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Development of Laboratory-Scale Gel-Propulsion Technology

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Selected gel propellants and simulants were formulated, prepared, rheologically characterized, and tested in the first phase of a program to develop gel-propulsion technology infrastructure. Hydrazine-based fuels, gelled with polysaccharides, were characterized as shear-thinning pseudoplastic fluids with low-shear yield stress (τ_{yield}), whereas inhibited red-fuming nitric acid (IRFNA) and hydrogen peroxide oxidizers, gelled with silica, were characterized as yield thixotropic fluids with significant τ_{yield}. Safe storage and handling procedures were established. A laboratory-scale experimental setup was used to hot fire successfully a small 100-N nominal thrust rocket engine with selected hypergolic neat-liquid and gelled bipropellant combinations. One-element pentad-type injectors were utilized in the tests to inject the propellants into the combustion chamber. Continuous tests of up to 25-s firing duration and multipulse operations of up to 20 cycles of 0.1-s on/0.5-s off were successfully conducted with gelled-hydrazine/IRFNA bipropellants. Neat-liquid and gelled mono–methyl hydrazine/IRFNA bipropellants were also tested. The combustion pressure ranged between 20 and 35 bars. Experimental characteristic velocity, c^*_{exp}, was determined as a function of the oxidizer-to-fuel (O/F) mass flow rate ratio. Maximum c^* efficiency of more than 95 and about 90% was obtained in continuous firings for the neat-liquid and gelled hydrazine/IRFNA, respectively. In both cases, the maximum c^*_{exp} values were obtained at higher O/F ratios than those that yield maximum theoretical c^*.

Nomenclature

A_t	=	nozzle throat area, m^2
c^*	=	characteristic velocity, m/s
c^*_{exp}	=	experimental characteristic velocity, m/s
$c^*_{\text{exp},0.50}$	=	c^*_{exp} determined by Eq. (3) and expression (4), m/s
$c^*_{\text{exp},0.95}$	=	c^*_{exp} determined by Eq. (3) and expression (5), m/s
c^*_{th}	=	theoretical characteristic velocity, m/s
I_{sp}	=	maximum theoretical specific impulse, s
$I_{\text{sp},0}$	=	I_{sp} for neat-liquid bipropellant combination, s
K	=	preexponential coefficient (consistency index), Pa · s^n
L^*	=	characteristic length, m
$\dot{m}_{\text{tot}}$	=	total mass flow rate of propellants, kg/s
n	=	power-law index
Pc	=	combustion pressure, bars
t	=	time, s
x_i	=	independent variable; see Eqs. (6) and (7)
Y_{FL}	=	mass fraction of gellant content in fuel gel
Y_{OX}	=	mass fraction of gellant content in oxidizer gel
$\dot{\gamma}$	=	shear rate, 1/s
ε	=	uncertainty interval
η	=	non-Newtonian viscosity, Pa · s
τ	=	shear stress, Pa
τ_{yield}	=	shear yield stress, Pa

Introduction

GELLED-PROPELLANT systems offer a number of advantages in comparison to neat-liquid-propellant systems. These benefits include improved safety in storage and handling; better compliance with insensitive munitions (IM) requirements; lower toxicity and fire hazards; reduced leakage, spillage, and slosh problems; and higher energy density (when solids loaded). In addition, their inherent thrust-modulation capability provides excellent application flexibility for utilization in smart tactical missiles,[1] divert and attitude-control systems,[2] advanced launch-vehicle boosters and upper stages,[3–6] sustainer engines for endo/exoatmospheric interceptors,[7] pilot-seat ejection systems,[8] and airbreathing propulsion systems.[1]

A significant effort has been made in the past 30 years worldwide to formulate and prepare unloaded and loaded (mostly metallized) gel propellants, study their properties and stability problems, investigate potential applications, and develop gelled-bipropellant propulsion systems. Most published studies deal with the rheological, flow, injection, and combustion characteristics of gels. Natan and Rahimi[9] have recently reviewed the main aspects of gel-propellant research and development. Munjal et al.[10] studied the effects of various parameters on the gellation process of unloaded and metallized unsymmetrical dimethyl hydrazine (UDMH) and red-fuming nitric acid (RFNA) using optical and photomicrographic techniques. Gupta et al.[11] conducted a comprehensive investigation of the rheological properties of unloaded and metallized UDMH gel. Extensive studies on the advantages, properties, combustion characteristics, and potential applications of selected metallized gel fuels, both Earth-storable and cryogenic, were conducted at NASA John H. Glenn Research Center at Lewis Field by Rapp and Zurawski,[12] and more recently and mostly by Palaszewski and Zakany,[4] Starkovich and Palaszewski,[5] and Palaszewski and Zakany[13] at NASA Glenn Research Center and in industry. Gellation and rheological characterization of metallized-UDMH and kerosene gels was reported by Varghese et al.[14] Performance evaluation and hypergolicity tests of those fuel gels with N_2O_4 were also conducted. Varma et al.[15] experimentally investigated the ability to prepare thixotropic gels of hydrazine-based fuels using various gellants. They also studied critical gellant concentrations, gellation times, the effect of metal additives, and storage characteristics.

