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This paper describes control experiments in liquid metal combustion. Preliminary results are reported for the effectiveness of open-loop control techniques in improving closed-cycle liquid metal combustion. The effects of non-axisymmetric nozzle shapes and pulsed oxidant flow rate on the combustion process are tested by measuring the total fuel utilization at the point of end-of-run pressurization, which is characteristic of this type of combustor, and by observing the jet/bath dynamics using X-radiography. Nozzle geometry and oxidant flow rate are the parameters used to control the combustion process. The reacting jet stability and rate of end-of-run pressurization is affected somewhat by the nozzle geometry, however, no significant effect is observed on the total fuel utilization achieved. Pulsed oxidant injection produces an expected large effect in bath/jet dynamics as the oxidant flow rate is pulsed from 3 to 20 gr/sec, but no statistically significant change in total utilization is demonstrated.

The causes of combustion chamber pressurization during the combustion process and at end-of-run are discussed. In an effort to explain significant pressurization of the combustion chamber developed during the combustion process, chamber pressure dependence on oxidant purity grade, oxidant flow rate and hydrogen content are reported. The presence of relatively small amounts of hydrocarbons introduced during combustor fabrication produces significant pressurization of the combustion chamber throughout the combustion period, while the chamber pressure has relatively little dependence on the oxidant mass flow rate or oxidant purity. No significant effect of pressurization caused by hydrocarbons on maximum fuel utilization is observed.

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Control Experiments in Liquid Metal Combustion*

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Abstract

Preliminary results are reported for the effectiveness of open-loop control techniques in improving closed-cycle liquid metal combustion. The effects of non-axisymmetric nozzle shapes and pulsed oxidant flow rate on the combustion process are tested by measuring the total fuel utilization at the point of end-of-run pressurization, which is characteristic of this type of combustor, and by observing the jet/bath dynamics using X-radiography. Nozzle geometry and oxidant flow rate are the parameters used to control the combustion process. The reacting jet stability and rate of end-of-run pressurization is affected somewhat by the nozzle geometry, however, no significant effect is observed on the total fuel utilization achieved. Pulsed oxidant injection produces an expected large effect in bath/jet dynamics as the oxidant flow rate is pulsed from 3 to 20 gr/sec, but no statistically significant change in total utilization is demonstrated.

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INTRODUCTION

LIQUID METAL COMBUSTION BACKGROUND

Closed-cycle liquid metal combustion (CLMC) used in underwater propulsion systems utilizes the combustion of an oxidant (SF_6) injected under choked conditions into a liquid Li metal bath in a closed combustion chamber. The combustion process during most of a "normal" run takes place as a submerged reacting jet. After a certain percentage of the fuel is consumed, a transition occurs in the combustion process from a localized, submerged reacting jet to a much more distributed combustion process. Since the fuel and products are immiscible and Li is about 25% as dense as the reaction products LiF and Li_2S, there is a strong tendency for remaining fuel to collect at the surface of the bath and much of the combustion shifts to the ullage area of the container. An End-of-Run (EOR) pressure spike is observed in the oxidant injector back pressure, due to incomplete consumption and accumulation of excess gaseous oxidant in the closed combustion chamber. This is accompanied by a sudden, large increase in ullage temperature, as evidenced by the rapid disintegration of thermocouples and other metal objects in the ullage that are not well thermally sunk. Fig. 1. shows typical injector upstream pressure data during liquid metal

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combustion. The end-of-run pressurization spike is seen in this graph about 180 seconds into the run. The rate of pressurization for the combustor sizes and geometries used is typically 50-150 kPa/sec.

