NASA CR 54824
AGC 9400-2

TECHNOLOGY REPORT

ACTIVATION AND INITIAL TEST OPERATIONS
LARGE ROCKET ENGINE - TURBOPUMP TEST FACILITIES

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

1 August 1967

CONTRACT NAS 3-2555

Prepared by:

AEROJET-GENERAL CORPORATION
LIQUID ROCKET OPERATIONS
SACRAMENTO, CALIFORNIA

AUTHOR: D. H. Clark

APPROVED: J. C. Moise
Manager
M-1 Engine Program

Technical Management:

NASA LEWIS RESEARCH CENTER
CLEVELAND, OHIO

TECHNICAL MANAGER: W. H. Rowe

APPROVED: W. A. Tomazic
M-1 Engine Project Manager

AEROJET-GENERAL CORPORATION
A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY

PRECEDING PAGE BLANK NOT FILMED.

ABSTRACT

Testing of the turbopump assembly for the M-1 Engine presented a major challenge because of the complexity of the tests, the size of the hardware, and the amount of propellants required. This report describes the facilities that were built, the activation procedures that were followed, and the facility checkout tests that were made to meet this challenge.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

LIST OF FIGURES

I. SUMMARY

The design, development, and activation of a large rocket turbopump test facility required for developing the NASA M-1 Engine turbopump assembly presented a major challenge in test complexity, hardware size, and propellant usage. Special techniques were evolved during facility activation as well as during initial facility operation because of the uniqueness of both the large cryogenic systems and the critical controls requirements. Although conventional procedures generally were followed during activation, special emphasis was placed upon checkout testing, which was planned to verify key facility design concepts. A portable analog computer was used successfully to simulate actual test conditions. Typical activation problems such as cleanliness and piping line restraint had to be overcome, and new problems such as the venting of large quantities of hydrogen gas and the need for rapid response, hot-gas relief for turbine overspeed protection had to be solved. Initial test operations confirmed the adequacy of the new facility design features and the techniques used. Also, the effectiveness of a permanent test controller embodying computing elements for automatic test profile programming of the critical turbopump parameters was demonstrated.

II. INTRODUCTION

The Test Zone E complex located in Aerojet-General's Sacramento Test Operations was selected as the site for these facilities. Appropriate test facilities were constructed to provide the developemnt test capability for the NASA/LeRC 1.5 million-lbf thrust, liquid oxygen/liquid hydrogen M-1 Engine Fuel (FTPA) and Oxidizer (OTPA) Turbopump Assemblies.

Construction of the basic facilities was initiated during 1962 and completed by the end of 1963. This was followed by an intensive period of facility activation to assure its full, operational readiness. It is the activities of this period as well as the subsequent initial test series, which demonstrated the operational readiness of the E-Zone test complex, that are described in this report. The facilities of this complex are described briefly in the next section for appropriate background information.

III. FACILITY DESCRIPTION

The M-1 turbopump facilities of the Zone E complex are shown in Figures 1 and 2. These facilities consist of Test Stands E-1 and E-3, Control Room E-1, and supporting facilities for liquid oxygen and liquid hydrogen unloading, storage, and distribution; high-pressure gaseous hydrogen and nitrogen storage; conversion and distribution systems; service shops; and utilities.

A closed-loop system was used to satisfy turbopump test requirements. This system consisted of a propellant run tank, a suction system leading to the pump inlet, a discharge system with back-pressure control, and return lines to a propellant catch tank. A schematic diagram of this system is shown in Figure 3.

