Engineering Notes

Liquid Oxygen and Liquid Methane Mixtures as Rocket Monopropellants

Richard L. Every* and James O. Thieme†
Continental Oil Company, Ponca City, Okla.

THIS note describes a preliminary evaluation of the specific impulse, characteristic velocity, pumpability, and sensitivity of the liquid oxygen (LOX) and liquid methane (LCH_4) system as a monopropellant. Since standard methods for evaluating a monopropellant[1] are not easily applicable to cryogenic fuels, it was necessary to develop rather elementary test procedures and to compare these data with identical measurements made with other monopropellants. Previous work[2,3] indicated that LOX and LCH_4 are miscible in all proportions above 90°K and are also shock-sensitive. Although shock sensitivities were reported, no quantitative data were available.

The methane and oxygen used in this study were of 99.9 mole-% purity. Prior to liquefaction, each gas was filtered through Ascarite and calcium sulfate to reduce carbon dioxide and water contamination. All samples were liquefied by condensation upon a copper coil through which liquid nitrogen (LN_2) was circulated. Since safety considerations were of paramount importance, the mixing of solutions was accomplished by remote control.

Specific Impulse and Characteristic Velocity

A simple ballistic bomb apparatus has been developed for liquid monopropellent evaluation.[4] It comprises 112-cm³ volume with a pressure gage holder and vent valve in one end and an electrically fired 20-mm-cannon primer held in an assembly at the opposite end (Fig. 1). The sample was charged to the bomb through the bomb head, which could be removed easily. To obtain a maximum pressure curve for a given sample, a series of determinations was made using various loading densities. The pressure was sensed with a piezoelectric crystal gage and recorded by photographing an oscilloscope. Straight-line extrapolations were made of the rise and decay portions of the pressure record, and the intersection of these lines was taken as the maximum pressure. Pressure corrections for heat losses during burning and for the igniter energy were estimated to be equal (about 1%) and opposite and were therefore ignored. The specific impulses (I_{sp}) and characteristic velocities (C^*) computed from tests on nitromethane and various LOX/LCH_4 mixtures are compared to calculated values[5] in Table 1. The good agreement obtained for nitromethane lends support to the validity of the method. The values obtained for LOX/LCH_4 are attractive for monopropellant use.

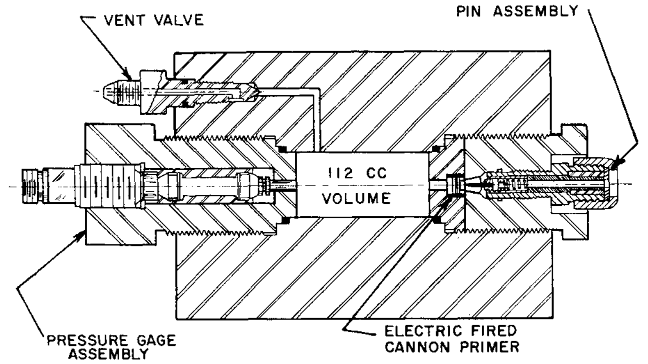

Fig. 1 Ballistic bomb assembly.

Table 1 Specific impulse and characteristic velocity values for $\gamma = 1.25$ and chamber pressure $P_c = 1000$ psi

Monopropellant	O/F ratio, by wt	I_{sp}, sec Expl.	I_{sp}, sec Calcd.	C^*, fps Expl.	C^*, fps Calcd.
Nitromethane	...	245	248[a]	5000	5010
LOX + LCH_4	2.5	209	...	4260	...
LOX + LCH_4	7.2	280	...	5710	...
LOX + LCH_4	3.6	297	...	6050	...
LOX + LCH_4 (bipropellant)	3.0	...	290[a]	...	...

[a] Corrected from P_c = 300 psi by I_{sp} (300 psi)/0.88 = I_{sp} (1000 psi).

Pumpability

A test was conducted to determine the effect of compressing gas bubbles in the solution under nonadiabatic conditions. A *J*-shaped pressure tube connected to a 3000-lb gage (Fig. 2) was submerged in a LN_2 bath. Methane gas was admitted to the *J*-tube through a 1-liter measuring vessel, and the pressure was noted. The gas was then allowed to condense in the *J*-tube, and the pressure was recorded again. The amount of LCH_4 in the *J*-tube was approximated from these data. The same procedure was followed on admission of oxygen. When the desired mixture was attained, the LN_2 bath was removed, and the solution was subjected to an overhead nitrogen pressure of 1400 psig. In another test, the solution was exposed to its own vapor pressure up to 1400 psig. No detonation occurred in any of these tests.