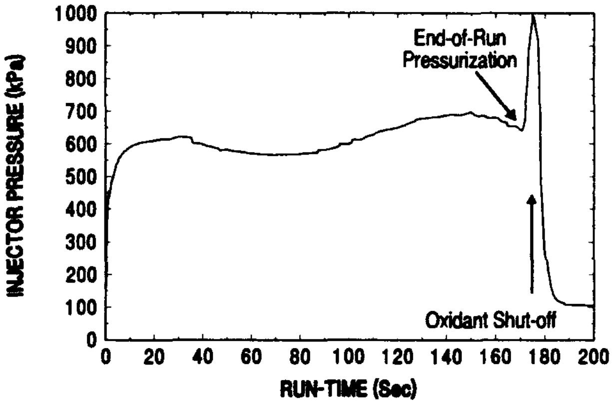

Figure 1. Upstream injector pressure vs. combustion run-time, shows typical End-of Run pressure spike.

Ullage combustion exposes containment surfaces to a high temperature, extremely corrosive environment and can result in a breach of the combustion chamber. The relatively high combustion chamber pressure unchokes the injector nozzles contributing to erosion of the injectors and may also lead to containment failure. For this reason, the reaction is normally terminated as soon as a rapid rise in injector pressure or an anomalous increase in temperature is detected above normal combustor operating temperature (1000 C). For the combustors and oxidant mass flow rates used in this work the fuel utilization is in the range of 50-75% when EOR pressurization is expected to occur, depending on the combustor geometry, orientation and most importantly the oxidant mass flow rate. A measure of combustor performance can be taken to be the total fuel utilization achieved at the time of onset of combustor pressurization as indicated by a sudden increase in injector pressure necessary to maintain oxidant mass flow at constant rate.

Obviously, the operating range and reliability of this type of combustion system would be improved if the EOR event is delayed. Several performance criteria are of practical interest, such as, the total fuel utilization achieved at shut-down, consistently high heat tranfer from the combustor to the coolant and prevention of containment failure. In order to improve combustor performance it is important to understand the cause and factors which affect the transition from submerged jet to distributed combustion. The object of this work is to test simple control strategies having the potential of affecting combustor performance, and to identify the causes of combustion pressurization in general both during normal combustor operation and at occurrence of the EOR event.

X-RADIOGRAPHIC DIAGNOSTICS RESULTS

Parnell[1] has performed X-radiographic diagnostics of experimental liquid metal combustors for several years. Among other studies, the reacting jet/bath dynamics have been documented and correlated to combustor performance. The EOR effect has been found to be highly related to jet/bath dynamics. At the time of EOR pressurization, the oxidant jet becomes greatly attenuated, as observed in X-radiographic video. The fuel/product bath takes on a "foamy" appearance and becomes much more quiescent compared to a bath agitated by a reacting jet. At this point the temperature increases in the ullage and free standing metal objects frequently disintegrate. By observing the appearance of the bath, the operator can predict with a high degree of confidence when EOR pressurization is about to occur.

COMBUSTION CHAMBER PRESSURIZATION STUDIES

An additional objective of this study is to explain the combustion chamber pressures developed throughout the combustion process before the EOR event occurs. Gilchrist[2] et al. have recently reported measurements of the chamber pressurization in liquid metal combustors. A pressure transducer is connected via a stainless steel tube to the combustion chamber ullage area. This technique measures the pressure at a much lower temperature than the bath temperature and the pressure port is subject to blockage by reaction products at the end of the run, but the results likely represent reasonably accurate values and trends for the chamber pressure P_c, since the pressures measured are much larger than the expected vapor pressures of the bath constituents at combustor operating temperatures. Initially as combustion begins P_c drops to a low level, about 10 kPA. As combustion proceeds P_c gradually increases to a level of about 100 kPA. Figure 7. (page 6 of this article) shows a typical chamber pressure measurement (lower curve). These pressures are surprisingly high. It has been assumed in the past that liquid metal combustors operate at low pressures, near vacuum. At lower oxidant flow rates these pressures approach the level required to unchoke the oxidant injectors and is an undesirable effect, due to the potential for injector erosion. Data is presented here on the effect parameters such as the oxidant mass flow rate, and collateral materials in the combustion chamber (included during fabrication) have on the combustion chamber pressure.

