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ALTITUDE TESTING OF THE J-2 ROCKET ENGINE IN PROPULSION ENGINE TEST CELL (J-4) (TESTS J4-1554-27 THROUGH J4-1801-01)

N. R. Vetter, D. E. Franklin, and W. W. Muse
ARO, Inc.

November 1967

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LARGE ROCKET FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

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FOREWORD

The work reported herein was sponsored by the National Aeronautics and Space Administration (NASA), Marshall Space Flight Center (MSFC), under System 921E, Project 9194.

The results of the tests presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Contract AF40(600)-1200. Program direction was provided by NASA/MSFC; engineering liaison was provided by North American Aviation, Inc., Rocketdyne Division, manufacturer of the J-2 rocket engine, and by Douglas Aircraft Company, manufacturer of the S-IVB stage. The testing reported herein was conducted during the period from April 18 through July 6, 1967, in Propulsion Engine Test Cell (J-4) of the Large Rocket Facility (LRF) under ARO Project Nos. KA1554 and KA1801. This manuscript was submitted for publication on August 11, 1967.

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This technical report has been reviewed and is approved.

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ABSTRACT

Five test periods which included 16 starts of the Rocketdyne J-2 Rocket Engine were conducted at pressure altitudes from 95,000 to 108,000 ft in Test Cell J-4. The tests were Saturn S-V/S-II start transient investigations using a flight configuration J-2 engine (S/N J-2052) and S-IVB battleship stage. Firing durations were programmed for 5 or 30 sec, and the accumulated firing time was 206.1 sec. These tests completed the first series of full-scale S-V/S-II start transient investigation testing to be conducted at pressure altitudes in excess of 95,000 ft.

CONTENTS

APPENDIXES

NOMENCLATURE

A	Area, $in.^2$
ASI	Augmented spark igniter
ES	Engine start; time at which helium control and ignition phase solenoids are energized
GG	Gas generator
GGOT	Gas generator outlet temperature
MOV	Main oxidizer valve

STDV Start tank discharge valve

t_o Time at which opening signal is applied to start tank discharge valve solenoid

VSC Indication of time duration of engine vibration measurement in excess of 150 g

SUBSCRIPTS

e Exit

t Throat

SECTION I
INTRODUCTION

Testing of the J-2 engine (S/N J-2052) using the S-IVB battleship stage has been in progress since July 1966 (Refs. 1, 2, and 3) at the Arnold Engineering Development Center (AEDC). The tests reported herein, J4-1554-27 through J4-1554-30 and J4-1801-01, were conducted during the period April 18, 1967 through July 6, 1967 in the Propulsion Engine Test Cell J-4 (Fig. 1) of the Large Rocket Facility (LRF). Although this is a continuing program, the ARO Project Number was changed from KA1554 to KA1801 for administrative purposes. Sixteen engine starts were made at pressure altitudes ranging from 95,000 to 108,000 ft. The accumulated firing time was 206.1 sec.

These tests were the first series of Saturn S-V/S-II start transient investigations to be conducted during the present J-2 test program. Testing conditions included worst-case gas generator conditions and a determination of gain factors for various engine start conditions.

SECTION II
APPARATUS

2.1 TEST ARTICLE

The test article was a J-2 rocket engine (Fig. 2) designed and developed by Rocketdyne Division of North American Aviation, Inc. This engine uses liquid oxygen and liquid hydrogen as propellants and has a thrust rating of 225,000 lb_f at an oxidizer-to-fuel mixture ratio (O/F) of 5.5. A S-IVB battleship stage (Refs. 1, 2, and 3) was used only as a source of propellant for the engine since the fluid dynamics upstream of the engine-vehicle interface do not simulate the S-II stage.

Major engine components at the beginning of this test period are shown in Table I. Major engine configuration changes accomplished during this test period are presented in Table II.

The J-2 rocket engine (Ref. 4 and Fig. 3) features the following major components:

1. Regenerative fuel-cooled, tubular-wall, bell-shaped thrust chamber (Fig. 4) with a throat area (A_t) of 170.4 in.^{2} and an expansion ratio (A_e/A_t) of 27.1.

2. Concentric-orificed, porous-faced thrust chamber injector.
3. Augmented spark igniter assembly to which fuel and oxidizer are routed and ignited at engine start to provide ignition energy for main chamber propellants.
4. Fuel turbopump which is composed of a two-stage turbine assembly, an inducer, and a seven-stage, axial-flow pump assembly.
5. Oxidizer turbopump which is composed of a two-stage turbine assembly and a single-stage centrifugal pump.
6. Motor-driven, propellant utilization valve which bypasses liquid oxygen from the discharge to the inlet side of the oxidizer pump to vary mixture ratio to provide simultaneous depletion of propellants.
7. Oxidizer and fuel bleed valves to allow trapped gas to be expelled from the engine propellant system before engine start.
8. Gas generator which consists of a combustion chamber, a propellant control valve, and an injector assembly. The gases produced by the gas generator are routed to the fuel and oxidizer turbines in series and are exhausted into the thrust chamber at an area ratio (A/A_t) of approximately 11.
9. Pneumatically actuated oxidizer turbine bypass valve. At engine start, the oxidizer turbine bypass valve is fully open, routing a large portion of fuel turbine discharge gas directly to the thrust chamber to obtain the desired oxidizer-to-fuel turbine spinup relationship. During engine acceleration to main stage, the valve is closed (the valve gate contains a flow nozzle which provides a turbine power balance mechanism).
10. Pneumatically actuated, start tank discharge valve permits release of the start tank gaseous hydrogen for turbine spinup during the engine start cycle. The helium control bottle, located within the hydrogen start tank, provides a high pressure helium supply to the engine pneumatic control system.
11. Pneumatically actuated butterfly-type main fuel valve.
12. Two-stage butterfly-type main oxidizer valve. The first-stage actuator positions the valve at the 14-deg position to obtain initial main chamber ignition; the second-stage actuator ramps the valve full open to accelerate the engine to main-stage operation. The valve vane is pivoted off-center, providing hydraulic torque in the closing direction at the 14-deg position.

13. Pneumatic control package which controls all pneumatically operated engine valves and purges.

14. Electrical control assembly which provides the electrical logic required for proper sequencing of engine components during operation.

15. Primary and auxiliary flight instrumentation packages which environmentally protect and contain sensors required to monitor critical engine parameters.

2.2 TEST CELL

Propulsion Engine Test Cell (J-4) (Ref. 5) is a vertically oriented test unit designed for static testing of liquid-propellant rocket engines and propulsion systems at pressure altitudes of 100,000 ft. The cell consists of four major components (1) test capsule, 48 ft in diameter and 82 ft in height, situated at grade level and containing the test article; (2) spray chamber, 100 ft in diameter and 250 ft in depth, located directly beneath the test capsule to provide exhaust gas cooling and dehumidification; (3) coolant water, steam, nitrogen (gaseous and liquid), hydrogen (gaseous and liquid), liquid oxygen and gaseous helium storage and delivery systems for operation of the cell and test article; and (4) control building, containing test article controls, cell controls, and data acquisition equipment. Exhaust machinery is connected with the spray chamber. This machinery maintains the test capsule at a pressure altitude of approximately 60,000 ft during the test period, with the exception of engine firing. During firing operations, the facility steam ejector, in conjunction with the exhaust machinery, provides a pressure altitude of 100,000 ft in the test capsule. A detailed description of the test cell is presented in Ref. 1.

The S-IVB battleship stage was installed on a support stand within the test capsule (Fig. 5), orienting the J-2 engine vertically downward on the centerline of the diffuser-steam ejector assembly. This assembly consists of a 20-ft-diam diffuser duct, 150 ft in length, containing a centerbody steam ejector. At the inlet to the diffuser is a 13.5-ft-diam diffuser insert, directly above which is a gaseous nitrogen annular ejector. The annular ejector is provided to suppress steam recirculation into the test capsule during steam ejector shutdown. The test cell is also equipped with (1) a gaseous nitrogen purge system for continuously inerting the normal air in-leakage of the cell; (2) a gaseous nitrogen repressurization system for raising test cell pressure, after engine cutoff, to a level equal to spray chamber pressure and for rapid emergency inerting of the capsule; and (3) a spray chamber liquid nitrogen supply and distribution manifold for initially inerting the spray chamber and exhaust ducting and for increasing the molecular weight of the hydrogen-rich exhaust products during engine operation.

2.3 INSTRUMENTATION

The engine instrumentation was comprised of (1) flight instrumentation for the measurement of critical engine parameters and (2) facility instrumentation which was provided as backup for the flight instrumentation and to measure additional engine parameters. The flight instrumentation was provided and calibrated by the engine manufacturer; facility instrumentation was initially calibrated and periodically recalibrated at AEDC. A description of selected instrumentation is contained in Ref. 3.

Pressure measurements were made using strain-gage-type pressure transducers. Temperature measurements were made using resistance temperature transducers and thermocouples. Oxidizer and fuel turbopump speeds were sensed by magnetic pickup. Fuel and oxidizer flow rates to the engine were measured by turbine-type flowmeters which are an integral part of the engine. Vibrations were measured by accelerometers mounted on the oxidizer dome and on the turbopumps. Primary engine valves were instrumented with linear potentiometers and limit switches.

The data acquisition systems were calibrated by (1) precision electrical shunt resistance substitution for the pressure transducers and resistance temperature transducer units, (2) voltage substitution for the thermocouples, (3) frequency substitution for shaft speeds and flowmeters, and (4) frequency-voltage substitution for accelerometers.

The types of data acquisition and recording systems used during this test period were (1) a multiple-input digital data acquisition system (MicroSADIC®) scanning each parameter at 40 samples per second, (2) single-input, continuous-recording frequency modulation systems recording on magnetic tape, (3) photographically recording galvanometer oscillographs, (4) direct inking, null-balance potentiometer-type X-Y plotters and strip charts, and (5) optical data recorders. Applicable systems were calibrated before each test (atmospheric and altitude calibrations). Television cameras, in conjunction with video tape recorders, were used to provide visual coverage during an engine firing.

SECTION III
SEQUENCE

Control of J-2 engine and test cell systems during the terminal countdown was centrally provided from the test cell control room. The less critical functions were manually controlled. Other functions were programmed to the facility countdown sequencer to provide (1) verification of systems readiness and (2) a time display for integrating the manual operations. The critical engine operations were controlled by a facility logic network which interconnected the required systems to safely start and shut down the engine. The facility controls are briefly described in the following section. A detailed description of facility and engine controls is contained in Refs. 1, 2, and 3.

The facility logic was an electrical control network designed to interconnect the engine control system, major stage systems, the engine safety cutoff system, observer cutoff circuits, and the countdown sequencer. The primary functions performed by the facility logic were to:

1. ascertain facility and engine systems ready to test,
2. apply start signal to engine control logic, and
3. initiate facility systems shutdown at expiration of sequencer-programmed run duration.

Automatic engine cutoff circuitry was provided in the facility logic (sequence monitor or start timer expiration) as well as in the engine start control solenoid. The engine start control solenoid monitored engine vibration and gas generator outlet temperature. Engine vibration (VSC), sensed by accelerometers mounted on the oxidizer dome, was required to sustain a level equal to or greater than ±150 g at frequencies betwen 960 and 6000 Hz for 200 msec to produce an engine cutoff.

SECTION IV
PROCEDURE

All consumable storage systems were replenished, and engine inspections and leak checks were conducted. Propellant tank pressurants and engine pneumatic and purge gas samples were taken to ensure that specification requirements were met. (Chemical analysis of propellants was provided by the propellant suppliers.) Facility sequence, engine sequence (Ref. 3 and Fig. 6), and engine abort checks were conducted within a 24-hr time period before an engine firing to verify the proper sequence of events. The abort checks consisted of electrically simulating engine malfunctions to verify the occurrence of an automatic engine cutoff signal. Engine and facility sequence checks consisted of verifying the timing of all engine and facility valves and events to be within specified limits. A final engine sequence check was conducted immediately preceding each test period.

Oxidizer dome, gas generator oxidizer injector, and thrust chamber jacket purges were initiated before evacuating the test cell (engine purges required for a typical test period are presented in Table III). After completion of instrumentation calibrations at atmospheric conditions, the test cell was evacuated to approximately 0.5 psia with the exhaust machinery, instrumentation calibrations at altitude conditions were conducted, and a cell air in-leakage evaluation was subsequently performed. Immediately before loading propellants on board the vehicle, the cell and exhaust ducting atmosphere was inerted. At this same time, the cell nitrogen purge was initiated, inerting the air leaking into the cell for the duration of the test period. The vehicle propellant tanks were then loaded, and the remainder of the terminal countdown was conducted. A typical terminal countdown is presented in Ref. 1.

Temperature conditioning of the various engine components was accomplished as required, using the facility-supplied engine component conditioning system.

SECTION V
RESULTS AND DISCUSSION

5.1 TEST SUMMARY

During this test series, 16 firings for a total firing duration of 206.1 sec were conducted between April 18 and July 6, 1967. Fifteen firings were in support of the Saturn II/J-2 engine application, and one firing (28A) was for a transient operation comparison of AS-202 flight data and AEDC test data. With the exception of firings 30A and 01A, all firings were conducted with an O/F ratio of 5.0. A propellant utilization valve excursion was made from null position to the full closed position (effective O/F ratio change from 5.0 to 5.5) on firings 30A and 01A. Temperature conditioning of the main oxidizer valve closing control line, main oxidizer valve second-stage actuator, helium regulator, and turbine crossover system preceded each firing; specific test requirements are presented in Table IV. Configuration changes made before each test are shown in Table II.

Specific test objectives and a brief summary of results obtained for the firings of this test series are presented in the following table:

Firing	Test Objectives	Results
27A	S-II fastest start and gas generator worst-case second peak with high start tank energy, warm thrust chamber, cold main oxidizer valve, and ambient crossover duct temperature.	Main chamber ignition occurred early, as expected, at $t_o + 0.963$ sec. A gas generator second peak of 2250°F was observed.
27B	S-II nominal start with nominal start tank energy, nominal thrust chamber, main oxidizer valve, and crossover duct temperatures.	Main chamber ignition occurred at $t_o + 0.998$ sec. A gas generator first peak of 2020°F was observed.
27C	S-II worst-case gas generator first peak; augmented spark igniter overheating and possible erosion with high start tank energy; cold thrust chamber and main oxidizer valve, and nominal crossover duct temperatures.	Thrust chamber and crossover duct temperatures were not within the specified limits. A gas generator first peak of 2090°F was recorded. Augmented spark igniter erosion occurred during test 27.
27D	S-II slowest start with possible high level fuel pump stall, low start tank energy, nominal thrust chamber, main oxidizer valve, and crossover duct temperatures.	Thermal conditioning limits were not met. A minimum fuel pump stall margin of 1100 gpm was measured.
28A	Simulated the J-2 engine transient operation of flight AS-202 (S-IB/S-IVB) to establish a basis for comparing flight and AEDC test results, low start tank energy, nominal thrust chamber, main oxidizer valve, and crossover duct temperature.	All major start conditions were within specifications; however, improper engine orificing prevented meeting of the firing objectives.

Firing	Test Objectives	Results
28B	S-II worst-case gas generator second peak, maximum main oxidizer valve hydraulic torque, and possible augmented spark igniter overheating and erosion, high start tank energy, warm thrust chamber, nominal main oxidizer valve and crossover duct temperatures.	Again, specified conditioning limits were met, but improper engine orificing existed. No augmented spark igniter erosion was observed.
28C	S-II worst-case gas generator first peak, and possible augmented spark igniter erosion-high start tank energy, cold thrust chamber, nominal main oxidizer valve and crossover duct temperatures.	Specified target conditioning limits were met. A gas generator combustion chamber pressure decay of 110-msec duration was recorded immediately after gas generator ignition. No augmented spark igniter erosion was observed.
29A	S-II slow start with possible high level fuel pump stall, low start tank energy, cold thrust chamber, nominal main oxidizer valve temperature, and cold crossover duct.	Test objectives were met. Firing 29A was the slowest start experienced during this test series. Thrust chamber ignition occurred at t_o + 1.026 sec; there were no fuel pump stall tendencies.
29B	Objectives the same as firing 29A, plus the determining of the effect of a warmer thrust chamber upon the gas generator first peak.	Start requirements satisfactorily met. Thrust chamber ignition occurred at t_o + 1.013 sec. There did not appear to be any pump stall tendencies. The gas generator first peak was 190°F higher than on firing 29A.
29C	A worst-case gas generator second peak with possible augmented spark igniter erosion, high start tank energy, warm thrust chamber jacket, nominal main oxidizer valve and crossover duct temperatures.	A gas generator first peak of 2020°F was noted. Thrust chamber ignition occurred at t_o + 0.954 sec. No augmented spark igniter erosion was noted. No significant gas generator second peak was measured.

Firing	Test Objectives	Results
29D	Objectives the same as firing 29C plus the determining of the effect of 100 psia less start tank pressure on the gas generator first peak.	Gas generator first peak was 2250°F, the highest of this test series. No augmented spark igniter erosion was noted. No significant gas generator second peak was measured.
30A	Effect of crossover duct conditioning on gas generator ignition and temperature, high start tank energy, cold thrust chamber jacket, nominal main oxidizer valve temperature, and cold crossover duct.	Data indicated unsatisfactory operation of the gas generator control valve. Engine inspection revealed an eroded fuel turbine.
01A	Investigate gas generator ignition characteristics for a S-II configuration worst-case gas generator second peak and possible augmented spark igniter erosion.	Main oxidizer valve component temperatures were colder than specified limits, which would cause a higher gas generator second peak than would be expected with specified values. No second peak of any significance occurred, and no augmented spark igniter chamber erosion was observed. A gas generator first peak of 2170°F was observed.
01B	Objectives the same as firing 01A, except for a colder thrust chamber (110°F colder than firing 01A), which would be expected to increase the gas generator first peak.	Specified conditions (which were closely attained) were such that the worst-case gas generator first peak of the 01 test period should have occurred. However, a decay of gas generator combustion chamber pressure occurred for a duration of 75 msec. Gas generator first peak was 1950°F.

Firing	Test Objectives	Results
01C	Objectives the same as firing 01B, except for a colder crossover duct (100°F colder than firing 01B), which should reduce the gas generator first peak.	Although the exact thermal conditioning specifications were not attained, conditions were such that the initial gas generator first peak should be less than for firing 01B. However, the peak was 2000°F, 50°F higher than firing 01B. A decay of gas generator combustion chamber pressure occurred immediately after ignition, although not as pronounced on firing 01B.
01D	A repeat of firing 01A	There was no significant gas generator second peak. Gas generator first peak was 1990°F, lower than expected, based on firing 01A results.

Test objectives were compromised on tests 27, 28, and 30. Test 27 results were inconclusive because of a prolonged main oxidizer valve second-stage operating time which was caused by an anomaly in the assembly of the main oxidizer valve (Section 5.7), test 28 results were not satisfactory because of improper orificing of the oxidizer turbine bypass valve nozzle and gas generator (Section 5.7) fuel supply line, and test 30 was conducted with an improperly operating gas generator control valve (Section 5.7).

Specific test results are summarized in Table V. Start and shutdown operating times of engine valves are presented in Table VI.

5.2 FAST, NOMINAL, AND SLOW STARTS

Firings 27A, 27B, and 27D were S-II fast, nominal, and slow start simulations, respectively, the differentiation being the time required to attain a combustion chamber pressure of 100 psia. The primary variable for a given engine hardware configuration is start tank energy as it affects propellant pump spinup during start tank discharge, the higher energy giving the faster start. Table V includes starting conditions, and Fig. 7

compares combustion chamber pressure, main oxidizer valve position, and propellant pump speeds during the start transient for firings 27A, 27B, and 27D.

Firing 29B was also a S-II slow start simulation. Starting conditions did not differ significantly from firing 27D, as shown in Table V; however, the fuel turbopump assembly was replaced between firings 27D and 29B. Figure 8 compares combustion chamber pressure, main oxidizer valve position, and propellant pump speeds during the start transient for firings 27D and 29B.

Starting conditions (low start tank energy with cold thrust chamber and crossover duct) for firings 27D and 29B were chosen to be conducive to fuel pump stall in the operating region above approximately 5000 gpm. Figure 9 shows fuel flow versus pump developed head for these two tests, compared to the line of stall inception for the pump design. A minimum stall margin of 800 gpm was attained on firing 29B.

5.3 GAS GENERATOR

5.3.1 Gas Generator Observations

Start transient gas generator operation for the J-2 engines/S-II stage flights was investigated in this series of tests over the expected range of conditions at engine start.

Major engine components replaced during this test series which are pertinent to the gas generator discussion were the gas generator, fuel turbopump, and main oxidizer valve assemblies. These engine modifications were performed subsequent to test 27. Incorrect orificing of the gas generator fuel supply line and the oxidizer turbine bypass valve nozzle during the conduct of these modifications resulted in a below nominal engine performance for test 28. Correct engine orificing was realized on all subsequent tests.

An inspection by the engine manufacturer of the main oxidizer valve, removed after test 27, revealed valve actuator friction in excess of normal (250-in.-lb, Ref. 3) existed as a result of an assembly anomaly. The significance of this anomaly is that the main oxidizer valve plateau times for test 27 were prolonged, resulting in significant gas generator second peak temperatures.