Successful hot-fire testing of laboratory-size, subscale, and full-scale gel-propellant engines for measurement of delivered performance and evaluation of potential operational problems has also been reported. Hodge et al.[1] of TRW reported on the design and development of rocket propulsion systems based on Earth-storable, gelled, solid-loaded mono–methyl hydrazine (MMH)/inhibited RFNA (IRFNA) bipropellant combination (also see Ref. 8). Fast-pulsing, as well as continuous, ground hot-fire tests of full-size engines were successfully conducted with high-performance

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efficiency. Promising flight tests of missiles with a gelled-propulsion system, provided by TRW, were recently reported.[1,16] Yasuhara et al.[2] of Aerojet, Propulsion Division, have applied advanced component-design techniques in the development and ground hot-fire testing of a divert and attitude-control propulsion system, composed of gelled, unloaded MMH/IRFNA bipropellant thrusters. Extensive hot-fire testing of a small-scale (89–178-N thrust) rocket engine, using neat-liquid, unloaded, and metallized (with 7-μm aluminum particles) gelled RP-1 as a fuel, and gaseous oxygen as an oxidizer, was conducted at NASA John H. Glenn Research Center.[4,13] Combustion, performance, and heat transfer characteristics were investigated and reported. The performance efficiency obtained with the gelled fuel was relatively low within a wide range of scatter, mostly due to the engine configuration and the use of nitrogen purge during the tests. The experiments with the gelled fuel revealed operational problems, such as residual fuel deposition on the combustion chamber walls with 0 and 5-wt % Al, and injector erosion, and metal, as well as metal oxide agglomeration in the nozzle, with the 55-wt % Al addition. At the Pennsylvania State University, Mordosky et al.[17] conducted combustion tests of gelled-RP-1 fuel with and without ultrafine aluminum powder (Alex) and gaseous oxygen in a laboratory-size instrumented rocket engine. The formulations tested were the same as those investigated at NASA John H. Glenn Research Center, and similar c^* efficiencies were obtained.

This paper describes activities performed in the first phase of a program aimed at the establishment of an infrastructure for the development of gel rocket-propulsion technology. The major objectives of that program phase were: 1) formulation, preparation, and characterization of selected Earth-storable gel propellants; 2) establishment of safe storage and handling procedures; 3) calculation of theoretical performance of selected gelled-bipropellant combinations; 4) design and construction of a laboratory-size, hot-fire testing setup for gel propellants; and 5) conduction of ground firing tests of a small gelled-bipropellant engine at continuous and multipulse modes of operation, to evaluate delivered performance and investigate operational issues regarding gel-propulsion systems.

Formulation and Preparation of Selected Gel Propellants

Various gels were formulated and prepared in the described program phase to serve as fuels, oxidizers, and simulants. The fuel gels included hydrazines and selected hydrocarbons. The hydrazines investigated were gelled hydrazine (N_2H_4), tested both in the monopropellant and bipropellant modes, and MMH, which provides comparable performance to hydrazine, with a lower freezing temperature, thus, enabling a wider range of applications. A well-established hydrazine infrastructure and accumulated experience with hydrazine thrusters have been beneficially used in the program. The prepared hydrocarbon fuel gels included various types of kerosene. Additives, such as aluminum or boron, were suspended in some of the gelled fuels to enhance their energetic value and volumetric specific impulse.

The oxidizer gels prepared and investigated in the program framework include IRFNA and hydrogen peroxide (HP), H_2O_2. Gelled IRFNA has been efficiently used as an oxidizer with gelled hydrazines, as will be described further. Gelled HP is being developed for use as an environmentally friendly ("green") oxidizer, using existing infrastructure.

Water-based inert simulants, that are rheologically matched to the gel propellants, have been prepared and used for safe and low-cost conduction of basic studies in rheology, injection and atomization, storage and flow in systems, and also in development of procedures for fueling and other handling activities.

Various organic gellants, mainly polyacrylates and polysaccharides, have been used in concentrations ranging between 0.3 and 5% to gel most fuels and simulants. Some of those required the addition of small amounts of stabilizing agents to the formulations. Gelled hydrazine and MMH fuels have been prepared using 2–4 wt % of the polysaccharide thickeners hydroxy ethyl cellulose (HEC) and hydroxy propyl cellulose (HPC), respectively, as organic gellants. HEC and HPC are water-soluble nonionic cellulose derivatives. They are used to produce pseudoplastic water solutions having a wide range of viscosity. Inorganic gellants, such as silica and metal oxides, were employed in various concentrations in the development of kerosene, IRFNA, HP, and some simulant gels. The silica used is a fine powder with standard tapped density of approximately 50 g/l. Carbopol hydrophilic powdered resins were used to produce water-based simulant gels. They are acrylic water-soluble polymers, which normally function as thickeners and stabilizers for suspensions or emulsions. Table 1 provides a summary of selected formulations, out of the various gel propellants and simulant gels that were prepared in the course of the presented program phase.

Table 1 Summary of selected gel compositions

Gel propellant	Gellant	Content, wt %
MMH	HPC	2–4
Hydrazine	HEC	2–4
JP-8	Silica	4–8
IRFNA	Silica	3–5
HP	Silica	5–7
Water-based simulants	Carbopol	0.3–1

The preparation of the gels was carried out according to common methods applicable for each of them. The gels of hazardous materials, such as hydrazines and IRFNA, were prepared in various mixing vessels, using marine impellers. Closed systems with nitrogen blankets released through multiple bubblers were used to isolate the materials from the environment. Hydrazine gels were prepared by filling the reactor with the fuel and slowly adding the polysaccharide gellant while stirring. The suspension was stirred for additional 2 h at room temperature at speeds suitable to varying gel viscosity to ensure complete dissolution of the gellant in the liquid. IRFNA gel was prepared by weighing the silica powder gellant in the vessel and adding the liquid while stirring. The stirring proceeded several hours to ensure homogenization. IRFNA was alternatively gelled using a procedure similar to the one used for hydrazine gels, namely, silica powder was carefully added to the neat IRFNA in the vessel. The simulants were prepared in the same way as the hydrazine gels. The prepared gels were pressure fed from the mixing vessels into the storage tanks.

