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OPERATION OF A LIQUID FLUORINE PUMP IN CAVITATING FLOW AT AN INDUCER TIP SPEED OF 188 FEET PER SECOND (57.3 m/sec)

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Lewis Research Center
Cleveland, Ohio

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ABSTRACT

A combination cavitating inducer and main-stage impeller was operated in liquid fluorine for 36 minutes. The inducer tip relative flow velocity was approximately 188 feet per second (57.3 m/sec). Both noncavitating and cavitating pump performance are presented. For approximately 18 minutes the inducer was operating with moderate to heavy cavitation. No cavitation damage was experienced. Titanium carbide cermet with nickel binder and aluminum oxide performed adequately as seal materials.

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SUMMARY

A combination cavitating inducer and main-stage centrifugal impeller was operated in liquid fluorine at a rotational speed of 18 000 rpm and at inducer tip relative flow velocities of approximately 188 feet per second (57.3 m/sec). The total operating time in liquid fluorine was 36 minutes, which was obtained in two runs of 13 and 23 minutes. For the noncavitating pump performance, the pump was operated over a range of flow rates from 296 to 83 gallons per minute (187×10^{-4} to 52.4×10^{-4} m^3/sec). A maximum pressure rise of 514 pounds per square inch (354×10^{4} N/m^2) was obtained at the minimum flow rate. For approximately 18 minutes, the inducer was operating with moderate to heavy cavitation present as estimated by the loss in performance at low values of net positive suction head as compared to the noncavitating performance. Post-test inspection of the inducer and the main-stage impeller revealed no damage from cavitation. Therefore, cavitation damage is not expected to be a serious problem in liquid-fluorine pumps for rocket engine applications at inducer tip relative flow velocities less than 188 feet per second (57.3 m/sec).

The titanium carbide cermet with nickel binder and aluminum oxide materials used for the rotating shaft seals showed no reaction with fluorine and performed adequately at a relative sliding velocity of approximately 11 000 feet per minute (55.9 m/sec).

Areas of adverse, corrosive, fluorine reactions were evidenced on both the inducer and the main-stage impeller in areas where repairs to eliminate porosity had been made on the castings. Such reactions emphasize the need for having sound and uncontaminated metals in fluorine systems.

INTRODUCTION

It is usually desirable to operate the pumps of rocket propellant feed systems at low inlet pressures with some degree of cavitation present. Such conditions enable the propellant tanks to be designed for low pressure, which keeps the overall weight of the rocket vehicle low. To prevent the pump performance from degrading due to cavitation at low inlet pressures, cavitating inducers are generally employed to produce enough pressure rise to prevent a loss in performance in the main-stage impeller.

Initially, in considering the pumping of liquid fluorine, an extremely reactive oxidizer whose use with liquid hydrogen is desirable because of the resulting high specific impulse and hypergolic ignition, there was concern that cavitation damage might result. However, no damage was observed on the centrifugal impeller of reference 1 as it operated in cavitating flow conditions at a rotational speed of 11 490 rpm. At the same rotational speed, the addition of a cavitating inducer ahead of the centrifugal impeller (ref. 2) allowed a reduction in inlet pressure from 63 to 14 psi (43.4×10^4 to 9.7×10^4 N/m^2) without a performance loss and with no cavitation damage to the impellers. However, there is little experience available in pumping liquid fluorine over a range of speeds and under cavitating flow conditions.

Experience has shown (refs. 3 and 4) that fixed type cavitation (fixed cavity on the body surface) is one of the most prevalent forms of cavitation occurring in rotating machinery and flowing fluids. For fixed type cavitation, the pitting rate varies with the physical properties of the liquid and with some high power of the flow velocity. Indications are that the pitting rate may increase with the sixth to eighth power of the flow velocity (ref. 4). The effect of the physical properties on cavitation are discussed in reference 5 and observations were made which indicate that cavitation erosion may be accelerated by the concurrent action of corrosive effects. Therefore, cavitation damage in high density, chemically reactive liquid fluorine (the most electronegative element) might be expected to be high - particularly if the relative flow velocity is high. It is therefore desired to obtain at least qualitative information on cavitation damage while pumping liquid fluorine at a higher rotative speed (higher relative velocity) than that used in the investigations of references 1 and 2.

The seals used in the fluorine pump investigation of reference 2 utilized aluminum oxide running against titanium carbide cermet with a nickel binder. These seal materials appear to be suitable for fluorine pump operation although some heavy wear was experienced due to high seal loadings. For the increased seal rubbing velocities corresponding to higher rotational speed, further research may be required to evolve suitable seal designs.

The purpose of this investigation is to determine qualitatively if resistance to cavitation damage and suitable seal operation could be obtained with a liquid-fluorine pump operating at higher speeds than those used in the tests of reference 2. The pump housings were reworked to incorporate a slightly larger diameter inducer, and a main-stage impeller with backward swept blades was used to obtain flow and pressure levels for the pump comparable to those used in reference 2. The pump was run at a rotative speed of 18 000 rpm instead of 11 490 rpm as in reference 2. The shaft and seal arrangements were the same except for some adjustment in seal pressure loading. Pump performance measurements were made to estimate the degree of cavitation occurring within the impeller. The tests were conducted at the NASA Plum Brook Facility.

