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HYDROGEN-FLUORINE AND HYDROGEN-OXYGEN ROCKET RESEARCH AT NASA'S LEWIS RESEARCH CENTER

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It is generally accepted that hydrogen offers the highest performance of all chemical rocket fuels. The best oxidizers for use with this fuel, when considering liquid bipropellant systems for rockets, are ozone, fluorine, and oxygen. Ozone, however, has never been reliably stabilized; so the available propellant combinations of highest energy are hydrogen-fluorine and hydrogen-oxygen.

High energy propellants, which produce high thrust per pound consumed, are most attractive for the upper stage systems of rocket vehicles, because smaller stages may be used to accomplish the desired mission. Every pound saved in an upper stage reflects a saving of several hundred pounds in the booster required. A proposed configuration for the Saturn C-2 vehicle (Fig. 1) will employ hydrogen-oxygen in the second, third, and fourth stages, while the first stage will use liquid oxygen and RP-1. Engines of 200,000 pounds thrust for the hydrogen-oxygen second stage are now being developed for the NASA by Rocketdyne under the designation J-2. The third stage engines will be uprated versions of Pratt & Whitney's Centaur engines; and the fourth stage engines will be those presently under development for Centaur. All of the hydrogen-oxygen propulsion systems for these three stages will involve relatively high combustion pres- [illegible] engine.

A fifth stage could be added to the Saturn C-2 to provide capability of soft-landing sizeable payloads on the Moon or selected planets. Such a stage would be used partially during the boost phase of flight on departure from earth; then it would be allowed to coast toward the destination, where it would be used again for controlled deceleration to a landing.

Analysis has indicated that cryogenic fluids, such as liquid hydrogen, liquid fluorine, and liquid oxygen, can be satisfactorily stored in deep space for the required transit times. Boiloff rates on the order of only one percent per year during coasting on planetary missions might be achieved by passive shielding from thermal radiation of the sun. Therefore, the fact that these very high energy propellants are liquified gases need not be a deterrent to their use in ambitious space missions.

A postulated fifth stage for Saturn could use either hydrogen-oxygen or hydrogen-fluorine (Fig. 2). If hydrogen-oxygen is used, best gains could be realized by using a pump-fed, high-combustion-pressure system, particularly so in view of the work already done on turbopumps for hydrogen and oxygen. If hydrogen-fluorine were chosen, either a pump-fed or a pressurized system could be selected since neither is currently under development in this country. A pump-fed hydrogen-fluorine system can offer performance advantages exceeding those of a corresponding hydrogen-oxygen vehicle. For example, considering a soft landing on Venus when boosted by the Saturn C-2, a hydrogen-oxygen fifth stage could deliver a payload of 6600 pounds; a similar, but smaller, stage with hydrogen-fluorine could deliver 7400 pounds.

A pressure-fed hydrogen-fluorine system would be strongly competitive with the pumped hydrogen-oxygen vehicle, the hydrogen-fluorine in this case delivering a payload of 6900 pounds. In addition, the pressurized hydrogen-fluorine system could have inherently greater reliability. It could use a far simpler propellant fluid system; hydrogen-fluorine requires no ignition system since the propellants ignite spontaneously; there is apparently greater freedom from combustion instabilities with hydrogen-fluorine since no destructible instabilities have thus far been observed; and the hydrogen-fluorine system would be less vulnerable to meteroid penetration by virtue of permitting a more compact structure through reduced tank volume requirements.

The NASA Lewis Research Center has conducted considerable research on both hydrogen-oxygen and hydrogen-fluorine. The results of the research on hydrogen-oxygen have contributed to the long range planning for Centaur and the upper stages of Saturn and Nova. Meanwhile, the studies with hydrogen-fluorine have contributed sufficient technology to permit development of full scale regeneratively-cooled hydrogen-fluorine engines and to establish ground-handling techniques for the safe use of fluorine.

Because of the urgent need for the very highest reliability possible in our space vehicles, emphasis in the present Lewis research program for hydrogen-fluorine is placed on its use in a pressurized top stage. Consequently, the work discussed here was primarily concerned with the use of hydrogen-fluorine at low combustion pressures to minimize tank pressures. On the other hand, the hydrogen-oxygen work involved moderately high combustion pressures because turbopump systems are already in an advanced state of development.

Areas of research interest are presented in figure 3. Both propellant combinations share in common the problems of determining whether or not chemical recombination occurs in the nozzle during expansion to provide highest performance, the achievement of the best possible combustion efficiency, utilization of unique engine throttling potential, and understanding the design requirements for the most effective cooling of the thrust chamber with hydrogen.

Of course, each propellant combination has its own unique problems. With hydrogen-oxygen, these are concerned with finding ignition techniques to assure reliable repeated starting in space and developing an understanding to avoid destructive combustion instabilities.

Hydrogen-fluorine problem areas include fluorine handling and fluid system stability. Although the high performance possibilities of hydrogen-fluorine are generally recognized, fluorine handling remains controversial. The potential hazards of using fluorine tend to discourage its consideration for rocket systems. Actually, this problem resolves itself to a matter of safely handling fluorine at the launch pad prior to a flight. In considering a pressure-fed rocket system, a premium is placed on attaining fluid systems having minimum pressure drops; to do this requires research to find the limits of stability of the fluid systems and their controls.

We shall now discuss the research conducted at Lewis in each of the above problem areas. The first research area involves the question of chemical equilibrium in the rocket nozzle. In any rocket combustion process, the exhaust gases can expand through the nozzle with no change in chemical composition (frozen expansion) or the chemical fragments formed at the high combustion temperatures can recombine while still in the nozzle to yield even greater energy release for propulsive thrust (equilibrium expansion). In actuality both of these processes occur in varying proportions.

Theoretical performance curves for hydrogen-fluorine appear in figure 4 in terms of vacuum specific impulse (pounds thrust per pound per second of propellant flow) as a function of the weight percent hydrogen in the propellant combination. Two sets of curves are shown. One set represents the maximum performance attainable if the expanding gases are chemically frozen; the other set of curves corresponds to equilibrium recombination during expansion. For both sets of curves, two nozzle area ratios were considered; that is, the exit area of the hypothetical nozzle was either 25 or 100 times the area at the nozzle throat. Area ratios near 25 are not unusual today for upper-stage engines. Higher ratios are desirable if the engine is intended for use in deep space. Two facts become evident from this figure: first, equilibrium expansion provides considerably higher performance than does frozen expansion; and second, with equilibrium expansion peak performance can be achieved with much less hydrogen. Since hydrogen has an extremely low density, the reduction of its tankage volume by a factor approaching 3 is very attractive. The higher the area ratio, the more these two effects are accentuated. The research problem, then, is that of determining experimentally how near the performance in actual engines approaches that afforded by equilibrium recombination in the nozzle.