A malfunction of the gas generator control valve was encountered on test 30 (Section 5.7) and resulted in abnormal valve opening and closing times. The cause of the malfunction has been attributed to moisture freezing inside the valve assembly.

Included herein will be a summary of the basic gas generator relations established during the previous AEDC tests and the results of the J-2 engine/S-II stage simulation tests, as related to the gas generator.

5.3.2 Gas Generator Relationships

Previous J-2 engine testing at AEDC (Refs. 1, 2, and 3) has established that the gas generator outlet temperature during the start transient is of primary concern. The transient gas generator temperatures experienced have been categorized as gas generator first peak temperature and gas generator second peak temperature. The gas generator first peak temperature is primarily affected by the following conditions:

1. Thrust Chamber Tube Temperature - Thrust chamber tube temperature dictates the resistance or backpressure to the main chamber fuel flow and, consequently, the fuel flow to the gas generator. Colder temperatures cause higher gas generator first peaks because of reduced fuel flow resistance, which results in reduced fuel flow to the gas generator and a higher O/F ratio.
2. Crossover Duct and Turbine Component Temperatures - Temperature differences between the crossover duct/turbine components and the start tank gases provide additional energy to the start tank gases during blowdown. Warmer duct/turbines temperatures cause higher gas generator first peaks because the additional energy imparted to the start tank gases from this hardware results in a higher oxidizer pump spinup, higher oxidizer pump discharge pressure, and therefore, higher gas generator O/F ratio.
3. Start Tank Conditions - Start tank temperature and pressure have separate effects on the gas generator first peak. Start tank temperature, in conjunction with crossover duct and turbine component temperature, affects the spinup of the oxidizer turbine. Colder temperature gases cause higher gas generator first peaks because the greater temperature differential (crossover duct/turbine component to start tank gas temperatures) results in an increase in energy imparted to the start tank gases, higher oxidizer turbine spinup, higher oxidizer pump discharge pressure, and therefore, higher gas generator O/F ratio.

Start tank pressure affects the spinup of both turbines at a rate nearly proportional to the nominal turbine spin speeds. An increase in start tank pressure causes a lower gas generator first peak temperature because the increase in turbine spinup rates results in an increase in the pump discharge pressures and, consequently, an earlier thrust chamber ignition. Since the gas generator temperature rise rates are essentially identical because of the proportional spinup rates of the turbines, and since thrust chamber ignition provides the mechanism for lowering the gas generator first peak temperature, then the earlier thrust chamber ignition results in a lower gas generator first peak.

The gas generator second peak is primarily affected by the main oxidizer valve timing and the conditions affecting the first peak. Second peak temperatures are lowered when the main oxidizer valve starts second-stage opening from the plateau, thus providing more oxidizer flow to the thrust chamber which increases the resistance to fuel flow, fuel pump discharge pressure, and gas generator fuel flow rate and reduces the gas generator O/F ratio. The main oxidizer valve plateau time (time that main oxidizer valve is at the 14-deg position) varies with the valve total opening time, which is controlled with an orifice in the closing control pressure side of the valve. Colder pneumatic gases and control system components also lengthen the valve opening time. Main oxidizer valve plateau time is also a function of hydraulic torque which, because of valve geometry, creates a closing force on the valve vane when the valve is at the 14-deg position.

5.3.3 Gas Generator Operation for Nominal S-II Start

Transient gas generator operation for a nominal S-II start simulation (firing 27B) is presented in Fig. 10. A summary of firing 27B conditions at engine start is presented in Table V.

Gas generator ignition occurred at $t_o + 0.678$ sec, and as observed from fuel pump discharge pressure (Fig. 10), ignition was characterized by gas generator backflow. The differential between gas generator fuel injector pressure and fuel pump discharge pressure also shows gas generator backflow when the gas generator fuel poppet was opened. Gas generator valve timings are listed in Table VI.

The recorded gas generator first peak temperature was 2020°F; the second peak temperature was 1890°F. The indicated second peak temperature represents a worst-case, since the engine main oxidizer valve for firing 27B with excessive valve actuator friction produced a longer than nominal valve plateau time. Based on observations from subsequent tests with the replacement main oxidizer valve which had lower valve friction, a second peak temperature did not exist for a nominal S-II start with a properly assembled main oxidizer valve.

5.3.4 Gas Generator Operation for Slow S-II Start

Firing 29A illustrates the effect of conditions producing a slow engine start on the gas generator operation. Conditions for firing 29A at engine start are presented in Table V. These included cold thrust chamber tube temperatures, cold crossover duct and turbine component temperatures, warm start tank temperature, and low start tank pressure.

The results of this test are presented in Fig. 11. The gas generator first peak temperature was 1590°F; a gas generator second peak temperature did not occur since the main oxidizer valve second-stage opening began before thrust chamber ignition. Gas generator backflow occurred during the opening of the gas generator control valve fuel poppet and at gas generator ignition for this test.

5.3.5 Worst-Case Gas Generator First Peak Temperature

A highest gas generator first peak of 2250°F was observed on firing 29D. With the exception of thrust chamber temperature, the start conditions established for firing 29D (Table V) met the limits for a worst-case gas generator first peak. Throat and exit temperatures were -177 and -170°F, respectively, at engine start; the thrust chamber temperature of -250°F, specified for a S-II application minimum, would be expected to increase the gas generator first peak because of less fuel system resistance and lowered fuel supply to the gas generator initially. The engine start transient for firing 29D is shown in Fig. 12.

5.3.6 Worst-Case Gas Generator Second Peak Temperature

Firings 27A, 29D, and 01A were conducted to evaluate the worst-case gas generator second peak temperature. Conditions at engine start for these firings are presented in Table V. Comparative results of these firings are presented in Fig. 13. The gas generator second peak for firing 27A was 2250°F; a second peak temperature did not occur on firings 29D and 01A. This significant difference can be explained by considering the main oxidizer valve opening characteristics for the three tests.

The time that the main oxidizer valve remains on the 14-deg plateau (about 16 percent open) influences the magnitude of the gas generator second peak temperature. While on the plateau, the main oxidizer valve offers a high resistance to oxidizer flow and, thereby, results in a faster buildup rate of oxidizer pump discharge and gas generator oxidizer injector pressures than for the corresponding fuel system pressures. Opening of the main oxidizer valve second stage results in an increase in thrust chamber pressure and fuel system resistance to flow, which produces gas generator conditions for lowering the (O/F) ratio and the second peak temperature. If the main oxidizer valve second-stage opening occurs before the second peak temperature begins, then a second peak will not occur as in the case of firings 29D and 01A.

The main oxidizer valve was replaced after test 27. An inspection of the valve by the engine manufacturer revealed excessive valve actuator friction. This excessive friction caused a long main oxidizer valve plateau time for firing 27A and the gas generator second peak temperature. The replacement valve with reduced valve friction began second-stage opening significantly sooner, and no gas generator second peak was experienced. Thermal conditioning of the main oxidizer valve closing control line, main oxidizer valve second-stage actuator, and pneumatic package was accomplished on all tests but averaged colder for the above mentioned firings than others. Normally, the main oxidizer valve plateau time would be increased with colder main oxidizer valve component temperature, enhancing the chances of gas generator second peak; however, the plateau time appeared to have been reduced by engine vibration (Section 5.5), nullifying the effect of valve temperature conditioning. The main oxidizer valve position is shown in Fig. 13.

These tests indicated that a gas generator second peak temperature problem does not exist for the J-2 engine/S-II stage application as currently defined.

5.3.7 Gas Generator Pressure Decay

A decay in gas generator combustion chamber pressure occurred immediately after ignition on firing 28C for approximately 110 msec. This was the first occurrence of such a decay on the J-2 engine starts to date at AEDC. Conditions at engine start for this test are presented in Table V. Below nominal engine performance was experienced because of incorrect orificing of the gas generator fuel supply line and oxidizer turbine bypass valve nozzle. The large gas generator fuel supply line orifice resulted in a fuel-rich operation for this test. However, the incorrect engine orificing is believed not to have had any effect on the pressure decay. Start transient gas generator operation similar to that of firing 28C was also observed on firings 01B and 01C.

The effects of gas generator combustion pressure decay on the engine start transient are shown in Fig. 14. Gas generator ignition occurred at t_o + 0.651 sec on start tank gases (gas generator chamber pressure and fuel pump discharge pressure were 135 and 65 psia, respectively, immediately after gas generator ignition). As observed from fuel pump discharge pressure, ignition was characterized by gas generator backflow into the fuel system and followed by a 110-msec unstable period. It is also noted that the gas generator oxidizer poppet valve was allowed to move in the closing direction momentarily by the backflow. The gas generator chamber pressure indicates that the decay occurred immediately after ignition. The gas generator backflow, therefore, prevented adequate propellant quality for combustion for 110 msec. The second gas generator ignition at t_o + 0.761 sec and the gas generator successfully bootstrapped.

5.3.8 Start Tank Pressure Gain Factor

Firings 29C and 29D were conducted to establish a start tank pressure relationship (gain factor) with the worst-case gas generator first and second peak temperature conditions expected for the S-II start application. Conditions attained at engine start for accomplishing this objective are listed in Table V. Start tank pressure for firing 29D (1204 psia) was 102 psia lower than for firing 29C; all other engine conditions for these firings were similar.

Comparative results of these firings are presented in Fig. 15. The gas generator first peak of 2250°F for firing 29D (with the lower start tank pressure) was 230°F higher than for firing 29C, producing a gain factor of 2.3°F/psi. Reiterating the explanation in Section 5.3.2, Fig. 15 shows that the lower start tank pressure for firing 29D results in a proportional reduction in fuel and oxidizer turbines spinup, pump discharge and gas generator injector pressures, and the same gas generator temperature rise rate. However, the lower oxidizer pump discharge pressure for firing 29D results in a slightly longer time to thrust chamber ignition, as reflected by the rapid increase in fuel pump discharge pressures at approximately t_o + 0.95 sec.

5.3.9 Fuel-Rich Operation of the Gas Generator

The gas generator was operated at a lower O/F than desired during test 28 because of an incorrectly orificed gas generator fuel supply line and an improperly sized oxidizer turbine bypass valve nozzle orifice. The target steady-state fuel turbine inlet temperature was approximately 1250°F at rated conditions (engine O/F of 5.5), or approximately 1100°F at an engine O/F of 5.0. Before test 29, the gas generator fuel supply line orifice was changed from 0.482- to 0.472-in. diameter, and the oxidizer turbine bypass valve nozzle orifice was changed from 1.420- to 1.300-in. diameter. Gas generator outlet temperatures obtained during firings 28B and 29C are presented in Fig. 16; start conditioning targets for both tests were similar, and the only factor affecting the gas generator first peak should be the gas generator fuel supply line orifice and the oxidizer turbine bypass valve nozzle orifice size. The gas generator first peak temperature was approximately 620°F less for firing 28B than firing 29C. Steady-state temperatures were 70°F less on firing 28B than for firing 29C.

5.4 AUGMENTED SPARK IGNITER OVERHEATING AND EROSION

Post-fire inspection of the augmented spark igniter chamber indicated erosion occurred during test 27. Analysis of the augmented spark igniter chamber fuel and oxidizer inlet pressures indicated maximum O/F ratio resulted during firing 27A, and the augmented spark igniter erosion probably occurred during this firing. The ignition detect temperature values are presented in Fig. 17, along with the augmented spark igniter chamber injector pressures. Although the absolute values of ignition detect temperature are incorrect, the relative magnitude between firings is indicated. Temperatures of fuel and oxidizer at the augmented spark igniter injector show that the oxidizer supply is immediately of good quality (as evidenced by an immediate temperature drop), whereas the fuel temperature drops more slowly, indicating a lag in good quality fuel.

5.5 MAIN OXIDIZER VALVE OPERATION AND TEMPERATURE CONDITIONING

A major factor affecting the engine transient operation is the main oxidizer valve second-stage opening time. Basically, the valve timing is affected by (1) the time required to vent closing control pressure from the actuator body, which is a function of helium gas density to be vented and the closing control orifice size, (2) hydraulic torque acting on the main oxidizer valve vane, (3) pneumatic actuator torque, and (4) friction. At the 14-deg position, hydraulic torque and friction tend to resist actuator opening torque; an increase in the closing control vent orifice diameter or gas temperature will decrease plateau and second-stage ramp times. One of the primary objectives for this series of tests was to simulate S-II interstage conditions on the main oxidizer valve and determine the effects on transient engine operation of any changes in main oxidizer valve timing. Components that were conditioned included the main oxidizer valve closing control line, second-stage actuator, and the helium regulator. Orifice sizes and pre-test sequence checks of the main oxidizer valve second-stage ramp times are presented in Table VII. The closing control orifice used for test 27 was a S-IVB thermostatically controlled orifice, whereas the orifices of tests 28, 29, 30, and 01 were S-II-type nonthermostatic orifices.

Hydraulic and pneumatic actuator torques acting on the main oxidizer valve at initial second-stage movement were calculated for each test and a friction value obtained (Table VIII). For all firings except two (27B and 29A), initial second-stage movement was noted during the time that vibration safety counts occurred. Plateau time was reduced for firings with vibration safety counts. For example, firings 27A and 27B will give an indication of plateau time with 160-msec vibration safety counts and 7-msec vibration safety counts, respectively. Indicated friction torque (difference between actuator and hydraulic torque) at initial second-stage movement was 193 in.-lb with 160-msec vibration safety counts (firing 27A) and 490 in.-lb with 7-msec vibration safety counts (firing 27B). All firings of test 27 exhibited a second plateau position from 15 to 17 deg (normal plateau is 14 deg) that was maintained for a maximum of 0.531 sec on firing 27A before the valve continued opening. Friction calculated for the main oxidizer valve used for test 27 was higher than predicted by the engine manufacturer. Disassembly of the valve after test 27 indicated the higher friction resulted from an error made in the original valve assembly (Section 5.7). Because of the valve assembly anomaly, vibration safety counts, and the varying start conditions, a temperature relationship to main oxidizer valve operation cannot be shown.

Friction torque recorded for tests 28, 29, 30, and 01 was lower than experienced on test 27, ranging from a maximum value of 162 in.-lb to a minimum of 17 in.-lb (Table VIII). Since vibration safety counts occurred during initial second-stage movement on all but two firings, and because of the different start conditioning limits, independent temperature effects on main oxidizer valve operation (friction and timing) cannot be obtained.

5.6 VIBRATION

Engine vibration in excess of 150 g at frequencies between 960 and 6000 Hz was measured on all 16 firings at approximately $t_0 + 1$ sec; durations ranged from 7 msec on 29A to 178 msec on 27C as shown in Table XIII.

No detrimental effects attributable to this vibration have been noted on engine components tested at AEDC to date.

Initial second-stage movement of the main oxidizer valve occurred during the periods of vibration safety counts on all but two firings (27B and 29A).

5.7 ANOMOLIES

Following test 27 the main oxidizer valve was removed and disassembled by the engine manufacturer. Rocketdyne Failure Analysis Report No. 007921 states that the valve was found to be incorrectly assembled. The end-play was not removed from the vane shaft, allowing the vane to bind on the lip seal. This resulted in an increase in friction of some 100 percent above nominal.

Before firing 27A the main oxidizer valve, fuel turbopump, and augmented spark igniter oxidizer supply line were replaced. This necessitated changes to the oxidizer turbine bypass valve nozzle and gas generator fuel and oxidizer supply line orifices. Data from firings 28A, 28B, and 28C indicated that the oxidizer turbine bypass valve nozzle and gas generator fuel supply line orifice were too large to give the desired engine performance; the nozzle and orifice were subsequently resized before firing 29A.

During firing 30A the gas generator control valve failed to operate properly, resulting in abnormal ignition and shutdown transients as shown in Fig. 18. During the shutdown transient the gas generator outlet temperature rose to approximately 2600°F, at which time the temperature transducer failed. Post-test inspection showed the fuel turbine first stage to be significantly eroded. Disassembly of the gas generator control valve by Rocketdyne showed a significant amount of water in the actuator. It is felt that freezing of this water resulted in the control valve malfunction.

SECTION VI
SUMMARY OF RESULTS

The results of the 16 firings of the J-2 rocket engine at pressure altitude conditions in Test Cell J-4 are summarized as follows:

1. These tests indicate that no gas generator outlet second peak temperature problem exists for the S-II stage.
2. Test conditions conducive to fuel pump stall in the flow rate region above 5000 gpm produced a minimum stall margin of 800 gpm.

3. A gas generator outlet first peak temperature to start tank pressure gain factor of 2.3°F/psi was determined from firings 29C and 29D.

4. Vibration in excess of 150 g was measured on all 16 firings at approximately $t_o + 1$ sec. No damage to engine components has been attributed to this vibration.

5. Initial main oxidizer valve second-stage movement occurred during the periods of vibration on 14 of 16 firings.

6. Test 27 objectives were compromised because of an improperly assembled main oxidizer valve.

7. Test 28 objectives were compromised because of incorrectly sized oxidizer turbine bypass valve nozzle and gas generator fuel supply orifice.

8. Test 30 objectives were compromised by a gas generator control valve malfunction.

REFERENCES

1. Muse, W. W. and Franklin, D. E. "Altitude Testing of the J-2 Rocket Engine in Propulsion Engine Test Cell (J-4) (Tests J4-1554-01 through J4-1554-11)." AEDC-TR-67-86, July 1967.

2. Simpson, J. N., Cantrell, F. E., and Kunz, C. H. "Altitude Testing of the J-2 Rocket Engine in Propulsion Engine Test Cell (J-4) (Tests J4-1554-12 through J4-1554-19)." AEDC-TR-67-115, September 1967.

3. Collier, M. R. and Dougherty, N. S. "Altitude Testing of the J-2 Rocket Engine in Propulsion Engine Test Cell (J-4) (Tests J4-1554-20 through J4-1554-26)." AEDC-TR-67-145, October 1967.

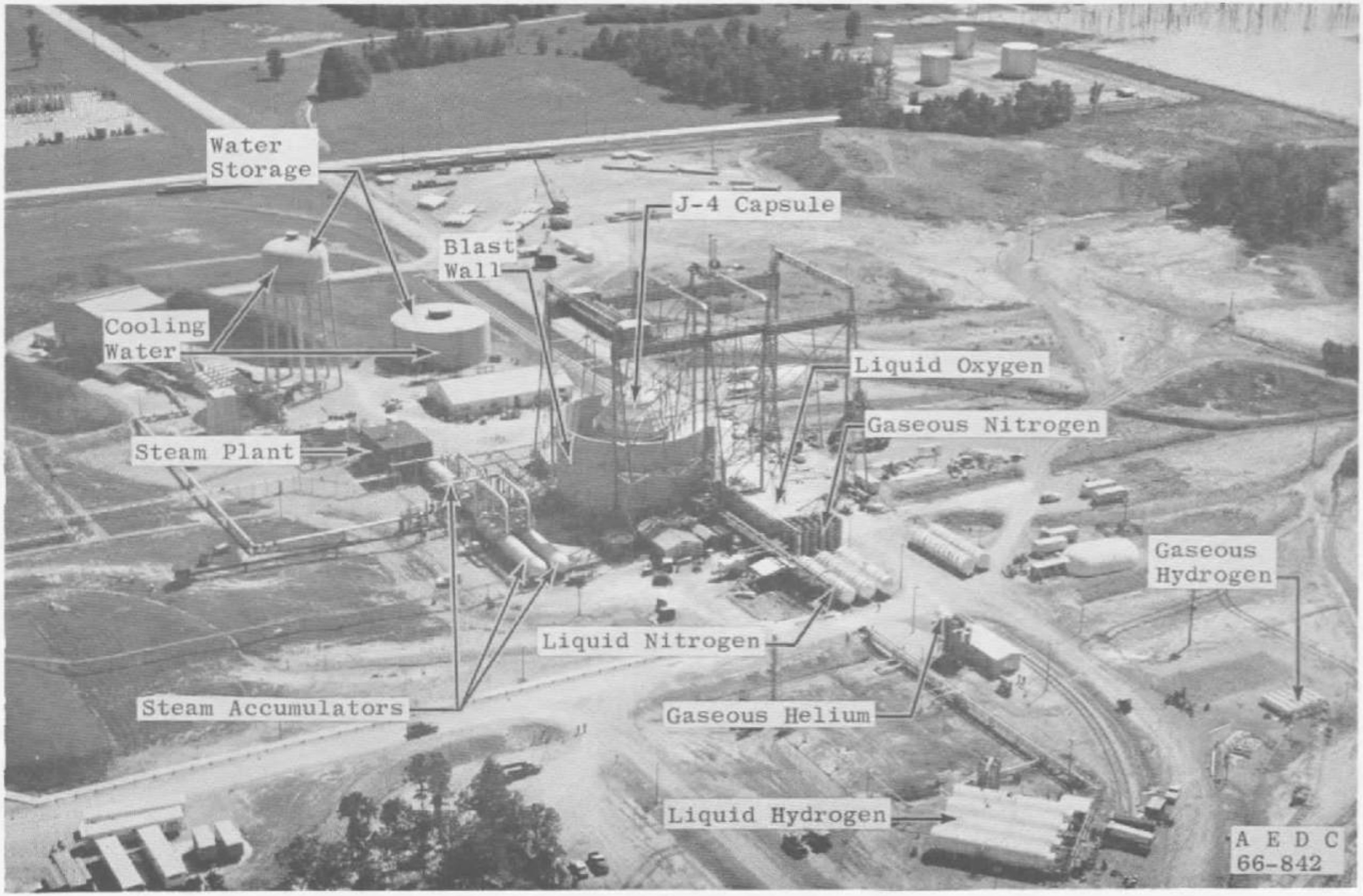
4. "J-2 Rocket Engine, Technical Manual Engine Data". R-3825-1, August 1965.