SYMBOLS

g	acceleration due to gravity, ft/sec^2; m/sec^2
H	total head, ft; m
ΔH_{loss}	$\Delta H_{ideal} - \Delta H_{actual}$, ft; m
H_{sv}	net positive suction head, $H_i - h_v$, ft; m
h_v	vapor head, ft; m
N	pump rotative speed, rpm
P	total pressure, lb/sq in.; N/m^2
p	static pressure, lb/sq in.; N/m^2
Q	flow rate, gal/min; m^3/sec
r	radius, ft; cm
S	suction specific speed, $N\sqrt{Q}/H_{sv}^{3/4}$
T	temperature, $^{\circ}$R; $^{\circ}$K
V'	relative velocity, ft/sec; m/sec
Z	axial distance, ft; cm
θ	circumferential angle, deg
$\bar{\omega}$	loss coefficient, $\Delta H_{loss}\Big/\left[(V_1')^2/2g\right]$

Subscripts:

i	inlet instrumentation plane (approximately 7 in. (17.78 cm) upstream of inducer)

o outlet instrumentation plane (downstream of scroll collector)

2 inducer outlet

APPARATUS AND PROCEDURE

Inducer

The inducer was designed to operate at a rotative speed of 18 000 rpm, a flow rate of 241 gallons per minute (152×10^{-4} m^3/sec) and a net positive suction head H_{sv} of 20 feet (6.1 m). The design suction specific speed was approximately 30 000. The inducer inlet tip radius was optimized for cavitating flow by using the method of reference 6. The optimized inlet tip angle was 84^o. The inducer was designed by the procedure given in reference 2 and used the distribution of loss coefficient $\overline{\omega}$ given therein. The distribution of total pressure rise ΔP was linear from 43.1 pounds per square inch (29.7×10^4 N/m^2) at the hub to 71.9 pounds per square inch (49.6×10^4 N/m^2) at the tip. The five bladed inducer was cast in stainless steel with a blade thickness of 0.0625 inch (0.159 cm). The inducer dimensions are given in figure 1.

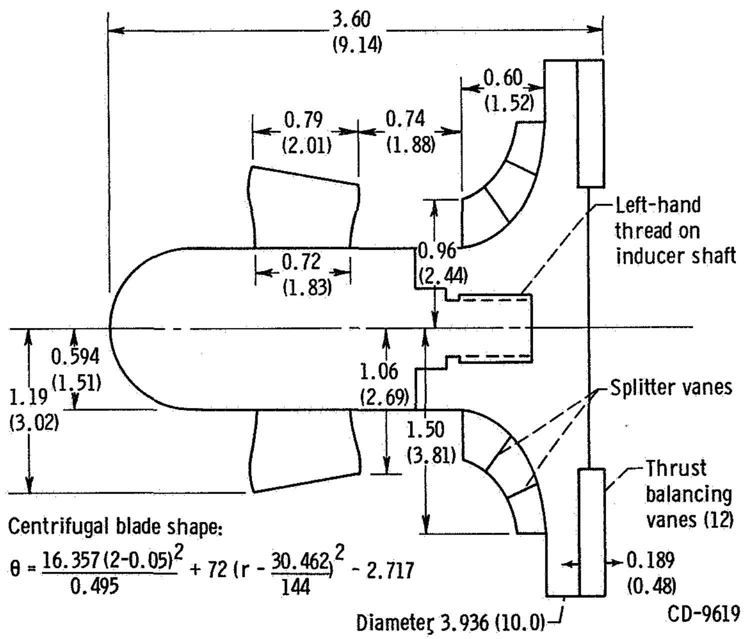
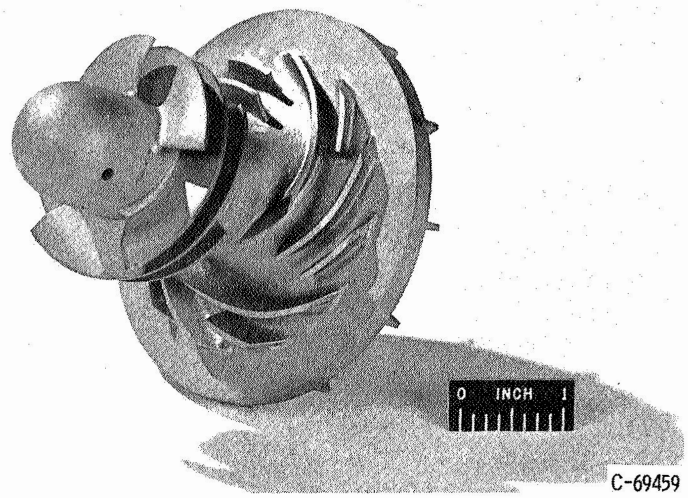


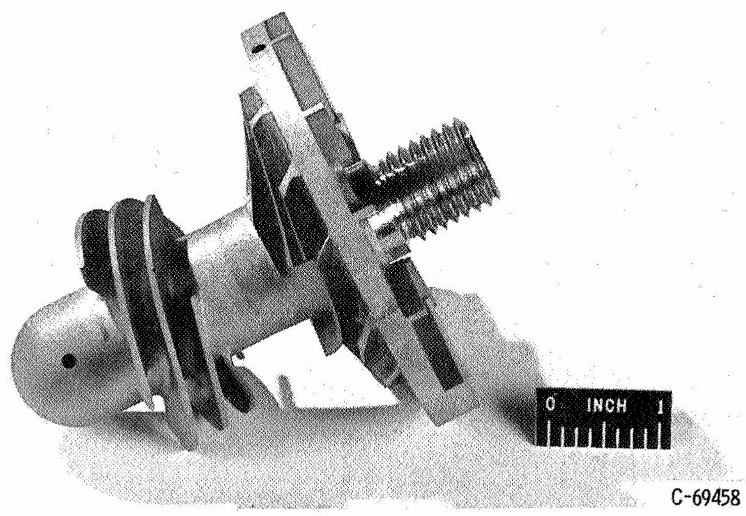
Figure 1. - Inducer and main-stage-pump profile in meridional plane. (Dimensions are in inches (cm).)