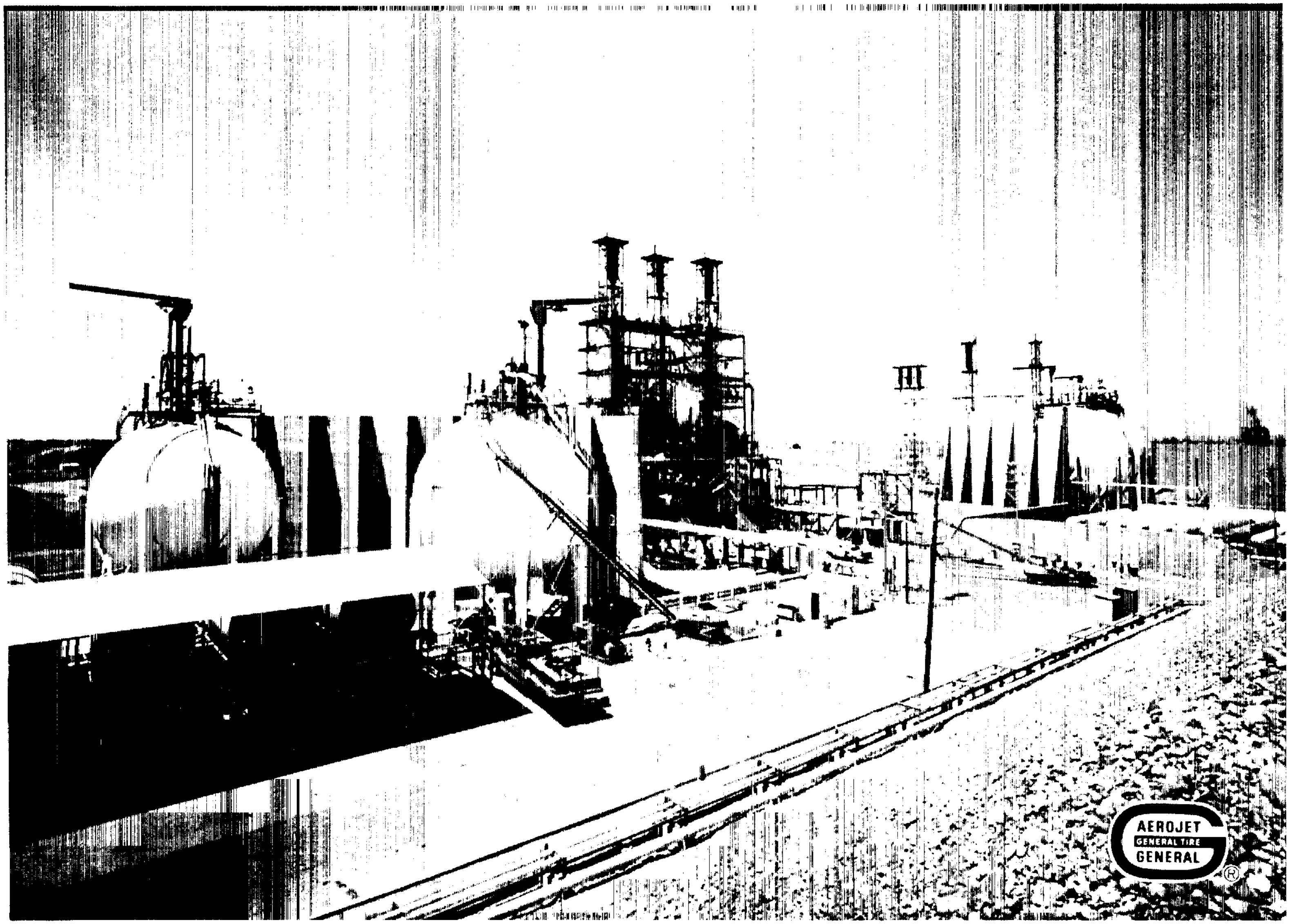

Figure 1. General View of E-Zone Facilities

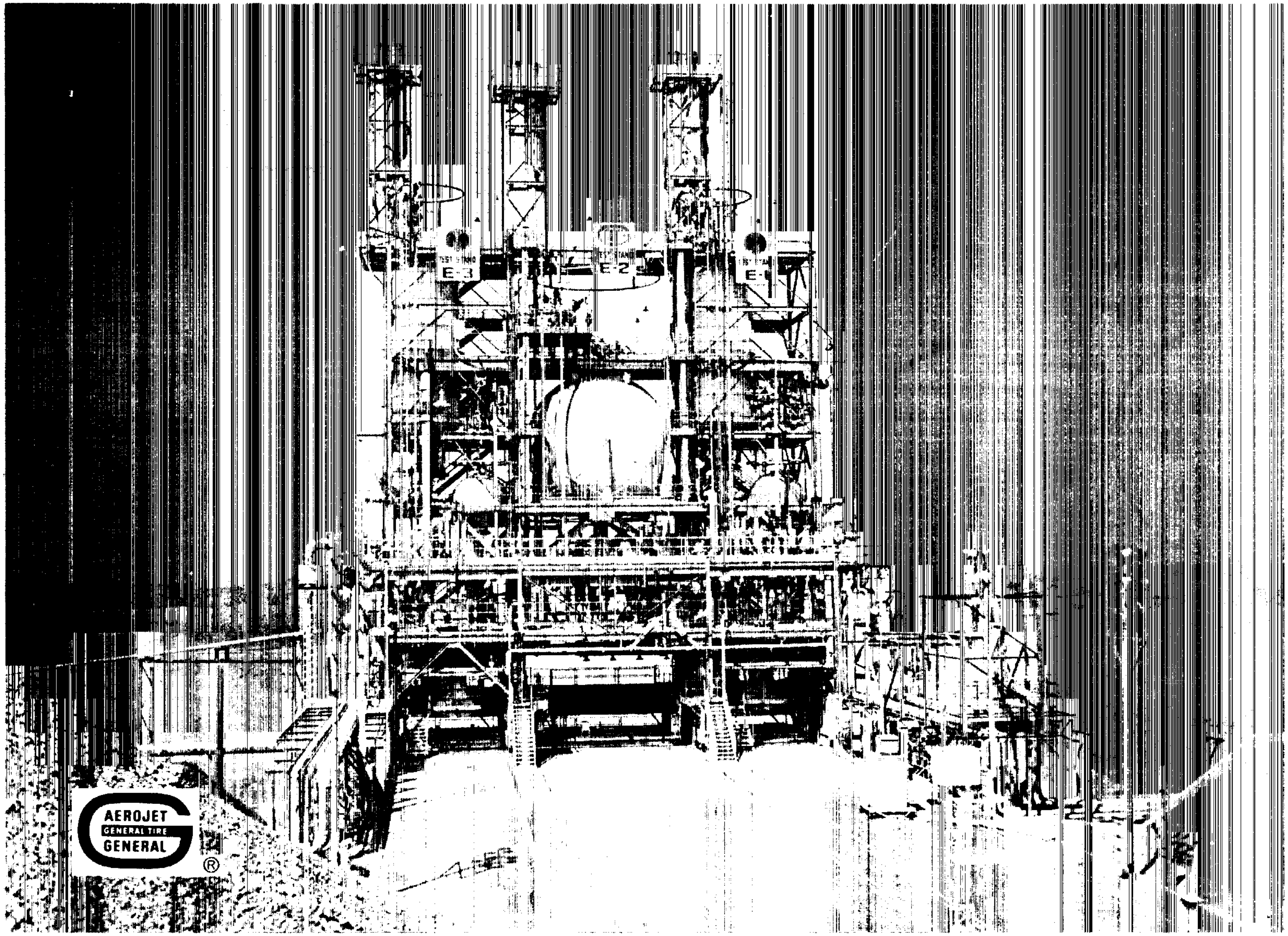

Figure 2. Test Stands E-1 and E-3

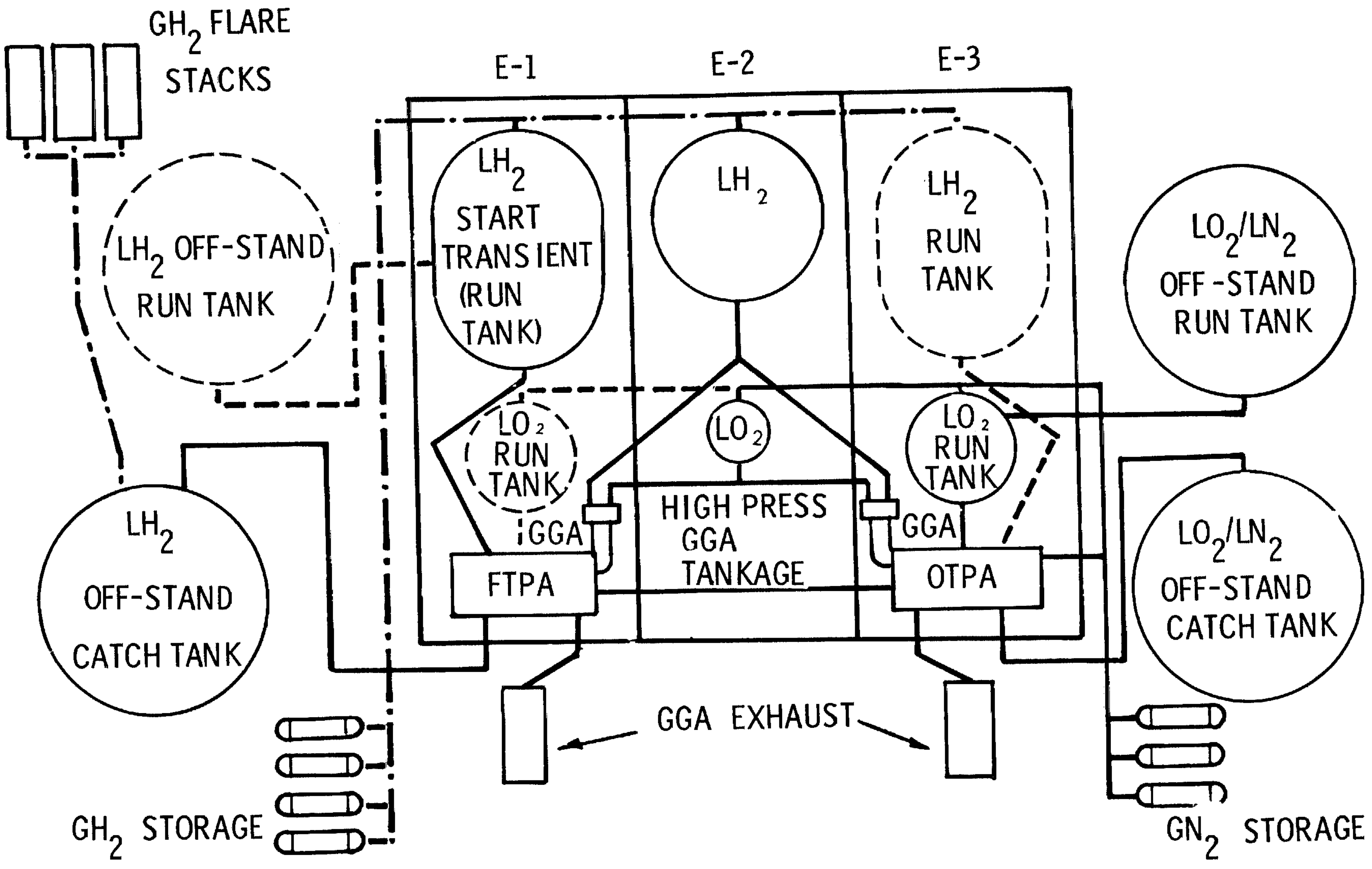

Figure 3. Schematic Diagram of Test Stands E-1 and E-3

The full-duration facility run tanks were not installed on the test stand because of the large quantity of propellants used and the physical size of the tanks (approximately 50-ft in diameter). For safety, the run tanks were placed several hundred feet from the stand in a protected area near other catch tanks of similar size. These off-stand run tanks were connected to the test stand tanks used for short duration start transient tests by 18-in. diameter interconnecting lines. Close coupled lines fed by the start transient tanks provided pump suction. Pump discharge was returned to the catch tank through a 12-in. diameter, high-pressure system, into a back-pressure flow-control valve, and then into an 18-in. diameter low-pressure system that empties into the catch tank. Because a turbine drive system also was required, both cold gaseous nitrogen and hot gas-generator drive systems were provided. During the actual testing, a preplanned computer program controlled the valve suction pressure, pump back-pressure, turbine speed, and main propellant flow. This control allowed a number of pump performance points to be obtained during each test.

A. DESIGN SAFETY CRITERIA

Safety considerations had a major influence on the test facility design and propellant storage and catch tanks.

The basic factor used to determine the propellant quantity-distance relationships was the quantity of fuel and oxidizer that could possibly mix and cause detonation equivalent to a prescribed weight of TNT. When this TNT equivalent was related to overpressure, it established the interline distance between the test stands, control rooms, tankage, and other structures. After an exhaustive investigation of available data based upon liquid hydrogen and liquid hydrogen-liquid oxygen combinations, an industry-established value of 60% TNT yield of one-fourth of the combined on-stand propellant was used as the design criteria for the most severe case.

For a more conservative approach to preclude this worst case, the design of a propellant flow control system with a response time of 5 sec was chosen; essentially, this rate allowed a maximum propellant accumulation equivalent to 5 sec of flow before emergency shutdown. This quantity of propellant was approximately 0.8% of the total tank volume and was equivalent to 10,290 lb of TNT. In comparison, one-fourth of the on-stand propellant volume for this test stand was equivalent to 299,000 lb of TNT. The 5-sec rule consisted of the time intervals needed to perform the following operations:

Tank outlet safety valve closure 1.5 sec
Manual reaction time to shutdown decision - 2.0 sec

A time equivalent also was calculated for the propellant isolated below the upper safety valve - - - - - - - - - 1.2 sec

Total Time 4.7 sec

Protective features of the facility design added to the conservatism of the 5-sec rule criteria. First, the propellant suction lines to overhead vessels were protected by two safety valves, each with a separate actuation system, and armored against fire and explosion damage. Second, concrete revetments (seen in Figure 1) separated the test stand and the off-stand run and catch tanks. Third, blast screens were installed around the test position to absorb energy and act as fire screens. Fourth, on-stand and off-stand Dewar vessels were designed with thick outer walls and structural supports for protection against a 10 psi overpressure blast.

B. CONTROLS SYSTEM

The extensive application of servo-controls to both gaseous and liquid flow systems was a unique aspect of the E-Zone facility design. The four basic controls systems are described briefly below.

1. Start Transient Tank Pressurization System