Experimental work to this end has been undertaken in both hydrogen-oxygen and hydrogen-fluorine thrust chambers. Figure 5 is a photograph of a test installation in one of the Lewis altitude facilities. The large funnel in the picture is a 100 to 1 area ratio nozzle on a small experimental thrust chamber. Experiments were conducted under altitude pressure environment to cause the nozzle to flow full. Typical results obtained in the investigation appear in figure 6 for both hydrogen-oxygen and hydrogen-fluorine. Measured vacuum specific impulse is plotted against percent fuel in the propellant. Combustion pressure for hydrogen-oxygen was 150 psia; that for hydrogen-fluorine was 40 psia. In both plots the dashed curves represent the frozen and equilibrium processes on a theoretical basis. It may be readily noted here that difference between theoretical performance values for hydrogen-fluorine is much greater than for hydrogen-oxygen; consequently, the question of which expansion process prevails is much more vital for hydrogen-fluorine.

The solid curves represent the experimentally determined performance values. For both propellants the achieved performance was an unusually high percentage of that predicted theoretically, above 90 percent of equilibrium values. The performance of hydrogen-fluorine clearly is not limited by the process of frozen expansion, since it very nearly achieves full equilibrium expansion. Hydrogen-oxygen performs so close to the frozen curve that we cannot conclusively accept the notion that frozen expansion predominates; performance deficiencies can be equally attributable to the combustion process prior to expansion.

Overall performance, as we have discussed it, has been related to spceific impulse. Specific impulse, I, is proportional to the product of characteristic velocity, C^*, and nozzle thrust coefficient, C_F. C^* is an indicator of combustion efficiency; C_F is a measure of nozzle efficiency, considering both chemical equilibrium and aerodynamic factors. The plots in figure 7 show performance efficiency in terms of I, C^*, and C_F for hydrogen-oxygen and hydrogen-fluorine as a function of percent fuel in the propellant. For both propellants, it appears that combustion efficiency, as indicated by C^*, is primarily responsible for the deficit in overall performance. Combustion efficiency can be improved or degraded by choice of design of the injector, which prepares the propellants for combustion in the thrust chamber. Practically, not much can be done to improve C_F through nozzle design without imposing severe weight penalties.

To improve combustion efficiency, studies have been made of injector design (Fig. 8). Experimental results are presented for H_2 - O_2 and H_2 - F_2 in plots of C^* efficiency as a function of percent fuel in the propellant. For hydrogen-oxygen, data from two injectors were used, a showerhead type and a coaxial, or concentric orifice, type. The latter yielded the higher performance, probably because it provided better propellant mixing. For hydrogen-fluorine, data are presented for only coaxial-type injectors, which differed in the number of injection elements per square inch of injector face area. It is quite apparent from these curves that reduction in the density of injection elements below about 6 per square inch of injector face is deleterious to efficiency. Increasing this density above 6 may enhance efficiency, though to a lesser degree. Uniformity of spacing of injection elements across the injector face is desirable to provide uniform mass flow distribution.

One of the bonuses of using hydrogen that has become apparent through experimental research is a rather unique capacity for engine throttling. This is brought about, in part, by the unusual physical properties of hydrogen. Hydrogen is an excellent coolant, but cooling passages for its use must be designed very carefully because hydrogen density is extremely responsive to changes in temperature and pressure. For engine throttling, however, propellant density changes can be quite advantageous, if they go in the right direction. If the propellants flow rate to a hydrogen-fueled engine is reduced, as in throttling, the availability of hydrogen for cooling is reduced and so its temperature rise increases. Consequently, the density of the hydrogen delivered to the injector decreases, providing about the same injector pressure drop at fractional thrust as at full thrust. This means that insofar as hydrogen feed systems are involved, a large range in supply pressure is not needed for throttling simply by control of propellant flow rate.

The data presented in figure 9 are a by-product of experimental thrust chamber programs. Although the objectives involved other parameters, the programs necessitated variation of combustion pressure. Thrust chamber assemblies of fixed geometry were used, only the propellant flow rates were changed. Thrust modulation with hydrogen-fluorine covered a range of about 6 to 1 on thrust without encountering limitations. Analyses have indicated that soft lunar landing may require about 5 to 1 thrust variation. The drop in performance at the lower chamber pressures resulted from decreased combustion efficiency. This need not be of particular concern because engine operation in flight would likely be at full thrust most of the time.

As has been indicated, no program has been conducted to investigate throttling capability per se; and so the throttling range of hydrogen-oxygen has not been exploited, although a 3 to 1 thrust range was covered. It should be noted, however, that destructive combustion oscillations were encountered at the higher combustion pressures with the particular thrust chamber components used.

It was mentioned earlier that hydrogen excels as a coolant. In figure 10 are presented curves which represent the Lewis Research Center experience with regeneratively-cooled thrust chambers. The cooling fraction needed, appearing as the ordinant on this graph, is simply the fraction of total cooling capacity that was needed for cooling the engine at the various conditions presented. If the cooling needs equal the cooling capacity, the cooling fraction would be 1; and, if this value of 1 were exceeded, the engine would burn out. The dashed curves represent hydrogen-oxygen data, and evidence the abundant capacity of hydrogen as a coolant. No burnout problems are apparent, unless localized heat transfer rates are increased tremendously by combustion instabilities such as screaming. Even for hydrogen-fluorine, with its higher combustion temperature, cooling appears to be generally adequate. Cooling demands for hydrogen-fluorine become greater, of course, when proportionally less hydrogen is used, which is the condition of greatest interest to us for high performance and high bulk density of propellants.

We have discussed research areas common to both hydrogen-oxygen and hydrogen-fluorine (Fig. 11). We shall now consider those problems of particular interest for hydrogen-oxygen, ignition and combustion stability.

Hydrogen and oxygen do not ignite spontaneously. Therefore, an ignition source must be provided and, expecially when pumped fluid systems are used, complex starting sequences must be developed involving precise timing of multiple components. Ignition presently is accomplished by spark plugs in the hydrogen-oxygen systems under development. At the Lewis Research Center we have investigated the ignition of hydrogen-oxygen by use of a third chemical. Figure 12 shows schematically how a third fluid ignition system has been used. This drawing shows the propellant injector on a thrust chamber. A small flow of gaseous fluorine is introduced into the injector at the time that hydrogen flow is started. Ignition is attained then liquid oxygen is introduced and fluorine flow is stopped. Hydrogen-oxygen flows are sustained. Gaseous fluorine flow rates as low as 3/10 of a pound per second are used routinely at Lewis in all starts of a 20,000-pound-thrust hydrogen-oxygen thrust chamber.