Main-Stage Impeller

The main-stage centrifugal impeller was designed with backward curved vanes for operation at a rotative speed of 18 000 rpm, a flow rate of 241 gallons per minute (152×10^{-4} m^3/sec) and an H_{sv} of 86 feet (26.2 m). An efficiency of 0.7, a slip factor of 0.90, and a pressure rise of 500 psi (345×10^4 N/m^2) were used for the impeller design. The impeller was designed by the stream filament method which is briefly summarized in reference 1. In general, the design procedure controls the velocities within the passage to prevent the formation of a theoretical eddy condition (reverse flow). The impeller was cast in stainless steel with 3 blades at the inlet and 12 blades at the outlet. The blade



(a) Front view.



(b) Side view.

Figure 2. - Liquid-fluorine inducer and main-stage pump.

thickness was 0.0625 inch (0.159 cm). Vanes were incorporated on the rear of the impeller to relieve the thrust load on the bearings. The main-stage impeller dimensions are given in figure 1, and photographs of the inducer and main-stage impeller are shown in figure 2.

Pump Assembly

A sketch of the pump assembly is shown in figure 3. The scroll collector described in reference 1 was used. This collector was designed for an impeller having radial or straight blades at outlet. As the present impeller incorporates backward curved vanes, a mismatched condition results between the scroll and the impeller as the scroll flow area should be approximately 50 percent larger. It was necessary to extend the back shroud of the main-stage impeller beyond the blade outlet in order to use the existing scroll collector. A smooth flow path was maintained from the outlet of the main-stage impeller blades to the inlet of the collector (fig. 3). The inducer and main-stage impeller are cantilevered. The pump shaft is supported by a single-row angular contact bearing (forward thrust only), a single-row angular contact-split-inner-ring bearing (two direction thrust), and a roller bearing (not shown). The bearings are lubricated by a pressurized

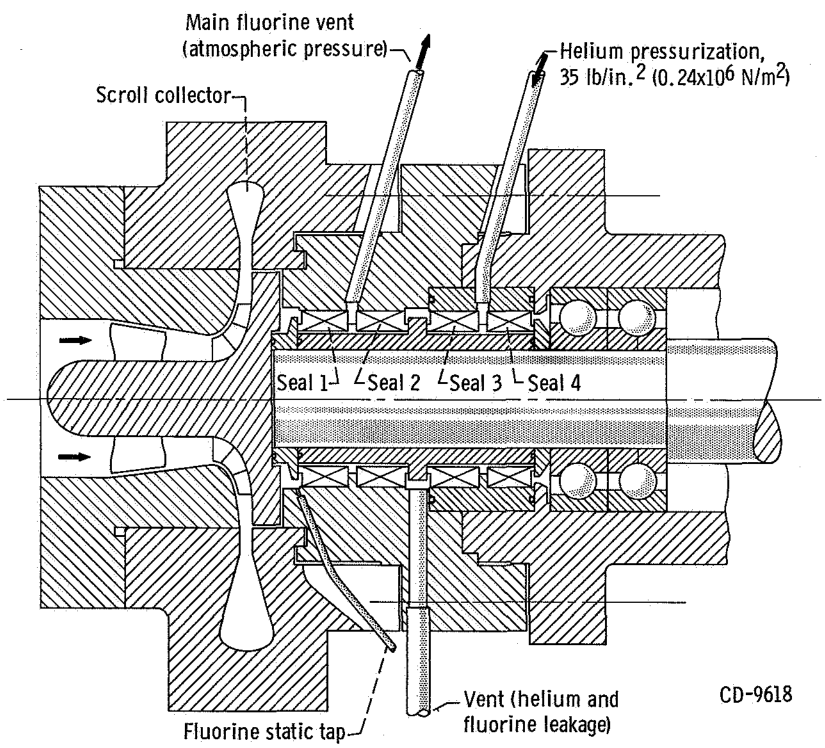


Figure 3. - Liquid-fluorine pump assembly.

oil system that uses heated Fluorolube oil. The seal configuration and materials were the same as that used in the investigation of reference 2. The liquid fluorine behind the main-stage impeller is sealed by two bellows-type seals (seals 1 and 2, fig. 3) placed back to back. Seal 1 is a face seal designed for higher external pressure, while seal 2 is a reverse seal designed for higher internal pressure. The cavity between the seals is vented to the atmosphere. The small amount of fluorine leakage from seal 1 is vented to the atmosphere. The fluorlube oil system is similarly sealed by the two reverse seals 3 and 4. The cavity between seals 3 and 4 is pressurized with helium gas to 35 psi (0.24×10^6 N/m^2). The cavity between the two sets of seals is vented to the atmosphere.