Command signals from a preset potentiometer on the firing console control the pressurization and vent valves for both the fuel and oxidizer tanks. A transducer, which is mounted to the tank, senses the gas pressure and originates a feed-back signal. The pressure and vent valves of the system are controlled by opposite polarity error signals. The pressurization valve opens when the command signal exceeds the feed-back signal, and the vent valve opens when the feed-back signal exceeds the command signal.

2. Gas-Generator Tank Pressurization

The fuel and oxidizer pressurization valves of the gas-generator tank are controlled by opposite polarity error signals in the same way that the start tank pressurization system valves are controlled.

3. Turbine Speed Control

For cold-gas tests, the valve that controls gas to the turbine drive receives a command signal from a programming device and feedback from a turbine speed transducer.

4. Q/N Constant Ratio Control System

Twelve-inch liquid flow control valves are used in both the hydrogen and oxygen systems to adjust the flow of propellants from the pump discharge to the catch tank. The valve control mechanism receives command signals from the turbine speed transducer through a Q/N ratio selector. Feedback signals also are received at the controller from the suction flowmeter. Because this circuit is a null-seeking loop,

$$\text{Error} = Q - KN = 0$$

Thus,

$$Q/N = K = \text{a constant.}$$

To preclude the possibility of operation under deadhead conditions, a 4-in. liquid flow control valve is used to by-pass the 12-in. control valve. The 4-in. valve receives command signals from a preset potentiometer at the firing console and feedback signals from the valve position indicator. In operation, this valve is opened to a predetermined position before the test and is sequenced to close after the test is completed.

IV. FACILITY ACTIVATION

A successful activation phase was considered essential before starting the actual tests to preclude the possibility of any serious malfunction resulting from any improper functioning of the new facilities. This was especially important because the test hardware was in its early stages of development. Additionally, this hardware was expensive and in some instances, it was "one-of-a-kind." During this activation phase, major emphasis was placed upon the checkout type of test, each of which was planned to simulate actual operating conditions as closely as possible. This technique provided a means for verifying the adequacy of design concepts which were either new or considered to be potential problem areas during the design phase.

Activation began with a planning phase during which the work was defined, test requirements and hardware interfaces were verified, and activation schedules were prepared. Key members of the activation team were briefed on design concepts as well as the actual test facility.

The facility activation sequence is briefly described below.

A. SYSTEM VERIFICATION

The construction contractor's work was verified during this phase. Each system was checked to ascertain possible problem areas such as improperly installed components, inadequate cleanliness, and improper line-component restraints.

B. ACTIVATION-ORIENTED CONTRACTOR WORK

The problem areas identified during system verification were corrected. New systems, previously identified as essential but purposely delayed to avoid issuing "change orders" to the basic construction contractors, were installed. Also, necessary interface modifications resulting from changes to either the test requirements or hardware configuration were accomplished.

C. COMPONENT FUNCTIONAL CHECKS

Basic components such as pumps, valves, and hoists were checked individually to verify their mechanical and electrical performance, timing, and adjustment. Each was subjected to several operational cycles to identify possible marginal characteristics under repeated operation.

D. CALIBRATIONS

Tank volume and liquid-level indicators, flowmeters, and instrumentation systems were calibrated. Control room instrumentation, facility controls, television monitors, and leak detectors were tested and cycled to demonstrate their readiness to monitor subsequent operations involving propellants.

