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PHOTOGRAPHIC STUDY OF LIQUID-OXYGEN BOILING AND GAS INJECTION IN THE INJECTOR OF A CHUGGING ROCKET ENGINE

by E. William Conrad, Ned P. Hannum, and Harry E. Bloomer

Lewis Research Center
Cleveland, Ohio

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Film Supplement C-228 available on request.

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~~declassified after 12 years~~

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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PHOTOGRAPHIC STUDY OF LIQUID-OXYGEN BOILING AND GAS INJECTION IN THE INJECTOR OF A CHUGGING ROCKET ENGINE*

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SUMMARY

High-speed motion pictures were taken of conditions in the injector liquid-oxygen cavity of an RL-10 rocket engine during throttled engine operation. Photographs were taken during operation of the engine in the chugging region as the helium gas was injected to stabilize combustion, during operation at rated thrust, and during transition into chugging conditions as the gas injection was discontinued.

Results of the investigation indicate that, during chugging rocket operation of the RL-10 engine, a high population of fairly large bubbles formed and collapsed within the liquid-oxygen cavity at the same frequency as the chamber pressure oscillations. When gaseous helium was injected into the liquid-oxygen cavity, a fog rapidly spread over the entire field of view, and the system immediately became stable.

The injection of gaseous helium at rated conditions produced a very slight increase in engine performance but not enough to produce a net gain in a typical mission payload with the extra equipment needed.

The inherent low-frequency system instability associated with the fuel system at low thrust levels was reduced by injecting either gaseous helium or hydrogen. Complete stabilization was achieved in some cases, and a reduction in the severity of the oscillations in others. This was apparently due to the anchoring of the phase change front to the location of the gas injection.

INTRODUCTION

Considerable effort has been directed toward throttling a pump-fed liquid-hydrogen - liquid-oxygen rocket engine. Major problems that have been encountered are combustion instability (chugging) and low-frequency (1 to 5 cps)

*Title, Unclassified.

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oscillations in the fuel system. Chugging regions of engine operation were defined, and the elimination of chugging by gas injection in the injector liquid-oxygen cavity has been presented earlier (ref. 1). Several questions have persisted concerning the distribution of the injected helium or oxygen gas (at the rates of only 0.4 and 4.0 percent, respectively, of the liquid-oxygen flow) to the liquid-oxygen tubes of the injector; also, the possibility that gas bubbles resulting from heat transfer from the warm hydrogen to the liquid oxygen in the injector cavity act only in localized regions. To gain insight into these and similar questions, high-speed motion pictures were made of the conditions in the injector liquid-oxygen cavity of an RL-10 engine during engine operation, including operation in the chugging region.

Both color and black and white films were made at 5000 frames per second through a $1\frac{1}{2}$-inch-diameter, 1/8-inch-thick sapphire port. Photographic coverage included operation in the normal chugging region as the helium gas was injected to stabilize combustion, operation at rated thrust, and operation during transition into chugging as the gas injection stopped. The information obtained is presented in the form of selected frames from the 16-mm movie film and a description of the corresponding engine operating conditions at that instant.

A motion-picture film supplement has been prepared and is available on loan. A request card and a description of the film are given at the back of the report.

The other major problem, the low-frequency instability of the fuel system, has also been investigated. The positive slope of the fuel pump characteristic line at low speeds was suspected of causing, or at least triggering, the instability. Subsequent operation with an adjustable orifice at the fuel pump discharge, a fuel pump of new design, and idle operation of the engine with the pumps not rotating have eliminated the pumps as the source of the instability. These further tests proved that the instability must be due to other causes, such as the two-phase flow transition in the hydrogen. Other investigations (refs. 2 and 3) had shown that a change in phase could cause such an instability.

Separate gas injections into the fuel system, using both hydrogen and helium gas, were tried as a possible solution. It was assumed that the gas injection would anchor the phase transition much like a flameholder in a combustion system. Gaseous weight flows of up to 20 percent of the fuel flow were injected into the line between the fuel pump discharge and the cooling jacket inlet. Photographic coverage was not attempted in this case, but the results were easily observable on recording instruments because of the low frequency of the oscillations.

APPARATUS

A pump-fed liquid-hydrogen - liquid-oxygen engine was used for investigation of the two throttling problems. The RL-10 is rated at 15,000 pounds of

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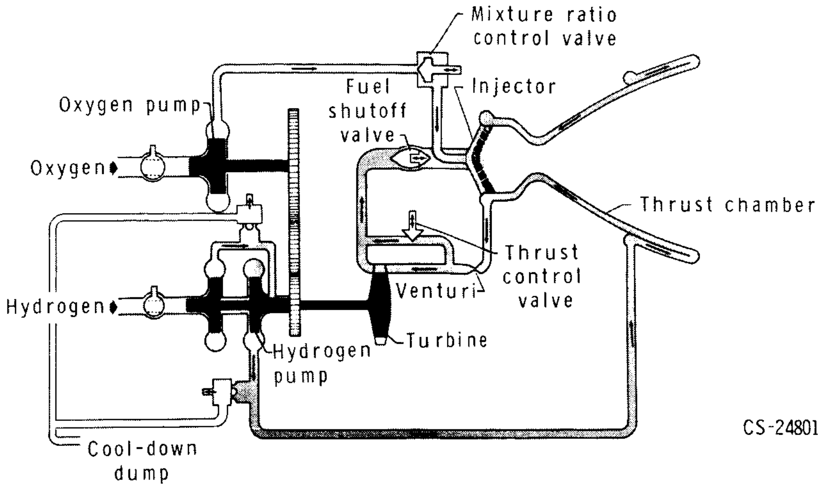

Figure 1. - Schematic of standard RL-10 engine cycle.

thrust at a chamber pressure of 300 pounds per square inch absolute and a mixture ratio of 5 when expanding to vacuum through a nozzle with an area ratio of 40. Figure 1 illustrates the standard RL-10 engine propellant flow schematic, and figure 2 shows the engine discussed herein, which was equipped with a "throttling kit" supplied by the engine manufacturer. As examination of the two figures shows, the throttling engine was provided with an additional turbine bypass valve and line to allow a greater amount of warm hydrogen from the cooling jacket to bypass the turbine and hence reduce pump speeds and resultant propellant flows. The engine can also be operated in a pressurized mode (without the pumps rotating) to permit operation below the 10-to-1 throttling range. Much of the engine system is not germane to the present subject and will not be discussed herein, but it should be noted that, before entering the injector cavity, the hydrogen is warmed to about 300° F while passing through the cooling jacket of the engine. Thus, the hydrogen in the injector is considerably warmer than the liquid oxygen (170° R), and heat transfer will occur.

