AGC-2414 (Vol. 2)

SECONDARY GAS GENERATOR SYSTEM

PRELIMINARY DESIGN

VOLUME II FINAL REPORT (APPENDICES)

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November 1962

Report No. 2414

SECONDARY GAS GENERATOR SYSTEM
PRELIMINARY DESIGN

VOLUME II - FINAL REPORT (APPENDICES)

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SPACE PROPULSION DIVISION
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- *Note: (1) An individual Table of Contents, including a list of tables and figures, is presented at the beginning of each Appendix.
- (2) Each Appendix is separately numbered.
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APPENDIX A
MODEL SPECIFICATION

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<u>No.</u>	<u>Title</u>
P-087844	Interface Control Drawing Gas Generator Output
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P-087846	Interface Control Drawing Liquid Oxygen Input
P-087847	Interface Control Drawing Nitrogen Purge Input
P-087797	Interface Control Drawing Electrical Connections
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P-087981	Block Diagram System Control
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P-087988	Interface Control Drawing Instrumentation Nitrogen Line
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CODE IDENT. NO. 70143

AGC-14098
19 October 1962

SYSTEM DEVELOPMENT SPECIFICATION

SECONDARY GAS GENERATOR SYSTEM, SPECIFICATION FOR

1. SCOPE

1.1 This specification defines the limits for a gas generator system to be used in testing special rocket engines.

2. APPLICABLE DOCUMENTS

2.1 Governmental documents.- The following document, of the issue in effect on the date of invitation for bids, forms a part of this specification to the extent specified herein.

STANDARD

Military

MIL-STD-143 Specifications and Standards, Order of Precedence

(Copies of the document required by contractors in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.)

2.2 Aerojet-General Corporation documents.- Unless otherwise specified, the following documents, of the latest issue in effect, form a part of this specification to the extent specified herein.

DRAWINGS

087797	Interface Control Drawing - Electrical Connectors
087844	Interface Control Drawing - Gas Generator Output
087845	Interface Control Drawing - Liquid Hydrogen Input

087846	Interface Control Drawing - Liquid Oxygen Input
087847	Interface Control Drawing - Nitrogen Purge Input
087980	Logic Diagram - Control Director
087981	Block Diagram - System Control
087982	Propellant Feed System
087988	Interface Control Drawing - Instrumentation Nitrogen Line

3. REQUIREMENTS

3.1 Qualification.- The gas generator system supplied under this specification shall be a system which has passed the qualification tests specified herein and is listed, or approved for listing, on the qualified products list.

3.2 Selection of specifications and standards.- Specifications and standards for necessary commodities and services not specified herein shall be selected in accordance with Standard MIL-STD-1143 (see 2.1), except as provided in 3.2.1 and 3.2.2.

3.2.1 Commercial parts.- Commercial parts having suitable properties may be used when, on the date of invitation for bids, suitable standard parts are not available. In any case, commercial utility parts such as screws, bolts, nuts, cotter pins, etc., having suitable properties may be used provided:

- (a) They can be replaced by standard parts (MS or AN) without alteration.
- (b) The corresponding standard part numbers are referenced in the parts list and, if practical, on the contractor's drawings.

3.2.2 Standard parts.- With the exception in 3.2.1, AN and MS standard parts shall be used where they suit the purpose. They shall be identified on the drawings by their part numbers.

3.3 Materials.- Materials shall be corrosion-resistant and suitable for the purpose intended. Materials which are subject to deterioration when exposed to climatic and environmental conditions during service usage shall be suitably protected to prevent such deterioration in a manner that will not prevent compliance with the performance requirements of this specification. Any protective coating that will crack, chip, scale, deteriorate under nuclear radiation, or retain nuclear radiation shall not be used. Organic materials shall not be used without specific approval of the contracting agency.

3.4 Design.- The gas generator system shall be designed to produce hot gas by the oxidation of a portion of the liquid hydrogen using liquid oxygen as the oxidizing agent. The system shall consist of three gas generator units, each of which shall include a gas generator with its own sensors, indicators, and controls. The system shall conform to AGC Drawing 087981 (see 2.2).

3.4.1 Gas generator.- Each gas generator used in the system shall consist of a suitable combustion chamber with an injector for liquid hydrogen and liquid oxygen, and a suitable igniting device. Each generator shall be mounted on a separate skid for handling by a forklift-type device. Each generator shall include a method for automatically purging the injector gaseous nitrogen. Propellant and purge feed shall conform to AGC Drawing 087982 (see 2.2).

3.4.1.1 Starting voltage.- The igniting devices shall initiate combustion when 110 volts ± 10 percent of alternating current at 400 ± 0.7 cycles per second, single phase (110 acv, 400 cps, 1 ϕ) is applied.

3.4.1.2 Propellant availability.- Propellants shall be available as shown in Table I under conditions of full flow:

TABLE I

Propellant Availability

Propellant	Pressure (psig) maximum	Density (lb/cu ft.)
Liquid Hydrogen	450	4.0 $\pm 5\%$
Liquid Oxygen	450	70 $\pm 2\%$

3.4.1.3 Gaseous nitrogen.- Gaseous nitrogen for purging shall be available at a pressure not greater than 450 pounds per square inch (psig) through a pressure regulator from 3600 psig. Pressurized nitrogen gas for instrumentation and control shall be available at a pressure not greater than 1000 psig.

3.4.1.4 Connections.-

3.4.1.4.1 Input connections.-

3.4.1.4.1.1 Hydrogen connection.- Liquid hydrogen shall be supplied by a vacuum-jacketed pipe which has a nominal diameter of 12 inches with a flanged connection, as indicated in the interface control on AGC Drawing 087845 (see 2.2).

3.4.1.4.1.2 Oxygen connection.- The liquid oxygen connection shall be an insulated pipe which has a nominal diameter of eight inches with a flanged connection as indicated on AGC Interface Control Drawing 087846 (see 2.2).

3.4.1.4.1.3 Nitrogen connection.- The purging nitrogen connection shall be a flanged pipe with a nominal diameter of eight inches as indicated on AGC Interface Control Drawing 087847 (see 2.2). Instrumentation and control nitrogen connection shall be a 1/2-inch pipe with coupling connection as indicated on AGC Interface Control Drawing 087988 (see 2.2).

3.4.1.4.2 Output connection.- The output connection of each gas generator shall be a flanged pipe connection which has a nominal diameter of 24 inches as indicated on AGC Interface Control Drawing 087844 (see 2.2).

3.4.2 Control system.- The control system shall be a modified open-loop system. It shall consist of the control systems of three gas generator units with executive function controls interlocked to form one master system. It shall accept remote signals for continuous automatic control, monitor, and display of critical system conditions. The control system shall be divided into three parts, each of which shall be mounted in a different location. Insofar as is possible, electrical and electronic components, which would be subject to radiation damage or would require preventive maintenance, shall not be mounted on the gas generator skids. Only those components, such as gas generator sensors, propellant control valves, ignition devices, and controls, attached directly to the gas generators shall be mounted on the skids. Manual controls, switches, and indicators shall be specified by the contractor for incorporation into the facility by the contracting agency. All other items, such as signal conditioners, repeaters, and relays, shall be mounted on panels suitable for rack mounting in a remote building. Input and output connectors shall be as specified on AGC Drawing 087797 (see 2.2). Control system logic shall conform to AGC Drawing 087980 (see 2.2).

3.4.2.1 Operating voltage.- The control system shall operate from a source which provides 28 ± 1 volts direct current, 110 vac 60 cps 1 ϕ , and 120/208 vac ± 10 percent 400 ± 0.7 cps 3 ϕ .

3.4.2.2 Over-ride.- All automatic controls shall be provided with manual over-ride facilities.

3.4.2.3 Sensors.- Sensors shall be provided to detect all necessary system operating conditions and provide signals to indicate normal or faulty operation and to prevent failure due to malfunction.

3.4.2.4 Indicators.- Indicators shall show the status of each gas generator in the system. They shall indicate safe or faulty operation (temperature, pressure, etc.), gas generator status (idle, full, flow, purge, or shutdown), and conditions leading to the presence of free oxygen.

3.4.2.5 Remote recording.- The control system shall include provisions for connection to remote recording devices which shall provide permanent records of critical system conditions.

3.4.2.6 Run-time and cycle indicators.- Modules with limited life expectancy shall be connected to run-time and cycle indicators which shall provide permanent records on the use of these components.

3.4.3 Maintenance.- Maintenance shall be limited to modules. Gas generator skids and components mounted thereon shall be considered as modules. Preventive maintenance shall be permitted only on those components which are not mounted on skids.

3.5 Performance.- The secondary gas generator system shall provide gas at the outlets of the gas generators at a minimum average absolute pressure of 315 pounds per square inch, with allowable pressure fluctuations of ± 5 percent, a minimum mass flow rate of 210 pounds per second, and a minimum temperature to molecular weight ratio (T/M) of 467 degrees Rankine pound-mole per pound for a maximum period of one hour per start.

3.5.1 Free oxygen.- The combustion products of the gas generator system shall be continuously free of all free oxygen.

3.5.2 Gas generator.-

3.5.2.1 Start-up.- Each gas generator shall provide a minimum flow rate between 1 and 10 percent of the flow rate in 3.5, not more than 10 seconds after application of the starting voltage of 3.4.1.1.

3.5.2.2 Response time.- Each gas generator shall be capable of producing its full propellant flow rate not later than 10 seconds after the operating controls have been set for full flow.

3.5.2.3 Idle.- When one gas generator of the system is on FULL FLOW, all other generators shall be on IDLE, which shall be from 1 to 10 percent of the flow rate of 3.5, continuously during operation of the system.

3.5.2.3.1 Purge during idle.- When any, or all, gas generators are on IDLE, the main injector manifold of these generators shall be in continuous purge. The total flow output of gas, including hot idle gas, shall not exceed 210 pounds per second.

3.5.3 Control system. - The control system shall continuously detect and indicate the performance of the gas generator system. In the event of the failure of one component, it shall automatically initiate action to begin shutdown procedures. It shall detect and indicate critical system conditions; and, in the event of significant deviation of one of the conditions, it shall automatically initiate action to begin shutdown procedures.

3.5.3.1 Purge action. - In the event of accidental loss of flame to one of the gas generators during operation, the control system shall detect the lack of flame, indicate the emergency, stop the flow of liquid hydrogen and liquid oxygen, and automatically purge the specific gas generator. The control system shall automatically purge the system from the propellant manifold to the atmosphere before ignition, upon accidental loss of flame in all three generators, and as part of the shutdown procedures.

3.5.4 Redundancy. - In the event of failure of one unit, a parallel unit shall automatically assume the failing function and provide continued and uninterrupted performance.

3.6 Environments. - The components of the system shall be capable of operating in the environments specified.

3.6.1 Gas generator skids. - The components on the gas generator skids shall operate satisfactorily in the following environments:

- (a) Temperature - 20°F (-6.6°C) to 130°F (54.4°C)
- (b) Relative humidity - 2 percent to 100 percent
- (c) Sand and dust - As specified for desert areas
- (d) Nuclear radiation - 5×10^5 rads gamma dose
- (e) Altitude - 4000 feet (25.84 inches of Mercury)

3.6.2 All other components. - All other components will not be subjected to environmental extremes; therefore, environments will not be a critical factor.

3.6.3 Non-operating environments. - Components of the gas generator system shall be capable of satisfactory operation after being exposed to the environmental extremes of transportation and storage in southwestern continental United States.

3.7 Operating life. - The gas generator system shall be capable of performing as specified herein for a minimum of 200 operational starts as a design objective.

3.7.1 Operational start. - For the purposes of this specification an operational start shall include purge, ignition, minimum output (1 to 10 percent), maximum output (100 percent), shut down, and purge for a maximum duration of one hour.

3.8 Interchangeability. - All parts having the same manufacturer's part number shall be physically and functionally interchangeable. Drawing number and part number changes shall be governed by the contracting agency's instructions.

3.9 Radio interference. - The design of the gas generator system shall include provisions for minimizing susceptibility to a radiation of radio interference.

3.10 Reliability. - The secondary gas generator system shall have reliability objectives as specified herein.

3.10.1 Mission. - The gas generator system shall have a minimum reliability objective of 0.75 of successfully completing a full one-hour operational mission (operational start).

3.10.2 Safety. -

3.10.2.1 Unit failure. - The gas generator system shall have a minimum reliability of 0.995 of bringing the test of a rocket engine to a safe emergency shutdown after the failure of one of the gas generator units.

3.10.2.2 Engine failure. - In the event of malfunction of the rocket engine being tested, the gas generator system shall have a minimum reliability of 0.9995 of maintaining adequate performance during an emergency shutdown.

3.11 Identification of product. - Components and parts of the gas generator system shall be identified, when possible, with the manufacturer's name, part number, name by which manufacturer calls the item, contract number, and, on limited life items, date of manufacture. Identification shall last for the life of the item identified, and be applied in a manner which shall not degrade its performance.

3.12 Workmanship. - Components, parts, and assemblies of the system shall be finished in a workmanlike manner. Welded assemblies shall be free of cracks and scale; machined parts shall have no gouges, chips, or burrs; electronic assemblies shall be free of loose solder with all soldered connections cleaned of flux.

4. QUALITY ASSURANCE PROVISIONS

4.1 Classification of tests.- Inspection and testing of the gas generator system shall be classified as follows:

- (a) Acceptance tests
- (b) Qualification tests

4.2 Acceptance tests.- Acceptance tests shall consist of:

- (a) Individual tests
- (b) Environmental tests

4.2.1 Individual tests.- Each system shall be subjected to the following tests as described under test methods of this specification:

- (a) Examination of product
- (b) Functional tests

4.3 Test conditions.- Unless otherwise specified, all tests required by this specification shall be made at an atmospheric pressure of 28 to 32 inches of mercury and at a temperature of 77°-17°F and a relative humidity of 80 percent or less. When tests are made with atmospheric pressure or temperature substantially different from the stated values, proper allowance shall be made for the change in instrument reading.

4.4 Test methods.-

4.4.1 Examination of product.- Each component of the gas generator system shall be examined for compliance with the applicable drawings and this specification with respect to materials, workmanship, markings, packaging, and any physical damage.

4.4.2 Functional tests.- Demonstration of performance of the system shall be in accordance with contracting agency instructions.

4.4.3 Environmental tests.- Each component of the system shall be subjected to the environmental tests specified in the applicable specifications.

4.5 Qualification tests.- Qualification tests shall include all the tests specified in test methods, (see 4.4) arranged in the same order plus the following test:

- (a) Purge the system, ignite and stabilize flow at minimum flow conditions. Lapse time: 10 seconds.
- (b) Increase flow from minimum rate to maximum rate. Transient time to achieve maximum flow of 3.5: 0.1 second.
- (c) Continue flow at maximum rate for 30 seconds.
- (d) Reduce flow from maximum rate to minimum rate. Transient time: 10 seconds.
- (e) Continue flow at minimum rate for 330 seconds.
- (f) Increase flow from minimum rate to maximum rate. Transient time to achieve maximum flow of 3.5: 0.1 second.
- (g) Continue flow at maximum rate for 110 seconds.
- (h) Reduce flow from maximum rate to minimum rate. Transient time: 110 seconds.
- (i) Continue minimum flow rate for 3000 seconds.
- (j) Shut down gas generator. Transient time: 10 seconds, or more if required.

4.5.1 Qualification test conditions.- Qualification tests shall be performed under simulated operating conditions subject to approval of the contracting agency.

4.6 Reliability demonstration.- The contractor shall provide a test plan to demonstrate the attainment of reliability. This test plan shall be subject to the disapproval of the contracting agency.

4.7 Radio-interference tests.- The gas generator system shall be tested for radiation and susceptibility in accordance with contracting agency's instructions.

5. PREPARATION FOR DELIVERY

5.1 Packaging.- The components of the gas generator system shall be packaged in a manner which shall assure delivery to the destination by common carrier in the proper operating condition.

5.2 Marking for shipment.- Each package shall be marked with the name and part number of the enclosed component and with the total number of packages in the system. Components shall be listed in the order in which they appear on the container when the container is upright.

6. NOTES

6.1 Intended use.- The gas generator system defined in this specification is intended to be used as an aspirator to provide the vacuum in the NERVA exhaust system.

Authorized for Release

Prepared by *R. E. C.* *W. C. McKee* *19 Nov 1962*
 R. E. C. W. C. McKee (Date)
 Dept
 Propulsion Division
 Plans
 f.

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APPENDIX A

APPENDIX A

RELIABILITY TEST PROGRAM REQUIREMENTS

10. SCOPE

10.1 Scope.- This appendix establishes the system reliability requirements for a gas generator to be used in testing special rocket engines.

20. RELIABILITY REQUIREMENTS

20.1 Program plan and test plan.- The subcontractor shall submit a reliability program plan and test plan in accordance with REON reliability and quality assurance program requirements.

20.2 Mission reliability.- The system shall perform the required mission with a minimum reliability of 0.75.

20.3 Safety reliability.- The safety reliability shall be defined as the probability of achieving a successful transient from minimum to maximum output, maintaining the output for three minutes, then shutting down safely. In the event of a malfunction in one gas generator, the two remaining gas generators shall be required to complete the above cycle with a minimum reliability of 0.995. In the event of a malfunction in the rocket engine system or other test facilities, the three gas generators shall be required to complete the above cycle with a minimum reliability of 0.9995.

20.4 Gas generator system mission.- The following shall be the system duty cycle:

- a. Purge system, ignite and stabilize flow at minimum flow conditions. Total time: 10 seconds.
- b. Increase flow from minimum rate to maximum rate. Transient time: 0.3 second.

- c. Continue flow at maximum rate for 30 seconds.
- d. Reduce flow from maximum rate to minimum rate. Transient time: 10 seconds.
- e. Continue flow at minimum rate for 330 seconds.
- f. Increase flow from minimum rate to maximum rate. Transient time: 0.3 second.
- g. Continue flow at a maximum rate for 110 seconds.
- h. Reduce flow from maximum rate to minimum rate. Transient time: 10 seconds.
- i. Continue minimum flow rate for 3000 seconds.
- j. Shut down gas generator. Transient time: 10 seconds.

20.5 Design reliability.-

20.5.1 Failsafe.- Any failure shall occur in such a manner not to cause complete loss of the system.

20.5.2 Design life.- All equipment shall be designed with a mean operating life of 200 hours before wearout point.

20.6 Reliability demonstration.- A demonstration by the subcontractor of a minimum reliability of 0.92 shall be required for a single gas generator unit including concomitant controls and switching device. This demonstration shall consist of 28 consecutive tests without failure in accordance with the duty cycle of 20.4.

- a. In the event of one system failure, a total of 44 such tests must be performed.

20.6.1 Demonstration hardware.- Reliability demonstration tests shall be made with hardware which reflects the final design. Demonstration test plans shall be coordinated with, and shall be subject to, the disapproval of the contracting agency.

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APPENDIX B

APPENDIX B

CONTRACTOR DOCUMENTATION

10. SCOPE

10.1 Scope. - This appendix defines the minimum documentation required by the contracting agency prior to acceptance of the gas generator system.

20. APPLICABLE DOCUMENTS

20.1 Governmental documents. - The following documents of the issue in effect on the date of invitation for bids form a part of this specification to the extent specified herein.

SPECIFICATION

Military

MIL-D-70327

Drawings, Engineering and Associated
Lists

STANDARD

Military

MIL-STD-7

Types and Definitions of Engineering
Drawings

PUBLICATION

M205

Military Outline of Form and In-
structions for the Preparation of
Specifications

(Copies of documents required by the contractor in connection with specific procurement functions, should be obtained from the contracting agency or as directed by the contracting officer.)

30. REQUIREMENTS

30.1 Requirements.- The contractor shall prepare specifications and drawings for the gas generator system and its components.

30.1.1 Specifications.- The contractor shall prepare specifications for all non-standard components. These specifications shall be detail design specifications. These specifications shall control details of design such as material and composition, physical and chemical characteristics, size, shape, weight, dimensions, etc. Performance requirements shall define proper functioning under required conditions but should not specify performance in excess of that required and obtainable within the limits of established design. The specifications shall establish the exact features of design to be used in the manufacture of the item components, and parts and thereby freezes resultant performance characteristics. Design may be controlled by reference to the applicable drawings.

30.1.2 Drawings.- The contractor shall prepare drawings for all parts, equipments, units, and components used in the system. The contractor shall not be required to provide drawings on standard parts. Type of drawings provided shall conform to Standard MIL-STD-7 (see 20.1).

30.2 Format and content.-

30.2.1 Preparation.- Specifications shall be prepared in accordance with Military Manual M205 (see 20.1) and supplementary instructions provided by the contracting agency.

30.3 Documentation review.-

30.3.1 Specification review.- The contractor shall submit 10 copies of each proposed specification to the contracting agency, not less than 45 days prior to delivery of the equipment. These specifications shall define the applicable items as representative of the system scheduled for delivery to the using site. These specifications may be preliminary or draft copies for this review. Review at this time is for the purpose of determining that the units satisfy the system needs.

30.3.2 Drawing review.- Drawings shall be reviewed by the contracting agency not less than 45 days prior to delivery of the equipment. Drawings may be reviewed as part of the specification review only when such drawings are referenced in the specifications.

30.4 Formal specification approval.- Specifications defining the system and its components shall be approved after qualification of the system and the contractor has certified that the specifications represent the qualified system.

NOTES 1 REMOVE ALL BURRS AND SHARP EDGES
2 BOLT CIRCLE DIA TO CONFORM WITH ASA B16.5

EXISTING

- ① MS3100A36-7-P
- ② MS3102A36-10-S
- ③ MS3102A36-10-S
- ④ MS3102A36-8-S
- ⑤ MS3102A36-10-P

REQUIRED

- ① MS3100A36-7-S
- ② MS3102A36-10-P
- ③ MS3102A36-10-P
- ④ MS3102A36-8-P
- ⑤ MS3102A36-10-S

INTERFACE CONTROL DRAWING —
ELECTRICAL CONNECTIONS

P-C87797

PROPELLANT FEED SYSTEM

P-087982

*UNION 810-6-(CARBON STEEL)
CODE IDENT NO. 02570*

*INTERFACE CONTROL DRAWING
INSTRUMENTATION NITROGEN LINE*

P-087988

APPENDIX B

PROCESS DESIGN CALCULATIONS

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- I. Pressure Drop Across Hot-Gas Conduit
 - A. Introduction
 - B. Calculations
- II. Gas Generator Injector Design
 - A. Summary of Design Conditions
 - B. Calculations
- III. Gas Generator Igniter Design
 - A. Summary of Design Conditions
 - B. Calculations

Figure* B-1 Electrical Diagram for Spark Plug Ignition System

*In addition to the figures listed here, reference is made to Figures 1 and 4 in the main body of the report.

I. PRESSURE DROP ACROSS HOT-GAS CONDUIT

A. INTRODUCTION

An approximate value of the pressure drop from the combustion chamber to the plenum chamber, ΔP_f , must be calculated to determine the combustion chamber pressure from the specified plenum chamber pressure. This calculation can be made with reasonable accuracy on the basis of a simplified model of the preliminary conduit dimensions furnished by REON as shown in Figure 1 of the report.

The hot-gas conduit was assumed to be equivalent to a system of 137 ft of 30-in. ID pipe with one expansion from 24-in. ID pipe and containing two 90°-long-sweep elbows followed by two parallel sections of the 24-in. sched. 160 pipe each of which are 75 ft long and contain one contraction from the 30-in. pipe, three 90° elbows, and one sudden expansion at $d/D = 1/2$.

B. CALCULATIONS

1. For the 30-in. portion of the conduit:

$$ID = 30.0 \text{ in.} = 2.50 \text{ ft}$$

$$Area = 706.86 \text{ in.}^2 = 4.91 \text{ ft}^2$$

$$\text{Density} = \rho = \frac{4.314}{379 \left(\frac{14.7}{320} \right) \left(\frac{2020}{520} \right)} = 0.0638 \frac{\text{lb}}{\text{ft}^3}$$

$$\text{Velocity} = V = \frac{\dot{W}}{\rho A} = \frac{210}{0.0638 (4.91)} = 670 \text{ ft/sec}$$

$$\text{Viscosity of gas} = 0.024 \text{ cp} \quad \text{Estimated from: } \mu_{H_2} = 0.0215 \text{ cp}$$
$$\mu_{H_2O} = 0.0379 \text{ cp}$$

$$\text{or } \mu = 1.613 \times 10^{-5} \frac{\text{lbm}}{\text{ft/sec}}$$

$$R_e = \frac{DV \rho}{\mu} = \frac{(2.5) (670) (0.0638)}{1.613 \times 10^{-5}} = 6.63 \times 10^6$$

$$@ E/D = 0.000066, \quad \lambda = 4f = 0.0113$$

$$\text{Equivalent length} = 137 + 22 + 2 (52) = 263 \text{ ft}$$

$$\begin{aligned} \text{Therefore: } \Delta P_f &= \frac{\lambda L \rho V^2}{2g_c D (144)} = \frac{(0.0113) (263) (0.0638) (670)^2}{64.3 (2.5) (144)} \\ &= 3.7 \text{ psi} \end{aligned}$$

2. For the 24-in. portion of the conduit:

$$ID = 19.376 \text{ in.} = 1.615 \text{ ft}$$

$$\text{Area} = 294.9 \text{ in.}^2 = 2.05 \text{ ft}^2$$

$$\rho = 0.0638 \frac{(316)}{(320)} = 0.0630 \text{ lb/ft}^3$$

$$\text{Velocity } V = \frac{\dot{W}}{2\rho A} = \frac{210}{2(0.0630)(2.05)} = 813 \text{ ft/sec}$$

$$Re = \frac{DV\rho}{\mu} = \frac{1.615 (813) (0.0630)}{1.613 \times 10^{-5}} = 5.12 \times 10^6$$

$$@ E/D = 0.000072, \quad \lambda = 4f = 0.0115$$

$$\text{Equivalent length} = 75 + 17 + (3) (40) + 38 = 250 \text{ ft}$$

$$\begin{aligned} \text{Therefore: } P_f &= \frac{\lambda L \rho V^2}{2g_c D (144)} = \frac{(0.0115) (250) (0.0630) (813)^2}{64.3 (1.615) (144)} \\ &= 8.0 \text{ psi} \end{aligned}$$

3. Therefore: Total pressure drop from the gas generator to the plenum chamber = 3.7 + 8.0 = 11.7 psi

II. APPENDIX B

This appendix includes a design summary and sample calculations for the gas generator injector designs, shown in Figure 4 and described in Section III, B, 3, of the test of the report.