E. INITIAL PROPELLANT SYSTEM CHILL-DOWN AND LOADING

An extensive analytical study was made of the large cryogenic propellant systems in Test Zone E to establish chill-down procedures.(1) This study contributed substantially to the facility design effort by providing thermal and stress analysis information obtained through the use of the Aerojet-developed thermal analysis computer. Basically, the study was concerned with techniques which were applicable to initial chill-down of large diameter cryogenic piping systems, and especially to liquid hydrogen and liquid oxygen propellant systems that utilized cryogenic boiloff gases at a predetermined rate for system chill-down. The principal areas of investigation were:

1. Various methods for chill-down of cryogenic piping systems.

2. Analysis of thermal stress at selected points in liquid hydrogen and liquid oxygen piping systems where cross-section transitions produce maximum thermal gradients.

3. Analysis of system chill-down characteristics when cold gaseous cryogens are used to reduce initial system temperatures, including time-equilibrium temperature predictions for systems exposed to various combinations of gas flow rate and initial temperature.

4. Analysis of cold-shock effects on critical cross-section transitions of the 19-in. liquid hydrogen catch line which were stabilized at equilibrium temperatures of 260°R, 160°R and 60°R.

5. Detailed thermal analyses of the liquid hydrogen and liquid oxygen propellant systems to determine the transient behavior of the system at selected changes in section. Stress analyses also were made for thermal conditions resulting from the most severe cold shocking anticipated for the system while flowing liquid hydrogen. Temperature extremes used for this analysis were from ambient to the recommended prechilled temperature achieved by a cold gas before introducing the cryogen to the system. As a result of this study, the large-diameter liquid hydrogen and liquid oxygen piping were fitted with bypass systems that used storage vessel boil-off gases to ensure proper chill-down.

---

(1) Schwartz, M. H., and Commander, J. C., Cooldown of Large Diameter Liquid Hydrogen and Liquid Oxygen Lines, NASA CR-54809, 20 April 1966

The rate of chill-down, system compatibility, purging cycles, line movements, fill-vent systems, instrumentation, and controls were the critical areas verified during the initial chill-down and tank loading operations.

Also, during the initial cool-down of the large piping systems and the large vessels (370,000-gal liquid hydrogen and 110,000-gal liquid oxygen/liquid nitrogen), the pressure and temperature instrumentation was displayed. In addition, television monitors and high-speed motion picture cameras were used to monitor strategic points where back-drop type grid and pointer networks were installed to measure actual line movement.

The initial chill-down of both the liquid hydrogen and liquid oxygen system revealed several locations at which either the anchors or other restraints and guides interfered with line movement. This condition was corrected by relocating the anchors or replacing them with piston-type dampers. A typical restraint of this kind is pictured in Figure 4.

For the final large line chill-down procedure, cold gas was used to prechill the line before the system was cold-shocked with liquid. The proposed method of backflowing chilled gaseous hydrogen or oxygen from the catch tank to the stand was discarded in favor of a more direct method of chilling the system by injecting liquid directly into the line at the test stand.

With increased testing rates, the bypass system could have been used advantageously to maintain the lines chilled between tests, utilizing the vessel boil-off gases otherwise vented to the atmosphere.

Operating experience with the hydrogen system showed that the calculated system prechill temperatures were conservative in that cold shocking was accomplished with exit temperatures less than those recommended without adverse effect. The only operating problem with the hydrogen system was the condensation of air on uninsulated bleed systems at locations where the lines discharged to a common vent header leading to a vent stack. Because of the limited test schedule remaining, this condition was not corrected by insulating the bleed systems; instead, drip pans were installed as an interim corrective measure. At the turbopump interfaces, the uninsulated lines were insulated temporarily with fiberglas batting and aluminum foil taped in place.

F. INITIAL HARDWARE INSTALLATION

The first test hardware to be installed in the test stand consisted of non-fireable mockup turbopump and gas generator assemblies. Installation of these mockups permitted the final interface connections and adjustments to be made without endangering prototype test hardware through either contamination or damage. After the adjustments were completed, the mockups were replaced by the actual test hardware and the instrumentation was installed. Figure 5 is a view of the stand at that time.