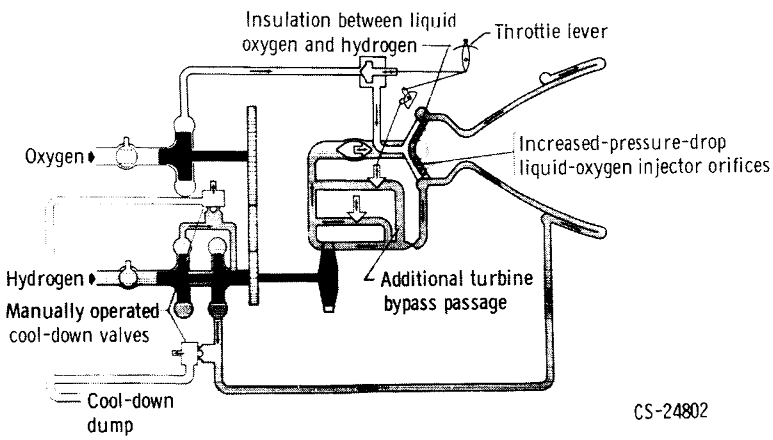

Figure 2. - Schematic of RL-10 engine cycle modified for throttling.

A cross-sectional drawing of the injector used in this investigation is

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shown in figure 3. A concentric tube injector was used that had 216 elements with 6-turn-per-inch swirlers in the liquid-oxygen tubes. Liquid-oxygen pressure drop at rated engine thrust was 60 pounds per square inch. As shown in figures 3 and 4, a $1\frac{1}{2}$-inch-diameter sapphire port was installed in the outer wall of the liquid-oxygen cavity. An annular inert gas purge was provided on the outside of the port to prevent frosting.

The thermal conductivity of the sapphire viewing port is about 60 percent that of stainless steel. Consequently, there was less heat transfer to the liquid oxygen from the warmer ambient surroundings through the sapphire port than through the stainless-steel outer wall of the liquid-oxygen cavity. It may be concluded that the liquid oxygen, as viewed through the port, was a representative sample.

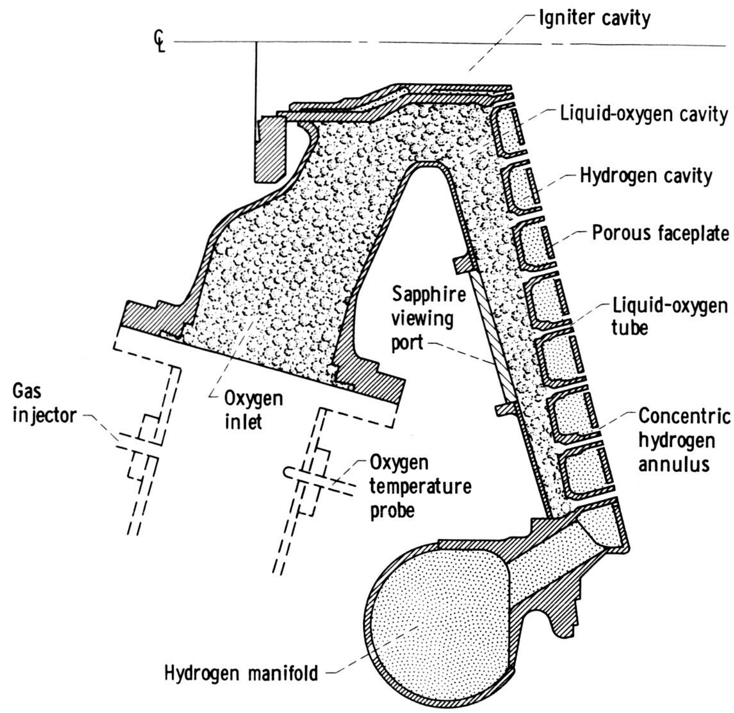

Figure 3. - Partial cross section of injector showing sapphire viewing port.

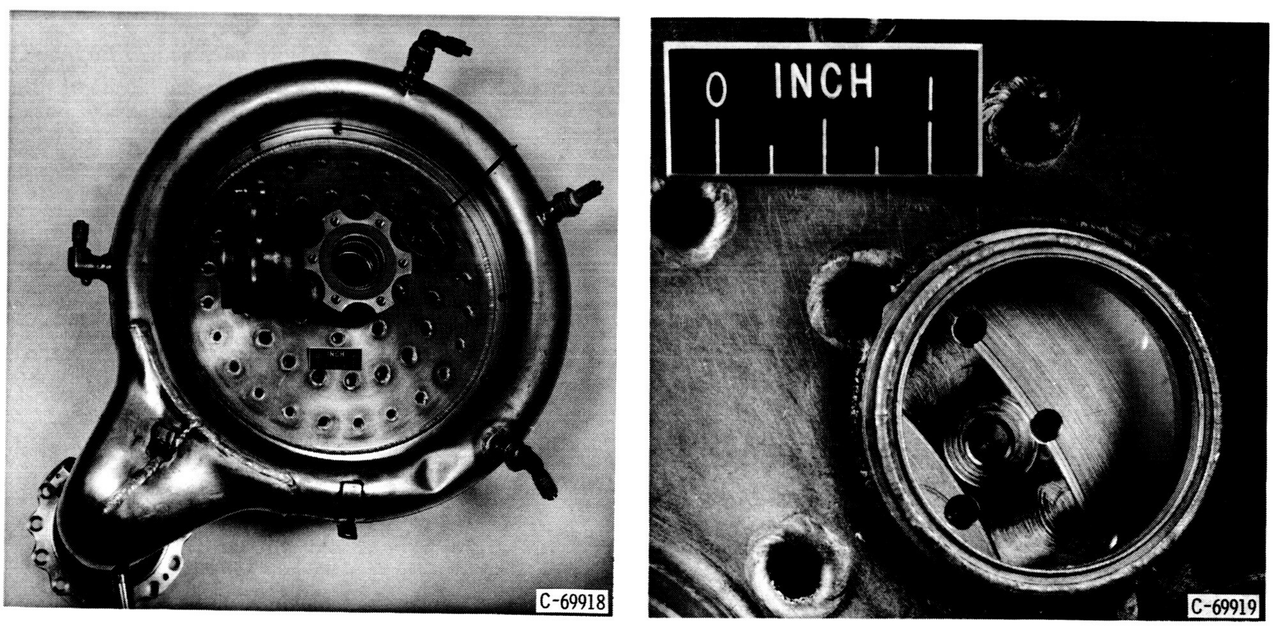

Figure 4. - Forward side of injector showing special viewing port.

