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ABSTRACT

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The performance of the liquid hydrogen flow system during the startup transient of a nuclear rocket was measured in a full-scale simulated engine system at Lewis Research Center. In-flight exhaust conditions were approximated by maintaining a nozzle outlet pressure of 1 psia. Data and general conclusions on overall system performance are presented for nonnuclear operation. The ability of the rocket system to bootstrap (i.e., to build up appreciable hydrogen flow and pressure in the nuclear reactor without extra-system assistance) was clearly demonstrated by using only the energy from hydrogen tank pressure and latent heat of engine components. The severity (small) and characteristics of two-phase flow oscillations during windmill were determined. No significant operational problems were encountered.

Author

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INTRODUCTION

Operation of a nuclear rocket engine will involve propellant flow phenomena and interactions imperfectly understood at the present time. Of particular concern are the propellant system transients encountered during the engine startup cycle. At the start of the project described herein, the nature and the magnitude of the transients that would be encountered were not known, even empirically. In fact, startup of a complete nuclear rocket system had not yet been attempted. The undefined startup problems might affect rocket engine control system design as well as design of the system itself.

Hence, tests of a full-scale nuclear rocket engine system were undertaken. Nonnuclear test runs only were made; that is, the only energy available to drive the propellant turbopump was the latent heat in the flow system components at the start of the run. There were three principal objectives of these tests:

(1) to evaluate the capability of the system to bootstrap[1]

(2) to find and solve operational problems encountered during nonnuclear system startup

[1]Bootstrap, as used here, is the achievement of appreciable propellant pressure in the reactor core, when the rocket starts from rest and utilizes no external means to accelerate propellant flow.

(3) to develop an analytical model of a nuclear rocket engine propellant flow system which will be helpful in the design of second generation nuclear rocket engines

Data for a number of additional experimental programs (principally system component evaluations) were obtained during each experimental run. Reports on the results of these additional experiments are in preparation.

EQUIPMENT AND PROCEDURE

To accomplish the foregoing nuclear rocket system test objectives, an existing facility (fig. 1) at the Plum Brook Station of the NASA-Lewis Research Center, was chosen in which to assemble the first simulated nuclear engine system. The facility has the necessary cryogenic handling capabilities; and, more important, an altitude exhaust system: rocket nozzle outlet pressure could be maintained at about 1 psia throughout a run.

Research hardware in the facility (fig. 2) consisted of a 2000-gallon liquid hydrogen run tank with a closed loop pressure vent system. The turbopump is a Rocketdyne 6-stage liquid hydrogen axial pump and a 6-stage axial gas turbine designated as the Mark 9.

The engine has a modified Rocketdyne RN-2, regeneratively cooled, bell-shaped nozzle. The modifications consisted of adding a hot gas bleed port and two windows for viewing the core. The reactor assembly is basically a KIWI-B1-B engine. For economic reasons, aluminum was substituted for beryllium in the reflector. The core is unfueled graphite. These modifications do not compromise the data obtained during the tests.

The manipulated variables other than tank pressure are delay time of turbine-power control-valve opening relative to initial opening of the pump discharge valve, and the manner in which the turbine-power control valve was manipulated during the run.

The test procedure follows. After the tank and all piping were cleaned and inerted, liquid hydrogen was loaded into the run tank. The tank shutoff valve was then opened and liquid hydrogen permitted to enter and cool the pump and pump discharge line to the pump discharge valve. This operation brought the pump to liquid hydrogen operating temperature before rotation commenced in order to ensure that the fluid in the pump bearings was liquid and not gaseous hydrogen. The altitude exhaust system was started and, simultaneously, the run tank pressure was raised to a preselected value (25, 35 or 50 psia). The pump discharge valve was then opened.

During initial tests, the hydrogen was forced through the system by tank pressure only; power was not applied to the turbine. These initial tests were used to evaluate whether significant flow oscillations occurred and to minimize the risk of damage to the pump while this evaluation was being made.

In subsequent tests, power was applied to the turbine and the system was permitted to bootstrap. Propellant flow increased rapidly until the turbine could no longer extract enough energy from the gas to sustain flow. The manipulated variables were changed in accordance with specific run objectives in these later runs.