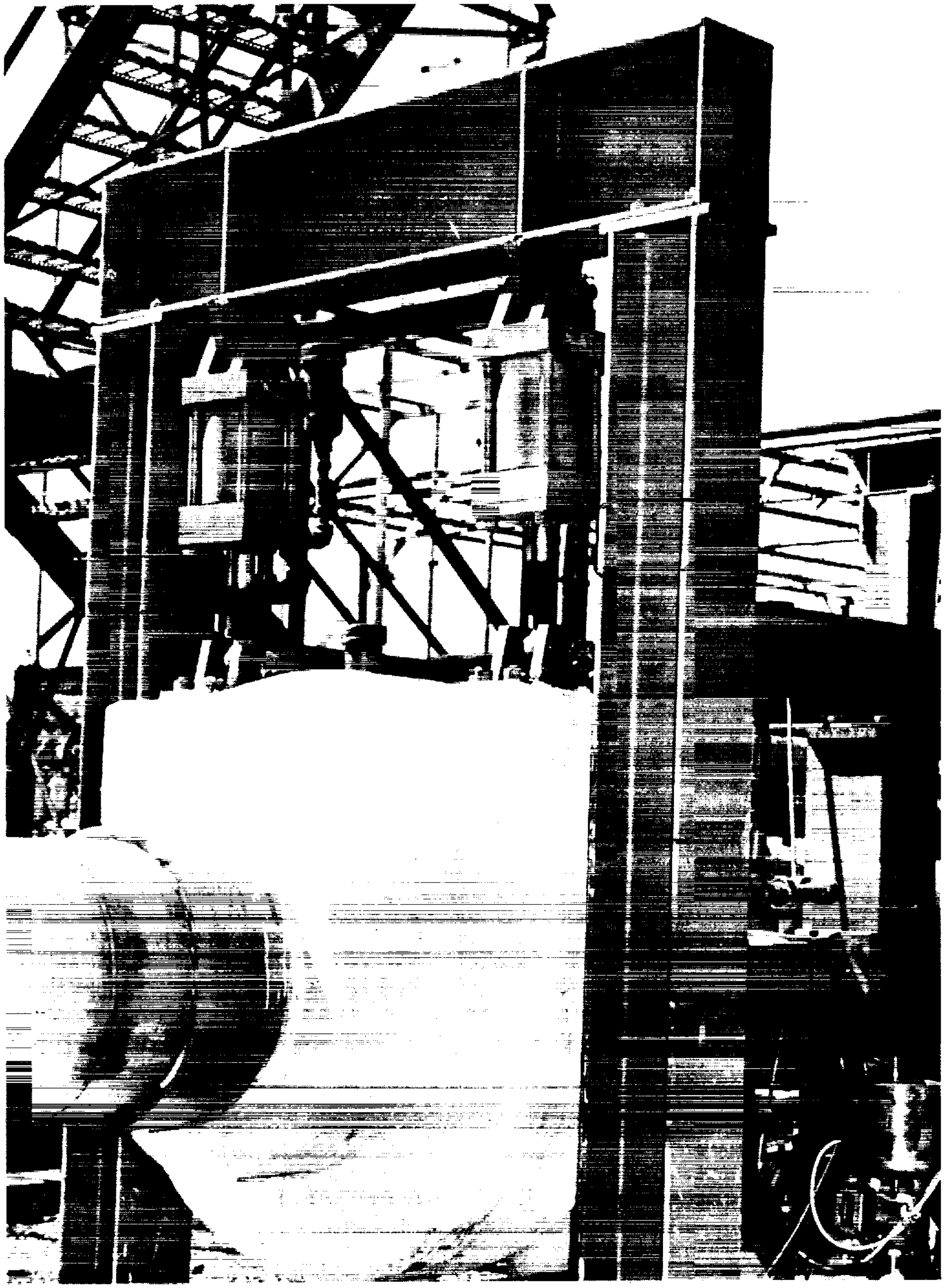

Figure 4. Typical Large Line Restraint System

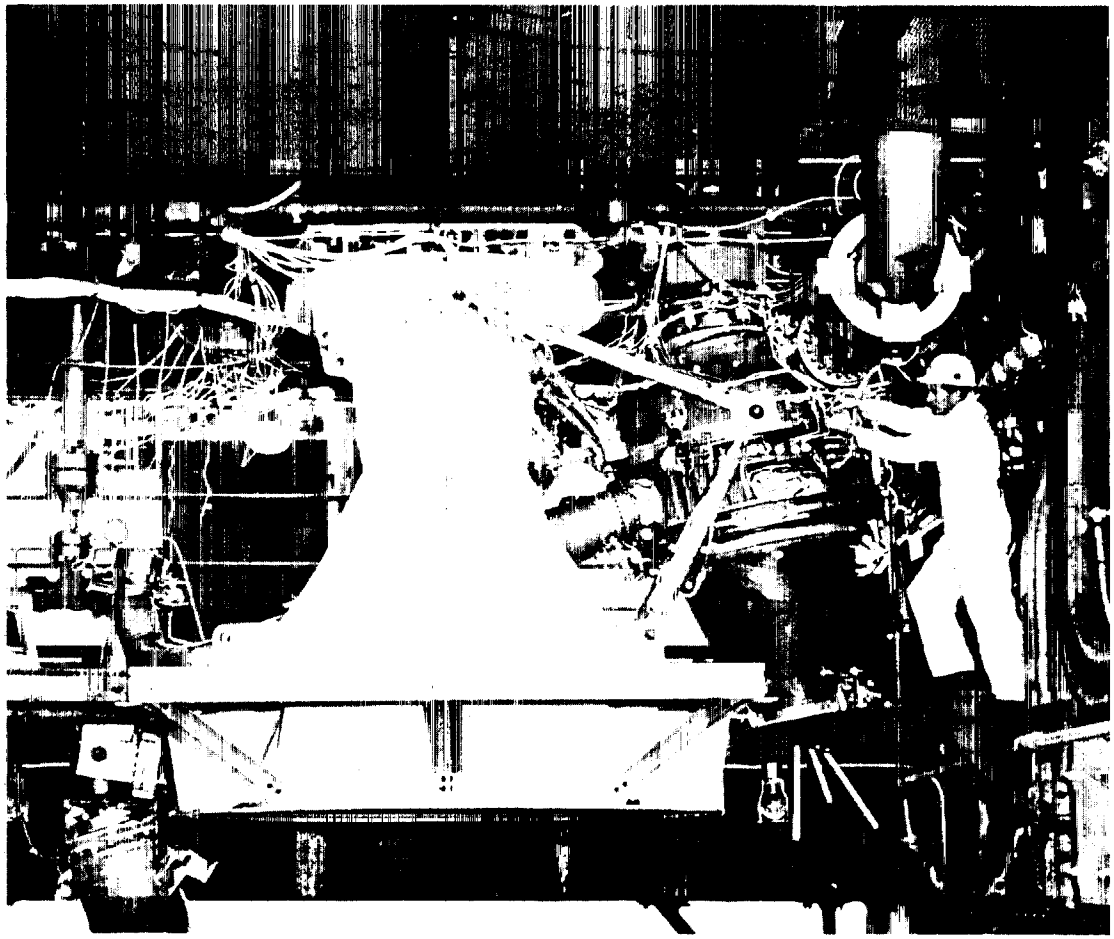

Figure 5. M-1 LO_2 Turbopump Installed on Test Stand E-3

G. OVER-ALL FACILITY-TEST HARDWARE SEQUENCING

A dry-run mechanical and electrical check was made to ensure that individual systems functioned properly. A dry run test then was made of the combined systems to adjust the over-all sequence of events to match the testing requirements. Particular emphasis was placed upon the servo-controlled systems.

H. TEST SIMULATION

Actual test conditions were simulated by performing both dry run and tank pressurization-outflow tests using a portable analog computer(2). This computer was programmed to verify the controller setup. It also subjected the test facility to various operating conditions of tank pressure, turbine speed, and turbopump Q/N by imposing inputs on the controller which simulated hardware operation. The permanent test controller embodied computing elements which allowed automatic test profile programming of the critical turbopump parameters.

A spool section was installed to replace the pump during the tank-outflow tests. Test Stand E-3 was equipped to test the OTPA and liquid nitrogen was used as the test fluid during the flow tests. Liquid hydrogen was used at Test Stand E-1, which had the FTPA test capability. Three flow tests were conducted at each stand to verify the over-all system operation and performance. In addition, information regarding limiting conditions was obtained. The following are the five major facility characteristics that were determined through these tests:

1. Control system stability
2. Gas flow characteristics
3. Chill-down characteristics and their effects upon the on-stand run vessel and the discharge lines
4. Propellant line water-hammer, temperature change, and pressure drop characteristics
5. Operational characteristics of all the piping components as well as the components of the run and catch vessels.

Start and shutdown transients, steady-state operating and back-pressure control valve cycling conditions were simulated during the flow tests. Back-pressure control valve cycling consisted of a valve position variation of ± 2% actuated at 2 cps and then at 4 cps. A closed-loop flow-control system

---

(2) Garcia, L. W., Friedland, H., and Lehmburg, A. E., Servo Control Systems and Analog Simulation in E-Zone, Aerojet-General Report No. 880-61, 10 March 1966

was incorporated for the second test. This system utilized a programmed voltage input to simulate pump speed and a feed-back signal from the flowmeter, completing the Q/N loop. For the third test, an open-loop flow-control system was used to open the valve in 25% increments. This test verified the system step-response as well as flowmeter operation during rapid changes in liquid flow.

This dynamic simulation of the servo-control systems and the successful outflow tests provided a high degree of confidence in the total facility capability prior to the first hot test firing.

V. PROGRAM REDIRECTION AND PHASEOUT

The M-1 Program effort was redirected by the NASA during the activation phase because of funding limitations which affected the extent to which the facilities ultimately would be used. The redirected effort, termed the "Phaseout Plan", was programmed to allow collection of the greatest amount of data possible using existing hardware and within the scope of the limited funds. The requirement for the large, long-duration, off-stand run vessels was eliminated together with the requirement to test the Oxidizer Turbopump Assembly (OTPA) with both liquid nitrogen and liquid oxygen; only liquid nitrogen testing was required. The requirement for combined OTPA and FTPA tests was deleted.

