NASA Technical Memorandum 107025
AIAA-95-2435

Metallized Gelled Propellants: Oxygen/RP-1/Aluminum Rocket Combustion Experiments

Bryan Palaszewski
Lewis Research Center
Cleveland, Ohio

and

James S. Zakany
NYMA, Inc.
Brook Park, Ohio

Prepared for the
31st Joint Propulsion Conference and Exhibit
cosponsored by AIAA, ASME, SAE, and ASEE
San Diego, California, July 10–12, 1995

National Aeronautics and
Space Administration

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Bryan Palaszewski
NASA Lewis Research Center
Mail Stop SPTD-2
21000 Brookpark Road
Cleveland, OH 44135

James S. Zakany
NYMA, Inc.
Lewis Research Center Group
2001 Aerospace Parkway
Brook Park, OH 44142

Abstract

A series of combustion experiments were conducted to measure the specific impulse, Cstar-, and specific-impulse-efficiencies of a rocket engine using metallized gelled liquid propellants. These experiments used a small 20- to 40-lb_f (89- to 178-N) thrust, modular engine consisting of an injector, igniter, chamber and nozzle. The fuels used were traditional liquid RP-1 and gelled RP-1 with 0-, 5-, and 55-wt% loadings of aluminum and gaseous oxygen was the oxidizer. Ten different injectors were used during the testing: 6 for the baseline O_2/RP-1 tests and 4 for the gelled fuel tests which covered a wide range of mixture ratios. At the peak of the Isp versus oxidizer-to-fuel ratio (O/F) data, a range of 93 to 99% Cstar efficiency was reached with ungelled O_2/RP-1. A Cstar efficiency range of 75 to 99% was obtained with gelled RP-1 (0-wt% RP-1/Al) while the metallized 5-wt% RP-1/Al delivered a Cstar efficiency of 94 to 99% at the peak Isp in the O/F range tested. An 88 to 99% Cstar efficiency was obtained at the peak Isp of the gelled RP-1/Al with 55-wt% Al. Specific impulse efficiencies for the 55-wt% RP-1/Al of 67-83 percent were obtained at a 2.4:1 expansion ratio. Injector erosion was evident with the 55-wt% testing, while there was little or no erosion seen with the gelled RP-1 with 0- and 5-wt% Al. A protective layer of gelled fuel formed in the firings that minimized the damage to the rocket injector face. This effect may provide a useful technique for engine cooling. These experiments represent a first step in characterizing the performance of and operational issues with gelled RP-1 fuels.

Nomenclature

Al	Aluminum
Cstar	Characteristic velocity (m/s)
IRFNA	Inhibited Red Fuming Nitric Acid
Isp	Specific Impulse (lbf-s/lbm)
lb_f	pound-force
MMH	Monomethyl Hydrazine
N	Newton
O/F	Oxidizer-to-Fuel Ratio
O2	Oxygen
P_c	Chamber Pressure
RP-1	Rocket Propellant-1
wt%	Weight Percent of Fuel Mass

Introduction

Metallized gelled liquid fuels have the potential for increasing the specific impulse, the density, and the safety of rocket propulsion systems. While the benefits and military applications of Earth-storable (IRFNA/MMH) gelled fuels and oxidizers are well established[1, 2], many questions still exist as to their application for NASA missions. Oxygen/RP-1/Al and other cryogenic metallized gelled propellants show promise in the design studies for NASA missions, assuming an engine efficiency comparable to traditional liquid fuels. In the mission studies, there is a relatively limited range of efficiencies where metallized propellants are most effective in reducing booster size and improving delivered payload. Experimental efforts to resolve the performance issue were therefore planned and conducted. The questions that arose prior to and during these investigations include: can propellants be fired successfully in a rocket engine, what is the combustion efficiency, are the metallized gelled propellants easily controlled, and are their flow properties predictable? The NASA experimental work presented here is applicable to small 20- to 40-lbf rocket engines and is a first step toward answering these questions. While all of the mentioned issues have not been fully addressed for all thrust levels, the data from these tests can guide future research and help pave the way for successful future testing.

A test program was conducted to determine the performance of a small-scale rocket engine of 20- to 40-lb_f (89- to 178-N) thrust with metallized gelled O_2/RP-1/Al. Repeatable flow properties of the fuels were also sought in the engine feed system. Testing was therefore conducted with O_2/RP-1/Al propellants with three metal loadings: 0- 5- and 55-wt% aluminum. The gelled fuel constituents were traditional RP-1, aluminum particles, a surfactant, and a gellant. Gaseous oxygen (O_2) was used for the oxidizer. Though liquid oxygen would likely be used in an operational vehicle, it was not available in the test facility. The aluminum was in the form of 7-micron-diameter particles. All testing was conducted with heat-sink engine hardware and typical triplet O-F-O injector designs.

Rocket specific impulse (Isp), Cstar- and Isp-efficiency, and heat transfer measurements were desired in this test program. Since no data were previously available for O_2/RP-1/Al rocket combustion, rocket performance measurements were sought and obtained. The purpose of the experiments was to determine the realistic combustion efficiency one might expect for O2/RP-1/Al metallized gelled fuels and to see if a rocket combustor could deliver the relatively high efficiency needed for successful NASA applications of metallized gelled combustion. Facility limits restricted the testing to a small combustor, so the efficiency might not be as high as predicted for a full-scale engine, but the data would nonetheless help guide future large-scale testing efforts. These experiments were also done to identify conditions or metal loadings that will provide better efficiency and other information that will improve the thinking in future trade studies.

During the combustion of metal particles, two-phase flow creates a mismatch in the combustion time scale of the liquid droplets and the solid particles[3]. Heat transfer measurements were envisioned so that some estimate might be made of the delay in ignition for the aluminum, as well as the engine wall temperatures. Both baseline non-metallized propellants and various metal loadings with gelled RP-1 were used to compare the combustion temperature and heat flux profiles at different axial locations in the combustion chamber. In this paper, however, only the rocket performance data will be addressed.

Background

Metallized gelled propellants have been studied analytically and experimentally for over 60 years[4]. The historical work has focused on the benefits of high specific impulse, high density, and safety[4, 5, 6, 7]. Current uses for these propellants lie in tactical and strategic missiles and aircraft ejection seats[1, 2, 7]. Extensive work has been conducted with metallized gelled Earth-storable propellants, such as hydrazine, Inhibited Red Fuming Nitric Acid (IRFNA), and monomethyl hydrazine (MMH)[1,2]. However, these propellants are not planned for use in future NASA launch vehicles due to environmental concerns. To explore the potential of metallized gelled fuels, NASA chose to pursue the propellant combinations that were more suitable to its future plans[3, 8-14]. The NASA Lewis Research Center has been conducting experimental, analytical, and mission studies concerning metallized gelled propellants since 1987. This work has concentrated on O_2/RP-1/Al and other propellant combinations and the issues related to using these gelled propellants with metal particle additives[8].

Why Metallized Gelled Propellants?

A series of propulsion and vehicle trades studies[8, 11, 12, 15, 16] had shown a potential benefit for metallized gelled fuels for NASA launch vehicles and have indicated that O_2/RP-1/Al can have significant benefits by increasing propellant density. Figure 1, based on data from Ref. 11, depicts the potential increases in payload enabled by high-density 55-wt% RP-1/Al. Using O2/RP-1/Al propellants in a Liquid Rocket Booster replacement of the Space Shuttle Solid Rocket Boosters (SRB)[11, 15, 16] allows for shorter boosters because of the propellant density increase. Alternatively, for the same booster size, O2/RP-1/Al has the potential for higher payload delivery mass over traditional solid propellants. With O2/RP-1/Al, the specific impulse is lower than that for O2/RP-1 propellants, even for the highest payload benefit cases. This payload increase is enabled because the high density of the metallized gelled fuel allows a larger mass of propellant to be placed in a smaller volume than traditional liquid propellants, and a larger total impulse is contained in the booster volume with the gelled fuel. Propellant safety is also enhanced by using gelled fuels, with propellant spillage being restricted and the leakage paths being minimized by the gel's viscosity[17].

Based on rocket engine and vehicle performance studies, 0,- 5-, and 55-wt% aluminum loadings in RP-1 seemed the most attractive[11]. During the course of these investigations, it became clear that gelled fuels with no metal additives may be more attractive to users than those with metal particles. A stepping-stone approach where gelled fuels are first used and then the users evolve toward metallized gelled propellants is a definite option. Future vehicles using gelled fuels may allow for slosh reduction, added safety, and leakage reduction. Therefore, gelled RP-1 (0 wt%) was one of the selected candidates. The 0-wt% loading provided a basis of comparison to estimate the gains or losses of gelling the RP-1. Based on a parametric engine performance analysis, the 5-wt% loading delivered the maximum predicted Isp for the O2/RP-1/Al combinations. This was one reason for the selection of this metal loading. Another reason is that, based on design of experiments methodologies, the selection of three different metal loadings would show the relative trends in performance, and allow the data to be compared to the theoretical trends.

Experimental Setup: Fuels and Rocket Engine

Fuel Preparation

Metallized gelled fuels with different metal loadings were investigated. Table I provides the constituents of the different fuels. The gelled RP-1 was prepared with a 6.5-wt% gellant concentration. This gellant loading was selected based on a series of gelling experiments in which a range of 1-10 wt% gellant was used. The 6.5 percent level was selected so that both the 0- and 5-wt% RP-1/Al had a similar viscosity. With the 5 wt% RP-1/Al fuel, 5 wt% gellant was added and with the 55 wt% RP-1/Al, the gellant fraction was 3.5 wt%. The metal particles act as pseudo-gellants and therefore less gellant is required as the metal loading increases. When mixing, it is important to add the "dry" elements first: adding metal, then gellant, then fuel. A very small wt% of liquid surfactant, Tween 85, is also added as the last component to the 55-wt% metal loaded fuel.

The metallized gelled propellant density is computed using:

$$\text{Gel Density (kg/m}^3) = \frac{1}{\frac{(1 - ML)}{\text{RP-1 Density}} + \frac{ML}{\text{Al Density}} + \frac{\text{SIO2 Loading}}{\text{SiO2 Density}}}$$

where:

ML	weight fraction of metal (Al) in the total weight of fuel
SIO2 Loading	weight fraction of gellant (SiO_2)in the total weight of fuel

One-half gallon (0.0019 m^3) batches of the fuel were prepared and a paint rejuvenator (or shaker) was used to mix the fuel components. The one-gallon (0.0038 m^3) can was typically half filled to allow for more effective mixing of the components during the shaking process. The dry components are very fine and powdery, requiring the operator to use a respirator.

Propellant preparation and transfer

A positive-displacement piston-cylinder was used to feed gelled fuel to the rocket engine. A simplified schematic of this arrangement is shown in Figure 2. To place the gelled fuel into the piston tank, a transfer tank system was constructed and consisted of a 10 gallon (0.038 m^3) pressure vessel that was rated for 150 psig. The gelled fuel was poured into the transfer tank, and after sealing the tank, it was pressurized to about 70 psig with nitrogen. The fuel was then transferred to the piston tank. Pressure was maintained on the hydraulic-fluid side of the piston to control the flow of gel into the tank and prevent any bubbles of other gases from mixing with the gel. The piston-cylinder's outflow path was then routed to the engine. Nitrogen was used because gelled fuels will evaporate when exposed to air and the remaining dry components can restrict flow passages. Much effort was exercised to minimize the fuel's air exposure prior to actual rocket testing.