RESULTS AND DISCUSSION

An analytical effort in progress has developed an analog computer program that gives good agreement with test data on the system and its components for quasistatic performance. Refinements to this computer program are being made to attempt to enable predictions of dynamic phenomena.

Until models of these dynamic phenomena are defined, the explanations of flow dynamics can be only empirical in nature. Hence, the results presented in this paper are concerned with what occurred rather than why it occurred. Part of the conclusions are concerned with oscillations of the propellant flow system. This paper is concerned only with the oscillations observed below a frequency of about 15 cps, the observed propellant-system oscillating frequency.

An initial set of runs was made to determine the severity of flow oscillations with no power to the turbine. Five conclusions were drawn from the results of these initial runs.

First of all, oscillations in the propellant system of the hydrogen weight flow, temperature, and pressure were considerably smaller in amplitude than had been expected from prior experiments on two-phase flow oscillations.[2,3] For example, figure 3 shows the variation of fluid static pressure with time at the inlet manifold of the nozzle coolant tubes.[4] Time traces for three runs at different tank pressures are shown. Although oscillations definitely occur, their amplitudes are much smaller than expected, and the higher-frequency larger-amplitude oscillations lasted for only a few seconds.

It should be remembered that observations on tests of one nuclear rocket

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[2]Ellerbrock, H. H.; Livingood, J. N. B., Straight, D. M.: Nuclear Rocket Propulsion; NASA SP-20; p. 27; 1962.

[3]Sanders, J. C.; Heppler, H. J.; Hart, C.E.: Nuclear Rocket Propulsion; NASA SP-20; p. 57; 1962.

[4]If only one location is to be used to illustrate the system response to two-phase flow, the nozzle coolant system response inlet is central to the flow system. More important, this inlet is in a two-phase flow condition during the bootstrap time interval of principal current interest.

engine without nuclear heating will not necessarily occur on different nuclear rocket engines or with nuclear-heated flow. Until a dynamic flow model is developed, it is not clear what effect a different set of system physical dimensions, for instance, would have on the amplitudes or frequencies of oscillations. Hence, it is of interest to further examine the oscillations observed, even though they were not a real problem in this or other test runs completed to date.

A second point from the initial runs is that the oscillations in the system are damped. Figure 4 is a plot of pressure against time at the nozzle coolant inlet for an unpowered run with flow produced only by 35-psia tank pressure. Some initial disturbance at the start of the run produces an oscillation that smoothly decreases in amplitude as the run progresses. The decrease in amplitude of the oscillations is somewhat similar to that of underdamped oscillations.

A third conclusion seen in figure 3 is the effect of tank pressure on the damping of system pressure oscillations. The tank pressure had a significant effect on the length of time at which higher frequency oscillations were observed. At 25-psia tank pressure, the chilldown oscillations persisted for more than 10 seconds.

A fourth point seen in figure 4 is that the characteristics of the oscillating system change with time. For a classical second-order system, the oscillating frequency is constant. The frequency of oscillation in figure 4 decreases with time. From the nature of the observed nonlinearity in figure 4, it would be expected that if a perturbation were introduced subsequently in the run the resulting pressure oscillations would occur at a lower frequency than observed herein. Data on subsequent bootstrap runs confirm this observation.

A fifth observation is that the large initial low-frequency transients die out by the time the nozzle coolant inlet reaches liquid-hydrogen temperature, but the system continues to oscillate long after two-phase flow has commenced.

BOOTSTRAP TESTS

With the foregoing assurances that system oscillations encountered were not large, were damped, and decreased in natural frequency as the run progress, bootstrap tests were undertaken.

The first important result of the set of bootstrap tests is that bootstrap can take place. It is conceivable that fluid resistance, turbopump efficiency, ambient back pressure (ground tests only) and/or fluid oscillations might have combined to prevent bootstrap.

