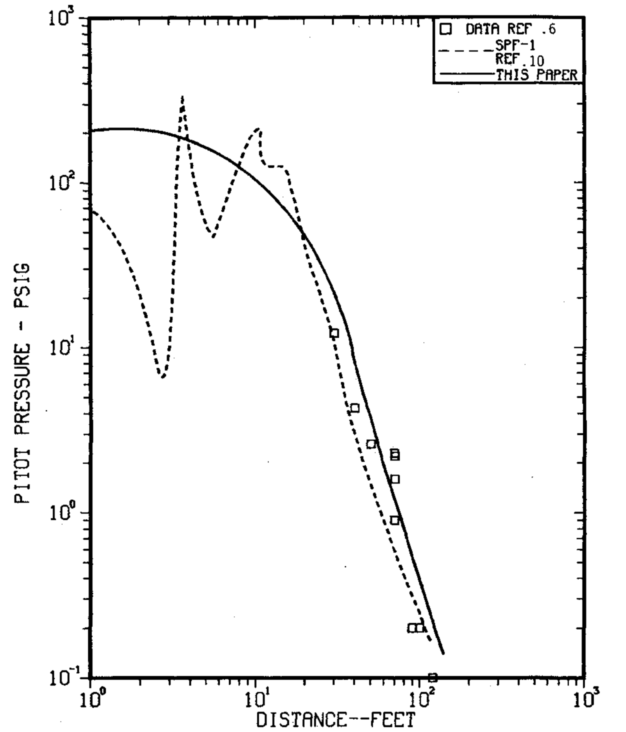

Fig. 11 MK56 DTRM, pitot pressure comparison, centerline, 22% aluminum.

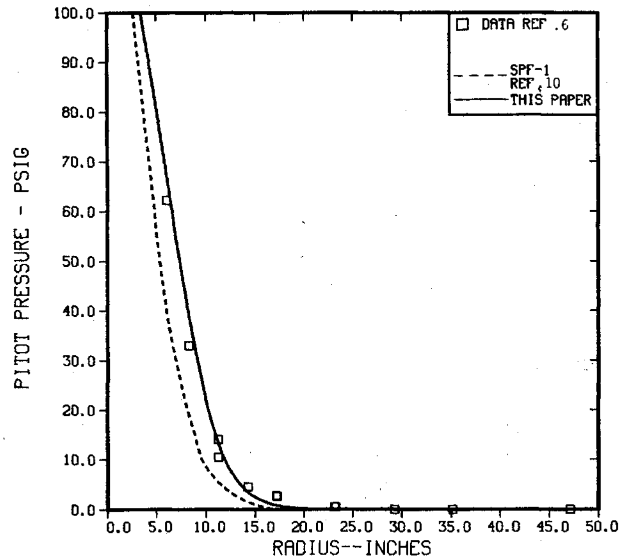

Fig. 12 MK56 DTRM, pitot pressure comparison, $X = 10.4$ ft, 22% aluminum.

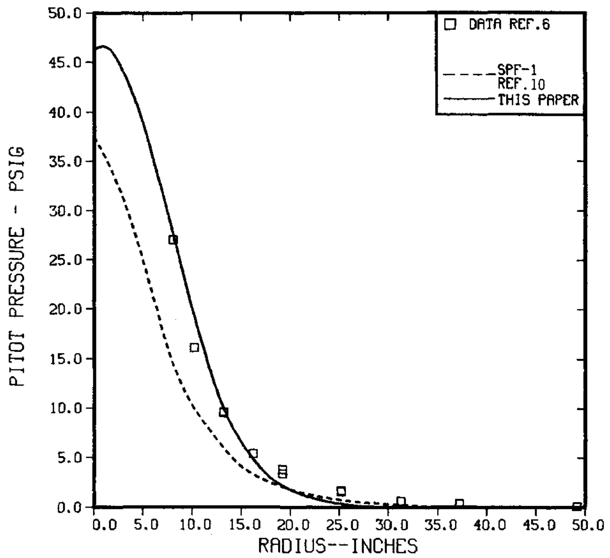

Fig. 13 MK56 DTRM, pitot pressure comparison, $X = 20.4$ ft, 22% aluminum.