Other chemicals have been used for ignition of hydrogen-oxygen at Lewis. These are listed on figure 13. Two techniques have been employed, as indicated on the figure. The first involves a third fluid lead. In addition to gaseous fluorine, chlorine trifluoride has also been successfully applied as an oxidizer lead fluid, in small scale tests. Reversing the situation and using a fuel, as the third chemical, to react spontaneously with oxygen, resulted in success with triethyl aluminum. The second technique of chemical ignition involves mixing all of the oxygen with fluorine in proportions that would be hypergollic with hydrogen. This mixture would be used throughout the entire firing period. Results showed that, depending upon the injector design used, the oxidant was required to contain 25 to 50 percent fluorine for spontaneous ignition. Of course, if such oxidant mixtures were employed in a flight vehicle, some overall performance advantage could be realized and possibly combustion instabilities of hydrogen-oxygen could be attenuated, but it might be expected that all the disadvantages of hydrogen-oxygen and those of hydrogen-fluorine would be combined in one rocket system.

Hydrogen-oxygen definitely can and has "screamed" in rocket engines. Evidence of our experience is presented in figure 14. The top film strip indicates stable combustion, the second shows oscillations in a rotating mode. Several other types of high frequency oscillations have also been identified. It seems that programs to study combustion instabilities never die and never fade away, so ours continues in search of further identification of modes of instability to permit an understanding of how they may be alleviated. Results to date qualitatively indicate that the probability of screaming instabilities with hydrogen-oxygen increase with increased combustion pressure, increased fuel percent, decreased fuel injection temperature, and increased combustion efficiency.

Now we come to the unique problem areas of hydrogen-fluorine (Fig. 15). Fluorine handling and studies of hydrogen-fluorine fluid systems stability at low system pressures will be depicted in the following movies (Movies - Fig. 16).

In summarizing the Lewis Research Center activities in research areas common to hydrogen-oxygen and hydrogen-fluorine (Fig. 3), we have seen that chemical equilibrium in rocket engine nozzles affords near-maximum experimental performance relative to theoretical data. Combustion efficiency is extremely high, nevertheless it is still subject to injector design. Engine throttling capabilities are enhanced by the high chemical reactivity of these propellants and by the unique physical properties of hydrogen. Thrust chamber cooling with hydrogen is ample for practical propulsive systems. Ignition of hydrogen-oxygen can be accomplished chemically, as an alternative to electrical ignition systems. Experimental research indicates combustion instability may be a potential problem with hydrogen-oxygen. Fluorine handling, which is largely a concern during launch site preparations, can be reliably accomplished simply by adhering scrupulously to good practice. This involves tight specifications, inspection, and cleanliness. Demonstration of the feasibility of reliable fluorine handling will continue throughout our research programs. Low pressure fluid system stability represents the problem area into which we are embarking in our present research. Needless to say, a stable pressurizing system can be had; the objective is to pursue the best.

While it is not the objective of this paper to compare the relative merits of hydrogen-oxygen and hydrogen-fluorine, these comments are offered. Because of the propellant mixture ratio difference, hydrogen-fluorine will permit greater structural economy; and because of higher chemical reactivity, improved throttleability is likely. Finally, research experience suggests that a pressurized hydrogen-fluorine system may provide greater reliability for the same performance because of the following factors:

1. Simplicity - minimum number of components
2. Hypergolicity - positive starts and restarts assured
3. Stability - screaming has not been encountered.

SATURN C-2 WITH DEEP SPACE VEHICLE

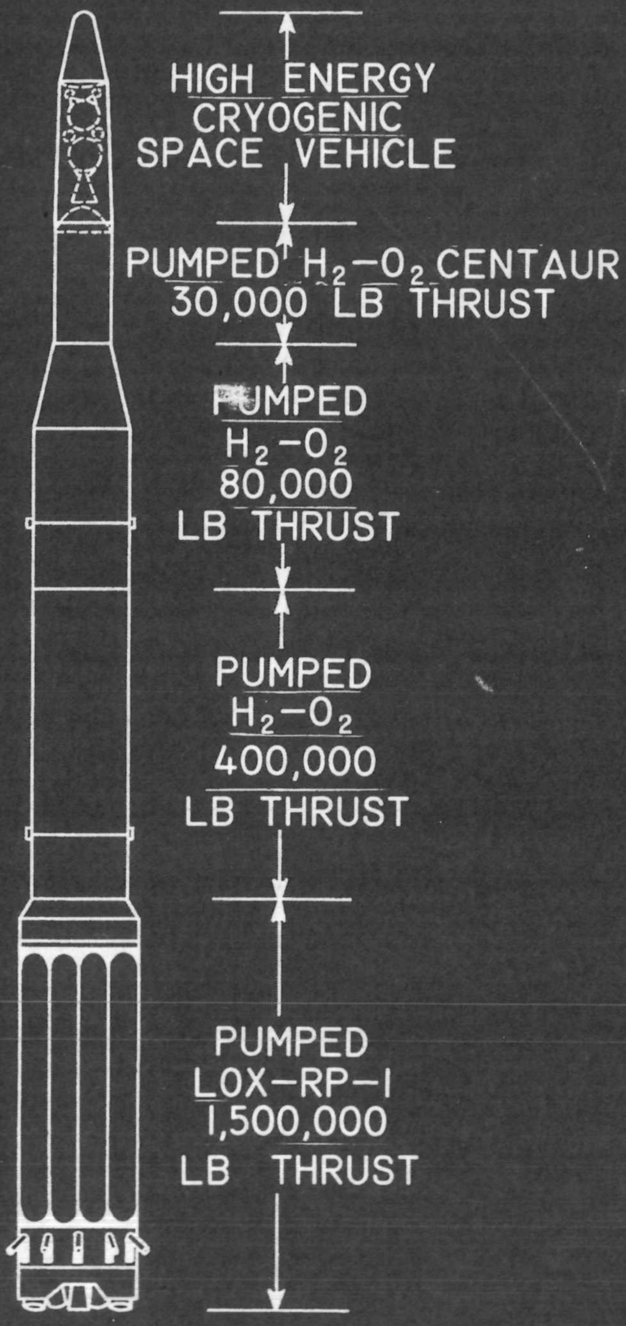
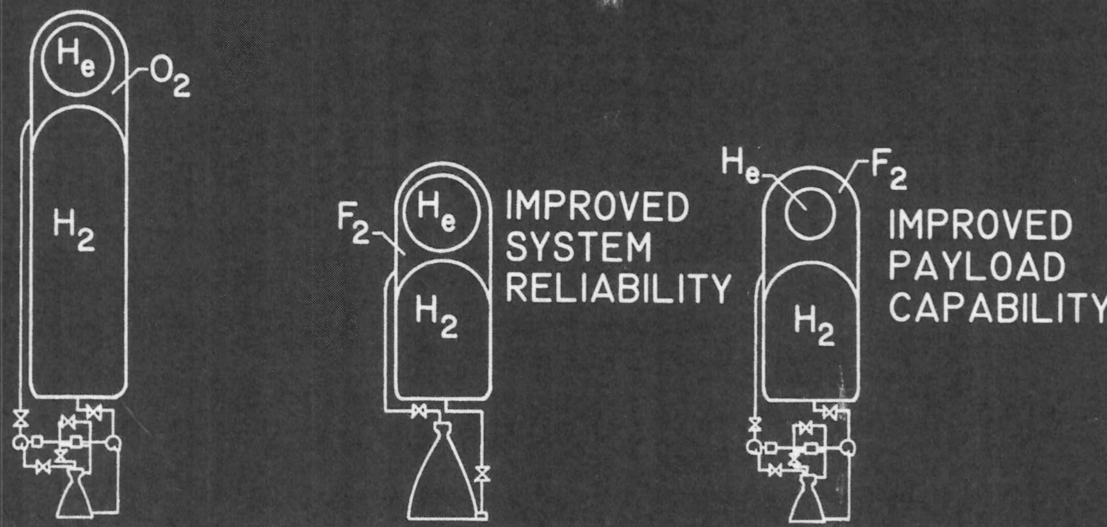