Gel Characterization and Rheological Modeling

Gel-propellant characterization is vital for the design and development of gel-propulsion systems. The data of foremost importance are related to thermochemistry and rheology. Other physical and chemical characteristics of interest include density, homogeneity, materials compatibility and stability. The physical stability of gels is of much concern with respect to their storage and conditions of use. Gel characterization should also be performed following extended periods of storage. Possible settling of gellant and suspended additive particles in storage and in acceleration environments that might exist in some applications must be carefully investigated. Gel characterization is also used for quality control. The understanding of the processes taking place during the operation of a gel-propulsion system is supported by familiarity with the rheological properties of the propellants.

Selected gels were chemically and physically characterized. The rheological characterization that is of special interest was carried out mainly by using a Thermal Analysis and Rheology Instruments (TAI) rotational rheometer with a cone and plate and parallel-plates geometries. This is also performed for the more hazardous propellants, using special equipment and procedures that ensure safe conduct of operations. No-slip condition verification during experiments took place. Special procedures for eliminating air-friction parasitic moments, inertia effects due to the rotating rheometer parts, and gap variations due to thermal changes were implemented.

The constitutive equations that were formulated using the rotational rheometer are one-dimensional equations conducted on the shear projection only. The generalized Herschel–Bulkley[9] constitutive model was found to be the most adequate one for the gels studied. This model expresses shear stress τ as a function of shear

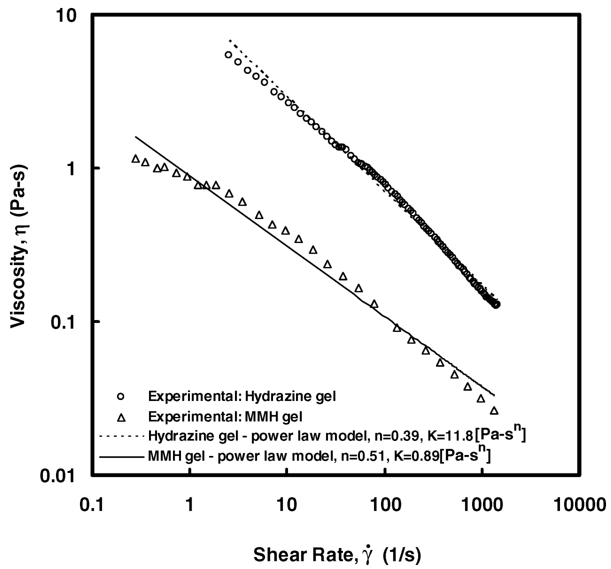


Fig. 1 Experimental non-Newtonian viscosity of MMH and hydrazine fuel gels as a function of shear rate.

rate $\dot{\gamma}$ with parameters of shear-yield stress τ_{yield}, exponent n, and preexponential coefficient K as follows:

$$\tau = \tau_{\text{yield}} + K\dot{\gamma}^n \tag{1}$$

Expression (1) reduces to the commonly used power-law model when $\tau_{\text{yield}} = 0$ and to the Bingham model equation when $n = 1$.

In the present work, hydrazine-based fuels, gelled with polysaccharide gellants were rheologically characterized as shear-thinning pseudoplastic fluids with low τ_{yield} in the shear-rate range of 1–1000 1/s, which is of interest for processes related to gel handling and feed in the experimental system. Therefore, their rheological behavior in that range can be suitably expressed by the power-law model. In contrast, IRFNA and HP oxidizers, gelled with silica, were characterized as yield thixotropic fluids with significant values of τ_{yield}. Figure 1 shows a typical variation of shear viscosity as a function of shear rate for hydrazine and MMH, determined by the rheological-characterization tests. The derived preexponential coefficient K and power-law index n are also indicated.

Shear-yield stress τ_{yield} is an important rheological parameter in the estimation of the properties of gelled propellants for the following reasons: 1) A stable phase is required during storage in static or airborne systems to prevent physical instability processes in the propellant, which might include suspended particles, and to enable damping of any sloshing in the tankage. 2) The yield stress might help in mitigating the consequences of any leakage in a storage or feed system, by slowing down or stopping any material flow. 3) The value of the yield stress dictates the initial pressure gradient that is necessary to initiate flow in piping lines, which may bring about rise in the required tank feed pressure. 4) Yield stress may also affect the propellant spray characteristics.

Determination and possible control of the yield-stress parameter are necessary for understanding the gel-propellant rheology and for the efficient design of test and propulsion systems. Quantitative evaluation of τ_{yield} has been the subject of a number of works. Boger[18] distinguishes between indirect and direct methods. The indirect method employs extrapolation of shear-stress vs shear-rate curve to zero rate. Extrapolation may be by polynomial approximation or constitutive models of the flow curve, which include τ_{yield} as a rheological parameter. Practical definition of τ_{yield} as the stress, under which no flow is experimentally observed, may be applied using modern rheometrical equipment, which allows modeling of material properties at the low scale of deformations. There are various direct methods mentioned in the literature,[19–23] but none of them has been recognized as an industry standard. Barnes and Walters[24] suggest to consider τ_{yield} merely as the detection limit of available characterization equipment. In their opinion, viscosity is always finite for non-Newtonian shear-thinning materials, and materials that flow under higher stresses will just flow slower under low stress. On the other hand, Hartnett and Hu[25] claim to have evidence that τ_{yield} is an engineering reality. In the present work several rheometrical procedures of the TAI rotational rheometer have been employed to estimate the yield stress.[26] For the gel propellants investigated, τ_{yield} was found to be lower than 20 Pa for the hydrazine-based fuels and in the range of 500–1000 Pa for IRFNA and HP oxidizers.