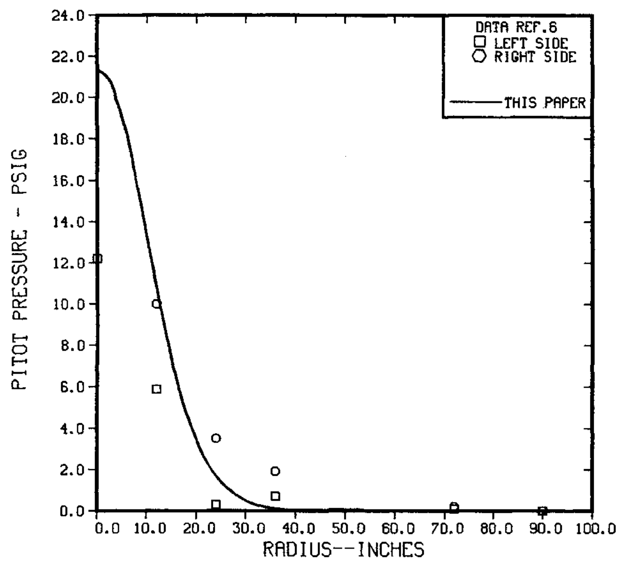

Fig. 14 MK56 DTRM, pitot pressure comparison, $X = 30$ ft, 22% aluminum.

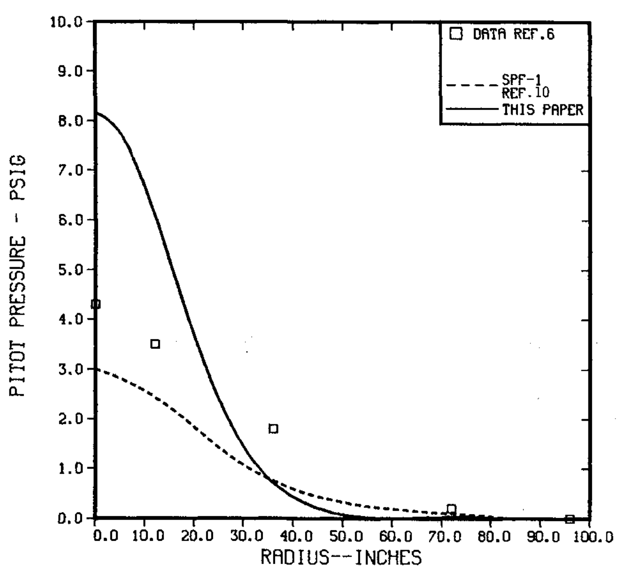

Fig. 15 MK56 DTRM, pitot pressure comparison, $X = 40$ ft, 22% aluminum.

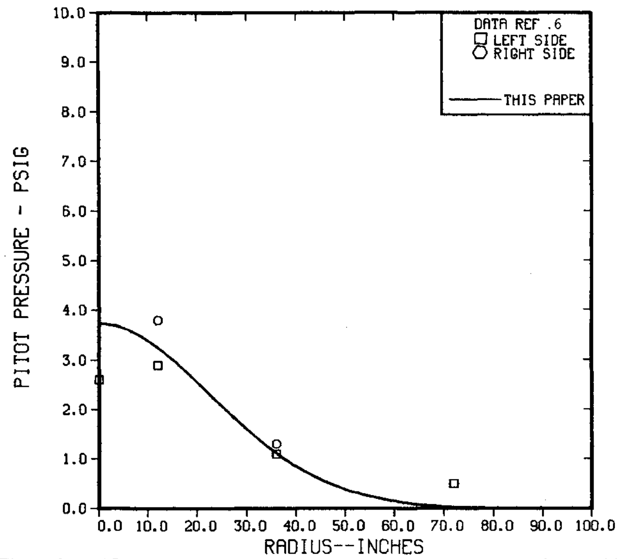

Fig. 16 MK56 DTRM, pitot pressure comparison, $X = 50$ ft, 22% aluminum.

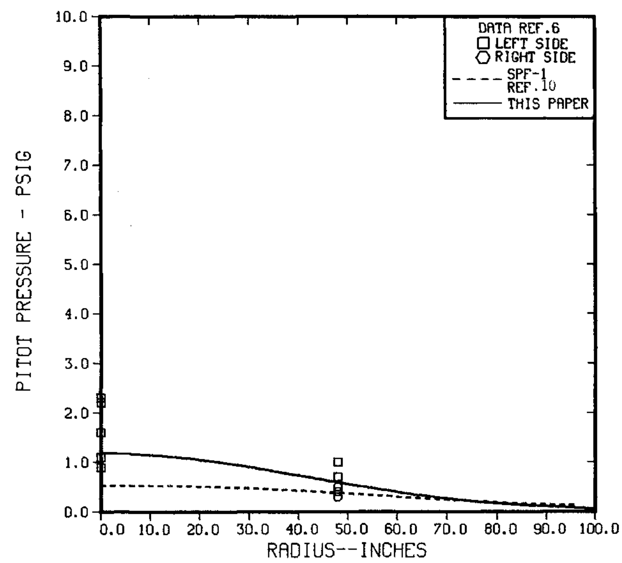

Fig. 17 MK56 DTRM, pitot pressure comparison, $X = 70.4$ ft, 22% aluminum.