Figure 5 shows a plot of pressure drop across the pump and weight flow rate at the pump during the course of the run. Pressure drop across the propellant flow system is the sum of run tank pressure and pump pressure drop. The best estimate of the pump stall line is as shown. It is important to note that time is very nonlinear in the curve of figure 5. As time progresses, the curve would seek to follow the intersection of the pump speed lines and the load fluid resistance line (not shown); this is the reason for the basic path the curve follows.

In the run of figure 5, propellant tank pressure was 35 psia and both the pump discharge valve and the turbine inlet valve were opened at zero time. Some time elapsed before sufficient power was available at the turbine to sustain a significant flow and pressure buildup, and during this time flow and pressure oscillations occurred. The system then built up weight flow and pressure to peak values. These peaks and subsequent decreases occurred because the latent heat present in the engine components was used up and, without nuclear heat, not enough energy was available at the turbine to sustain flow and pressure. Oscillations also occurred at the same time as the pump entered stall.

Figure 6, which is the same run as in figure 5, shows time histories of pump speed, propellant weight at the pump, and static pressures at the nozzle coolant inlet manifold and the reactor core outlet. Several points on these curves are of interest:

(1) With a 1-psia vacuum at the rocket nozzle outlet, there is a rapid buildup of pressure in the core outlet to substantial values.

(2) There are at least two perturbations; they occur in the early part of bootstrap and when the run is terminated.

(3) The frequency of pressure and flow oscillations decreases as the run progresses.

(4) As in figure 4, the oscillations resulting from each perturbation are underdamped.

(5) The damping coefficient on pressure oscillations increases as time increases.

Figure 7 is a plot of pressure, flow rate, and pump speed for a different run. In this run, the turbine power was controlled after 16 seconds to maintain a base pump speed of 4500 rpm, and perturbations in pump speed were introduced as shown by changes in turbine power control valve. The following points are evident:

(1) There are at least two sets of oscillations which occur in the early part of the run.

(2) The frequency of pressure and flow oscillations decreases with time.

(3) The oscillations are underdamped, and coefficient increases with time.

(4) Flow oscillations lead pressure oscillations.

From the foregoing, a simple, empirical model can be constructed of what is happening in the system - a model not evident at the outset of the tests. No attempt is made here to explain why the oscillations occur - only what is happening.

Consider the propellant flow system (or a considerable portion of it) as an oscillator. Whenever this system is perturbed it oscillates. The natural frequency of these system oscillations decreases with time. In the bootstrap run of figure 7, the natural frequency decreased from about 3 cps to 0.9 cps. In the unpowered cooldown run of figure 3, the decrease was from about 14 cps to 1.7 cps. The damping coefficient for the system oscillations increased with time.

A second aspect of the model is that several different events seem to perturb the system and produce oscillations.

First of all, the system was perturbed and oscillated on each run, when flow was first established.

A second set of oscillations seems to have commenced at the same time the pump entered the stall region; that is, as bootstrap progressed the system fluid load line in figure 3 crossed the pump stall line and the pump entered the stall region. Whether oscillations were initiated by a stall phenomenon, whether small amplitude oscillations were magnified when the pump entered stall, or whether stall and oscillations were the result of some third phenomenon is not yet clear. Lack of pump stall data at low speeds particularly makes analysis difficult.[5] However, available data are consistent with the model of propellant flow oscillations that, each time the pump enteres stall, the system experiences an underdamped oscillation at a natural system frequency.

Finally, another set of oscillations was observed whenever there was a rapid change in turbine power settings, as illustrated in figure 7. There could be other events, such as flow separation or unchoking of an orifice, which initiated oscillations. The foregoing are those that have been identified.

Possibly the most important conclusion of all is the absence of real operating problems during the runs. Equipment has not yet been disassembled for detailed inspection. However, all available observations in a total of 26 experimental tests concerning the startup of a full-scale nuclear rocket engine system without nuclear power indicate that no significant problems in pump stall, pump cavitation, boiling of liquid hydrogen, shrinkage and cooperation of cooperating parts, inadequate turbine power to accelerate the propellant supply pump, or unstable system oscillations. That is, all indications to date from the data on nonnuclear startup are that the bootstrap startup of a nuclear rocket in space can be accomplished.