The main injector consists of three concentric rings (two fuel rings with a central oxidizer ring). The pilot injector is a pentad configuration consisting of four fuel streams impinging on a central oxidizer stream.

A. SUMMARY OF DESIGN CONDITIONS

1. Total flow for the gas-generator system = 210 lb/sec
2. The main injector of each gas generator will be designed for 97% of total flow.
3. The pilot injector of each gas generator will be designed for 1% of total flow.
4. Mixture Ratio = 1.14
5. Fuel Density = $\rho_f = 4.0 \text{ lb/ft}^3$
6. Oxidizer Density = $\rho_o = 71.0 \text{ lb/ft}^3$
7. Injector Fuel Velocity = $V_f = 350 \text{ ft/sec}$
8. Injector Oxidizer Velocity = $V_o = 100 \text{ ft/sec}$
9. Thickness of Injector Plate = 3 in.
10. Diameter of chamber = 19.314 in.
11. Nominal Element Diameter of the Main Injector = (0.6) (Chamber diameter) = 11.6 in.
12. Diameter of Fuel Supply Line (at injector) = 19.314 in.
13. Diameter of the two oxidizer supply lines = 3 in.

B. CALCULATIONS

1. Injector Orifice Sizes

a. Required Flows

$$(1) \text{ Total Pilot Flow} = (.01)(210) = 2.1 \text{ lb/sec}$$

$$\text{For mixture ratio of 1.14: } \dot{W}_O = 1.12 \text{ lb/sec}$$

$$\dot{W}_f = 0.98 \text{ lb/sec}$$

$$(2) \text{ Total Main Flow} = (.97)(210) = 203.7 \text{ lb/sec}$$

$$\text{For Mixture Ratio of 1.14: } \dot{W}_O = 108.5 \text{ lb/sec}$$

$$\dot{W}_f = 95.2 \text{ lb/sec}$$

b. Pilot Pentad Injector Sizes

(1) Oxidizer Orifice

$$(a) \text{ Area} = A = \frac{\dot{W}}{\rho_v} = \frac{1.12}{(71)(100)}$$

$$A = 1.58 \times 10^{-4} \text{ ft}^2 = 0.0227 \text{ in.}^2$$

$$\text{Diameter of Oxidizer Orifice} = 0.170 \text{ in.}$$

(2) Fuel Orifice

$$\text{Similarly the diameter of each fuel orifice} = 0.179 \text{ in.}$$

c. Main Concentric Ring Injector Sizes

(1) Oxidizer Annulus

$$(a) \text{ Area of Annular Ring } A = \triangle D$$

$$\text{where } \triangle = \text{width of the annulus}$$

$$D = \text{diameter of the annulus}$$

$$(b) \text{ Area required} = \frac{\dot{W}}{\rho_v} = \frac{108.5}{(71)(100)}$$

$$A = .0153 \text{ ft}^2 = 2.20 \text{ in.}^2$$

$$(c) \triangle = \frac{A}{\pi D} = \frac{2.2}{\pi(11.6)} = 0.0603 \text{ in.}$$

(2) Fuel Annuli

$$(a) \text{ Area required} = \frac{95.2}{(4.0)(350)} = 0.066 \text{ ft}^2 = 9.80 \text{ in.}^2$$

$$(b) \text{ Area per annular ring} = 4.90 \text{ in.}^2$$

$$(c) \text{ Diameter of outer fuel ring} = 12.850 \text{ in.}$$

$$\text{Outer ring } \Delta = \frac{4.90}{\pi (12.850)} = 0.121 \text{ in.}$$

$$(d) \text{ Diameter of inner fuel ring} = 10.350 \text{ in.}$$

$$\text{Inner ring } \Delta = \frac{4.90}{\pi (10.350)} = 0.150 \text{ in.}$$

2. Manifold Configuration

The following tables list the manifold configurations, velocities and estimated pressure drops for both the pilot and main injectors. Pressure drops were calculated on the basis of the "K" values listed by the Crane Co., and the equation

$$H = K \frac{V^2}{2g}$$

where

H = Loss of head in feet

K = Coefficient

V = Velocity, ft/sec

2g = 64.4 ft/sec²

Line friction losses were neglected. Head loss due to velocity changes were calculated using the formula:

$$H = \frac{(V_2)^2 - (V_1)^2}{2g}$$

a. Pentad Injector

(1) Oxidizer

<u>Location</u>	<u>Cross Sectional Area, in²</u>	<u>Velocity, ft/sec</u>	<u>Head Loss, ft</u>
1/2-in. supply line	0.196	11.6	-
Injector Orifice	0.023	100	Entrance 62.1
		Total	<u>62.1</u>

b. Head Loss Due to Velocity Changes

$$H = \frac{(V_2)^2 - (V_1)^2}{2g} = \frac{(100)^2 - (11.6)^2}{64.4} = 153.5 \text{ ft}$$

c. Total Pressure Drop

$$H = 62.1 + 153.5 = 215.6 \text{ ft}$$

$$\Delta P = \frac{(215.6) (71)}{(144)} = 106 \text{ psi}$$

d. Manifold Volume = 10.8 in.³

(2) Fuel

(a) Head Losses

<u>Location</u>	<u>Cross-Sectional Area, in²</u>	<u>Velocity, ft/sec</u>	<u>Head Loss, ft</u>
1-in. supply port	0.785	44.8	Entrance 15.6
Manifold	0.982	36.0	-
Injector Orifice (each orifice)	0.0252	350	Entrance 952.0
		Total	<u>967.6</u>

(b) Head Loss Due to Velocity Changes

$$H = \frac{(350)^2 - (36.0)^2}{64.4} = 1885 \text{ ft}$$

(c) Total Pressure Drop

$$H = 967.5 + 1885 = 2852.5 \text{ ft}$$

$$\Delta P = \frac{(2852.5) (4)}{14.7} = 79.4 \text{ psi}$$

(d) Manifold Volume = 87.3 in.³

b. Main Concentric-Ring Injector

(1) Oxidizer

(a) Head Losses

<u>Location</u>	<u>Cross-Sectional Area, in.²</u>	<u>Velocity, ft/sec</u>	<u>Heat Loss, ft</u>
3-in. supply line	16.7 (2 lines)	13.3	
External 4-in. manifold	228.0	1.0	
Six 2-1/8-in. supply lines	18.8	11.6	Entrance 1.1
Internal manifold (at rear injector face)	79.0	2.8	
Internal porting (through Injector Plate)	9.1	24.1	Entrance 4.5
Internal manifold	22.8	9.64	Exit 0.5
Injector	2.2	100	Entrance 62.2
Total			68.3

(b) Total Head Loss Due to Velocity Changes

$$H = \frac{V_2^2 - V_1^2}{2g} = 165 \text{ ft}$$

(c) Total Pressure Drop

$$H = 68.3 + 165 = 233.3 \text{ ft}$$

$$\Delta P = \frac{(233.3) (71)}{14.7} = 115 \text{ psia}$$

(d) Oxidizer Manifold Volume = 1188 in.³

(2) Fuel

Inner and outer fuel injectors sized to provide the same cross-sectional area.

(a) Head Losses

<u>Location</u>	<u>Cross-Sectional Area in.²</u>	<u>Velocity, ft/sec</u>	<u>Head Loss, ft</u>
Internal Porting (through Injector Plate)	27.6	125	Entrance 121
Internal Manifold	69.0	50	Exit 14
45° Manifold	48.8	71	Entrance 16
Injector Entrance	5.3	325	Entrance 558
Injector Exit	4.9	350	----
		Total	<u>709</u>

(b) Total Head Loss Due to Velocity Changes

$$H = \frac{V_2^2 - V_1^2}{2g} = 1968 \text{ ft}$$

(c) Total Pressure Drop

$$H = 709 + 1968 = 2677 \text{ ft}$$

$$\Delta P = \frac{(2677)(4)}{(144)} = 74.4 \text{ psi}$$

(d) Fuel Manifold Volume = 15,200 in.³

III. GAS GENERATOR IGNITER DESIGN

This appendix presents the design summary and sample calculations for the gas generator igniter design shown in Figure 4 and described in Section III, B, 4, of the main body of the report. There will be two separate spark igniters, each recessed in a cavity near the pilot pentad. These spark igniters will be of the high energy capacitor discharge type. Such a commercially available system can be supplied by General Laboratories Associates, Inc., of Norwich, New York. An electrical diagram of this ignition system is shown in Figure B-1. The proposed system would include 0.3 joule capacitor ignition exciter that will provide a 100/sec, 15,000 volt spark. The exciter will require a 15-29V, 5-amp power source. This system is capable of operating up to two minutes per start for a total duration of 200 hours. After the pilot pentad is lit, the igniter propellant flows will be shut off and fuel will be bled from the pentad supply line to provide igniter cooling.

A. SUMMARY OF DESIGN CONDITIONS

The flow for each igniter shall represent 10% of the design pilot pentad flow. Other design conditions (mixture ratio, injection velocities, etc.) shall be as defined in Section II, of this appendix.

B. CALCULATIONS

1. Injector Orifice Sizes

a. Required Flows (10% of Pentad Flows)

$$\text{Fuel} = 0.098 \text{ lb/sec}$$

$$\text{Oxidizer} = 0.112 \text{ lb/sec}$$

b. Igniter Orifice Diameters

$$\text{Required Area, ft}^2 = \frac{\dot{W}}{\rho v}$$

(1) Fuel Orifice

$$V = 350 \text{ ft/sec}$$

$$\text{Area} = \frac{0.098}{4.0 (350)} = 7.0 \times 10^{-5} \text{ ft}^2 = 0.0101 \text{ in.}^2$$

$$\text{Diameter of Fuel Orifice} = 0.113 \text{ in.}$$

(2) Oxidizer Orifice

$$V = 100 \text{ ft/sec}$$

$$\text{Area} = \frac{0.112}{(71)(100)} = 1.58 \times 10^{-5} \text{ ft}^2 = 0.00228 \text{ in.}^2$$

$$\text{Diameter of Oxidizer Orifice} = 0.054 \text{ in.}$$

c. Pressure Drops

(1) Fuel

(a) Head Losses

<u>Location</u>	<u>Cross-Sectional Area, ft²</u>	<u>Velocity, ft/sec</u>	<u>Head Loss, ft</u>
3/8-in. Supply	0.1105	32.2	---
Two 3/16-in. Ports	0.054	65.5	21
Internal Manifold	.560	6.3	---
Injector Orifice	0.0101	350	950
Total			971

(b) Head Loss Due to Velocity Changes

$$H = \frac{V_2^2 - V_1^2}{2g} = 1950 \text{ ft}$$

(c) Total Head Loss

$$H = 971 + 1950 = 29.21 \text{ ft}$$

$$\Delta P = 81.5 \text{ psi}$$

(d) Manifold Volume = 10.5 in.³

(2) Oxidizer

(a) Head Losses

<u>Location</u>	<u>Cross-Sectional Area, in.²</u>	<u>Velocity, ft/sec</u>	<u>Head Loss, ft</u>
3/8-in. Supply	0.1105	2.1	-
3/16 Port	0.027	8.5	-
Injector Orifice	0.0023	100	<u>62.2</u>
Total			62.2

(b) Head Loss Due to Velocity Changes

$$H_1 = \frac{V_2^2 - V_1^2}{2g} = 156 \text{ ft}$$

(c) Total Head Loss

$$H = 156 \text{ ft} + 62.2 \text{ ft} = 218.2 \text{ ft}$$

$$\Delta P = 108 \text{ psi}$$

(d) Manifold Volume = 4.5 in.³

Figure B-1

APPENDIX C

PROPELLANT AND PURGE FEED SYSTEM

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- I. Rapid Start Calculations
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 - B. Nitrogen Supply Line Size and Pressure Drop
 - C. Main Injector Purge
 - D. Idle Flow Injector Purge
 - E. Supply Line Size Verification

Table C-1 Equipment List - Valves

I. RAPID START CALCULATIONS

It is required that the gas generator (GG) can go from idle to full flow rate through the injector plate within 0.1 seconds. A simple mathematical model is assumed, as described below, to evaluate the feasibility of this requirement.

The model is described by the equation

$$1) \quad f = m \dot{x} + D \ddot{x}$$

where $f = P \cdot A$ (fuel source pressure x pipe cross-sectional area)

m = mass of fluid within pipe of length

D = damping such that the desired steady state flow rate is achieved.

x = fluid position

Let f = force in pounds

m = mass in slugs

D = damping in lb x sec/ft

$\dot{x}$ = fluid velocity in ft/sec

L = pipe length in feet

P = source pressure in lb/ft²

ρ = fluid density in lb/ft³

d = pipe diameter in in.

A = pipe cross-sectional area in ft²

$\dot{w}$ = fluid flow rate in pounds /sec

$\dot{w}_{ss}$ = desired steady state flow

$\ddot{w}$ = time rate of change of flow rate

Since $m = \frac{\rho LA}{g}$, $f = PA$, $\dot{x} = \frac{\dot{w}}{\rho A}$ and $D = \rho \frac{PA^2}{\dot{w}_{ss}}$ the equation (1) becomes

$$2) \quad PA = L \frac{\ddot{w}}{g} + \frac{PA}{\dot{w}_{ss}} \dot{w}, \text{ and } \dot{w} = 0 \text{ at } t = 0$$

$$\text{Hence } \dot{w} = \dot{w}_{ss} (1 - e^{-t/\tau})$$

$$\text{Where } \tau = L\dot{w}/gPA$$

Additional delay will result from the time required to open the valve. It appears that τ should be in the range of 0.02 to 0.04 sec. if the desired response time of 0.1 sec is to be obtained.

$$\begin{aligned} \text{For example let } \dot{w} &= 110 \text{ lb/sec} \\ L &= 300 \text{ ft} \\ P &= (500 \text{ psi}) (144 \text{ in.}^2/\text{ft}^2) \\ g &= 32.2 \text{ ft/sec}^2 \end{aligned}$$

$$\text{Then } \tau \approx 1.3 \cdot 10^{-2}/A \text{ and } A \text{ should exceed } 0.33 \text{ ft}^2 \text{ to } 0.65 \text{ ft}^2.$$

$$\text{The diameter} = 24 \sqrt{A/\pi}$$

$$\text{hence } d \geq 7.8" \text{ to } 10.9" \text{ for the conditions assumed above.}$$

The required pipe size is reasonable so that with a fast acting valve that will open in less than 0.02 to 0.04 sec., near full flow should be achievable within 0.1 seconds.

II. PURGE FLOW CALCULATIONS*

A. Chamber Purge

Assume $\dot{w} = 210 \text{ lb/sec}$, $P_1 = 400 \text{ psia}$, $P_2 = 320 \text{ psia}$, $T = 530^\circ\text{R}$, then

$$\rho_1 = 2 \text{ lb/ft}^3, P_2/P_1 = 0.8, S = 3.15 (P_2/P_1 = 0.8, k = 1.4), C = 0.65$$

$$\text{using the equations } \dot{w} = \frac{CAS \sqrt{Z}}{12} \quad \text{and } d = \sqrt{\frac{4A}{\pi}}$$

* Flow rates shown are maximum values which can be decreased if desired.

$$\text{then } d = \sqrt{\frac{48 \dot{w}}{C \pi S \sqrt{P}}} = \sqrt{\frac{(48) (210)}{0.65 \pi 3.15 \sqrt{2(400)}}} = 7.44 \text{ inches (orifice)}$$

Sonic flow across this orifice ($S = 3.885$)

$$\dot{w} = \frac{(0.65) \left(\frac{7.44^2 \pi}{4} \right) (3.885) \sqrt{2 (400)}}{12} = 260 \text{ lb/sec}$$

Assuming an 8 inch Schedule 40 pipe (I.D. = 7.98 in., Area = 50.0 in.²), the flow velocity

$$V = \frac{\dot{w}}{\rho A} = \frac{(210) (144)}{(2.0) (50.0)} = 304 \text{ fps (a } = \sqrt{kgRT} = \sqrt{(1.4)(32.2)(55.2)(530)} = 1150 \text{ fps)}$$

Alternate solution - $\dot{w} = 210 \text{ lb/sec}$, $P_1 = 500 \text{ psia}$, $P_2 = 320 \text{ psia}$, $T_1 = 530^\circ\text{R}$

then $\rho_1 = 2.5 \text{ lb/ft}^3$, $P_2/P_1 = 0.64$, $S = 3.78$ and

$$d = \sqrt{\frac{(48) (210)}{0.65 \pi 3.78 \sqrt{2.5(500)}}} = 6.08 \text{ in. (orifice)}$$

Sonic flow across this orifice ($S = 3.885$)

$$\dot{w} = \frac{(0.65) \left(\frac{6.08^2 \pi}{4} \right) (3.885) \sqrt{2.5 (500)}}{12} = 216 \text{ lb/sec}$$

Recommended Chamber Purge Pressure = 400 psia

8 inch Schedule 40 pipe

7.44 inch flow control orifice (perhaps a check valve can accomplish this function)

B. Nitrogen Supply Line Size and Pressure Drop

Assume 6 inch. Schedule 160 pipe (ID = 5.189 inches, Area = 21.15 in.²)

$$P_1 = 3600 \text{ psia}, T = 530^\circ\text{R}, \rho_1 = 18 \text{ lb/ft}^3, \dot{w} = 210 \text{ lb/sec}$$

$$V = \frac{(210)(144)}{(18)(21.15)} = 79.4 \text{ fps}$$

$$\text{Viscosity of } N_2 = 0.0292 \text{ centipoise}$$

$$\text{Reynolds Number} = \frac{6.32\dot{w}}{d\mu} = \frac{(6.32)(210)(3600)}{(5.189)(0.0292)} = 31,600,000$$

$$\text{Friction Factor} = 0.01$$

$$\Delta P = 0.000336 \frac{f_w^2 V}{d^5} = \frac{(0.01)(756,000)^2 \left(\frac{1}{18}\right)}{(5.189)^5} = 28.3 \text{ psi/100 ft}$$

Recommended Supply Line Size = 6 inch

Supply pressure to regulator would drop approximately 100 psi at 210 lb/sec flow. This represents no problem since the regulator will drop the pressure to 400 psi.

C. Main Injector Purge

1. Hydrogen Manifold Purge Flow Rate

$$\text{Injector area } 9.8 \text{ in}^2$$

$$\text{Assume } P_1 = 400 \text{ psia}, T_1 = 530^\circ\text{R}, \rho_1 = 2.0 \text{ lb/ft}^3$$

Sonic flow rate through this injector would be:

$$\dot{w} = \frac{(0.65)(9.8)(3.885)\sqrt{(2.0)(400)}}{12} = 58.4 \text{ lb/sec.}$$

2. Hydrogen Purge Line Size

Assume 4 inch line - Schedule 40 (ID = 4.026 inch, Area = 12.73 in.²)

$$\text{Then flow velocity, } V = \frac{(58.4) (144)}{(2.0) (12.73)} = 330 \text{ fps (a = 1150 fps)}$$

3. Oxygen Manifold Purge Flow Rate

Injector area 2.2 in.²

Assume $P_1 = 400$ psia, $T_1 = 530^\circ\text{R}$, $\rho_1 = 2.0$ lb/ft³

Sonic flow rate through this injector would be:

$$\dot{w} = \frac{(0.65) (2.2) (3.885) \sqrt{2.0 (400)}}{12} = 13.1 \text{ lb/sec}$$

4. Oxygen Purge Line Size

Assume 2 inch line - Schedule 40 (ID = 2.067 inch, Area = 3.355 in.²)

$$\text{Then flow velocity, } V = \frac{(13.1) (144)}{(2.0) (3.355)} = 280 \text{ fps (a = 1150 fps)}$$

and $\Delta P = 1.0$ psi/ft

D. Idle Flow Injector Purge

1. Hydrogen Manifold Purge Flow Rate

Injector area 0.1008 in.²

Assume $P_1 = 400$ psia, $T_1 = 530^\circ\text{R}$, $\rho_1 = 2.0$ lb/ft³

Sonic flow rate through this injector would be:

$$\dot{w} = \frac{(0.65) (0.1008) (3.885) \sqrt{2.0 (400)}}{12} = 0.60 \text{ lb/sec}$$

2. Hydrogen Purge Line Size

Assume 1/2 inch line (ID = 0.430 in, Area = 0.145 in.²)

$$\text{Then flow velocity, } V = \frac{(0.6) (144)}{(2.0) (0.145)} = 297 \text{ fps}$$

and $\Delta P = 5.3 \text{ psi/ft}$

3. Oxygen Manifold Purge Flow Rate

Injector area 0.0227 in.²

Assume $P_1 = 400 \text{ psia}$, $T_1 = 530^\circ\text{R}$, $\rho_1 = 2.0 \text{ lb/ft}^3$

Sonic flow rate through this injector would be:

$$\dot{w} = \frac{(0.65) (0.0227) (3.885) \sqrt{2.0 (400)}}{12} = 0.14 \text{ lb/sec}$$

4. Oxygen Purge Line Size

Assume 3/8 inch line (ID = 0.305 in., Area = 0.073 in.²)

$$\text{Then flow velocity, } V = \frac{(0.14) (144)}{(2.0) (0.073)} = 137 \text{ fps}$$

and $\Delta P = 1.6 \text{ psi/ft}$

E. Supply Line Size Verification

Assuming all purges operate simultaneously (sonic flow)

$$\dot{w} = 260 + 58.4 + 13.1 + 0.6 + 0.1 = 332 \text{ lb/sec}$$

$$\text{and } \Delta P = 3.36 \times 10^{-4} \left(\frac{f \dot{w}^2}{\rho d^5} \right) = 3.36 \times 10^{-4} \frac{(0.01) (332)^2 (3600)^2}{(18) (5.189)^5}$$

$$= 70.8 \text{ psi/100 ft}$$

Supply pressure to regulator would drop approximately 300 psi at this flow rate which is still reasonable.

TABLE C-1 EQUIPMENT LIST - VALVES

Function	Valve Type	Description	Size	Number
Main LO ₂ Valves	Ball Valves	Similar to Whittaker P/N 136405	3 in.	2
Main LH ₂ Valves	Ball Valves	Similar to Whittaker P/N 136405	3 in.	4
Idle Flow Valve	Bipropellant Valve	Aerojet Design	O ₂ -3/8 in. H ₂ -5/8 in.	1
Idle Flow Control Valve-LO ₂	Shutoff Valve-Pilot Operated	Similar to Consolidated Con. 153W51	3/8 in.	1
Idle Flow Control Valve-LH ₂	Shutoff Valve-Pilot Operated	Similar to Consolidated Con. 153W51	5/8 in.	1
Main Valve Open. Con. Valves	Pneumatic Solenoid Valves	3-way, normally open	1/4 in.	3
Main Valve Closing Con. Valves	Pneumatic Solenoid Valves	3-way, normally closed	1/4 in.	2
Main Inj. Purge Con. Valve O ₂	Shutoff Valve-Solenoid Con.	Axial valve, normally open	2 in.	1
Main Inj. Purge Con. Valve H ₂	Shutoff Valve-Solenoid Con.	Axial valve, normally open	4 in.	1
Idle Injector Purge Con. Va. O ₂	Pneumatic Solenoid Valve	2-way, normally open	3/8 in.	1
Idle Inject. Purge Con. Valve H ₂	Pneumatic Solenoid Valve	2-way, normally open	1/2 in.	1
GG Chamber Purge Con Valve	Shutoff Valve-Solenoid Con.	Axial valve, normally closed	8 in.	1
Purge Check Valves, Main Flow O ₂	Cryogenic Check Valve	Split gate, swing type	2 in.	1
Purge Check Valves, Main Flow H ₂	Cryogenic Check Valve	Split gate, swing type	4 in.	1
Purge Check Valves, Idle Flow O ₂	Cryogenic Check Valve	Poppet type	3/8 in.	1
Purge Check Valves, Idle Flow H ₂	Cryogenic Check Valve	Poppet type	1/2 in.	1
Purge Check Valve, Chamber	Hot-Gas Check Valve	Split gate, swing type	8 in.	1
Flow Calibration Orifice LO ₂	Fixed Orifice	Sharp Edged Orifice	Hot run sized	1
Flow Calibration LH ₂ Orifice	Fixed Orifice	Sharp Edged Orifice		
GG Chamber Purge Flow Limiter	Fixed Orifice	Sharp Edged Orifice (Possibly inter- graded with check valve)	7.5 in.	1

APPENDIX D

CONTROL SYSTEM

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I. INTRODUCTION

The following is a description of an electrical control system for the three gas generators.

Each of the three gas generators is provided with an independent controller. A degree of redundancy is provided in this approach so that a controller malfunction would not result in a failure of the gas generator complex. Since only one gas generator runs at full power at a given time, the individual controllers are enabled from a master controller called the director. Manual and automatic command signals are routed through the director to the appropriate gas generator controller. The director also controls transfer from one gas generator to another in the event of malfunction.