Figure 1

HIGH ENERGY PROPELLANTS FOR VENUS SOFT LANDING

STAGE GROSS WEIGHT – 17,000 LB



	PUMP-FED H_2-O_2	PRESSURE-FED H_2-F_2	PUMP-FED H_2-F_2
PAYLOAD	6600 LB	6900 LB	7400 LB
COMPLEX FLUID SYSTEM	YES	NO	YES
IGNITION SYSTEM	YES	NO	NO
COMBUSTION INSTABILITIES OBSERVED	YES	NO	NO
TOTAL TANK VOLUME	425 CU FT	270 CU FT	250 CU FT

Figure 2

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AREAS OF RESEARCH

H_2–O_2 AND H_2–F_2

CHEMICAL EQUILIBRIUM IN NOZZLE

COMBUSTION EFFICIENCY

ENGINE THROTTLING

THRUST CHAMBER COOLING

H_2–O_2	H_2–F_2
IGNITION (STARTING)	FLUORINE HANDLING
COMBUSTION STABILITY	FLUID SYSTEM STABILITY

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Figure 3

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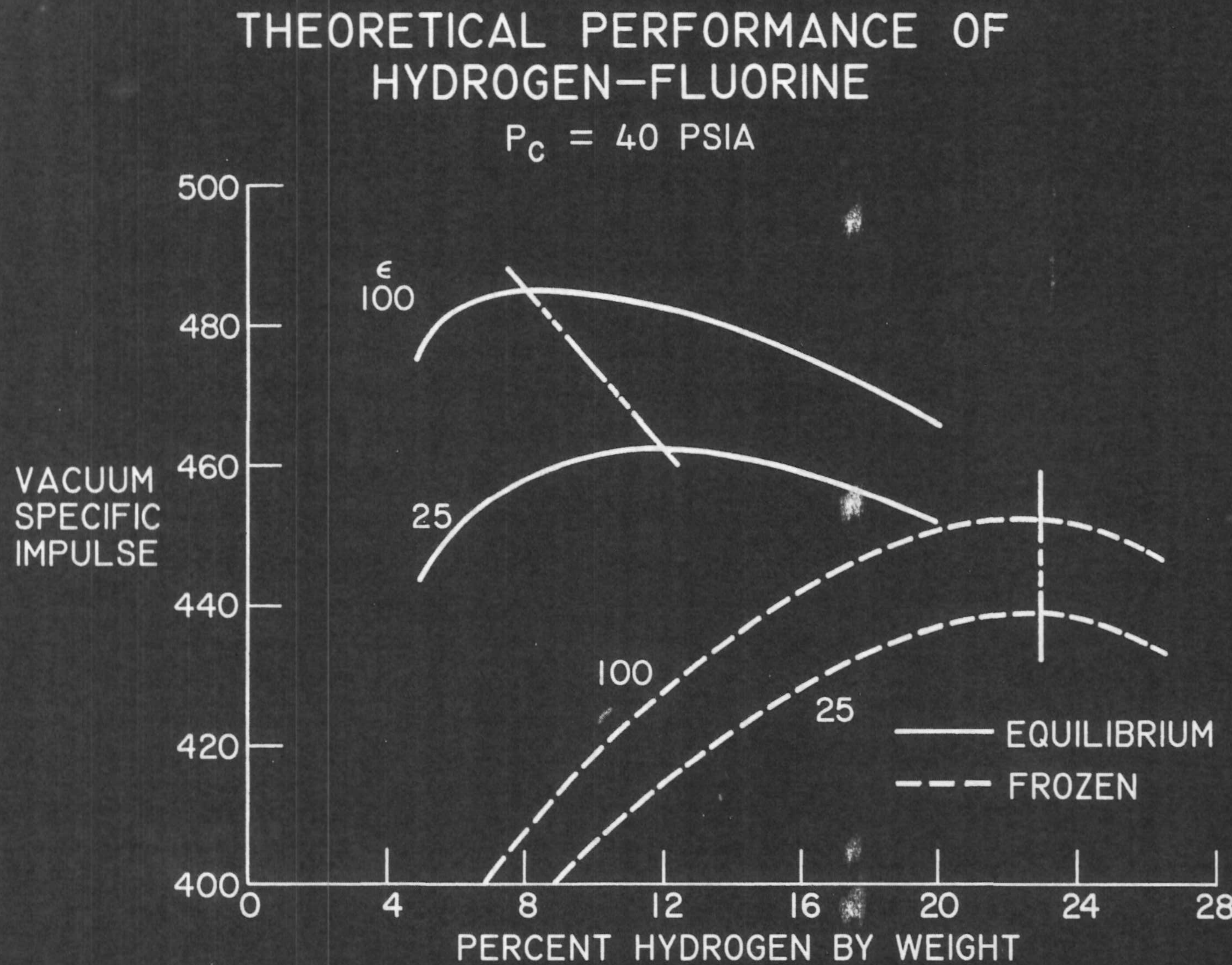
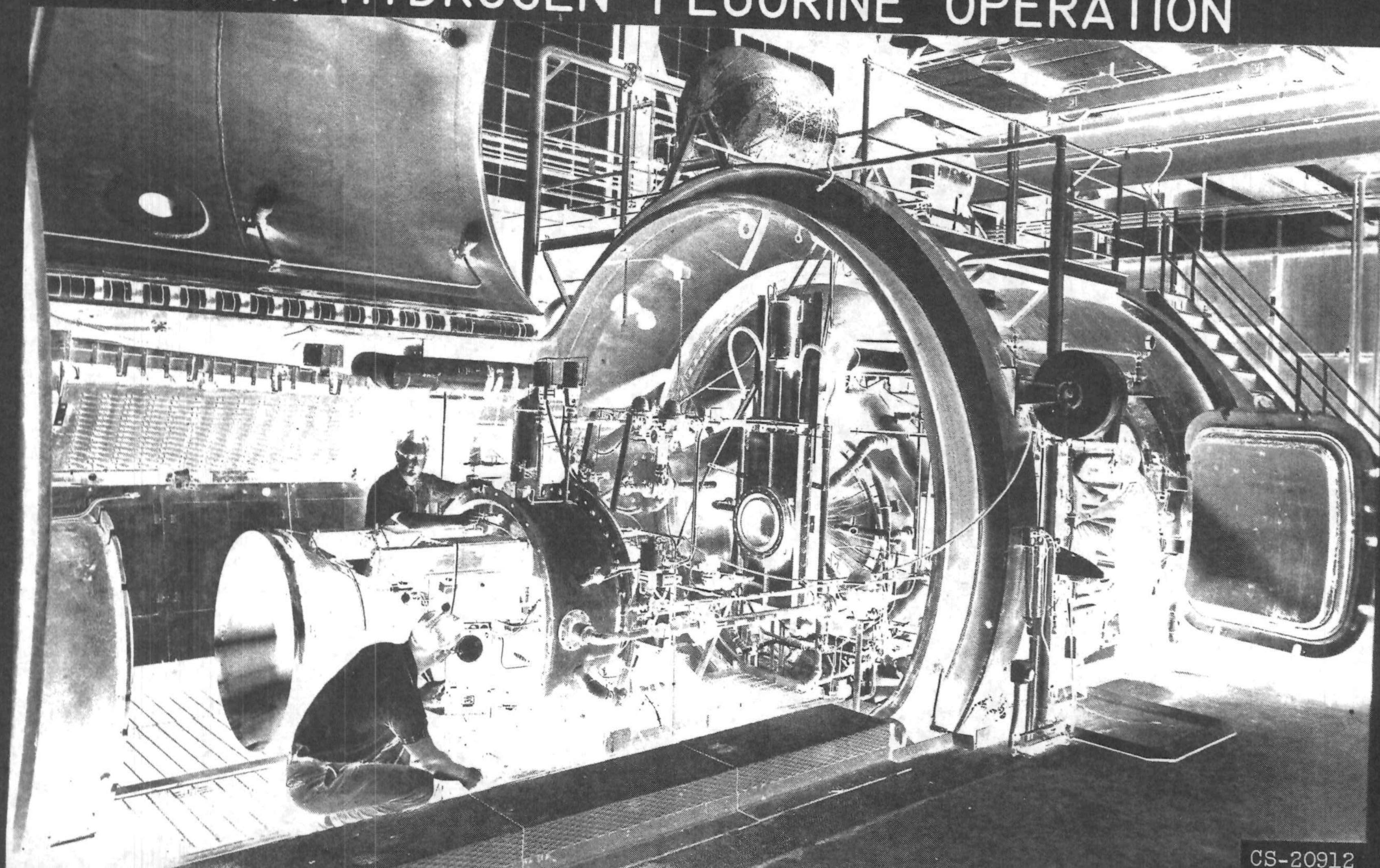