Thixotropy is an important time-dependent rheological phenomenon that is identified with gels. It is defined as a decrease of the apparent viscosity under constant shear stress or shear rate, followed by gradual recovery when the stress or shear rate is removed. More generally, it is the reversible and isothermal reduction in time, until a finite value of a rheological property of the system, such as viscosity, elastic modulus, or yield stress, is reached for a constant shear rate. The importance of thixotropy for a gel propellant lies in the possibility to liquefy it, that is, to reduce its shear viscosity, in order to improve and control the processes of feed and injection into the combustion chamber. The degree of thixotropy in a gel propellant depends on a number of variables, such as the type and quantity of gellant, the quantity of suspended solids, and temperature.

There are two main factors concerning thixotropy and gel propellants: 1) the significance of the thixotropic effect in comparison to shear thinning, and 2) the time constants of the reversibility of the material (its restructuring) in comparison to its viscosity decrease. The time-dependent effect of thixotropy has been mentioned in various publications.[11,12] Quantitative evaluation of the thixotropic effect by mathematical modeling, conducted by Rahimi and Natan[27] for gels simulating inorganic gel fuels, concluded that the effect is insignificant for those fuels.

Storage and Handling Considerations

The storage and handling of gelled propellants generally require the same precautions and safety procedures as those of the corresponding liquid propellants. These involve considerations of toxicity, explosion, and fire hazards, but sometimes also serious corrosion problems.

The gelled hydrazines are ordinarily treated according to the procedures established over the years for the neat liquids. This includes separate storage areas, equipped with the necessary safety alarms, and protective equipment. The underlying degree of conservatism in the mentioned approach has already been expressed by Hodge et al.[1] and quantified using tools such as the ALOHA pollutant dispersion analysis computer program.[28] Oxidizers are stored at the required safe distance from the fuels. The long-term storage of IRFNA requires special care to be taken, to prevent corrosion and leakage. Materials compatibility considerations include both directions of compatibility: on one hand, the effect of the gel propellants on the materials of construction and, on the other hand, the effect of the materials on the gelled propellants, as described in the following.

First, as an example of the effect of the gel propellants on the materials of construction, the small amount of fluorides in the gelled IRFNA might be depleted by reaction with the silica gellant, thus, raising a question whether the RFNA is still inhibited enough for long-term storage (Refs. 29 and 30). Special care was taken in the selection of materials for static and dynamic sealing. Though the Kalrez elastomer performs well in static conditions, it was found in this work that in dynamic conditions types of Teflon® had to be employed.

Second, an example of the effect of materials on the gelled propellants, is given. For instance, in H_2O_2 storage and handling, special care has to be taken not to induce its decomposition unnecessarily. Similar care has to be taken with hydrazines and the other propellants.

Flow and injection of gels are unit operations in which the rheological characteristics of the gels are of much importance. Because gels require higher pressure drops for flowing than neat liquids, the equipment has to be accordingly selected. The higher pressures used impose additional safety requirements. Feed system design for prevention of blockage due to crusting and accessibility for cleaning is necessary when dealing with gels. Test systems usually include special branches of the corresponding liquid propellant that enable flushing gel lines, and GN_2 tubing for further purge and drying of the lines.

Theoretical Performance of Hot-Fire Tested Gel Propellants

Neat-liquid- and gelled-hydrazine/IRFNA and MMH/IRFNA bipropellant combinations were evaluated for theoretical rocket engine performance and investigated for combustion characteristics and operational issues by instrumented hot-fire testing. This choice was based on known hypergolicity characteristics, preliminary testing, and long-term extensive experience with those combinations in other places, as quoted in the literature.[1,2,4,13]

Chemical-equilibrium calculations of the theoretical rocket performance were conducted using the NASA John H. Glenn Research Center CEA96 code.[31] The calculations were carried out for shifting equilibrium over a wide range of oxidizer-to-fuel (O/F) ratios for a combustion pressure of 70 bars with adapted nozzle at sea level. The heats of formation of the fuel polymeric gellants were theoretically calculated from the known composition, and the computed results were verified by calorimetric measurements.

The gelling agents affect the viscosity and density of the gel propellants and decrease the theoretical rocket performance of the neat liquids being gelled, as expected. The variation of the maximum theoretical specific impulse I_{sp} with mass fraction of the gellants for the MMH/IRFNA combination is presented in Fig. 2a. The I_{sp} surface shown is created by assembling the points corresponding to the optimum O/F mass flow rate ratio for a range of bipropellant combinations with various gellant mass fractions. The variation of I_{sp} is approximately linear in both gellant base coordinates and can be described by the following correlation with a correlation coefficient R^2 greater than 0.99:

$$I_{sp} = I_{sp,0}\exp(-0.5Y_{OX} - 0.03Y_{FL}) \tag{2}$$

The maximum theoretical specific impulse $I_{sp,0}$ is achieved by the neat-liquid propellant combination. As expected, the influence of the IRFNA gelling agent, inert silica, on the reduction in specific impulse is much larger than that of the organic gelling agent of MMH.

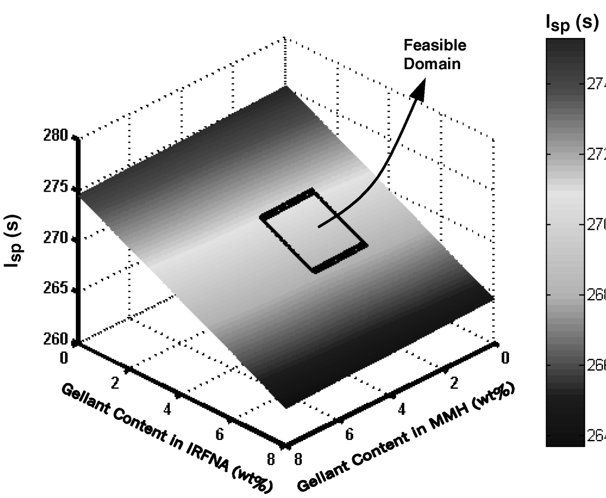
A feasible domain for the gel-bipropellant composition combinations can be established as shown in Fig. 2b, which is the I_{sp} surface top view. The active constraints are being determined as those combinations with the minimum gelling agent content, enabling the required rheological properties of the gel propellants. The limits of nonactive constraints are being determined as those above which a too viscous gel is obtained. Such compositions are not applicable as gel propellants due to the very high-pressure drops required for their injection and atomization and because of their relatively low energetic performance.