II. DESIGN DISCUSSION

A. CONTROLLER DESIGN

The controllers perform switching and sequencing operations. Their outputs control ignition, purge, and propellant valves.

Inputs are provided from gas generator transducers and the director. Logical propositions are satisfied by combinations of switching circuits. The sequences of events are generated by sequence times or program generators. Normal sequences progress until a malfunction or manual-override occurs. Then, a malfunction sequence is started to control a safe shutdown or transfer to another generator.

Generally speaking, a unique sequence is used to control various transitions in the gas generator power level. An example is phasing the generator ignition and valve actuations from full-off to ignition, to idle-flow, to full-flow. This is also true of malfunction sequences.

B. SIGNAL CONDITIONERS

The predominate signals used to monitor gas generator performance will be pressure and temperature. If the transducers used produce proportional

outputs, these will be quantized and converted to digital form. In this manner, switch-closures can be used to indicate limits for pressure and temperature. These can be easily and reliably transmitted to the controller.

All commands emanating from the controller to the gas generator will be in digital form (on-off). These are used to control the valves and the ignition spark system.

C. CONTROLLER LOGIC

Digital control is performed by satisfying a series of logical propositions in a predetermined time sequence. As used in this report, a logical proposition means that a set of functions represented by switch-closures has a unique combination. This combination can be electrically detected by proper interconnections of the switches. All variables may be of either the "on and off" or "1" and "0" type. Three basic operations are performed: NOT, OR, and AND. NOT is an inversion. OR and AND combinations are detected by "gates". An example of an "AND" gate is a number of relay contacts in series. If each contact represents a separate function (variable), then all variables must be true (all contacts closed) in order to complete the circuit.

A time sequence is used to sample and control as a time function. A fixed program of events normally occurs. If an incorrect logical proposition exists at a particular time, the normal sequence is disabled and a special malfunction sequence is initiated. At some point in the malfunction sequence, a return to a normal sequence is made if the abnormality has been corrected. Otherwise, shutdown or transfer to another gas generator is made.

III. SEQUENCE OF EVENTS

A. DEFINITION OF FUNCTIONS

Various functions will be identified as abbreviations in the following table:

<u>Abbreviation</u>	<u>Name</u>	<u>From</u>	<u>To</u>
OFF	Off to full flow command	Nerva Control	Director
IFP	Idle to full flow command	" "	"
FIP	Full flow to idle command	" "	"
FOP	Full flow to off command	" "	"
ARM	Arm	" "	"
RDY	Ready to Fire	Director	Nerva Control
T_o, T_1, T_2	Sequence timer intervals	Sequence Timer	Control Logic
M_1, M_2	Malf. sequence timer intervals	Malf. Sequence Timer	Control Logic
P_c	Pressure switch	Gas Gen.	Controller
T_c	Temperature switch	" "	"
$IGN_{1,2}$	Ignition detection	" "	"
NEF	Nerva engine is firing	Nerva Control	Director
NEF	Nerva engine is not firing	" "	"
STI	Start sequence timer #1	" "	"

B. NORMAL SEQUENCE

The following is a list of chronological events that take place in the control system of the gas generators:

1. Manually preset the prime gas generator selection switch.
Manually preset the first and second alternate gas generators.
2. Manually initiate main propellant (LH_2 and LO_2) valves open.
Open purge supply main valve. Visually verify satisfactory feed pressures.
3. Operate ARM switch. This energizes power busses to gas generator valves and ignition.
4. Controller self-check verified operates ready light at control console.

5. Nerva Control signals power level (OFP).
6. Nerva Control signals gas generator FIRE.
7. FIRE signal starts sequence timer #1.
STI = OFP • RDY • FIRE • FIP • IFP • FOP
8. Time T_1 energizes all purge valves and spark ignition
(2 sec).
9. Time T_2 energizes ignitor valves (2 sec).
10. Time T_3 verifies ignition of ignitor and turns off spark
(2 sec).
11. Failure to verify ignition starts malfunction sequence No. 1
(full shutdown).
12. Time T_4 energizes idle valves (2 sec).
13. Time T_5 verifies idle ignition satisfactory (2 sec).
14. Failure to verify idle starts malfunction sequence No. 1
(full shutdown).
15. Time T_6 energizes full flow valves (2 sec).
16. Time T_7 verifies full flow satisfactory (0.3 sec) and closes
system purge valve.
17. Failure to verify full flow satisfactory starts malfunction
sequence No. 1 (full shutdown) if NEF.
18. Nerva Control signals FIP. The director selects the prime
gas generator and starts sequence timer #2 in the prime controller.
19. Time T_8 energizes full flow valves closed. System purge is
inhibited if NEF.
20. Time T_9 verifies idle OK on all generators.
21. Failure to verify starts malfunction sequencer timer #2.
22. Nerva Control signals IFP. This starts sequence timer #3.
23. Time T_{10} opens full flow valves (0.3 sec).

24. Time T_{11} verifies full flow satisfactory.
25. Failure to verify starts malfunction sequence time #3.
26. Nerva Control signals FOP. This starts sequence timer #4.
27. Time T_{12} closes all propellant valves. System purge is energized.
28. Time T_{13} turns off purge.
29. Time T_{14} de-energizes ARM buss. Gas generator secured signal is generated. All sequence timers are reset.

C. MALFUNCTION SEQUENCES

1. Malfunction sequence No. 1 is initiated for failure to verify ignitor on, or idle ignited, or full-flow ignited (initially).
2. Time M_1 turns off all propellant valves.
3. Time M_2 turns off purge.
4. Malfunction sequence No. 2 is initiated for failure to verify idle ignited after return from full-flow.
5. Time M_3 shuts off propellant valves on failed generator. A signal is sent to the director to select a new generator for the next full-flow command.
6. Malfunction sequence No. 3 is initiated for failure to verify full-flow satisfactory while the Nerva engine is firing.
7. Time M_4 turns propellant valves off on failed generator and sends signal to director to select and turn on an alternate gas generator.

IV. LOGIC DIAGRAM EXPLANATION

A. CONTROLLER

Figure D-1 is an elementary logical diagram of the proposed controller. Functional areas illustrated are "AND" gates, "OR" gates, and

sequence and malfunction sequence timers. Input signals are shown as three-letter abbreviations. A "barred" abbreviation denotes a "NOT" or inverted function. For example, in the case of an "AND" gate having two inputs, A and B, an output could be produced only if A were true and NOT B = $\bar{B}$ were true. Another way of stating this proposition would be to say that the presence of A and the absence of B will produce an output.

It will be noted that each sequence timer produces outputs when energized. These are labeled T_1, T_2, T_3 , etc. The malfunction sequence timers produce time outputs of M_1, M_2, M_3 , etc. The sequence timer outputs are applied to various gates as shown.

An example of the sequence control is as follows: Receipt of ARM is "anded" with $\overline{T_{14}}$. This energizes the power relay until time T_{14} is produced at the end of the shutdown sequence. The power relay applies power through its contacts to the valve and ignition power busses. A ready (RDY) signal is derived from ARM relay actuation, presence of proper feed pressures, and any other required signals (logic for deriving RDY is not shown). The power level signal, OFF, is "anded" with RDY, FIRE, $\overline{FIP}$, $\overline{IFP}$, and $\overline{FOP}$. The presence of the barred terms means that they must not be present in order to start sequence timer No. 1. This prevents an incorrect sequence from being initiated should an incorrect power level command be present. After FIRE has been received, the AND gate produces an output which starts sequence timer No. 1. The outputs of this timer are "anded" with various functions to actuate spark ignition and valves, and verify ignition and proper gas generator operation. An AND gate with the inputs T_1 and $\bar{T}_3$ controls spark ignition. T_1 turns the spark on and T_3 turns the spark off. Timer T_3 , no output is obtained from the gate. If ignition is unsatisfactory, an output will be obtained which energizes malfunction sequence timer No. 1. This timer sequences a shutdown by first closing propellant valves and then turning off purge valves. The foregoing example illustrates the use of gates to sample, compare, and actuate. The sequence timers provide a programming capability.

B. DIRECTOR

Figure D-2 is an elementary logical diagram of the proposed Controls Director. Controller input signals are routed to the appropriate gas generator controller by a system of gates. A group of gates is used for each controller. These are enabled by the combination of a six-position preselector switch and a gas generator selector switch. The preselector provides any combination of a prime, a first alternate, and a second alternate gas generator. The gas generator selector switch always enables the prime selected generator controller for firing at full flow. Any malfunction during Nerva engine firing or shutdown will advance the selector switch to the first alternate controller. A second malfunction will advance the selector to the second alternate controller. Not shown in the diagram is logic to interlock gas generator controllers to prevent improper simultaneous events.

V. CONTROL CIRCUITRY COMPONENTS

A. DISCUSSION

Most of the control functions are performed by switching and timing circuitry. The choice of components to perform these functions is based on the following criteria in an approximate order of importance.

1. Reliability/life expectancy
2. Speed of response requirements consistent with non-destructive shock wave
3. Environment
4. Duty cycle
5. History of experience
6. Cost
7. Power requirements
8. Physical size
9. Efficiency

Relays have been chosen as the basic switching device. Silicon diodes will be used as decoupling devices and also as gates in some instances. Relay speed of operation varies from 1 to 35 milliseconds depending on the type used. These speeds are compatible with the speed of devices which they control.

Modern relays are rugged, reliable devices not subject to catastrophic failure when properly derated. An extensive background of experience exists for similar control circuitry using relays.

Silicon diodes are the most reliable type of rectifiers with the exception that they are vulnerable to momentary overloads. However, in this application, the diodes will all be used in low level circuits and will be adequately protected against transient overloads.

Sequencing or programming may be done with individual time delay devices, electronic counters, and electromechanical programmers such as perforated tape and motor-ran-switch devices. The small number of programmed functions in this controller indicate the use of individual time delay devices. A good variety of high quality solid state timers is commercially available. A solid state timer has advantages of repeatability, reliability, and accuracy, over other type of timers where short time delays are required.

A typical example of a relay controller is shown in Figure D-3. The wiring diagram for this controller is shown in Figure D-4. This particular controller was designed by the Power/Equipment Division for use on the gas generator for the Titan Accessory Power Supply (APS).

B. SIGNAL CONDITIONERS

Temperature measurements made with proportional output devices must be converted to switch closures to indicate over and/or under temperature. A stable amplifier will be used to boost the voltage output of the transducer. The amplifier output will be compared to a voltage reference which represents a temperature reference. If an inequality is present, a relay will be energized which will signal the controller to take corrective action.

A second-harmonic type of magnetic amplifier will be used because of its insensitivity to radiation, shock, vibration, and temperature variation.

C. PACKAGING

The controllers and director will be constructed in a manner suitable for rack mounting. Modular construction will be extensively used. Plug-in components and subassemblies will be used where reliability will not be compromised. MS type connectors will be used on the back of each chassis for connection to facility cabling. Units will operate without forced air cooling or controlled ambient temperature. However, free vertical air convection should be provided in the racks.

The signal conditioners must be mounted close to the gas generator. These are magnetic amplifier types which will be encapsulated and hermetically sealed units. The enclosure recommended for the signal conditioning system is a cast aluminum box with an O-ring seal on the cover. Input and output wires will be routed through hermetic seal connectors and/or conduit.

D. MANUAL OVERRIDES

Three types of manual overrides will be used: emergency shut-down, emergency start, and emergency system purge. Since the sequence of valve actuations is time critical, automatic programming may be required even on "manual". However, the degree of "automation" required will be reduced to lowest possible level. Any electronic control required for manual operation will be separate from and bypass the gas generator controller. Hence, the valves and ignition can be directly controlled by manual initiation. Separate controls will be provided for each gas generator. These will be mechanically and electrically interlocked to prevent system damage from incorrect operation.

E. LIST OF MANUAL CONTROLS AND INDICATORS

The approximate number and type of controls and indicators is shown in the table below.

<u>Function</u>	<u>Type</u>	<u>No.</u>
Test/automatic/off	3 pos. sw	1
Manual/auto ARM	2 pos. sw	1
Manual/auto FIRE	2 pos. sw	1
Gas generator selector	3 pos. sw	3
Purge override injector	2 pos. sw	6
Master purge override injector	2 pos. sw	2
Purge override system	2 pos. sw	3
Master purge override system	2 pos. sw	1
Shutdown override	2 pos. sw	3
Master shutdown override	2 pos. sw	1
Full flow override	2 pos. sw	3
Ignitor go/no-go	Panel Lights	3
Idle ignition go/no-go	Panel Lights	3
Full flow go/no-go	Panel Lights	3
Feed pressure indicators	Pressure gages	12
Malfunction indicators	Panel Lights	9
Reon system control monitors	Panel Lights	4
Cycle indicator	Decimal Display	1

The totals are 25 switches and 35 indicators.

VI. INSTRUMENTATION

The gas generator instruments will be similar to the instruments specified in the Data Acquisition Section of "Instrumentation and Control System Design Criteria", Test Cell ETS-1, NNRDC, Volume 4, published by the Nerva Program. While the nuclear radiation environment will not be

severe, adequate consideration will be given to this factor to assure reliable data acquisition.

Definitive instrumentation requirements will necessarily be established during subsequent development programs. However, temperature and pressure sensors will be located in several locations throughout the combustion chamber and plenum in order to establish relevant levels pertinent to correct gas generator operation. Other sensors that may be found to be required include free oxygen and free hydrogen indicators as well as LO_2 and LH_2 flow and pressure measuring devices.

Except for the radiation environment, the temperature and pressure ranges expected during gas generator operation do not indicate instrumentation different from that already being used by Aerojet on other test facilities.

Figure D-1

Figure D-2

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SCHEMATIC DIAGRAM OF GAS GENERATOR CONTROLLER

Figure D-3

Figure D-4

APPENDIX E

THERMAL ANALYSIS

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E-5	Response Time - Pressure
E-6	Response Time - Hot-Gas Flow Rate

I. OUTLINE OF THERMAL ANALYSIS

Thermal analysis of the gas generator system incorporates the following:

1. Temperature gradients (axial and radial) in the gas generator steel shell.
2. Axial temperature gradient in the injector plate.
3. Insulation requirement for the chamber exit duct flange.
4. Determination of the insulation requirement for the gas generator-exit duct
5. Account of heat input from gas generator system to the enclosure vault.
6. Thermodynamic analysis of the propellant feed system.
7. System transient behavior.

II. SUMMARY OF RESULTS

A. TEMPERATURE GRADIENTS (AXIAL AND RADIAL) IN THE GAS GENERATOR STEEL SHELL

To eliminate severe axial gradients in the steel shell and cryogenic feed flange dome, the gas generator design shown in Fig E-3 is recommended. Based on a preliminary estimate, the maximum axial temperature gradient in the dome, with insulation thickness in excess of 1 in. on the dome exterior surface, should be no greater than $100^{\circ}\text{F}/\text{ft}$. With adequate dome flange gap insulation, the maximum temperature of the dome and flange section on the dome side is no greater than 80°F . The maximum radial temperature drop in the dome flange section on the hot gas side is 100°F .

The temperatures of the dome without the flange are indicated in Figure E-1.

Gas generator radial temperature differences and maximum shell temperatures as a function of insulation thickness are shown in Figure E-2. For the 10° radial drop specified by stress requirements, the insulation thickness and maximum shell temperature are 2.5 in. and 1555°F , respectively.

B. AXIAL TEMPERATURE GRADIENT IN THE INJECTOR PLATE

In order to meet the stress specification of a 1000°F plate temperature drop, a 0.2 in. thickness of Rokide insulation is required on the hot plate surface.

An alternate means of meeting the stress requirement is to drill slots at sufficient plate locations to allow uniform hydrogen injection across the plate.

C. INSULATION REQUIREMENT FOR THE CHAMBER EXIT DUCT FLANGE

For the stress specification of 100°F radial temperature drop, the insulation requirement is 2 in.

D. INSULATION REQUIREMENT FOR THE GAS GENERATOR EXIT DUCT

An insulation thickness of 0.35 in. or greater will maintain a total gas temperature drop of 5°F .

E. ACCOUNT OF HEAT INPUT FROM GAS GENERATOR SYSTEM TO ENCLOSURE VAULT

Heat loss to the surroundings from the gas generator and an exit duct with 0.35 in. insulation is 6.7984×10^6 Btu/hr.

F. THERMODYNAMIC ANALYSIS OF THE PROPELLANT FEED SYSTEM

The pressure drops through the hydrogen and oxygen supply lines are 2.8 psi and 8.9 psi, respectively at the maximum rated flow of 100 and 110 lb/sec.

G. SYSTEM TRANSIENT BEHAVIOR

The transient behavior of the ejector nozzle has been determined from a simplified model of the gas generator and piping systems as shown in Figure E-3. The density and pressure in the nozzle plenum, and flow through the nozzle are shown in Figures E-4, E-5, and E-6, respectively of this appendix. The time required for these variables to reach 98% of their steady-state values is about 0.67 sec.

III. TEMPERATURE GRADIENTS (AXIAL AND RADIAL) IN THE SHELL

A. FIRST DESIGN

First, the design shown in Sketch E-1 was considered.

The axial temperature gradient in the steel shell was determined by the fin approximation to obtain rapid and conservative results.

1. Assumptions and Conditions

a. Steel shell is approximated as an infinite rectangular fin perfectly insulated on the top.

b. The steel shell section on the hot gas side is assumed to be at 1561°F .

c. Liquid hydrogen is at 40°R

2. Thermal System Model

Sketch E-1

3. Calculations

Fin Parameter:

$$m = \sqrt{\frac{2h}{kb}}$$

where h is equivalent heat transfer coefficient on uninsulated side

k is thermal conductivity of fin material

b is fin thickness

$$k = 11 \text{ Btu/hr-ft}^2\text{-F}$$

$$b = \frac{2.3}{12} = 0.1915 \text{ ft}$$

To evaluate h , the gas heat transfer coefficient (h_g) is required.

$$Re = \frac{\dot{W}d}{A\mu}$$

Where Rd is Reynold's number

$\dot{W}$ is gas flow rate

d is diameter of generator

μ is viscosity of gas

A is cross sectional area for gas flow in generator

$$\dot{W} = 210 \text{ lb/sec}$$

$$d = 19.28 \text{ in.} = 1.605 \text{ ft}$$

$$\mu = (0.6) \mu_{H_2O} + (0.4) \mu_{H_2}$$

$$\mu = \frac{(0.6)(0.092)}{3600} + (0.4)(1.4)(10^{-5})$$

$$\mu = 2.093 \times 10^{-5} \text{ lb/ft-sec}$$

$$A = (0.785)(1.605)^2 = 2.02 \text{ ft}^2$$

$$Re = \frac{(210)(1.605)}{(2.093)(10^{-5})(2.02)} = 7.99 \times 10^6$$

Critical $Re = 3000$

Flow is turbulent

Use Dittus's and Boelter's equation:

$$NU = .0265 (Re)^{0.8} (Pr)^{0.33}$$

Where NU is Nusselt Number

Pr is Prandtl Number

$$Pr = 0.6 Pr_{H_2O} + 0.4 Pr_{H_2}$$

$$Pr = (0.6)(1.06) + (0.4)(0.69)$$

$$Pr = 0.91$$

$$Nu = (0.0265) (7.99 \times 10^6)^{0.8} (0.91)^{0.33} = 5520$$

$$h_G = \frac{k_G}{d} (5520)$$

Where k_G is thermal conductivity of gas

$$k_G = 0.60 k_{H_2O} + 0.40 k_{H_2}$$

$$= (0.6) (0.065) + (0.4) (0.267)$$

$$k_G = 0.1459 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

$$h_G = \frac{(0.1459)(5520)}{1.605} = \frac{500 \text{ Btu}}{\text{Hr-ft}^2\text{-}^\circ\text{F}}$$

Effective thermal resistance for bottom fin surface is assumed to be the same as that for bottom shell surface.

$$\frac{1}{U} = R = \frac{1}{h_G A} + \frac{L}{k_r A}$$

A is shell area for heat transfer

k_r is thermal conductivity of Rokide

L is thickness of Rokide

k_r is 0.75 Btu/hr-ft²-°F (Source - Structural Materials Division)

$$A = \frac{3.142 (24-4.6 - 0.12) (5)}{12} = 25.2 \text{ ft}^2$$

$$R = \frac{1}{(500) (25.2)} + \frac{5 \times 10^{-3}}{(0.75) (25.2)}$$

$$R = 3.442 \times 10^{-4} \frac{\text{hr}^\circ\text{F}}{\text{Btu}}$$

$$U = \frac{1}{3.442 \times 10^{-4}} = 2.905 \times 10^3 \text{ Btu/hr-}^\circ\text{F}$$

$$h = \frac{2.905 \times 10^3}{25.2} = 115.28 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

$$m = \sqrt{\frac{(2)(115.28)}{(11)(0.1915)}} = 10.46 \text{ ft}^{-1}$$

$$\cosh mL = \frac{t_s - t_{H_2}}{t_L - t_{H_2}} \quad (1)$$

cosh is hyperbolic cosine

L is length of fin

t_s is steel temperature at fin section on hot gas side

t_{H_2} is hydrogen temperature

t_L is fin temperature at certain length of fin

$$t_s - t_{H_2} = 1561 + 460 - 40 = 1981^\circ\text{F}$$

$$\Delta t_L = \frac{1981}{\cosh mL}$$

$m \text{ (ft)}^{-1}$	L (ft)	mL	$\cosh mL$	$T_L \text{ }^\circ\text{F}$
10.46	0.1	1.046	1.595	1242
10.46	0.2	2.092	4.110	482
10.46	0.3	3.138	11.58	171
10.46	0.4	4.184	32.71	61
10.46	0.5	5.230	92.9	21
10.46	0.6	6.28	267	7.4
10.46	0.7	7.32	755	2.6

The results indicate that there is an axial temperature difference of 1978°F in 0.7 ft. This gradient will cause excessive stress in the structure. To reduce this gradient, insulation of the inside of the dome is required. This is not feasible because

a. Insulation materials, such as asbestos, lose their effectiveness when soaked in the cold hydrogen.

b. The double vacuum jacket required presents mechanical difficulties.

B. SECOND DESIGN

Then, the design shown in Sketch E-2 was considered.

The axial temperature gradient in the steel shell was determined for the condition of no insulation on the outside surface of the dome.

Sketch E-2

10-087-116-1

1. Assumptions and Conditions

- a. Steel shell is approximated as an infinite rectangular fin insulated on the bottom.
- b. Steel shell section on the hot gas side is 1500°F and ambient air is at 70°F.

2. Thermal System Model

3. Calculations

(2)

$$\cosh mL = \frac{t_S - t_A}{t_L - t_A}$$

Where t_A is air temperature

$$t_S - t_A = 1500 - 60 = 1430^\circ\text{F}$$

$$\Delta t_L = \frac{1430}{\cosh mL}$$

$$m = \sqrt{\frac{2h}{kb}}$$

$h = h_c + h_r = 10.28 \text{ Btu/hr-ft}^2 \text{ } ^\circ\text{F}$ (Reference 1), based on an average Δt of 1000°F.

Where h_c is heat transfer coefficient for convection between outside dome surface and air.

h_r is linearized coefficient for radiation heat exchange between outside dome surface and enclosure.

Δt is temperature difference between outside dome surface and air.

$$k = 11 \text{ Btu/hr ft } ^\circ\text{F}$$

$$b = 2.3/12 = 0.1915 \text{ ft}$$

$$m = \sqrt{\frac{(2)(10.28)}{(11)(0.1915)}} = 3.11 \text{ ft}^{-1}$$

$m \text{ (ft}^{-1}\text{)}$	$L \text{ (ft)}$	mL	$\cosh mL$	$t_L \text{ (}^\circ\text{F)}$	$t \text{ (}^\circ\text{F)}$
3.11	0.25	0.778	1.32	1085	1155
3.11	0.50	1.55	2.462	580	650
3.11	1.0	3.11	11.24	127	197
3.11	2.0	6.22	251	5.7	75.7
3.11	3.0	9.33	5650	0.253	70.25

Temperature vs length is indicated in Figure E-2. The results indicate a temperature difference that does not satisfy stress requirements.

C. THIRD DESIGN

Next, a 1-in. exterior dome surface insulation is specified and the axial temperature gradient is calculated.

1. Conditions and Assumptions

- a. Temperature of fin on hot gas side is 1500°F
- b. Temperature of weld point (connection of dome shell to H₂ duct) is 70°F. This value is based on results obtained for the jacketed H₂ duct.
- c. Bottom of fin is completely insulated.

2. Thermal System Model

3. Calculations

$$\cosh mL = \frac{t_s - t_{\text{weld}}}{t_L - t_{\text{weld}}} \quad (3)$$

$$t_s - t_{\text{weld}} = 1500 - 70 = 1430$$

$$\Delta t_L = \frac{1430}{\cosh mL}$$

Place 1 in. insulation on the top surface.