COMBUSTOR PERFORMANCE CRITERIA

The principal evaluation criterion for the performance of these control techniques tested is the point of occurrence of the EOR pressurization. A large dependence of the amount of fuel consumable on the rate of oxidant flow has been reported. For combustors of the size used in this work total fuel utilizations achieved varied from about 50% at 3 gr/sec oxidant mass flow rate to 75% at 8 gr/sec oxidant flow rate. Fig. 2 is a comparison of two combustion tests performed in the same container and orientation, but with much different oxidant flow rate histories. The Figure illustrates the range of total utilizations which occur with variation of oxidant flow rate. In previously published studies maximum utilization measured in such tests is the total percentage consumption of the fuel at oxidant shut-off. The time of oxidant shut-off, however, is operator dependent and for purposes of comparison here the utilization at the time of initiation of EOR pressurization is used as a figure of merit usually a few percentage points less than the utilization at shut-off. The point of onset of EOR pressurization is indicated in Figure 1. The Li utilization is calculated from the amount of SF_6 injected using the stoichiometry of the relation

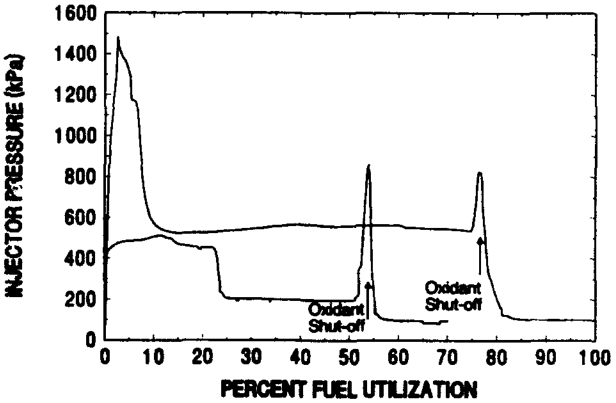

Figure 2. Injector pressure vs. utilization for two liquid metal combustor tests having high (upper curve) and low (lower curve) oxidant flow rates. Lower oxidant flow rates result in lower fuel utilizations.

$$8Li + SF_6 \rightarrow 6LiF + Li_2S ,$$

which yields a weight ratio of SF_6 to Li of 2.63.

EXPERIMENTAL

COMBUSTOR DESIGN

Some parameters which may effect combustor pressurization are; rate of entrainment of fuel into the reacting jet or fuel/oxidant mixing efficiency, degree of fuel/product mixing and oxidant flow rates. Experiments were performed to determine the influence of injection nozzle geometry and pulsed oxidant mass flow rate on bath dynamics and combustor performance. Non-axisymmetric nozzle shapes affect the efficiency of fuel oxidant mixing in the reacting jet. Pulsed oxidant mass flow rates is expected to increase fuel/product stirring.

Two types of combustors are used in this work, a cylindrical (HEB) combustor which produces steam at a temperature of about 400°C and a prismatic, "narrowbody" (NB) combustor which is water-cooled. These combustors have been described in more detail elsewhere[2]. The HEB combustion chamber has of diameter of 8.4 cm and a length of 42 cm. The NB combustor has chamber dimensions, 6.7x11.8x30.7 cm. These combustors are filled with up to 900 gr of Li and 25% that much by weight start charge. The unfilled volume (ullage) occupies about 20-25% of the total volume. A squib ignites the pyrotechnic charge which heats the fuel to the point were combustion proceeds spontaneously as sulfur hexaflouride is injected.

NON-AXISYMMETRIC INJECTOR NOZZLES

Three tests were performed of the effects of non-axisymmetric injection nozzle geometries on liquid metal combustion. The nozzles tested were designed and fabricated by K. Schadow and coworkers at the Naval Air Weapons Center (NAWC). Two types of nozzles were tested, a 3:1 aspect ratio slot nozzle with exit dimensions of 0.134x0.406 cm and a 3:1 aspect ratio tapered slot nozzle with throat dimensions of 0.129x0.391 cm and exit dimensions of 0.170x0.51 cm. These types of nozzles were shown to increase mixing in gas/liquid systems by K. J. Wilson[3] et al. They were also more stable[4] at lower flow rates. The motivation for this experiment is to test whether enhanced entrainment of fuel or jet stability prolongs submerged combustion and delays transition to combustion chamber pressurization.