Combustion Testing Description

The combustion testing was conducted in Cell 21 at NASA Lewis which was configured to test low thrust rocket engines (nominally 50 pounds thrust) at sea level or altitude conditions. Only minor modifications to the cell were necessary to safely handle the gelled RP-1/Al propellant mixtures and to capture the exhaust products for analysis and disposal. A propellant feed subsystem was installed to supply the engine with metallized gelled propellant and the main component of this system was a high pressure hydraulic piston cylinder. This cylinder was fed with the propellant mixture from a pressurized transfer tank. After being charged with gelled fuel, the piston cylinder was pressurized with hydraulic fluid. Propellant flow was then regulated by limiting the flow of hydraulic fluid into the piston cylinder by controlling the fluid pressure upstream of a cavitating venturi. The results obtained with this method were highly repeatable and the propellant remained fluid and its mass flow rate was held nearly constant with only small variations during a run. Variations in the fuel mass flow rate with the differing engine conditions were manageable. Throughout most of the test matrix, the fuel feed system parameters (venturi types, gelled fuel tank pressure settings, etc.) were kept constant and the oxidizer load pressures were changed to achieve various propellant mixture ratios. Another modification to the test cell was the addition of an exhaust recovery system. This modular system of scrubbers, pumps, and collection filters allowed the experiment to be accomplished with far less environmental impact than any similar metallized gelled testing conducted in this facility. Since the exhaust products were collected, they could easily be examined for further data concerning the combustion of the fuel mixtures.

While the RP-1 and RP-1/Al are liquids or gels, all of the other propellants in the cell, O_2, H_2, and N_2, are provided in gaseous form. Both the O_2 and H_2 are used for the engine igniter and are provided from high-pressure trailers. Nitrogen is used as a purge gas to protect the igniter and engine after engine shutdown. The liquid RP-1 propellant is delivered to the engine from an 8-gallon (0.0303 m^3) pressurized tank attached to the cell. Gelled propellants are pressurized and fed using the piston-cylinder tank. Mass flow rates of the propellants were measured by Coriolis-force mass flow meters, in the case of RP-1 and the gelled propellants, and by pressure transducer outputs coupled with choked jeweled orifices in the feed lines in the case of gaseous propellants. Flow of the liquid propellants was limited by cavitating venturis. In all cases, upstream load pressures determined the mass flow rates of the propellant. The test matrix conditions (variations in O/F) were satisfied by varying these load pressures and by changing the flow control devices.

Several data acquisition systems were employed to provide the cell operator and the researcher with timely and complete data. High fidelity research data was collected with a high-speed data acquisition system and it was used for highly transient rocket engine measurements of chamber pressure and engine propellant manifold pressures. The system provides a 50 kHz sampling rate with 100 data channels. Immediate performance data was available on the strip-chart data logging chart recorder. This recorder could display up to 16 channels of data sampled at 200 kHz. Steady state data was collected and presented by a low-speed system, with a 1-second sampling rate and it was used to record more steady state data on propellant line and tank pressures and temperatures. This system supports over 100 channels. Pressures were measured in the combustion chamber on the injector face and in some cases on the chamber wall near the injector face. Flow pressures and temperatures of the propellant and purge gases were measured upstream and downstream of the orifices. The mass flow meters were used to determine the RP-1 and the gelled propellant flow rates. Propellant tank temperatures and pressures were also measured, as well as the position of the positive-displacement cylinder of the gelled propellant piston-cylinder.

In addition to digital data, each run was recorded by a video camera and saved on video tape (VHS format). Selected runs were also filmed with a high speed film camera at 2000 frames per second. Several still photographs were taken between and during each run. Extensive photographic records were collected of the test hardware before and after run sets. These photographic data were useful in describing the unusual coloring in the exhaust plumes and determining how propellant buildup in the nozzle may have caused these plume color variations.

Engine Hardware

A heat-sink combustion chamber and nozzle composed of oxygen-free electronic copper were used. Figure 3 shows a diagram of the engine configuration. In conducting these tests, modular hardware was desired so that a wide range of injector oxidizer-to-fuel (O/F) ratios could be tested. Also, any damaged hardware could be removed and easily replaced. During the testing, a wide range of O/F ratios were investigated and the injector elements were designed to accommodate this range based on the facility limits and pressure drop across the injector. The injectors were designed for an O/F range of 1.2-4.2 for O_2/RP-1 and 1.4-3.7 for O_2/RP-1/Al. The chamber spool piece had a 2.6-inch inside diameter and was 6 inches long and the nozzle had a 0.6-inch diameter throat. The nozzle expansion ratio was 2.4:1.

The injector elements are a gaseous-oxidizer O-F-O triplet designs and both four- and eight-element patterns were tested. All of the elements were arranged in a mutually perpendicular pattern. Due to the use of a metallized gelled fuel, there is the potential of the RP-1 evaporating and the remaining mix of particles and gellant drying in the fuel passages. Using a removable fuel dome minimized the difficulty of cleaning of propellant particles from the flow passages and flowing propellants through the dome eliminated the possibility of them being trapped in a complex set of flow passages in the internal body manifold. The injectors therefore used an oxidizer manifold within the injector body and have a fuel dome set atop it.

The igniter assembly consisted of a 0.210 in^3 (3.437-cm^3) volume hydrogen-oxygen mixing chamber, a spark igniter, and a 0.187 in (0.475-cm) diameter flame propagation tube. Hydrogen and oxygen entered the mixing chamber through opposing inlets. Hydrogen was also directed along the exterior of the flame propagation tube to cool it. A high O/F ratio was maintained in the igniter assembly to reduce the flame temperature.

Engine Mounting, Startup, and Shutdown

The engine, including the injector, igniter, chamber and nozzle, was mounted to the test stand with stainless steel rods that are screwed into and protrude from the injector body. All of the engine components were assembled with threaded bolts. Three metal seals and one elastomeric O-ring are needed for assembling and sealing the engine components. After the engine is mounted in the test stand, the major connections are for the primary fuel and oxidizer manifolds, the igniter fuel and oxidizer and the purge flows for all of the flow paths except the primary fuel. A typical ignition sequence begins with the O2/H2 torch igniter firing for 1 second, and after 0.2 to 0.4 seconds of operation, the fuel and oxidizer valves are turned on sequentially, with a 0.2 to 0.3 second fuel lead. After main engine ignition has occurred, the igniter flow is shut off and a nitrogen purge is initiated to prevent the igniter from being consumed by the main combustion flow. The total steady-state operating time of the engine was 0.5 seconds. This purge flow pressure is a minimum of 30 psi higher than the main chamber pressure to assure that no combustion products build up in the thin igniter tube. This purge flow is on during the entire engine firing after the igniter is shut down and it significantly increased the total flow rate in the engine by anywhere from 10-40 percent of the primary propellant flow rates. Figure 4 shows the effect of the added nitrogen flow on the chamber mixture ratio. The O/F is plotted versus the chamber mixture ratio (O/F_C), where the O/F_C is computed assuming that the nitrogen flows are "fuels" and this mass flow is in the denominator or:

$$O/F_C = \frac{\text{Oxidizer flow rate}}{\text{Fuel flow rate + N2 purge flow rate}}$$

In the figure, it is clear that the O/F can be seriously affected by the nitrogen purge flow. However, the high O/F cases are the most strongly influenced. These purge flow rates were included in all of the Isp calculations, and the added nitrogen does significantly reduce the overall engine Isp. The other purge issue not addressed is the location of the nitrogen plume in the chamber. The igniter purge flow is centrally located in the injector and exhausts into the chamber, while the injectors surround the igniter and the main combustion flow is occupying the complete chamber volume. The degree of mixing between the purge and main flows is not accounted for in the theoretical performance calculation. Additional analyses can be conducted to determine the effect of the localized nitrogen flow on engine performance.

Table II provides a summary of the typical mass flow rates and performance for a 55-wt% RP-1/Al engine firing and shows the associated nitrogen purge flow rate. The engine had an overall mass flow rate of 0.1238 lbm/s (0.0562 kg/s), the O2 flow was 0.0564 lbm/s (0.0256 kg/s), and the gelled RP-1/Al mass flow was 0.461 lbm/s (0.2091 kg/s). The nitrogen purge flow protecting the igniter is 17.3 percent of the total mass flow of the engine. Clearly, this is not an insignificant percentage of the flow. Larger scale operational rocket engines would have no such purge flow. Experiments in larger thrust engines (> 10,000 lbf) would have a decidedly small percentage of an igniter purge and will offer more representative results.

Combustion Experiments: Results, and Observations

Engine Performance and Efficiency

The results presented are based on initial analyses of the test data. All of the results presented are for the heat sink engine. The overall Isp, Cstar efficiency, Isp efficiency, and other important data are presented to show some of the important features and potential difficulties with metallized gelled fuels. The theoretical engine performance[18] was calculated using a standard rocket performance computer code for each fuel type to predict the theoretical maximum of Isp and Cstar. The experimental efficiency of the rocket engine was computed based on the measurements of chamber pressure, the throat area of the engine, the nozzle thrust coefficient, the propellant flow rates, and other parameters.

The basic simplified computations for Isp, Cstar efficiency and Isp efficiency are shown below:

Theoretical Vacuum Specific Impulse

$$IVT = \frac{F}{WTOT} \quad \text{(lbf-s/lbm)}$$

where:

IVT = Theoretical Vacuum Specific Impulse
WTOT = Total Mass Flow Rate in the Engine (including N2 purges)

$$F = CF * PC * MPL * AT$$

where:

CF = Thrust coefficient at nozzle exit
PC = Chamber Pressure
MPL = Momentum Pressure Loss
AT = Throat area

Cstar efficiency

$$CSXP = \frac{PC * MPL * AT * G}{WTOT} \quad \text{(ft/s)}$$

where:

CSXP = Experimental Cstar

G = Gravitational Constant

and:

$$NCSP = \frac{CSXP * 100}{CST} \quad (\%)$$

where:

NCSP: Cstar efficiency (based on chamber pressure)
NISPP = Cstar efficiency
CST = Cstar predicted using Ref. 18

Isp efficiency

$$NISPP = \frac{IVT * 100}{IVAC} \quad (\%)$$

where:

NISPP = Isp efficiency
IVAC = theoretical vacuum specific impulse predicted using Ref. 18

Results

The test results of Isp, Cstar efficiency and Isp efficiency are plotted versus the main combustor O/F range tested for each fuel and these figures are described in the succeeding sections. The O/F provided in the figures is the main combustor O/F, and not the chamber O/F (O/F_C) described in a preceding section. In each set of data for the gelled fuels, there is a wider range of variability than that seen with the ungelled RP-1. This variability is caused by the deposits of metal in the chamber and the nozzle, the erosion of the injector, and the potential of gelled propellant density variations as the propellant flowed through the feed system to the injector. These effects are described in the section on observations. Some of the engine performance numbers appear to be very low. These low values represent outliers where the correct engine ignition or the correct flow rate was not achieved. These outliers are caused by propellant flow blockages, or configuration changes when switching from runs of igniter tests to operating the complete engine system. Figures 5, 6, and 7 summarize the results. In Figure 5, the peak Isp produced by each fuel and the range of Isp variation near the peak value are shown. The theoretical predictions do not exactly match the experimental trends for the 0- and 5-wt% RP-1/Al. The trend is not concerning the values of the Isp, but the relation between the different values. With the 0- and 5-wt% RP-1/Al, the theoretical trend is a small increase in Isp for both of these fuels over RP-1 and a reduction in Isp for the 55-wt% RP-1/Al. While a small increase in Isp was predicted for the 0- and the 5-wt% RP-1/Al, there was no increase in Isp over RP-1 that is demonstrated in the experimental data. There is, however, a very small increase in the experimental Isp going from the 0-wt% RP-1/Al to the 5-wt% loading, consistent with the predicted theoretical trend. The 55-wt% RP-1/Al follows the reduced Isp trend noted in the theoretical predictions.