Tests were conducted to determine whether violent stirring or agitation, as found in an impeller-type pump, would detonate the mixture. A 1.75-in. stainless-steel propeller (30° angle with vertical) was run in 200 cm³ of LOX/LCH_4 mix-

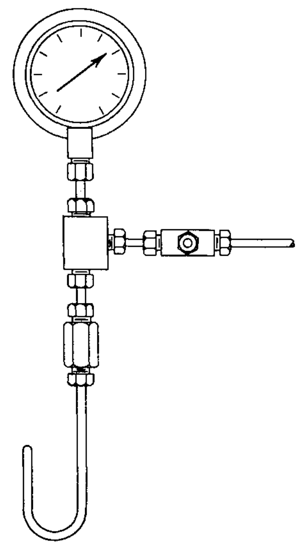

Fig. 2 Equipment for pressure sensitivity tests.

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* Senior Research Scientist, Central Research Division.
† Associate Research Scientist, Central Research Division.

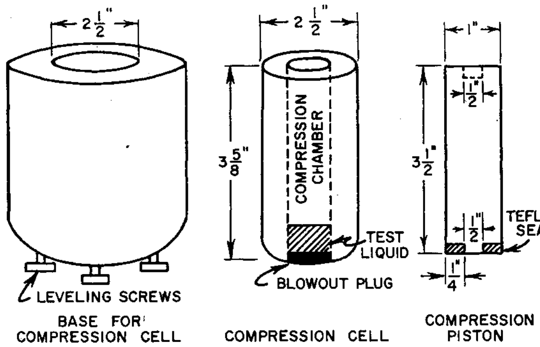

Fig. 3 Adiabatic compression equipment.

ture at 1900 rpm in a 2.75-in. glass dewar. In some tests, 1–2 g of impurities, such as rust and dirt, were added to the monopropellant before stirring. No explosions or detonations were experienced in these tests. From these simple tests, we believe that a LOX/LCH_4 monopropellant could be safely handled in available equipment.

Impact Sensitivity

The fundamental significance of a simple impact (falling weight) test cannot be exactly defined; however, this test is considered useful as a rapid and simple means to rate liquid monopropellants as to their relative explosion limits. Furthermore, it can be an important laboratory tool to determine the handling safety of new and uncharacterized materials before substantial quantities are prepared. The system used in this test consisted of a 2-in.-diam stainless-steel beaker, a $\frac{3}{8}$-in. steel guide rod about 6 ft long and a 1.62-in.-diam, 11.7-lb piston. These diameters were chosen arbitrarily so that the liquid would not be confined to the beaker upon impact. The piston had a $\frac{1}{2}$-in. hole so that it would slide easily on the vertical guide rod.

The beaker was rinsed with the liquid to be tested and dried with a lint-free cloth. The piston was then placed on the guide rod at a predetermined height. A 10-cm³ sample was subcooled with LN_2 and transferred to the uninsulated beaker. Tests were conducted after the sample had warmed to its boiling point as evidenced by small bubbles rising to the surface. The first test in each case was a 6-in. piston drop. If no explosion occurred, the height was increased by 2-in. increments until an explosion occurred. Three tests were then performed at that height to substantiate the first positive result. The weight was then lowered 2 in., and three more tests were made; if 2 out of 3 proved negative, the test was terminated. Otherwise, the weight was again lowered 2 in., and so on, until the lower limit of sensitivity was determined. Results of these tests are given in Table 2.

The (Oxidized/Fuel) O/F ratio nearest stoichiometric (3.6) is the most sensitive under these test conditions. No explosions were obtained at ratios larger than 7.2 or smaller than 2.5 at the upper limit of our apparatus (about 66 ft-lb). Negative results were also obtained with other monopropellants, nitromethane, n(normal)-propyl nitrate, and hydrazine, at the upper impact limit. Since these latter tests were carried out at room temperature (well below their normal boiling points), it is plausible to assume that the observed impact insensitivities may have been due to the absence of microscopic bubbles within the liquids.