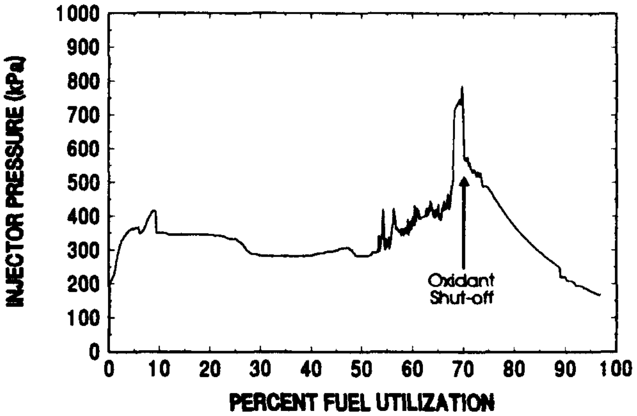

Figure 3. Injector Pressure vs. fuel utilization for elliptical orifice injector with a diverging exit.

One tapered 3:1 aspect ratio slot nozzle and two straight 3:1 slot nozzles were tested in liquid metal combustors, and the effect on total fuel utilization measured. X-radiography was performed during two of the tests to determine whether there was a visible effect of the injection geometry on jet dynamics. The utilization results for these and other tests in the table. As shown in Figs. 3 and 4, the transition from normal operation to EOR pressurization was not as smooth or as steep as in the previous examples shown. This may be due to an effect on the rate of pressurization caused by the injection geometry or it may be merely an increased tendency of the more narrow injectors to plug with reaction products at high utilizations. The utilizations achieved were within the range normally seen in other liquid metal combustion tests. X-radiography showed a more stable jet operation but not a dramatic difference from those produced by conventional injectors.

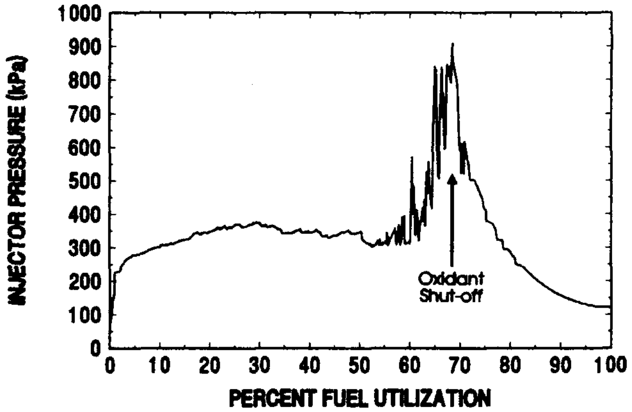

Figure 4. Pressure vs. fuel utilization for elliptical orifice injector.

PULSED OXIDANT MASS FLOW RATE

Since the fuel and reaction products readily separate, it has been suggested that the degree of agitation of the bath influences the performance of liquid metal combustors. Previous work by Gilchrist[5] et al. has shown that oxidant flow rate can affect total fuel utilization achieved before the onset of chamber pressurization. Two tests were performed in which the oxidant mass flow rate was pulsed by a factor of 4-8 times, and the utilization at EOR was observed to determine whether combustor performance would be affected. X-radiography was used to observe any changes in jet dynamics.

The oxidant supply system was modified so that the oxidant flow to the combustor could be switched from a low pressure to high pressure, using a solenoid valve triggered by a function generator. Pulsing the oxidant mass flow rate provided periodic bath agitation while maintaining a relatively low average mass flow rate. The injector pressure was typically switched from about 300 kPa to 2000 kPa to achieve corresponding mass flow rate pulses of 3 and 20 gr/sec respectively. Two pulsed-oxidant flow tests were performed and are shown in the table. The first test had a base oxidant mass flow rate of 3 gr/sec. Pulses of up to 20 gr/sec about 1 sec wide were applied every 5 seconds to produce average mass flow rate of 4.5 gr/sec. In the second pulsed-oxidant flow test, pulses of 20 gr/sec were applied every 3.5 seconds with a base flow rate of 4.5 gr/sec and an average mass flow rate of 9.0 gr/sec.