5. Test Facilities Handbook (6th Edition). "Large Rocket Facility, Vol. 3." Arnold Engineering Development Center, November 1966.

6. Dubin, M., Sissenwine, N., and Wexler, H. U. S. Standard Atmosphere, 1962. December 1962.

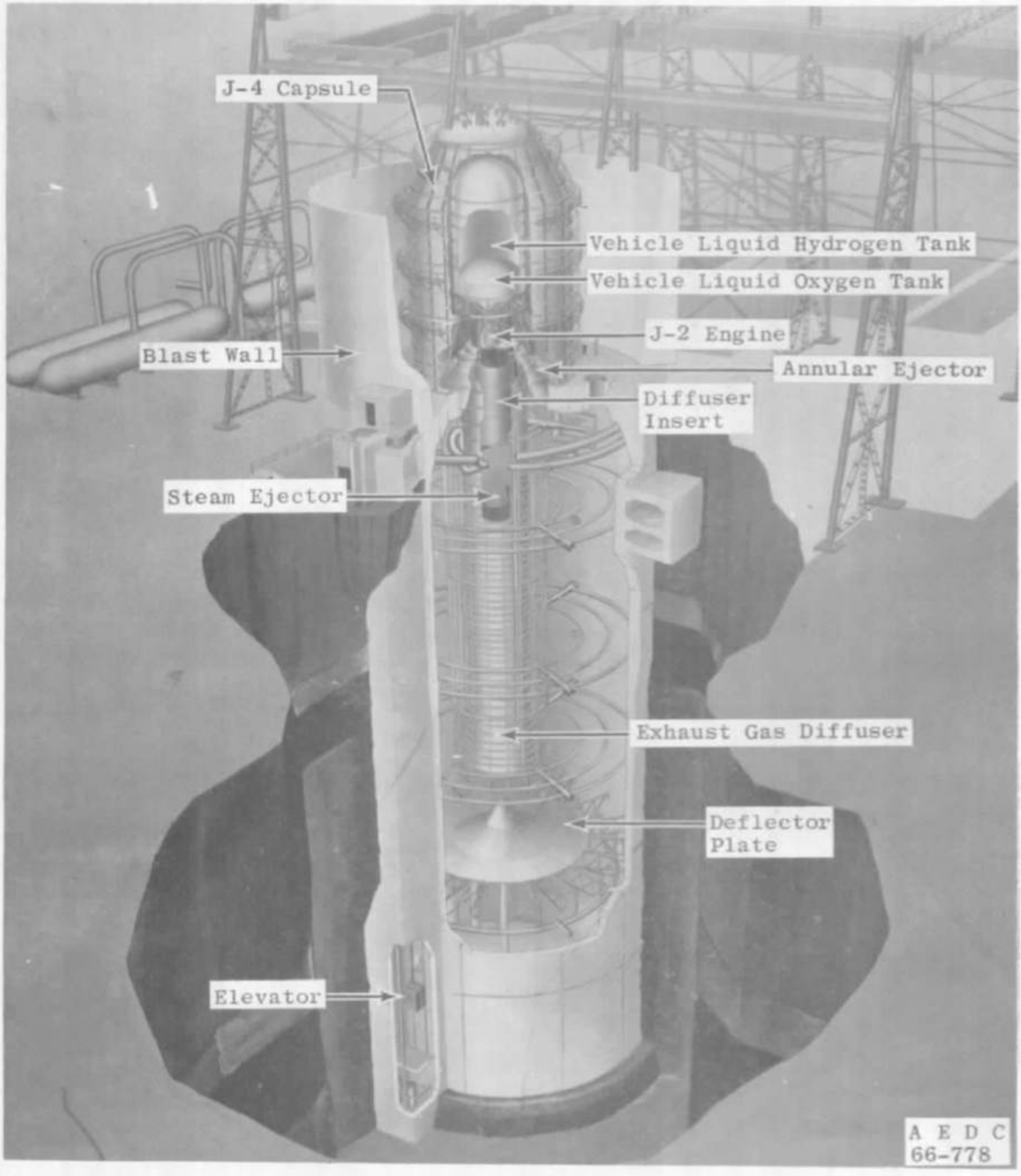
APPENDIXES

I. ILLUSTRATIONS
II. TABLES



a. Aerial View

Fig. 1 Propulsion Engine Test Cell J-4



b. Cutaway View
Fig. 1 Concluded

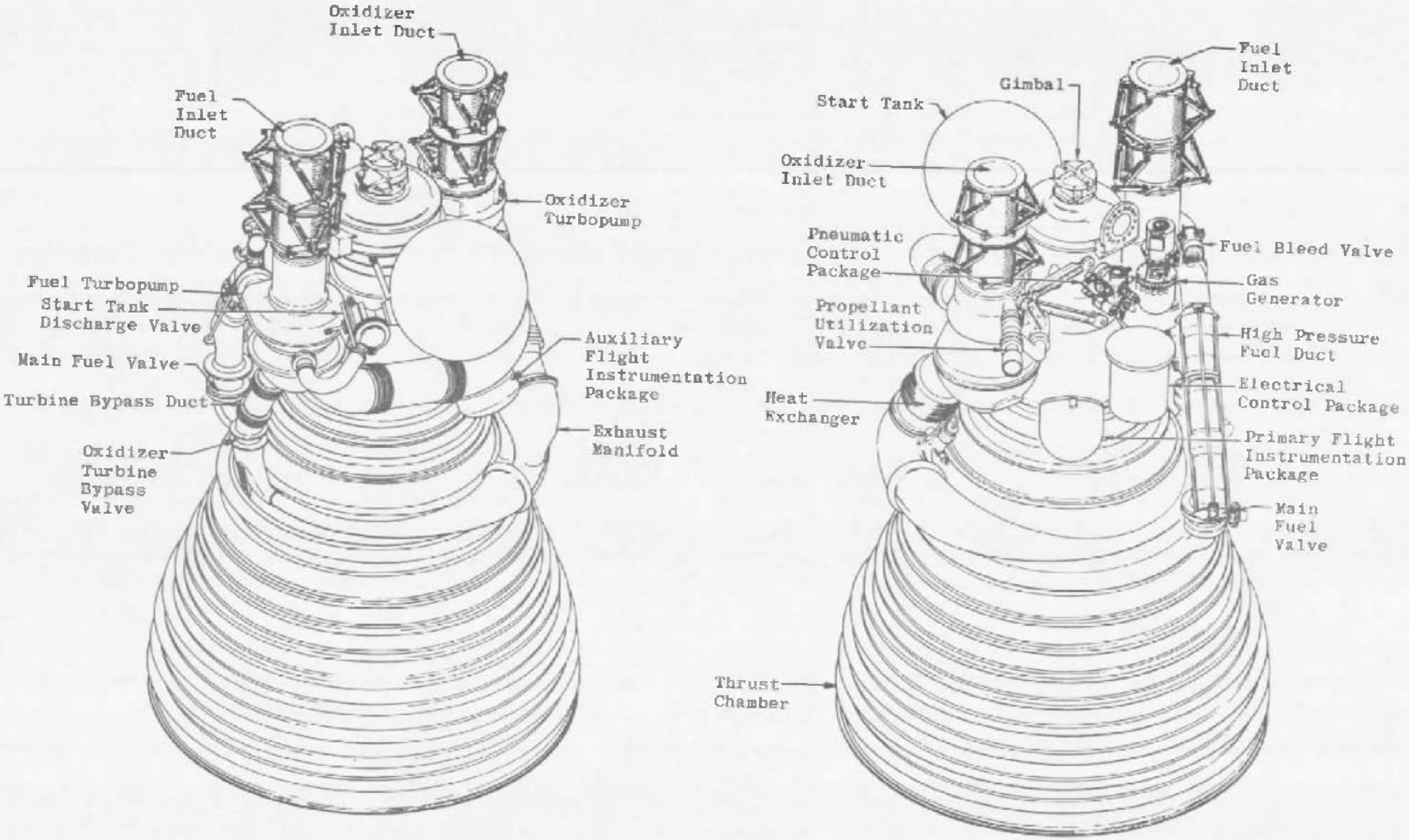
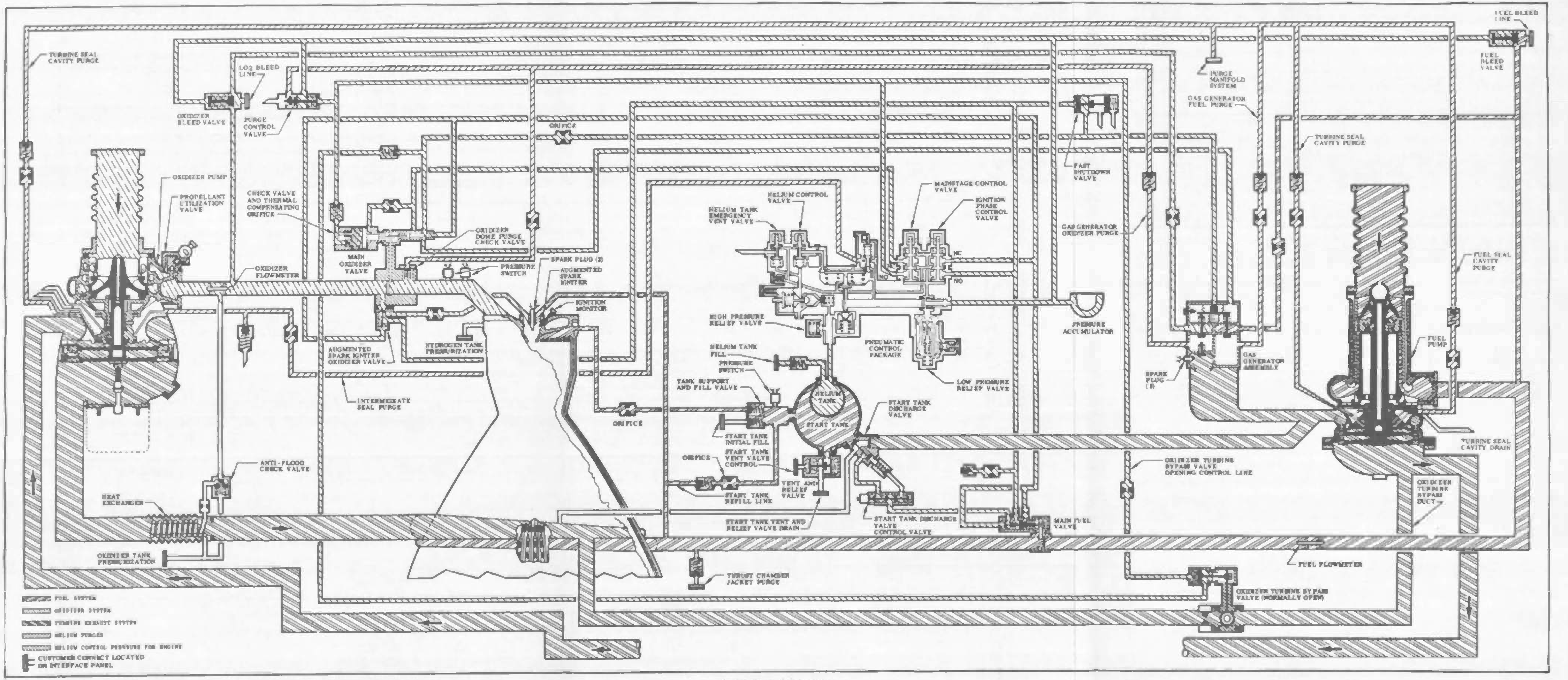
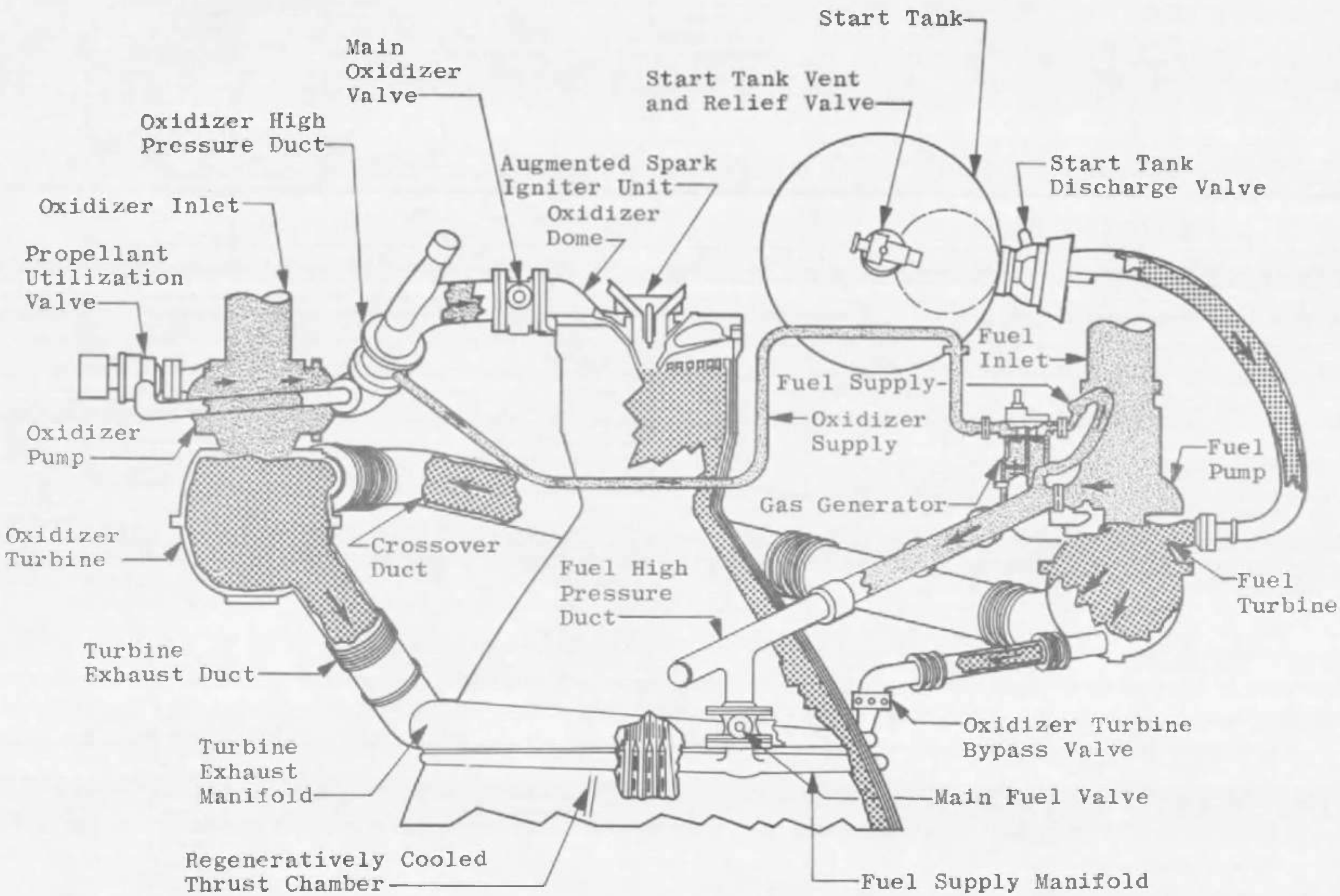