THEORETICAL PERFORMANCE OF
HYDROGEN–FLUORINE
P_c = 40 PSIA
VACUUM
SPECIFIC
IMPULSE
500
480
460
440
420
400
0
4
8
12
16
20
24
28
PERCENT HYDROGEN BY WEIGHT
ϵ
100
25
100
25
EQUILIBRIUM
FROZEN

Figure 4

TEST INSTALLATION FOR HYDROGEN-FLUORINE OPERATION



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C-54256

Figure 5

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THRUST CHAMBER PERFORMANCE

AREA RATIO = 100:1, DIVERGENCE ANGLE = 15°

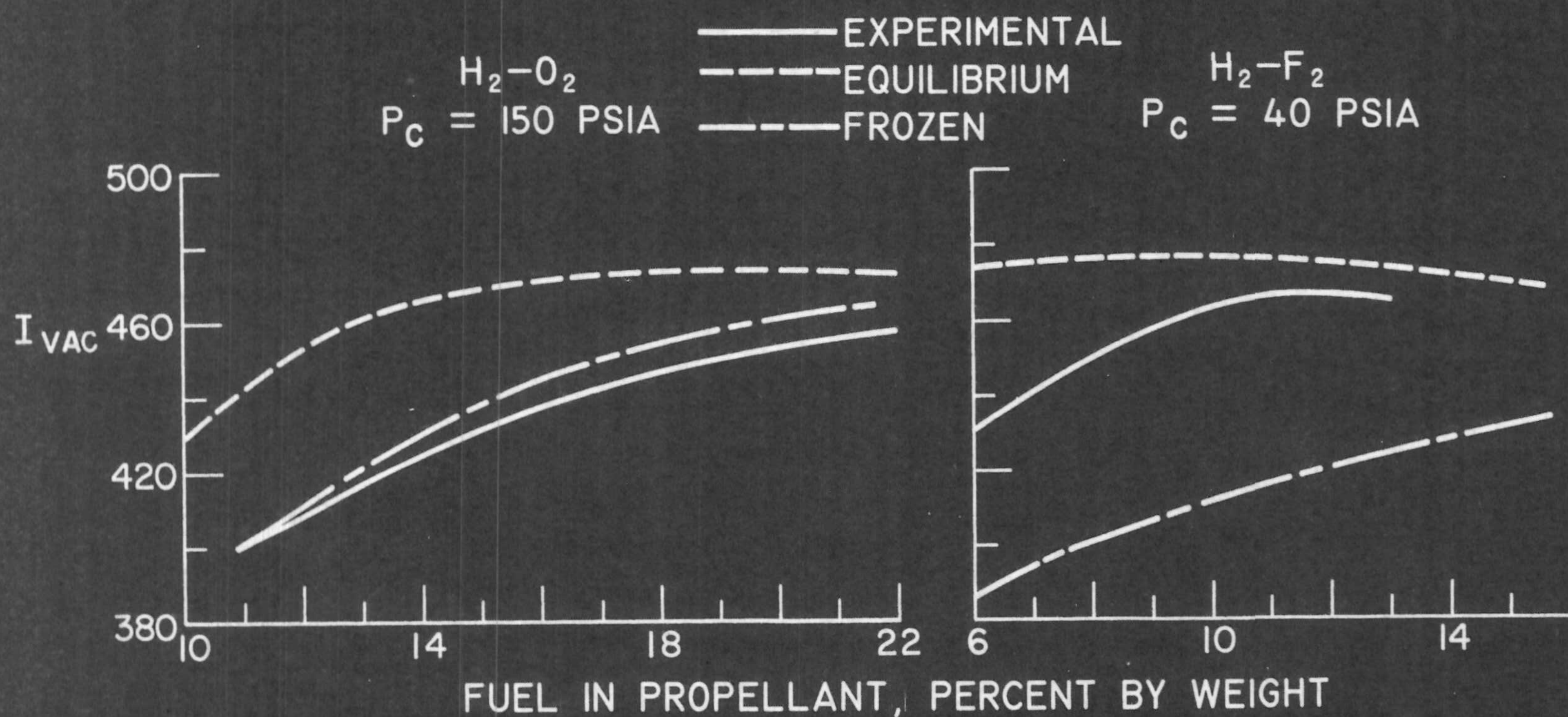

Figure 6

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PERFORMANCE EFFICIENCY

$$I \approx C^* C_F$$

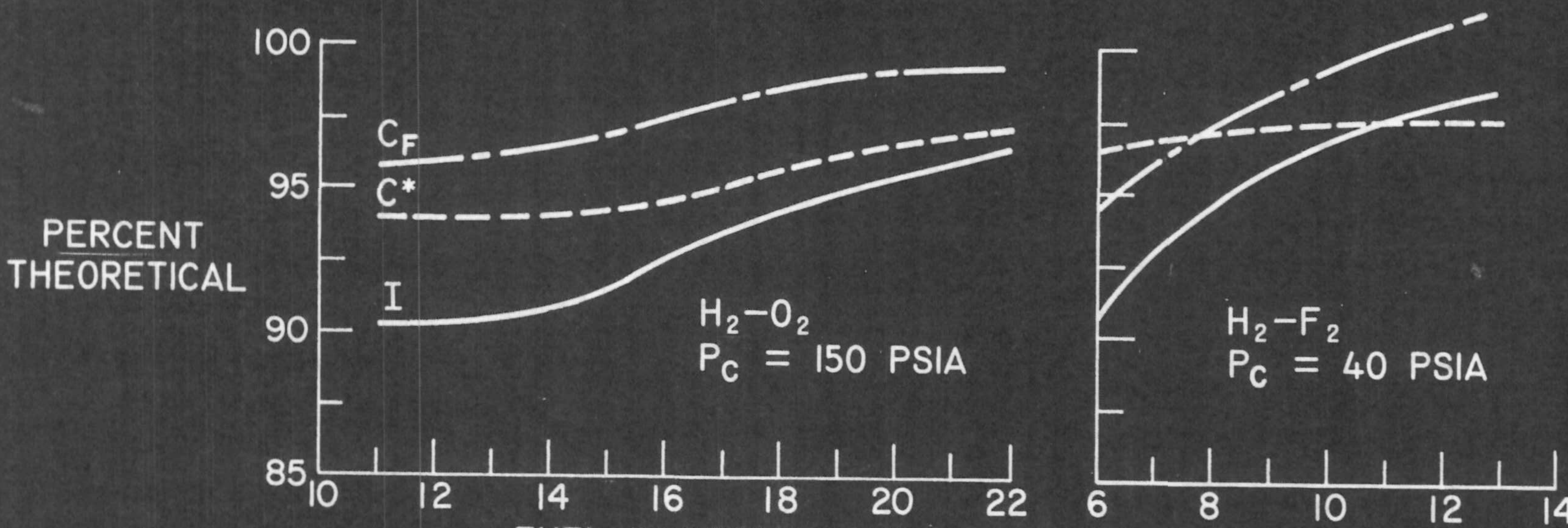

Figure 7

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[redacted]

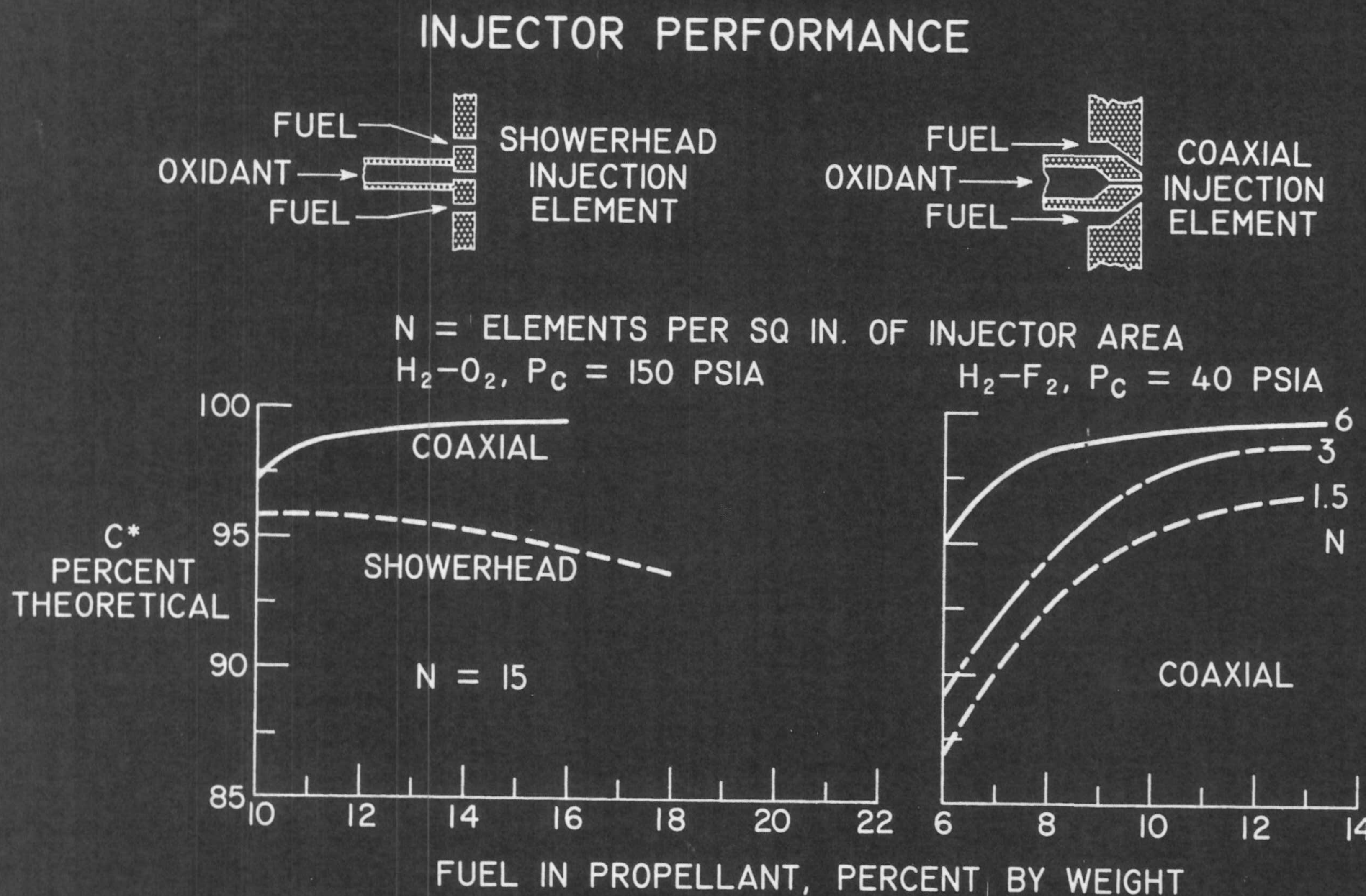

Figure 8

[redacted]