Test Facility

The test facility is the same as that described in reference 2. A schematic of the facility is shown in figure 4. It is a closed-loop system in which the liquid fluorine is

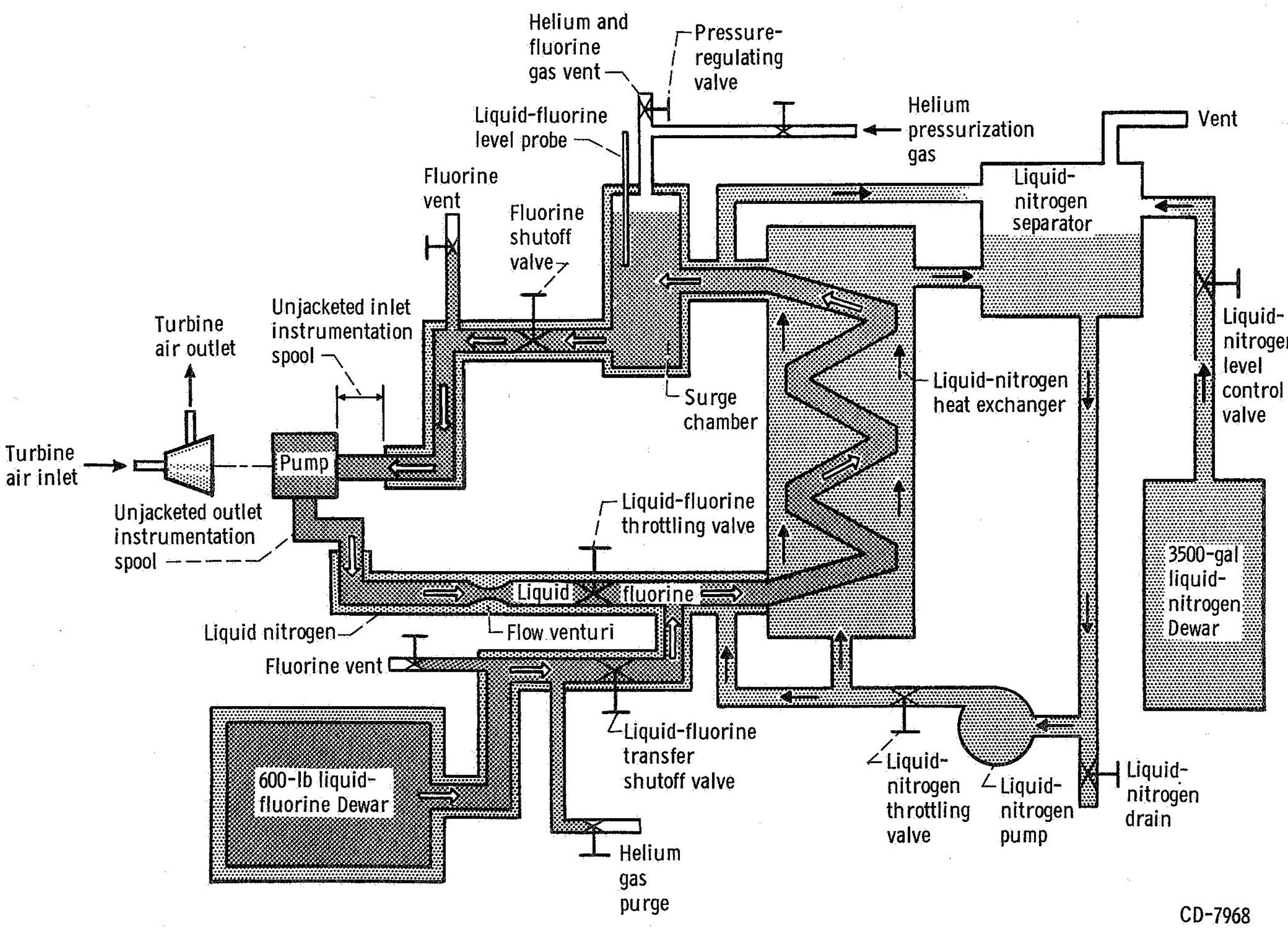


Figure 4. - Schematic of liquid-fluorine pump facility.

circulated by the research pump. Liquid nitrogen is used as a coolant in a heat exchanger, jackets, and troughs surrounding the liquid-fluorine lines in order to obtain long test times. The pump inlet and outlet instrumentation spools were not jacketed with liquid nitrogen. Operation of the test loop is described in reference 1.

Instrumentation

The instrumentation was the same as that described in reference 2. It consisted of total-pressure probes, static-pressure taps, and platinum resistor temperature probes located in unjacketed lines 7 inches (17.78 cm) upstream of the inducer and 2 inches (5.08 cm) downstream of the scroll collector outlet. Static taps were also located 1/4 inch (0.635 cm) downstream of the inducer. A venturi section was instrumented to obtain flow rates. Shaft rotative speed was determined by a magnetic pickup located on the drive turbine shaft. The platinum resistor temperature probes were checked at saturation temperatures (atmospheric pressure) for liquid nitrogen and liquid oxygen which brackets liquid-fluorine saturation temperature (154° R or 85.6° K).

All research data were recorded on magnetic tape in conjunction with a high-speed digital recorder.