Fig. 2 J-2 Rocket Engine



a. Mechanical Schematic

Fig. 3 Schematic of the J-2 Engine



b. Simplified Propellant and Hot Gas Flow Diagram

Fig. 3 Concluded

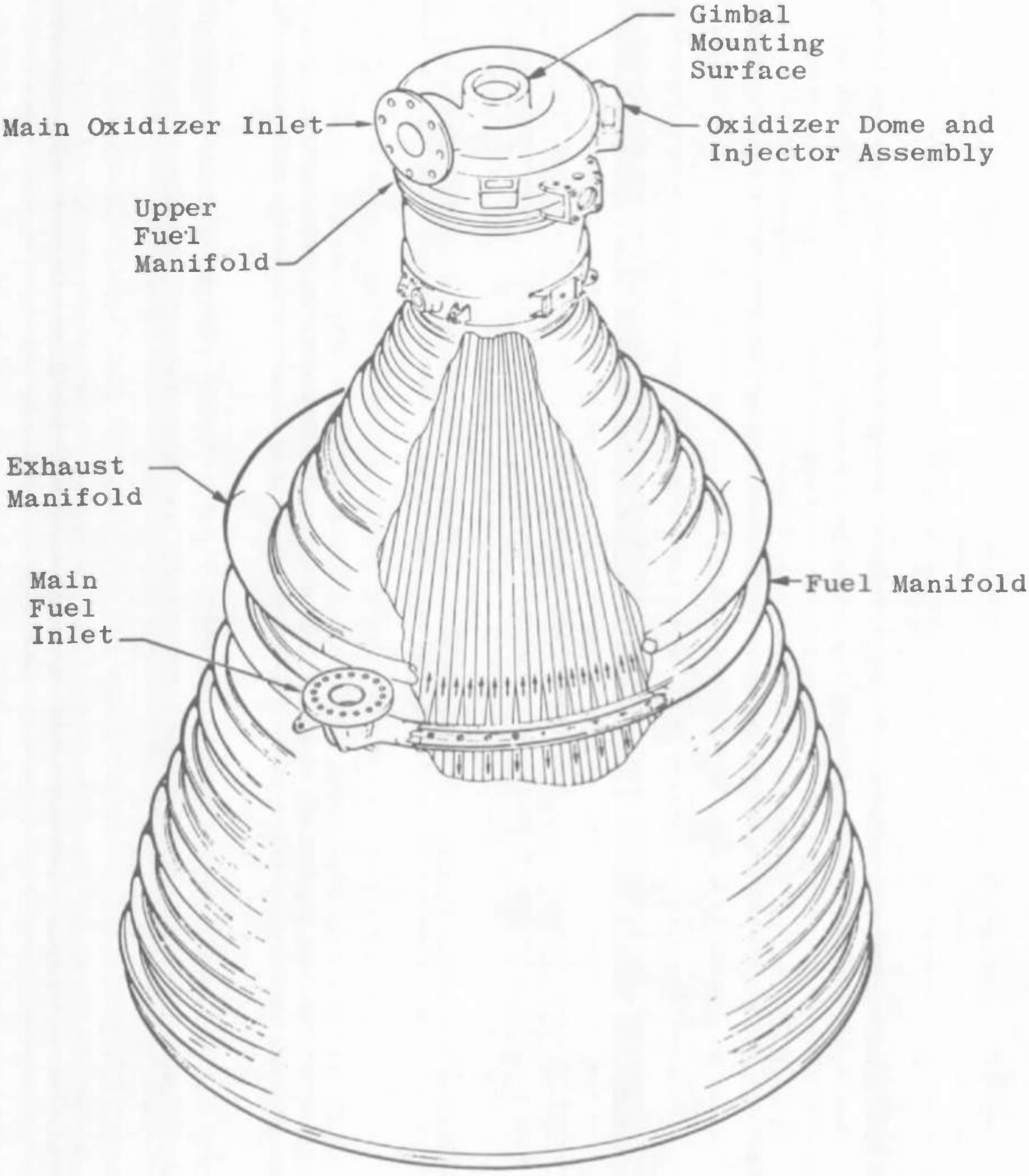


Fig. 4 Details of Thrust Chamber

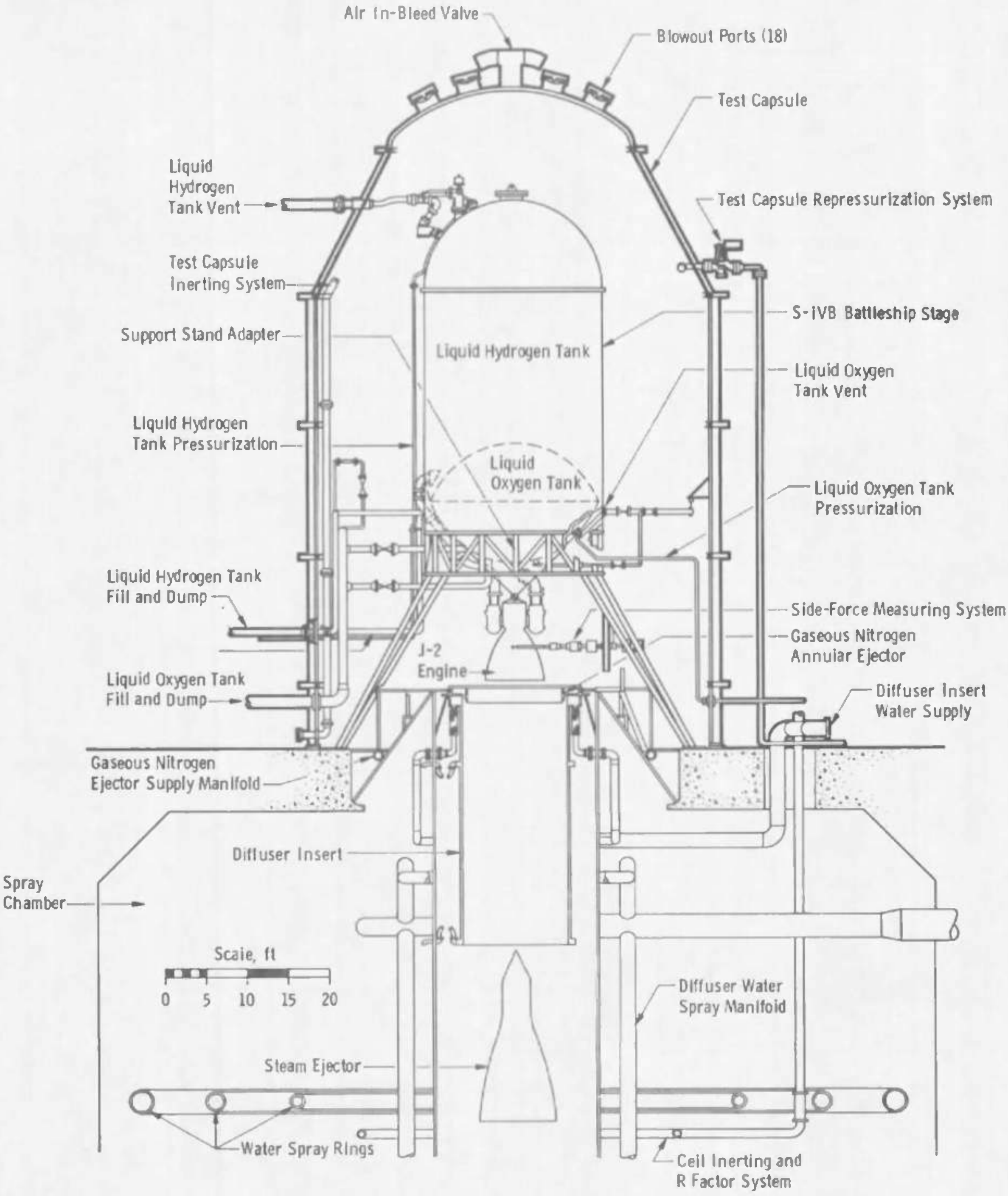
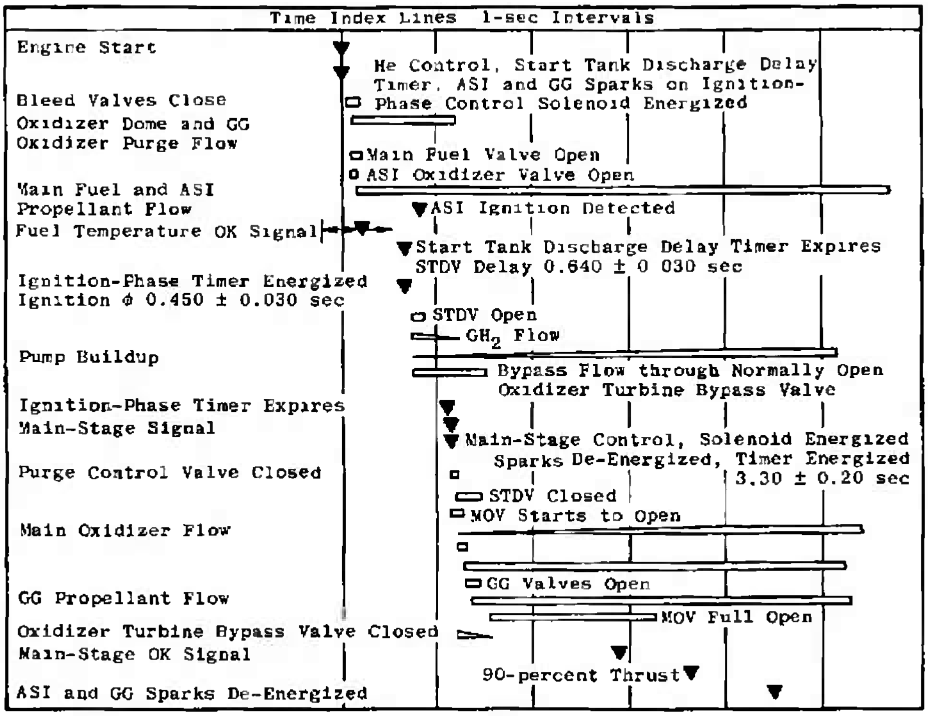


Fig. 5 Installation in Test Cell J-4



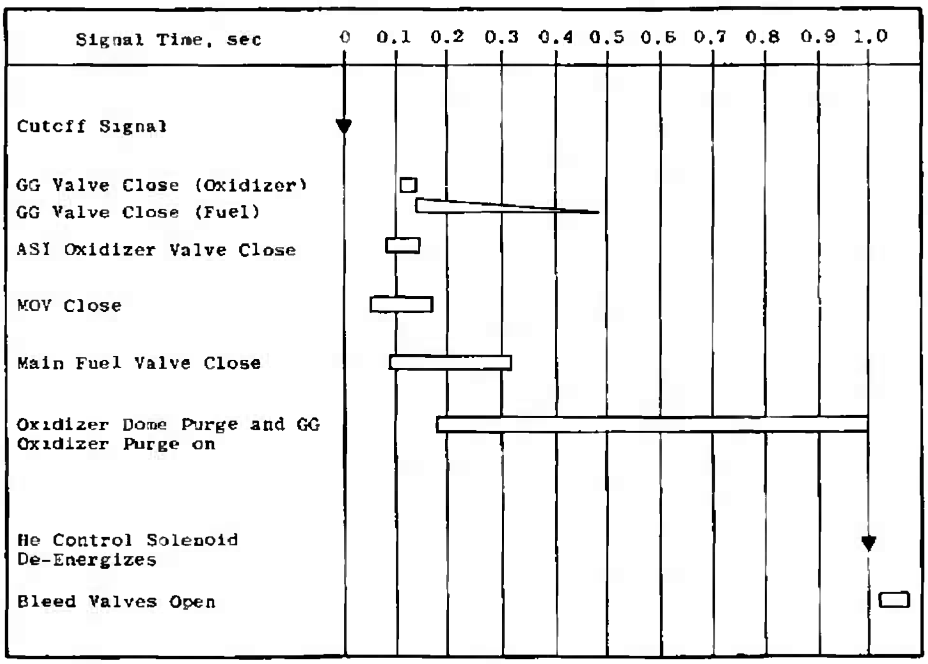
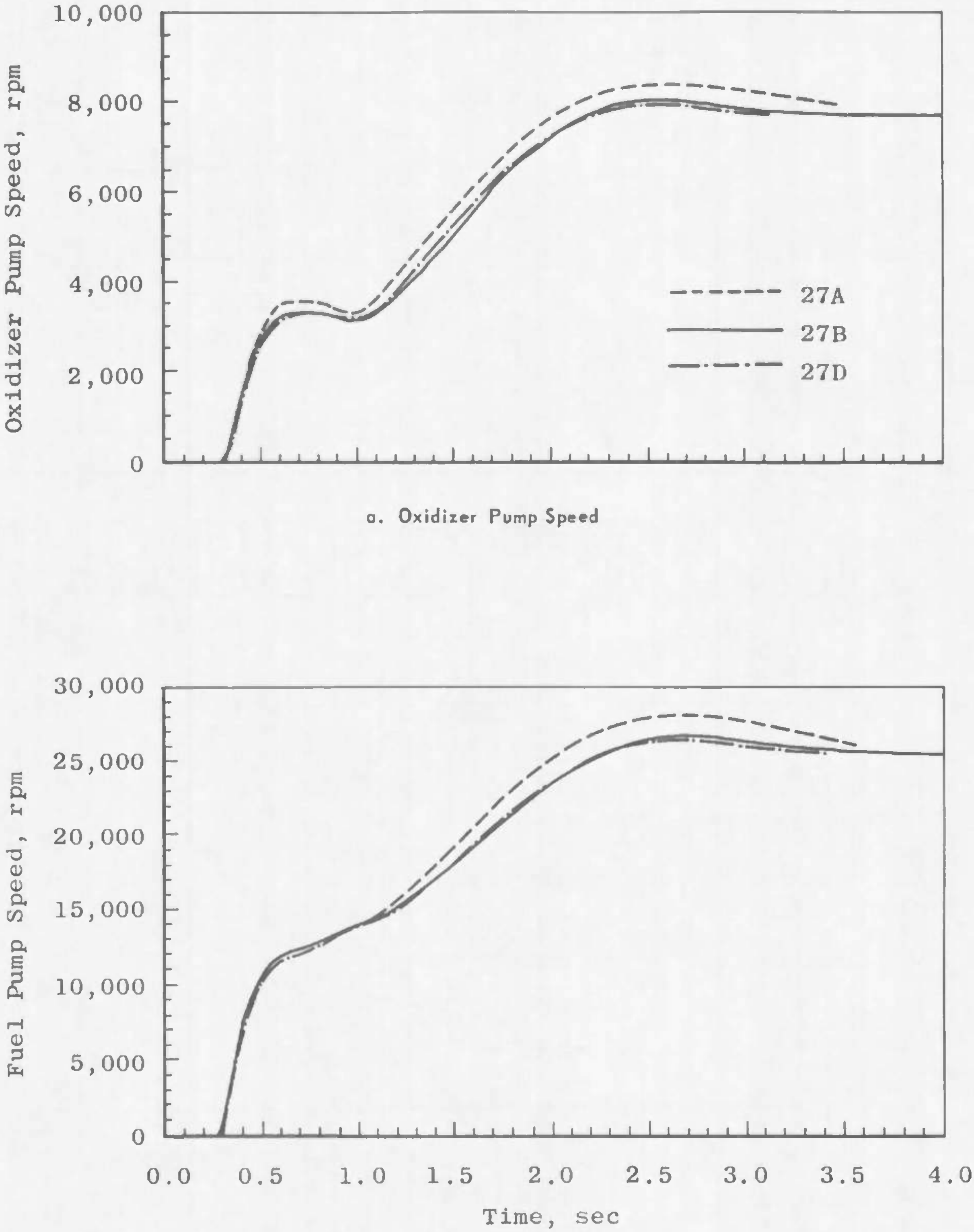