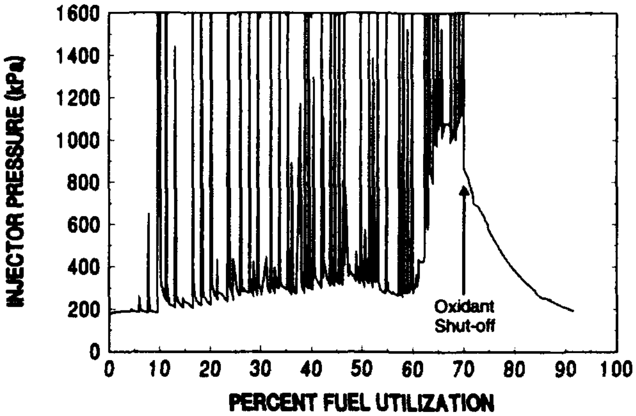

Figure 5. Injector Pressure vs. fuel utilization for 1st pulsed-oxidant flow test.

The total utilization results are shown in the table. Although X-radiographic images showed dramatic effects in jet dynamics and bath agitation when oxidant flow was pulsed, no statistically significant effect is seen in fuel utilization results. The percent fuel utilization achieved in the first test is high considering the average flow rate was only 4.5 gr/sec, but not enough tests have been performed at this intermediate flow rate to determine if this is a real improvement or a statistical fluctuation.

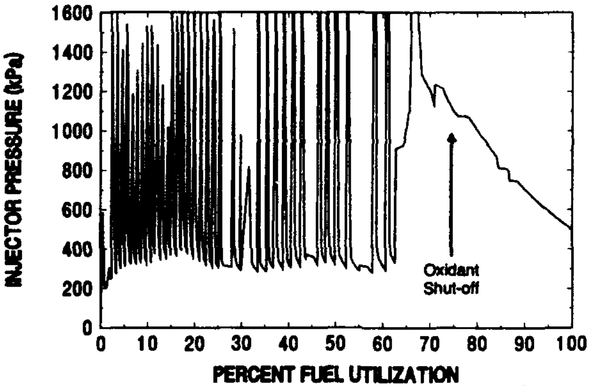

Figure 6. Injector pressure vs. fuel utilization for 2nd pulsed-oxidant flow test.

CHAMBER PRESSURE MEASUREMENTS

The lower curve in the Fig. 7 shows a typical combustion chamber pressure profile during a normal liquid metal combustion run. P_c drops upon ignition to as low as 10 kPa. Then, the pressure increases gradually to about 100 kPa (or about an atmosphere) at 60-70% utilization. Near test termination (about 70-80% utilization) a pressure spike is often seen in the chamber pressurization which correlates to the pressure spike that occurs in the injector upstream pressure.

One of the objects here is to determine if some of the materials introduced during fabrication of the combustor contribute to pressurization of the combustor or if the increasing pressure during the combustion process is a consequence of the combustion process in itself. In these combustion experiments and in real systems, there are several means by which hydrocarbons are introduced into the combustor during fabrication. The principal means is that a heavy lubricant is used during the lithium fill operation. Steel rods are used to cast holes during the lithium-pour operation to make space for the pyrotechnic charge. A heavy grease is applied to the casting rods so that they can be pulled from the lithium after it is solidified. Some of the lubricant will obviously remain in the lithium as well. Additionally, the pyrotechnic binder, squib wire insulation and high temperature epoxy used in the combustion chamber are sources of hydrocarbon which remain in the combustion chamber. Hydrogen will react with lithium, however, the product LiH is not stable at combustor operating temperatures (LiH decomposes at ~1245°K) and hydrogen gas or some gaseous species containing hydrogen may be a source of pressurization of the combustion chamber.