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PROCEDURE

The gas used to eliminate chugging was injected into the liquid oxygen through an existing instrumentation port in the liquid-oxygen inlet flange of the injector. No attempt was made to distribute the gas flow or to control the bubble size in the gas-liquid mixture. After engine test conditions were obtained, the high-speed camera was started manually. For those conditions requiring movies of the transition between stable and unstable operation, the gas flow was timed to start (or stop) 0.5 second after the camera was started. For these transition conditions, the gas flow rate was preset to ramp to a previously determined rate adequate to achieve stability. Each film record is approximately 1 second long.

In an attempt to eliminate the low-frequency fuel system oscillations, gas was injected into the fuel through an instrumentation port between the fuel pump discharge and the cooling jacket inlet. The flow rate was controlled manually as the engine was operating. The effects were observed on control room instrumentation, and corresponding adjustments in gas flow were made.

RESULTS AND DISCUSSION

Oxidant System Instability

The frames taken from the motion picture and presented herein are correlated with chamber pressure and oxidant-fuel ratio (O/F) by reference to the engine operating map of figure 5. The region of chugging instability is shown by the shaded area. The letters A to E are used to identify operating conditions depicted in the subsequent figures.

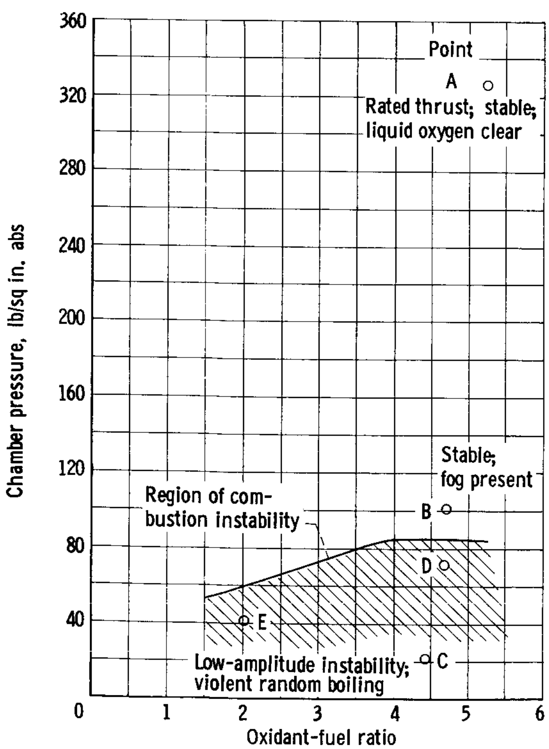
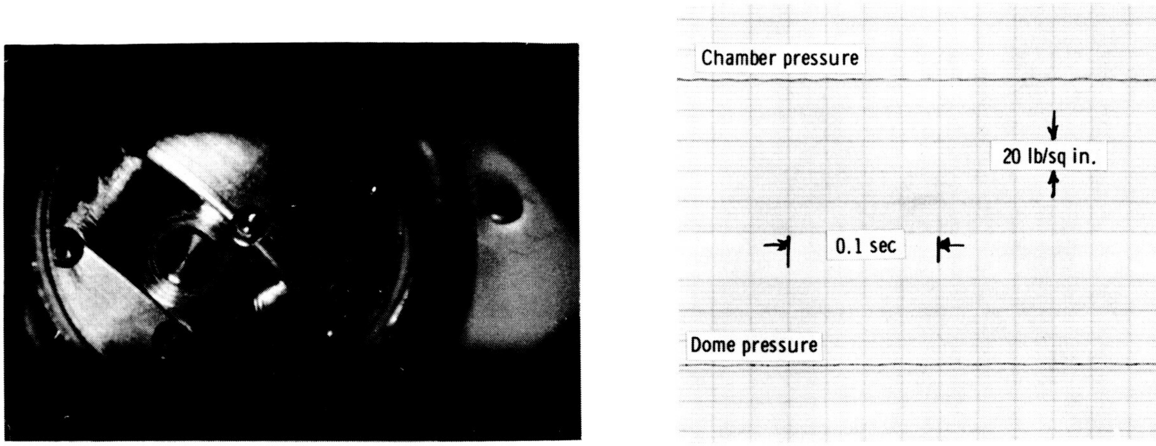
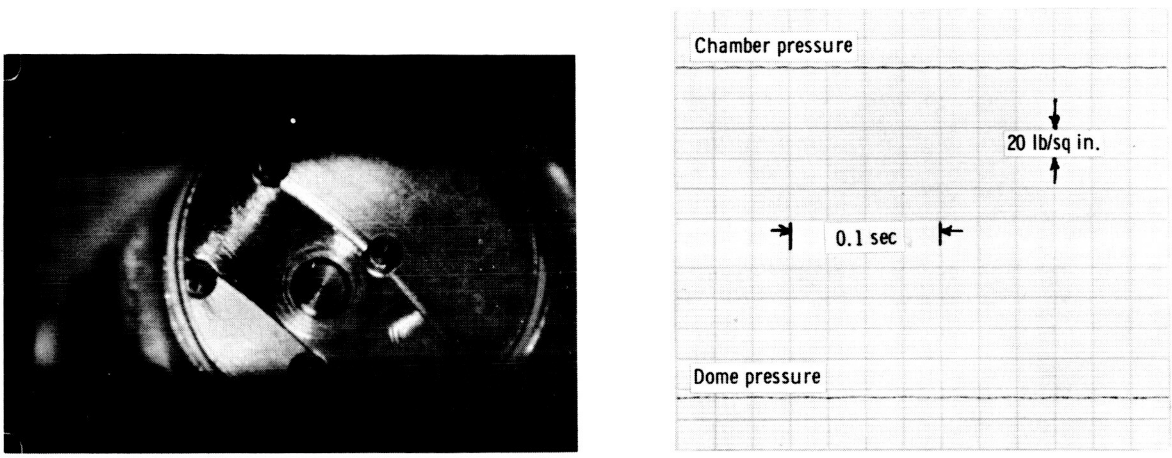


Figure 5. - Combustion stability limits (chugging).