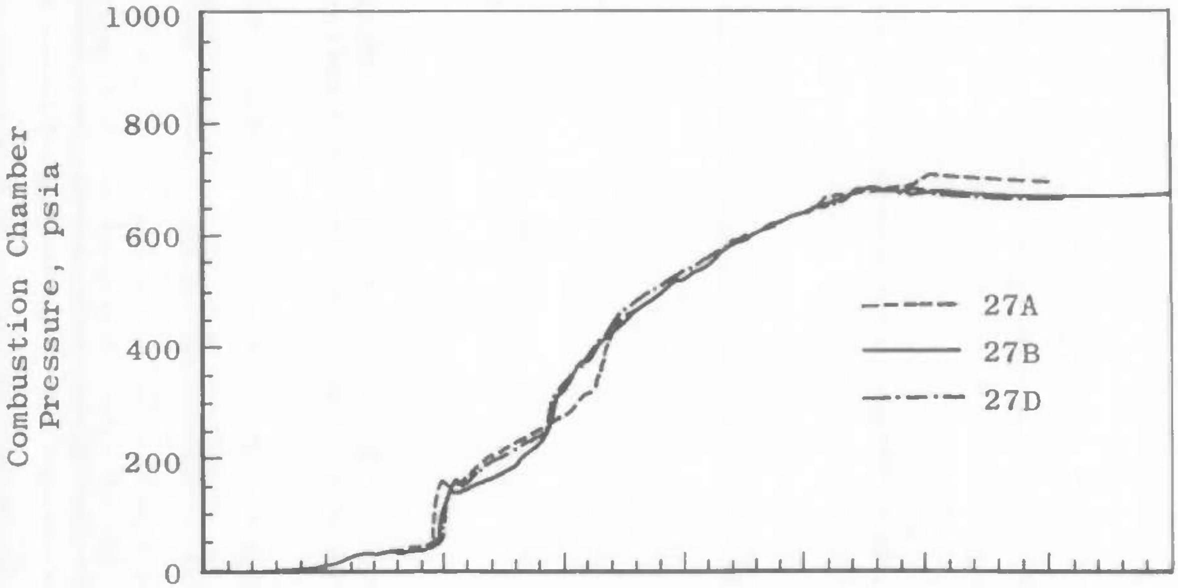
Fig. 6 Engine Start and Cutoff Sequence



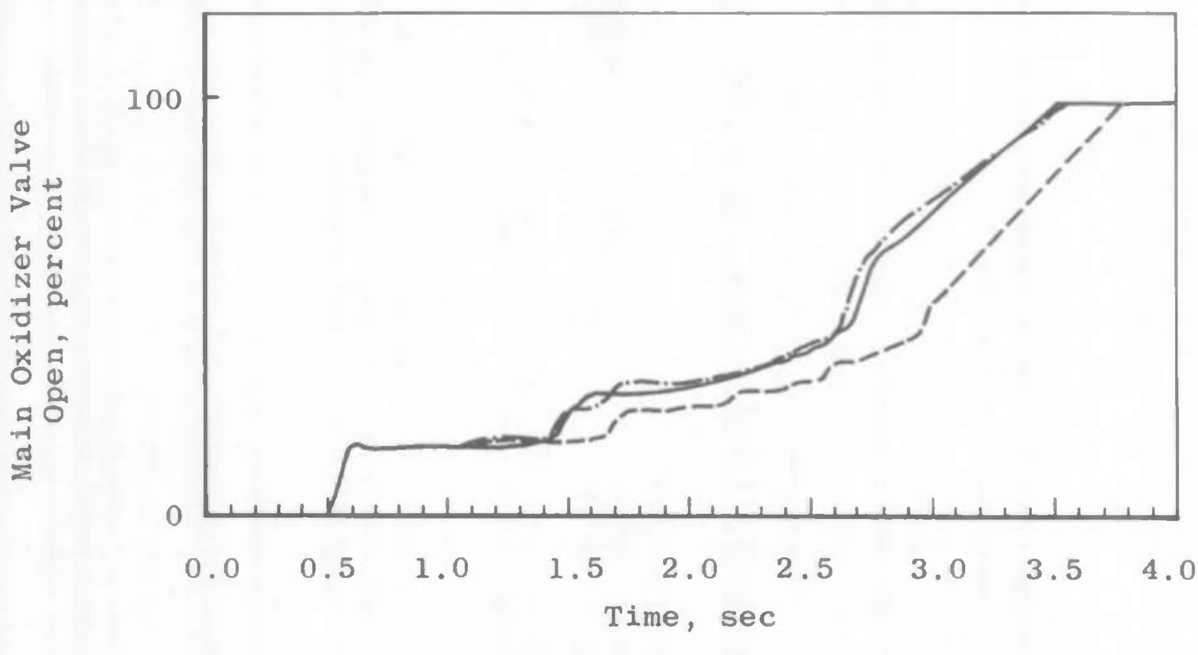
a. Oxidizer Pump Speed

b. Fuel Pump Speed

Fig. 7 Start Transient for Firings 27A, 27B, and 27D

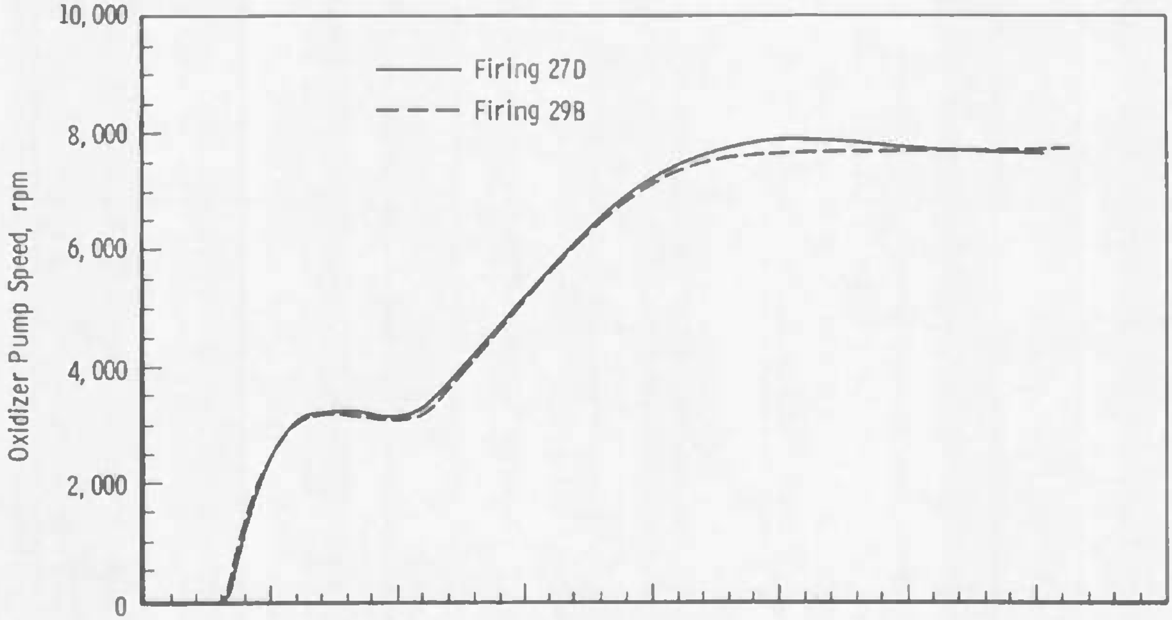


c. Combustion Chomber Pressure

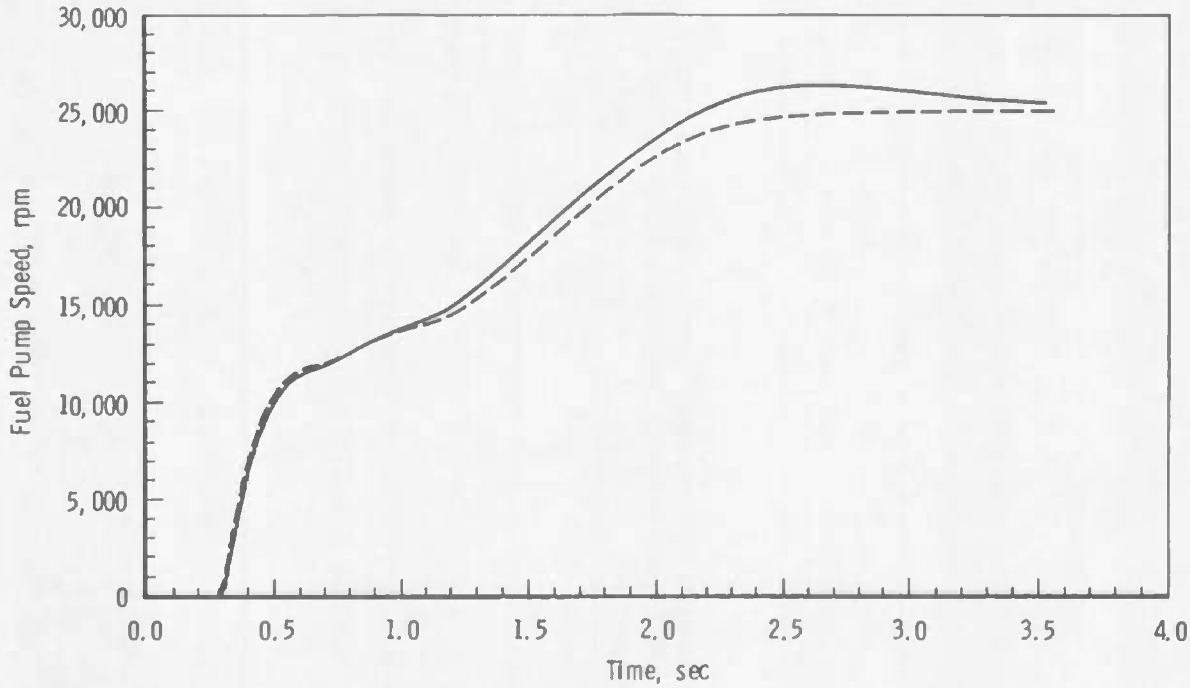


d. Main Oxidizer Valve Position

Fig. 7 Concluded

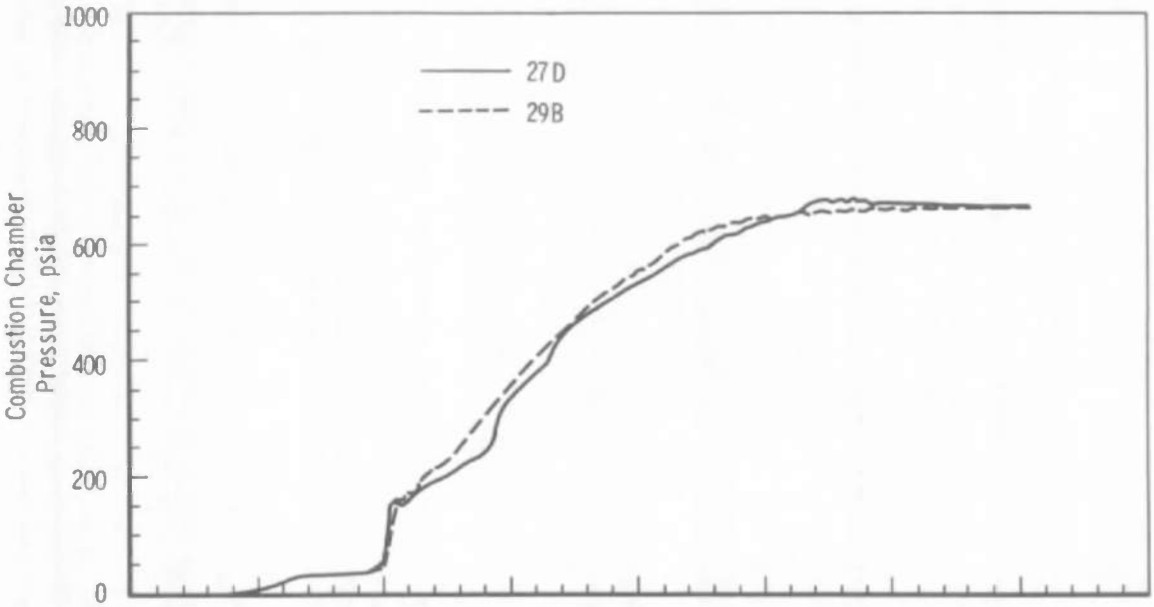


a. Oxidizer Pump Speed

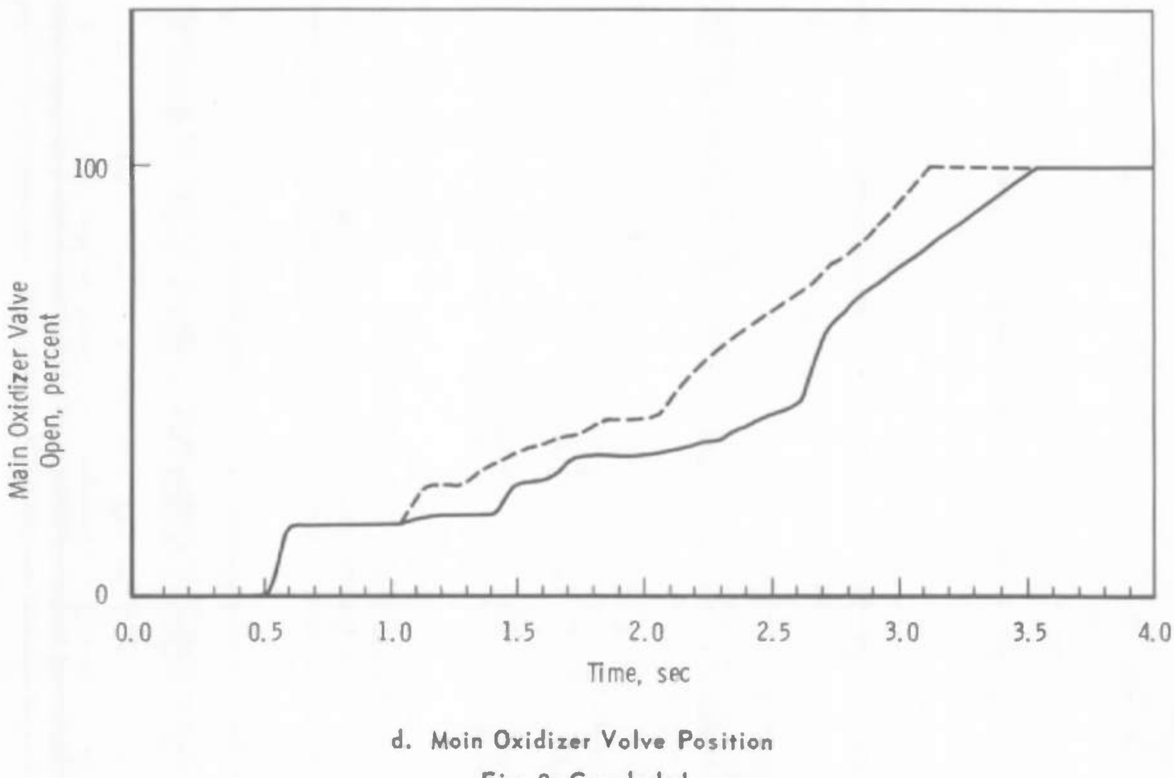


b. Fuel Pump Speed

Fig. 8 Start Transient for Firings 27D and 29B



c. Combustion Chomber Pressure



d. Moin Oxidizer Volve Position

Fig. 8 Concluded

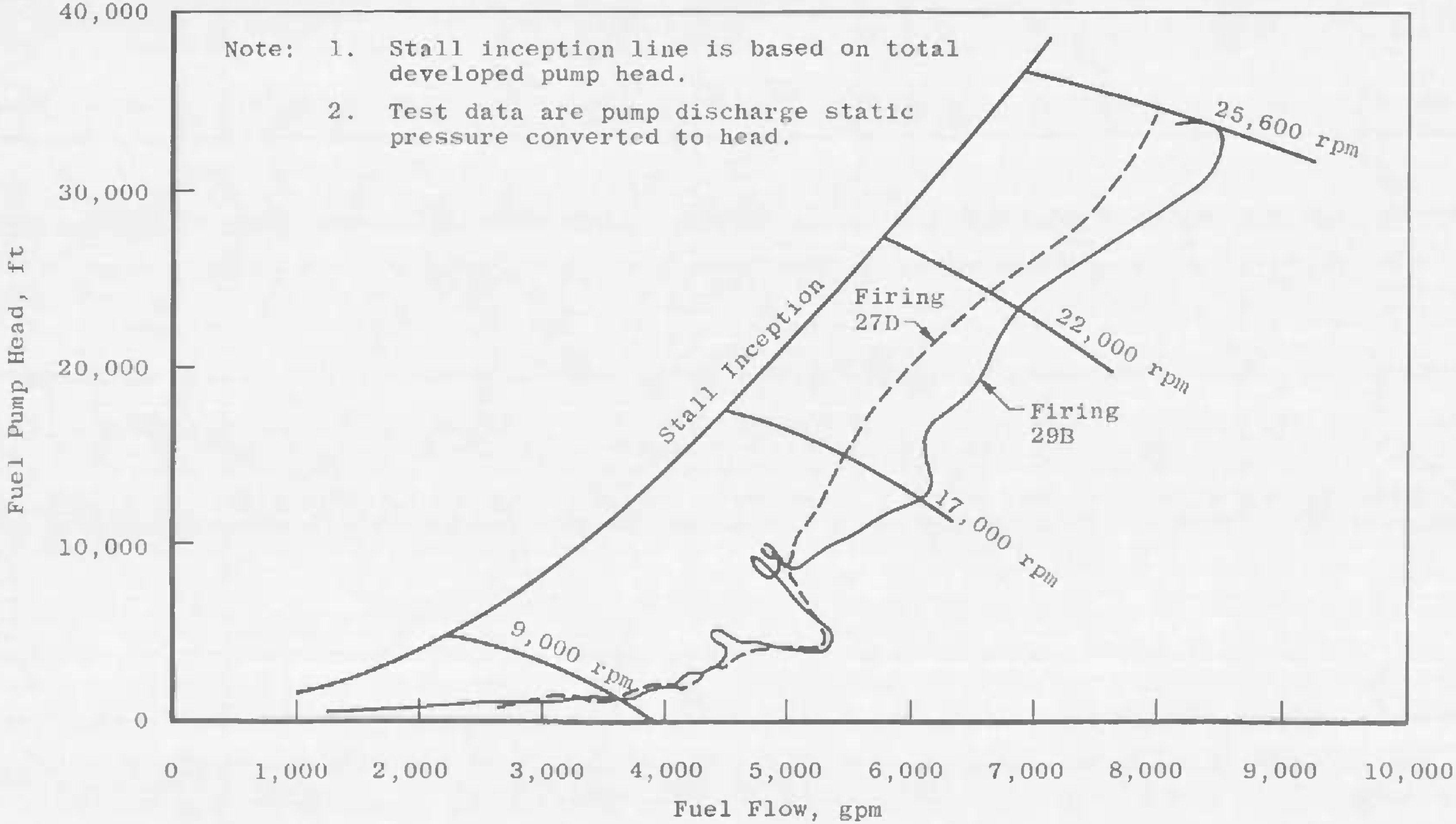
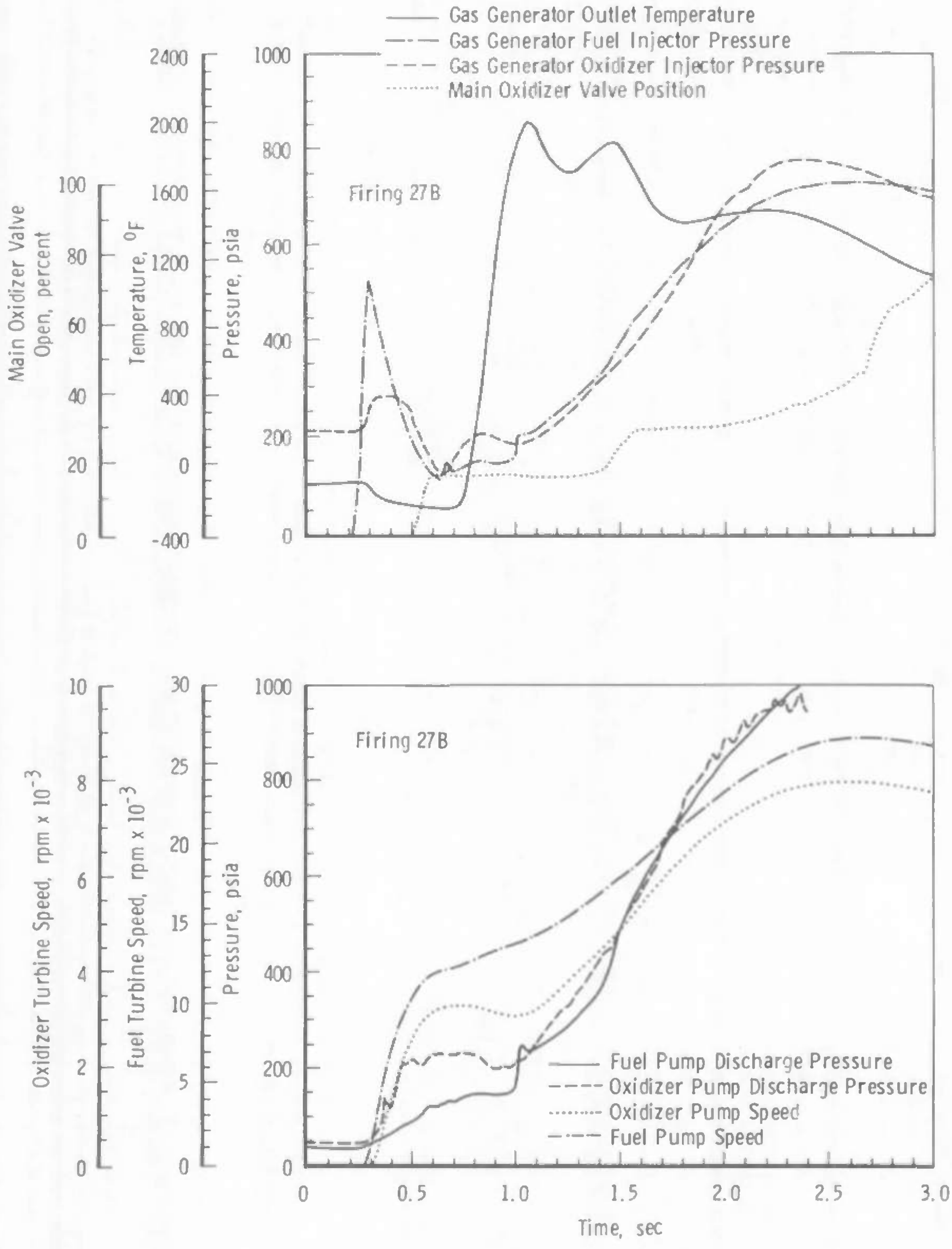
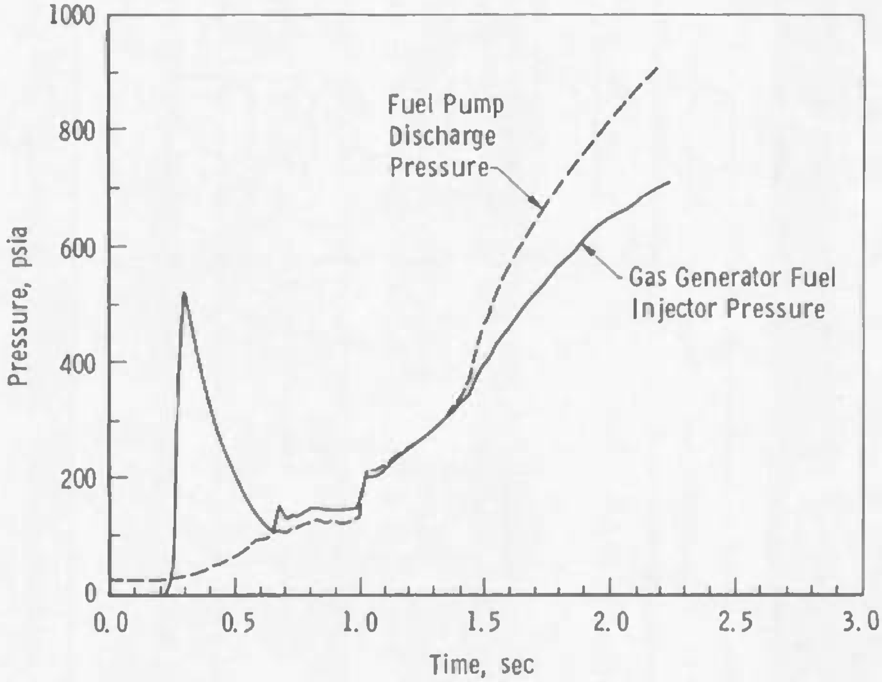


Fig. 9 Fuel Pump Flow versus Head



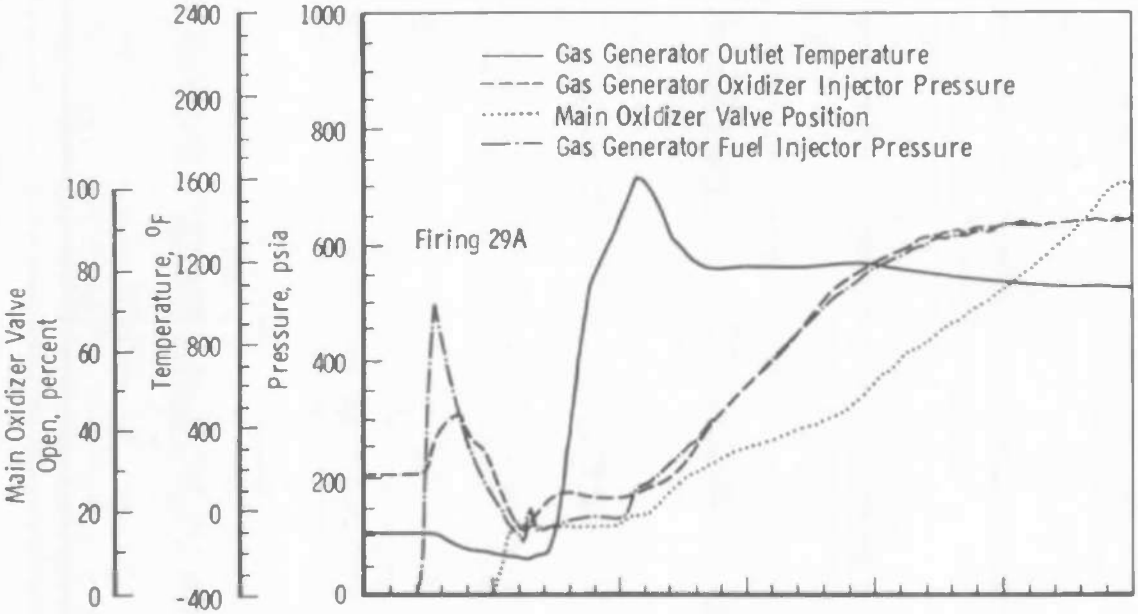
a. Ignition Transient

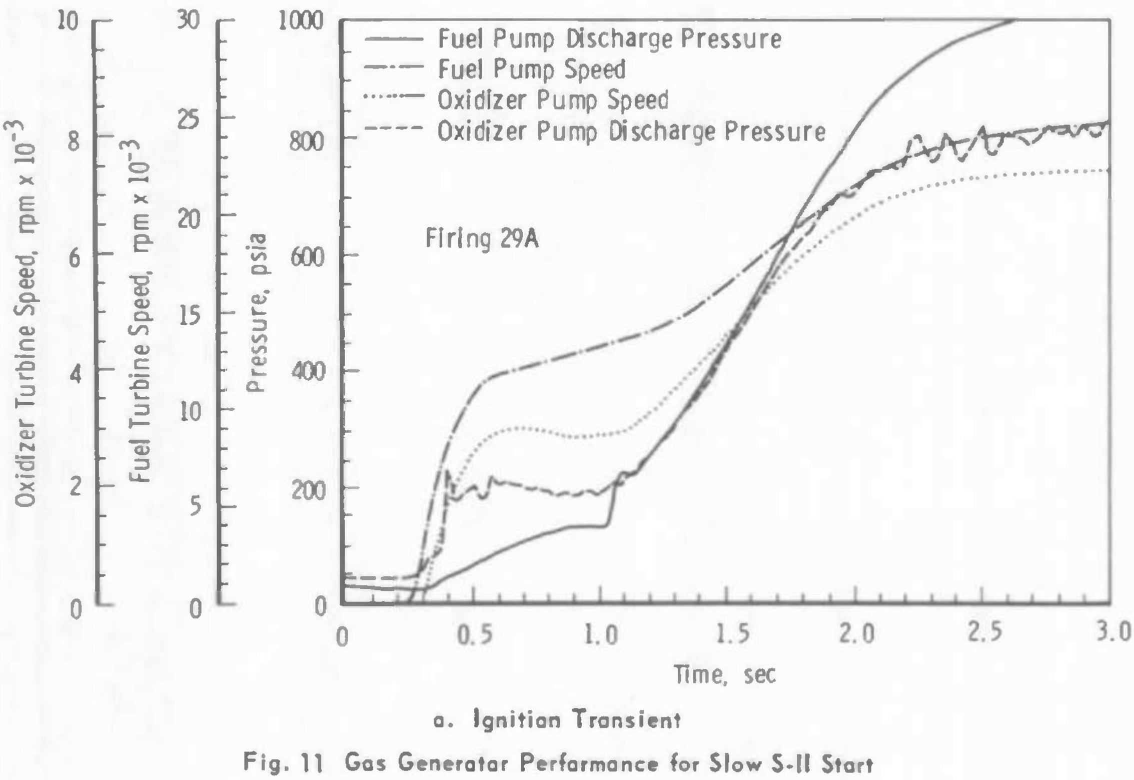
Fig. 10 Gas Generator Performance for Nominal S-II Start