Experimental Setup

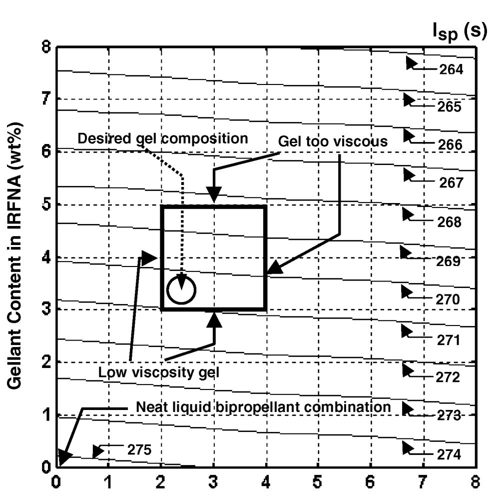
The experimental part of the program has been carried out in the RAFAEL, Armament Development Authority, Ltd., Propulsion Laboratory, which contains miscellaneous facilities for ground testing of various rocket motors and engines, airbreathing propulsion systems, and gas generators. The experimental setup consisted of a small rocket engine with a 100-N nominal thrust, propellant supply and feed system, as well as a computerized data acquisition and control system.

A laboratory-size rocket engine was designed, manufactured, and used for hot-fire combustion testing of selected gel-propellant combinations. A modular hardware design was implemented to enable the examination of different combinations of injectors, combustion chambers and nozzles, and to facilitate the replacement of damaged parts. The engine configuration is schematically shown in Fig. 3. The stainless-steel combustion chamber is 8.0 cm long and has an internal diameter of 2.6 cm. A cylindrical insert (or sleeve) made of copper-infiltrated tungsten, with a 2.2 cm internal diameter, was placed free standing in the combustion chamber. This choice of refractory-metal lining of the combustion chamber proved to be very successful in enabling many firing tests with the same insert without any erosion.

A one-element, pentad-type (quintuplet) injector with unlike impingement, made of stainless-steel, was utilized to inject the gel propellants into the combustion chamber. The gelled fuel was forced



a) I_{sp}-variation surface



b) Feasible domain of gel-propellant compositions

Fig. 2 Effect of gellant content on the theoretical maximum specific impulse of bipropellant gelled-MMH/IRFNA bipropellant combination.

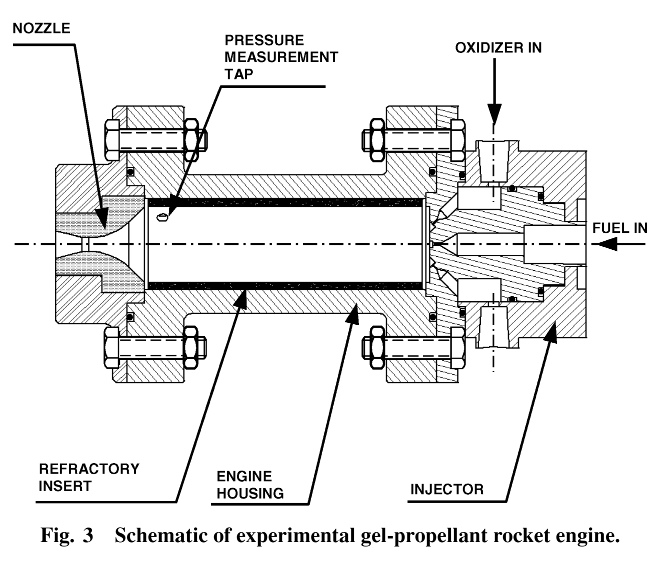


Fig. 3 Schematic of experimental gel-propellant rocket engine.