Effective thermal resistance for top fin surface is assumed to be same as that for top shell surface.

$$\frac{1}{U} = R = \frac{1}{(h_c + h_r) A} + \ln \left(\frac{X_2/X_1}{k 2 \pi L} \right) \quad (4)$$

Where

X_1 is radius to inside insulation surface

X_2 is radius to outside insulation surface

k is thermal conductivity of insulation

L is arbitrarily selected length of shell

$$h_c + h_r = 2.43 \text{ based on } \Delta t \text{ of } 200^\circ\text{F (Reference 1).}$$

$$X_2 = 13 \text{ in.}$$

$$X_1 = 12 \text{ in.}$$

$$A = (2) (3.142) \frac{(13)}{(12)} \frac{(24)}{(12)} = 13.6 \text{ ft}^2$$

Where L is taken as 24 in.

$$R = \frac{1}{(2.43) (13.6)} + \frac{\ln 13/12}{(0.11) (2) (3.142) (2)}$$

$$R = 0.7258 \frac{\text{hr-}^\circ\text{F}}{\text{Btu}}$$

$$U = 1.377 \text{ Btu/hr-}^\circ\text{F}$$

$$A = \left[13.6 + \frac{(2)(3.142)(24)(12)}{144} \right] 0.5 = 13.09 \text{ ft}^2$$

$$h = \frac{U}{A} = \frac{1.377}{13.09} = 0.1052 \text{ Btu/hr-ft}^2 \text{ }^\circ\text{F}$$

$$m = \sqrt{\frac{2h}{kb}}$$

$$m = \sqrt{\frac{(2)(0.1052)}{(11)(0.1915)}} = 0.3160 \text{ ft}^{-1}$$

$m \text{ (ft}^{-1}\text{)}$	$L \text{ (ft)}$	mL	$\cosh mL$	$t_L \text{ (}^\circ\text{F)}$	$t \text{ (}^\circ\text{F)}$
0.316	1	0.316	1.050	1362	1432
0.316	2	0.632	1.210	1182	1252
0.316	3	0.948	1.480	966	1036
0.316	4	1.264	1.910	749	819
0.316	5	1.580	2.531	565	635

The results for this run indicate that there is a linear axial temperature variation with dome length when insulation thicknesses in excess of 1 in. on the dome exterior surfaces are utilized. For a 2-ft dome, the axial temperature gradient is 1430°F. (Reference to Figure E-1) According to stress specifications, this gradient is too severe.

D. FOURTH DESIGN

Therefore, the design shown in Sketch E-3, on the next page, is selected.

Sketch E-3

1. Axial Temperature Gradient

By incorporating the dome-generator flange, it is estimated that

a. The maximum axial temperature gradient in the dome, with insulation thickness in excess of 1 in. on the dome exterior surface, should be no greater than 100°F/ft .

b. With adequate dome flange gap insulation, the maximum temperature of the dome and flange section on the dome side is no greater than 80°F .

c. The maximum radial temperature drop in the dome flange section on the hot gas side is 100°F .

These are rough estimates based on experience. A thermal nodal analysis should be performed to obtain accurate results. Also effects of inserting O_2 lines through the dome should be investigated.

2. Radial Temperature Gradients

A parametric analysis was performed to determine maximum steel temperature and radial temperature drops as a function of insulation thickness.

a. Conditions and Assumptions

- (1) Air and enclosure are at 50°F
- (2) No axial gradients in the shell, hot gas side.
- (3) Inside surface temperature of Rokide is at gas temperature.

b. Gas Generator Cross Section

Hot Gas

$$(T_g = 1561^{\circ}\text{F})$$

c. Calculations

$$q = \left(\frac{1}{R_F + R_S + R_1 + R_C + R} \right) (T_g - T_{\infty})$$

$$R_r = \frac{\ln (X_2/X_1)}{k_r 2 \pi L}$$

$$R_s = \frac{\ln (X_3/X_2)}{k_s 2 \pi L}$$

$$R_i = \frac{\ln (X_4/X_3)}{k_i 2 \pi L}$$

$$R_{C+R} = \frac{1}{(h_c + h_r) A}$$

Where

q is heat loss by conduction

R_r is resistance of Rokide

X_2 is radius to outer surface of Rokide

X_1 is radius to inner surface of Rokide

k_r is thermal conductivity

L is length of shell

R_s is resistance of steel

X_3 is radius to outer surface of steel

k_s is thermal conductivity of steel

R_i is resistance of insulation

X_4 is radius to outer surface of insulation

k_i is thermal conductivity of insulation

$R_{(C+R)}$ is combined resistance to convection and radiation between outer surface and air and outer surface and enclosure, respectively.

$h_c + h_r$ is combined heat transfer coefficient by convection and radiation.

A is surface area corresponding to X_4

Insulation thicknesses between 1 in. and 4 in. were selected.

The computation for the 2-in. insulation thickness is indicated.

$$R_r = \frac{\ln (9.7/9.64)}{(0.75)(2)(3.142)(5)} = 2.6387 \times 10^{-4} \frac{\text{hr}^\circ\text{F}}{\text{Btu}}$$

$$R_s = \frac{\ln(12/9.7)}{(15)(2)(3.142)(5)} = 4.5155 \times 10^{-4} \frac{\text{hr}^\circ\text{F}}{\text{Btu}}$$

$$R_i = \frac{\ln(14/12)}{(0.11)(2)(3.142)(5)} = 4.462 \times 10^{-2} \frac{\text{hr}^\circ\text{F}}{\text{Btu}}$$

Assume a Δt of 200°F between insulation outer surface and air.

$$h_c + h_r = 2.42 \text{ Btu-hr-ft}^2\text{-}^\circ\text{F} \quad (\text{Reference 1})$$

$$A = 2\pi \left(\frac{14}{12} \right) (5) = 36.658 \text{ ft}^2$$

$$R_{C+R} = \frac{1}{(2.42)(36.658)} = 1.1272 \times 10^{-2} \frac{\text{hr}^\circ\text{F}}{\text{Btu}}$$

$$q = \left(\frac{1}{0.026387 \times 10^{-2} + 0.045155 \times 10^{-2} + 4.462 \times 10^{-2} + R_{C+R}} \right) (1511)$$

$$q = \left(\frac{1}{4.5335 \times 10^{-2} + R_{C+R}} \right) (1511)$$

$$q = \left(\frac{1}{4.5335 \times 10^{-2} + 1.1272 \times 10^{-2}} \right) (1511)$$

$$q = 2.6684 \times 10^4 \text{ Btu/hr}$$

$$\Delta T_s = q R_s = (2.6684 \times 10^4)(4.5155 \times 10^{-4}) = 12.05^\circ\text{F}$$

$$\Delta T_r = q R_r = (2.6684 \times 10^4)(2.6387 \times 10^{-4}) = 7.04^\circ\text{F}$$

$$\Delta T_i = q R_i = (2.6684 \times 10^4)(4.462 \times 10^{-2}) = 1191^\circ\text{F}$$

$$\Delta T_{C+R} = 301^\circ\text{F}$$

Now guess $\Delta T_{C+R} = 275^\circ\text{F}$, $h_c + h_r = 2.85 \text{ Btu-hr-ft}^2\text{-}^\circ\text{F}$

$$R_{C+R} = \frac{1}{(2.85)(36.658)} = 0.9572 \times 10^{-2} \frac{\text{hr}^\circ\text{F}}{\text{Btu}}$$

$$q = \left(\frac{1}{4.5335 \times 10^{-2} + 0.9572 \times 10^{-2}} \right) (1511) = 2.75183 \times 10^4 \text{ Btu/hr}$$

$$\Delta T_i = (2.75183 \times 10^4)(4.462)(10^{-2}) = 1228^\circ\text{F}$$

$$\Delta T_s = (2.75183 \times 10^4)(4.5155)(10^{-4}) = 12.43^\circ\text{F}$$

$$\Delta T_r = (2.75183 \times 10^4)(2.6387)(10^{-4}) = 7.26^\circ\text{F}$$

$$\Delta T_{C+R} = 264^\circ\text{F Calculated}$$

$$\Delta T_{C+R} = 275^\circ\text{F Assumed}$$

The results are indicated in Figure E-2.

For the radial steel temperature drop of 10°F , specified by stress considerations, the insulation requirement is 2.5 in.

IV. AXIAL TEMPERATURE GRADIENT IN THE INJECTOR PLATE

A. CASE A - NO ROKIDE

1. Conditions and Assumptions

- a. Plate surface on cold hydrogen side is at 50°R .
- b. Maximum heating rate on surface facing hot hydrogen is 1 (BTU/in.²sec).
- c. Plate with no slots-to obtain conservative results.
- d. No radial temperature gradients.

2. Thermal System Model

3. Calculations

Heat balance on surface facing the hot gas.

$$q_k = q_c + q_r \quad (6)$$

$$U(T_w - T_l) = h_g A (T_g - T_w) + 0.173 A \epsilon' w \left[\epsilon_g \left(\frac{T_g}{100} \right)^4 - \alpha_g \left(\frac{T_w}{100} \right)^4 \right] \quad (7)$$

- where q_k is heat flow through plate by conduction
 q_c is heat exchange by convection between plate surface facing hot gas and the hot gas.
 q_r is radiation from hot gas.
 A is cross sectional area of plate.
 T_w is temperature of surface facing hot gas.
 T_l is temperature of surface facing liquid H₂

h_g is hot gas heat transfer coefficient
 T_g is gas temperature
 E'_w is effective wall emittance
 E_g is total gas emittance
 U is conductance through plate and Rokide
 α_g is absorptance of the gas

$$U = \frac{KA}{L} = \frac{(11)(1.985)}{(0.25)} = 87.4 \frac{\text{BTU}}{\text{Hr}^\circ\text{F}}$$

$$h_g = 360 \text{ BTU/hr-ft}^2\text{-}^\circ\text{F}, \text{ Basis of } 1 \text{ BTU/in.}^2\text{sec maximum heating rate.}$$

Gas constituents:

$$\left. \begin{array}{ll} 14.4\% & \text{H}_2\text{O} \\ 85.6\% & \text{H}_2 \end{array} \right\} \text{ Mole per cent}$$

System Pressure

$$P_{\text{Tot}} = 315/14.7 = 21.43 \text{ ATM}$$

Gas Partial Pressure

$$P_{\text{H}_2\text{O}} = (0.144)(21.43) = 3.09 \text{ ATM}$$

Equivalent gas length:

For right circular cylinders

$$L = 0.77D = (0.77) \frac{(19.28)}{12} = 1.235 \text{ ft}$$

(Reference 1)

Therefore:

$$P_{\text{H}_2\text{O}} L = (1.235)(3.09) = 3.816 \text{ ATM-ft}$$

Gas temperature = $1561^{\circ}\text{F} = 2021^{\circ}\text{R}$

At this temperature

$$\epsilon_{\text{H}_2\text{O}} = 0.34$$

The total pressure correction ≈ 1.50
(Reference 1)

Total gas emittance:

$$\epsilon_g = (1.50)(0.34) = 0.51$$

Effective wall emittance:

$$\epsilon'_w = \frac{w + 1}{2} = \frac{0.75 + 1}{2} = 0.875$$
$$\alpha_g = \epsilon_w = 0.75 \text{ (at } T_w)$$

Substituting into equation (7)

$$87.4(T_w - 50) = (360)(1.985)(2021 - T_w) + (6.173)(1.985)(0.875) \left[(0.51) \left(\frac{2021}{100} \right)^4 - (0.75) \left(\frac{T_w}{100} \right)^4 \right]$$

Solving for T_w :

$$T_w = 1805^{\circ}\text{R}$$

$$\Delta T_{\text{Plate}} = (1805 - 50) = 1755^{\circ}\text{R}$$

This temperature drop does not meet stress requirements.

B. CASE B - 0.06" ROKIDE COATING

1. Conditions and Assumptions

- a. Plate surface on cold hydrogen side is at 50°R .
- b. Maximum heating rate on surface facing hot hydrogen is $1 \text{ (BTU/in.}^2\text{ sec)}$.
- c. Plate with no slots-to obtain conservative results.
- d. No radial temperature gradients.

2. Thermal System Model

3. Calculations

Consider 0.06" Rokide on surface facing hot gas

$$\frac{1}{U} = R = R_p + R_r$$

where R is total resistance of plate and Rokide

$$R_p = \frac{1}{87.4}$$

$$R_r = \frac{L_r}{k_r A} = \frac{0.06/12}{(0.75)(1.985)}$$

$$R = 1.4798 \times 10^{-2} \quad \frac{\text{HR } ^{\circ}\text{F}}{\text{BTU}}$$

$$U = 67.57 \text{ BTU/HR } ^{\circ}\text{F}$$

Substituting into equation (7)

$$67.57(T_w - 50) = (360)(1.985)(2021 - T_w) + (0.173)(1.985)(0.875) \left[(0.51) \left(\frac{2021}{100} \right)^4 - 0.75 \left(\frac{T_w}{100} \right)^4 \right]$$

Solving for T_w :

$$T_w = 1857^\circ\text{R}$$

$$q_k = 67.57 (T_w - 50)$$

$$q_k = 1.221 \times 10^5 \text{ BTU/hr}$$

$$\Delta T_p = R_p q_k = \frac{1}{87.4} (1.221)(10^5) = 1397^\circ\text{F}$$

This plate condition does not meet with stress requirements.

C. CASE C - 0.20" ROKIDE COATING

1. Conditions and Assumptions

- a. Plate surface on cold hydrogen side is at 50°R .
- b. Maximum heating rate on surface facing hot hydrogen is 1 (BTU/in.²sec).
- c. Plate with no slots-to obtain conservative results.
- d. No radial temperature gradients.

2. Thermal System Model

3. Calculations

Now consider 0.20" Rokide on surface facing hot gas.

$$R = \frac{1}{87.4} + \frac{0.2/12}{(0.75)(1.985)}$$

$$R = 2.2635 \times 10^{-2} \frac{\text{HR}^\circ\text{F}}{\text{BTU}}$$

$$U = 44.17 \frac{\text{BTU}}{\text{HR}^\circ\text{F}}$$

Substituting into equation (7)

$$4.17(T_w - 50) = (360)(1.985)(2021 - T_w) + (0.173)(1.985)(0.875) \left[0.51 \left(\frac{2021}{100} \right)^4 - 0.175 \left(\frac{T_w}{100} \right)^4 \right]$$

Solving for T_w :

$$T_w = 1909^\circ\text{R}$$

$$q_k = 44.17 (1909 - 50) = 8.2112 \times 10^4 \text{ BTU/HR}$$

$$\Delta T_p = \left(\frac{1}{87.4} \right) (8.2112) (10^4) = 939.4^\circ\text{F}$$

Therefore, 0.2" Rokide on the plate surface facing the gas will result in a satisfactory axial temperature drop through the plate.

An alternate means of meeting the stress requirement is to drill slots at sufficient plate locations to allow uniform hydrogen injection across the plate.

V. INSULATION REQUIREMENT FOR CHAMBER EXIT FLANGE

A. CONDITIONS AND ASSUMPTIONS

1. Air and enclosure are at 50°F
2. No axial gradients in the flange
3. Inside surface temperature of Rokide is 1561°F
4. Temperature drop through steel is 100°F

B. FLANGE CROSS SECTION

Hot gas ($T_g = 1561^\circ\text{F}$)

Notation is as for the gas generator steel.

C. CALCULATIONS

Since cylinder length was not specified, an arbitrary length of 5 ft is selected for simplicity in calculation. The insulation thickness requirement does not vary with cylinder length.

$$R_T = 2.6387 \times 10^{-4} \frac{\text{hr}^\circ\text{R}}{\text{Btu}} \quad (\text{as for generator, III.D.2.c.})$$

$$R_s = \frac{\ln(X_3/X_2)}{k_s 2\pi L} = \frac{\ln(23/9.7)}{(15)(2)(3.142)(5)} = 1.8322 \times 10^{-3} \frac{\text{hr}^\circ\text{F}}{\text{Btu}}$$

Since ΔT_s is 100°F :

$$q = \frac{1}{R_s} (100)$$

$$q = \frac{1}{1.8322 \times 10^{-3}} (100) = 5.457 \times 10^4 \text{ Btu/hr}$$

$$q = \frac{T_2 - T_\infty}{R_i + R_{C+R}} \quad (8)$$

Where T_2 is temperature at outer surface of steel

$$\Delta T_r = q R_r = (5.457 \times 10^4) (2.6387 \times 10^{-4}) = 14.4^\circ\text{F}$$

$$T_2 = 1561 - 14.4 - 100 = 1396.6^\circ\text{F}$$

Substituting into equation (8)

$$5.457 \times 10^4 = \frac{1396.6}{R_1 + R_{C+R}}$$

$$R_1 + R_{C+R} = 2.5593 \times 10^{-2} \frac{\text{hr}^\circ\text{F}}{\text{Btu}}$$

Assume various insulation thicknesses

Consider 2 inches -

$$R_1 = \frac{\ln (X_4/X_3)}{k_1(2\pi L)} = \frac{\ln 25/23}{(0.11)(2)(3.142)(5)} = 2.44 \times 10^{-2} \frac{\text{hr}^\circ\text{F}}{\text{Btu}}$$

$$R_{C+R} = (2.5593 - 2.44)(10^{-2}) = 0.1193 \times 10^{-2} \frac{\text{hr}^\circ\text{F}}{\text{Btu}}$$

$$\Delta T_1 = R_1 q = (2.44 \times 10^{-2}) (5.457)(10^4) = 1331^\circ\text{F}$$

$$\Delta T_{C+R} = R_{C+R} q = (0.1193)(10^{-2})(5.457)(10^4) = 65.25^\circ\text{F}$$

$$T_\infty = 1561 - \Delta T_r - \Delta T_s - \Delta T_1 - \Delta T_{C+R}$$

$$T_\infty = 1561 - 14.4 - 100 - 1331 - 65.25$$

$$T_\infty = 50.35^\circ\text{F} \text{ agrees with specified } T_\infty = 50^\circ\text{F}$$

Therefore, utilization of 2 in. insulation will result in a 100°F radial temperature drop in the steel flange.

Length of the flange was later specified as 8 in.

$$\text{Total heat loss} = \left(\frac{8/12}{5}\right) (5.457)(10^4) = 7.2753 \times 10^3 \frac{\text{Btu}}{\text{hr}}$$

VI. INSULATION REQUIREMENT FOR HOT-GAS CONDUIT

A. GIVEN CONDITIONS AND ASSUMPTIONS

1. Gas flow rate is 210 lb/sec.
2. Composition of gas: 40% H₂ by weight) Mixture ratio of 1.14.
60% H₂O)
3. Ambient air temperature is 50°F.
4. Duct inlet temperature is 1561°F.
5. Enclosure is at 70°F.
6. Inner steel surface temperature is same as bulk gas temperature.
7. Total gas temperature drop in duct is 5°F.
8. Schematic as indicated in Figure 4 of Reference 2.

B. FOR THE FOLLOWING DUCT CONFIGURATION:

C. CALCULATIONS

The heat balance equation is as follows:

$$q_{\text{conduction}} = q_{\text{convection}} + q_{\text{radiation}} \quad (9)$$

($q_{\text{conduction}}$) and ($q_{\text{convection}} + q_{\text{radiation}}$) are expressed as

$$q_{\text{conduction}} = \left[\frac{\ln X_2/X_1}{k_s 2\pi L} + \frac{\ln X_3/X_2}{k_i 2\pi L} \right] (T_{1w} - T_{2w}) \quad (10)$$

$$q_{\text{convection}} + q_{\text{radiation}} = \epsilon A_{2w} \epsilon_{2w} (T_{2w}^4 - T_E^4) + h_c A_{2w} (T_{2w} - T_A) \quad (11)$$

Where

$q_{\text{conduction}}$ is heat loss by conduction through the steel and insulation.

$q_{\text{convection}}$ is heat interchange by convection between insulation surface and air.

$q_{\text{radiation}}$ is heat interchange by radiation between outer insulation surface and enclosure.

X_1 is radius to inner steel surface.

X_2 is radius to outer steel surface.

X_3 is radius to outer insulation surface.

k_s is thermal conductivity of the steel.

k_i is thermal conductivity of the insulation.

L is length of duct.

T_{1w} is temperature of inner steel surface.

T_{2w} is temperature of outer insulation surface.

σ is Stefan-Boltzman constant, 1.713×10^{-9} Btu/hr-ft² - °R⁴

A_{2w} is surface area of duct at X_3 .

ϵ_{2w} is emittance of outer insulation surface.

T_E is enclosure temperature.

h_c is convection coefficient.

T_A is air temperature

Consider the 30-in.-diameter duct:

$$L = 159.83 \text{ ft}$$

$$\Delta T_{\text{Total}} = 5^\circ\text{F}$$

$$\Delta T_{30'' \text{ Duct}} = \left(\frac{159.83}{10 + 69 + 159.83} \right) (5) = 3.345^\circ\text{F}$$

$$\text{Heat Loss} = \dot{W} C_p \Delta T_{30'' \text{ Duct}}$$

$$\dot{W} = \text{Flow rate} = 210 \text{ lb/sec}$$

$$C_p = \text{Specific Heat}$$

$$C_p = 0.6 C_{p_{\text{H}_2\text{O}}} + 0.4 C_{p_{\text{H}_2}}$$

$$C_{p_{\text{H}_2\text{O}}} = 0.555 \text{ Btu/lb-}^\circ\text{F} \text{ (Reference 1).}$$

$$C_{p_{\text{H}_2}} = 3.645 \text{ Btu/lb-}^\circ\text{F}$$

$$C_p = (0.6)(0.555) + (0.4)(3.645)$$

$$C_p = 1.7905 \text{ Btu/lb-}^\circ\text{F}$$

$$\text{Heat loss} = (210)(3600)(1.7905)(3.345) = 4.5278 \times 10^6 \text{ Btu/hr}$$

Heat loss = $q_{\text{conduction}} = q_{\text{convection}} + q_{\text{radiation}}$, by equation (9).

$$X_1 = \frac{30}{2} = 15 \text{ in.} = 1.25 \text{ ft}$$

$$X_2 = \frac{35}{2} = 17.5 \text{ in.} = 1.458 \text{ ft}$$

$$k_g = 15 \text{ Btu/hr-ft-}^{\circ}\text{F (Reference 1)}$$

$$h_1 = 0.11 \text{ Btu/hr-ft-}^{\circ}\text{F}$$

$$T_{1w} = 1561 - 1/2 (3.345) = 1559^{\circ}\text{F} = 2019^{\circ}\text{R}$$

$$\epsilon_{2w} = 0.80$$

$$h_c = 0.27 \left(\frac{T_{2w} - T_A}{2 X_3} \right)^{0.25} \quad \text{For natural convection}$$

Substituting values into equations (10) and (11):

$$\frac{4.528 \times 10^6}{2\pi(159.83)} = \left[\frac{1}{15} \ln \frac{17.5}{15} + \frac{1}{0.11} \ln \frac{X_3}{17.5} \right]^{-1} (2019 - T_{2w})$$

$$\frac{4.528 \times 10^6}{2\pi(159.83)} = 0.1713 \times 10^{-8} (X_3)(0.8)(T_{2w}^4 - 530^4) + 0.27 \left(\frac{T_{2w} - 510}{2 X_3} \right)^{0.25} X_3 (T_{2w} - 510)$$

Solving the equations simultaneously

$$T_{2w} = 1160^{\circ}\text{F}$$

$$\text{and } X_3 = 17.85 \text{ in.}$$

Therefore, the minimum insulation thickness requirement for the 30-in. duct is 0.35 in. Insulation thickness requirement for the other duct sections is less than 0.35 in.

VII. HEAT INPUT TO ENCLOSURE VAULT

A. Input from hot-gas conduit:

Total heat loss for 5^oF drop

$$q = \dot{W} C_p \Delta T$$

$$q = (210)(3600)(1.7905)(5) = 6.7681 \times 10^6 \text{ Btu/hr}$$

B. From gas generator - exit duct flange for a 100°F radial temperature difference.

$$\text{Total loss} = 7.2753 \times 10^3 \text{ Btu/hr}$$

C. From gas generator for a 10°F radial temperature difference

$$\text{Total loss} = 2.2979 \times 10^4 \text{ Btu/hr}$$

D. Total heat loss to the enclosure vault is 6.7984×10^6

The primary heat input to the enclosure vault is from the gas generator exit duct.

An analysis should be performed to determine duct insulation thicknesses that will result in tolerable heat inputs to the enclosure.

VIII. ANALYSIS OF REON PROPELLANT FEED LINES

A. LIQUID HYDROGEN LINE

1. Determination of the Temperature Rise in the 300-ft Line

a. Given Assumptions and Conditions

1. 12-in. ID vacuum-jacketed pipe.
2. No heat conduction from inner pipe to outer pipe.
3. Liquid flow rate of 100 lb/sec.
4. Natural convection of heat from outer pipe to 100°F ambient air.
5. The inner pipe is at the temperature of the liquid hydrogen.
6. All radiating surfaces are black, i.e., the emissivities and absorptivities are 1.0.
7. The line does not touch the ground which is 100°F.
8. The inner and outer pipes are very close together.
9. The outer pipe is 16 in. diameter.
10. Liquid hydrogen temperature is approx 50°R
11. The line is two straight concentric cylinders.
12. The temperature rise in the hydrogen line is small enough to consider the hydrogen temperature approximately constant along the pipe. (This must be verified).

b. Calculations

The heat balance on the complete line is:

$$\sigma A_1 (T_2^4 - T_1^4) = h_c A_2 (T_a - T_2) + G_s A_p + \sigma F_{2-s} A_2 (T_s^4 - T_2^4) + \sigma F_{2-G} A_2 (T_G^4 - T_2^4) \quad (12)$$

Where A_1 is the surface area of the inner pipe, $A_1 = \pi \left(\frac{12}{12}\right) L$, ft²

A_2 is the surface area of the outer pipe, $A_2 = \pi \left(\frac{16}{12}\right) L$, ft²

L is the length of the line, 300 ft.