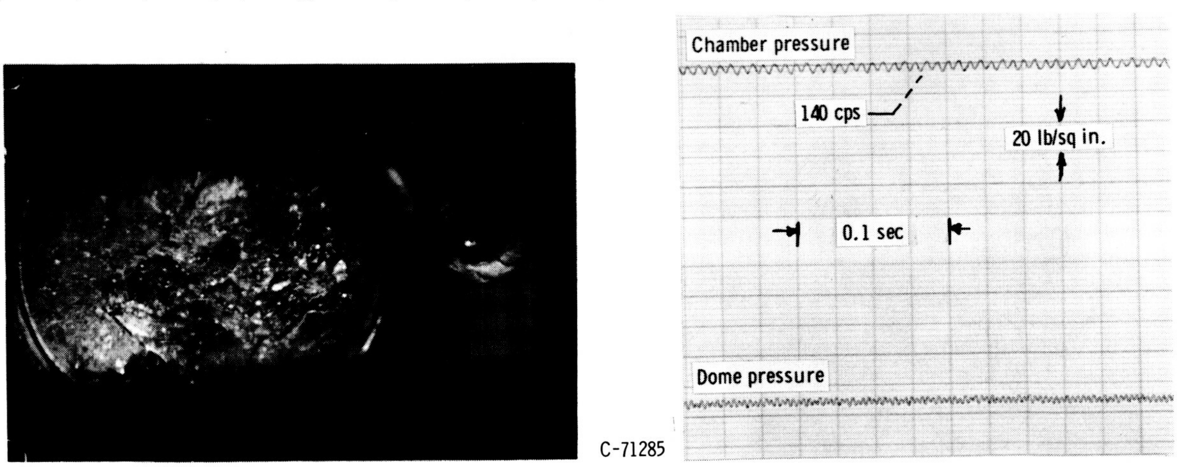
The photographs of figure 6 illustrate three liquid-oxygen conditions observed in the liquid-oxygen cavity during ostensibly steady operation and without inert gas injection. The liquid-oxygen temperatures indicated in the figure were measured in the supply line at the cavity inlet and, therefore, will be slightly lower than the temperature in the cavity itself. Point A corresponds essentially to operation at rated thrust. The liquid oxygen appears completely clear and free of bubbles, and the only optical evidence of its presence is occasional striations due to density gradients and subsequent changes in refractive index. The accompanying oscillograph traces show both chamber pressure and liquid-oxygen cavity pressure to be



(a) Point A; rated thrust; stable; chamber pressure, 326 pounds per square inch absolute; oxidant-fuel ratio, 5.25; liquid-oxygen temperature, 242° R; liquid-oxygen dome pressure, 399 pounds per square inch absolute.



(b) Point B; stable; fog present; chamber pressure, 101 pounds per square inch absolute; oxidant-fuel ratio, 4.72; liquid-oxygen temperature, 205° R; liquid-oxygen dome pressure, 116.4 pounds per square inch absolute.



(c) Point C; low-amplitude instability; violent random boiling; chamber pressure, 22 pounds per square inch absolute; oxidant-fuel ratio, 4.43; liquid-oxygen temperature, 169° R; liquid-oxygen dome pressure, 28.1 pounds per square inch absolute.

Figure 6. - Appearance of liquid oxygen in injector dome at various chamber pressures.

smooth and steady.

Point B corresponds to operation at a chamber pressure just above the chugging region (fig. 5). At this condition, large regions of fog randomly floated across the viewing area and obliterated the opposite face of the injector cavity. The fog apparently was comprised of extremely small bubbles, and their presence would indicate that saturation occurred (because of heat transfer to the liquid oxygen from the warm hydrogen) at least in localized regions of the cavity. The fog apparently broke away from these localized warm regions and flowed as an entrained gas along with the liquid-oxygen stream (radially outward); however, discrete bubbles were not discernible. Chamber pressure and liquid-oxygen cavity pressure traces were still smooth. Reference to a Mollier chart for liquid oxygen indicates that the saturation temperature is about 209° R at the measured liquid-oxygen cavity pressure of 116 pounds per square inch absolute; thus the liquid oxygen was essentially at saturation conditions.

Point C was obtained at a chamber pressure of only 22 pounds per square inch absolute and was unique in that it was obtained with the engine pumps completely stopped and propellant supply occurring by tank pressure alone. This pressurized mode of operation, however, should have had no significant effect on the conditions in the liquid-oxygen cavity. Ostensibly, the engine operation was stable and was in the region previously determined (ref. 1) to be below the region of chugging. Careful examination of the accompanying chamber pressure trace (fig. 6), however, revealed that a very low amplitude pressure oscillation was present at a frequency of 140 cps. Violent random boiling occurred within the liquid-oxygen cavity. Many discrete bubbles could be seen, and large vapor pockets were observed forming and detaching in the outer right portion of the viewing area. The more violent boiling action near the outer edge corresponds with expectation inasmuch as the liquid-oxygen cavity is surrounded by the fuel manifold filled with warm hydrogen. A study of the film supplement to this report does not, however, disclose any visible cyclical disturbance in the liquid-oxygen cavity despite the small cyclical changes in chamber pressure.

Fully developed chugging of relatively low intensity occurred at point D and is illustrated in figure 7. Visually, chugging is seen as the formation and collapse of bubbles in the liquid-oxygen cavity at the same frequency as the oscillations in chamber pressure. This film sequence was taken before gaseous helium was introduced into the liquid-oxygen cavity supply line to stabilize the system. By visual correlation of the pictures with the accompanying pressure traces, the following sequence of events may be postulated. During each chugging cycle, a large number of bubbles appear in the liquid oxygen as the liquid-oxygen cavity pressure drops. The bubble size and population increase, the pressure drop across the injector increases, and propellant atomization and combustion improve. The subsequent rise in chamber pressure decreases the liquid-oxygen flow and raises the pressure in the liquid-oxygen cavity and thus drives the bubbles back into the liquid phase. The poorer atomization with the pure liquid oxygen (and low pressure drop accompanying this configuration) probably produces a decrease in combustion efficiency and chamber pressure and thus a decrease in liquid-oxygen cavity pressure. As the liquid-oxygen cavity pressure decreases, the saturation