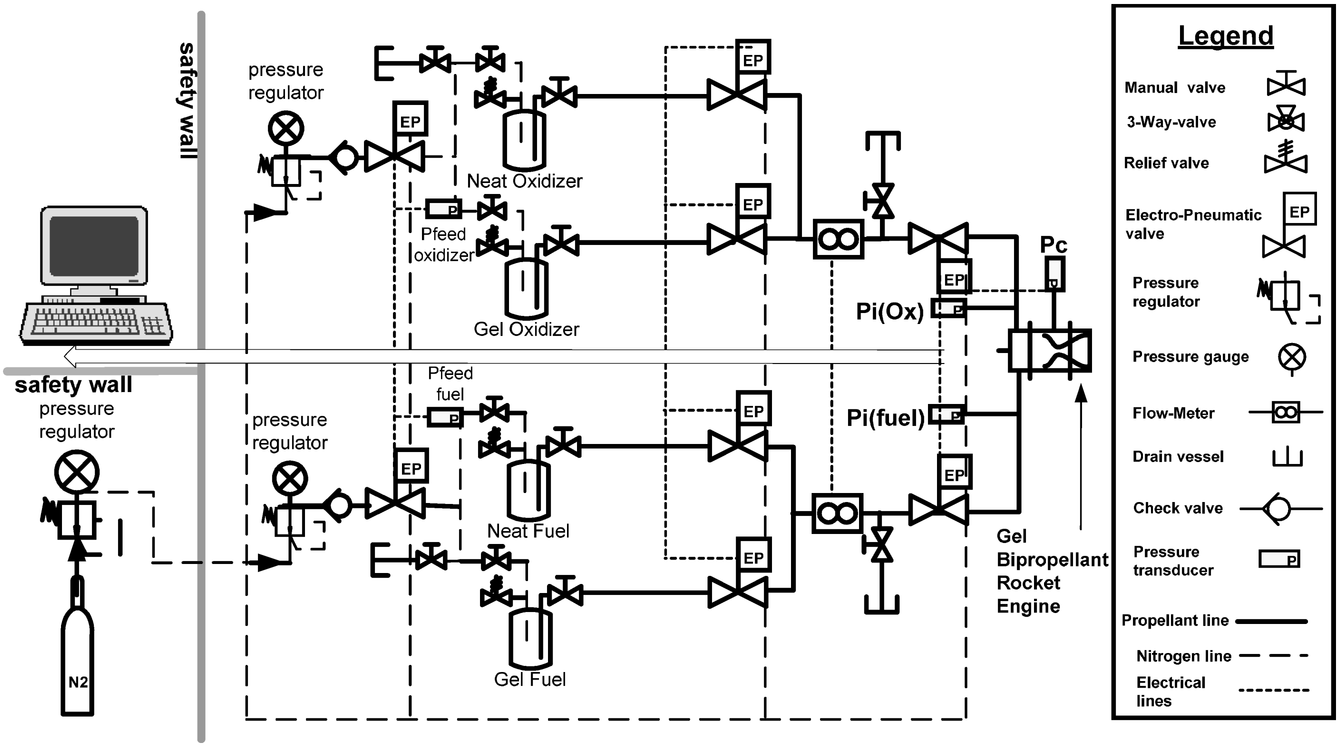


Fig. 4 Schematic of gel-propellant feed and control system for rocket engine testing.

through a central orifice, and the oxidizer was injected through four equally spaced orifices, inclined at 45 deg to the central line. Proper spray impingement was assured by close-tolerance machining and verified by cold-flow injector tests. Two injector feed configurations have been successfully tested: a direct tube-to-orifice feed and an oxidizer-manifold feed. A nozzle-throat insert, made of high-density graphite or copper-infiltrated tungsten, was installed in the stainless-steel nozzle housing to minimize any throat erosion or damage (Fig. 3). Two throat diameters, 0.4 and 0.6 cm, were used to cover a wide range of combustion pressures. The corresponding L^* values were, therefore, 2.4 and 1.1 m, respectively.

All engine components were assembled using threaded screws. The rocket engine was mounted to a specially designed test stand using stainless-steel rods and brackets. A few promising tests were conducted with a combustion-chamber sleeve and nozzle-throat insert made of a newly developed cermet-type material.

The propellant supply system is schematically shown in Fig. 4. It comprises a fuel branch and an oxidizer branch, each containing neat-liquid and gel supply tanks and lines, equipped with pressure relief and control valves and measuring devices. The neat-liquid propellants have been used for comparative hot-fire testing, posttest line and injector flush, and a check of the control system before each series of tests with gels. The propellants are expelled from the 5-liter stainless-steel supply tanks into the injector-feed system by gaseous nitrogen, whose pressure is separately regulated in each branch (Fig. 4). The feed pressure used in the tests was in the range of 25–65 bars. Gaseous nitrogen is also used for operation of the control valves and purging the feed lines. The total propellant mass flow rate and O/F ratio were coupled process parameters of the testing, affected and controlled by the total pressure drops in each of the feed lines. This coupling may cause difficulties in isolation of parameters during a test, due to the unique rheological nature of gel propellants. Kalrez (for static application only) and Teflon seals, known for their compatibility with acids, were successfully used in the IRFNA-feed system.

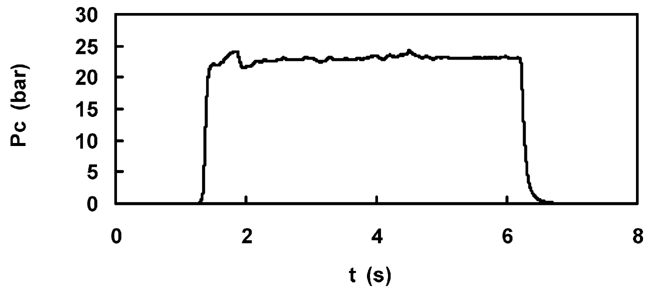
Computerized command, data logging, and initial data reduction and analysis subsystems were included in the experimental setup. Data acquisition and control were carried out using a workstation computer. The sampling rate used in the reported series of tests was 1000 Hz. For investigation of high-frequency phenomena, a sampling rate capability that is two orders of magnitude higher will be employed. Mass flow rate measurements were carried out using Coriolis-type flowmeters and positive displacement piston (PDP) components, combined with linear variable differential transformers (LVDT) installed in the feed lines. The former instruments enabled successful mass flow rate measurement of the non-Newtonian propellants due to their principle of operation, which is independent of the fluid rheological properties, and due to their compatibility with strong acids, whereas the latter are advantageous for measurements in short-pulse operation. Piezoelectric pressure transducers were installed at the aft end of the combustion chamber and at the injector fuel and oxidizer passages, close to the injection orifices, for the instantaneous measurement of chamber and injection pressure during a test run.

The hot-fire tests were monitored and recorded by video equipment. Standard procedures, such as calibration and priming of propellant lines, were carried out before each test series. Safety aspects of possible propellant leakage, and of dispersion of propellant fumes and gaseous combustion products, were carefully handled.