σ is Stefan-Boltzman constant, 1.713×10^{-9} Btu/hr-ft²-°R⁴

A_p is the projected area of the outer pipe to the sun.

$$A_p = DL = \frac{16}{12} L, \text{ ft}^2$$

h_c is the natural convection heat transfer coefficient, Btu/hr-ft²-°F

For $T_a = 100^\circ\text{F}$, assume $T_2 \approx 50^\circ\text{F}$ then $\Delta T = 50^\circ\text{F}$

$$\text{and } T_f = \frac{T_a + T_2}{2} = \frac{100 + 50}{2} = 75^\circ\text{F and}$$

$$(G_s \times P_p)_1 = 1.5 \times 10^6 (50) \left(\frac{16}{12}\right)^3$$

$$\text{Then } h_c = 0.27 \left(\frac{\Delta T}{D_2}\right)^{\frac{1}{4}} = 0.251 (\Delta T)^{\frac{1}{4}} \quad (13)$$

(From McAdams, "Heat Transmission," pg. 177, 3rd Ed.)

T_1 is the temperature of the inner pipe

T_2 is the temperature of the outer pipe

T_a is the ambient air temperature, 100°F

T_G is the temperature of the ground, 100°F

T_s is the temperature of the sky, -40°F

G_s is the solar constant, 255 Btu/hr ft²

F_{2-G} is the radiation shape factor from pipe to ground

F_{2-s} is the radiation shape factor from pipe to sky

Assume: $F_{2-G} = 0.5$ and $F_{2-s} = 0.5$

Equation (12) then becomes

$$\pi \left(\frac{4}{3}\right) L \sigma (T_2^4 - T_1^4) = \pi \left(\frac{4}{3}\right) L (255) \left(\frac{1}{T_2}\right)^{\frac{5}{4}} + 255 \left(\frac{4}{3}\right) L + .5 \pi \left(\frac{4}{3}\right) L \sigma (T_s^4 - T_2^4) + .5 \pi \left(\frac{4}{3}\right) L \sigma (T_G^4 - T_2^4) \quad (14)$$

On simplifying, Equation (14) becomes

$$2.333 \sigma T_2^4 = .334 (100 - T_2)^{5/4} + 256.2 + \sigma T_1^4 \quad (15)$$

If $T_1 = 50^\circ\text{R}$, then

$$\sigma T_2^4 = .1435 (100 - T_2)^{5/4} + 109.8 \quad (16)$$

The solution of Equation (16) yields $T_2 = 59.5^\circ\text{F}$. The total heat transferred to the liquid hydrogen in 300 ft of pipe is:

$$q = \sigma A_1 (T_2^4 - T_1^4) = \pi \left(\frac{12.5}{12} \right) (300) \left[(519.2)^4 - (50)^4 \right] (.1713 \times 10^{-8}) \quad (17)$$

$$q = 1.222 \times 10^5 \text{ Btu/hr}$$

This heat is absorbed by the liquid hydrogen flowing in the line, thus:

$$q = \dot{W} C_p \Delta T \quad (18)$$

Where $\dot{W}$ is the weight flow of hydrogen, 100 lb/sec

C_p is the specific heat of the liquid hydrogen at the temperature and pressure under consideration.

$$C_p = 3.02 \text{ Btu/lb } ^\circ\text{F (at } 50^\circ\text{R and 450 psia)}$$

ΔT is the temperature rise in the hydrogen after flowing 300 ft.

Therefore,

$$1.222 \times 10^5 = 100 (3600) (3.02) \Delta T \quad (19)$$

$$\text{or } \Delta T = 0.11 ^\circ\text{F}$$

Thus, assumption (1) above is valid since 0.11°F is small compared to the 50°R wall temperature. The liquid hydrogen flows with essentially constant enthalpy throughout the 300 ft length of pipe.

2. Determination of the Loss of Total Pressure in 300 ft of Line.

a. Given conditions and assumptions

- (1) The line is 300ft of vacuum-jacketed commercial steel pipe
- (2) The line is 12-in. ID.
- (3) There are 2 gate valves (fully open) in the line.
- (4) There are six 90° standard elbows.
- (5) There is one sharp entrance.

- (6) There is one sudden enlargement.
- (7) Liquid hydrogen flow rate is 100 lb/sec.
- (8) The liquid hydrogen flows along the line with constant temperature (substantiated by Section (1) above).

b. Calculations

The equation expressing weight flow rate ($\dot{W} \sim \text{lb/sec}$) to fluid density ($\rho \sim \text{lb/ft}^3$), pipe cross-sectional area ($A \sim \text{ft}^2$), and fluid velocity, ($V \sim \text{ft/sec}$) is

$$\dot{W} = \rho AV, \text{ or } 100 = \rho \left(\frac{\pi}{4} \right) \left(\frac{12}{12} \right)^2 V \quad (20)$$

$$\text{thus } \rho V = 127.3 \quad (21)$$

For 515 psia: ($T = 48.0^\circ\text{R}$, $\rho = 4.26 \text{ lb/ft}^3$, thus $V = 29.9 \text{ ft/sec}$)

($T = 42.1^\circ\text{R}$, $\rho = 4.49 \text{ lb/ft}^3$, thus $V = 28.4 \text{ ft/sec}$)

For 397 psia: ($T = 48.0^\circ\text{R}$, $\rho = 4.18 \text{ lb/ft}^3$, thus $V = 30.5 \text{ ft/sec}$)

($T = 42.1^\circ\text{R}$, $\rho = 4.43 \text{ lb/ft}^3$, thus $V = 28.8 \text{ ft/sec}$)

It is seen that there is very little variation in density for the pressure range 400 to 500 psia. Average values of velocity, density, and viscosity will be used to compute the Reynolds' Number. The viscosity of liquid hydrogen in the range of temperatures and pressures under consideration is $\mu = 100 \times 10^{-6} \text{ poise} = 58 \times 10^{-12} \frac{\text{lb-hr}}{\text{ft}^2}$

The Reynolds Number is then

$$\text{Re} = \frac{\rho V D}{\mu} = \frac{127.3(3600)(12/12)}{58 \times 10^{-12}(3600)^2(32.2)} = 1.90 \times 10^7 \quad (22)$$

For commercial steel pipe ($e/d = .00015$), the friction factor (f) is

$$f = .0188$$

The equivalent length of pipe is (from Reference 4)

2 gate valves 2 (7) = 14 ft

6 - 90° elbows 6 (31.5) = 188 ft

1 entrance 1 (18) = 18 ft

1 expansion 1 (15) = 15 ft

300 ft of pipe 1 (300) = 300 ft

Total 535 ft

The pressure drop along the pipe is then given by

$$\begin{aligned}\Delta P &= f \frac{L}{D} \rho \frac{V^2}{2g} \\ &= .0128 \frac{(535)}{(1)} (4.34) \frac{(29.4)^2}{2 (32.2)(144)} \\ &= \underline{2.8} \text{ psi}\end{aligned}\tag{23}$$

Thus the pressure drop for the liquid hydrogen flowing in the line is 2.8 psia and is essentially constant for the range of temperatures and pressures considered (42°R to 48°R and 400 psi to 500 psi, respectively).

B. LIQUID OXYGEN LINE

1. Determination of Temperature Rise in 300 ft Line

a. Given Conditions and Assumptions

- (1) 6-in. ID vacuum-jacketed pipe
- (2) No heat conduction from inner to outer pipe
- (3) Liquid flow rate of 110 lb/sec
- (4) Natural convection of heat from the outer pipe to 100°F ambient air.
- (5) The inner pipe is at the temperature of liquid oxygen.
- (6) All radiating surfaces are black, i.e., the emissivities and absorptivities are 1.0.
- (7) The line does not touch the ground which is 100°F.
- (8) The inner and outer pipes are very close together.
- (9) The outer pipe diameter is 8 in.
- (10) Liquid hydrogen temperature is approximately 252°R.
- (11) The line is two straight concentric cylinders.
- (12) The temperature rise in the oxygen line is small enough to consider the oxygen temperature approximately constant along the pipe. (This must be verified).

b. Calculations

The heat balance on the complete line is

$$\sigma A_1 (T_2^4 - T_1^4) = h_c A_2 (T_1 - T_2) + G_s A_p + \sigma F_{2-s} A_2 (T_s^4 - T_2^4) + \sigma F_{2-g} A_2 (T_g^4 - T_2^4)\tag{24}$$

Where: A_1 is the surface area of the inner pipe, $A_1 = \pi \left(\frac{6}{12}\right) L$, ft^2

A_2 is the surface area of the outer pipe, $A_2 = \pi \left(\frac{8}{12}\right) L$, ft^2

L is the length of the line, 300 ft.

σ is the Stefan-Boltzman constant, $1.713 \times 10^{-9} \frac{\text{Btu}}{\text{hr ft}^2 \text{ } ^\circ\text{R}^4}$

A_p is the projected area of the outer pipe to the sun

$$A_p = DL \frac{8}{12} L, \text{ft}^2$$

h_c is the natural convection heat transfer coefficient,
 $\text{Btu/hr ft}^2 \text{ } ^\circ\text{F}$

For $T_a = 100^\circ\text{F}$, assume $T_2 \approx 50^\circ\text{F}$, then $\Delta T = 50^\circ\text{F}$

$$\text{and } T_f = \frac{T_a + T_2}{2} = \frac{100 + 50}{2} = 75^\circ\text{F and}$$

$$\begin{aligned} (G_r \cdot P_r)_f &= 1.5 \times 10^6 (50) \left(\frac{8}{12}\right)^2 \\ &= 3.18 \times 10^7 \end{aligned} \quad (25)$$

$$\text{Then } h_c = 0.27 \left(\frac{\Delta T}{D_2}\right)^{1/4} = .298 (\Delta T)^{1/4}$$

(From McAdams, "Heat Transmission," pg 177, 3rd Ed.).

T_1 is temperature of inner pipe.

T_2 is temperature of outer pipe.

T_a is the ambient air temperature, 100°F .

T_G is the temperature of ground, 100°F

T_s is temperature of sky, -40°F .

G_s is the solar constant, 255 Btu/hr ft^2 .

F_{2-G} is radiation shape factor from pipe to ground.

F_{2-s} is radiation shape factor from pipe to sky.

$$\text{Assume } F_{2-G} = 0.5, F_{2-s} = 0.5$$

Equation (24) then becomes

$$\begin{aligned} \pi \left(\frac{6.5}{12}\right) L \sigma (T_2^4 - T_1^4) &= \pi \left(\frac{8}{12}\right) L (.298)^{5/4} (T_2 - T_2) + 255 \left(\frac{8}{12}\right) L + .5 \pi \left(\frac{8}{12}\right) L \sigma (T_s^4 - T_2^4) \\ &\quad + .5 \pi \left(\frac{8}{12}\right) L \sigma (T_G^4 - T_2^4) \end{aligned} \quad (26)$$

On simplifying, Equation (26) becomes

$$2.231 \sigma T_2^4 = .366 (T_a - T_2)^{5/4} + 236.6 + \sigma T_1^4 \quad (27)$$

If $T_1 = 252^\circ\text{R}$, then

$$T_2^4 = .1642 (T_a - T_2)^{5/4} + 109.1 \quad (28)$$

The solution of Equation (28) yields $T_s = 60.5^\circ\text{F}$.

The total heat transferred to the liquid oxygen in 300 ft of pipe is:

$$q = A_1 (T_2^4 - T_1^4) = \pi \left(\frac{6.5}{12} \right) (300) \left[(520.2)^4 - (252)^4 \right] (.1713 \times 10^{-8}) \quad (29)$$

$$q = 0.640 \times 10^5 \text{ Btu/hr}$$

This heat is absorbed by the liquid oxygen flowing in the line, thus:

$$q = \dot{W} C_p \Delta T \quad (30)$$

Where $\dot{W}$ is the weight of flow of oxygen, 110 lb/sec

C_p is the specific heat of the liquid oxygen at the temperature and pressure under consideration.

$$C_p = .536 \text{ Btu/lb } ^\circ\text{F}$$

ΔT is the temperature rise in the oxygen after flowing 300 ft.

Therefore,

$$.640 \times 10^5 = 110 (3600) (.536) \Delta T \quad (31)$$

or $\Delta T = 0.30^\circ\text{F}$

Thus, assumption (1) above is valid since 0.30 is small compared to the 252°R wall temperature. The liquid oxygen flows with essentially constant enthalpy throughout the 300-ft length of pipe.

2. Determination of Loss of Total Pressure in 300-Ft of Line

a. Given conditions and assumptions

- (1) The line is 300 ft vacuum-jacketed commercial steel pipe.
- (2) The line is 6-in. ID.
- (3) There are 2 gate valves (fully open) in the line.
- (4) There are six 90° standard elbows.
- (5) There is one sharp entrance.
- (6) There is one sudden enlargement.
- (7) Liquid oxygen flow rate is 110 lb/sec.
- (8) The liquid oxygen flows along the line with constant temp.
(Substantiated by Section (1) above.)

b. Calculations

The equation expressing weight flow ($\dot{W} \sim \text{lb/sec}$) to fluid density ($\rho \sim \text{lb/ft}^3$), pipe cross-sectional area ($A \sim \text{ft}^2$), and fluid velocity ($V \sim \text{ft/sec}$) is

$$\dot{W} = \rho AV \text{ or } 110 = \left(\frac{\pi}{4}\right) \left(\frac{6}{12}\right)^2 \rho V \quad (32)$$

$$\text{thus } \rho V = 560.4 \quad (33)$$

For fluid temperatures of

$$252^\circ\text{R}, \rho = 50.5 \text{ lb/ft}^3, \text{ thus } V = 11.1 \text{ ft/sec.}$$

$$\text{and } 261^\circ\text{R}, \rho = 47.0 \text{ lb/ft}^3, \text{ thus } V = 11.9 \text{ ft/sec.}$$

The viscosity of liquid oxygen at an average temperature of 257°R is

$$\mu = 5.75 \times 10^{-10} \text{ lb-hr/ft}^2$$

The Reynolds number is then

$$\text{Re} = \frac{\rho V D}{\mu} = \frac{560.4 (6/12)(3600)}{5.75 \times 10^{-10}(3600)^2(32.2)} = 4.27 \times 10^6 \quad (34)$$

This Reynolds number is essentially constant over the pressures and temperatures under consideration. For commercial steel pipe ($e/d = .00030$), the friction factor (f) is

$$f = .0148$$

The equivalent length of pipe is (from Reference 4).

$$2 \text{ gate valves } 2(3.4) = 6.8 \text{ ft}$$

$$6\text{-}90^\circ \text{ elbows } 6(16.4) = 98.6 \text{ ft}$$

$$1 \text{ entrance } 1(9.0) = 9.0 \text{ ft}$$

$$1 \text{ expansion } 1(16.6) = 16.6 \text{ ft}$$

$$300 \text{ ft of pipe } 1(300) = 300.0 \text{ ft}$$

$$\text{Total } 431 \text{ ft}$$

The pressure drop along the pipe is then given by

$$\begin{aligned} \Delta P &= f \frac{L}{D} \rho \frac{V^2}{2g} \\ &= .0148 \frac{431}{.5} (48.8) \frac{(11.5)^2}{2(32.2)(144)} \\ &= 8.9 \text{ psi} \end{aligned} \quad (35)$$

Thus, the pressure drop for the liquid oxygen flowing in the line is 8.9 psi and is essentially constant for the range of temperatures considered (252°R to 261°R). From thermodynamic data for liquid oxygen at 460 psig in the Dewar, a liquid oxygen temperature of less than 257°R is necessary in order that no vapor appear at the interface. For liquid oxygen at 420 psig in the Dewar, a liquid oxygen temperature of less than 253.5°R is necessary in order that no vapor appear at the interface.

IX. SYSTEM RESPONSE TIME

A. INTRODUCTION - A solution for the transient behavior of the gas generator and piping system has been based on the model shown in Figure E-3. The flow of liquid oxygen and hydrogen into the system is regulated by the gas generator header orifices. The flow out of the system is regulated by the ejector nozzle. The piping and generators have been assumed to be a bounded volume of 11.27 FT^3 . The flow into the volume was assumed to be a liquid; and the change of phase was assumed to occur without explosion or shock waves. The volume is further assumed to be perfectly insulated and without frictional losses.

The equations used to describe the transient response were:

1. A mass balance equation.
2. An equation of state.
3. A chemical reaction equation.
4. A nozzle flow equation.
5. An orifice equation

These equations resulted in a non-linear first order differential equation which was solved graphically. Boundary conditions for this solution were:

1. The pressure upstream of the LO_2 and LH_2 remained constant at 420 psia.
2. The initial system pressure and temperature was 9.5 psia and 1560°R.
3. The ejector nozzle was choked initially with 6.3 lb/sec flow; and remained choked throughout the time period considered.

B. NOMENCLATURE

1. Symbols

A	Area, Ft^2
A*	Throat Area, Ft^2
C, C_1	Constants
C_p	Specific heat at constant pressure, $\text{Btu/lb } ^\circ\text{F}$
H	Enthalpy, Btu/lb
H°	Enthalpy at conditions of ΔH°_R , Btu/lb
M	Molecular Weight, lb/lb-mol
P	Pressure, psi
ΔH°_R	Heat of reaction at specified conditions, Btu/lb fuel
ΔP	Pressure difference, psi
R	Gas constant $1445/M$, $\frac{\text{ft-lb}}{\text{lb } ^\circ\text{R}}$
T	Temperature $^\circ\text{F}$ or $^\circ\text{R}$
V	Volume
$\dot{W}$	Weight flow rate, lb/sec
W	Total weight of gas in pipe, lb
ρ	Density, lb/ft^3 or lb/in.^3
θ	Time, seconds
$d/d\theta$	Derivative with respect to time, sec^{-1}

2. Subscripts

H_2	Hydrogen
O_2	Oxygen
O	Injector plate upstream
I	Inside pipe or tank
R	Reactants
P	Products

C. DERIVATION AND CALCULATIONS

The mass balance equation is

$$\dot{W}_{in} - \dot{W}_{out} = \frac{dw}{dt} = V \frac{d\rho}{dt} \quad (36)$$

Where

$$\dot{W}_{in} = \dot{W}_{O_2 in} + \dot{W}_{H_2 in}$$

and the weight flow in is given by

$$(\dot{W}_{C_2 in} + \dot{W}_{H_2 in})^2 C = P_0 - P_1 \quad (37)$$

For $\dot{W}_{O_2 in} + \dot{W}_{H_2 in} = 210 \text{ LB/SEC}$ and $\Delta P = 100 \text{ psi}$

$$(210)^2 C = 100 \frac{\text{LB}_f}{\text{IN}^2}$$

$$C = \frac{100}{(210)^2} \frac{\text{LB}_f \text{ SEC}^2}{\text{LB}_M^2 \text{ IN}^2}$$

Thus,

$$\dot{W}_{O_2 in} + \dot{W}_{H_2 in} = \frac{P_0 - P_1}{C} = 21 (P_0 - P_1)^{1/2}, \quad P \text{ in psi} \quad (38)$$

The flow out is assumed to behave as $\frac{\dot{W} \sqrt{T}}{R A^*} = \text{constant} \quad (39)$

Since the flow is assumed to be initially choked, and the area is unchanged

$$\frac{\dot{W} \sqrt{T}}{P} = C_1 \quad \text{and} \quad \dot{W} = \frac{C_1 P}{\sqrt{T}} \quad (39)$$

The mass balance equation can now be written in full

$$21 (P_0 - P_1)^{1/2} - \frac{C_1 P}{\sqrt{T}} = V \frac{dP}{dT} \quad (40)$$

A relationship for the temperature can be obtained from the chemical reaction for the combining O_2 and H_2

$$H_R = - (H_R - H_R^0) + (H_P - H_P^0)$$

where H_R corresponds to the energy of the reacting H_2 ; $(H_R - H_R^0)$ corresponds to the energy required to raise the entering fluids to the reaction enthalph H_R^0 ; and $(H_P - H_P^0)$ corresponds to the energy required to move the product enthalpy from the enthalpy of reaction to the enthalpy of temperature T .

$$(\dot{W}_{H_2R})(-H_R^0) = -\dot{W}_{O_2}(H_R - H_R^0) - \dot{W}_{H_2}(H_R - H_R^0) + (\dot{W}_{O_2} + \dot{W}_{H_2})(H_P - H_P^0) \quad (41)$$

If average specific heats can be assumed, then

$$(\dot{W}_{H_2R})(-\Delta H_R^0) = -\dot{W}_{O_2}(H_R - H_R^0) - \dot{W}_{H_2}(H_R - H_R^0) + (\dot{W}_{O_2} + \dot{W}_{H_2})(C_{p \text{ avg}}^T - C_{p \text{ avg}}^{T^0}) \quad (42)$$

where T^0 is the assumed reference for the reaction. Further from the T-S and H-S diagrams for O_2 and H_2 the terms $\dot{W}_{O_2}(H_R - H_R^0)$ and $\dot{W}_{H_2}(H_R - H_R^0)$ are approximately constant for the range of pressures expected. Now the reaction equation becomes:

$$(\dot{W}_{H_2R})(-\Delta H_R) = -\dot{W}_{O_2}(\Delta H_{O_2}) - \dot{W}_{H_2}(\Delta H_{H_2}) + (\dot{W}_{O_2} + \dot{W}_{H_2})(C_p^T - C_p^{T^0}) \quad (43)$$

Where $\dot{W}_{H_2} R$ is the hydrogen rate used in the reaction; and will be assumed to be in a constant proportion to the total H_2 flow; i.e.,

$$\dot{W}_{H_2} R = \dot{W}_{H_2} \frac{98-84}{98} = .142 \dot{W}_{H_2}$$

for a mixture ratio of 1.14. Equation then becomes

$$.142 \dot{W}_{H_2} (-\Delta H_R) = \dot{W}_{O_2} (\Delta H_{O_2}) - \dot{W}_{H_2} (\Delta H_{H_2}) - (\dot{W}_{O_2} + \dot{W}_{H_2}) (C_p T - C_p T^0) \quad (44)$$

This equation is now independent of P, hence it can be assumed that T is constant for all $\dot{W}_{O_2}$ and $\dot{W}_{H_2}$ assumed. The weight flow out can now be written as

$$\dot{W}/P = C \quad (39)''$$

dropping the subscript on P.

$$C = 210/320 = .656 \frac{LB_m}{SEC} \frac{IN^2}{LB_f}$$

and $\dot{W} = .656 P$ where P is in $\frac{LB_f}{IN^2}$.

The mass balance is now written

$$21 (P_0 - P)^{1/2} - .656 P = V \frac{d\rho}{d\theta} \quad (40)'$$

where P_0 and P are given in $\frac{LB_f}{IN^2}$

The equation of state can now be used to relate P and θ

$$\theta = \frac{P}{12 RT} \frac{LB_m}{IN^3} \quad (45)$$

and R is given as an average for the mixture as $R = 358 \frac{FT LB_f}{LB_m ^\circ R}$

The temperature T will be assumed constant at $2020^\circ R$. Then

$$\theta = \frac{P}{(12)(358)(2020)} = \frac{P}{.867 \times 10^7} \quad (45)'$$

where the pressure is assumed to be instantly uniform throughout the entire volume. The initial pressure P_0 is assumed constant at 420 psia thus,

$$21 (420 - .867 \times 10^7 e)^{1/2} - (.656)(.867)(10^7) e = V \frac{de}{de} \quad (40)$$

changing the units of e to $\frac{LB_m}{FT^3}$

$$21 (420 - \frac{8670 \times 10^3}{1728} e)^{1/2} - (\frac{.656)(8670)(10^3)}{1728} e = V \frac{de}{de}$$

$$21 (420 - 5017 e)^{1/2} - 3295 e = V \frac{de}{de} \quad (46)$$

Rearranging Equation (46)

$$1489 (.0837 - e)^{1/2} - 3295 e = V \frac{de}{de} \quad (46)'$$

and

$$1489 (.0837 - e)^{1/2} - 2.21 e = V \frac{de}{de}$$

The volume V is assumed to be the entire volume of the gas generators and all the associated ducting to the nozzle plenum, thus:

$$V = 1427 FT^3$$

Dividing Equation (46)' through by V

$$\frac{1489}{1427} (.0837 - e)^{1/2} - 2.21 e = \frac{de}{de} \quad (47)$$

Rearranging Equation (47) gives

$$\int_0^e de = .958 \int_0^e \frac{de}{(.0837 - e)^{1/2} - 2.21 e} \quad (48)$$

Once the limits of integration are determined, Equation (48) can be integrated to give the density as a function of time. The initial density can be found from Equation (45)

$$e_1 = \frac{9.5(144)}{358(2020)} = 0.0019 LB/FT^3$$

The final density ρ_2 is taken as 98% of the steady state value ρ_2' from equation

$$\rho_2' = \frac{(320)(144)}{(358)(2020)} = .0638 \frac{\text{LB}_m}{\text{FT}^3}$$

$$\rho_2 = (.98)(.0638) = .0615 \frac{\text{LB}_m}{\text{FT}^3}$$

The time - density equation is now

$$\rho = .958 \int_{.0019}^{.0615} \frac{d\rho}{(.0837 - \rho)^{1/2} - 2.21\rho} \quad (48)'$$

Equation (48)' was integrated by a graphical numerical method to give the results shown in Figure E-4. The pressure results shown in Figure E-5 were calculated from Equation (45) using Figure E-4 results, $T = 2020^\circ\text{R}$ $R = 358 \frac{\text{FT LB}}{\text{LB}^\circ\text{R}}$. The weight

flow results shown in Figure E-6 were calculated using Figure E-5 results and Equation (39)''.

X.