Based upon the redirected planning, the approach to facilities activation was altered from a parallel effort at Test Stands E-1 and E-3 to a sequential approach. The first effort was to provide a cold gaseous nitrogen drive for the OTPA and to pump liquid nitrogen from the smaller run tank on Test Stand E-3. Next, Test Stand E-1 was activated and operated for FTPA testing using cold gaseous nitrogen drive to pump liquid hydrogen from the on-stand run tank. Then, Test Stand E-3 was activated and operated to test the gas generator, and the gas generator subsequently was used to drive the OTPA. A similar sequence was followed for the FTPA at Test Stand E-1. The primary test objectives for this test series were:

A. Develop the M-1 turbopump utilizing a gas generator as the driving media.

B. Determine the compatibility of the test facility and the turbopump/gas generator combination.

1. Verify fluid flow, pressure and temperature characteristics of the cryogenic propellant systems.

2. Verify gas dynamic characteristics of the pressurization systems and the ability of the servo-operated valves to control pressurization, turbine speed (cold gas tests), and back pressure-flow control.

3. Determine integrity of facility systems such as propellant lines, components, and structural mounts, when exposed to the test environment conditions.

4. Verify performance or adequacy of auxiliary systems and procedures, such as purge, dehydration, and leak check.

5. Verify performance of 18-in. flowmeter.

6. Test each of the four major hardware configurations:

   a. Oxidizer turbopump - cold gas (N_2) drive
   b. Oxidizer turbopump - gas generator drive
   c. Fuel turbopump - cold gas (GN_2) drive
   d. Fuel turbopump - gas generator drive

A Critical Experiment Review was conducted with cognizant engineering managers to review all aspects of the imminent turbopump assembly test phases as described in Item 6 above. This review considered test hardware readiness, test facility readiness, test objectives and requirements, malfunction (mode of failure analysis), and areas of vulnerability. Before starting each phase, all action items generated as a result of this review had to be answered and justified.

VI. PROBLEMS AND SUCCESSES

The brevity of this report precludes a discussion of all of the problems that were encountered and solved and the successes experienced during the activation and initial operation of E-Zone. Nevertheless, some of the more significant aspects are discussed in subsequent paragraphs.

A. SYSTEM CLEANLINESS

Industry remains plagued with system cleanliness even after 15 years of rocket test facility construction experience. As each new test facility is designed and constructed, the requirements for system cleanliness increase, cleaning methods improve, and specifications become more rigorous. Yet, extremely stringent inspection and increased awareness on the part of construction contractors to the increased precautions and improvements did not eliminate cleanliness problems. Several major E-Zone systems required recleaning by the construction contractor.

The critical cleaning areas were the liquid oxygen systems, the associated gaseous nitrogen systems, and the hydraulic actuation systems. Improper use of lubricants by the construction contractor, particularly in the liquid oxygen systems, was one of the major problems. In recleaning these systems, black light was used extensively for visual inspection in conjunction with the conventional wipe-sample millipore tests. Detailed, step-by-step procedures were formulated for system inspections. These procedures included the determination of contaminated areas, recleaning operations, and subsequent acceptance inspection. The activation crew played an important role in surveillance of these operations. For the hydraulic system, procedures were developed for filling the reservoir, checking oil contamination, and flushing the pump and system. Flushing blocks were installed in place of the servovalves. Pydraul F-9 was used as the hydraulic actuation fluid because of its close proximity to the cryogenic systems and for its compatibility with liquid oxygen.

B. PIPING RESTRAINTS AND HARDWARE INTERFACING

The criteria for line restraints became more complex as the activation phase progressed because of Aerojet-General's and industry's experience with large cryogen systems at other test stands, the results of special cryogenic system cool-down studies, and increased interface load and dynamic effect restrictions.

The restraints were designed to isolate or minimize those loads which could be transmitted to the test hardware from the facility piping system. The restraints also were designed to take out loads from the facility piping to prevent overstressing of the valve flanges and the vessel nozzles.

To provide a fail-safe mode, the restraint criteria was based upon anticipated hardware malfunction and its effect upon the test stand piping. This criteria also considered the effect of higher propellant velocities which could result from rapid back pressure, flow control valve closure, and the rapid TPA flow transients. Conventional designs utilizing pipe guides, rollers, and spring hangers were used to satisfy these criteria. Hydraulic-cylinder-type dampers were used to permit piping system freedom of movement for slow cryogenic effects but restrain higher velocity dynamic effects.

"Back-stop" type restraints were used for fail-safe line protection. These restraints permitted necessary but limited line movements to prevent overstressing and also provided a positive restraint at the end of the limit. They also served to minimize damage from line whipping in the event of a complete line rupture. Back-stop restraints were installed at most of the hardware interfaces and at key locations along piping runs where contractions in piping length caused by cryogenic temperatures would be guided to eliminate the possibility of overstressing the material.

In addition to isolating the loads imposed by the facility piping, both the restraints and the piping system had to be flexible enough to provide work space and movement for hardware installation and component replacement without major disassembly of the system. And, the restraints and piping also had to accommodate the dynamic movement of the hardware during the test.

Bellows sections and hinged gimbal joints were used for flexibility in the 12-in. discharge line and the 18-in. suction and return line to the catch tank. The factors considered in establishing the qualification procedure for these components included the demonstration of spring rate, combined pressure-extension and compression cycling, dynamic vibration, proof, leak, and burst testing.

Relatively thin-walled stainless steel tubing (2-in. in diameter for liquid oxygen and 3-in. in diameter for liquid hydrogen) was used in the high pressure, 2150 psig, gas-generator system piping. A number of bends was provided to assure the flexibility needed to satisfy load limits at the gas-generator valve inlet interface.

Conventional pump testing and checkout procedures using break-away torque checks were established to identify any unusual loading conditions at the various pump interfaces which could have developed during handling and installation. These checks were performed at the following intervals:

1. Prior to removing the TPA from the transporter
2. After the TPA was mounted to the test stand
3. After the suction lines were connected
4. After the discharge lines were connected
5. After the turbine exhaust duct was connected
6. After pump chill-down (this was a remote torque check using a gaseous nitrogen spin).

The restraint system designed for the gas-generator discharge manifold (pentapus) piping was one of the most critical. This system was closely coupled, weighed approximately 6 tons and was subjected to a large and rapid temperature change. Before testing, the turbine inlet end of this line was very cold because of cryogenic bleed-in of the pump, which cold-soaked the piping for several hours. Immediately after the test began, hot gases at approximately 1200°F, flowed through this line. Consequently, a line movement of approximately 3/4-in. was necessary to preclude buildup of damaging stresses. Isolation of the piping load at the turbine inlet manifold was of major concern. To permit this movement and yet provide the necessary support and limited movement, a restraint system was designed which incorporated a system of heavy slotted plates with pin-type rollers inserted in the slots to guide the movement.

Alignment of this system to preclude excessive flange loading and to ensure the mating of the pipe flanges to the manifold without leakage was a considerable operating problem. The roller-restraint system design itself alleviated the problem considerably, and, when combined with a procedure for flange make-up using dial indicators and satisfying rigorous bolt torquing requirements, it solved this problem.