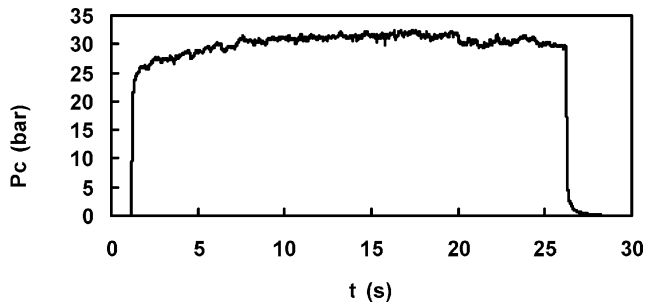
Discussion of Results

Preliminary open-air hypergolicity experiments were conducted with the hydrazine/IRFNA and MMH/IRFNA bipropellant gels. Ignition was obtained on static contact of small lumps of the fuel and oxidizer gels, with the MMH/IRFNA combination exhibiting slightly greater ignition delay. No ignition occurred on spray impingement of the gels over a wide range of the O/F ratio, using the pentad-element injector in an unconfined configuration. However, fast ignition was obtained when the same spray impingement took place in a confined space created by an open-end tube.

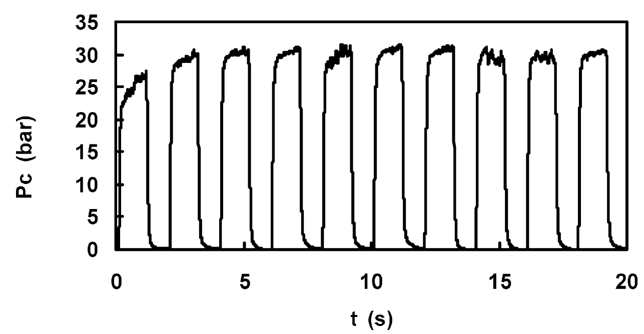
Most hot-fire tests, using the already described experimental setup, were carried out with the gelled-hydrazine/IRFNA bipropellants. Firing tests were conducted in both the multipulse and continuous operation modes. Combustion pressure ranged between 20 and 35 bars. The injector pressure drop varied between 4 and 8 bars. The mass flow rates ranged from 11 to 30 g/s for the fuel



a) Continuous firing: 5-s on



b) Continuous firing: 25-s on



c) Multipulse firing: 10 cycles of 1-s on/1-s off

Fig. 5 Combustion pressure profiles of typical hot-fire tests with gelled-hydrazine/IRFNA bipropellant combination.

and from 15 to 40 g/s for the oxidizer. Typical combustion pressure traces are shown in Fig. 5 for various feed pressures. Hypergolic ignition usually occurred within a few milliseconds from the start of propellant injection. Pressure vs time traces for continuous firings of 5 and 25 s with gelled hydrazine/IRFNA are presented in Figs. 5a and 5b, respectively. The relatively long startup and shutoff pressure transients were affected by the large characteristic length L^* and the long response time of the engine control valves (estimated to be about 200 ms). Figure 5c shows the pressure vs time trace for a multipulse firing with 10 cycles of 1-s on/1-s off. The ability to achieve multiple on-command engine shutoff and reignition with gelled propellants has been demonstrated. Increase of combustion pressure level due to rising combustion efficiency and decreasing heat transfer losses can be noticed for the first three pulses of the multipulse firing shown in Fig. 5c. The shortest tested duty cycle of the experimental multipulse firings was 0.1-s on/0.5-s off.

Careful measurement of the nozzle throat diameter was carried out before and after each test. No measurable erosion of the throat was found, neither with the graphite, nor with the tungsten nozzle insert. A thin layer of muddy, about 0.5 mm-thick, silica residue, deposited on the walls of the combustion chamber, was revealed after most continuous-firing tests.

A series of test firings was conducted to investigate the effect of O/F ratio on the experimental characteristic velocity for gelled-hydrazine/IRFNA propellants and for the corresponding neat-liquid propellants. The experimental average-per-test characteristic velocity c^*_{exp} was calculated using the following expression:

$$c^*_{\mathrm{exp}} = \int_{t_1}^{t_2} A_t P_c(t)\,\mathrm{d}t \Bigg/ \int_{t_1}^{t_2} \dot{m}_{\mathrm{tot}}\,\mathrm{d}t \tag{3}$$

For each test, two values of c^*_{exp}, $c^*_{\mathrm{exp},0.50}$ and $c^*_{\mathrm{exp},0.95}$, were calculated, corresponding to two different definitions of the time interval between t_1 and t_2, according to the following expressions, respectively:

$$P_c(t) > 0.50 P_{c,\max} \qquad t_1 < t < t_2 \tag{4}$$

$$P_c(t) > 0.95 P_{c,\max} \qquad t_1 < t < t_2 \tag{5}$$

These definitions were determined by the characteristics of the experimental setup, which affected the shape of the combustion pressure vs time traces.

The already mentioned two c^*_{exp} values were determined for a particular test firing using the measured data. A chemical equilibrium code[31] was utilized to calculate the theoretical value of c^*, c^*_{th}, for given test conditions. The ratio between the experimental and theoretical c^* values yields the c^* efficiency, which is an indicator of the rocket engine combustion efficiency. The variation of the experimental and theoretical characteristic velocity as a function of the O/F ratio for neat-liquid and gelled-hydrazine/IRFNA propellants is shown in Figs. 6 and 7, respectively. These experimental results were obtained for a combustion pressure range of 20–35 bars with the L^* value of 1.1 m. Note that a design point might be obtained in which the maximum c^* efficiency, with respect to $c^*_{\mathrm{exp},0.95}$, is higher than 95% for the neat-liquid propellant and is about 90% for the gelled propellants. Furthermore, it was found that in both cases the optimal O/F ratio obtained in the tests, which yields maximum c^*_{exp}, is higher than the O/F ratio that provides maximum theoretical c^*. That shift of optimal O/F ratio toward higher values, which is much larger with the neat liquids, may be attributed to the specific spray characteristics obtained from the particular injector configuration