REFERENCES

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2. Memo to J. R. DaVolio from J. M. Haygood on 21 September 1962.
3. Eckert, E. R., Drake, R. M., "Heat and Mass Transfer", McGraw-Hill Book Co., New York, 1959.
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Figure E-1

SCHEMATIC DIAGRAM OF GAS GENERATOR AND PIPING SYSTEM MODEL

$$W_{H_2} = C_1 \sqrt{P_{H_2} - P}$$

$$W_{O_2} = C_2 \sqrt{P_{O_2} - P}$$

$$W_{OUT} = C_3 \frac{P}{\sqrt{T}}$$

GAS DENSITY RESPONSE TIME

Figure E-4

PLENUM PRESSURE RESPONSE TIME

Figure E-5

FLOW RATE RESPONSE TIME

Figure E-6

APPENDIX F

STRESS ANALYSIS

Table of Contents

- I. Gas Generator Assembly
 - A. Introduction
 - B. Stress Analysis of the Assembly
 - 1. Cryogenic Feed Flange
 - 2. Combustion Chamber
 - 3. Injector Plate
- II. Skid
- III. Symbols
- IV. References

Table F-1 Computer Output for Flangeless Configuration

Figure F-1 Schematic Diagram for Flangeless Configuration

I. GAS GENERATOR ASSEMBLY

A. INTRODUCTION

The computer output presented in Table F-1 shows the large negative margins that exist in the flangeless configuration shown in Figure F-1. In order to avoid discontinuities in this section of the gas generator, two flanges separating the combustion chamber and cover, are recommended. A pressure of 425 psi and an approximate temperature of 500°F is the basis for design using insulation inside the dome and between the flanges. According to the ASME code, 17700 psi is the allowable stress for 310 stainless steel at 500°F.

B. STRESS ANALYSIS OF THE ASSEMBLY

1. Cryogenic Feed Flange

a. Dome

The dome, or head, is a truncated cone with a base diameter of 18 in., a top diameter of 12-3/4 in., and a length of 20 in. The required thickness is:

$$t = \frac{PD}{2 \cos \alpha (SE - 0.6P)}$$

$$t = \frac{425 \times 21.56}{2 \cos 7.5^\circ (17700 \times 1.00 - 0.6 \times 425)}$$

$$t = 0.265 \text{ in.}$$

Because of the heavy flange necessary to mate the shell flange, a heavier conical head (1.218 in. wall) is recommended to offset discontinuity stresses.

b. Flange

This flange is subject to an internal pressure of 425 psi and an approximate temperature of 500°F. Dimensions for an ASA 24-in. 1500-lb std flange (310 stainless steel material) permits an internal pressure of 3125 psi at 500°F. A more accurate stress analysis will provide a more efficient design.

2. Combustion Chamber

a. Cylinder

The cylinder is subject to a pressure of 325 psi and a temperature of 1555°F, and is made of Inconel with an allowable rupture strength of 1560 psi at 1550°F/100 hours.

The required thickness is:

$$t = \frac{PR}{SE - 0.6 P}$$

$$t = \frac{325 \times 9.69}{1560 \times 1.00 - 0.6 \times 325}$$

$$t = 2.31 \text{ in.}$$

A shell with a 24 in. OD and a minimum thickness of 2.31 in. is recommended. Discontinuity stresses which exist at the flange joints and thermal stresses which exist due to the radial temperature gradient will be calculated when further analysis is required.

b. Forward Flange

This flange is subject to an internal pressure of 325 psi and a maximum temperature of 1555°F. An ASA 24-in. 1500-lb std flange (Inconel material), allows an internal pressure of 345 psi at 1400°F and a more accurate stress analysis will again provide a more efficient design.

c. Aft Flange

This flange is subject to the same temperature and pressure conditions as the forward flange. Therefore, the same ASA 1500-lb std flange (Inconel material) is recommended.

3. Injector Plate

The injector plate is subject to a differential pressure of 100 psi and a temperature gradient of 519°F maximum (with .20 Rokide 'Z' on the injector face) to -420°F minimum. The 310 stainless steel used allows a stress of 17605 psi for 519°F.

Required thickness:

$$t = \left[\frac{3 \bar{W}}{8 \pi m S} (3m + 1) \right]^{1/2}$$

$$t = \left[\frac{3 \times 100 \times \pi \times 10^2}{8 \times \pi \times 3.3 \times 17605} (3 \times 3.3 + 1) \right]^{1/2}$$

$$t = 0.84 \text{ in.}$$

For a 3 in. thick injector plate, the curvature resulting from the thermal gradient will be:

$$\begin{aligned} \frac{1}{r} &= \frac{\beta \Delta t}{h} \\ &= \frac{10 \times 10^{-6} (519 + 420)}{3.00} \\ &= 0.003130 \end{aligned}$$

from which:

$$\begin{aligned} r &= \frac{1}{0.003130} \\ &= 0.320 \text{ in.} \end{aligned}$$

$$\begin{aligned}
 \text{The maximum deflection at center} &= 320 - 320 \cos 1^\circ 48' \\
 &= 320 - 319.84 \\
 &= 0.16 \text{ in.}
 \end{aligned}$$

II. SKID

This skid is made of (6 [18) rolled structural steel sections and consists of two parallel beams that are tied by two cross beams. Assuming a weight of 20,000 lb for the generator, the maximum stress in the cross beams is:

$$f = \frac{0.5 \bar{W} L}{8 Z}$$

$$f = \frac{0.5 \times 20,000 \times 24}{8 \times 9.8}$$

$$f = 6825 \text{ psi}$$

The maximum stress in the parallel beams is:

$$f = \frac{0.5 \bar{W} a}{2 Z}$$

$$f = \frac{0.5 \times 20,000 \times 30}{2 \times 9.8}$$

$$f = 15,300 \text{ psi}$$

III. SYMBOLS

P	=	Design pressure, psi
D	=	Inside diameter, in.
S	=	Allowable stress, psi
E	=	Joint efficiency
α	=	Half apex angle of cone
$\bar{W}$	=	Total load, lb
m	=	Reciprocal of Poisson's ratio
β	=	Coefficient of thermal expansion in./in. °F
r	=	Curvature radius, in.
Δt	=	Temperature differential, °F
h	=	thickness, in.
L	=	Length of span, in.
I	=	Moment of inertia, in. ⁴
Z	=	Sectional modulus, in. ³
a	=	Distance from loading point to supporting point, in.

IV. REFERENCES

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TABLE F-1

DOCUMENT NUMBER

PAGE OF

24 IN OD GAS GENERATOR P=325 PSI MAX T=1500 F SBM 9-26-62

LOAD DEFLECTION
IDENTIFICATION IDENTIFICATION

CRITICAL MARGIN OF SAFETY = -.8514 AT 12 12

SUMMARY OF MINIMUM MARGINS OF SAFETY AT EACH JOINT

LOAD IDENTIFICATION	DEFLECTION IDENTIFICATION	MAGNITUDE OF CRITICAL STRESS	TYPE OF CRITICAL STRESS	ALLOWABLE STRESS	MARGIN OF SAFETY
1	1	844.16	MULT. LOC.	17500.00	HIGH
2	2	942.89	MERID INNER	17500.00	HIGH
3	3	1204.45	MERID INNER	17100.00	HIGH
4	4	1499.93	MERID INNER	17000.00	HIGH
5	5	1677.39	MERID INNER	16750.00	3.9357
6	6	1888.99	HCCP INNER	16000.00	7.4701
7	7	2192.97	HCCP INNER	14000.00	5.3845
8	8	2885.93	HCCP OUTER	10400.00	2.6037
9	9	3878.30	MERID OUTER	6800.00	.7533
10	10	6556.97	MERID OUTER	4000.00	-.3900
11	11	9183.73	MERID OUTER	2350.00	-.7441
12	12	10091.46	MERID OUTER	1500.00	-.8514
13	13	8054.30	MERID OUTER	1500.00	-.8138
14	14	3350.28	HCCP OUTER	1500.00	-.5523
15	15	2310.05	HCCP INNER	1500.00	-.3507
16	16	1883.35	HCCP INNER	1500.00	-.2035
17	17	1682.38	HCCP INNER	1500.00	-.1034
18	18	1658.15	HCCP INNER	1500.00	-.0954
19	19	1686.64	HCCP OUTER	1500.00	-.1107
20	20	1692.03	HCCP OUTER	1500.00	-.1135
21	21	1690.12	HCCP OUTER	1500.00	-.1125
22	22	1688.99	HCCP INNER	1500.00	-.1119
23	23	1688.40	HCCP INNER	1500.00	-.1116
24	24	1688.25	HCCP INNER	1500.00	-.1115
25	25	1688.29	HCCP OUTER	1500.00	-.1115

TABLE F-1 (cont.)

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Schematic Diagram for Flangeless Configuration

APPENDIX G

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I. OUTLINE OF EVALUATION OF MATERIALS

A. COMPONENT PARTS OF SECONDARY GAS GENERATOR SYSTEM EVALUATED.

1. Combustion Chamber, Hot Side
2. Injector
3. Combustion Chamber, Cold Side
4. Propellant Feed Piping
5. Gaseous Nitrogen Piping

B. CONSTRUCTION MATERIALS

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 - a. Combustion Chamber, Hot Side -- Nuclear Grade Inconel
 - b. Injector -- Nuclear Grade Inconel
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II. PROPOSED SYSTEM

A. COMPONENTS OF SECONDARY GAS GENERATOR SYSTEM

1. Combustion Chamber, Hot Side
 - a. Material Selection, First Choice

The combustion chamber hot side is expected to be heated to a maximum metal temperature of 1537°F. for varying periods of time up to one hour maximum. It is required that the system be designed to allow up to 200 start-ups reflecting the cyclic service conditions to be experienced. Of importance, therefore, is the choice of a construction material with favorable relaxation properties as well as suitable high temperature properties when subjected to a nuclear environment. Nuclear Grade Inconel, Mil-N-22987 Specification Material (0.10% maximum Cobalt) considered from these desirable properties as well as cost, availability, weldability and fabricability, as determined to date, is considered to be most favorable choice of materials investigated for application.

- b. Other Materials Reviewed

Several groups of alloys were considered for application, but were eliminated from final consideration for the reasons specified. Materials considered were:

- (1) Iron-base alloys: A-286, Discaloy, 19-9DL. These alloys are not generally recommended for service at temperatures in excess of 1300°F.
- (2) Cobalt base alloys: S-816, V36, N155. These alloys are not recommended for service in a nuclear environment; in addition, cost, availability in required forms, sizes and weights, plus anticipated problems in weldability and fabricability of heavy sections were reasons for elimination from consideration.
- (3) Iron-Nickel base alloys: Al-901, and Nickel base alloys: R-41 and M 252. Although each of these materials possess good short time, high temperature properties, none could be recommended seriously for application. Al-901 alloy is not generally considered for use at temperatures in excess of 1400°F. While the material can be welded by the TIG process, joint efficiency of welds is reportedly only 80-90% of base metal strength after aging thermal treatment. R-41 and M252 alloys have nominal 10-11% Cobalt content together with other unfavorable availability and fabrication problems.
- (4) Austenitic Stainless Steel Alloys: Each of the alloys investigated, Types 304, 309, 310, 316, 321, and 347 Stainless Steel have the common properties of good availability and relatively good fabricability and weldability. A distinct limitation of each of these alloys is the lack of high temperature strength, as measured by rupture and creep at the operating

temperature of 1537°F. The Type 304 material is subject to carbide precipitation in the range of 800-1500°F, as is the Type 316 Stainless Steel material in a range of 800-1650°F. Types 309 and 310 Stainless Steel precipitate carbides when heated and held in a range of 1200-1950°F for extended periods of time. Types 321 and 347 Stainless Steel, both stabilized grades, offer excellent oxidation resistance at elevated temperatures, but relaxation of these alloys is not considered favorable for the operating conditions.

- (5) Inconel X Hastelloys, B, C, and X: Investigation of these alloys did not seem merited for the specific application due to the high cost of these materials, the difficulty of fabrication in heavy sections, and the limited availability of raw materials in the required weights, shapes and sizes. In addition, the Hastelloys contain a nominal Cobalt content of 1-2.5%.

2. Injector

It has been predicted that the face of the injector, if not insulated, will in extended run periods (one hour maximum duration), approach the temperature level of the combustion chamber, hot side. If this condition can be expected to be experienced, it is recommended that the injector be made from Nuclear Grade Inconel material for the same reasons as outlined under Combustion Chamber, hot side. Conversely, if thermally insulated from the hot zone or cooled by regenerative methods

utilizing the present cryogenics a reduced temperature level in the injector can be expected permitting the use of Type 310 Stainless Steel material. Calculations prepared for Materials Section indicate that 0.20 inches of Rockide "Z" insulation band can be expected to reduce the temperature of the hot side face of the injector to approximately 519°F.

3. Combustion Chamber, Cold Side

(a) Material Selection, First Choice

Design indicates that the maximum temperature to be experienced on the cold side of the combustion chamber will be approximately 500-600°F. It is recommended that the cold side of the combustion chamber which consists of a flange (thermally insulated from a mating Inconel flange on the combustion chamber hot side) and miscellaneous piping components ending at flanged interfaces be manufactured from Type 310 Stainless Steel alloy. This alloy has been previously investigated for response to cryogenic services and is reportedly suitable for the low temperature services on basis of the limited test information.

(b) Other Materials Reviewed

Type 304 L (Extra low carbon) stainless steel, has likewise had limited tests at application involving -423°F cryogenic temperatures. This alloy has been found to exhibit extremely low ductility (1-2%) at the low level temperatures.

4. Propellant Feed Piping

The propellant feed piping system will be capable of conveying cryogenics from flange interface to the cold side of the combustion chamber of the Gas Generator System. Line sizes can be scheduled from readily procurable ASA dimensional parts. It is recommended that these piping arrangements be manufactured from Type 310 Stainless Steel alloy.

It is proposed that the liquid hydrogen line be of vacuum jacketed construction. The liquid oxygen line, likewise, should be thermally insulated from ambient temperature conditions.

5. Gaseous Nitrogen Piping

Carbon Steel piping can be used for conveying the Gaseous Nitrogen to be used as purge gas. Pipe can be specified in accordance with ASTM A106-Grade B standard. Carbon Steel flanges can be specified in accordance with ASTM A105-Grade II standard. Flange connections shall be used near the Gas Generator combustion chamber, hot and cold sides, and those sections of the purge lines to be connected to the Inconel and Type 310 Stainless Steel materials will respectively be of the same material.

III. PROPOSED MATERIALS INVESTIGATION PROGRAM

A. COMBUSTION CHAMBER, HOT SIDE

The combustion chamber is nominally sized at 24" O.D. with a 2.31" wall thickness requirement based on an allowable design stress of 1500 psi at 1555° F/ASME Pressure Vessel Code. A cylindrical Inconel section approximately 27" in length will be girth welded to weld type flanges of the same material. The nominal thickness to be welded is heavier than that covered by general fabrication experience to date, for this material, and investigation and development of procedure, methods, specifications and standards will be necessary. It is anticipated that a recognized qualified vessel/piping fabricator will be selected to do the actual fabrication of components.

It is anticipated that the following Materials Support work efforts will be required over the initial six months of the program cycle.

1. Investigate with vendor sources, the adequacy of presently available weld wires and choose weld joining procedure and method based on available information and vendor recommendations.
2. Investigate methods chosen in section I. B. 5. by welding sections of similar thickness, developing techniques and practices necessary for program application.
3. Perform non-destructive tests during and at completion of weld (dye penetrant and radiography) to help in development of specifications and applicable standards.
4. Perform destructive tests on material samples including weld joints after cyclic thermal cycles from ambient temperatures to 1555°F.
5. Coordinate with other groups in development of AGC Standards and Specifications covering material procurement and quality assurance standards.
6. Monitor fabrication techniques and methods at piping/vessel fabricator's plant.

B. INJECTOR

The present concept of design envisions the use of metal or Teflon "O" rings to allow for relative movement of the injector in reference to the cold and/or hot sides of the combustion chamber without seal loss and escape of either hot gases from the hot side of the combustion chamber or cryogenic from the cold side of the combustion chamber. Movement (distortion) of the injector is expected to take

place due to thermal stresses as a result of thermal gradients through the cross section from hot to cold side. It is anticipated that the metal surface temperature of the injector face exposed to the thermal conditions of the hot side of the combustion chamber would (in a one hour test cycle time) approach, if not equal, the hot side metal temperature expected of 1555°F, if not thermally insulated. The opposite injector face, at the same time, can be assumed to be at a cryogenic temperature level, thus creating a thermal gradient through the section of approximately 2000°F.

In order to reduce the level of this thermal gradient (and hence, the imposed thermal stress) several methods for cooling the hot side face have been considered. These include: regenerative cooling, and thermal blanketing insulation. Either method could be expected to reduce the thermal temperature gradient through the injector, thereby reducing thermal stress and distortion. It has been reported, however, that approximately .014" maximum distortion of the injector will occur with the hot face side reduced to a level of 519°F from 1555°F by 0.20" Rockide "Z" multiple layer coating. This amount of distortion could cause serious problems with sealing and it is quite possible that an alternate method of cooling the injector will be needed. Investigation is anticipated as required in the following areas:

1. Investigate the proposed use of Teflon "O" ring seal principle (on cold side of combustion chamber) for:
 - a. Compatibility with expected temperature levels of 500-600°F predicted in this area.
 - b. Compatibility with nuclear environment.
2. Determine the effectiveness of thermal blanket insulation(s) techniques on hot side face of injector.

3. Review possible vendor sources to determine if a quality cast injector configuration could be made to allow for regenerative cooling methods.
4. Coordinate and develop specifications and standards to permit adequate quality assurance level of the injector.

C. COMBUSTION CHAMBER, COLD SIDE

The cold side of the combustion chamber in the areas immediately adjacent to the hot side (with sandwich insulation), is estimated to reach a temperature range of 500-600°F. At other positions, cryogenic piping will be in direct contact with the cold side of the combustion chamber or the final design itself may necessitate that the combustion chamber cold side be in direct contact with cryogenic propellants.

The material chosen for this application, namely Type 310 Stainless Steel, is reportedly satisfactory for service to -423°F and hence, capable of adequately containing the liquid hydrogen propellant. On the basis of initial review, therefore, this material seems adequate with Type 304L Stainless Steel as possible back-up material.

To fully demonstrate the capabilities of 310 and 304L Stainless Steels to perform reliably in the cryogenic atmospheres, it is felt that additional data should be obtained. It is anticipated, therefore, that a series of low temperature tensile tests to be conducted at -423°F (liquid hydrogen temperature) are required to specifically determine:

1. The elongation properties at the test temperatures.
2. Investigate properties of welded test specimens at the test temperatures.

D. PROPELLANT FEED PIPING

The material choice of Type 310 Stainless Steel for this piping is the same as chosen for the combustion chamber. Problems envisioned are, therefore, the same as previously discussed, and the described investigations and tests to be performed will, accordingly, help to resolve any problems in this area.

E. GASEOUS NITROGEN PIPING

No foreseeable problems are anticipated in construction or operation of the Gaseous Nitrogen Piping system. Carbon Steel piping can be utilized from the storage vessel to flange interfaces with either Inconel or Type 310 Stainless Steel being used for actual connections to the combustion chamber. No material problems or investigations are contemplated in this area.

IV. REFERENCES

1. Figures G-1, G-2, and G-3 - Allegheny Ludlum High Temperature Alloys
2. Figures G-4, G-5, G-6, G-7, G-12, and G-13, Tables G-1 and G-2 -
 American Society for Metals Handbook, 8th Edition, Volume I, 1961
3. Figures G-8, G-9, G-10, and G-11 - Haynes Stellite Company, Division
 Union Carbide Corporation, Hastelloy, Corrosion Resistant Alloy,
 Brochure, 1957
4. Table G-3, G-4, and G-5 - Defense Metals Information Center,
 Battelle Memorial Institute Report No. 148, February 14, 1961,
 (Review of Current Data on the Tensile Properties of Metals
 at Very Low Temperatures)

TABLE G-I

Short Time Properties
Cr-Ni Stainless Steels (Annealed)

<u>Alloy</u>	<u>Temp. °F.</u>	<u>Tensile Strength (10^3)psi</u>	<u>Yield Strength 0.2% (10^3)psi</u>
304	1200°	48.0	15.5
	1325°	34.0	14.0
	1500°	23.0	13.0
	1600°	20.0	10.0
	1800°	----	----
309	1200°	55	22
	1400°	36	20
	1600°	21	18.5
	1800°	10	14.5
310	1200°	57.2	22.6
	1350°	42.7	21.1
	1500°	30.3	19.7
	1800°	11.0	----
	2000°	7.0	----
316	1200°	50.6	22.6
	1400°	30.7	21.0
	1600°	18.0	19.0
	1800°	9.0 - 10.0	----
321	1200°	55.8	19
	1350°	41.5	18.9
	1500°	26.0	17.2
	1600°	18.5	12.0
	1800°	----	----
347	1200°	52.3	24.5
	1350°	39.2	22.8
	1500°	26.4	18.6
	1600°	----	----

TABLE G-II

Short Time Properties
Thermal Treatment as Noted

<u>Alloy</u>	<u>Temp.</u>	<u>Tensile Str. (10^3)</u>	<u>Yield Str. 0.2% (10^3) psi</u>
Inconel*	1200°	70-75	30-35
(Nuclear	1400°	30-35	20-25
Grade	1600°	17-20	10-12
72Ni min.	1800°	10-12	8-10
10 C max.			
6-10 Fe			
14-17 Cr			
.10 max			
Cobalt)			
Inconel X **	1200°	125-130	80-85
(73 Ni	1400°	95-100	70-75
15 Cr	1500°	70-75	35-40
7 Fe	1600°	35-40	----
2.5 Ti	1800°	----	----
0.9 Al			
1 Cb			
Hastelloy B***	1200°	75-80	40-45
(65 Ni	1400°	65-70	38-42
28 Mo	1600°	55-60	35-38
5 Fe	1800°	35-40	32-35
0.12 C			
1.0-2.5 Co			
Hastelloy C	1200°	100-105	50-55
13-16 Cr	1400°	80-85	43-48
15-19 Mo	1600°	50-55	35-40
3.5-5.5 W	1800°	20-25	----
4.0-7.0 Fe			
1.0-2.5 Co			
Bal. Ni			
Hastelloy X	1250°	75-80	35-40
47 Ni	1500°	45-50	30-35
22 Cr	1750°	20-25	15-20
20 Fe	2000°	----	----
9 Mo			
1.0-2.5 Co			

* Hot Rolled

** Annealed and aged

*** Solution annealed condition

TABLE G-3

TENSILE PROPERTIES OF FULL HARD TYPE 304 ELC SHEET^(a) AND
HELIARC BUTT WELDS - 0.012 IN. THICK, WELDS ROLL PLANISHED
SOURCE: WATSON AND CHRISTIAN, CONVAIR

<u>TEST TEMP °F</u>	<u>DIRECTION</u>	<u>YIELD STRENGTH 1000 PSI</u>	<u>TENSILE STRENGTH 1000 PSI</u>	<u>ELONGATION PERCENT</u>	<u>NOTCHED- UNNOTCHED RATIO $K_t = 6.3$</u>	<u>WELD JOINT EFFICIENCY PERCENT</u>	<u>ELONGATION PERCENT</u>
78	Long.	158	176	6	1.09	51	2
	Trans.	153	191	5	1.09	45	1
-100	Long.	186	198	5	1.09	76	3
	Trans.	182	216	7	1.12	69	3
-320	Long.	187	251	33	1.04	88	4
	Trans.	190	255	37	1.18	88	3
-423	Long.	231	279	1	1.09	94	4
	Trans.	233	305	2	1.05	93	4

(a) Analysis: 18.0 Cr, 10.4 Ni, 0.023 C, 1.54 Mn, 0.026 P, 0.011 S, 0.66 Si.

TABLE G-4 TENSILE PROPERTIES OF 310 SHEET AND HELIARC BUTT
WELD JOINTS - 0.020 IN. THICK, 0.75% COLD ROLLED

WELDS ROLL PLANISHED

SOURCE: WATSON AND CHRISTIAN, CONVAIR

TEST TEMP °F	DIRECTION	YIELD STRENGTH 1000 PSI	TENSILE STRENGTH 1000 PSI	ELONGATION PERCENT	NOTCHED- UNNOTCHED RATIO $K_t = 6.3$	WELD JOINT EFFICIENCY PERCENT	ELONGATION PERCENT
78	Long.	157	181	2	1.07	49	2
	Trans.	163	199	4	0.97	45	2
-100	Long.	190	204	3	1.08	55	2
	Trans.	192	225	8	1.05	50	2
-320	Long.	223	251	10	1.11	66	2
	Trans.	225	273	11	1.07	61	2
-423	Long.	261	290	(a)	1.12	70	2
	Trans.	280	317	10	1.03	63	2

(a) Scattered results, 1 to 12 per cent.

TABLE G-5

TENSILE PROPERTIES OF TYPE 310 SHEET (a)

SOURCE: WATSON AND CHRISTIAN, CONVAIR.

TEST TEMP. OF.	DIRECTION	YIELD STRENGTH 1000 psi	TENSILE STRENGTH 1000 psi	ELONGATION PER CENT	NOTCHED- UNNOTCHED RATIO $K_t = 6.3$
<u>0.020 IN. THICK, 40 PER CENT COLD ROLLED</u>					
78	Long	138	153	4	1.10
	-	-	-	-	-
-100	Long	156	170	13	-
	Trans.	151	180	12	-
-320	Long	182	221	24	1.07
	-	-	-	-	-
-423	Long	200	276	28	1.00
	Trans.	218	263	25	1.11
<u>0.020 IN. THICK, 60 PER CENT COLD ROLLED</u>					
78	Long	153	174	3	1.03
	-	-	-	-	-
-320	Long	205	233	17	1.06
	-	-	-	-	-
-423	Long	232	278	18	1.06
	Trans.	226	285	16	1.08
<u>0.020 IN. THICK, 75 PER CENT COLD ROLLED</u>					
78	Long	160	179	3	1.10
	-	-	-	-	-
-320	Long	215	242	13	1.11
	-	-	-	-	-
-423	Long	254	281	14	1.11
	Trans.	247	298	2	1.01

(a) ANALYSIS: 25.3 Cr, 19.6 Ni, 0.04 C, 1.66 Mn, 0.70 Si

Figure G-1

Figure G-2

Figure G-3

Figure G-4

Figure G-5

Figure G-6

Figure G-7

Figure G-8

Figure G-9

Figure G-10

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APPENDIX H

RELIABILITY

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I. PREFACE

The Reliability Department of the Space Propulsion Division is responsible for the conduct of the overall reliability program. This department establishes policies and procedures for the direction of the reliability effort in all stages of design development, procurement, in-plant testing, and production. It assures that corrective action is taken whenever equipment failures or discrepancies occur. The requests for engineering changes result from design reviews and failure analyses. All necessary design changes will be coordinated with the Secondary Gas Generator System Project.