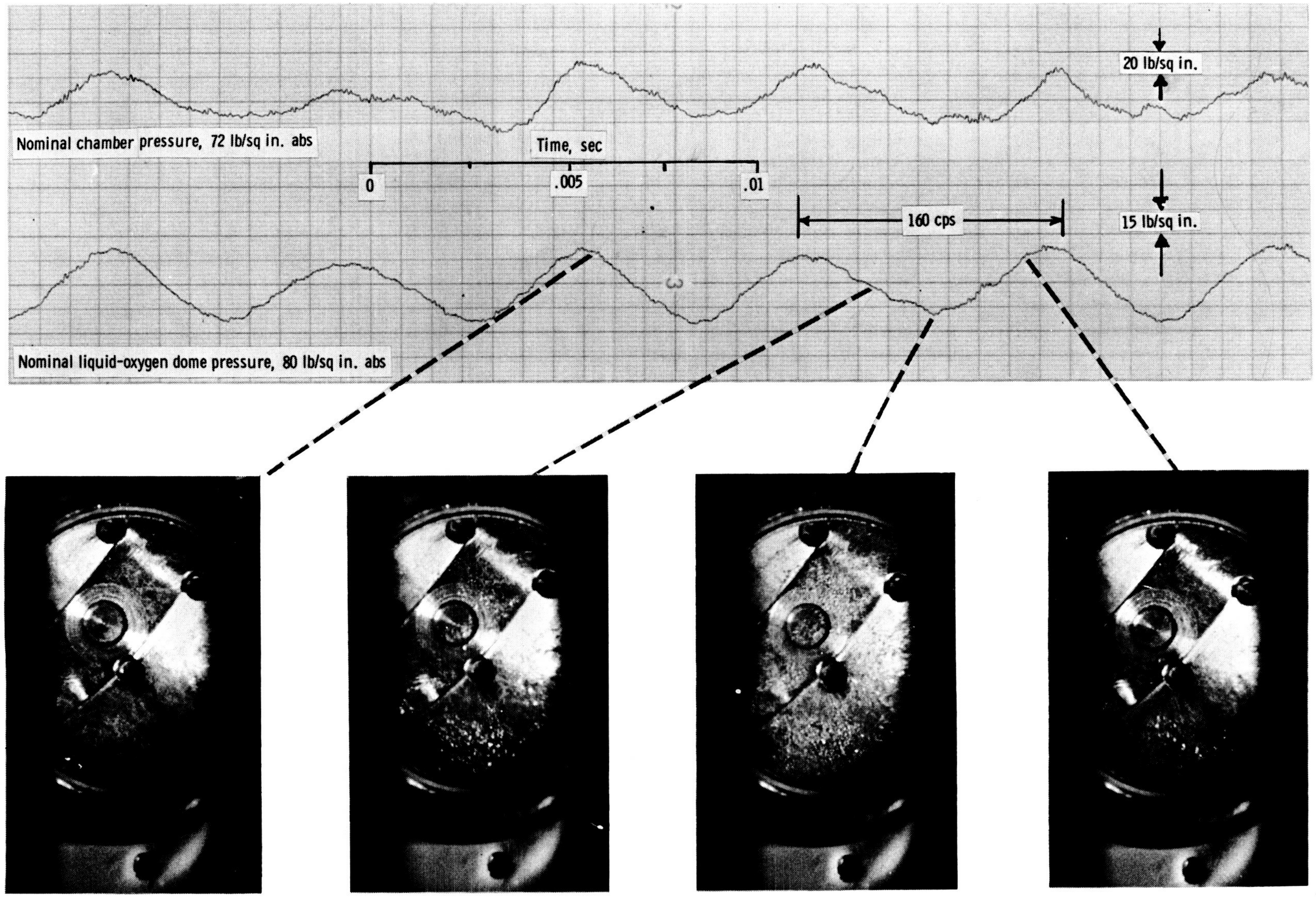


Figure 7. - Appearance of liquid oxygen in injector dome during chugging operation.

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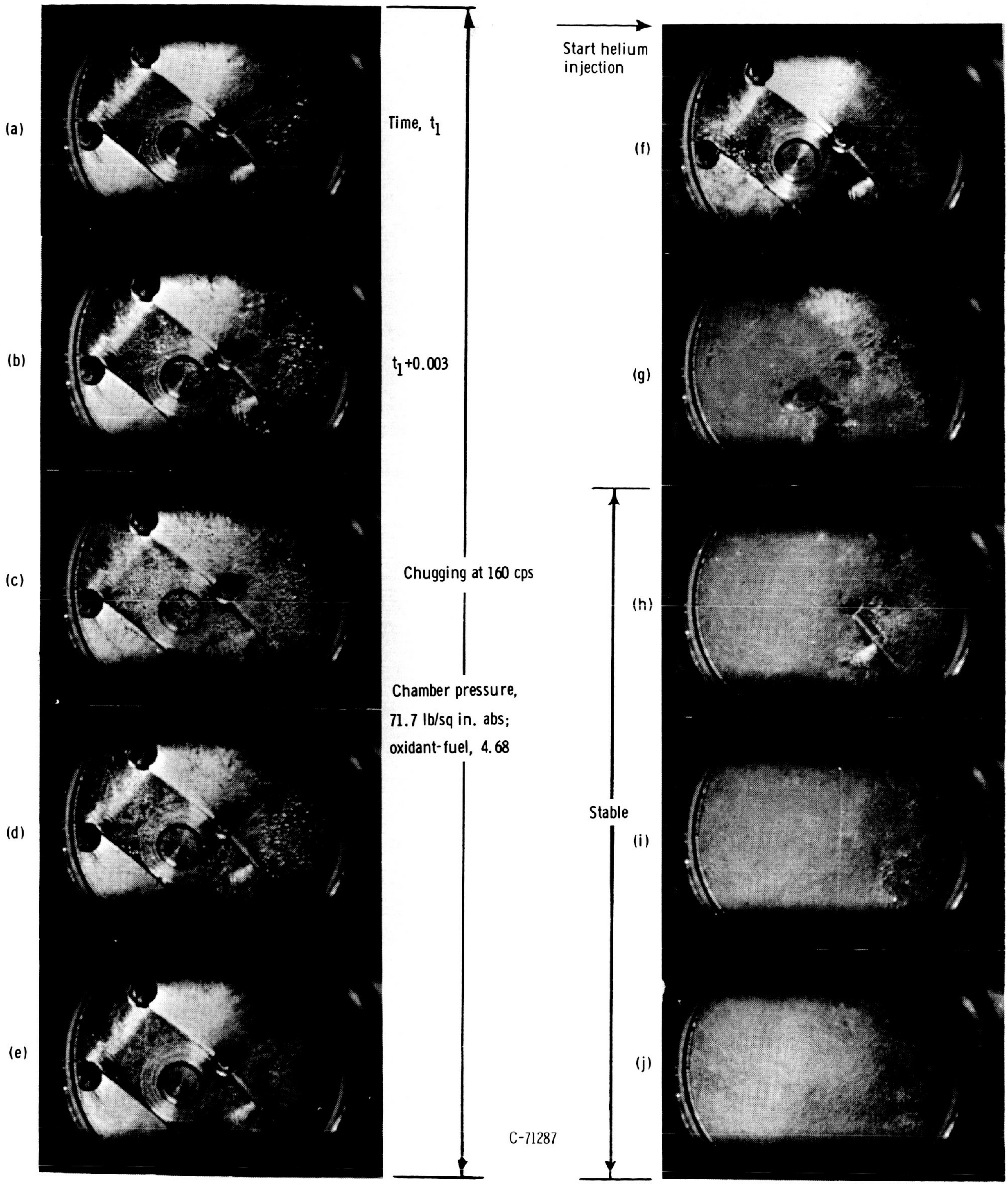