b. Detail of Fuel System Pressure Differential

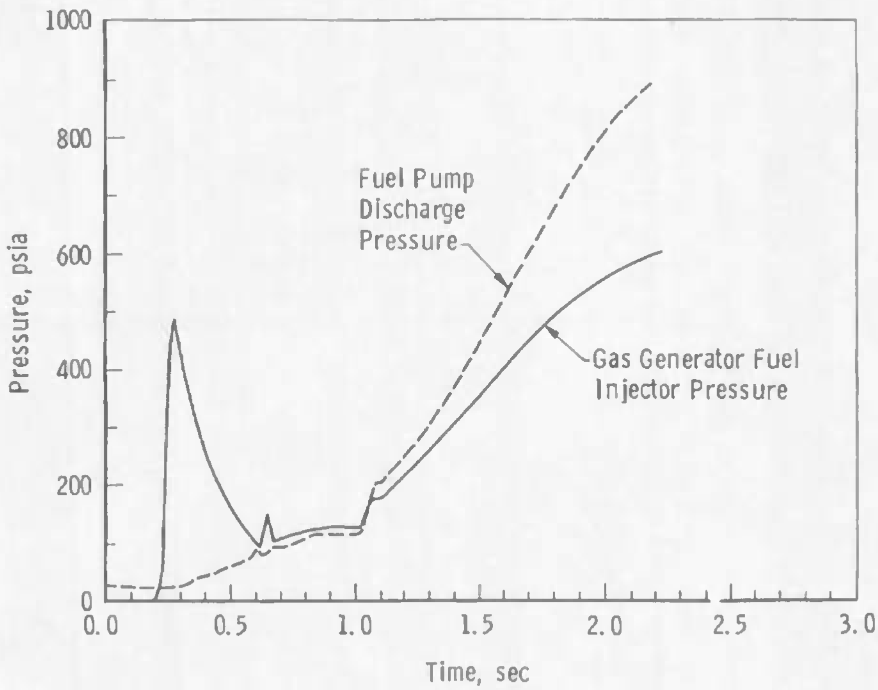
Fig. 10 Concluded





a. Ignition Transient

Fig. 11 Gas Generator Performance for Slow S-II Start



b. Detail of Fuel System Pressure Differential

Fig. 11 Concluded

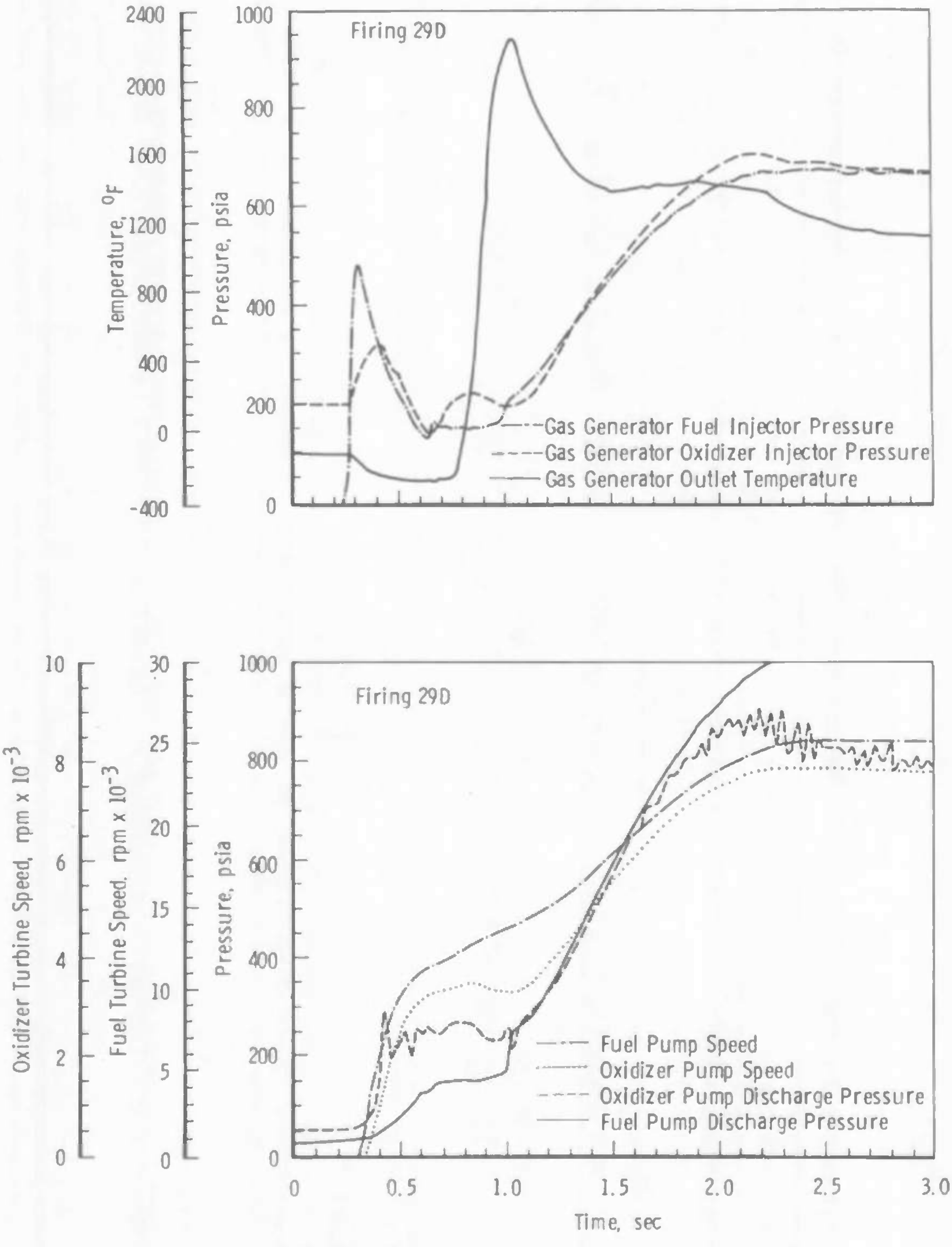
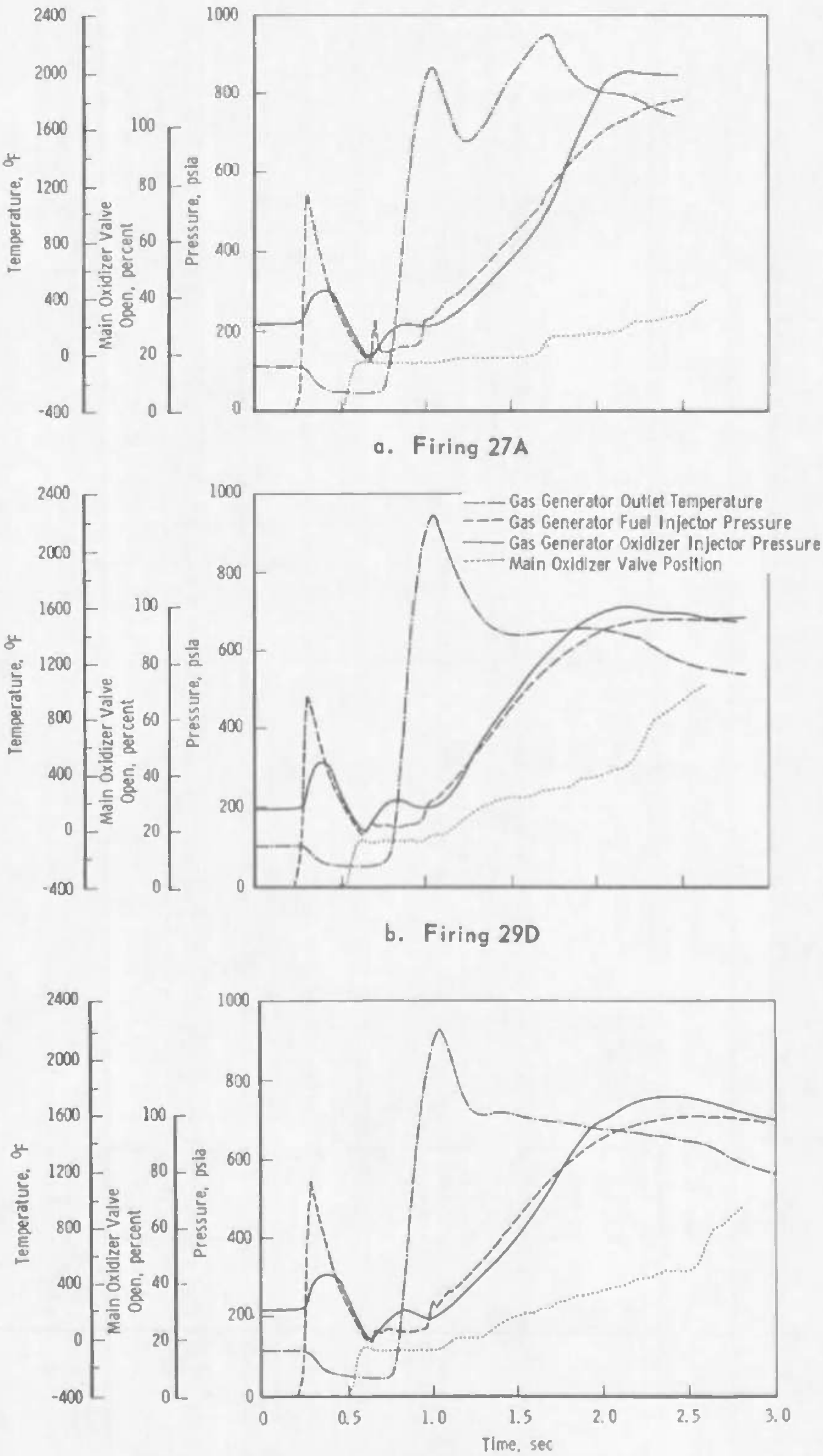


Fig. 12 Gas Generator Performance for Worst-Case First Peak Temperature



a. Firing 27A

b. Firing 29D

c. Firing 01A

Fig. 13 Gas Generator Performance for Worst-Case Second Peak Temperature

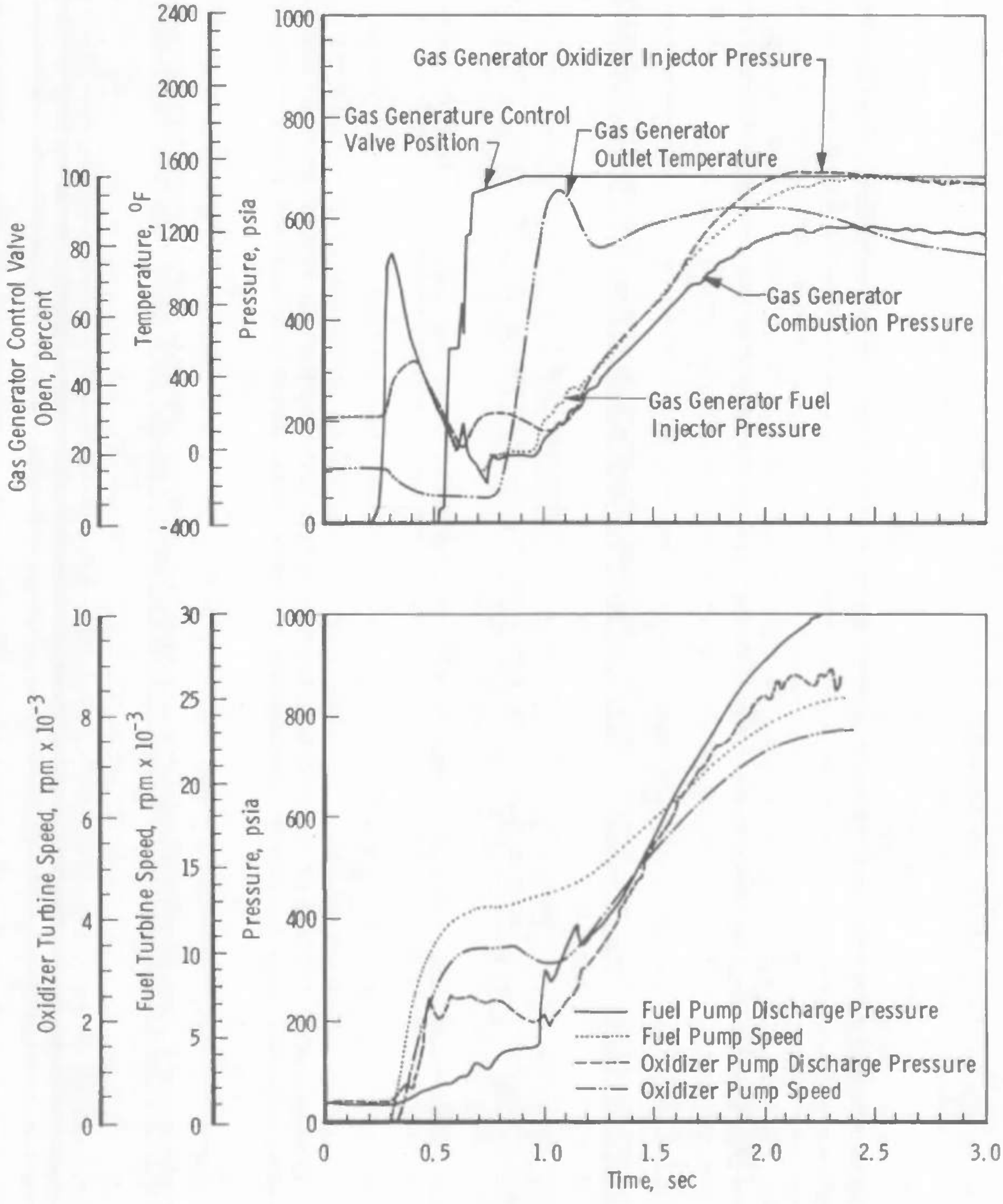


Fig. 14 Gas Generator Performance with Pressure Decay

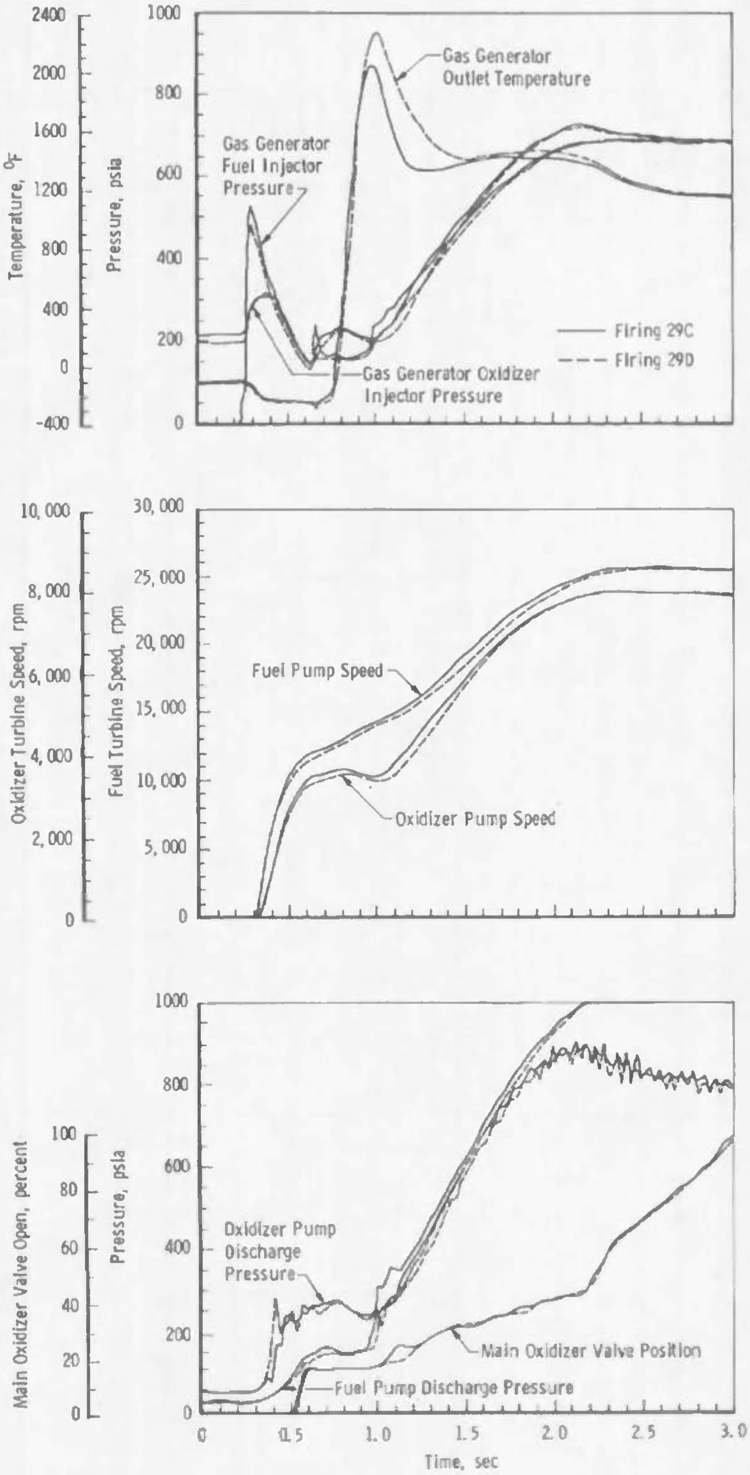


Fig. 15 Gas Generator Performance for Start Tank Pressure Gain Factor Determination

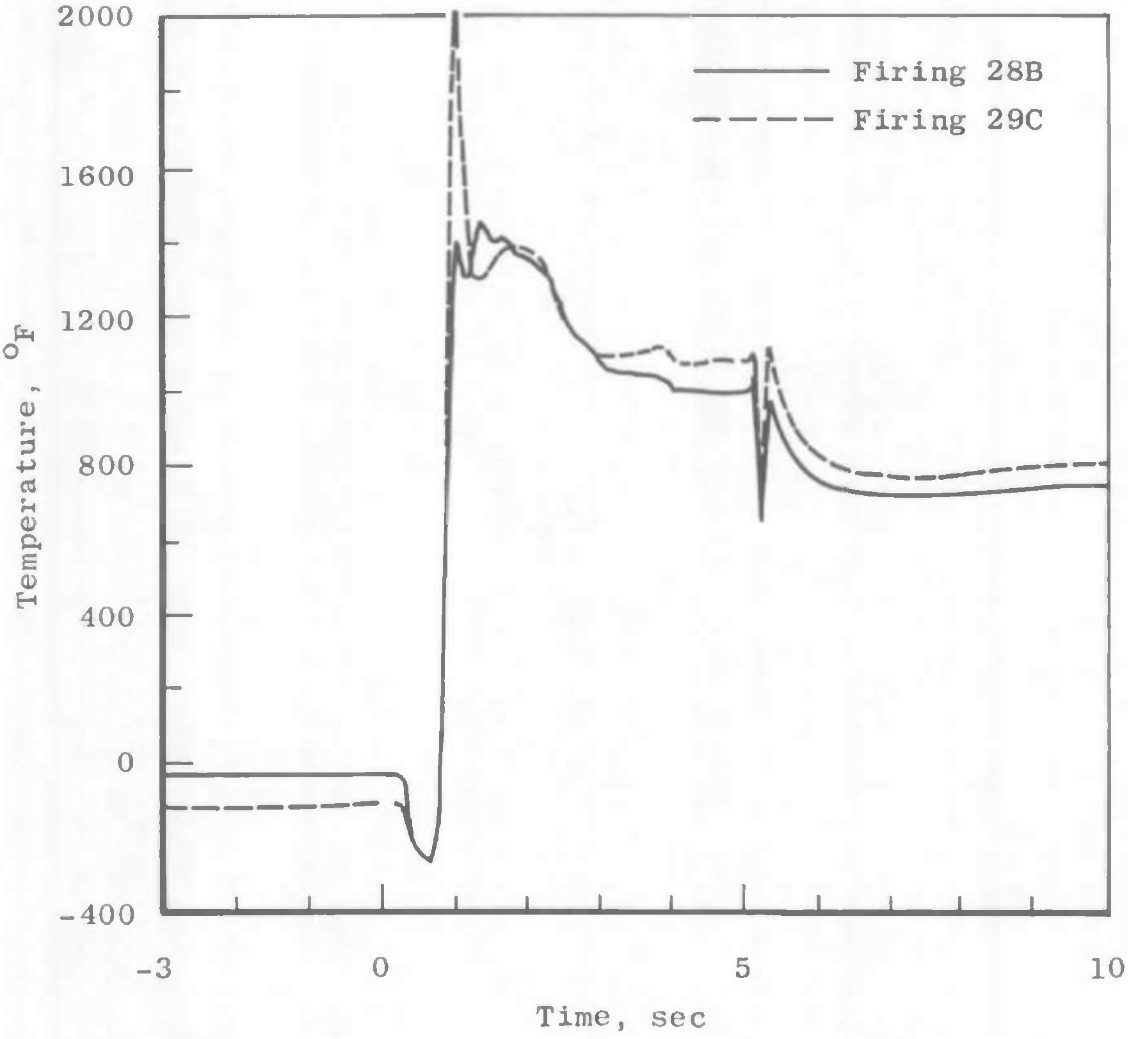
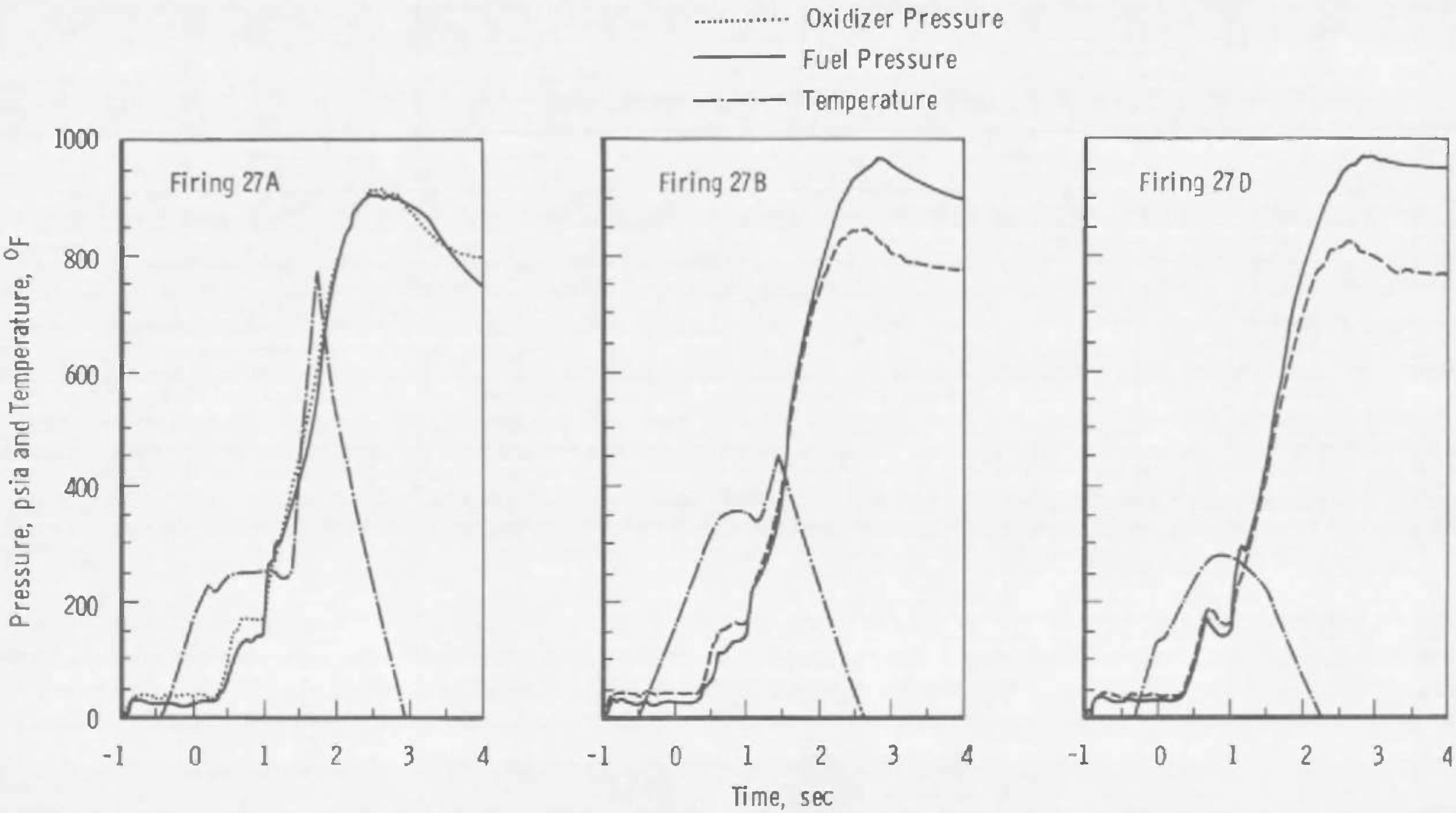
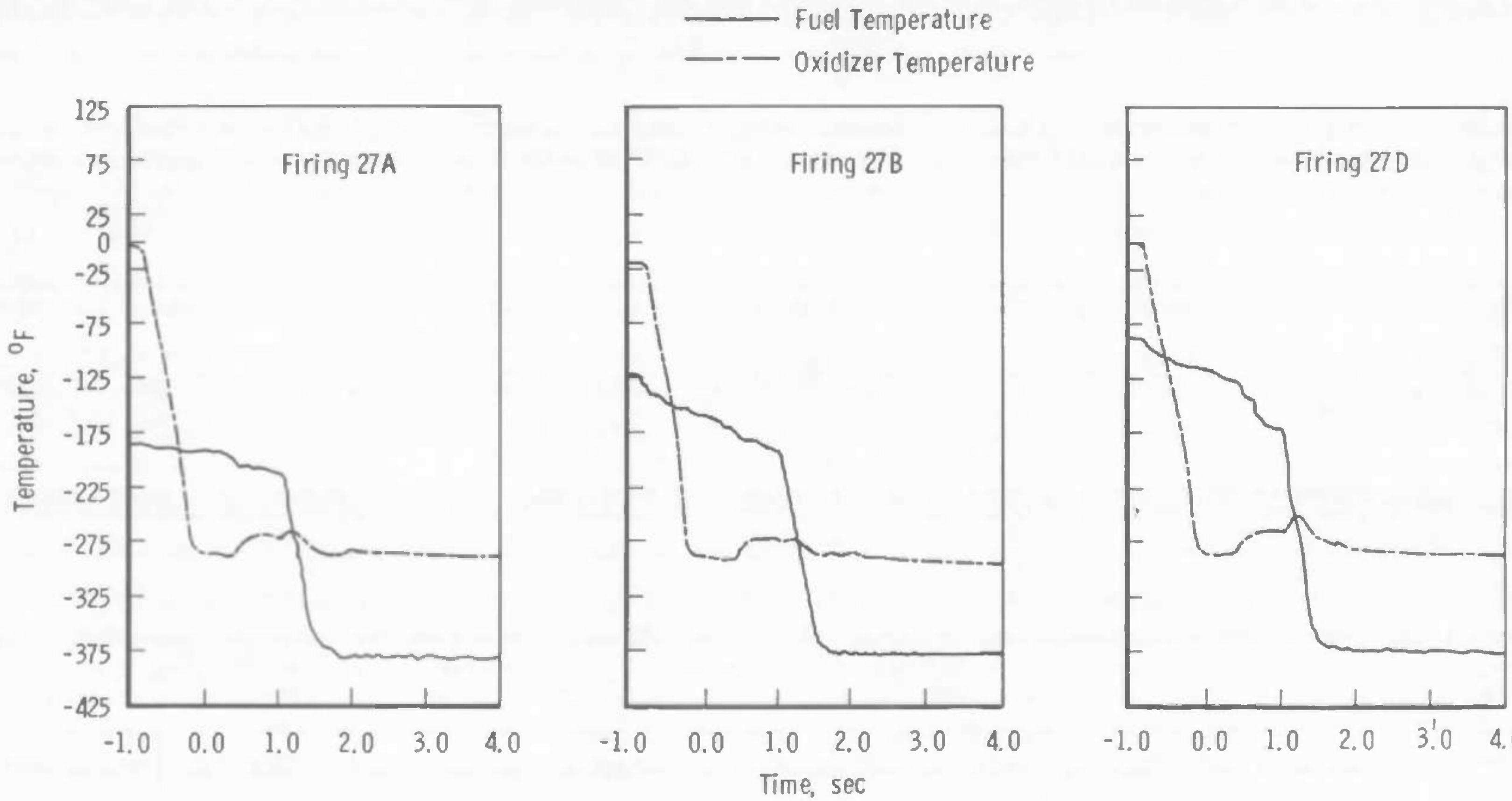