The Product Effectiveness Division at the Azusa Plant is responsible for assuring that company products meet acceptable standards of quality. The Quality Assurance Department of this division implements the necessary recording and other functions required to support the overall reliability program. It furnishes reliability training aids and assists in conducting actual training. When the need for corrective action is established by engineering and reliability personnel connected with the Secondary Gas Generator System Project, the information concerning this need will be fed back to the Product Effectiveness Division.

II. INTRODUCTION AND SUMMARY

The Program Plan describes the reliability program of the Space Propulsion Division of the Liquid Rocket Plant at Azusa for the Secondary Gas Generator System.

The program is designed to assess and apportion overall system reliability; thus, it includes an analysis of components, sub-system, and system operational requirements. Mission analyses will be conducted to establish functional performance limits, operating time and environmental conditions under which the achievement of reliability goals is to be demonstrated. The program covers all phases of the life-cycle from design to delivery to the customer.

Management of the reliability and quality assurance program is vested in the Reliability Department of the Space Propulsion Division. This department will have responsibility for design review, statistical analysis and monitoring of test data in order to ensure that the reliability goals of the system are obtained. Statistical methods used are described in the program plan. Testing will be designed to obtain maximum data from the minimum number of tests. All data obtained will be monitored on a continuing basis, in order that corrective action may be taken and reliability goals reapportioned if necessary.

An education and indoctrination program in reliability will be carried out for all employees in order that they may have a better understanding of reliability and its importance.

III. TECHNICAL DISCUSSION OF THE RELIABILITY PROGRAM

A. PURPOSE

The purpose of the reliability program is to assure that contractual reliability requirements are met throughout the Secondary Gas Generator System Program.

B. PROGRAM PLAN

1. General

The reliability program assures that high levels of reliability will be designed into the system, verified by a sound test program, maintained throughout manufacture, transportation and storage, and improved through a closed loop feedback system. Thus, it is evident that such a program will extend throughout the life cycle of the Secondary Gas Generator System Program and will influence functions from operational planning of the system through contracting, research, development, testing procurement, fabrication, assembly, inspection, packaging, shipping, storage maintenance, integration with other systems, and operational use.

2. Organization

The reliability organization chart for the Secondary Gas Generator system is presented in Figure H-1.

The reliability management function consists of organizing staffing, planning, directing and controlling the entire reliability program effort and reports to the Division General Manager.

The reliability project engineer directs the reliability program of the Secondary Gas Generator Project and reports to the reliability manager. The reliability project engineer is responsible for the implementation of the following specific tasks: design review and reliability studies, testing and evaluation, failure and operating time reporting, reliability indoctrination and training, coordinated quality assurance program, supplier and subcontractor control, and documentation and reporting.

IV. RELIABILITY ADMINISTRATION

A. OVERALL RELIABILITY FUNCTION

The management effort required to organize, synthesize, and effect the overall reliability functions for the Secondary Gas Generator System Program will be accomplished by the Reliability Department of the Space Propulsion Division. The Reliability Department is responsible for both the management of these functions and the development of the technical and engineering needs to produce an effective reliability program. This provides an organized approach to obtain the highest levels of reliability and quality in the Secondary Gas Generator System consistent with customer requirements and cost.

The Reliability Department will be aided, as applicable, by strong support programs, such as (1) statistical engineering - including test data analysis and test planning; (2) design review; (3) failure evaluation; and (4) documentation, reports, and data collection control systems.

B. SCOPE OF THE RELIABILITY PROGRAM

The reliability program assures that high levels of reliability will be designed into the system, verified by a sound test program, maintained throughout manufacture, transportation and storage, and improved through a closed loop feedback system. Thus, it is evident that such a program extends throughout the life cycle of the Secondary Gas Generator system, and influences functions from operational planning of the system through contracting, research, development, testing, procurement, fabrication, assembly, inspection, packaging, shipping, storage, maintenance, and operational use. It will include the surveillance and integration of the reliability programs of associated contractors, sub-contractors, and suppliers. It will have tangible effects upon, and receive support from, both the technical and management personnel in all participating companies.

C. RELIABILITY MANAGEMENT PROGRAM

1. Program Plan

The objectives of the reliability program are:

- a. to produce a system with the required contractual level of reliability,
- b. to assure that reliability and all other operational characteristics, including safety, of the system are produced as specified,
- c. to minimize degradation in reliability and other operational characteristics due to inadequate materials, faulty workmanship, improper packaging, rough handling and stresses occurring during transportation, fatigue and stresses occurring during storage, and
- d. to provide an effective system as economically as possible.

2. Allocation of Responsibilities

One of the principal parts of a reliability program, to assure the objectives, is the assignment of responsibility and the delegation of commensurate authority to the proper organizational unit. This will assure the performance of the necessary control functions to meet reliability goals and to satisfy customer requirements at the lowest possible cost. Only one person or organizational unit can have primary responsibility for the performance of a function, although others may share in this responsibility by approving, auditing, coordinating, or providing assistance. Responsibility will be assigned only to a person or group having capability of performance. It is, also, necessary that the proper time for the performance of these functions be indicated and enforced.

3. Budgeting

A sound, well balanced, reliability program is one which achieves an optimum balance between implementation and cost so as to maximize the net worth of the system. Accordingly, a complete budget is prepared and submitted as a part of the definitive reliability program plan. This budget indicates the funds required for the completion of each task assignment. Actual costs of performance for each task assignment will be compiled through the normal project-accounting system and compared with the budget at the end of each month. Resultant data will be monitored and controlled by the Secondary Gas Generator System Reliability Project Manager. In case of major discrepancies between planned and actual expenditure rates, corrective action shall be taken. Proven budgetary control systems and procedures in use at Aerojet-General shall be used to guide control and expenditure of reliability funds for the system.

4. Planning and Programming

a. The Secondary Gas Generator System Reliability Program will be organized and scheduled to permit periodic review of program status with a minimum of effort. The Secondary Gas Generator System Reliability Manager has the responsibility for program review. Primary control will be exercised through the use of PERT and Milestone charts (Figure H-2), showing the overall status of all functions in the reliability program. As work is accomplished, it will be reflected on the master control charts, together with an estimate of the percentage of the task which has been completed. Reviews will assure that the program continues to remain adequate as it progresses and that all effort affecting the reliability of the product is being performed in accordance with the program plan. These reviews will permit periodic updating and alteration of the program as the results of the review indicate that this is necessary to assure timely accomplishment of specified reliability goals.

b. A PERT network of events will be developed to assure scheduled flow of hardware in order to meet the requirements of the reliability test programs on all levels from parts to the integrated Secondary Gas Generator system. Schedule dates will be assigned to critical events; alternate methods of achievement will be programmed if the intended path causes a delay.

The network will provide close surveillance of:

- (1) Part suppliers
- (2) Delivery schedules
- (3) Subcontractor fabrication schedules
- (4) Test plan and procedures availability
- (5) Test completion date when the result is required

before testing of the next higher assembly can begin. Concurrent testing will be utilized wherever possible. Aerojet-General Corporation will provide assistance to vendors or contractors to ensure the desired hardware availability and success of the reliability test program.

5. Standards of Performance

For each area of responsibility and for each function, standards of performance will be established. These standards will comply with all relevant specifications and other customer requirements. These standards will be reviewed periodically and, if necessary, supplementary standards will be prepared to implement the product effectiveness program.

6. Monitoring and Auditing

The Reliability Manager of the Secondary Gas Generator system program will be responsible for continuous monitoring and auditing effort of reliability engineering and quality assurance programs.

Specific audits will be conducted to assure compliance with written procedures for inspection and testing periodically by quality assurance supervision and audit personnel. This check will include investigation of the availability of required documents, and evaluation of the adequacy of the preparation of associated quality documents. Also, periodic product audits will be made similarly by removing accepted parts and assemblies from various points in the fabrication system and reinspecting them under the surveillance of a quality assurance auditor. Reports will be submitted to the Reliability Department Manager and other cognizant departments.

D. SUPPORTING ORGANIZATIONS

A corporate Reliability Assurance Staff, which functions through the Aerojet-General Corporate Director of Reliability and Quality Assurance, is an integral organizational component of the Secondary Gas Generator system program. This staff is comprised of specialists who are experienced in the mathematical and statistical aspects of reliability, experiment design, and data analysis. Emphasis is placed by this group on the planning of test programs to assure that program objectives are obtained at minimum cost and time to the customer. Five major responsibilities of this group are:

1. Make studies in the mathematical and conceptual aspects of reliability theory.
2. Formulate, develop and assist in implementation of reliability programs for major projects from the proposal stage through the qualification testing for customer acceptance. This assistance is also continued throughout the production phase.
3. Provide statistical direction for design, development and qualification test programs, including preparation of test designs and procedures for data analysis.
4. Conduct training programs in concepts and applications of statistics, other than statistical quality control.
5. Coordinate exchange of information and program planning among the various engineering reliability activities within the company.

V. RELIABILITY STATISTICAL ANALYSIS

Although there have been many definitions of reliability, almost all include the same basic elements of probability, performance, environment, time and confidence; the last is generally included for demonstration purposes. For the purpose of this proposal effort, the following definition of the Secondary Gas Generator reliability will be employed:

The Gas Generator System reliability is "the probability that the Gas Generator System will perform its proposed mission, as specified, without failure."

It will be the responsibility of Reliability Engineering to insure that this reliability is as high as is economically feasible.

Aerojet-General recognizes that the inherent reliability of the Secondary Gas Generator System is established in the design. Diligent manufacturing, assembly operations, testing and monitoring can assure that the designed reliability is achieved but cannot improve design reliability. Therefore, during the design phase of the Secondary Gas Generator system program, reliability aspects will be carefully considered and incorporated into the design under the scope of a comprehensive reliability program. Several of the important considerations that are discussed in this section are reliability design analysis, system effectiveness, safety margins and safety factors, materials and components, parallel systems and redundancy, and error propagation.

A. RELIABILITY DESIGN ANALYSIS

An important consideration in the development of the Secondary Gas Generator design will be the results of a comprehensive design analysis performed by Aerojet-General Reliability Engineering. The reliability design analysis approach proposed for the Secondary Gas Generator program will be reflected primarily by analytical techniques which will insure that reliability becomes inherent in the design. Concurrent with design efforts, analysis steps will occur. In logical sequence these steps are: functional analysis, analysis of environments, malfunction mode review, system analysis, alternative analysis,

reliability prediction and establishment and allocation of system goals. The scope and methodology applied in the completion of these steps are described in the following paragraphs. Much of the methodology and techniques employed in the Secondary Gas Generator design analysis will be derived from the Aerojet-General Corporate publication "Reliability Methods Handbook, Volume II." Periodically, as hardware becomes available and as more definitive data is obtained from Aerojet-General, as well as from subcontractors testing programs and other sources of reliability information and design data, this analysis will be revised to inform other activities of current reliability considerations and goals.

B. FUNCTIONAL ANALYSIS

1. Block Diagrams

Functional block diagrams are very useful in presenting the total reliability relationship among the various task performing functions of the system. Such diagrams, which show the functional reliability relationships among the constituent subsystems, form the basis for developing reliability equations, making failure hypotheses, and predicting system reliability. Therefore, in the normal process of system design, the first step will be to initially divide the Secondary Gas Generator system into logical task performing subsystems. These subsystems are further divided into subassemblies and component groups. When the system becomes well defined, these groups will then be further defined in terms of basic component parts.

2. Functional Relationships

The functional block diagrams will be prepared by considering the functional-reliability relationships among the constituent subsystems. Such relationships are classified as either dependent or independent. Dependence in the functional sense indicates that failure of an element will cause system failure. Independence in the functional sense indicates that failure of an element results in the task function being performed by an alternate (redundant) element without resulting in a failure of the system. In preparing a reliability block diagram, dependent elements are represented as being in series and independent elements are represented as being in parallel. The reliabilities of dependent

elements combine by what is commonly known as the product rule. This rule states that the reliability of a configuration which may be a system, subsystem, subassembly, etc., is the product of the reliabilities (r's) of its functional elements. Mathematically,

$$R_s = r_1 \cdot r_2 \cdot r_3 \cdots r_n$$

where R_s = reliability of the configuration and r's = reliabilities of the elements. Figure H-3 illustrates this concept. Reliabilities of independent combine in a parallel fashion as shown in Figure H-4. The equation for the reliability of several redundant elements is:

$$R_s = 1 - (1-r_1) (1-r_2) (1-r_3) \dots (1-r_n)$$

where the r's = the reliabilities of the redundant elements. Then, by completely describing the Secondary Gas Generator system through a series of functional block diagrams, a mathematical model will be constructed which will be employed in making a system prediction and allocating reliability goals.

3. Malfunction Model Review

As part of the design analysis of the Secondary Gas Generator, a malfunction mode review will be performed by Reliability applying the results of the analysis of environments to the system functional breakdown. In recent programs at Aerojet-General this type of review has successfully defined salient reliability hazards, allowing corrective actions early in the design formulation phase.

The malfunction mode review will discuss each principal function of the gas generator, its possible modes of failure, the consequence of these failures, and proposed methods to effect or eliminate their effect. Failure hypotheses will be made, based upon conceptual designs, and areas in which failures are most likely to occur will be listed.

4. System Analysis

The reliability system analysis approach proposed for the Secondary Gas Generator program will incorporate the results of the functional, environmental and malfunction analyses to assess the reliability aspects of the gas generator configuration and lay the groundwork for making a system prediction and assigning reliability goals. Designs will be analyzed to determine if reliability principles and techniques have been incorporated. This analysis will further act as a guide for the selection and application of material and components. Load analyses will be made as soon as tentative detailed designs are completed to determine if components are properly derated. Also, combined component tolerances will be evaluated relative to design tolerances to assure circuit operation well within design limits. Redundancy will be required when analysis reveals critical function areas of low inherent reliability.

5. Alternative Analysis

A roadblock to developing a high system reliability is to concentrate reliability efforts on the sophistication of an initial design. Therefore, early in the development effort care will be given to insure that all alternate subsystems and component designs are investigated. These designs will be analyzed and compared for their contribution to Secondary Gas Generator reliability. An open-minded outlook towards the creation of new, more reliable, configurations will be constantly maintained.

6. Reliability Prediction

a. Purpose

The next logical step in the reliability design analysis will be to quantitatively predict the reliability of the Secondary Gas Generator. The prediction will not only present a definitive estimate of the adequacy of the gas generator design, but will uncover areas of poor reliability for early remedial action. The prediction will be a numerical indication of design maturity and will point out over-designed, as well as under-designed items. If the design is unsatisfactory, the prediction will not only bring the error to light, but will, also, provide a means for calculating the magnitude of the

changes that must be made in the nominal values and the tolerances of the component part characteristics to obtain the required distribution of system characteristics.

b. The Prediction Plan

The prediction will be based upon the results of the system analysis and applied to the mathematical model of the Secondary Gas Generator. The value of a prediction, however, is greatest at the earliest possible stage in the design-development cycle because changes can be affected with the least possible expense and delay. A first prediction will, therefore, be made shortly after contract award, primarily intended to indicate potential trouble areas. All new reliability data, test results and information will be added to any previously collected and evaluated, so that a continuous or instantaneous estimate of reliability will be known. The prediction will become more accurate as data becomes more plentiful. Formal predictions will be made at key points in the development program.

c. Preliminary Reliability Estimates

The estimated projected reliability of a gas generator unit consisting of concomitant controls and switching devices is:

.9217

The estimated projected reliability of a control unit is:

.99

The estimated projected reliability of a gas generator i.e., (valves, injector combustion chamber, etc.) is:

.931

7. System Goals and Allocations

a. The Secondary Gas Generator Goal

Based upon REON requirements and initial reliability estimates, a gas generator system goal will be established at the onset of the development program. Reliability goals provide a means whereby the progress of a program may be monitored. The reliability goal must be wisely allocated and adjusted among the various subsystems and components, and periodic estimates made of the confidence growth in achieving the reliability goal.

b. Allocation of System Goals

Applying the system goal to the Secondary Gas Generator mathematical model, each component in the system will be assigned a reliability goal. The reliability values assigned to the various components are predicated upon available data, past experience and best engineering estimates as to the ability of the various components to perform in the usage environment. Should subsequent studies or test results reveal that a component's reliability goal is unrealistic and incapable of attainment at the present state of the art, re-evaluation of the reliability apportionment at the next higher tier system level will be necessitated. Apportioning the reliability, not only emphasizes weak spots, but allows facile observation of the reliability aspects of the system. Upon determination of specific design configurations, the allocation of reliability goals to the subsystems will be adjusted (traded off) to arrive at the most economic means of achieving the required reliability.

c. Sources of Reliability Information

Through active participation in the IDEP program and from the gas generator data evaluation effort, a catalog of component performance and reliability characteristics will be compiled. For various electronic components, failure rate data is available from industrial sources and published in reports. These failure rate estimates are supplemented by careful engineering evaluation of the specific component application conditions,

stresses and environments, since rate application of the available data is considered unwarranted. An industry liaison program will be established to obtain failure data on other types of mechanisms used in the gas generator system. As performance and failure data on various component parts used in the gas generator system become available through testing programs, failure rates for these parts will be estimated and added to the failure catalog. This convenient source of reliability information will be used for system predictions, reliability assessment and component evaluation task

D. STATISTICAL TECHNIQUES

Aerojet-General has conveniently summarized in one comprehensive publication (Reliability Methods Handbook - Volume II), the technical and statistical methods needed to meet program reliability requirements. This handbook is the product of extensive research in technical, statistical, and mathematical writings appearing in the open literature and in government publications. In addition, the handbook includes reliability methods developed by company specialists to provide solutions to engineering problems requiring a new or unique approach. Condensed versions of the technical methods appear in the handbook, including technical discussions on reliability apportionment, system reliability prediction, complex systems analysis, sensitivity testing, testing to failure, safety margins, design and analysis of experiments, and probability distributions. Presentation of a reliability engineering method is followed by an illustrative, numerical example. Many of the examples in the handbook are taken from engineering investigations on which Aerojet-General reliability and statistical specialists provided consultation services to assist project management. Sections of the handbook are used in reliability engineering indoctrination courses.

The real value of data collection is found in the analysis, correlation, and regenerative effect of the feedback of the data. The methods that will be employed in the analysis of the test results will utilize the standard, appropriate, statistical and engineering techniques dictated by the test plans. The analyses will denote design weaknesses and suggest design changes. All failures will be analyzed and failure analysis reports will be prepared as part of Task 2. The results of the analyses will be distributed to all the contractor organizations, affected subcontractors, and pertinent government agencies. Statistical data analyses will act as design aids during development and process controls during production.

VI. DESIGN REVIEW AND RELIABILITY CONTROL

A properly planned and administered design review program, while not a "cure-all", will do much to create high overall reliability during the Development phase of the Secondary Gas Generator System Program. The design review described here will assure that components and materials experts have been consulted about each design at suitable times, that reliability specialists have examined and approved the various phases of the design, that the advice of manufacturing engineers has been sought, that proper engineering records are being maintained, and generally that all those having direct interest in each design have been fully informed and consulted. The list of advantages to be gained from a design review program is endless.

A. THE RELATION OF DESIGN REVIEW TO RELIABILITY

The use of the very powerful tool called statistics has a major place in reliability engineering, but it cannot alone be expected to provide the desired results. A careful analysis of the definition of reliability will show that, unless every step in the engineering, manufacturing and use of the system under consideration is carefully analyzed, controlled and improved, it cannot be said that a reliability program is in full operation. Circuit design, mechanical layout, component application and quality, materials and processes, selection, fabrication, assembly and wiring, quality control, test, manual preparation, training, maintenance and operator ability are only a few of the very obvious areas that can either improve or degrade reliability. Then, it can be seen that the design review allows the science of reliability to tangibly influence product development.

B. PURPOSE AND REVIEW FACTORS

The reliability design review is an audit of engineering concepts and, where possible, documentation in conjunction with actual equipment. It will be performed by engineers with specialized design and manufacturing experience for the purpose of detecting factors that might contribute to unreliable operation, either in the form of a short operating life or erratic, unstable, or substandard performance. The design review precedes the finalization of the detailed design and is continually kept current. Correct use of the design review permits early detection of problem areas and rapid feedback of corrective action to the designers.

The design of the Secondary Gas Generator system includes two major aspects--the functional design and the physical design. The former includes factors involved in the inherent performance capability and life, and the latter includes factors involved in producibility, use, and protection from expected operating and shipping environments. The two categories are related, and both must be evaluated in terms of the reliability requirements. Thorough design reviews lead to a proper balance of these requirements, to a minimization of the total risks, and to judicious planning for action.

The following outline lists the general design review considerations and factors that are evaluated in all reviews:

1. Reliability Review of Design Requirements and Approach

- a. Functional Requirements: Electrical and mechanical functions; end-of-life characteristics imposed by operating life requirements.
- b. Environmental Requirements: Conditions of temperature, shock, and vibration which the system may encounter during handling, shipping, or operation.
- c. Design Approach: Evaluation of methods used in the solving of basic design problems

2. Reliability Review of Functional Design

- a. Performance Level: Mean electrical and mechanical performance; analysis of errors and test results; prediction of mean life, modes of failure, redundancy, human factors, and maintenance requirements.
- b. Design Implementation: Adequacy of components, parts and materials used, list of critical parts; stress analysis and application review; evaluation of tradeoffs affecting design reliability.

3. Reliability Review of Physical Design

- a. Environmental Protection: Evaluation of the following:

protection against electrical interference, breakdown, and other electrical factors; response to shock, vibration, and other mechanical factors; thermal design; protection against environmental factors.

b. Producibility: Process, assembly and inspection techniques.

4. Reliability Review of Post-Fabrication Requirements

Adequacy of maintainability provisions, maintenance instructions, training manuals, packing and shipping requirements, and spare-parts analysis.

Competent design review can improve the inherent reliability of the system and result in a more economical expenditure of manufacturing and testing funds by identifying components, parts, assemblies, processes, and fabrication techniques that require improvement.

C. PROCEDURE

The design review procedure (Fig. H-5) will provide for formal reviews scheduled at major mileposts. A continual informal design review will be conducted as design detail is completed; this review includes reliability analysis at the system, assembly, subassembly, component, and part levels. This technique keeps cognizant persons constantly aware of actual design progress and permits assistance to be given as needed.

D. REVIEW AND CONTROL OF TECHNICAL DOCUMENTATION

All technical documentation, including drawings, specifications, acceptance test procedures, design logs, fabrication and process instructions, will be reviewed and approved by Reliability Assurance prior to utilization on the program. Also, all proposed changes will be subject to review and approval by Reliability Assurance. The same considerations given to the basic design to assure a reliable system design, including design reviews and systems predictions, will be applied to design changes.

Supplier documentation will be reviewed as necessary to assure the inclusion of only those components parts in the Secondary Gas Generator System which meet their respective reliability allocations.

E. SYSTEM PRODUCIBILITY REVIEW

Optimum system reliability is achieved when reliability is inherent in the design and is then properly controlled in the manufacturing cycle by minimizing product degradation. To achieve this, fabrication and maintenance considerations will be reviewed for compliance with the system requirements.

VII. RELIABILITY TEST PROGRAM

An essential component of the Secondary Gas Generator Reliability Engineering Program is a thorough statistical engineering function. Statistical engineers will assist in mathematical reliability analyses and in the making of reliability predictions. They will perform composite tasks of test planning, data evaluation and reliability assessment. They will, also, assist all design and reliability groups by making statistical analyses and providing statistical consulting service.

A. TEST PLANNING

The Secondary Gas Generator test program, as detailed in the test plan, will be continuously monitored by reliability engineering to assure the effective use of statistical methodology to attain maximum information for a minimum cost. Tests will be planned as scientifically designed experiments in which sample sizes and ground rules will be established prior to actual testing.

B. STATISTICAL TEST DESIGNS

Each test design will depend upon the particular mode of failure being investigated. In all cases, the tests will be statistically planned to optimize the results of the testing. For instance, several modes of failure may be investigated during one series of tests and the effects of several natural and induced environments may be investigated simultaneously. The tests will be planned so that mathematical confidence levels may be attached to the results and the maximum amount of information is obtained. Every scientific investigator would like to conduct experimental tests that are informationally and economically optimum. Therefore, all relevant factors must be carefully considered and evaluated prior to selecting a specific test plan. The following paragraphs describe some of the testing methods available for consideration.

1. Sequential Testing

One method of establishing a minimum MTBF with a confidence σ or $(1 - \beta)$ is to test the component by a sequential testing method. The major advantage of sequential testing plan is that on the average they require about 70% fewer test hours than other plans (e.g., testing a certain time and evaluating minimum MTBF). The major drawback of sequential testing plans is that the exact number of items needed cannot be determined. One can, however, determine the average number of items needed. This can be used to advantage in pre-selecting sample sizes. The pre-selected sample sizes will be small; at least 70% less than other sampling plans. If one doesn't wish to take the chance of the tests running longer than anticipated a truncated test can be set up on the sequential basis. A definite time limit is set for the test and it is truncated at the end of this time period. Criteria are used, to evaluate the results. In general, it will be recognized that good items will be accepted rapidly while poor items will be rejected rapidly; questionable items will require somewhat longer testing. A general explanation of the test procedure follows.