Figure 8. - Appearance of liquid oxygen during elimination of chugging by gaseous-helium injection. Helium flow rate, 0.4 percent of liquid-oxygen weight flow. Point D.

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pressure is again reached; bubbles evolve from the liquid state, and the cycle is repeated. While this model of likely events appears to fit the data at hand, it cannot yet be established conclusively because of the lack of precise timing correlation between the motion picture and the oscillograph records required to establish the exact phase relation.

The sequence of stills in figure 8 (point D) shows the chugging cycle immediately prior to and following the introduction of gaseous helium, which appears as a fog in the lower left area of the pictures. (The liquid-oxygen supply tube attached to the center of the injector cavity was to the left and below the viewing window (fig. 4, p. 4). Discrete bubbles within the fog were too small to be seen, as was the case with the fog at point B, shown in figure 6 (p. 6). The fog quickly dispersed across the entire viewing port area at the velocity of the oxygen flow along a radius of the liquid-oxygen cavity. The combustion immediately became stable, and chugging was entirely eliminated.

The specific impulse increased about 30 points during gas injection. This increased impulse represented the level that would be expected from extrapolation if chugging had not occurred (fig. 9).

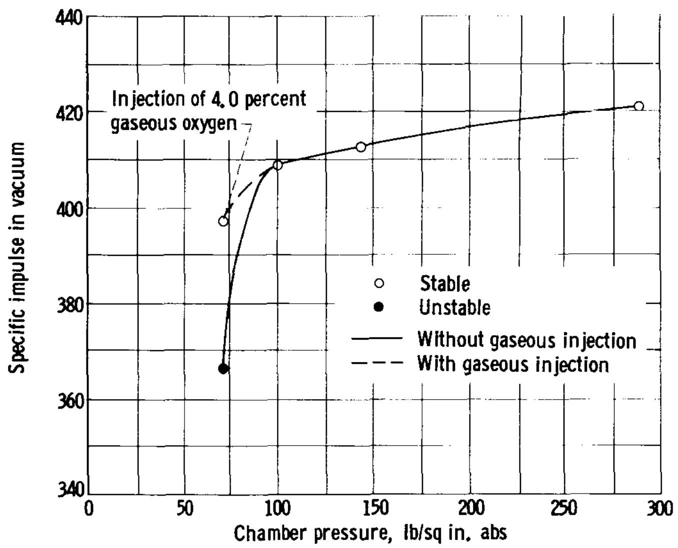

Figure 9. - Elimination of chugging and restoration of performance by gas injection. Oxidant-fuel ratio, 5.0.

The reverse sequence is illustrated in figure 10 for point E, which is within the region of maximum chugging amplitude. In this case, the engine, operating stably with gas injection, was caused to chug by shutting off the injectant. For both of the aforementioned tests the helium flow rate was approximately 0.012 pound per second or 0.4 percent of the liquid-oxygen flow by weight.

At rated conditions, the RL-10 engine operates at 96 percent of theoretical shifting equilibrium specific impulse. Despite this very respectable level of performance, one point in impulse is of considerable importance to missions such as Centaur-Surveyor; one point in impulse produces a 26-pound change in Centaur payload for the Surveyor mission. Accordingly, gas injection was used at rated conditions (point A) in an attempt to produce improved atomization and an accompanying increase in combustion efficiency and impulse, even though the increase would necessarily be much smaller than the 30 points obtained at 25 percent thrust. Liquid-oxygen appearance during injection was similar to the pictures of figure 8. The injection of helium (0.04 lb/sec or 0.133 percent of liquid oxygen by weight) produced only a negligible increase in performance. The extra weight of the