The normal hydrocarbon content of test combustors such as these is estimated to be 2-3 grams. Since the sources of hydrogen could not be easily eliminated additional hydrocarbon was added to one test to determine how much contribution it makes to chamber pressure. Ten grams was added to ensure that the effect is significant compared to a "normal" test. The upper curve in Fig. 7 shows a pressure profile of a combustion run for a combustor to which, in addition to a normal charge of 740 grams of lithium ten grams of high-temperature silicone lubricant (Dow Corning High Vacuum grease) was introduced. The pressure was several times greater than the normal pressure and follows roughly the same trend, except that there was no initial pressure drop at the beginning of combustion. The curve is clipped at 300 kPa, because the pressure transducer range was exceeded. The graph shows that hydrocarbons in amounts not much greater than are normally present in these combustors can cause significant combustion chamber pressurization.

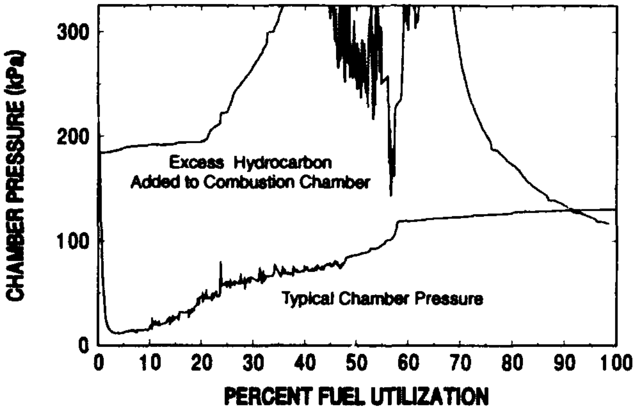

Figure 7. Combustion chamber pressure measurements of tests with and without addition of 10 grams of excess hydrocarbon lubricant.

Another possible source of pressurization is the nitrogen content of the oxidant gas. The Chemically Pure (CP) grade SF_6 introduces a significant amount of nitrogen during the combustion process, and the total amount of nitrogen increases linearly with utilization. It has been suggested that this may be the source of the linearly increasing pressurization of the combustion chamber during most of the run. However, use of a higher purity gas (Instrument Grade) produced no measurable difference in chamber pressurization. Since hydrocarbon content had a large enough effect to explain combustor pressurization, the effects of nitrogen were not further pursued.

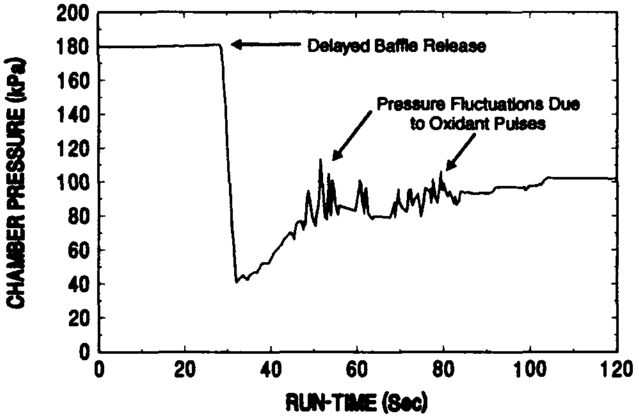

Figure 8. Combustion chamber pressure as the oxidant mass flow rate is pulsed from 3 to 20 gr/sec at 4 sec intervals. Pulse widths are about 1 second.

Chamber pressure measurements indicated a small degree of dependence of chamber pressure on mass flow rate. Fig. 8 shows the chamber pressure of one of these tests. The relative small fluctuations in chamber pressure (about 20 kPa) implies that the chamber pressure, at least until the end-of-run is almost independent rate of oxidant mass flow rate flow. The pressure fluctuations shown in this graph represent a 10-20% change in chamber pressure due to a change in mass flow rate of 3 gr/sec to 20 gr/sec.

Table. Summary of fuel utilizations achieved at EOR in liquid metal combustion tests.