RESULTS AND DISCUSSION

The data presented in this investigation (figs. 5 to 7) were obtained from two pump runs with a total operating time of 36 minutes in liquid fluorine. The pressure rise as a function of flow rate at five net positive suction heads was obtained in the first run (13 min). In the second run (23 min), the cavitation performance of the pump was evaluated by lowering the H_{sv} until the pressure rise deteriorated, while speed and the flow rate were held constant. Some of the first run data were also repeated during the second run. The data presented herein are used to show the operating range of the pump and to indicate the effect of cavitation on the pump performance in order to estimate the severity of cavitation.

The overall pump performance at a rotative speed of 18 000 rpm is presented in figure 5. The performance curve for a net positive suction head H_{sv} of 70 feet (21.3 m) is essentially the noncavitating performance of the pump inasmuch as the performance curve for the next lower value of H_{sv} shows only a small dropoff in performance at high flows. For the noncavitating condition, the pump was operated over a range of flow rates from 296 to 83 gallons per minute (187×10^{-4} to 52.4×10^{-4} m^3/sec). A maximum total-pressure rise of 514 pounds per square inch (354×10^4 N/m^2) was obtained at the minimum

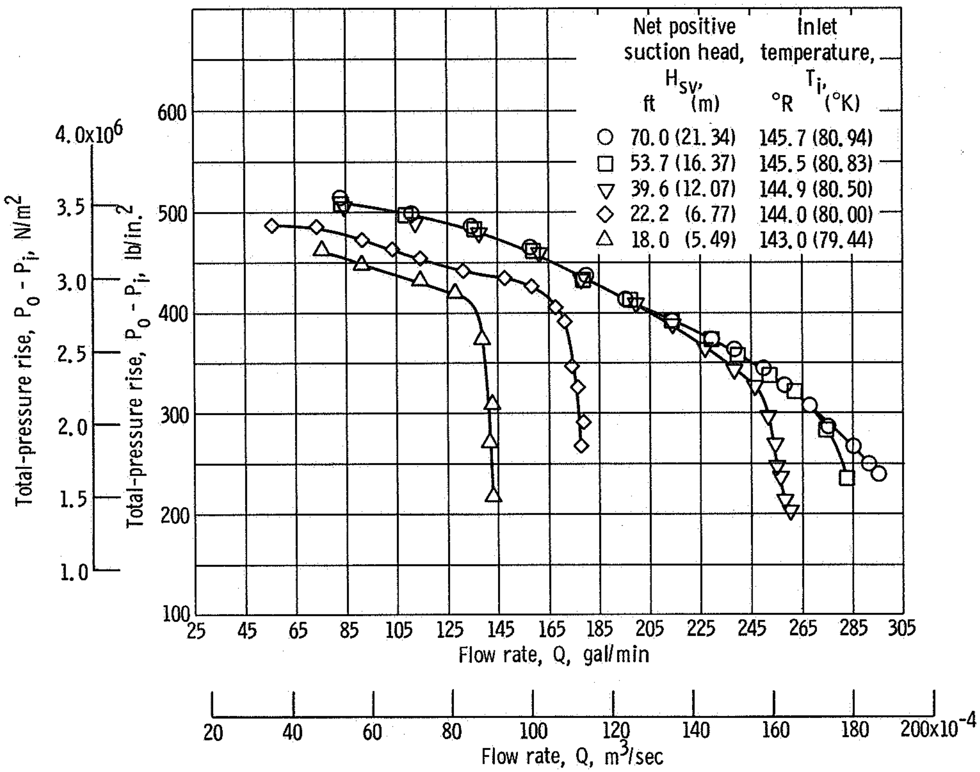


Figure 5. - Liquid-fluorine-pump performance at several net positive suction heads. Pump rotative speed, 18 000 rpm.

flow rate. There is a considerable loss in pressure rise and flow rate at the lower values of H_{SV}, and cavitation in the inducer might be expected to be moderate to heavy. Since the performance curves at the low H_{SV}'s are totally displaced from the noncavitating performance curve, cavitation evidently is occurring in the main-stage impeller as well as in the inducer.

The inducer static-pressure rise shown in figure 6 corresponds to the overall pump performance data of figure 5. There is a loss in inducer performance as H_{SV} is reduced from 70 to 53.7 feet (21.3 to 16.4 m). Thus, cavitation is present in the inducer even at high H_{SV}'s in amounts substantial enough to degrade the inducer performance. At the highest flow rates for the two lowest values of H_{SV}, the suction specific speed S is approximately 24 000 (fig. 6) and the pressure rise has deteriorated to very low values indicating the presence of heavy cavitation.