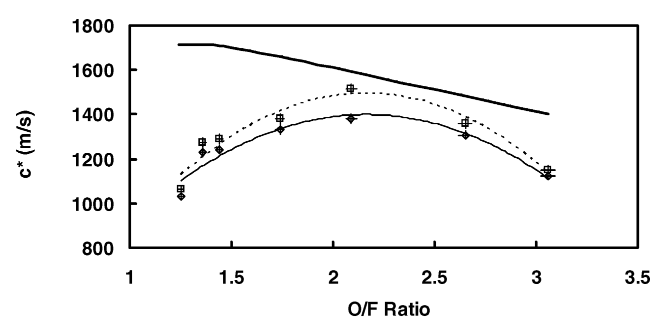


Fig. 6 c^* vs O/F Ratio for neat-liquid-hydrazine/IRFNA propellants: ——, theoretical performance c^*_{th}; ◇, experimental performance and curve fit $c^*_{\mathrm{exp},0.50}$; and □, experimental performance and curve fit $c^*_{\mathrm{exp},0.95}$.

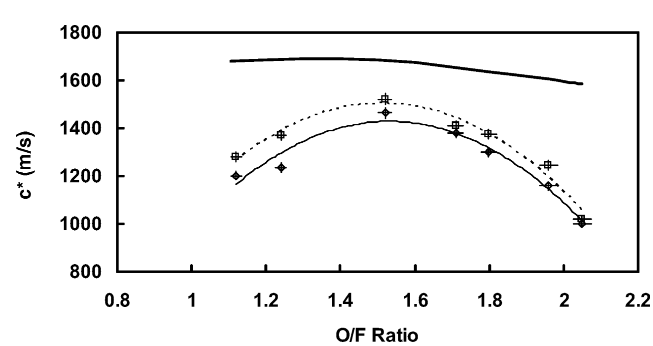


Fig. 7 c^* vs O/F Ratio for gelled-hydrazine/IRFNA propellants: ——, theoretical performance c^*_{th}; ◇, experimental performance and curve fit $c^*_{\mathrm{exp},0.50}$; and □, experimental performance and curve fit $c^*_{\mathrm{exp},0.95}$.

(pentad) used.[32] Maximum c^* efficiency was obtained at oxidizer-rich conditions.

Experimental uncertainty was estimated by the small-sample method,[33] using the following expressions for the uncertainty intervals in the calculations of characteristic velocity and O/F mass flow rate ratio:

$$\varepsilon_{c^*} = \sqrt{\sum_i \left(\frac{\partial c^*}{\partial x_i} \varepsilon_{x_i} \right)^2} \tag{6}$$

where $\forall x_i \in [Pc, \dot{m}_{\rm tot}, A_t]$, and

$$\varepsilon_{\rm O/F} = \sqrt{\sum_i \left(\frac{\partial ({\rm O/F})}{\partial x_i} \varepsilon_{x_i} \right)^2} \tag{7}$$

where $\forall x_i \in [\dot{m}_{\rm OX}, \dot{m}_{\rm FL}]$

The uncertainty in the nozzle throat area was calculated for maximum throat-diameter measurement inaccuracy of ±0.01 mm. The maximum full-scale rated inaccuracy for the pressure transducers and Coriolis-type flowmeters was used for estimating the uncertainty in measured pressure and mass flow rates. The uncertainty intervals, calculated by expressions (6) and (7), are indicated by error bars for individual points in Figs. 6 and 7.

Summary

All objectives of the first phase of a program to develop gel-propulsion technology infrastructure have been successfully achieved. Selected gel propellants and simulants were formulated, prepared, rheologically characterized, and tested. Hydrazine-based fuels, gelled with polysaccharides, and IRFNA and HP oxidizers, gelled with silica, were rheologically characterized as shear-thinning pseudoplastic fluids with low $\tau_{\rm yield}$, and as yield thixotropic fluids with high $\tau_{\rm yield}$, respectively. Safe storage and handling procedures were established. Most activities concentrated on Earth-storable hypergolic hydrazine/IRFNA and MMH/IRFNA gelled-bipropellant combinations. A standard chemical-equilibrium code was used to evaluate the quantitative effect of gellant content on the theoretical performance. A laboratory-scale experimental setup, comprising a small 100-N nominal thrust rocket engine, was established and successfully utilized for controlled hot-fire testing. Fast hypergolic ignition was usually obtained with the mentioned combinations. Continuous test firings of up to 25 s and multipulse operation of up to 20 cycles of 0.1-s on/0.5-s off were successfully conducted with gelled hydrazine/IRFNA. To achieve shorter on pulses and shorter engine startup and shutoff time periods, the use of fast-response flow control valves is necessary.

Investigation of the effect of O/F ratio on the experimental characteristic velocity $c^*_{\rm exp}$ in continuous operation yielded maximum average c^* efficiency greater than 95%, and about 90% for neat-liquid and gelled hydrazine/IRFNA, respectively. In both cases, the optimal O/F ratio is higher than the theoretical one. This shift in optimal O/F ratio is much greater for the liquids than for the gels. It is believed that these differences are caused by the specific injector configuration used in the tests (pentad), and by the differences in the rheological characteristics of gels vs liquids, which significantly influence the spray pattern, atomization, and mixing. It was, therefore, concluded that other kinds of injectors, such as vortex type,[1] should also be examined. Crusting problems were not encountered in the described testing. Crusting is the formation of a hard layer on the gel-propellant surface due to evaporation of the liquid component of the gel, when exposed to air or heat.

Limited testing of a cermet substance revealed its potential as a durable structural material in high-temperature oxidizing environments. Further characterization and testing of advanced structural materials will help in improving gel-propellant engine design.

The knowledge and experience gained in the feasibility study, described in this paper, will be used in the next phase of the program to develop infrastructure for gel-propulsion technology.

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