Figure 6 shows the Cstar efficiency ranges from the experiments. All of the fuels showed a high upper bound on the Cstar efficiency: near 99 percent. The RP-1 varied from 97 to 99 percent and the gelled RP-1 (0 wt%) had a range of 75 to 99 percent. The 0-wt% RP-1/Al showed the greatest variation in the efficiency. With the 5-wt% fuel, the dispersion in efficiency was from 94 to 99 percent, while the 55 wt% variability was 88 to 99 percent. A summary of the Isp efficiency is presented in Figure 7 and all of the gelled fuels had similar variations in the efficiency data. The RP-1 efficiency only varied from 81-86 percent, while the gelled RP-1 (0 wt%) efficiency ranged from 61-85 percent. The other fuels had a slightly narrower range of variation, with 62 to 84 percent with the 5-wt% RP-1/Al and 67-83 percent with the 55-wt% fuel.

O_2/RP-1

Figure 8 presents the Isp versus O/F for the O2/RP-1 engine. The maximum Isp for the RP-1 was 223 lbf-s/lbm and was located near an O/F of 2.1. This peak is different from the typically computed peak near 2.7 for O2/RP-1[11]. The difference is due to the added nitrogen purge gas in the flow. The Cstar efficiency is plotted versus O/F in Figure 9. With the O_2/RP-1, the maximum Cstar efficiency of 99% occurred in the O/F range of 1.7 to 2.2. The data also showed a lowest Cstar efficiency of 93% in this O/F range. The Isp efficiency is shown in Figure 10 and, for the RP-1 (ungelled), the efficiency was in the range of 80 to 86%, again in the O/F range of 1.7 to 2.2. The maximum Isp efficiency of 86% occurred at an O/F of 1.7.

RP-1/Al: 0-wt% Al

In Figure 11, the Isp of the 0-wt% RP-1/Al engine is provided. The maximum Isp for the 0 wt% RP-1/Al was 220 lbf-s/lbm and was located in the range of O/F from 2.0 to 2.4. Figure 12 illustrates the engine's Cstar efficiency. With the gelled RP-1 (0-wt% RP-1/Al), the O/F for the maximum Cstar efficiency was not restricted to a narrow peak, but had high values at several points between an O/F of 0.8 to 5.4. This fuel demonstrated a very high Cstar efficiency of up to 99% at an O/F of 0.8, 2.5, and 5.4. The Isp efficiency for the 0-wt% RP-1 was 61% to 85% and the data for the range of O/F ratios are shown in Figure 13.

RP-1/Al: 5-wt% Al

As shown in Figure 14, at a 5 wt% RP-1/Al loading, the Isp peak occurred in the range of an O/F of 2.0 to 2.3. The peak Isp was 220.3 lbf-s/lbm at an O/F of 2.0 and the lowest Isp at this O/F was 205 lbf-s/lbm. Also, the performance has a band of variability over the entire O/F range, but the variation is narrow and the performance was more repeatable compared to the 0-wt% and 55- wt% RP-1/Al. Using 5 wt% O_2/RP-1/Al, a range of 95-99 % Cstar efficiency was delivered. The efficiency data, provided in Figure 15, had a very flat response, with a broad peak in the curve from an O/F of 2.4 to 3.6. The Isp efficiency, depicted in Figure 16, had a similar broad peak, but its peak ranges from 1.1 to 3.6. This data had a maximum of 83.8% at an O/F of 1.1.

RP-1/Al: 55-wt% Al

As shown in Figure 17, at a 55 wt% RP-1/Al loading, the Isp peak occurred in the range of an O/F of 1.2 to 2.0. The peak Isp was 197.2 lbf-s/lbm at an O/F of 1.23. Also, the performance varied about 10 to 15 percent over the entire range of O/F. Figures 18 and 19 show the Cstar efficiency and Isp efficiency versus O/F for 55-wt% gelled RP-1/Al, respectively. The Cstar efficiency for this propellant was as high as 99% (at an O/F of 2.0) and low as 88% at a similar O/F. With Isp efficiency, the values ranged from 82.7% at an O/F of 2.0 and the lowest value at that O/F is 73%.

Observations

Dispersions in performance. In all of the gelled propellant data, there are somewhat large variations in the performance and engine efficiencies. These variations are due to the potential propellant density variations in the mixed fuel. As the propellant sits in the tank during a day of testing, the metal particles will settle to some extent. This settling is, however, easily overcome with gellants that are specifically designed for long-term storage[17] but they were not used in this test program because of their cost of production. Also, when the engine is fired, there is a coating of uncombusted propellant and combustion products that forms on the engine walls. As the engine is fired multiple times, the coating may add to or detract from the engine performance as it reacts with the newly injected "fresh" propellants. At a minimum, the O/F of the engine is not precisely equal to the planned O/F. Other influences creating dispersions were the fouling of the chamber pressure taps by the gelled fuel combustion products. This was most evident during the 55-wt% RP-1/Al testing. After 10-15 runs, the pressure transducer would have to be removed and residual propellant would be cleaned from the transducer. Also, the tube connecting the transducer to the injector face tap would be cleaned out. Only very slow fouling of the transducers occurred during the testing of the gelled 0- and 5-wt% RP-1.

Self-protection of injectors. During the testing with gelled RP-1 and the 5-wt% RP-1/Al, some residual propellant was found in the rocket chamber, coating the entire injector face and all of the chamber walls. This residual propellant was actually a mix of unburned fuel (with a gray or clear pink color) and some black or combustion products. This effect was perhaps due to the fuel lead of 0.2 to 0.3 seconds used in the ignition sequence of the engine. After many firings, this added propellant did not completely undergo combustion, and formed this smooth layer on all the internal surfaces. While no clogging of the injector ports occurred, there is the potential for the gel to obstruct the ports to a small degree. Once this thin layer was removed with a soft cloth, the metal surfaces exhibited minimal erosion. An improved cooling technique might be derived from this effect.

With the ungelled RP-1 and 55-wt% RP-1/Al, there was no protective effect layer formed. There was discoloration and blackening of the O_2/RP-1 injector faces and injector-face erosion, pitting, and metal deposition that occurred with the 55-wt% RP-1/Al. The greatest damage was done to the 55-wt% RP-1/Al injectors after they had been used, removed, cleaned, and replaced in the engine. Residual metal particles that had been retained in the O2 manifold and the other injector flow passages were areas where O2 attacked the metal and, in some cases, caused severe injector damage.

Propellant buildup in nozzle's converging section. During the testing, there tended to be a small buildup of gelled fuel in the converging region. With the engine mounted horizontally, this buildup of propellant was located primarily on the lower portion of the nozzle's converging section and it had several noticeable effects on the combustion. When firing the gelled fuel with 0- and 5-wt% RP-1/Al, the bottom of the exhaust plume tended to appear clear, while the upper portion was much more optically thick or white and this effect was captured on video, still photography and high-speed film. This propellant buildup seemed to sweep particles out of the lower part of the plume. The effects of this sweeping may be the cause of the somewhat larger dispersions in the Isp efficiencies of the 0- and 5-wt% RP-1/Al tests when compared with the ungelled RP-1 and 55-wt% RP-1/Al.

Metal agglomerations in the nozzle. When testing the 55-wt% RP-1/Al, metal agglomerations occurred in the nozzle. After 15, 2-second firings, the agglomeration had reduced the throat diameter from 0.6 inches to 0.45 inches. Several finger-like filaments extended out if the nozzle along its walls. This agglomeration was a hardened metal buildup that could not be easily brushed off. After taking the nozzle off the rig, the agglomeration could be chipped off with a chisel and once loosened, came off in large segments. At first, the coating on the nozzle was very thin, but after the first ten firings, the buildup of metal became very large and thick.

Injector erosion: 55-wt% RP-1/Al. Firings with the 55% RP-1/Al resulted in good performance, but the injector erosion was much greater than with any other fuel. Firing an injector for the first time produced no significant injector damage. Metal particles would tend to dry onto the injector surface and become sites for O2 to attack the metal. After removing the injector and attempting to clean it and remove the metal particles from it, conditions for O2 cleanliness were not maintained. Subsequent firings caused very significant injector damage, resulting in burning of residual metal particles in the O2 manifold and in the O2 posts. A method of eliminating the deposition of dried metal particles on the metal injector surfaces and ways of improving the cleaning process of the O2 manifolds will be important for future testing programs.

Concluding Remarks

Rocket combustion experiments were conducted with metallized gelled propellants using RP-1/Al fuels. These first combustion experiments with RP-1/Al were a focus for learning about and documenting the actual rocket performance and any potential operational pitfalls. This work is an ongoing set of analyses to determine the viability of gelled propellants and their possible applications to NASA missions. Additional analyses are planned of calorimeter rocket engine heat transfer measurements with RP-1, 0-, 5-, and 55-wt% RP-1/Al gelled fuels. Continuing system studies will use the data from these and other experiments to find the appropriate uses of metallized gelled propellants.

High efficiency combustion of metallized gelled propellants was realized with even simple 4- and 8-element triplet injectors. With metallized gelled fuels, Cstar efficiencies of 70 to 99 percent were achieved, with the range of Cstar efficiency for the 55 wt% RP-1/Al being 80 to 99 percent. Though the high metal loading, 55-wt% RP-1/Al, engine runs experienced some agglomeration and erosion difficulties, the 0- and 5-wt% tests ran well, with a high Cstar efficiency, and demonstrated a self-protective layer of gelled propellants and combustion products. The most interesting results occurred with the 0% and 5% RP-1/Al formulations. A thin layer of gelled fuel and combustion products formed throughout the chamber and protected the face of the injector from virtually all burning, scoring, or other damage.

Firings with the 55% RP-1/Al resulted in good performance, but the injector erosion was the greatest of any of the tested fuels. Improving the cleaning process of the O2 manifolds, or preventing the flow of particles into the manifolds would allow more cost effective and longer-lived testing of the 55-wt% RP-1/Al. More easily disassembled manifolds and injectors would allow better access to flow passages that would trap metal particles. Prevention of the deposition of dried metal particles onto all engine surfaces will be very important for future high metal loading metallized propellant testing programs.

Though the performance obtained with the metallized gelled fuels is lower than that required for beneficial applications to NASA missions, these results show the ways of improving future engine designs. Historical data with metallized gelled fuels has implied that engines at higher thrust levels are able to deliver the required high efficiency and Isp. Larger scale experiments will likely allow more realistic flow conditions, reduced influence of igniter purges, and allow researchers to gather more engine data in a more- representative high-thrust rocket environment.

Acknowledgements

We'd like to thank NASA Headquarters, Office of Advanced Concepts and Technology for their support of this work. Also, many thanks to Paul Molnar for his mechanical skills and the team of Bill Furfaro, Ed Pluta, Pablo Gutierrez, and Steve Culler for their electronics experience and assistance. Also, thanks to John Blankenship for his injector design work. Also, particular kudos to Diane Linne, Jack Reed, Gayle Roth, Jack Swoboda, and Joe Zoeckler. A special note to the efforts of J. P.