The cavitation performance of the inducer and main-stage impeller is presented in figure 7 for several medium to high flow rates. In these tests, for each performance curve the speed and flow rate were held constant and the net positive suction head was lowered from a high value until the pressure rise deteriorated. The dashed line (fig. 7) indicates the beginning of the pressure-rise breakdown region for the range of flows shown. In this region any slight reduction of H_{SV} results in a significant drop in pres-

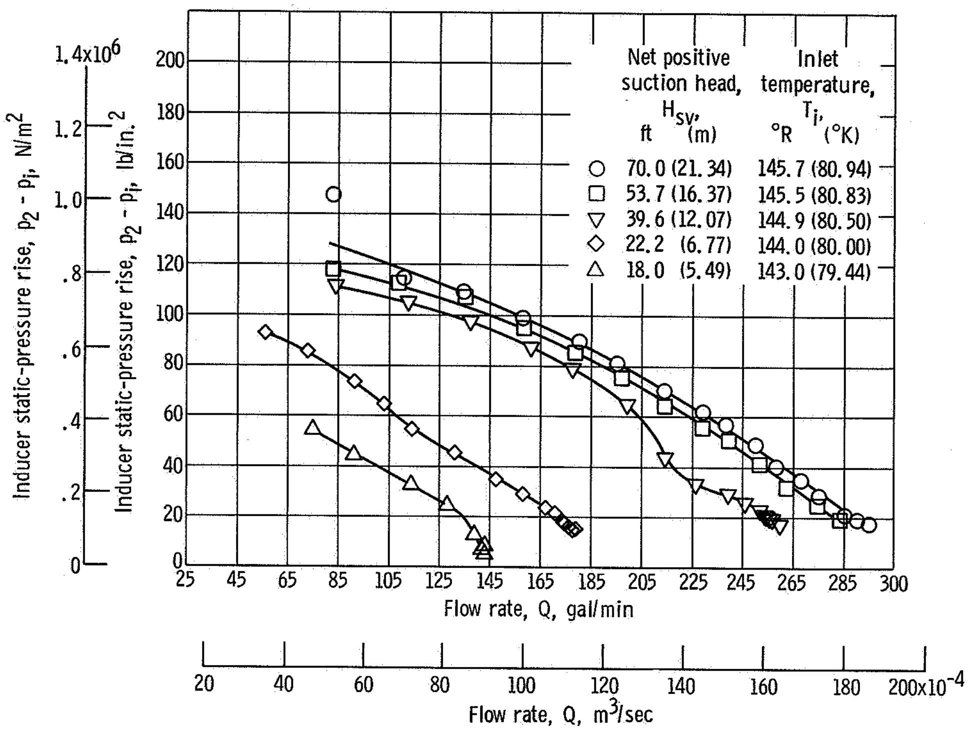


Figure 6. - Inducer static-pressure rise at several net positive suction heads. Inducer rotative speed, 18 000 rpm.

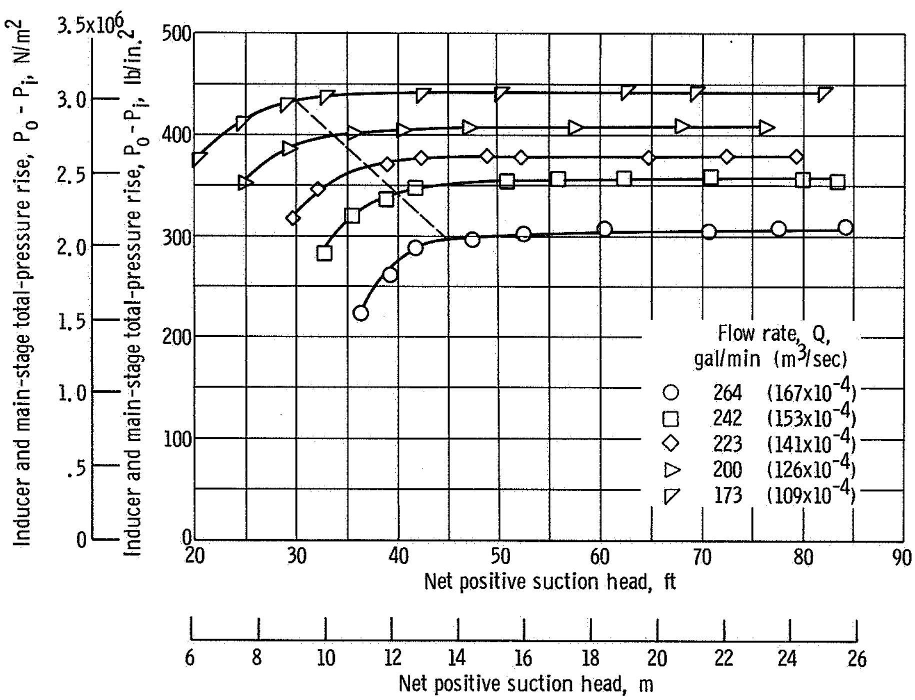


Figure 7. - Cavitation performance of liquid-fluorine pump at five flow rates. Pump rotative speed, 18 000 rpm.

sure rise produced by the pump. Also, as indicated in reference 3 by photographs of cavitation as related to pump performance, tip vortex cavitation and blade surface cavitation extend throughout the inducer in the pressure-rise breakdown region. It is probable that tip vortex cavitation was occurring in the inducer even at high values of H_{sv} (ref. 3).

The tests conducted in reference 2 caused no cavitation damage to the inducer which was operating in cavitation at a relative flow velocity of approximately 116 feet per second (35.4 m/sec). In the present tests, the relative flow velocity was increased by 62 percent to approximately 188 feet per second (57.3 m/sec). For approximately half of the total test time of 36 minutes, the inducer was operating at or less than an H_{sv} of 39.6 feet (12.1 m). As indicated by the loss in inducer performance at these low values of H_{sv} (fig. 6), the inducer was probably operating in moderate to heavy cavitation. A visual inspection of the impellers revealed no indication of cavitation damage. Thus, the results of this investigation indicate that even at relative flow velocities as high as 188 feet per second (57.3 m/sec) cavitation damage should not be a problem in liquid-fluorine pumps for rocket applications.