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[5]However, a significant achievement in the overall program was the creation of a technique which predicts off-design-point acceleration outside the stall region. This analytical effort is being reported separately.

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Figure 1. - B-1 facility, Lewis Research Center.

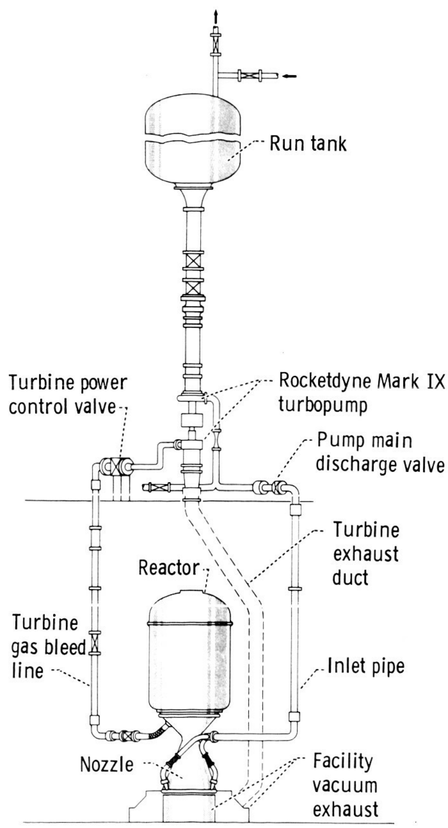

Figure 2. - Nuclear rocket system test hardware.

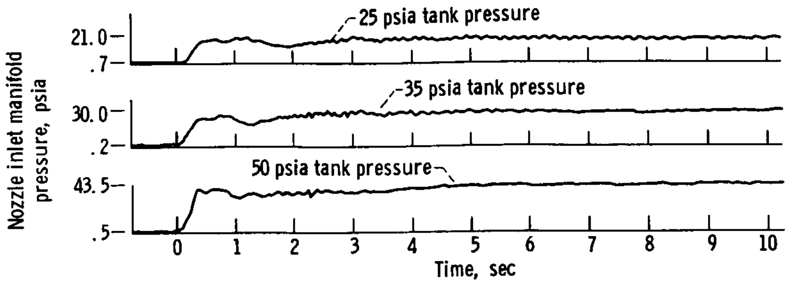

Figure 3. - Tank pressure effect.

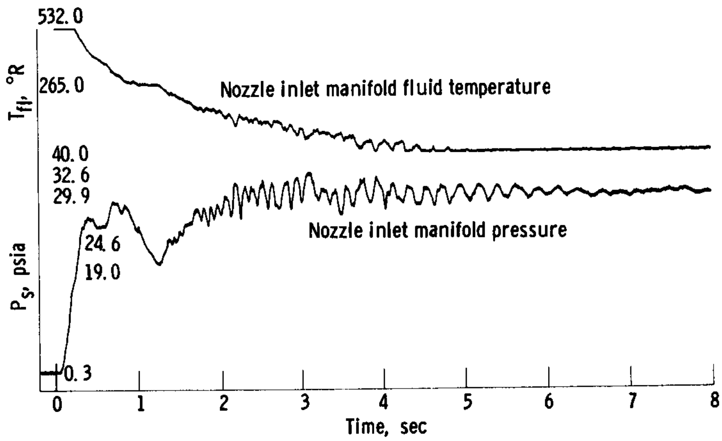

Figure 4. - Cooldown oscillations.