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Table I. Metallized Gelled Fuel Components: Weight Percentages

Metal Loading	Component			
	RP-1	Al	SiO2	Surfactant (Tween 85)
0%	93.5	0.0	6.5	0.0
5%	90.0	5.0	5.0	0.0
55%	40.8	55.0	3.5	0.7

Table II. Typical Metallized Gelled Propellant Engine Flow Rates and Performance: 55-wt% RP-1/Al, Run 706

Fluid	Mass Flow Rate (lbm/s, kg/s)	
O2	0.0564	(0.0256 kg/s)
RP-1/Al	0.0461	(0.0209 kg/s)
N2	0.0214	(0.0097 kg/s)
Total	0.1238	(0.0562 kg/s)

Other parameters for engine run 706	
Thrust (lbf, N)	24.42, (108.6)
O/F	1.23
Chamber O/F	0.84
Isp, (lbf-s/lbm, Pc)	197.24
Isp, vacuum (lbf-s/lbm)	248.08
Pc (psi)	66.90
Cstar Efficiency	95.31
Isp Efficiency	79.51

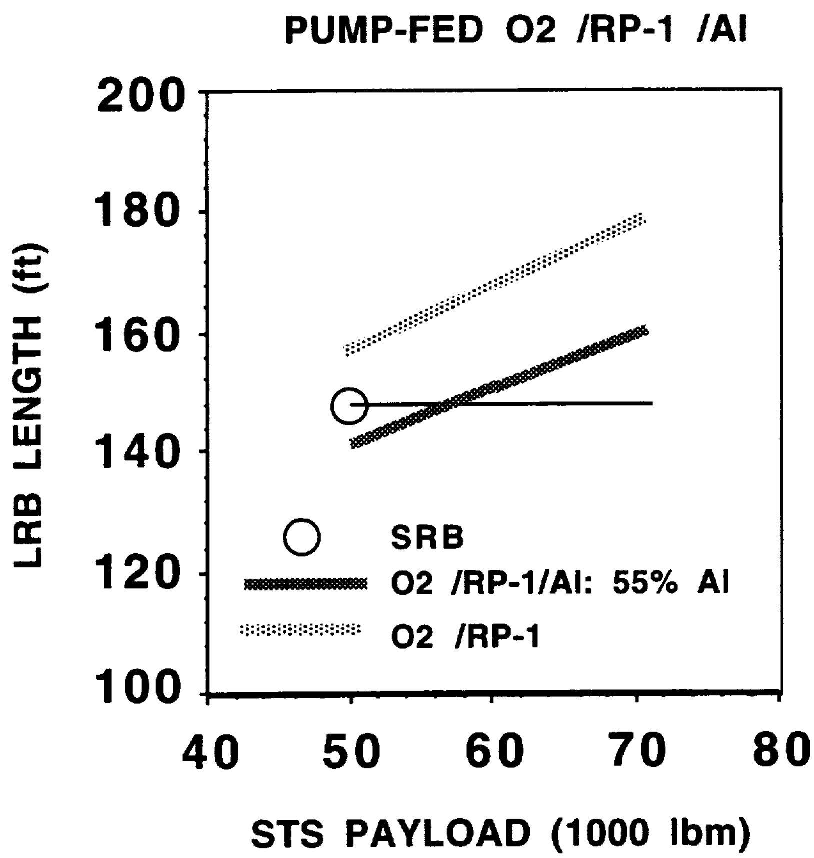