Fig. 16 Gas Generator Outlet Temperature for Firings 28B and 29C



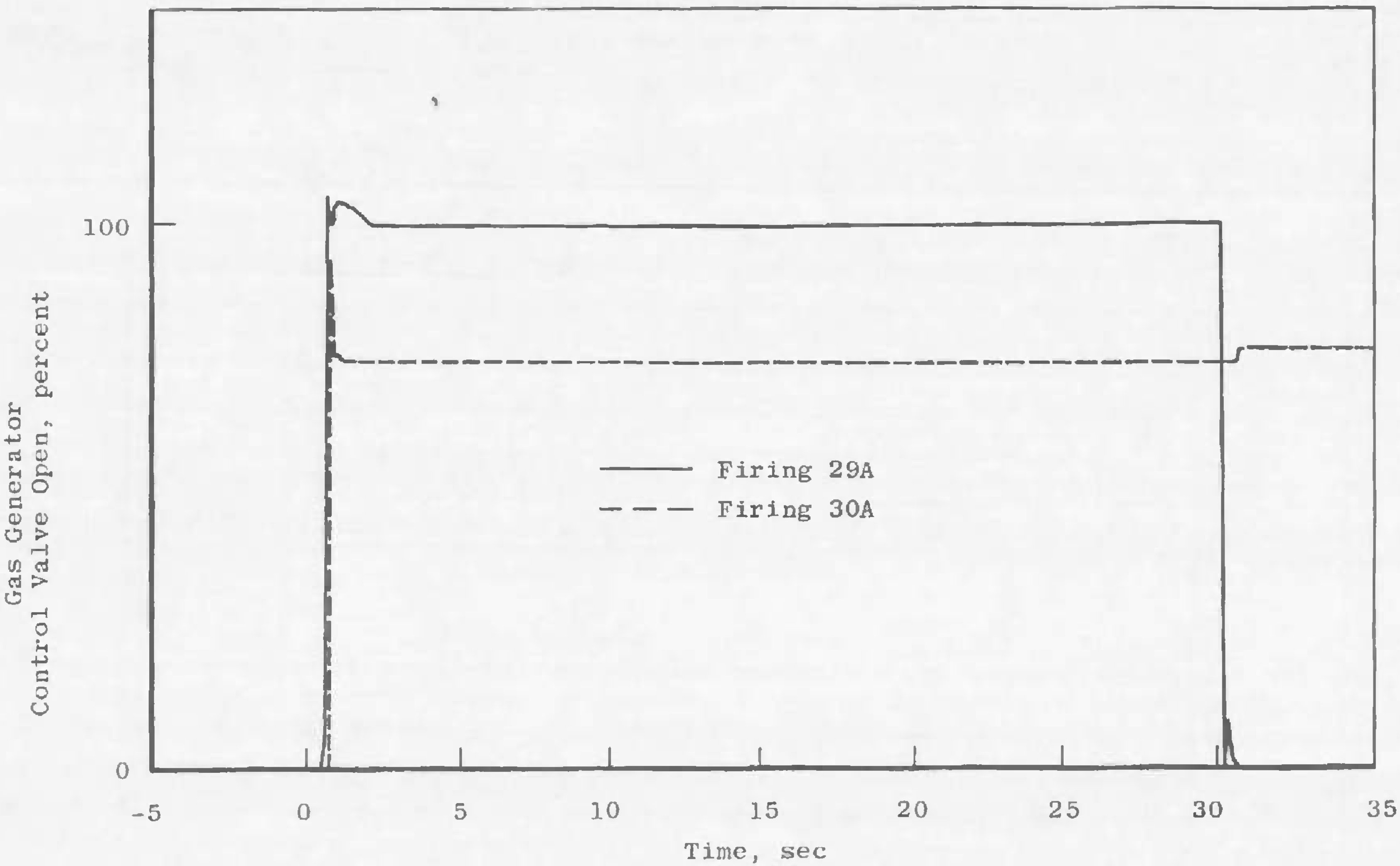
a. Injector Pressures and Combustion Temperature

Fig. 17 Augmented Spark Igniter Performance for Test 27



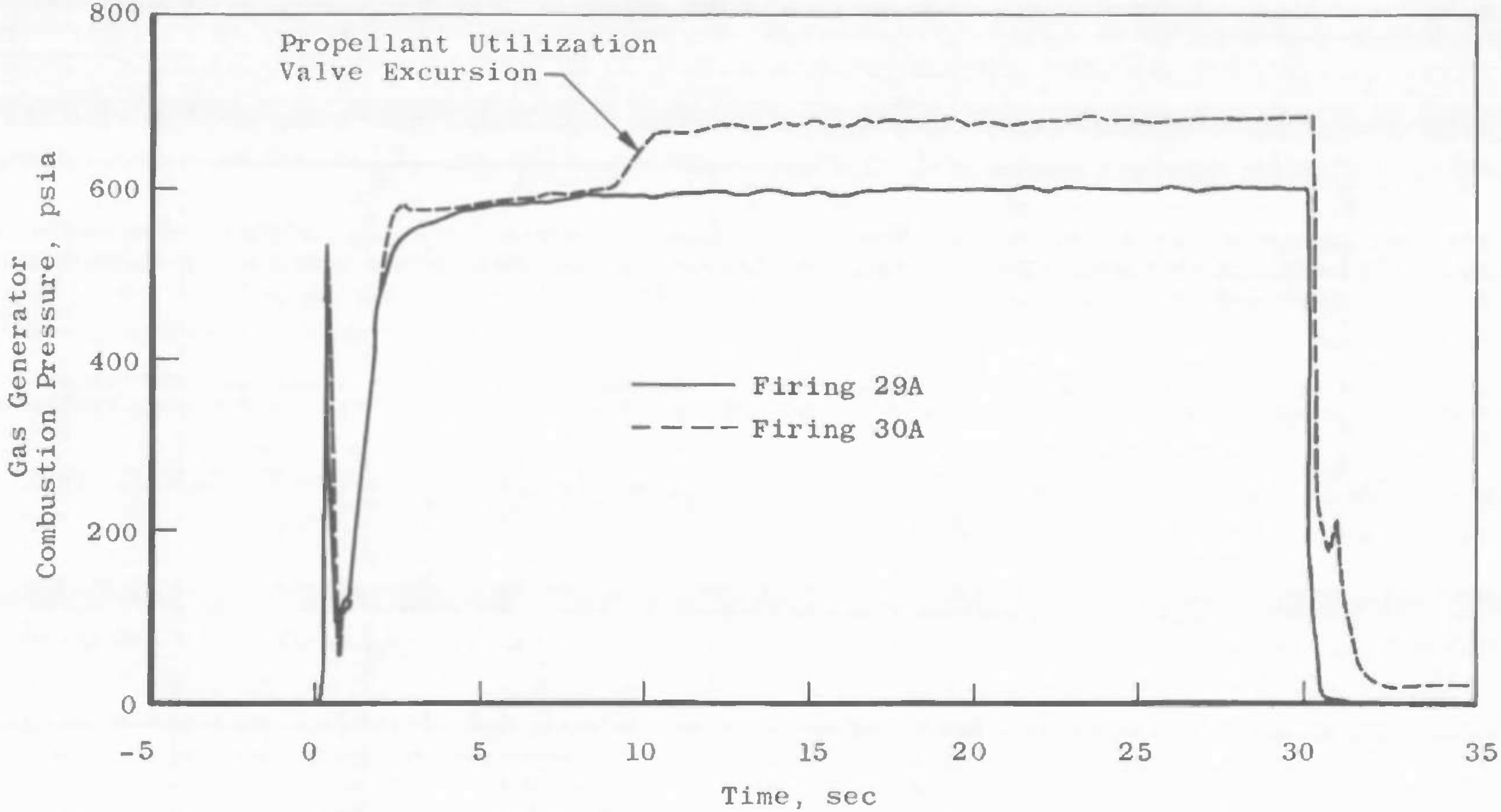
b. Injector Temperatures

Fig. 17 Concluded



a. Control Valve Position

Fig. 18 Gas Generator Malfunction



b. Combustion Pressure

Fig. 18 Concluded

TABLE I
MAJOR J-2 ENGINE S/N J-2052 COMPONENTS
(EFFECTIVE TEST J4-1554-27)

Part Name	P/N	S/N
Thrust Chamber Body	206600-31	4076553
Thrust Chamber Injector Assembly	208021-11	4084917
Fuel Turbopump Assembly	459000-121	4078258
Oxidizer Turbopump Assembly	458175-71	6623549
Start Tank	303439	0064
Augmented Spark Igniter	206280-21	3661349
Gas Generator Fuel Injector and Combustor	308360-11	2008734
Pneumatic Control Assembly	556947	4079720
Electrical Control Package	502670	4078604
Primary Flight Instrumentation Package	703685	4078716
Auxiliary Flight Instrumentation Package	703680	4078718
Main Fuel Valve	409120	4056924
Main Oxidizer Valve	410431	4087228
Gas Generator Control Valve	309040	4055754
Start Tank Discharge Valve	306875	4079062
Oxidizer Turbine Bypass Valve	409930	4048489
Propellant Utilization Valve	251351-11	4068944
Fuel Bleed Valve	309034	4077749
Oxidizer Bleed Valve	309029	4077746
Pressure Actuated Purge Control Valve	557823	4073021
Fuel Flowmeter	251225	4077752
Oxidizer Flowmeter	251216	4074114

TABLE II

ENGINE CONFIGURATION MODIFICATION

Configuration Modification	Test Effectivity
Change Augmented Spark Igniter Oxidizer Orifice Diameter	J4-1554-27
Change Main Oxidizer Valve Opening Time	-27
Replace Fuel Turbopump Assembly	-28
Replace Gas Generator Assembly and Control Valve	-28
Replace Main Oxidizer Valve	-28
Replace Augmented Spark Igniter Oxidizer Supply Line	-28
Change Main Oxidizer Valve Opening Time	-29
Change Gas Generator Fuel Supply Orifice and Oxidizer Turbine Bypass Valve Nozzle Diameter	-29
Change Main Oxidizer Valve Opening Time	-30
Replace Fuel Turbopump Assembly	J4-1801-01
Replace Gas Generator Assembly and Control Valve	-01

TABLE III
ENGINE PURGE SEQUENCE AT AEDC

		Air On / Propellant Drop / Pre-conditioning / Engine Start (a) / Engine Cutoff / Restart Test Engine Start / Engine Cutoff
Turbopump and Gas Generator (Purge Manifold System)	Helium, 82 - 125 psia 50 - 200°F at Customer Connect Panel, 6 scfm Nominal	10 min; 1-3 min; 2-min; (b); Minimum Following Recirculation; 1-3 min; (b); 10 min
Oxidizer Dome and Gas Generator Oxidizer Injector (Engine Pneumatic System)	Helium, 400 ± 25 psig at Engine Pneumatic Package Outlet, 50 to 200°F at Helium Fill Customer Connect, 230 scfm Nominal	15 min; 1 sec (Supplied by Engine Helium Tank during Start and Cutoff Transient
Oxidizer Dome (Facility Line to Instrumentation Port CO3A)	Nitrogen, 400 - 450 psig, 100 - 200°F at Facility Check Valve, 200 scfm Minimum	Duration of Hold; 10 min
Oxidizer Turbopump Intermediate Seal Cavity (Engine Pneumatic System)	Helium, 400 ± 25 psig at Engine Pneumatic Package Outlet, Engine Ambient Temperature, 2600 - 7000 scfm	15 min; Main-Stage Operation (Supplied by Engine Helium Tank)
Thrust Chamber Jacket (Purge and Preconditioning through Customer Connect Line)	Helium, 40 - 60 psig, 50 - 200°F at Customer Connect Panel, 60 scfm Nominal	In Addition To; 15 min; Any Time Water Is On; Any Time Water Is On
	Helium, 12 - 14 psig 50 - 200°F at Customer Connect Panel, 10 scfm Nominal	Except When High Purge On; Duration of Hold; 10 min
	Helium, 1000 psig at Customer Connect Panel, 10 - 20 lb_m/min	

Note: (a) Normal post-test purge procedures shall be used following an aborted test.

(b) May be turned on any time after stabilized main stage is obtained.

TABLE IV
TEST MATRIX SUMMARY

Firing Number		27A	27B	27C	27D	28A	28B	28C	29A	29B	29C	29D	30A	31A	31B	31C	31D
Firing Duration, sec		30.0	5.0	5.0	5.0	30.0	5.0	5.0	30.0	5.0	5.0	5.0	5.0	30	5	3	3
Fuel Pump Inlet Conditions at Engine Start	Pressure, psia	34^{+0}_{-1}	34 ± 1	30^{+1}_{-0}	34 ± 1	41 ± 1	30^{+0}_{-1}	30^{+1}_{-0}	28^{+1}_{-0}	28^{+1}_{-4}	32^{+2}_{-0}	33^{+1}_{-3}	35^{+1}_{-0}	28.0^{+1}_{-0}	26.0^{+1}_{-0}	26.2^{+1}_{-0}	38.0^{+1}_{-0}
	Temperature, °F	-422.1 ± 0.2	-421.3 ± 0.4	-420.1 ± 0.4	-421.1 ± 0.4	-423.2 ± 0.2	-422.1 ± 0.4	-420.1 ± 0.4	-421.1 ± 0.4	-421.4 ± 0.4	-421.4 ± 0.4	-421.4 ± 0.4	-424.1 ± 0.4	-421.4 ± 0.4	-421.4 ± 0.4	-421.4 ± 0.4	-421.4 ± 0.4
Oxidizer Pump Inlet Conditions at Engine Start	Pressure, psia	32^{+0}_{-1}	35^{+1}_{-0}	30^{+2}_{-1}	35 ± 1	41 ± 1	32^{+5}_{-1}	37^{+0}_{-1}	35 ± 1	38 ± 1	41^{+0}_{-1}	41^{+0}_{-1}	41^{+0}_{-1}	41.0^{+0}_{-1}	41.0^{+1}_{-0}	41.0^{+1}_{-0}	41.0^{+1}_{-0}
	Temperature, °F	-295.2 ± 0.4	-294.0 ± 0.4	-293.1 ± 0.4	-294.8 ± 0.4	-293.1 ± 0.4	-295.2 ± 0.4	-293.3 ± 0.4	-294.1 ± 0.4	-293.0 ± 0.4	-293.2 ± 0.4	-295.2 ± 0.4	-293.2 ± 0.4	-295.1 ± 0.4	-294.2 ± 0.4	-295.2 ± 0.4	-295.2 ± 0.4
Start Tank Conditions at Engine Start	Pressure, psia	1300 ± 10	1250 ± 10	1300 ± 10	1200 ± 10	1210 ± 10	1300 ± 10	1300 ± 10	1200 ± 10	1300 ± 10	1300 ± 10	1300 ± 10	1300 ± 10	1300 ± 10	1300 ± 10	1300 ± 10	1300 ± 10
	Temperature, °F	-200 ± 10	-250 ± 10	-200 ± 10	-200 ± 10	-170 ± 10	-200 ± 10	-200 ± 10	-200 ± 10	-200 ± 10	-200 ± 10	-200 ± 10	-200 ± 10	-200 ± 10	-200 ± 10	-200 ± 10	-200 ± 10
Thrust Chamber Temperature Conditions at Engine Start, °F	Throat	-165 ± 10 (a)	-200 ± 10 (a)	-210 ± 10 (a)	-200 ± 10 (a)	-220 ± 10	-150 ± 10 (a)	-260 ± 10 (a)	-250 ± 15	-150 ± 15	-150 ± 15	-150 ± 15	-200 ± 15	-190 ± 15	-200 ± 15	-200 ± 15	-200 ± 15
	Exit	-150 ± 10	-200 ± 10	-250 ± 10	-200 ± 15	-150 (b)	-150 ± 15	-250 ± 10	---	---	---	---	---	---	---	---	---
Fuel Lead Time, sec		1.0 ± 0.05	1.0 ± 0.05	1.0 ± 0.05	1.0 ± 0.05	1.0 ± 0.05	1.0 ± 0.05	1.0 ± 0.05	1.0 ± 0.05	1.0 ± 0.05	1.0 ± 0.05	1.0 ± 0.05	1.0 ± 0.05	1.0 ± 0.05	1.0 ± 0.05	1.0 ± 0.05	1.0 ± 0.05
Fuel in Engine Time, min		60	10	60	15	150	60	60	15	15	60	60	60	T - 60	T - 50	T - 20	T - 30
Oxidizer in Engine Time, min		60	60	60	15	150	10	60	15	15	60	60	60	T - 60	T - 60	T - 60	T - 40
Propellant Recirculation Time, min		10	10	10	10	17	10	10	10	10	10	10	10	T - 10	T - 10	T - 10	T - 10
Main Oxidizer Valve Second-Stage Actuator Temperature, °F		-225 ± 10 (d)	-160 ± 10 (d)	-225 ± 10 (d)	-146 ± 15 (d)	-112^{+0}_{-11} (d)	-110^{+0}_{-10} (d)	-100^{+0}_{-10} (d)	-140 ± 10	-140 ± 10	-150 ± 10	-170 ± 10	-150 ± 10	-150 ± 10	-150 ± 10	-150 ± 10	-150 ± 10
Main Oxidizer Valve Closing Control Line Temperature, °F		-100 ± 10 (d)	-50^{+10}_{-1} (d)	-100 ± 10 (d)	0 ± 10 (d)	-35 ± 10 (d)	-60 ± 10 (d)	-80 ± 10 (d)	0 ± 10	0 ± 10	-60 ± 10	-80 ± 10	0 ± 10	-85 ± 10	-85 ± 10	-82 ± 10	-60 ± 10
Main Oxidizer Valve Second-Stage Ramp Time, sec (Dry Sequence)		---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Pneumatic Control Package Temperature, °F		-200 ± 10 (d)	-50^{+10}_{-1} (d)	-100 ± 10 (d)	0 ± 10 (d)	-55 ± 10 (d)	-75 ± 10 (d)	-75 ± 10 (d)	0 ± 20	0 ± 20	-60 ± 20	-60 ± 20	0 ± 20	-85 ± 10	-85 ± 10	-81 ± 12	-85 ± 10
Crossover Duct Temperature, °F		Ambient	-30^{+0}_{-5} (d)	0 ± 10 (d)	0 ± 10 (d)	-60 ± 10 (d)	0^{+0}_{-10} (d)	0^{+0}_{-10} (d)	-100 ± 25	-100 ± 25	0^{+25}_{-10}	0^{+55}_{-10}	-100 ± 25	0^{+15}_{-10}	0^{+15}_{-10}	-100 ± 15	0^{+15}_{-10}
Gas Generator Oxidizer Bootstrap Line		---	---	---	---	(c)	---	(c)	(c)	(c)	---	---	---	---	---	---	---
Propellant Utilization Valve Position at Engine Start, deg		0	0	0	0	0	0	0	0	0	0	0	0	---	---	---	---
J-2 Engine Mission Simulation		S-II / AS-501	S-II / AS-501	S-II / AS-501	S-II / AS-501	S-IVB / AS-502	S-II / AS-501	S-II / AS-501	S-II / AS-500	S-II / AS-500	S-II / AS-500	S-II / AS-500	S-II / AS-500	S-II / AS-500	S-II / AS-500	S-II / AS-500	S-II / AS-500