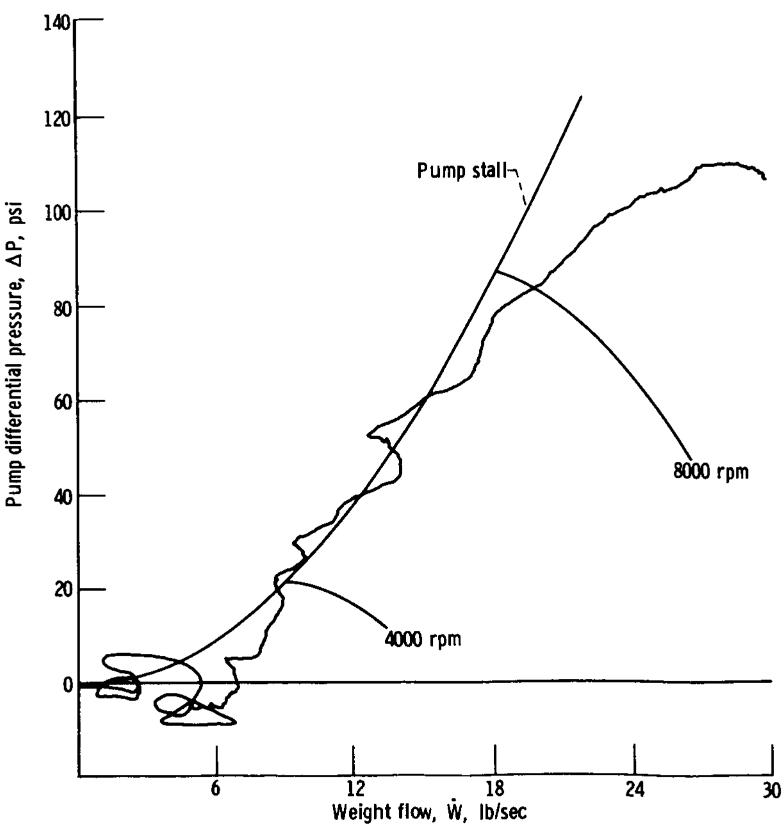

Figure 5. - System bootstrap.

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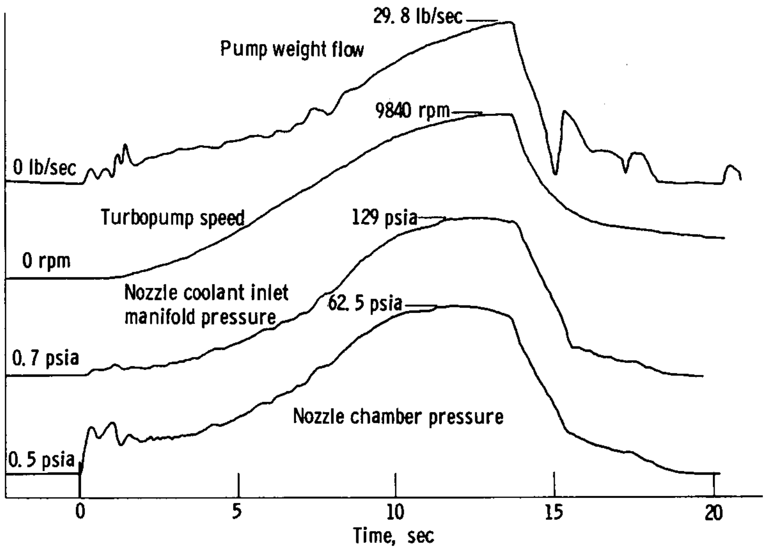

Figure 6. - Bootstrap transients.

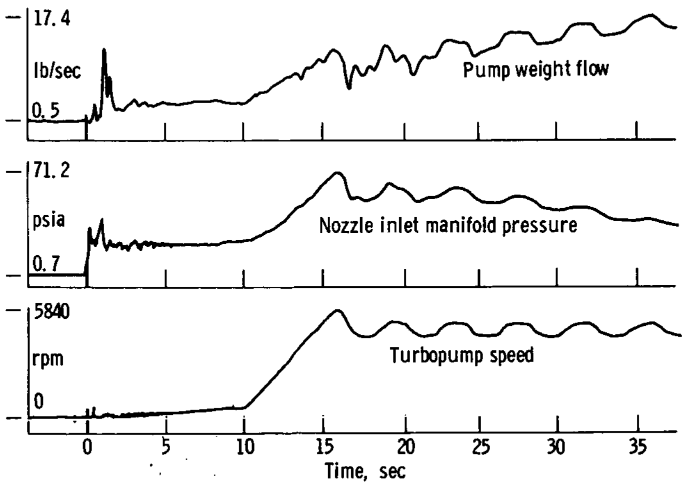

Figure 7. - Induced oscillations.