Figure 1. Liquid Rocket Booster Length versus Payload Mass

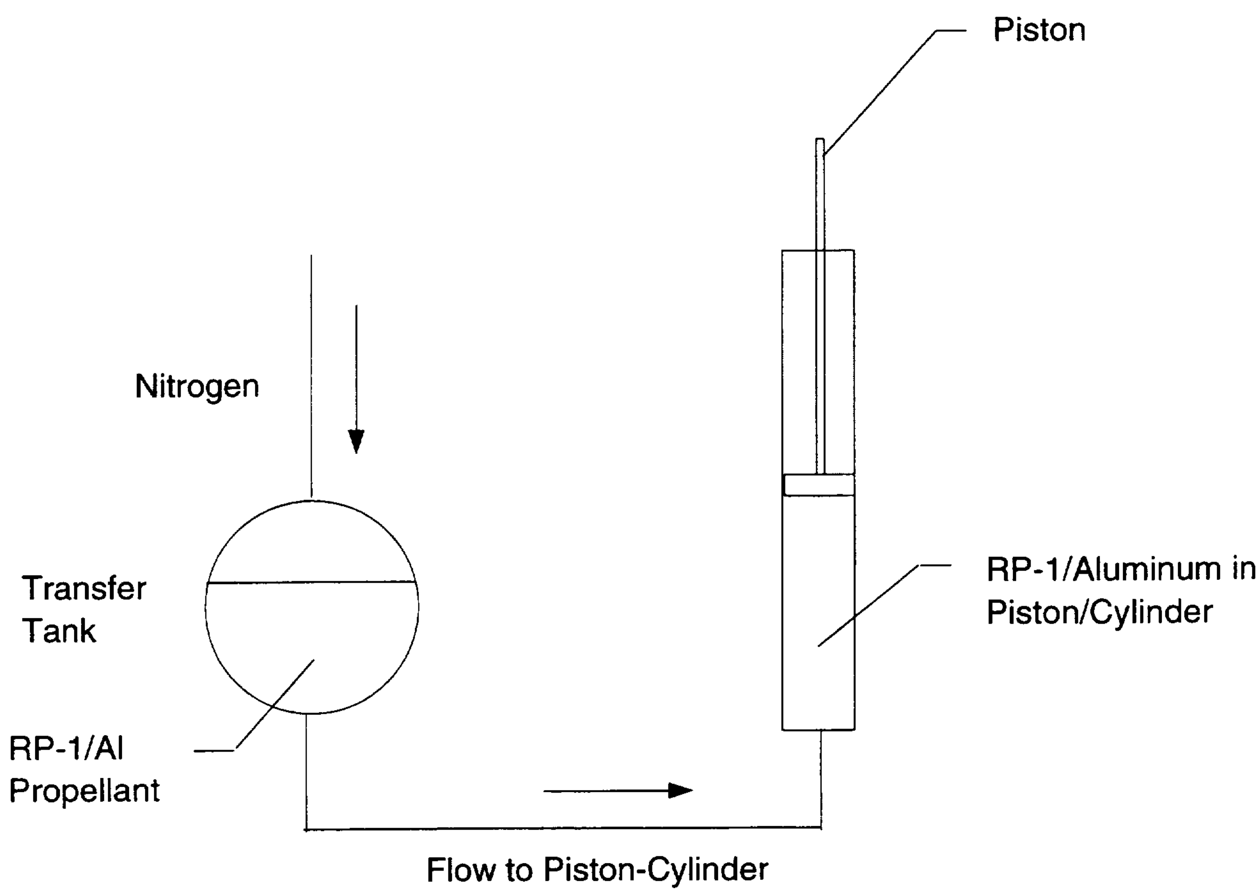

Figure 2. Gelled Propellant Transfer Tank System Schematic

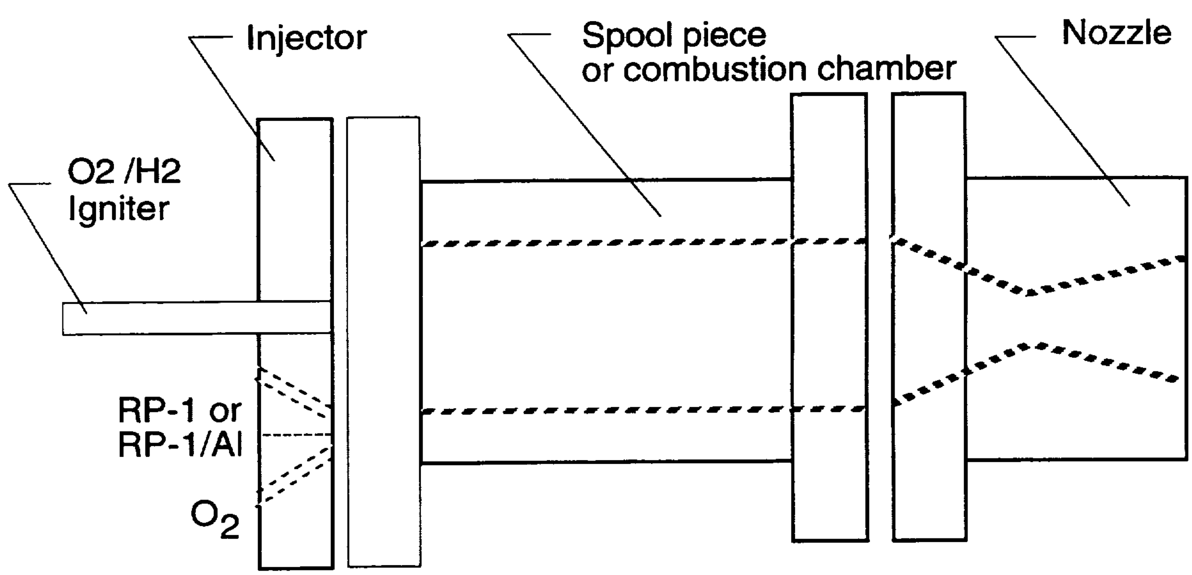

Figure 3. Simplified Diagram of Engine Components and Configuration

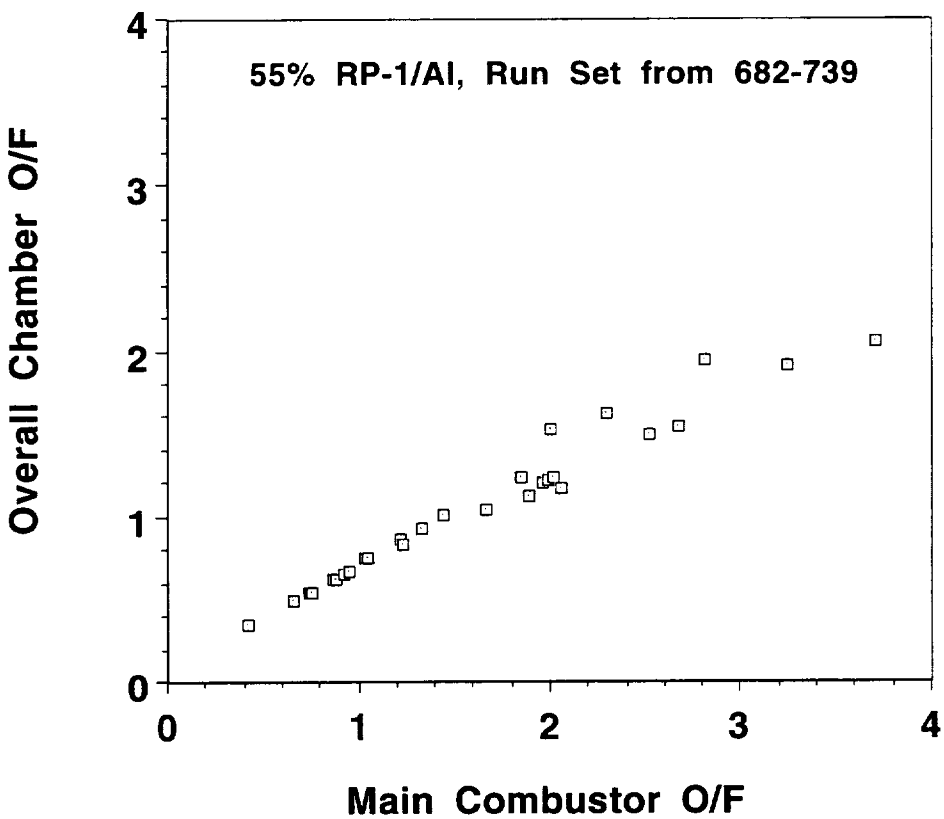

Figure 4. Propellant O/F versus Chamber O/F: 55-wt% RP-1/Al with O_2

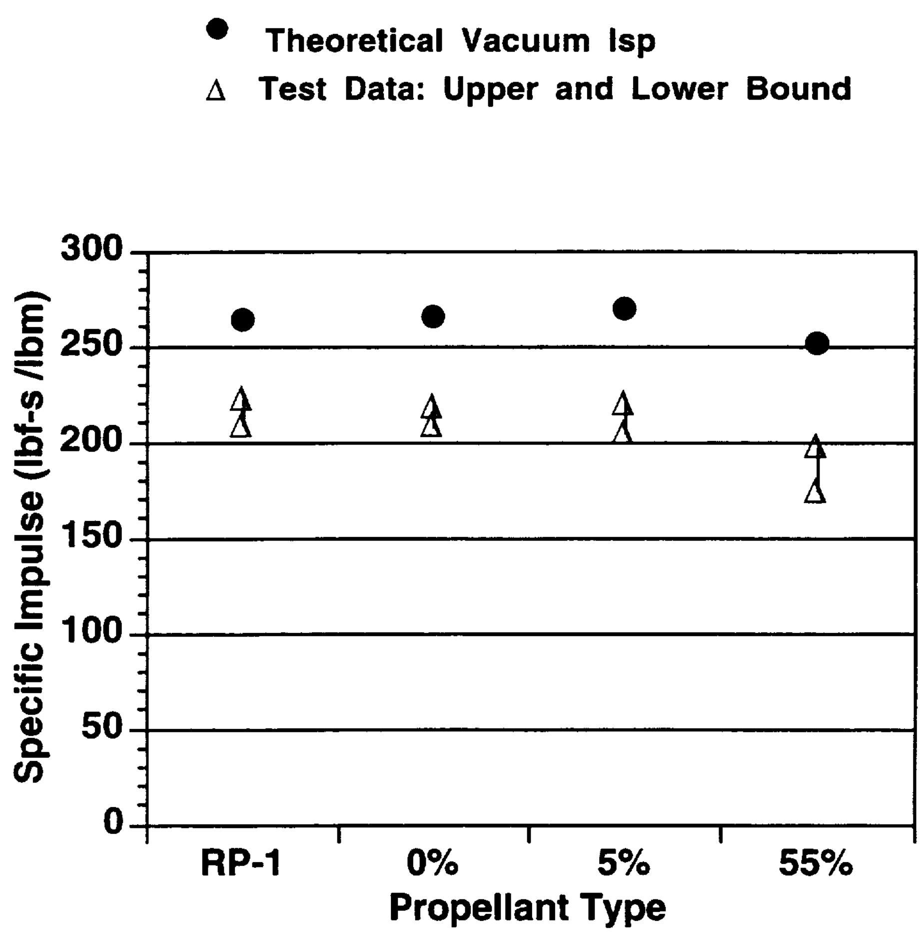

Figure 5. Theoretical and Experimental Peak Isp for all Propellants

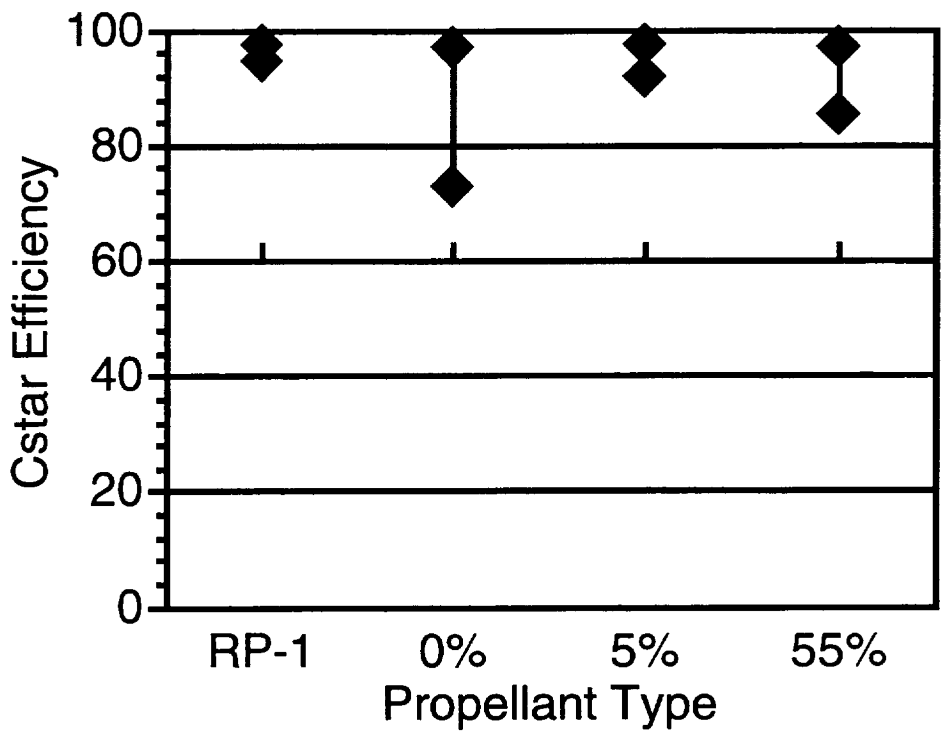

Figure 6. Summary of Experimental Cstar Efficiency Ranges for all Propellants: At Peak Isp

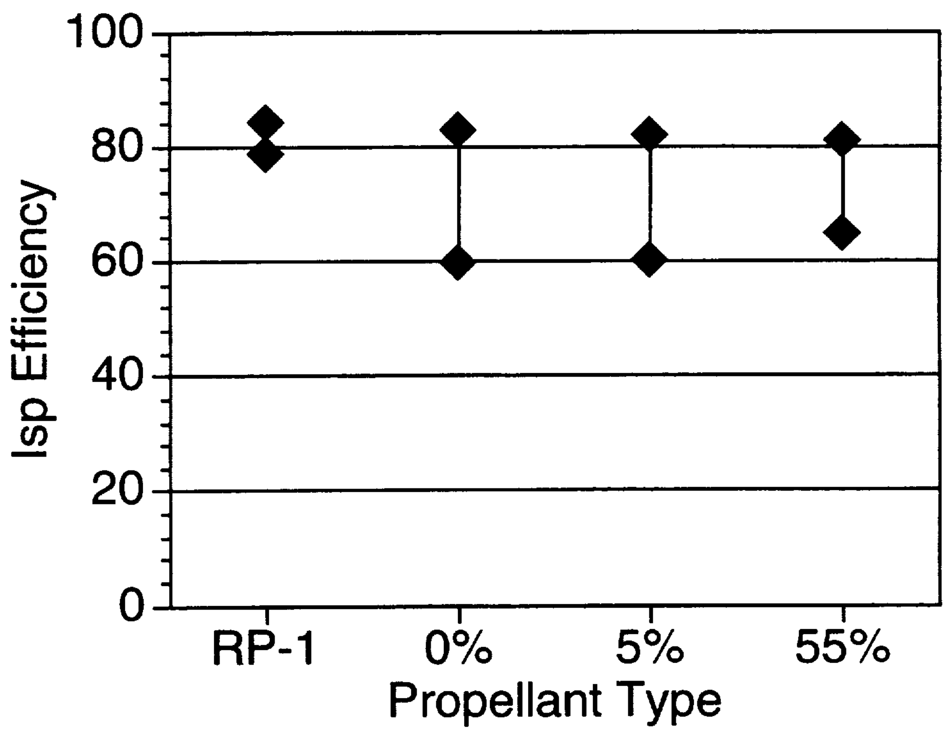

Figure 7. Summary of Experimental Isp Efficiency Ranges for all Propellants: At Peak Isp