To determine the significance of metal-to-metal contact (piston on beaker bottom), a polystyrene foam pad was placed in the beaker and tested with the most sensitive mixture. The insertion of the foam pad reduced the sensitivity from 19 ft-lb to 32 ft-lb undoubtedly because of suppression of "hot spot" formation.

Table 2 Minimum energy necessary to explode LOX/LCH_4 in an unconfined chamber

O/F ratio by wt	Impact sensitivity, ft-lb
7.2	56
5.1	21
3.6	19
3.6 (polystyrene foam pad on beaker bottom)	32
2.8	25
2.5	50

Table 3 Adiabatic compression sensitivity

Compound	Literature value,[1] ft-lb	Experimental value, ft-lb
n-propyl nitrate	0.445	13.7
Nitromethane	0.690	23.4
LOX/LCH_4	...	>66.0[a] (no explosion)

[a] Limit of experimental apparatus.

Adiabatic Compression Sensitivity

One possible cause of the destructive decomposition of fuels is the rapid compression of small gas bubbles in contact with the fuel. Rapid compression can result from mechanical shock to fuel containers or from rapid closing of valves in fuel lines containing entrained gas bubbles. The equipment for the adiabatic compression tests was designed to simulate conditions that might occur in an actual fuel line and incorporates a device for applying pressure very rapidly to a gas bubble in contact with a liquid fuel sample. It consisted of a thick-walled stainless-steel chamber, a stainless-steel piston with Teflon seal, and a hammer (Fig. 3). A blowout plug in the bottom of the chamber prevented total destruction of the cell in positive tests. The piston was machined to fit the compression chamber with very small tolerances. The Teflon seal on the piston tended to seal tighter when pressure was applied. To conduct a test, the compression chamber was loaded with 2 cm³ of test liquid with a hypodermic syringe. The piston was then fitted into the chamber, and the hammer was adjusted to the desired height. The test room was then evacuated, and the hammer was released to drive the piston into the test chamber. To determine the lower limit of sensitivity, the same procedure was followed as with the impact sensitivity tests. Results for nitromethane, n-propyl nitrate, and LOX/LCH_4 (O/F = 3.6) are given in Table 3.

Literature values[1] were based on compression of 0.2–0.8 cm³ bubbles over 0.5–0.6 cm³ of sample, whereas our values were obtained by compressing 10-cm³ bubbles over a 2-cm³ sample. Because of this difference, these data should be compared on a relative basis; the ratios of values for n-propyl nitrate/nitromethane agree well. The LOX/LCH_4 monopropellant is seen to be three times as safe as nitromethane and five times as safe as n-propyl nitrate. The inertness of the LOX/LCH_4 mixture under these test conditions (compared to the piston impact tests) may be caused by the piston not striking the bottom of the test chamber to cause a hot spot.

Conclusions

Results of these experiments indicate that a LOX/LCH_4 monopropellant has a very good specific impulse (~300 sec) and a characteristic velocity of better than 6000 fps. Although LOX/LCH_4 mixtures are potentially hazardous, the tests conducted indicate that they can be pumped and handled with conventional apparatus. Under conditions of adiabatic compression, thought by some to be the cause of many accidental explosions, LOX/LCH_4 is three times as safe as nitromethane and five times as safe as n-propyl nitrate.

References

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Topology and Kinematics of a Complex Rigid System

C. F. Harding*
Douglas Aircraft Company, Santa Monica, Calif.

THE coupled Euler equations of motion for multiple-part satellites present a problem in attitude-control studies because of the numerous coordinate transformations that have to be performed and that are not directly apparent when written in vector-dyadic form. The manner in which different parts of the system are identified has a decisive effect on the ease of reduction by a computer to scalar components as required in practical application. The purpose of this note is twofold. The first purpose is to give a topological classification of the various parts that exhibits in detail the physical interaction among the parts. This is of great importance in computer programing in that, given the identification for a particular part, the identification of all parts with which it interacts is obtained by a simple algebraic operation on the former's identification. Thus the computer has the capability of associating just those parts, relative to a given part, that are necessary to effect a series of coordinate transformations to the main body. The second purpose is to derive the necessary formulas that relate quantities and their time rates, as seen in a coordinate system attached to each part, to the values of these quantities relative to the reference frame of the main body. The formulas so obtained, in connection with the topology of each part, are given in a compact form that readily lends itself to the use of tensor notation and so programed on a computer. The text ends with a detailed example for the case of an unbalanced 2-gimbal gyro. The acceleration of the center of mass of the rotor is required with components on the main body. The motion of the rotor, however, is known only relative to the coordinate system of the inner gimbal, the inner gimbal relative to the outer gimbal, and so on.