C. HYDROGEN CATCH-TANK VENTING

Turbopump assembly tests were made by pumping propellant from a run tank to a catch tank as described earlier. During these tests, venting of liquid hydrogen was necessary because of the liquid hydrogen flash-off as the propellant was being pumped from the run tank to the catch tank. The hydrogen flash-off resulted from the heat rise in the pump, heat leaks in the system, and other system heat gains in the back-pressure control system; consequently, catch tank venting was necessary to preclude excessive buildup of the back-pressure. Flare-stack burning was considered the most practical method of disposing of the gas, and a three parallel flare-stack configuration as shown in Figure 6 was selected. A hydrogen gas flow of 300-400 lb/sec was expected, and a flow of this volume through one vent stack would have been excessive. Then, too, the torch from a single flare stack would have produced flame heights that could restrict the air traffic over E-Zone, which is directly below the landing traffic pattern for an Air Force Base.

The flare stacks were of the John Zink design with a molecular seal (nitrogen purge) to prevent air from flowing back into the vent line.

The three parallel vent stacks operated satisfactorily at high vent rates; however, at the end of the test when the vent rates were low detonations occurred in two of the three stacks. Hydrogen gas also burned in the vent line upstream of the flare stacks.

From an analysis of the problem it was concluded that all of the hydrogen gas was venting through only one of the flare stacks at low flow rates. Thus, air was aspirated into the otehr two hot flare stacks where it combined with residual hydrogen and detonated. Initially, an attempt was made to eliminate the aspiration by increasing the nitrogen purge to the molecular seal; however, excessive quantities of nitrogen were required to completely eliminate the detonations and the burning. When this failed, the vent piping system was significantly modified by installing 12-in. diameter, swing check valves immediately upstream of flare stacks 2 and 3. Subsequent operation with this configuration proved highly successful at all flow rates.

D. TURBINE OVERSPEED PROTECTION AND HOT GAS RELIEF

Extreme conditions can occur in a new test facility, especially where the initial tests are made with new hardware, that can impose severe perturbations upon the test hardware. For this reason, fail-safe systems were incorporated into the facility wherever possible for maximum protection of the hardware.

One such extreme condition is turbine overspeed, which usually results from excessive power applied to the turbine or a sudden unloading of the pump. Severe hardware damage can result if this condition is not corrected immediately. Normally, electronic overspeed trip (OST) units designed by

Figure 6. Hydrogen Vent Flare-Stacks of Test Stand E-1

Aerojet-General are used to protect against this condition. These very sensitive units initiate a rapid response-shutdown signal in the event that the turbine speed exceeds a predetermined limit. However, the use of only these units was not considered adequate for the M-1 turbopump assembly testing because of the large line volume in the manifold connecting the gas generator to the turbine. The OST shutdown signal commands closure of the gas generator valve, however, the large volume of gas downstream of this valve could continue to cause the overspeed condition for a significant period of time after valve closure. This manifold configuration, called the "pentapus" because of its five-nozzles, was needed to simulate the engine hot gas interconnecting line.

The problem of effecting high-speed relief of the gas volume in the pentapus was resolved by installing a blow-off cap on the bottom pentapus nozzle. In operation, signals from the OST simultaneously commanded closure of the gas-drive valve, or gas generator valves, and actuated a specially-designed, shaped explosive charge, which completely severed the blow-off end cap from the flange on the pentapus. The relief gas was directed into a 24-in. exhaust gas carry-off duct. Screen mesh was packed into the end cap assembly to minimize the increased volume in the blow-off cap and to provide acoustical dampening. It was also necessary to externally cool the explosive charge ring using a gaseous nitrogen purge because of its close proximity to the hot-gas flow. Response time design criterion for this system was an upstream pressure decay from 200 psi to zero in 0.06 sec. Several programmed OST checkout tests were conducted and the blow-off cap device performed satisfactorily. It also performed satisfactorily in actual tests during which overspeed occurred.

E. HYDROGEN FLOW RATE DISCREPANCY

It is axiomatic in rocket engine testing that when actual test performance results are lower than the predicted hardware performance, a test facility problem is suspected.

During the testing of a fuel turbopump assembly, the liquid hydrogen flow rate measured by the 18-in. turbine-type flowmeter, indicated that the flow rate was approximately 17% lower than the calculated rate based upon predicted pump performance. The accuracy of the flowmeter was suspected as the cause of this difference, and its error was confirmed by the flow data from the tank liquid-level system. The flowmeter used in the test had been calibrated in water because calibration in liquid hydrogen at rated flow conditions was impossible; high-volume hydrogen calibration facilities did not exist. An estimate of meter factor resulting from the shift from water to cryogenic calibration was made based upon experience. It was found, however, that the shift in water-to-propellant calibration could not account for the 17% discrepancy; consequently, the flowmeter was judged to be faulty. The meter was removed at the conclusion of the FTPA test program, disassembled, and inspected. Excessive wear and discoloration indicated that the secondary bearings had rubbed against the motor hub. The meter also was given a turning torque test at liquid nitrogen temperature and exhibited in this test a drag sufficient enough to cause a 15% to 20% decrease in rpm.

The experience gained in large-size, cryogenic flowmeter technology during the design, activation, and operation of the E-Zone facilities was the subject of a previously published report.(3)

F. FUEL TURBOPUMP COOL-DOWN AND BLEED-IN PROCEDURE

In addition to the normal problem of excluding air from hydrogen systems prior to hydrogen bleed-in, a requirement was established for an extensive dehydration procedure for the FTPA. This procedure was adopted to preclude any possible icing in the critical seal and bearing clearance areas. Generally, this procedure required a heated gaseous nitrogen purge at 50 psi until a gas sample at the pump bearing cavity lift-off seal indicated a -57°F dew point. This was followed by a heated gaseous helium purge of 140°F at 50 psi, which was continued until a gas sample showed no trace of nitrogen. This purge was then followed by a gaseous hydrogen sweep purge which was recycled approximately 25 times from 25 psi to approximately 2 psi until a chromatograph analysis of the gas indicated acceptable limits. At this point, the system was considered acceptable for liquid hydrogen bleed-in.

Initially, the hydrogen bleed-in procedure called for a cold gas pre-chill before the system was cold-shocked with liquid hydrogen. Cold gas for the chill-down was obtained from the propellant vessel boil-off. This procedure proved to be unnecessarily slow and a more direct method of introducing liquid hydrogen into the 18-in. pump suction line through a 2-in. bypass valve was adopted. This new procedure proved to be quite satisfactory.

G. CALIBRATION OF PUMP-SHAFT THRUST MEASURE SYSTEM

Static calibration of the thrust measuring system mounted within both the fuel and oxidizer turbopumps was required for correlation of the readout with the calibrated load forces. This system was calibrated on the stand by removing the turbine exhaust duct and installing an external hydraulic cylinder and load cell to the shaft. The output load of the hydraulic cylinder was controlled by a servo-control system which was closed-looped with one bridge of the thrust measuring system. This external servo-control system was mounted on the hydraulic cylinder and was capable of applying force to the shaft in both positive (toward turbine exit) and negative (toward pump suction direction) directions. This system was calibrated three times in 5000 lb increments at ambient conditions with loads ranging from zero to +25,000 lb and from zero to -15,000 lb. Breakaway torque measurements were also taken at each of the calibration increments.