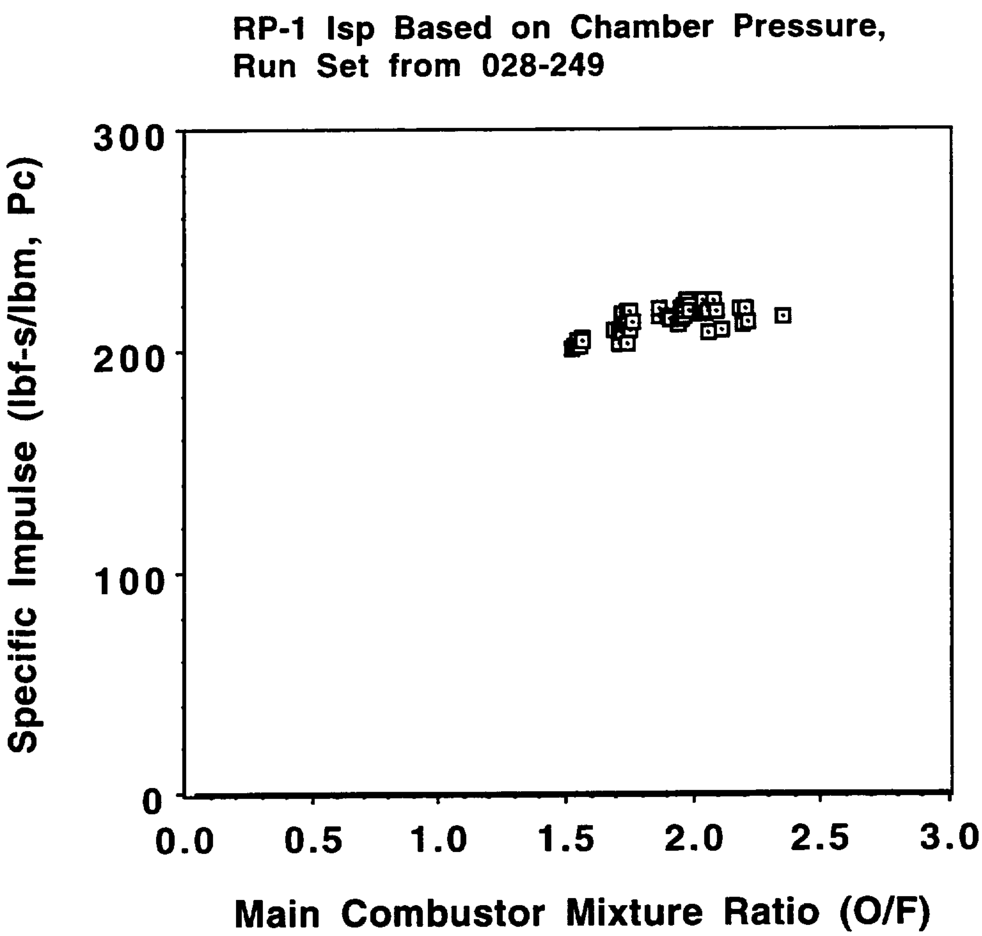

Figure 8. Isp versus O/F: RP-1 with O_2

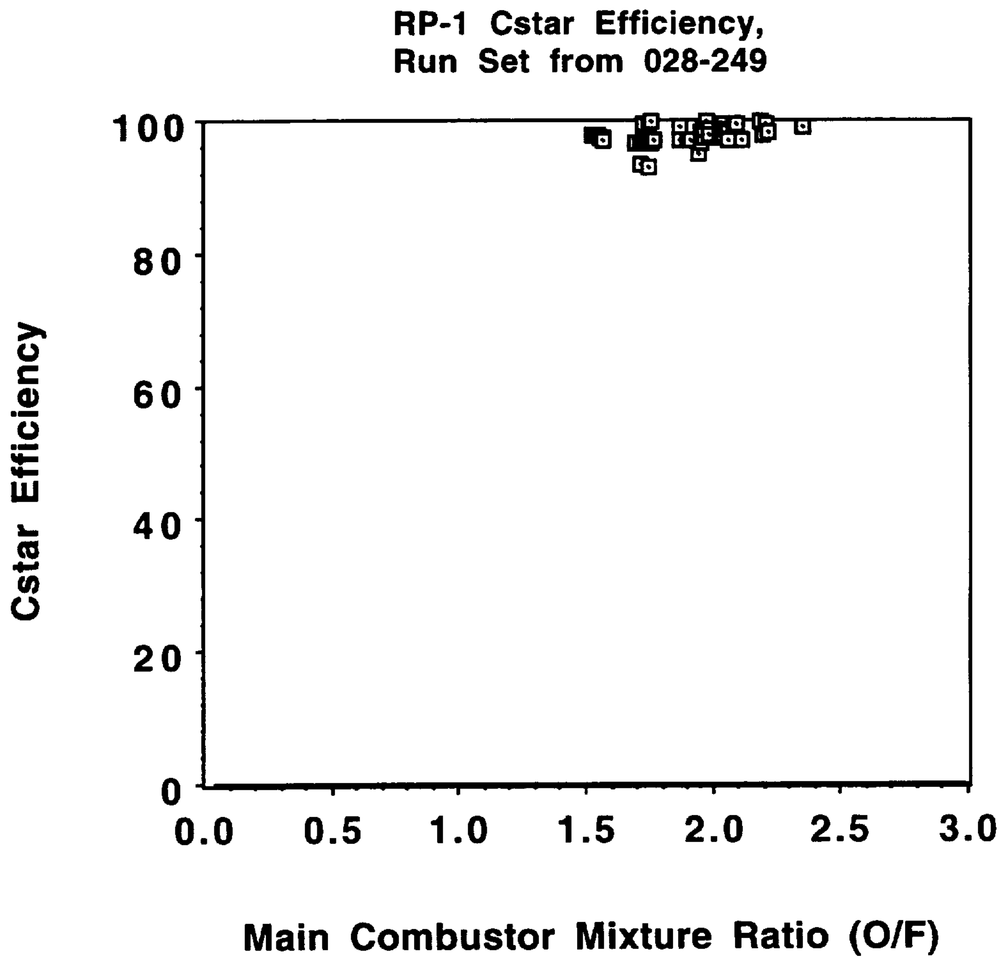

Figure 9. Cstar Efficiency versus O/F: RP-1 with O_2

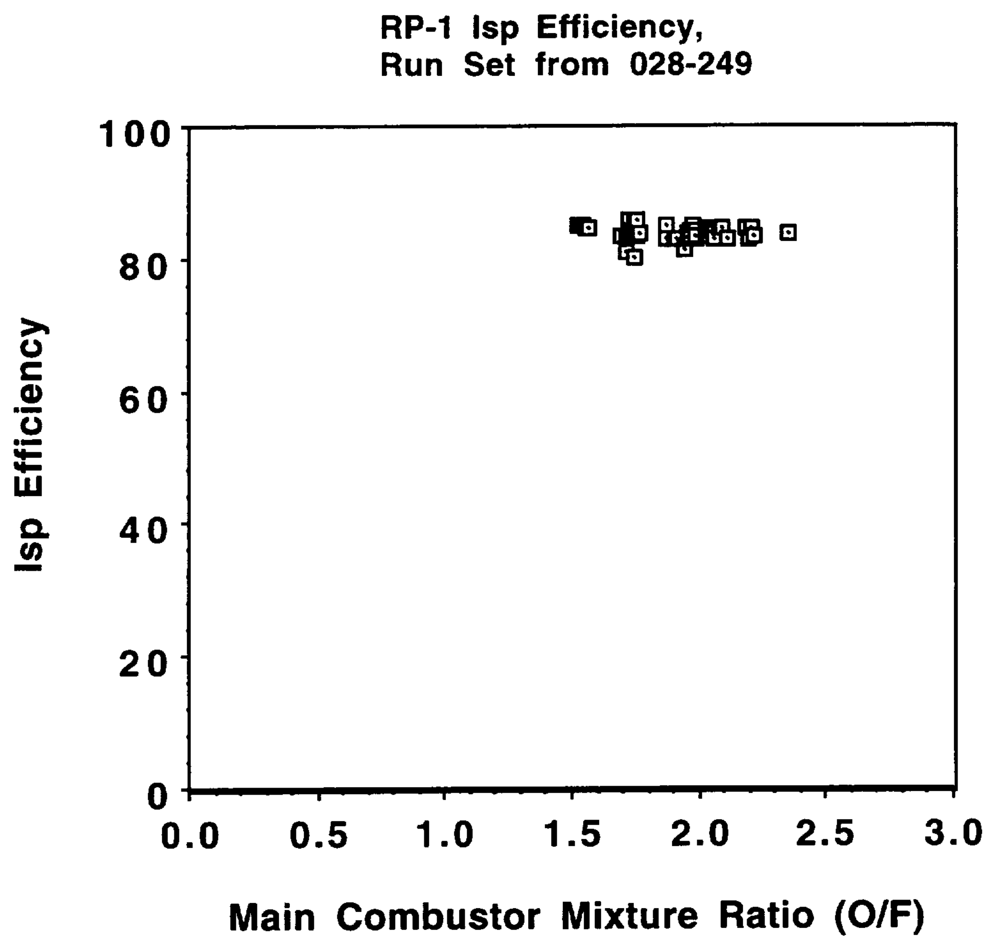

Figure 10. Isp Efficiency versus O/F: RP-1 with O_2

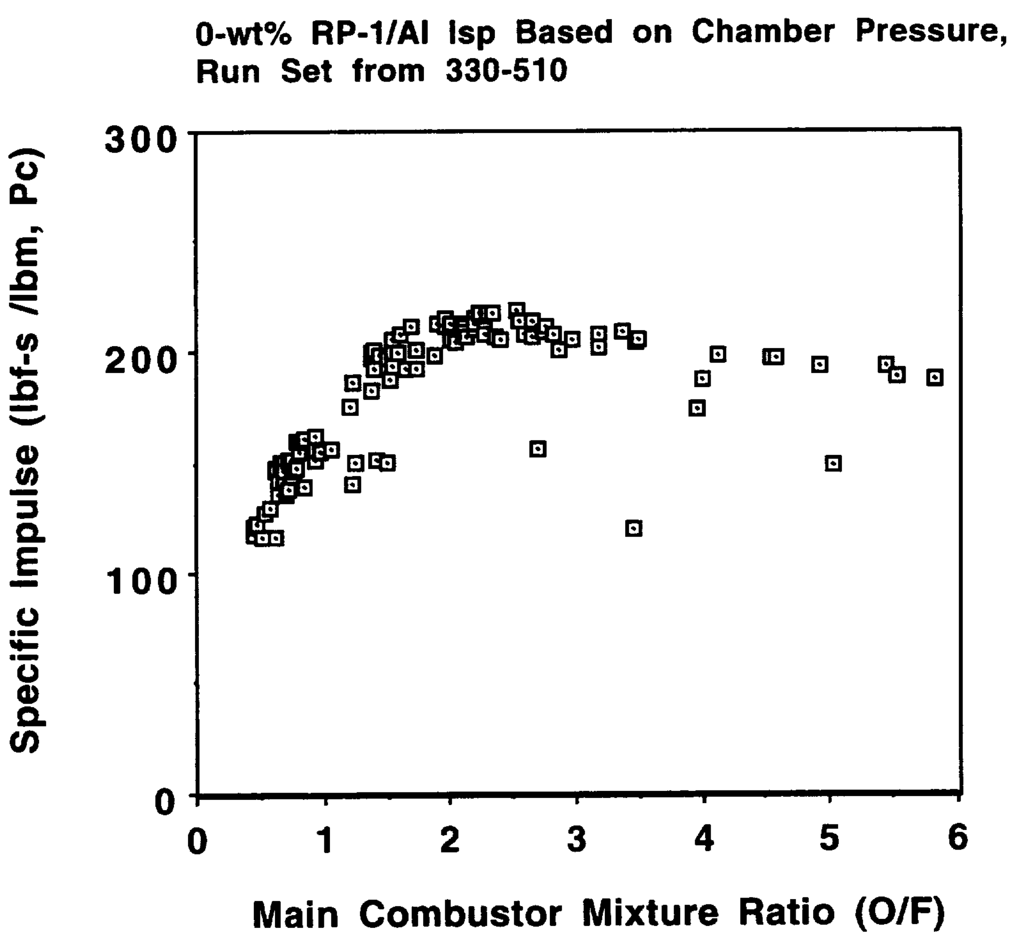

Figure 11. Isp versus O/F: 0-wt% RP-1/Al with O_2

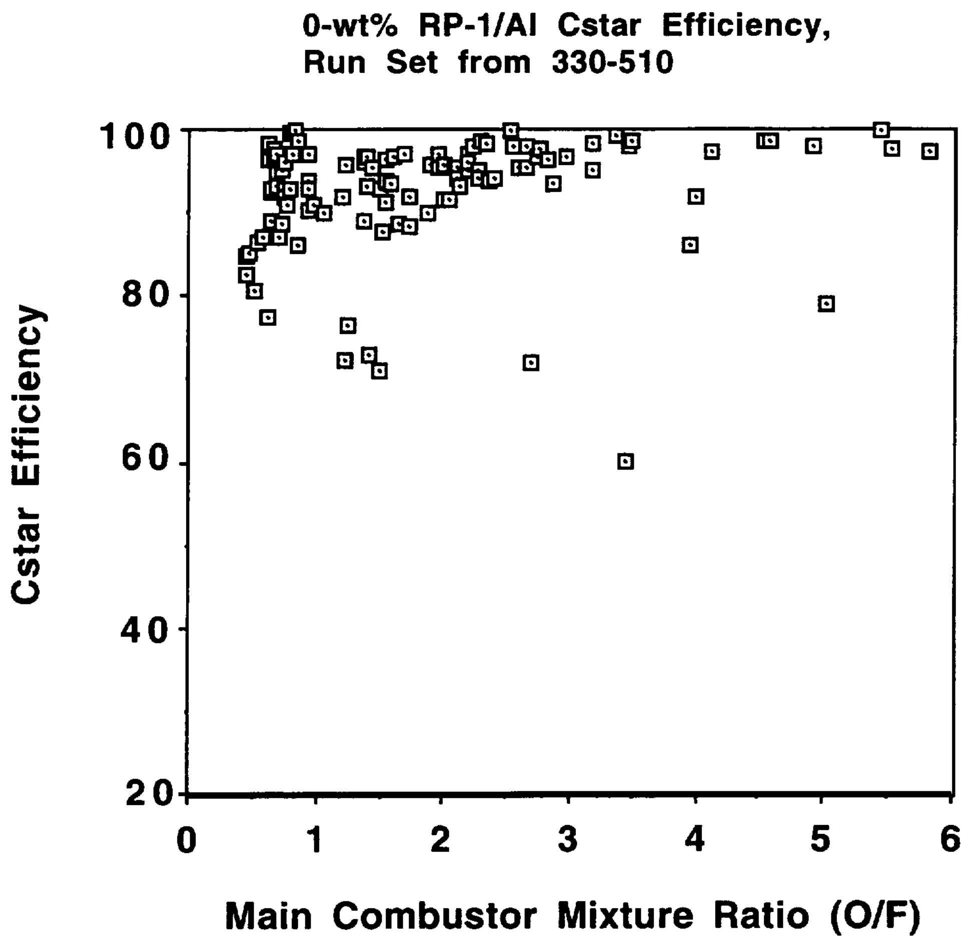

Figure 12. Cstar Efficiency versus O/F: 0-wt% RP-1/Al with O_2

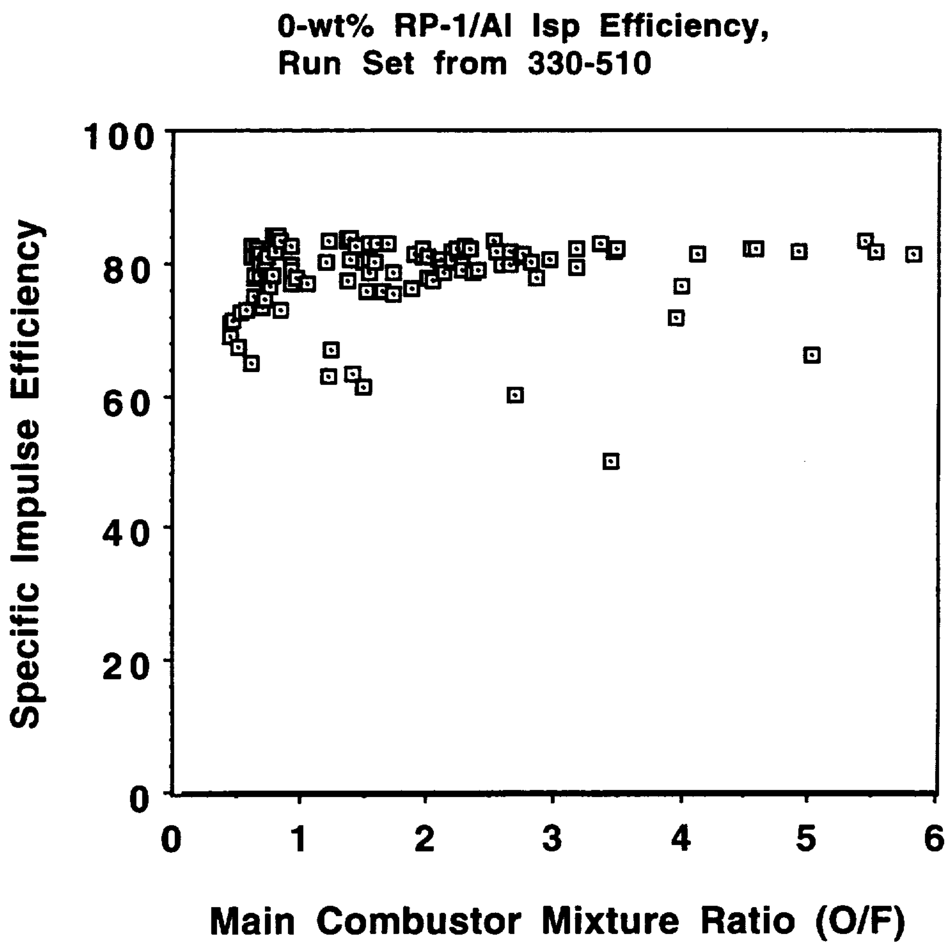

Figure 13. Isp Efficiency versus O/F: 0-wt% RP-1/Al with O_2

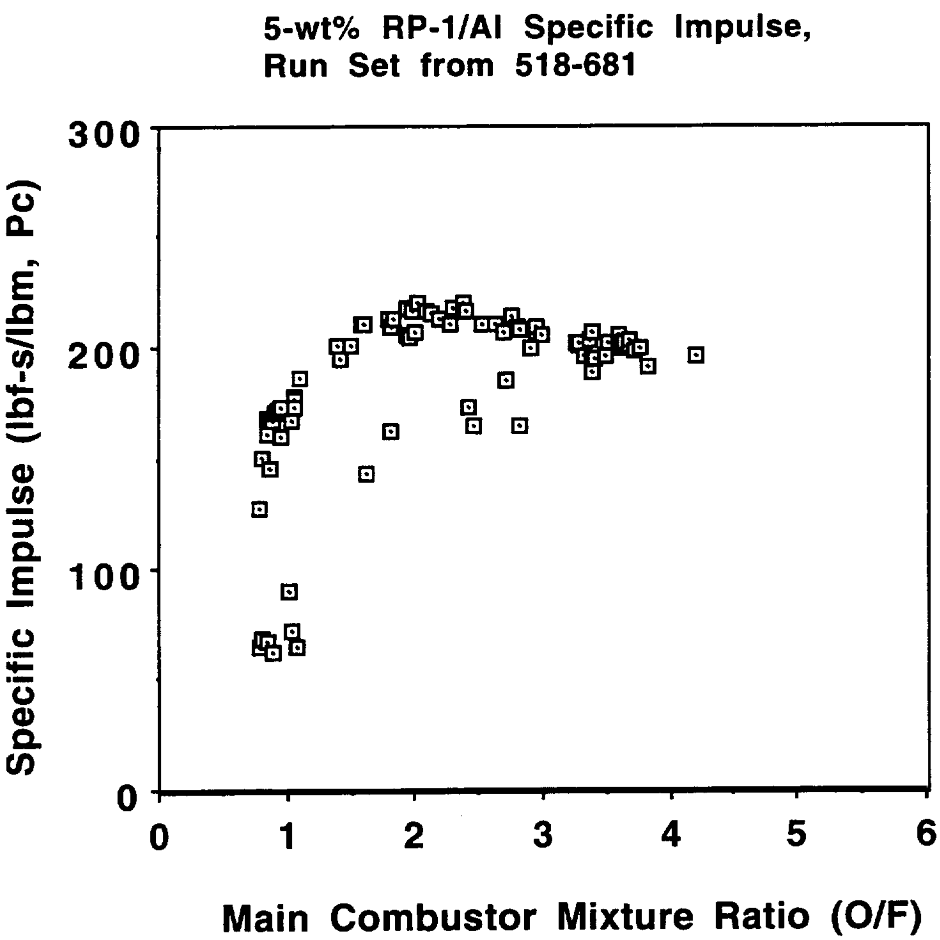

Figure 14. Isp versus O/F: 5-wt% RP-1/Al with O_2

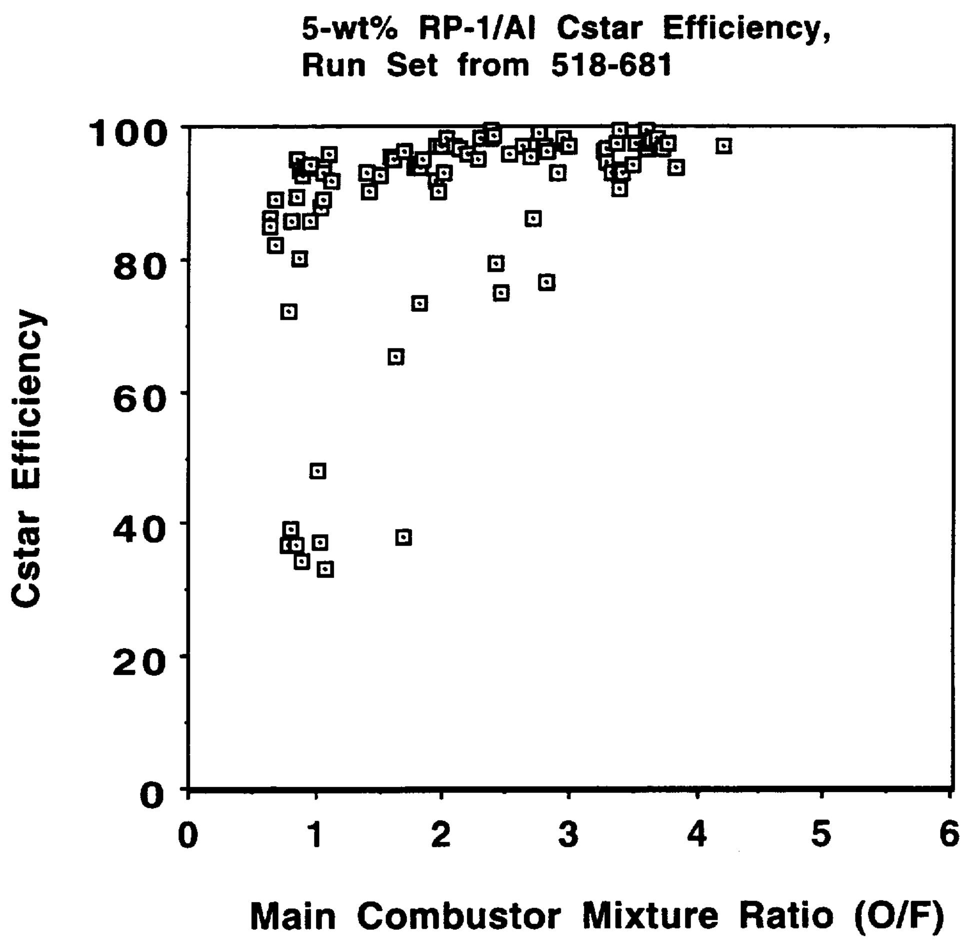

Figure 15. Cstar Efficiency versus O/F: 5-wt% RP-1/Al with O_2

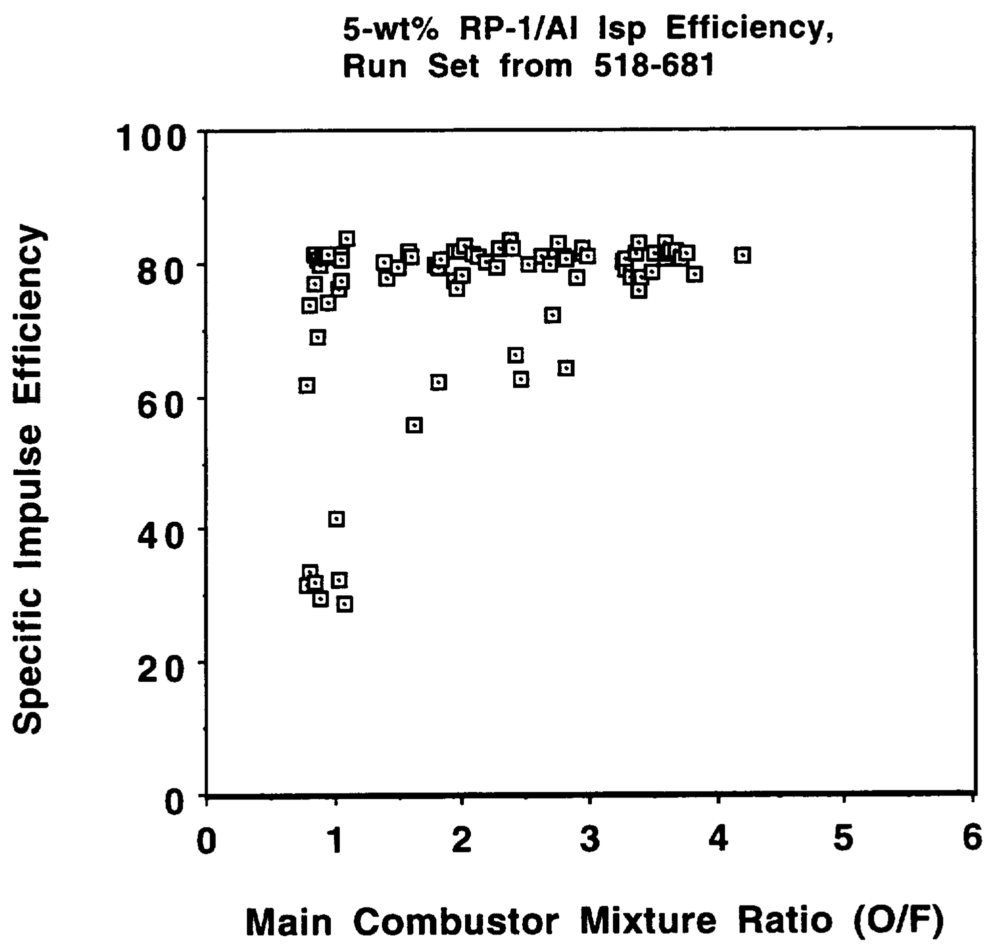

Figure 16. Isp Efficiency versus O/F: 5-wt% RP-1/Al with O_2

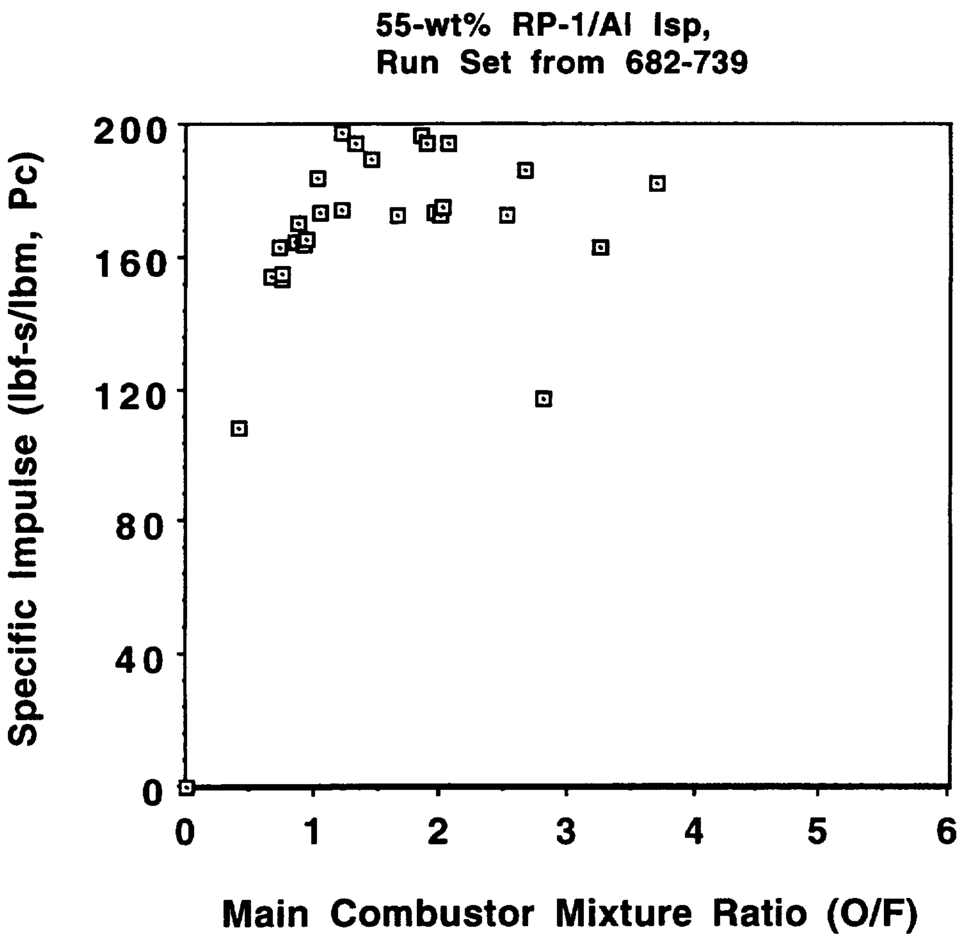

Figure 17. Isp versus O/F: 55-wt% RP-1/Al with O_2

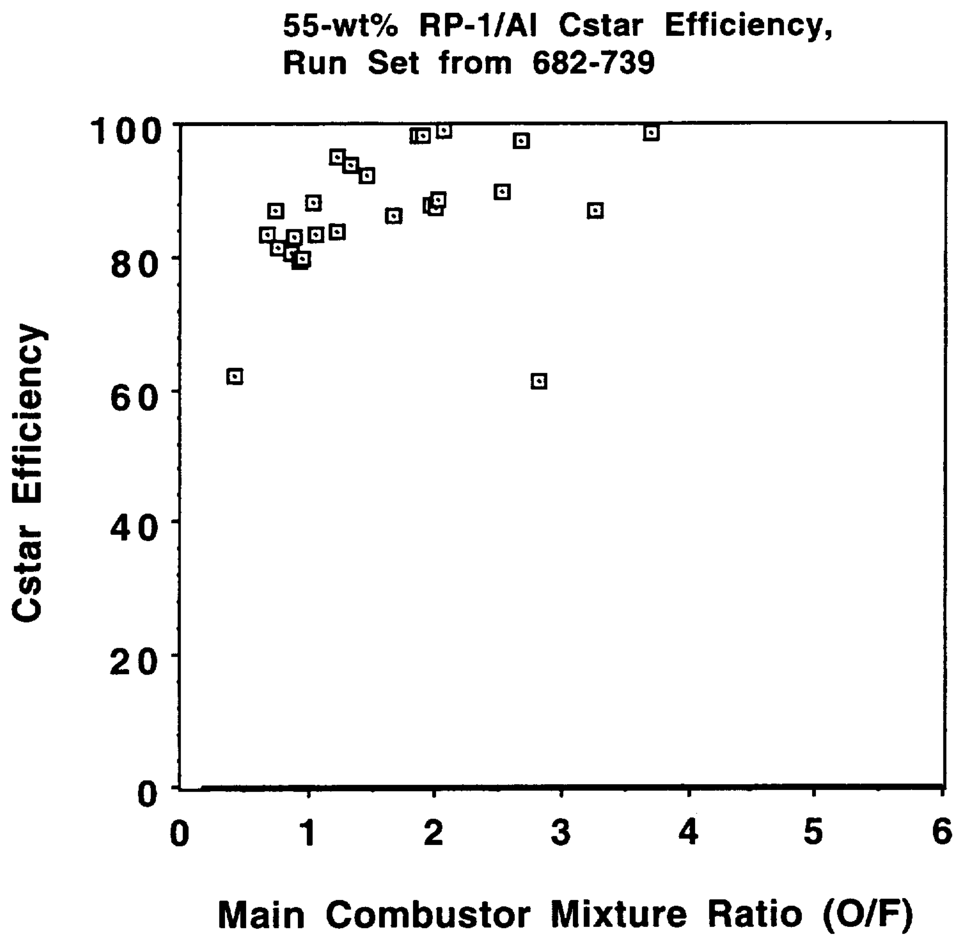

Figure 18. Cstar Efficiency versus O/F: 55-wt% RP-1/Al with O_2

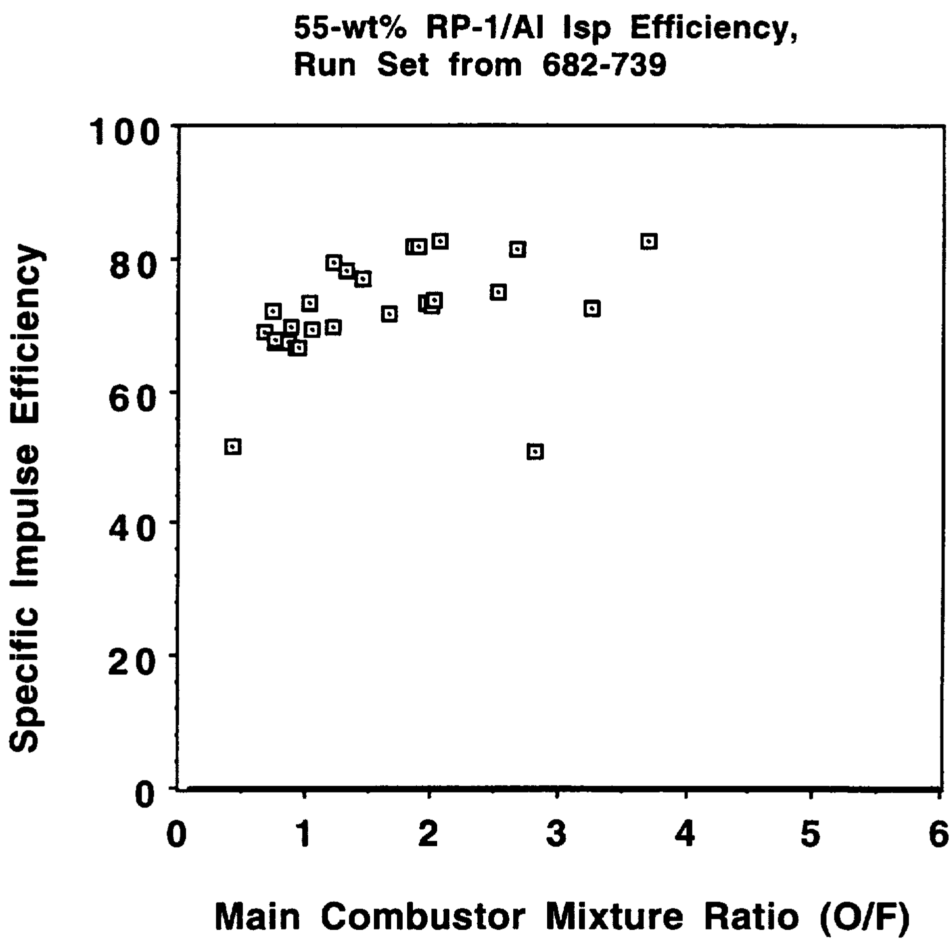

Figure 19. Isp Efficiency versus O/F: 55-wt% RP-1/Al with O_2

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 1995	Technical Memorandum

4. TITLE AND SUBTITLE
Metallized Gelled Propellants: Oxygen/RP-1/Aluminum Rocket Combustion Experiments