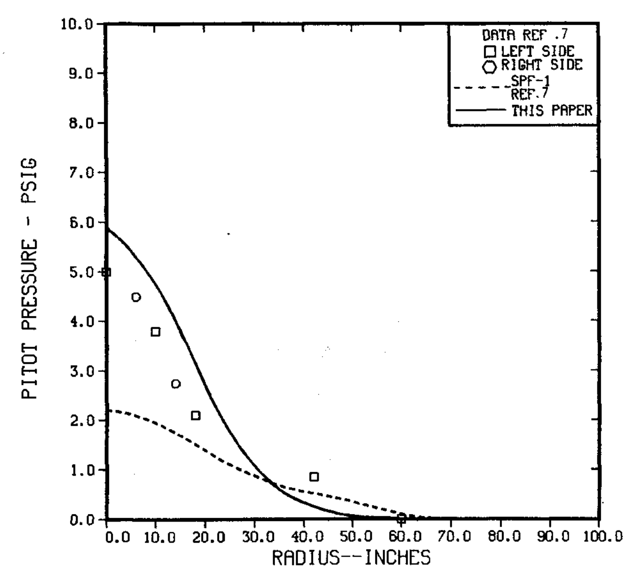

Fig. 18 MK104 DTRM, pitot pressure comparison, $X = 40$ ft, 22% aluminum.

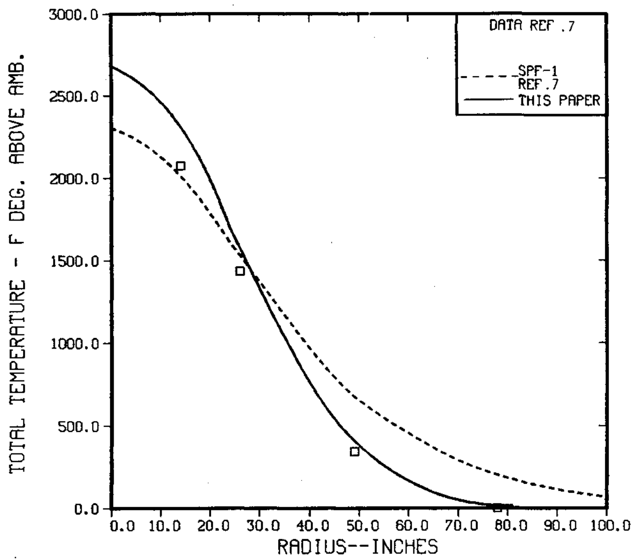

Fig. 19 MK104 DTRM, total temperature comparison, $X=40$ ft, 22% aluminum.

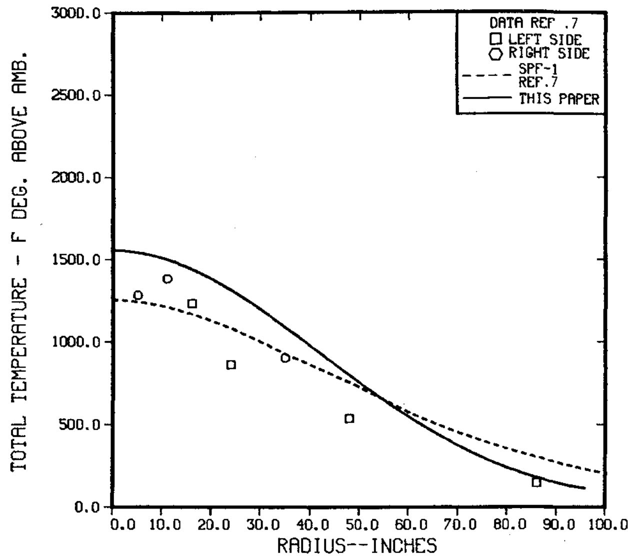

Fig. 21 MK104 DTRM, total temperature comparison, $X=55$ ft, 22% aluminum.