Test Description	Combustor Type	Average Mass Flow Rate (gr/sec)	Fuel Utilization
Tapered 3:1 Slot Nozzle	NB	6.0	63%
3:1 Slot Nozzle (Test #1)	NB	6.0	72%
3:1 Slot Nozzle (Test #2)	NB	6.0	65%
Pulsed Oxidant Flow Rate (Test #1)	HEB	4.5	62%
Pulsed Oxidant Flow Rate (Test #2)	HEB	9.0	63%
Reduced Oxidant Flow Rate (at 23% fuel utilization)	NB	3.0	52%
Normal Oxidant Flow Rate	NB	6.0	74%
Hydrocarbon Addition (10 grams)	HEB	6.0	63%

DISCUSSION

The effort to extend submerged combustion has not been very successful. These results are preliminary and more testing needs to be done, but in case it does not prove feasible to extend the submerged-jet mode of combustion, the next step is to attempt to make the ullage combustion mode acceptable.

In some cases it is evident that a large excess of lithium fuel remains at the bath surface towards the end of the combustion run. Fig. 9 is a radiograph of the low-flow test referred to in the Table and in Figure 2. Less than 60% of the fuel was consumed in this test. The low density strata indicated in the figure (about 15% of the volume of the bath) was composed of mostly lithium. The lower volume was a mousse of reaction products and the rest of the lithium fuel or about 25% of the original volume of fuel. So, in this case there was a large surplus of fuel at the bath surface when the combustor pressurizes with excess oxidant gas (presumably). In order to prevent the EOR pressurization effect it is necessary to understand why excess oxidant accumulates when there is a large amount of fuel available for combustion.

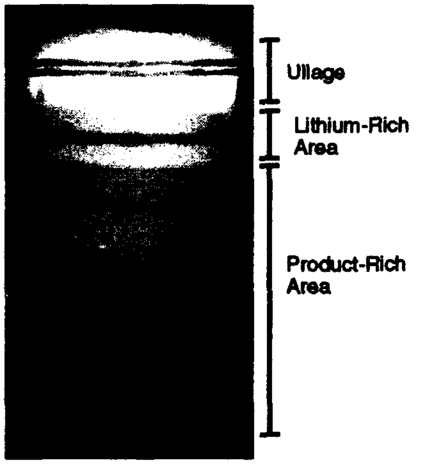

Figure 9. X-Radiograph of prismatic combustor immediately after oxidant shut-off, showing fuel/product stratification.

The high temperatures occurring at EOF in many of these combustors indicate that some level of combustion continues in the ullage at EOR, but it is apparently not fast enough to consume the injected SF_6. Cho[5] and Blake[6] et al. have discussed the importance of vaporization in liquid metal combustion. An unusual characteristic of the SF_6/Lithium reaction is the very high ratio of enthalpy of vaporization[7] to that of reaction, about 0.35. If the reaction is a gas/gas reaction then at least 35% of the heat of reaction must go into vaporization of Li for the reaction to proceed as a gas/gas reaction. The rate of reaction in combustors such as those used here is very high, and it is reasonable to assume that in order for the reaction to take place at the required rates the reaction must be predominately a gas/gas reaction[9]. In a submerged jet the reaction is surrounded by molten Li and a relatively large part of the reaction energy is apparently available for Li vaporization, at least until the proportion of reaction products builds up to the point where too much heat is dissipated into the reaction products.