5. FUNDING NUMBERS
WU–232–01
NAS3–27186

6. AUTHOR(S)
Bryan Palaszewski and James S. Zakany

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–9838

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM–107025
AIAA–95–2435

11. SUPPLEMENTARY NOTES
Prepared for the 31st Joint Propulsion Conference and Exhibit, cosponsored by AIAA, ASME, SAE, and ASEE, San Diego, California, July 10–12, 1995. Bryan Palaszewski, NASA Lewis Research Center and James S. Zakany, NYMA, Inc., 2001 Aerospace Parkway, Brook Park, Ohio 44142 (work funded by NASA Contract NAS3–27186). Responsible person, Bryan Palaszewski, organization code 5310, (216) 977–7493.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Categories 20 and 28

This publication is available from the NASA Center for Aerospace Information, (301) 621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

A series of combustion experiments were conducted to measure the specific impulse, Cstar-, and specific-impulse-efficiencies of a rocket engine using metallized gelled liquid propellants. These experiments used a small 20– to 40–lb_f (89– to 178–N) thrust, modular engine consisting of an injector, igniter, chamber and nozzle. The fuels used were traditional liquid RP–1 and gelled RP–1 with 0–, 5–, and 55–wt% loadings of aluminum and gaseous oxygen was the oxidizer. Ten