The seal configuration (fig. 3) and the seal materials used in this investigation were the same as those used in reference 2. A cross-sectional view of the primary liquid-fluorine seal is shown in figure 8. The seal consists of a welded 347 stainless-steel bellows attached to a casing with a stainless-steel endpiece attached to the free end of the bellows. An aluminum oxide ring or nosepiece was flame sprayed on the endpiece. The nosepiece rubs against a rotating mating ring attached to the pump shaft which was fabri-

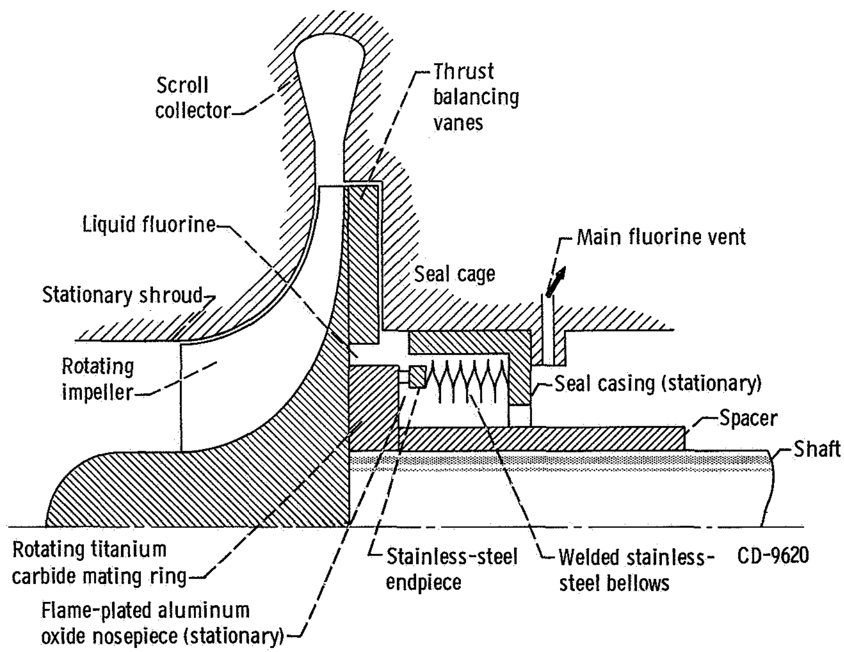


Figure 8. - Cross-sectional view of primary liquid-fluorine seal.

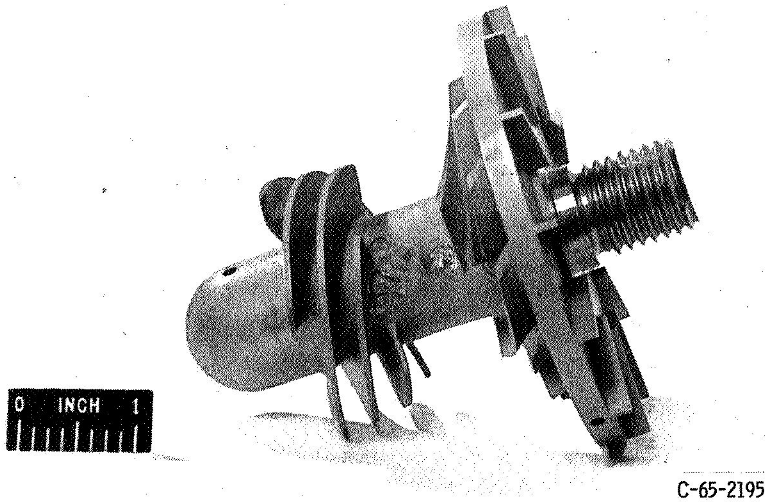
cated from titanium carbide cermet with a nickel binder. During operation in fluorine, nickel fluoride is formed on the surface of the mating ring which is beneficial in reducing friction and wear of the seal materials (ref. 7). The seal was designed for higher pressure on the outside of the bellows and pressure balanced such that a force was exerted on the nosepiece proportional to the pressure drop across the nosepiece. The same pressure balance was used for this investigation as was used for the tests of reference 2. In addition, a spring load of 8 pounds (35.6 N) was impressed on the nosepiece by compressing the bellows at installation. The spring load was the minimum recommended for the seal installation and gave the best wear rate in the tests of reference 2.

During the first test (13 min), the thickness of the aluminum oxide nosepiece was reduced by wear from 0.013 to 0.009 inch (0.033 to 0.023 cm). There was no appreciable wear on the titanium carbide mating ring. In the second test (23 min), the aluminum oxide nosepiece (0.013 in. thick (0.033 cm)) was worn down to the stainless-steel endpiece attached to the end of the bellows. Based on the wear rate of the first test, metal to metal contact probably occurred near the end of the test. The wear track of the stainless-steel endpiece on the titanium carbide mating ring was smooth and polished, and there was no indication of adverse fluorine reaction with the metallic parts. Although the pressure balance of the seal was changed by the erosion of the aluminum oxide nosepiece, the spring load due to the compression of the bellows at installation was adequate to prevent excess fluorine leakage at the end of the test.