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THRUST CHAMBER THROTTLING

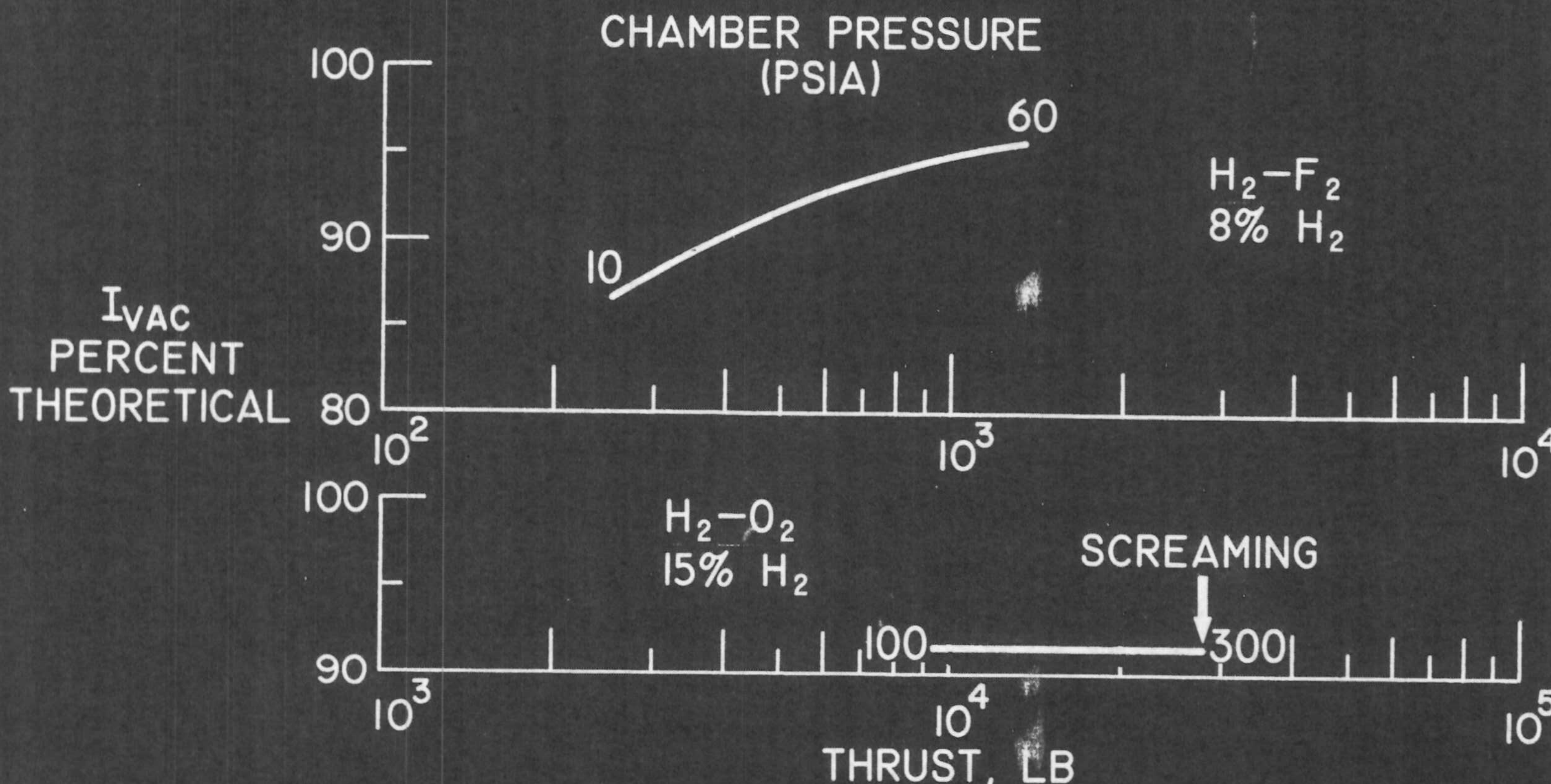

Figure 9

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THRUST CHAMBER COOLING

CHAMBER PRESSURE – 300 PSIA

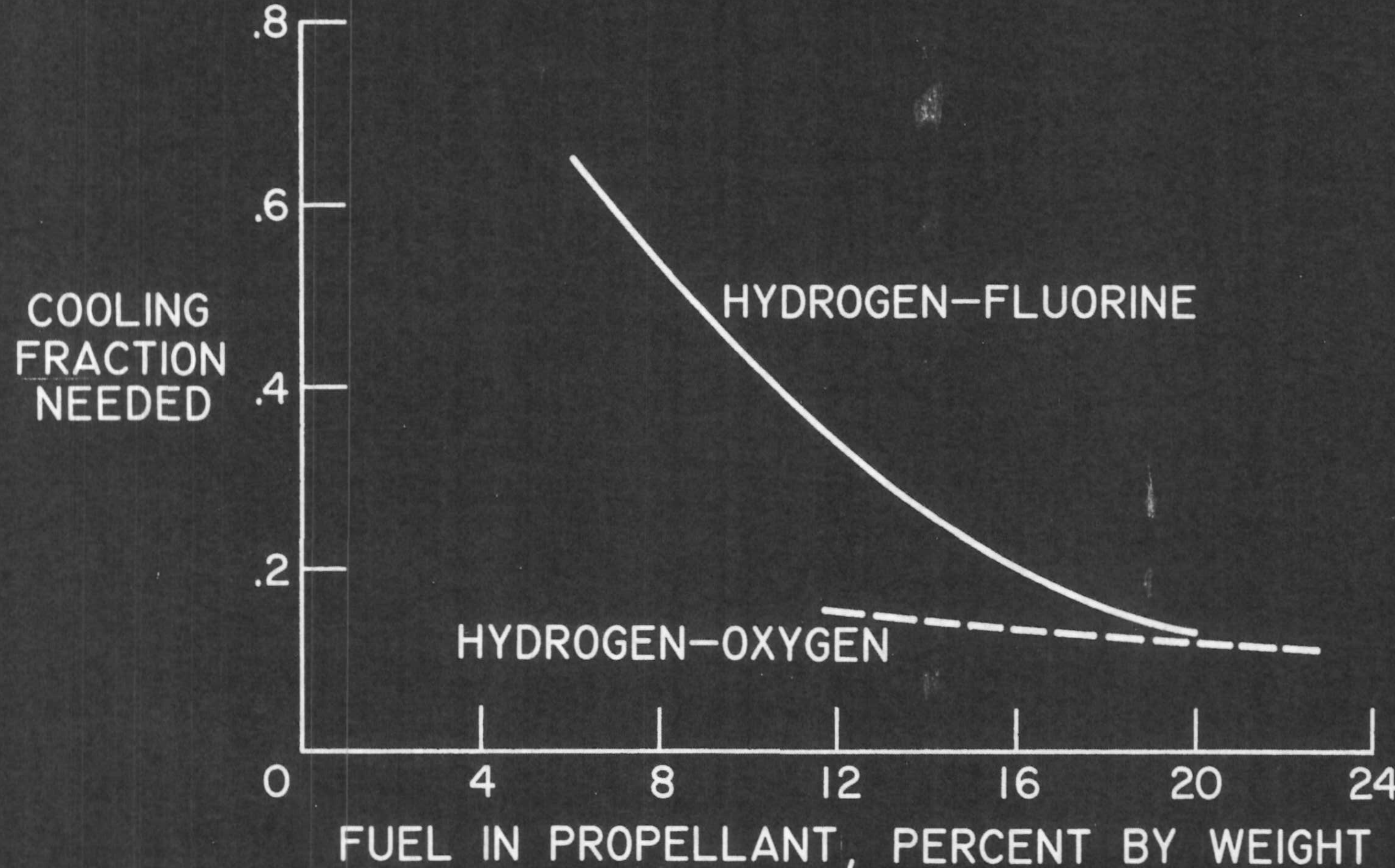

Figure 10

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AREAS OF RESEARCH

H_2–O_2 AND H_2–F_2

CHEMICAL EQUILIBRIUM IN NOZZLE

COMBUSTION EFFICIENCY

ENGINE THROTTLING

THRUST CHAMBER COOLING

H_2–O_2

IGNITION (STARTING)

COMBUSTION STABILITY

H_2–F_2

FLUORINE HANDLING

FLUID SYSTEM STABILITY

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Figure 11

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H_2-O_2 ENGINE IGNITION

CHEMICAL STARTING

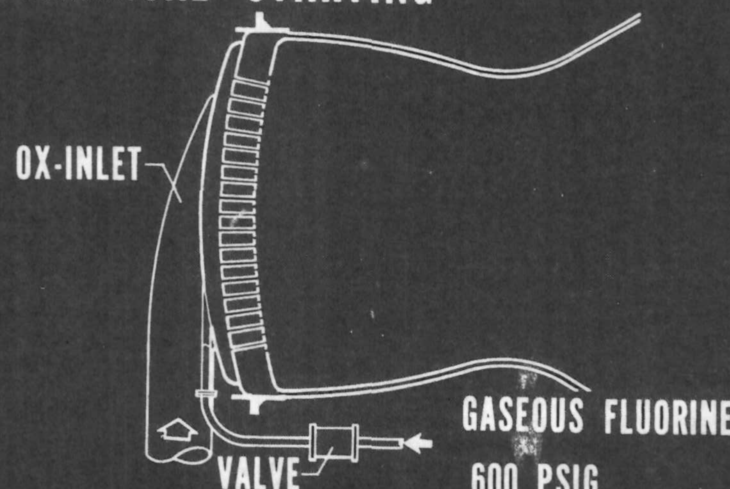

Figure 12

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CHEMICAL IGNITION

H_2-O_2