(a) Monitor Exit Thermocouple TEC-1E and Thrust Thermocouple TTC-1P; the Warmer Location to be within the Specified Limits
(b) Condition for 1-hr Minimum at Target Temperature
(c) Condition with Ambient Temperature Gaseous Nitrogen for a Minimum of 1 hr
(d) Guideline
(e) Conditioning System "On" when Propellants in Engine and "Off" at T - 90 sec

TABLE V
SUMMARY OF TEST RESULTS

Firing Number		27A	27B	27C	27D	28A	28B	28C	29A	29B	29C	29D	30A	31A	31B	31C	31D
Test Date		4/18/67	4/18/67	4/18/67	4/18/67	5/9/67	5/9/67	5/9/67	5/18/67	5/18/67	5/18/67	5/18/67	5/25/67	7/6/67	7/6/67	7/6/67	7/6/67
Pressure Altitude at Engine Start, ft (Ref. 6)		108,000	107,000	106,000	99,000	104,000	105,000	95,000	98,000	99,000	100,000	99,000	102,000	[illegible]7,000	100,000	108,000	108,000
Firing Duration, sec		30.069	5.069	5.070	5.070	30.072	5.071	5.069	30.072	5.070	5.071	5.073	30.072	30.076	5.073	5.073	5.072
Fuel Pump Inlet Conditions at Engine Start	Pressure, psia	34.7	33.5	30.2	32.0	41.0	26.1	29.9	28.4	27.8	28.6	28.5	28.5	29.0	26.1	28.5	29.0
	Temperature, °F	-421.5	-421.3	-420.1	-421.1	-421.8	-421.9	-420.1	-421.3	-421.6	-421.6	-421.6	-421.5	-420.8	-421.2	-421.0	-421.4
Oxidizer Pump Inlet Conditions at Engine Start	Pressure, psia	37.5	35.2	38.1	35.4	41.2	37.4	38.7	35.0	34.0	40.3	40.1	40.2	40.4	40.4	40.3	40.8
	Temperature, °F	-295.7	-294.2	-295.3	-293.9	-295.4*	-294.5*	-295.1*	-294.1	-294.6	-295.4	-295.1	-295.0	-295.6	-294.7	-295.0	-295.7
Start Tank Conditions at Engine Start	Pressure, psia	1226	1242	1290	1194	1262	1306	1310	1198	1196	1308	1204	1303	1307	1293	1290	1290
	Temperature, °F	-304	-253	-303	-208	-178	-312	-315	-197	-212	-311	-308	-300	-304	-306	-308	-301
Helium Tank Conditions at Engine Start	Pressure, psia	3180	3196	3238	3105	3045	3093	3179	2945	3020	3136	3027	2133	2307	2198	2196	2539
	Temperature, °F	-304	-268	-305	-205	-189	-310	-316	-304	-217	-324	-315	-301	-304	-305	-302	-301
Thrust Chamber Temperature Conditions at Engine Start, °F	Throat	-184	-105	-172	-141	-218	-169	-249	-258	-174	-178	-177	-280	-193	-237	-270	-170
	Exit	-184	-198	-160	-147	-200	-186	-238	-237	-178	-158	-170	-240	-152	-335	-229	-204
Fuel Lead Time, sec		1.012	1.015	1.013	1.009	1.008	1.009	1.010	1.009	1.013	1.009	1.016	1.014	1.010	1.014	1.011	1.014
Fuel in Engine Time, min		110	103	164	27	182	60	279	171	74	79	71	106	69	---	73	112
Oxidizer in Engine Time, min		110	103	164	27	182	60	279	171	74	79	71	106	69	---	73	112
Propellant Recirculation Time, min		10	13	16	19	73	10	10	10	10	13	10	10	10	10	18	10
Gas Generator Outlet Temperature, °F	First Peak	2030	2020	2090	1800	1450	1400	1430	1590	1780	2070	2250	1120	2170	1950	2000	1990
	Second Peak	2250	1590	1690	1620	1200	1450	1330	1180	1270	1390	1430	---	---	---	---	---
Main Chamber Ignition (P_c = 100 psia) Time, sec (Reference t_0)		0.865	0.998	0.983	1.003	0.963	0.945	0.984	1.026	1.013	0.984	0.972	1.000	0.965	0.999	1.004	0.962
Main Oxidizer Valve Second-Stage Initial Movement, sec (Reference t_0)		1.040	1.104	1.100	1.024	0.993	0.866	0.880	0.974	1.017	0.973	0.981	1.002	0.988	1.002	1.007	0.984
Main-Stage Pressure No. 2, sec (Reference t_0)		1.715	1.710	1.710	1.711	1.608	1.594	1.711	1.802	1.704	1.587	1.631	1.853	1.633	1.744	1.790	1.867
550-psia Chamber Pressure Attained, sec (Reference t_0)		2.125	2.098	2.104	2.079	1.980	1.853	1.869	2.054	1.890	1.871	1.805	2.105	1.913	2.042	2.088	1.927
Crossover Duct Temperature at Engine Start, °F	TFTD-3	56	44	0.76	61	-38	13	11	-66	-79	14	34	-90	-19	-17	-60	-18
	TFTD-1	55	-48	-7.7	-50	-33	16	12	-90	-74	18	20	-90	-51	-53	-52	-52
Main Oxidizer Valve Closing Control Line Temperature at Engine Start, °F		-120	-88	-130	-28	-38	-85	-82	+1.3	-23	-110	-107	-1	-139	-102	-98	-81
Main Oxidizer Valve Second-Stage Actuator Temperature at Engine Start, °F		-234	-187	-205	-148	-185	-140	-157	-150	-160	-151	-155	-181	-167	-182	-148	-127
Pneumatic Control Package Temperature at Engine Start, °F		-123	-73	-110	-13	-43	-87	-72	14	+6	-95	-92	-74	-110	-115	-100	-90
Propellant Utilization Valve Position at Engine Start, deg		Null	Null	Null	Null	Null	Null	Null	Null	Null	Null	Null	Null-to-Full Closed at t_0 + 10 sec	Null-to-Full Closed at t_0 + 10 sec	Null	Null	Null

*MicroSADIC Value Minus 1°F

TABLE VI
SUMMARY OF SELECTED ENGINE VALVE TIMING

Firing Number	Start Tank Discharge Valve, Open			Main Fuel Valve, Open			Main Oxidizer Valve, First Stage Open			Main Oxidizer Valve, Second Stage Open		
	Time of Open Signal	Valve Delay Time, sec	Valve Open Time, sec	Time of Open Signal Reference to STDV	Valve Delay Time, sec	Valve Open Time, sec	Time of Open Signal Reference to STDV	Valve Delay Time, sec	Valve Open Time, sec	Time of Open Signal Reference to STDV	Valve Delay Time, sec	Valve Open Time, sec
27A	0	0.159	0.148	-1.018	0.054	0.060	0.440	0.065	0.059	0.410	0.659 1.190	2.598 2.170
27B	0	0.162	0.147	-1.013	0.088	0.068	0.441	0.065	0.071	0.441	0.856 0.978	2.171 2.061
27C	0	0.170	0.158	-1.012	0.063	0.067	0.439	0.063	0.064	0.439	0.649 1.070	2.490 2.080
27D	0	0.168	0.145	-1.009	0.066	0.067	0.440	0.063	0.067	0.440	0.675 0.986	2.349 1.960
28A	0	0.150	0.138	-1.008	0.067	0.075	0.442	0.060	0.065	0.441	0.550	2.157
28B	0	0.163	0.151	-1.009	0.055	0.068	0.443	0.050	0.055	0.440	0.508	2.233
28C	0	0.173	0.158	-1.008	0.065	0.070	0.440	0.064	0.057	0.440	0.545	2.307
29A	0	0.151	0.138	-1.010	0.055	0.070	0.443	0.058	0.050	0.440	0.540	1.920
29B	0	0.157	0.145	-1.011	0.053	0.064	0.445	0.068	0.055	0.445	0.575	2.010
29C	0	0.168	0.153	-1.005	0.052	0.070	0.440	0.055	0.060	0.440	0.530	2.058
29D	0	0.169	0.153	-1.012	0.052	0.067	0.440	0.055	0.055	0.440	0.540	2.050
30A	0	0.160	0.150	-1.013	0.058	0.067	0.445	0.058	0.054	0.446	0.500	2.370
01A	0	0.158	0.148	-1.010	0.053	0.050	0.442	0.051	0.054	0.442	0.548	2.383
01B	0	0.159	0.132	-1.014	0.055	0.048	0.441	0.052	0.060	0.441	0.500	2.452
01C	0	0.168	0.155	-1.011	0.056	0.052	0.442	0.064	0.056	0.442	0.561	2.417
01D	0	0.158	0.150	-1.013	0.059	0.048	0.440	0.058	0.050	0.440	0.549	2.420

Firing Number	Gas Generator Fuel Poppet, Open			Gas Generator Oxidizer Poppet, Open			Oxidizer Turbine Bypass Valve, Close			Start Tank Discharge Valve, Close		
	Time of Open Signal Reference to STDV	Valve Delay Time, sec	Valve Open Time, sec	Time of Open Signal Reference to STDV	Valve Delay Time, sec	Valve Open Time, sec	Time of Close Signal Reference to STDV	Valve Delay Time, sec	Valve Close Time, sec	Time of Close Signal Reference to STDV	Valve Delay Time, sec	Valve Close Time, sec
27A	0.440	0.119	0.037	0.440	0.219	0.103	0.440	0.114	0.284	0.440	0.100	0.270
27B	0.441	0.119	0.029	0.441	0.202	0.098	0.441	0.221	0.277	0.441	0.105	0.281
27C	0.439	0.119	0.032	0.439	0.201	0.088	0.439	0.222	0.286	0.439	0.106	0.283
27D	0.440	0.113	0.030	0.440	0.201	0.078	0.440	0.220	0.272	0.440	0.108	0.290
28A	0.442	0.088	0.049	0.442	0.178	0.081	0.442	0.208	0.270	0.442	0.088	0.278
28B	0.440	0.093	0.055	0.440	0.193	0.071	0.440	0.222	0.278	0.440	0.107	0.281
28C	0.443	0.093	0.050	0.448	0.182	0.060	0.440	0.233	0.272	0.440	0.100	0.292
29A	0.440	0.090	0.048	0.440	0.181	0.061	0.440	0.223	0.275	0.440	0.104	0.274
29B	0.445	0.098	0.045	0.445	0.185	0.061	0.445	0.227	0.278	0.445	0.105	0.289
29C	0.443	0.088	0.062	0.440	0.192	0.068	0.440	0.231	0.285	0.440	0.105	0.289
29D	0.440	0.093	0.021	0.440	0.195	0.066	0.440	0.230	0.318	0.440	0.108	0.288
30A	0.448	---	---	0.445	---	---	0.446	0.210	0.283	0.446	0.099	0.278
01A	0.442	0.090	0.068	0.442	0.187	0.076	0.442	0.271	0.300	0.442	0.105	0.293
01B	0.441	0.098	0.065	0.441	0.192	0.080	0.441	0.288	0.380	0.441	0.102	0.282
01C	0.442	0.097	0.054	0.442	0.195	0.058	0.442	0.265	0.277	0.442	0.107	0.292
01D	0.440	0.092	0.080	0.440	0.185	0.060	0.440	0.280	0.296	0.440	0.100	0.277

TABLE VI (Concluded)

Firing Number	Main Fuel Valve		Main Oxidizer Valve		Gas Generator Oxidizer Poppet		Gas Generator Fuel Poppet		Oxidizer Turbine Bypass Valve	
	Delay* Time, sec	Closing Time, sec	Delay* Time, sec	Closing Time, sec	Delay* Time, sec	Closing Time, sec	Delay* Time, sec	Closing Time, sec	Delay* Time, sec	Opening Time, sec
27A	0.117	0.314	0.100	0.228	0.035	0.017	0.076	0.034	0.259	0.513
27B	0.127	0.352	0.064	0.207	0.034	0.016	0.078	0.028	0.239	0.508
27C	0.127	0.353	0.065	0.211	0.035	0.014	0.077	0.025	0.241	0.492
27D	0.128	0.334	0.064	0.200	0.033	0.017	0.080	0.028	0.232	0.500
28A	0.132	0.306	0.100	0.208	0.032	0.014	0.078	0.025	0.235	0.550
28B	0.125	0.345	0.065	0.201	0.030	0.013	0.076	0.021	0.229	0.557
28C	0.135	0.300	0.070	0.205	0.031	0.014	0.077	0.022	0.233	0.570
29A	0.130	0.370	0.095	0.205	0.032	0.012	0.070	0.020	0.239	0.561
29B	0.125	0.360	0.075	0.215	0.033	0.013	0.080	0.020	0.242	0.563
29C	0.125	0.355	0.075	0.200	0.033	0.013	0.076	0.020	0.240	0.574
29D	0.125	0.353	0.070	0.200	0.035	0.014	0.076	0.020	0.238	0.580
30A	0.133	0.368	0.098	0.266	---	---	---	---	0.230	0.491
01A	0.115	0.323	0.098	0.199	0.018	0.029	0.070	0.225	0.282	0.803
01B	0.122	0.365	0.070	0.203	0.019	0.027	0.072	0.020	0.259	0.702
01C	0.124	0.354	0.070	0.206	0.019	0.032	0.076	0.020	0.268	0.721
01D	0.118	0.341	0.070	0.205	0.018	0.030	0.072	0.020	0.261	0.684

*Delay times are referenced to engine cutoff.

TABLE VII
MAIN OXIDIZER VALVE PRE-TEST DRY SEQUENCE TIMING

Test Number	Opening Time				Main Oxidizer Valve Closing Control Orifice Size, diam	Specified Second-Stage Ramp Time, msec
	First Stage		Second Stage			
	Delay, msec	Travel, msec	Delay, msec	Travel, msec		
27	45	46	475	1425	10.82 scim, Thermostatic Orifice	$1430 {+20 \atop -10}$
28	49	41	497	1470	0.260 in.	$1450 {+10 \atop -20}$
29	51	44	472	1323	0.270 in.	$1350 {+10 \atop -20}$
30	48	50	516	1454	0.260 in.	$1430 {+20 \atop -10}$
01	48	50	507	1480	0.260 in.	$1430 {+20 \atop -10}$

TABLE VIII

SUMMARY OF MAIN OXIDIZER VALVE OPERATION AND THERMAL CONDITIONING

Test Number	Thrust Chamber Ignition, sec	Engine Vibration		MOV Second Stage Initial Movement, sec	MOV Friction Value	Main Oxidizer Valve Ramp Time		TSOVAL, °F[1]		TSOVF,[1] °F	TSOVC, °F	POVCC,[1] psia	PHRO,[1] psia	TBHR,[1] °F	THET,[1] °F	PHET,[1] psia
		Duration	Initial Occurrence*			Measured	Sequence Average	-1	-2							
27A	0 963	160	0.956	1 040	193	2 698	1 423	-120	-21	---	-234	---	-2 98	-123	-304	3189
27B	0 998	5 / 7	0 895 / 0 990	1 104	490	2 171		-85	-46	---	-187		28 52	-73	-260	3195
27C	0 982	178	0.980	1 100	173	2 498		-130	-49	---	-206	---	-2.48	-110	-305	3238
27D	1 003	109	0 998	1 024	29	2 349		-28	-10	- -	148	---	-2 98	-13	-209	3185
28A	0 986	91	0 982	0 993	86	2 167	1 450	-33	-38	-114	-165	-0 16	-2 98	-43	-189	3045
28B	0 945	65	0 945	0 966	17	2 325		0 40	-85	-85	146	0 34	-2 23	-62	-310	3097
28C	0 984	162	0 982	0 990	55	2 307		-29	-92	-102	-157	0 76	-2 64	-72	-315	3179
29A	1 026	7	1 026	0 974	115	1 920	1 322	-17	+1 3	-101	-150	2.41	-1 51	-14	-204	2945
29B	1 013	88	1 015	1 017	162	2 010		-1 14	-23	-105	-160	2 41	-2 59	8	-217	3026
29C	0 954	6 / 120	0 907 / 0 953	0 973	84	2 050		-30	-110	-100	-151	1 33	-2 01	-95	-324	3135
29D	0 972	11 / 18	0 927 / 0 975	0 981	96	2 050		-40	-107	-105	-155	57 8	-3 67	-92	-315	3027
30A	1 000	141	0 998	1 002	18	2 370	1 454	-8 4	-1 4	161	-161	3 13	-0 57	-24	-301	2123
01A	0 965	120	0 969	0 988	28	2 362	1 480	-133	-130		-168	-4 02	2 72	-122	-304	2309
01B	0 999	13	0 999	1 002	29	2.453		-102	-102		-151	-0 65	-4 02	-124	-305	2162
01C	1 004	149	1 002	1 037	46	2 417		-79	-98		-147	1 24	-2 85	-109	-307	2199
01D	0 962	168	0 948	0 984	100	2 420		-46	-81		124	2 47	-2 85	-108	-301	2542

*Times presented are referenced to start tank discharge valve (t_o)

[1] Values recorded at engine start

TSOVAL - Main oxidizer valve closing control line temperature

TSOVF, TSOVC - Main oxidizer valve second stage actuator temperature

TBHR - Helium regulator temperature

THET - Helium tank temperature

POVCC - Main oxidizer valve closing control pressure

PHRO - Helium regulator outlet pressure

PHET - Helium tank pressure

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ALTITUDE TESTING OF THE J-2 ROCKET ENGINE IN PROPULSION ENGINE TEST CELL (J-4) (TESTS J4-1554-27 THROUGH J4-1801-01)

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

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13 ABSTRACT

Five test periods which included 16 starts of the Rocketdyne J-2 Rocket Engine were conducted at pressure altitudes from 95,000 to 108,000 ft in Test Cell J-4. The tests were Saturn S-V/S-II start transient investigations using a flight configuration J-2 engine (S/N J-2052) and S-IVB battleship stage. Firing durations were programmed for 5 or 30 sec, and the accumulated firing time was 206.1 sec. These tests completed the first series of full-scale S-V/S-II start transient investigation testing to be conducted at pressure altitudes in excess of 95,000 ft.

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altitude testing						
start transient investigations						
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16-3

1. Rocket motors -- J-2
2. " " -- Ignition
3. " " -- Performance.