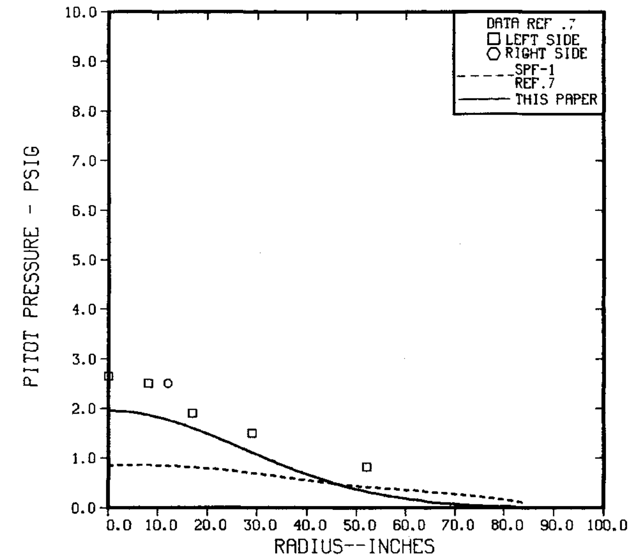

Fig. 20 MK104 DTRM, pitot pressure comparison, $X=55$ ft, 22% aluminum.

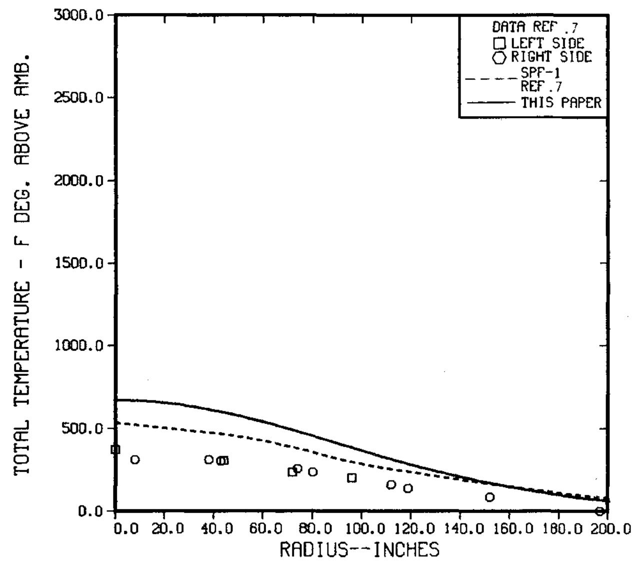

Fig. 22 MK104 DTRM, total temperature comparison, $X=90$ ft, 22% aluminum.

Axial locations $X=30$ and 50 ft (Figs. 14 and 16, respectively) give pressure data on both sides of the pretest geometric vertical center plane. Asymmetry is apparent in the data. Furthermore, beyond 25-30 ft, ground effects may be perturbing the exhaust downward through attachment. "Each rocket motor was restrained in a horizontal attitude approximately 5 ft above the ground plane and allowed to exhaust over a reasonably level terrain...."[6] Although "ground attachment" is a possibility, the evidence that it occurred is insufficient and inconclusive.

The SPF-1(KW) pitot pressure results consistently underestimate the data. If one considers the asymmetry at station 30, the apparent correlation of SPF-1(KW) with the axial data, even at that location in Fig. 11, becomes less tenable.

The radial profile comparisons of the total temperature and the pitot pressure for the MK104 DTRM are given in Figs. 18-22.

Again, SPF-1(KW) gives good agreement with the available temperature data—the method of this paper gives equally good agreement. However, SPF-1(KW) again seriously underestimates the pitot pressure data. On the other hand, the method of the paper is in good agreement for both the MK56 DTRM and MK104 DTRM pitot pressure data.

As stated earlier, the most critical element for predicting exhaust plume heating or loading is an accurate model of the flowfield plume. For the present, the method of this paper appears to be more effective when compared to the available data.

Conclusion

A method[2] published in 1970 to define the low-altitude free plume properties of pressure, temperature, and velocity has been updated to explicitly consider the aluminum in the propellant. On the average, the results of the method agree with 70 centerline temperature data points within 1% with a standard deviation of 31% for nine rockets loaded with 0-22% aluminized propellants.

For the MK56 DTRM total temperature comparison, the results from SPF-1(KW)[3] and the method of this paper are in good agreement with the data and also agree closely. The comparison with the MK104 DTRM limited temperature data also shows reasonable correspondence between each method as well as the data.

The pressure data and the method presented herein are in good agreement for both the MK56 DTRM and the limited MK104 DTRM pitot pressure data. The SPF-1(KW) is in relatively poor agreement with the available pitot pressure data and consistently underestimates the measurements.

It is concluded that the method presented herein is effective in determining the low-altitude flowfield plume parameters used in the prediction of exhaust plume impingement heating and pressure loading.

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