THIRD FLUID LEAD

OXIDANT — GASEOUS FLUORINE, AT 20K 0.5 LB NEEDED
CHLORINE TRIFLUORIDE

FUEL — TRIETHYL ALUMINUM

OXIDANT MIXTURE

O_2/F_2 —	SHOWERHEAD INJECTOR	50/50 NEEDED
	SWIRL CUP INJECTOR	75/25 NEEDED

Figure 13

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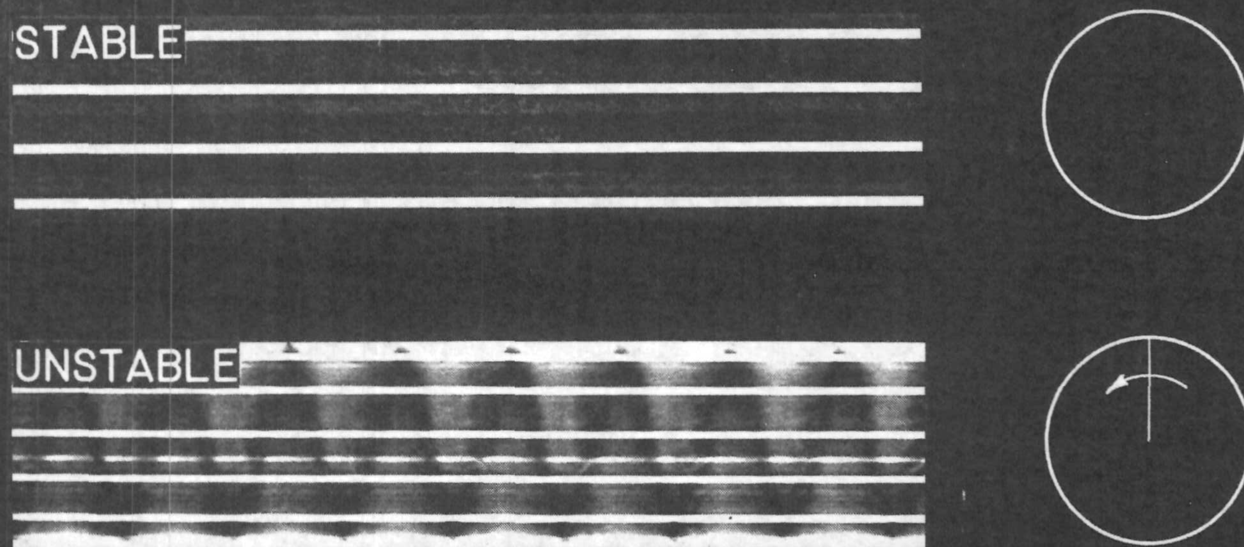
HYDROGEN–OXYGEN COMBUSTION OSCILLATIONS



PROBABILITY OF OSCILLATIONS WITH HYDOGEN–OXYGEN INCREASES WITH:

1. INCREASED CHAMBER PRESSURE
2. INCREASED FUEL PERCENT
3. DECREASED FUEL INJECTION TEMPERATURE
4. INCREASED COMBUSTION EFFICIENCY

Figure 14

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AREAS OF RESEARCH

H_2-O_2 AND H_2-F_2

CHEMICAL EQUILIBRIUM IN NOZZLE

COMBUSTION EFFICIENCY

ENGINE THROTTLING

THRUST CHAMBER COOLING

H_2-O_2

IGNITION (STARTING)

COMBUSTION STABILITY

H_2-F_2

FLUORINE HANDLING

FLUID SYSTEM STABILITY

~~CON~~ Figure 15 ~~IAL~~