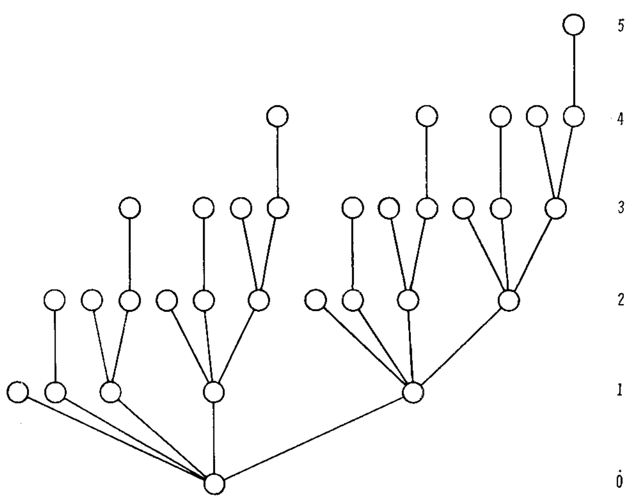

Fig. 1 Topology of interactions.

Topology

We shall consider a system of rigid bodies such that any two parts can interact only through relative rotation about a common fixed axis. The possibility of any closed-loop relationship between three or more parts will be excluded. It is felt that this is broad enough to include most real situations to be found in practice. Extremely complex interactions can occur, but they are all reducible to a simple topological classification of two dimensions. A convenient part will be isolated and called the main body, so that all other parts can be referred to this one by the notation to be developed. An interaction group is tentatively defined as a set of parts (elements) such that a given part of the total system either does or does not belong to the group depending upon whether that part can or cannot interact directly with some element of the group. If the main body interacts with each group, we have a closed set and, in fact, just one primitive interaction group (satellite), and so we modify the definition by excluding the main body as a member. The separation into disjoint groups provided by excluding the main body leads to identification of any rigid part of the system by its topological relationship to the main body. An element of a group is said to be removed by k if k is the smallest integer obtainable by counting from zero at the main body to the element in question through an unbroken chain of interconnected parts (Fig. 1),† the order of a group being next defined as the largest value of k obtained as one ranges over all elements of the group. Each part of the total system can now be specified by means of an ordered block of l characters ($j_1\, j_2\, \ldots\, j_l$) in the manner suggested by Fig. 2. In general j_1 indicates the number of an l-order group, j_2 the number of an appropriate element that is removed by 2 from the main body in this group, j_3 the number of an element removed by 3 and attached to the previous element, etc. In case one is speaking of an element removed by k in an l-order group, the numbering would just be $j_1\, j_2\, \ldots\, j_k$ 0

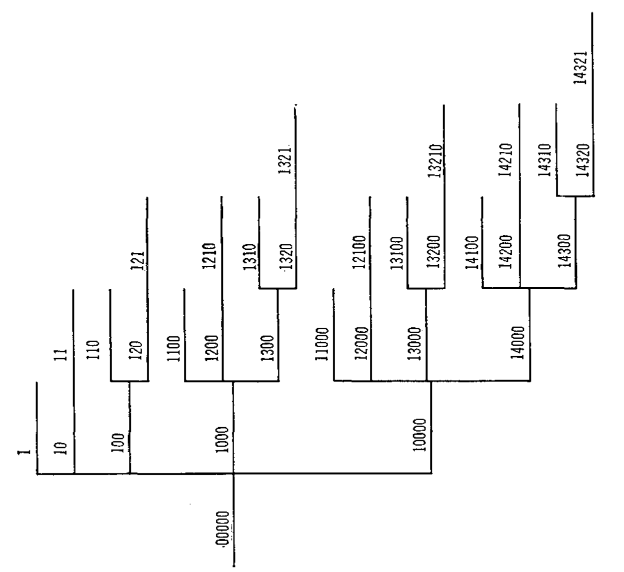

Fig. 2 Identification of elements.

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* Research Engineer, Stability and Control Branch, Advance Flight Mechanics Department, Missile and Space Systems Division.

† For example, the rotor of a 2-gimbal gyro is removed by 3, whereas an inertia wheel is only removed by 1.