different injectors were used during the testing: 6 for the baseline O_2/RP–1 tests and 4 for the gelled fuel tests which covered a wide range of mixture ratios. At the peak of the Isp versus oxidizer–to–fuel ratio (O/F) data, a range of 93 to 99% Cstar efficiency was reached with ungelled O_2/RP–1. A Cstar efficiency range of 75 to 99% was obtained with gelled RP–1 (0–wt% RP–1/Al) while the metallized 5–wt% RP–1/Al delivered a Cstar efficiency of 94 to 99% at the peak Isp in the O/F range tested. An 88 to 99% Cstar efficiency was obtained at the peak Isp of the gelled RP–1/Al with 55–wt% Al. Specific impulse efficiencies for the 55–wt% RP–1/Al of 67–83 percent were obtained at a 2.4:1 expansion ratio. Injector erosion was evident with the 55–wt% testing, while there was little or no erosion seen with the gelled RP–1 with 0– and 5–wt% Al. A protective layer of gelled fuel formed in the firings that minimized the damage to the rocket injector face. This effect may provide a useful technique for engine cooling. These experiments represent a first step in characterizing the performance of and operational issues with gelled RP–1 fuels.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Metal propellants; Gelled liquid propellants; Rocket combustion; Hydrocarbon fuels	34
	16. PRICE CODE
	A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	