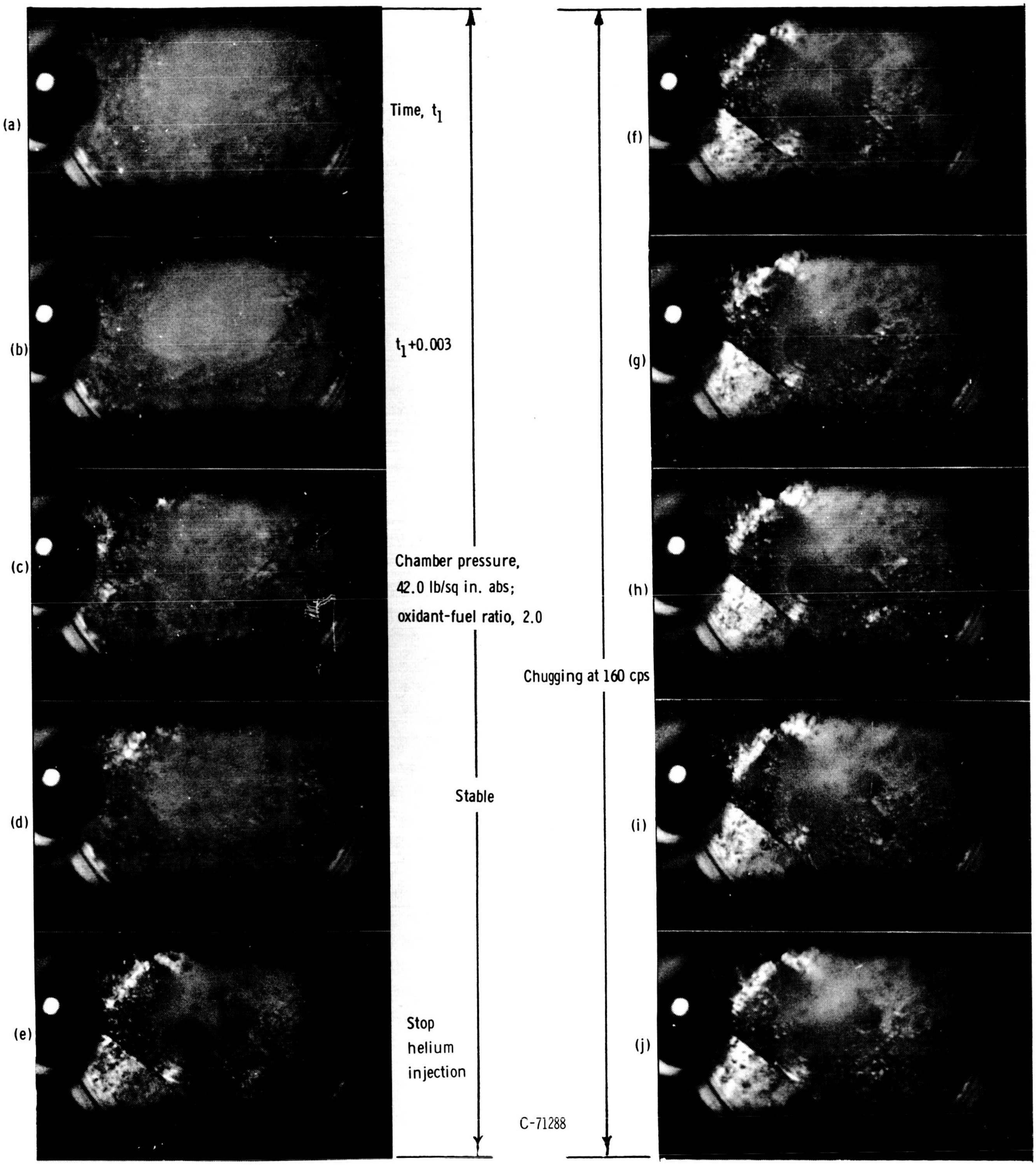

Figure 10. - Appearance of liquid oxygen as helium injection is stopped and chugging operation begins. Helium flow rate, 0.4 percent of liquid-oxygen weight flow. Point E.

equipment required for a mission application would more than offset the payload gain.

Fuel-System Instability

Although gaseous injection and/or increased injector pressure drop can be used to eliminate chugging (unpublished data), a further problem prevents the achievement of a desired 10-to-1 throttling capability with the RL-10. This difficulty is the existence of a region of fuel-system instability of 1 to 5 cps. The region is approximated on the map of figure 11. The transition areas indicated between the stable and mild instability regions and also between the mild and severe instability regions are not well-defined lines but rather only approximate areas. It should be noted that the oscillations in the severe region were such that oxidant-fuel ratio oscillations were divergent and required engine abort to avoid overheating (except during operation in the pressurized mode).

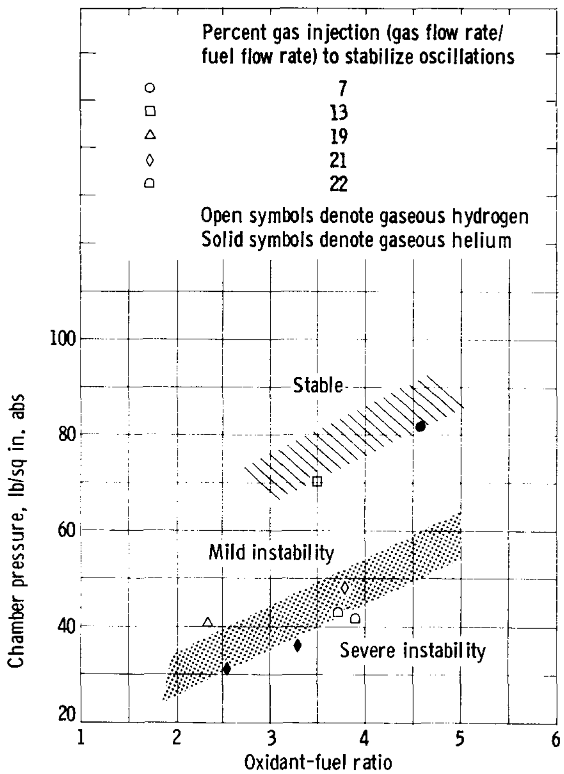

Figure 11. - Approximate region of fuel-system instability showing stabilizing effects of gas injection into fuel system.

As noted in the INTRODUCTION, the fuel system oscillations appear to be associated with a phase change in the cooling jacket. Several investigations have been made into this type of apparently inherent system instability. One of these investigations (ref. 2) included visual studies of the transition from liquid into two-phase flow of hydrogen in a glass-walled tube with heat input. The results have shown that the very irregular interface activity with flow pulsations correlates roughly with a spring mass analogy. Intermittent wetting and retreat of the liquid interface occurred with a high degree of irregularity. It has also been found, through analog studies, that when an abrupt density change occurs, such that the ratio of densities is greater than 3, flow instabilities may occur (ref. 3). If the reasoning suggested in references 2 and 3 is extended, it seems that an abrupt density change in the cooling jacket is the likely control factor for these oscillations in the fuel system of the RL-10. The fuel-system instability data were analyzed in the light of the results of these other investigations.

During engine operation above a chamber pressure of approximately 90 pounds per square inch absolute, the pressure of the hydrogen in the cooling jacket is always above the critical pressure (190 lb/sq in. abs) and, consequently, there is no interface between phases (density is a continuous property). As the engine operating point was moved into the mild instability region from the stable region, it was observed that the pressure at the discharge of the cooling jacket became less than the critical pressure of hydrogen. Further throttling to lower chamber pressures (consequently lower jacket pressures) meant that there must have been an interface between phases and, consequently, a discontinuity in the density occurring at some location in the cooling jacket or the inlet line to the jacket. Reference to the hydrogen temperature-entropy diagram (fig. 12) shows that the ratio of the density change across this interface is 2.1 at a pressure of 175 pounds per square inch absolute (chamber pressure of approximately 60 lb/sq in. abs at an oxidant-fuel ratio of 4.0) and is as high as 15.5 at a pressure of 50 pounds per square inch absolute (chamber pressure of approximately 11 lb/sq in. abs at an oxidant-fuel ratio of 1.8) assuming an isobaric heat addition. This system then appears to meet the instability criteria of reference 3. As the operating point was moved into the severe instability region from the mild instability region, it was observed that the cooling jacket inlet pressure approached and, in some cases, became lower than the critical pressure for hydrogen. It was, therefore, likely that a phase change was occurring in, or just before, the inlet manifold to the cooling jacket (discharge of the fuel pump). The fuel pump discharge temperature was below the critical temperature for hydrogen (59.4° R).