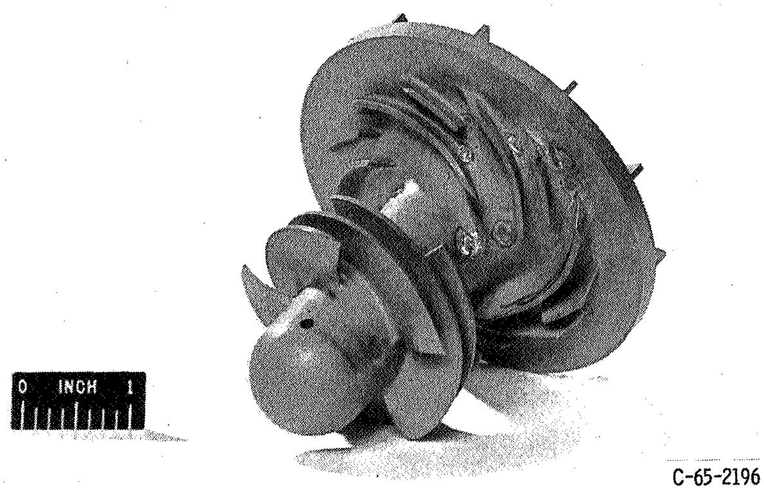
The wear rate of the aluminum oxide in the first test was 0.004 inch (10.15×10^{-3} cm) in 13 minutes as compared to 0.004 inch (10.15×10^{-3} cm) in 6 minutes for the best test of reference 2. However, the relative sliding velocity of the seal materials was approximately 11 000 feet per minute (55.9 m/sec) as compared to 7000 feet per minute (35.5 m/sec) in the tests of reference 2. Thus, the wear rates obtained in the present investigation were considerably better than those obtained in the tests of reference 2. The better wear rate may be attributed in part to a lower fluorine pressure in the cavity region behind the impeller due to a more efficient pump down of this region by the thrust balancing vanes. This pressure was approximately one-third that obtained in reference 2 and correspondingly reduced the load on the aluminum oxide nosepiece due to the pressure balance of the seal. Based on the results of this investigation, titanium carbide cermet (nickel binder) and aluminum oxide performed adequately as seal materials and gave no indication of reaction with liquid fluorine.

Improved wear rates probably could be obtained by using a ring of solid aluminum oxide for the nosepiece as an insert in the seal endpiece. Poor bonding between the sprayed aluminum oxide and the base metal which was evidenced in the tests of reference 2 contributed to the high wear rates of those tests.

Substitution of titanium carbide (nickel binder) for aluminum oxide for the seal nosepiece rubbing against the same material has been used successfully in fluorine-oxygen tests (ref. 8) and should prove to be an excellent combination for liquid-fluorine pumps.



(a) Side view.



(b) Front side.

Figure 9. - Areas of fluorine reaction with stainless-steel rotors.

Inspection of the inducer and main-stage impellers after the first test of 13 minutes revealed many areas where adverse corrosive reactions occurred (figs. 9(a) and (b)). All of these areas coincided with areas where repairs to eliminate porosity had been made on the castings. In these repaired areas, the porous regions had been enlarged until sound metal was obtained and then patched with a tin-bismuth solder. The impellers were immersed in boiling water for 2 hours in an attempt to remove the flux used in the soldering process. They were then degreased and cleaned ultrasonically before installation. The fluorine reaction probably occurred during passivation of the test loop (exposure of the system to fluorine gas) which preceeds a liquid-fluorine pump test. The reaction most likely was initiated by flux which remained in the repaired areas after the soldering process. No further fluorine reaction occurred in the second test. This experience, which fortunately did not result in a burnout, emphasizes the need for having sound and uncontaminated metals in fluorine systems.

SUMMARY OF RESULTS

An inducer and a main-stage pump were operated in liquid fluorine at a rotative speed of 18 000 rpm and with inducer tip relative flow velocities of approximately 188 feet per second (57.3 m/sec). At high values of net positive suction head H_{sv} (noncavitating performance), the pump was operated over a range of flow rates from 296 to 83 gallons per minute (187×10^{-4} to 52.4×10^{-4} m^3/sec) and a maximum pressure rise of 514 pounds per square inch (354×10^4 N/m^2) was obtained at the minimum flow rate. At low values of H_{sv}, the inability of the inducer to produce an adequate pressure rise due to cavitation resulted in cavitation in the main-stage impeller and low overall pump performance.

The total operating time in liquid fluorine was 36 minutes. For approximately 18 minutes, moderate to heavy cavitation was present in the inducer.

The following results were realized from the investigation:

1. Inspection of the inducer and main-stage impellers after operation in highly reactive liquid fluorine at inducer tip relative velocities of approximately 188 feet per secone (57.3 m/sec) revealed no damage from cavitation. At this velocity level cavitation damage, therefore, is not expected to be a serious problem in liquid-fluorine pumps for rocket engine applications.

2. Titanium carbide cermet (nickel binder) and aluminum oxide performed adequately as seal materials and gave no indication of reaction with liquid fluorine at relative sliding velocities of approximately 11 000 feet per minute (55.9 m/sec).

3. Adverse fluorine reactions, which occurred in areas where the inducer and main-stage impeller were repaired, emphasize the need for sound and uncontaminated metals in liquid-fluorine systems.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 22, 1968,
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