The calibration procedure was repeated with the turbopump at cryogenic temperature. Breakaway torque measurements were not made, however, because of the safety hazard to personnel who would have had to make the measurements in close proximity to locations of potential cryogenic liquid leakage.

---

(3) Deppe, G. R., Large-Size Cryogenic, Turbine-Type Flowmeter Technology, NASA CR-54810, 1 June 1966

During turbopump operation, the net axial shaft thrust (bearing load) was monitored by strain gage readout of the shaft thrust measuring system. This measurement was considered a key shutdown parameter in providing turbopump protection at extreme conditions. In several tests, it was the parameter that effected shutdown.

H. LARGE COMPONENT HANDLING

Increased attention during the facility design effort to the need for removal of the large facility components could have contributed to more efficient test operations. This was especially ciritcal within the close work spaces of the test stand. Maintenance and the periodic inspection of components such as the 18-in. flowmeters and ball valves required the time-consuming removal of these components. Fortunately, these units proved to be highly reliable, and their removal for maintenance and calibration was held to a minimum.

VII. CONCLUSIONS

Engine hardware that meets performance expectations during the early stages of a test program exerts a significant influence upon the performance of the facility-testing operations of any program. This is particularly true if no serious in-test malfunctions occur. A substantial contribution to this successful over-all program performance is made by special facility design features, emphasis upon system performance demonstrations during activation, and alert, knowledgeable test operations. The following successfully achieved factors tend to bear out this conclusion:

A. The number of tests originally scheduled to obtain the necessary performance data was reduced by 25%. This reduction was possible because an increased number of data points were obtained during each test.

B. Rapid excursions to limiting conditions (i.e., pump stall) were possible within the 10 sec to 15 sec test durations. The ability to achieve this control was due to the excellent performance of the flow control systems.

C. Various hardware configurations were efficiently adapted to the test stand.

D. Increased operational efficiency resulted in improved propellant "use factors", ratio of propellant pumped to total propellant delivered to the facility. This was a significant cost factor as approximately 1.75 million gallons of liquid hydrogen as well as 5500 tons of liquid oxygen and liquid nitrogen were consumed. The total propellant costs were in excess of one million dollars.

E. Testing was accomplished without sustaining any significant damage to either the test hardware or the test facility.

BIBLIOGRAPHY

Deppe, G. R., Large-Size Cryogenic, Turbine-Type Flowmeter Technology, NASA CR-54810, 1 June 1966.

Garcia, L. W., Friedland, H., and Lehmburg, A. E., Servo-Control Systems and Analog Simulation in E-Zone, Aerojet-General Report No. 8800-61, 10 March 1966.

Schwartz, M. H. and Commander, J. C., Cooldown of Large Diameter Liquid Hydrogen and Liquid Oxygen Lines, NASA CR-54809, 20 April 1966.

AEROJET GENERAL TIRE GENERAL
AEROJET-GENERAL CORPORATION
SACRAMENTO • CALIFORNIA

SACRAMENTO PLANT

11 October 1967
9410D:5525:SLS:tf

National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

Attention: Mr. William A. Tomazic
M-1 Project Manager
M-1 Engine Project Office

Subject: Technology Report, Activation and Initial Test Operations
Large Rocket Engines - Turbopump Test Facilities
(NASA CR-54824)

Dear Mr. Tomazic:

The subject report (Enclosure 1) is forwarded for your information.

Additional reports have been distributed as delineated in the subject report.

Very truly yours,

AEROJET-GENERAL CORPORATION

J. Franyovich for

S. L. Sachs, Manager
Documentation
M-1 Program

Encl: (1) Technology Report, Activation and Initial Test
Operations Large Rocket Engines - Turbopump
Test Facilities

A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY

DISTRIBUTION LIST FOR REPORT NO. CR-54824

W. A. Tomazic (5 copies)
NASA
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135
Mail Stop 500-305

W. F. Dankhoff (1 copy)
Mail Stop 3-13

Robert Godman (1 copy)
Mail Stop 3-6

William Rowe (1 copy)
Mail Stop 60-6

H. H. Hinckley (1 copy)
Mail Stop 500-210

Dan Williams (1 copy)
Mail Stop 501-1

Lewis Library (2 copies)
Mail Stop 60-3

Al Ross (1 copy)
Mail Stop 100-1

Office of Reliability &
Quality Assurance (1 copy)
Mail Stop 500-203

Patent Counsel (1 copy)
Mail Stop 77-1

Technical Information Division (1 copy)
Mail Stop 5-5

Major E. H. Karalis (1 copy)
AFSC Liaison Office
Mail Stop 4-1

NASA Scientific & Technical
Information Facility (6 copies)
Technical Information Abstracting
and Dissemination Facility
Box 5700
Bethesda, Maryland

Library (1 copy)
NASA-Ames Research Center
Moffett Field, California 94035

Library (1 copy)
NASA
Flight Research Center
P.O. Box 273
Edwards AFB, California 93523

Library (1 copy)
NASA
Goddard Space Flight Center
Greenbelt, Maryland 20771

Library (1 copy)
NASA
Langley Research Center
Langley Station
Hampton, Virginia 23365

Library (1 copy)
NASA
Manned Spacecraft Center
Houston, Texas 77058

Aeronautical Systems Division (1 copy)
Air Force Systems Command
Wright Patterson Air Force Base
Dayton, Ohio 45433

J. W. Thomas, Jr. (5 copies)
I-E-E
NASA
George C. Marshall Space Flight Center
Huntsville, Alabama 35812

Library (1 copy)
George C. Marshall Space Flight Center
NASA
Huntsville, Alabama 35812

NASA Headquarters (1 copy)
Attn: RPX/W. W. Wilcox
Washington, D. C. 20546

Library (1 copy)
NASA
Western Operations Office
150 Pico Boulevard
Santa Monica, California 90406

Library (1 copy)
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91103

A. O. Tischler (1 copy)
NASA
Code RP
Washington, D. C. 20546

F. C. Schwenk (1 copy)
NASA
Code NPO
Washington, D. C. 20546

Dr. E. B. Konecci (1 copy)
National Aeronautics and Space Council
Executive Office of the President
Executive Office Building
Washington, D. C.

H. V. Main (1 copy)
Air Force Rocket Propulsion Laboratory
Edwards Air Force Base
Edwards, California

T. Iura (1 copy)
Aerospace Corporation
2400 East El Segundo Blvd.
P. O. Box 95085
Los Angeles, California 90045

Pratt & Whitney Aircraft Corporation (1 copy)
Florida Research & Development Center
P.O. Box 2691
West Palm Beach, Florida 33402

Rocketdyne (1 copy)
Library Dept. 586-306
Division of North American Aviation
6633 Canoga Avenue
Canoga Park, California 91304

Arnold Engineering Development Center (1 copy)
Arnold Air Force Station
Tullahoma, Tennessee

Dr. K. Boyer (1 copy)
Los Alamos Scientific Laboratory
CMF-9
P.O. Box 1663
Los Alamos, New Mexico

Chemical Propulsion Information Agency (1 copy)
John Hopkins University
Applied Physics Laboratory
8621 Georgia Avenue
Silver Spring, Maryland