The hydrogen at the jacket inlet was below this critical condition of pressure and temperature when the engine was operating in the pressurized mode. Large oscillations were present in the fuel flow, but these oscillations were not divergent. It was possible, therefore, to operate at this condition without apparent damage to the hardware.

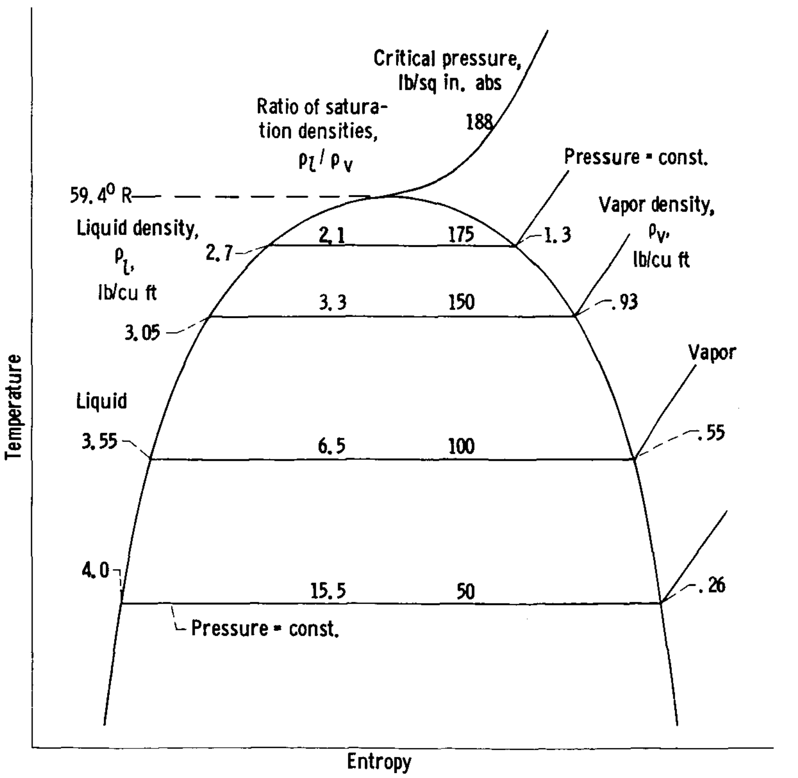

Figure 12. - Density change between saturated liquid and saturated vapor for parahydrogen.

It was reasoned that, if an unstable transition interface from liquid to vapor (such as those observed in ref. 1) were responsible for the system oscillation, anchoring this interface at a discrete location would reduce or eliminate the instability. In the region just upstream of such a transition interface, the hydrogen should be ready for transition, and it was expected that very small disturbances or heat inputs would produce an immediate phase change. To accomplish this transition in a hopefully more stable manner, gaseous hydrogen (or helium) was injected through an instrumentation port just upstream of the cooling jacket inlet to trigger the phase change at a discrete location.

As can be seen from the data points in figure 11, gaseous weight flows, of either helium or hydrogen, approximately 20 percent of the liquid-hydrogen weight flow, did stabilize the fuel system in the region of severe oscillations (all data points represent stable operation); this result lends support to the hypothesis. With only a small amount of gas injection, the oscillations ceased being divergent and continued to decrease in amplitude with increased gas flow rate. At the high-amplitude condition, the frequency of oscillation was approximately 1 cps and increased to about 5 cps as the gas injection rate increased. This process of stabilizing the fuel-system oscillations does not establish clearly defined parameters in the system, but indicates that the amplitude is controlled by the abruptness of the phase change as it is affected by the gas injection flow rate. The gas injection rates are probably too high to be practical unless an engine cycle change is considered. This might be done by preheating some of the hydrogen gas and using it as the injectant and stabilizing influence. Insight gained by the experiment strongly suggests that mechanical devices such as screens might provide stability of the transition front in a manner analogous to a flameholder in a combustion system.

CONCLUDING REMARKS

During chugging operation of the RL-10 engine, numerous rather large bubbles form and collapse within the liquid-oxygen cavity at the same frequency as the oscillations in chamber pressure.

A chugging rocket engine was stabilized by injecting gaseous helium into the liquid-oxygen cavity. This resulted in a higher injector differential pressure and a decoupling of the oxygen feed system. This injectant appeared to be a fog of very fine bubbles when observed through a specially installed viewing port. As the injection began, the fog spread rapidly over the entire field of view and most likely over the entire oxygen cavity. There was no evidence of localization of the injected gas.

Gas injection at rated engine conditions was attempted to determine if any gain in combustion performance could be achieved by better oxygen atomization. The injected gas produced a uniform fog in the liquid-oxygen cavity. The performance measurements indicate an almost negligible increase in specific impulse such that the extra equipment required would more than offset the payload gain.

The low-frequency instability of the fuel system was stabilized by injecting either gaseous helium or gaseous hydrogen into the propellant line just upstream of the cooling jacket inlet. Achievement of stability by this method supported the hypothesis that this fuel-system instability is due to the abrupt

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change in density of the propellant as it is heated in the cooling jacket.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, August 7, 1964

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2. Ellerbrock, H. E., Livingood, J. N. B., and Straight, D. M.: Fluid-Flow and Heat-Tranfer Problems in Nuclear Rockets. Proc. NASA-Univ. Conf. on Sci. and Technology of Space Exploration, Chicago (Ill.), Nov. 1-3, 1962. NASA SP-20, 1962.

3. Stenning, A. H.: Instabilities in the Flow of a Boiling Liquid. Paper 62-WA-155, ASME, 1962.

A motion-picture film supplement C-228 is available on loan. Requests will be filled in the order received. You will be notified of the approximate date scheduled.

The film (16 mm, 14 min, color, sound) contains data film showing the liquid oxygen in the injector cavity during chugging operation and while gas is being injected. Also included are the results of gas injection, explanations of injection procedures, a simplified schematic diagram of the engine cycle, and pictures of the injector and viewing port.

Film supplement C-228 is available on request to:

Chief, Technical Information Division
National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

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