In the ullage, however, there is a different situation, in that, there is a great deal of heat loss to the cooled container walls. The mode of combustion in the ullage is essentially "pool" combustion, which means that heat transfers to the Li surface occurs by radiation[9]. The amount of radiative energy transferred to the fuel surface must be large enough to vaporize the required amount of fuel. The mass rate of burning then per unit area is limited by the equation

$$\dot{m}_{Li} h_L \approx \epsilon \sigma (T_f - T_{Li})^4$$

where $\dot{m}$ is the mass rate of burning per unit surface area, h_L is the enthalpy of vaporization of lithium, ϵ is the emissivity of the surface (nearly unity), σ is the Stefan-Boltzmann constant, T_f is the flame temperature and T_{Li} is the temperature of the surface. Given the areas and oxidant flow rates typical of these combustors the flame temperature in the ullage must be thousands of degrees C. above the bath temperature in order for the combustion to continue in the ullage as a gas/gas reaction. Such temperatures can not be developed in the ullage because the current containment materials will not withstand the heat, but also because the flame loses energy due to radiation and mass transport of the reaction products to the cooled walls surrounding the ullage. The heat losses to the cooled walls preclude the transfer of enough heat to the Li surface to vaporized the required amount of fuel for the reaction to proceed in gas/gas phase. The gas/liquid reaction rate is too low to consume the fuel at the injected rate and the chamber becomes rapidly pressurized. A simple test of this interpretation would be to install a thermal barrier of highly heat-resistant material between the ullage and the cooled container walls and determine whether combustor operation is affected.

CONCLUSIONS

Although the jet may be somewhat more stable at the flow rates used in these experiments, the use of non-axisymmetric geometries for oxidant injection did not have a measurable effect on onset of EOF combustor pressurization or total fuel utilization. Pulsed control of oxidant flow rates did have a expected large effect on combustion dynamics, increasing the degree of bath circulation. There may have been some improvement in total achievable fuel utilization at lower flow rates (4.5 gr/sec), but more tests are needed for confirmation. No significant effect is observed on total fuel utilization achieved at flow rates approaching 8 gr/sec.

Tests have been performed to determine the effect of the introduction of nitrogen and hydrogen-containing compounds on chamber pressure during "normal" combustion, before end-of-run pressurization occurs. The introduction of a lubricant containing hydrogen in amounts close to those normally introduced during combustor fabrication has been found to significantly increase the combustion chamber pressure. This is important, because previous tests indicate that the normal combustor pressure can be relatively high leading to possible injector failure and containment breach. The high pressures generated by the presence of excess hydrocarbons did not result in a lower total fuel utilization for the single test performed to date. Future tests need to be performed to quantify the dependence of the combustion pressure on hydrogen content.

References

1. L. A. Parnell, J. T. Gilchrist and M. L. Sorensen, AIAA/SAE/ASME/ASEE 26th Joint Propulsion Conference, Orlando, FL, AIAA-90-2750(1990).

2. J. T. Gilchrist, B. P. Ayers and L. A. Parnell, AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference, Monterey, CA, AIAA-93-2205(1993).

3. K. J. Wilson, E. Gutmark, K. C. Schadow and R. A. Smith, "Supersonic Submerged Heated Jets," AIAA/SAE/ASME/ASEE 28th Joint Propulsion Conference, Nashville, TN AIAA-92-3138 (1992).

4. T. R. Ogden, L. A. Parnell and E. W. Hendricks, AIAA Paper No. 92-3139, AIAA/SAE/ASME/ASEE 28th Joint Propulsion Conference, Nashville, TN (1992).

5. D. H. Cho, ONR Workshop on Closed Liquid Metal Combustion, State College, Pa, Nov. 19-20, 1986.

6. T. R. Blake and L. A. Parnell,AIAA Paper No. 92-3140, AIAA/SAE/ASME/ASEE 28th Joint Propulsion Conference, Nashville, TN (1992).

7. L. D. Chen, K.-Y. Hsu and H.-Y. Lyu, 27th JANNAF Combustion meeting, Cheyenne, Wyoming, Nov. 509, 1990.

8. Personal communication T. R. Blake.

9. R. M. Fristrom and A. A. Westenberg, *Flame Structure*, McGraw-Hill Book Co., New York (1965).

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Nomenclature

EOR	end-of-run
h_L	enthalpy of vaporization
$\dot{m}$	mass rate of burning per unit surface area
P_c	combustion chamber pressure
T_f	flame temperature
T_{Li}	Li surface temperature
ϵ	surface emissivity
σ	Stefan-Boltzmann constant