α ; the alpha (α) risk is the risk that good equipment will be considered bad (Producer's risk).

β ; the (β) risk is the risk that bad equipment will be considered good. (Consumer's risk).

$\bar{T}_2$ is the minimum MTBF that is desired

$\bar{T}_1$ is a multiple of $\bar{T}_2$

n is the number of failures occurring during the test

t is the duration of the test, a function $f(\alpha, \beta, \bar{T}_1, \bar{T}_2, n)$. It can be shown that:

$$\frac{-\ln \frac{\beta}{1-\alpha} + n \ln \frac{\bar{T}_1}{\bar{T}_2}}{\frac{1}{\bar{T}_2} - \frac{1}{\bar{T}_1}} > t > \frac{-\ln \frac{1-\beta}{\alpha} + n \ln \frac{\bar{T}_1}{\bar{T}_2}}{\frac{1}{\bar{T}_2} - \frac{1}{\bar{T}_1}}$$

In the literature $\bar{T}_1/\bar{T}_2 = 1.5$ therefore, $\bar{T}_1 = 1.5 \bar{T}_2$. If the multiplier is much less than 1.5 the test would increase in duration provided the equipment was in fact superior. The good equipment (relative to t) would be rejected more frequently than the alpha error indicates. If the multiplier is much more than 1.5; bad equipment (relative to t) would be accepted more frequently than the beta risk indicates.

Now t is set equal to each side of the equation and two equations are evolved of the form:

$$\frac{t}{\bar{T}_1} = k_1 n + c_1 \quad \text{and} \quad \frac{t}{\bar{T}_1} = k_2 n - c_2, \quad \text{where } k_1, k_2, \text{ and } c_1, c_2$$

are constants derived from the functions of α , β , and $\bar{T}_1$. The component is tested until either $\frac{t}{\bar{T}_1} > k_1 n + c_1$ or $\frac{t}{\bar{T}_1} < k_2 n - c_2$, where n is the number of failures. we propose testing to a confidence level (γ) of .90. Therefore, in the special case of $\bar{T}_1 = 1.5 \bar{T}_2$, $1 - \gamma = \alpha = \beta = .10$, the equations become:

$$\frac{t}{\bar{T}_1} > .81n + 4.4, \quad \frac{t}{\bar{T}_1} < .81n - 4.4$$

2. Testing-to-Failure

The test-to-failure method has advantages over testing-to-specified levels, namely; variables data is obtained, numerical failure probabilities can be induced and sample sizes are greatly reduced. The risk associated with testing-to-specified levels is that only qualitative remarks

can be made about the results. If no failures occur, the component under test is labeled "good"; but the degree of this "goodness" cannot be assessed without testing large samples for long periods of time. This becomes increasingly important when considering components that exhibit low failure rates.

The test-to-failure process applies increasing levels of stress (the stress selected is the one the component is most susceptible to) until failure occurs on each of a sample of components. Estimates of the central tendency and variation of the component's strength are then made from a histogram analysis of the failure points. The particular method suggested assumes a normal distribution of failure stresses and judges the adequacy of the component by measuring the spread between the average observed component strength ($\bar{X}$) and maximum service stress (M) expressed as a multiple of the observed standard deviation, i.e.

$$\text{Safety Margin} = k = \frac{\bar{X} - M}{S}$$

There are limitations, however, by assuming normal distribution. When the sample size is small one tends to get a biased estimate. This can be corrected to a certain degree by using N-1 (N = sample size) in computing standard deviation (S).

Figures H-6 describe the required k versus sample size (N) for several levels of reliability at .50 thru .95 confidence levels. By way of example a sample calculation follows:

<u>SPECIMEN NO.</u>	<u>FAILURE POINTS (X)</u>	<u>DEVIATION (X-$\bar{X}$)</u>	<u>(X-$\bar{X}$)²</u>
1	99	4	16
2	82	13	169
3	96	1	1
4	90	5	25
5	102	7	49
6	98	3	9

<u>SPECIMEN NO.</u>	<u>FAILURE POINTS (X)</u>	<u>DEVIATION (X-$\bar{X}$)</u>	<u>(X-$\bar{X}$)²</u>
7	94	1	1
8	103	8	64
9	90	5	25
10	88	7	49
11	106	11	121
12	$\frac{92}{\sum X = 1140}$	3	$\frac{9}{\sum (X-\bar{X})^2 = 538}$

$$\text{Strength Average, } \bar{X} = \frac{\sum X}{N} = \frac{1140}{12} = 95$$

$$\text{Standard Deviation, } S = \sqrt{\frac{\sum (X-\bar{X})^2}{N-1}} = 6.99$$

$$\text{Maximum Stress, } M = 70$$

$$\text{Safety Margin, } k = \frac{\bar{X} - M}{S} = \frac{95-70}{6.99} = 3.58$$

$$\text{Reliability, } R \text{ (from Figure H-6)} = .993$$

3. Stationary Life Testing

Because of its simplicity, most reliability tests belong to this category. Here the components or systems are life-tested under operating and environmental conditions which are identical to, or at least similar to those in which the components are intended to be used. Although the life-testing data provides the needed reliability information directly, it has the disadvantage that the results are applicable to only one stress level.

4. Univariate Life Testing

Most of the accelerated or increased severity tests belong to this group. Here the factors of environmental stress are deliberately varied, one at a time, above and below the normal level. This kind of test is useful in the exploratory stage of finding a simple level of increased severity for the purpose of decreasing test time. The results of this test can be interpreted to anticipate the effects of over-stress conditions on component life.

5. Multivariate Life Testing

In the multivariate test all factors effecting reliability are varied at all levels simultaneously. The layout of such an experiment is called the factorial design; the results of multivariate testing can be used to not only assess the effects of individual stresses, but of all interactions between stresses. The chief advantage of this procedure is that prior knowledge of component characteristics is not required and engineering judgements are minimized.

6. Factorially Designed Testing

Much use of this test technique can be made in the spacecraft industry. It can be used when two or more environments and their interactions affect a component or system and it is intended to determine these effects through testing. The method precludes performing an excessive number of tests incurring unnecessary costs, or on the other hand, an insufficient number of tests in any parameter which may be necessary to formulate valid conclusions. The design maximizes the gainable knowledge with a minimum sampling of test data. The factorial designed experiment, when compared to the classical method has the advantages of increased accuracy, knowledge of interactions and, by randomization of the test sequence, minimizing biases.

C. DETERMINATION OF THE NUMBER OF TESTS

An important area of the statistical engineering program is aiding in the determination of the sample size required for a given test program. Of course, if a statistical test pattern is utilized, for example, a Latin Square, the number of tests are predetermined by the design. However, monetary trade-offs can be effected in the tests-to-failure, determination of safety margins and sequential test programs.

1. Time-to-Failure Tests

If a piece of equipment must have at least a specified reliability at a given confidence level, the reliability specification can be related to the time scale by means of tolerance factors. If the distribution of life times is exponential, a lower tolerance limit is given by:

$$K_E (K, R, \gamma) \hat{\theta} = \frac{-\ln R \cdot 2k \cdot \hat{\theta}}{\chi^2 (1 - \gamma, 2k)}$$

where $\hat{\theta}$ is the estimate of mean time to failure, k is the number of failures observed in estimating mean time to failure; R is the proportion of population exceeding lower tolerance limit (reliability); γ is the confidence level; and $\chi^2 (1 - \gamma, 2k)$ is the value of chi square corresponding to a probability of $1 - \gamma$ with $2k$ degrees of freedom. When the required operating time for a successful mission is T_0 , it is required that:

$$K_E (K, R, \gamma) \hat{\theta} \geq T_0$$

or

$$K_E (k, R, \gamma) \geq T_0$$

As an example, Figure H-7 gives K_E (k , 0.99, 0.90) for values of k up to 100. This curve can be used to establish a lower tolerance limit given k and $\hat{\theta}$. When T_0 is known, it can also be used to determine the magnitude of $\hat{\theta}$ necessary to demonstrate reliability for a given number of tests to failure. Since expected time to failure, $\hat{\theta}$, is generally known to some degree from design analysis, or may be realistically estimated, $\frac{T_0}{\hat{\theta}}$ can be used with this curve to determine sample size when planning a development or qualification program.

2. Stress-to-Failure Tests

A component must have a specified reliability at a certain confidence level under applied loads or stresses. Again tolerance factors can be used to relate reliability requirements to the stress scale. Often the distribution of stresses at which failure occurs can be described directly or indirectly by the normal distribution. If the population standard deviation is known, then a lower tolerance limit is given by:

$$S_M = \bar{S} - K_N(n, R, \gamma) \sigma$$

where $\bar{S}$ is the estimate of average stress-to-failure level and σ is the known standard deviation, then:

$$K_N(n, R, \gamma) = U_a - \sqrt{n} + U_r$$

where n is the sample size used to estimate average stress to failure, R is the required reliability, γ is the confidence level, U_a is the standard normal deviate exceeded with probability $(1 - \alpha)$, and S_M is the maximum stress level that the component will withstand with the required reliability. Since there is γ assurance that only $(1 - R)\%$ of stresses below S_M will cause a failure, it can be stated with γ confidence that the $R\%$ of stresses below S_M will not cause a failure. When the specified stress limit is S_0 , then it is required that:

$$\bar{S} - K_N (n, R, \gamma) \sigma \geq S_0$$

or

$$K_N (n, R, \gamma) \geq \frac{\bar{S} - S_0}{\sigma}$$

Figure H-8 gives $K_N (n, 0.99, 0.90)$ for values of n up to 100. This curve can be used to establish a lower tolerance limit, given n , σ and S . When S_0 and σ are known, this can be used to determine the magnitude of S necessary to demonstrate reliability for a given number of tests to failure. Thus, the approximate value of a specified number of tests can be determined. Since design analysis provides information on expected stress limits, the curve may also be used to determine required sample sizes. When σ is unknown, a priori, a tolerance limit can be determined from the estimated standard deviation and estimated average by using the non-central t distribution.

D. PRETEST GROUND RULES

In all categories of development and reliability testing, the planning will be thorough and complete before the test is conducted. Not only will the test method be selected and the test procedure be written, but provisions for test data analysis will be made to insure that the resultant test data is amenable to analysis. Test proposals will be prepared containing the following minimum amount of information:

1. Purpose of the test.
2. Performance characteristics to be tested.
3. Environmental or test conditions with allowable limits.
4. Parameters to be measured and tolerance limits.
5. Type and amount of hardware to be tested.
6. Instrumentation and equipment.
7. Test facility and location.

8. Test procedure to be followed.
9. Test report forms.
10. Provisions for data analysis.

E. STATISTICAL DATA EVALUATION

Secondary Gas Generator test planning includes an essential allied function to statistical test planning, viz: an organized program for the collection, processing and statistical analysis of test data. The purpose of the integrated data evaluation program are manifold. It establishes an integrated systems approach, eliminates redundancy of effort and duplication of cost, maintains a control, sequential in nature, throughout all phases of the Gas Generator program, and provides empirical data for feedback, analysis and action.

F. RELIABILITY TESTING

In addition to development, qualification, and testing, certain tests will be performed on some components and subsystems to assess reliability. However, the reliability test program will be an integrated portion of the development test program. When test results indicate equivocal reliability, engineering design changes will be required and the development program will not be allowed to proceed until adequate reliability has been assured. Reliability testing will be optimized by the effective use of statistical methodology.

The Secondary Gas Generator system manufactured by Aerojet-General will be tested on the system level to demonstrate reliability.

VIII. RELIABILITY SURVEILLANCE

A. RELIABILITY MONITORING

Reliability monitoring is a design tool or concept whereby, when the Secondary Gas Generator system reliability has been quantitatively specified and apportioned to all elements of the product, new estimates of the Secondary Gas Generator system reliability will be made at predetermined times or monitoring points during the design and manufacture. The Secondary Gas Generator system reliability program will provide for two types of reliability monitoring. The first, and probably the more extensive of the two, is continuous product surveillance. This mode of reliability monitoring will provide for day by day observation of product development and production. The second type of reliability monitoring consists of a series of predetermined monitoring points during the program which are coincidental with major development and production phases and the reliability growth cycle of Secondary Gas Generator system program beginning with the design study phase and concluding with product obsolescence. Reliability monitoring functions will be performed by Reliability personnel at all test, assembly and use facilities. Figure H-9 shows the proposed Reliability monitoring system in block diagram form. Reliability functions appear in blocks and routing of data feedback, requests for corrective action, and data status and reporting channels are shown by interconnecting lines.

1. Continuous Monitoring

Continuous reliability monitoring of Secondary Gas Generator system program will be performed by responsible engineers throughout the program. The assigned responsibilities of the reliability engineer will be divided into major classifications: In-line, advisory and/or liaison. Line responsibilities will include: specification review, design review, statistical test planning and evaluation, environmental analysis, failure reporting surveillance, failure analysis, and determination of corrective action and follow-up. Liaison activities will consist of: parts approval, verification and vendor control, quality control coordination, program data evaluation, and liaison with Aerojet-General field operations.

2. Monitoring Points

A Reliability - Point - Monitoring Plan will be developed providing for reliability monitoring points at major milestones in the development and production phases of the Secondary Gas Generator system program. Points will be chosen to be coincidental with commencement and/or completion of significant phases of the program. At each of these points, a statistical evaluation will be made of the present-status reliability. Considerations will be made to assure that all phases of the reliability program are progressing as planned. The system achieved reliability will be calculated utilizing experience failure data. Corrective action, which has been employed in reliability problem areas, will be reviewed for validity and system effectiveness.

3. Reliability reporting will be accomplished in accordance with reliability program requirements as dictated in MIL-R-27542.

B. FAILURE EVALUATION

Proper evaluation and analysis of equipment failures during the development and production of the Secondary Gas Generator system is dependent upon comprehensive and coherent failure data recording and feedback techniques. Documentation of success, as well as failure data, is essential to an efficient and meaningful failure evaluating program. All equipment failures recorded during Secondary Gas Generator system program, from development testing through system obsolescence, will be forwarded to Reliability Engineering for analysis. Each failure will be analyzed to determine the mode and cause of failure. Failure analysis reports (Fig. H-10) will be prepared, summarizing the analysis and proposing a corrective action. The analysis will discuss the impact of the failure upon mission reliability, placing special emphasis on all critical failures. Failure analyses will also be made on discrepancies reported during field usage of the equipment

1. Classification of Failures

Failure classifications will be made in accordance with the standard failure philosophy; viz., Critical, Major, and Minor.

a. Critical Failure

A critical failure, whether catastrophic or a degradation of performance in nature, would normally cause a safety hazard, or mission abort.

b. Major Failure

A major failure, or defect in excess of tolerance limits, would not normally, in itself, cause mission abort, but might affect the reliability of the system due to cumulative tolerance build-up.

c. Minor Failure

A minor failure is classified as one other than critical or major which is determined to have had no significant effect on the ability of the item to perform in the manner intended, except that secondary failures shall also be included in this category.

2. Effects of Classification

Classification of failures will be used as an important factor in planning the extent of inspection, requirements for special test equipment, and in formulating sound engineering judgments as to the disposition of discrepancies that develop during fabrication and test.

C. REPORTING, ANALYSIS, AND CORRECTIVE ACTION

1. Failure Reporting

Reporting of equipment failures, occurring during production and testing of gas generator hardware, will be accomplished at the test, assembly and use facilities through the utilization of an integrating failure reporting system as indicated in Fig. H-11. Upon failure of system hardware, Quality Control personnel will initiate a failure discrepancy report (see Fig. H-12). The first (original) copy of the report will be immediately forwarded to Reliability Engineering and a failure analysis and investigation will be initiated. The failure will be coordinated with the applicable Reliability Log (AGC Form 02-52), see Figs. H-13 and H-14. The Reliability Log is maintained at all test and checkout areas at the test, assembly and use facilities. The hard copy of the failure report will remain with the failed part until the failure mode has been established and corrective action has been initiated, at which time it will be forwarded

to Reliability Engineering. Data collection and storage will be accomplished through the use of computer facilities.

2. Failure Analysis

All part failures will require analysis to determine if the cause is due to misapplication or to a component deficiency. Parts which fail at field sites shall be returned to Aerojet-General for analysis. Parts suppliers will, also, be required to provide a monthly analysis on part discrepancies discovered during the suppliers' acceptance testing. The Failure Report, Fig. H-12, will be used for failure analysis reporting. Analysis of failures will differentiate between those due to equipment failure and those due to human error in handling, transporting, storage, maintaining, and operating the equipment. Failures occurring during excluded tests, as described in MIL-R-27542, will not be considered in system failure data compilation.

3. Corrective Action

During the course of system analysis, design review, component analysis evaluation tests and other activities in which Reliability groups may become engaged, various conditions may be disclosed that have an actual or, could have, a potentially serious effect on component and, hence, system reliability. It will be the responsibility of Reliability Engineering to bring any such conditions to the attention of the responsible design engineers and/or project personnel. To assure that proper action is taken by the responsible design activity to remedy and resolve such conditions as may be brought to their attention, a Reliability Action Request (RAR) Form will be initiated by Reliability Engineering. To facilitate follow-up and for reference purposes, each form will be identified by a serial number. This is a reply-by-endorsement type of form on which the reliability engineer will describe the problem or condition encountered and requests investigation and corrective action. The respondent will be required to reply indicating the results of any further investigation made and the nature of the remedial action intended or already taken to resolve the problem or condition.

To assure that prompt and timely action is taken to resolve such problems that are brought to the attention of Design Engineering, a monthly summary and status report of all Reliability Action Requests will be published. This report

will list all RAR's on which action was taken during the month, or which remain unresolved from previous months, by date of requests, RAR serial number and part number, and will indicate current status. When work on a particular action request is completed, it will be listed on the monthly summary report as complete and is then omitted from subsequent status reports.

D. DATA COLLECTION

The reliability, as well as the Secondary Gas Generator system development are greatly influenced by the adequacy and efficiency of the data collection function. The result of measurement or test is information -- information describing stress-strain results which permit comparison to a standard or correlation with an effect. It is essential that information pertaining to the functional capabilities of materials, processes, and devices used in the Secondary Gas Generator system be obtained. The information required will extend from the raw materials used, through vendor and manufacturing processes, into performance under environmental stresses, and finally to the performance during flight. The gas generator data collection program will supply data and feedback for many purposes other than reliability. However, it is through an integrated data control and feedback system that reliability engineering will be able to collect, process, and disseminate required information. The system will allow the collection of all data at one time on one document, storage on master magnetic tape files, and production of many allied reports, both historical and analytical in nature.

E. DATA PROCESSING

A coordinated gas generator data center will be established to accommodate gas generator data requirements. This data center will be organized as an effective and economical tool for the measurement of reliability and quality and the ready control of related information. The gas generator data center will be specifically designed to be compatible with existing government and contractor data systems, to permit ease of handling and processing data, and to integrate data pertinent to all Aerojet-General and subcontractor activities. This integration will be implemented by continued and expanded use of common reporting forms, reporting procedures and codes, and with specified data center personnel assigned to the task of determining that these items are in fact truly common and integrated.

1. Electronic Computers

The data center will employ electronic data processing methods, and will have the following IBM computers at its disposal:

- a. IBM 7090 with mass random storage.
- b. IBM 1410 with mass random storage.
- c. IBM 1401 with random storage.
- d. IBM 1009 data transmission link.

With the above-listed equipment the data center has the flexibility and expansion potential needed for growth and control. The IBM 1009 is a moderate-speed data-transmission link which will be tied in to expedite the flow of data to and from subcontractors. This electronic method of transmitting data will reduce potential human error which could result from manual transcribing or rearranging of data.

2. Machine Processing

Vendors or subcontractors who do not have equipment compatible with the IBM 1009 may use a dial-patch arrangement or other methods. The data will be programmed to enable the procuring agency, program manager, subcontractors, and associated agencies to receive periodically, or on a call basis, printed tabulations of the following:

- a. Correlation of environmental, test, and quality assurance data with design and specification requirements for reliability studies and evaluations.
- b. Failure modes and related causes from the development phase to field use with corresponding corrective action and follow-up.
- c. Actual failure rate data compared to predicted failure rates.
- d. Development, production and field performance listing the frequency of usage and operating time for parts, components, subsystems, and systems from qualified parts list.
- e. Hardware which has performed for its full intended operational time, cycles, or storage life.

IX. RELIABILITY EDUCATION AND INDOCTRINATION

Indoctrination education in reliability concepts, directed to the achievement of the Secondary Gas Generator system goals, will be developed to accomplish the following:

A. Define the program reliability and quality objectives for all management, professional, technical, and support personnel; for contractor, subcontractor, and procuring agency personnel, and to establish the role that each must perform in achieving these goals.

B. Disseminate technical data affecting the reliability and quality of the Secondary Gas Generator system program to all design, manufacture, quality control, test and other personnel responsible for system, subsystem and component development. An educational program is proposed that will feature seminars, visual aids (pamphlets, posters and bulletins) movies and individual contact by reliability engineers, in-plant and at subcontractor facilities. The program will be carefully planned to meet the individual requirements of management, technical and engineering personnel, and manufacturing groups. For example, the material presented to operating personnel in the assembly and test areas will emphasize the responsibility of each individual to assure that quality work is done, including complete documentation. The importance of descriptive, well-written reports on tests and failures used for reliability analyses will also be stressed. Personal contacts with operating personnel will be continued throughout the program. Similarly, material for personnel in other job categories, including design and development engineering, will be tailored specifically to the user.

SECONDARY GAS GENERATOR SYSTEM
RELIABILITY ORGANIZATION

10-067-116-1

Figure H-1

LEGEND:
▲ Start
△ Complete
▲ Report

SECONDARY GAS GENERATOR
RELIABILITY MILESTONE CHART

SECONDARY GAS GENERATOR

		1	2	3	4	5	6	7	8	9	10	11	12
1. RELIABILITY ADMINISTRATION:													
a. Reliability Program Plan;	a.	▲	△	▲									
b. Liaison: Customer and Procurement (Sub Contractor)	b.	▲		▲			▲			▲		▲△	
2. RELIABILITY ANALYSIS													
a. Design Criteria: (1) Functional Analysis													
(2) Failure Mode Analysis	a(1)	▲		▲			▲			▲		△▲	
b. Systems Analysis: Reliability Prediction;													
Goals and Allocation	a(2)	▲		▲			▲			▲		△▲	
3. RELIABILITY CONTROL:													
Design Review of Engineering		▲		▲			▲			▲		△▲	
Documents; Manufacturing etc.													
4. TEST PROGRAMS													
a. Prepare Reliability Test Plan and Review Specifications and Procedures	a.	▲			△								
b. Monitoring and Analysis of:													
(1) Development Tests	b(1)		▲	▲			△▲						
(2) Reliability Tests	b(2)							▲		▲	△		
(3) Acceptance Tests	b(3)										▲	△▲	
5. DATA GATHERING AND PROCESSING FAILURE REPORTING AND ANALYSIS		▲		▲			▲			▲		△▲	
6. RELIABILITY EDUCATION AND INDOCTRINATION		▲		▲			▲			▲		△▲	

Figure H-2

FUNCTIONALLY DEPENDENT ELEMENTS

FIG. H-3

FUNCTIONALLY INDEPENDENT ELEMENTS

$$R_S = 1 - (1 - R_1) (1 - R_2) \text{ OR } R_S = R_1 + (1 - R_1) R_2$$

FIG. H-4

DESIGN REVIEW PROCEDURE FLOW CHART

Figure H-6

TOLERANCE FACTORS FOR
 EXPONENTIAL DISTRIBUTION ($R = 0.99, \gamma = 0.90$)

Comparison of Stress vs. Strength

Figure H-8

10-067-116-1

Figure H-9

FAILURE ANALYSIS REPORT				
1. GENERAL				
FAILURE AND CONSUMPTION REPORT NO.	DATE OF ANALYSIS	FACILITY	LOCATION	
2. IDENTIFICATION				
NAME	NUMBER	TYPE OR MODEL	MANUFACTURER	SERIAL NO.
3. HISTORY, 4. ANALYSIS, 5. CONCLUSIONS, 6. RECOMMENDATIONS, 7. APPROVAL. (Use space as necessary for these items including reverse side)				

FLOW CHART
FOR
FAILURE REPORT (AGC 3-052-003)

Figure H-11

AGC 3 052-003

Aerojet-General CORPORATION

52		SIGNATURE	
RELIABILITY REVIEW	DATE	OTHER	DATE

INSTRUCTIONS FOR COMPLETION OF RELIABILITY LOG

This form shall be attached to all the items which are to be functionally tested, prior to test, and shall be completed and affirmed subsequent to test by Quality Control.

Box 0 Enter "1" after "NO." (Number "2" for second form, Number "3" for third, etc.)
Space after "OF" will be completed concurrent with Box #5 and will reflect total number of log forms for this term.

Box 1 The part number of the attached item shall be entered in Box Number 1.
Example: 2-059575. (Need not be repeated on attached forms.)

Box 2 The serial number of the attached item shall be entered in Box Number 2.
Example: A-16. (Need not be repeated on attached forms.)

Box 3 A functional description of the item shall be entered in Box Number 3.
Example: Helium Pressure Regulator, Hydraulic System Gimbal Actuation.
(Need not be repeated on attached forms.)

Box 4 List the date the item was received from a vendor, or completed or repaired by Aerojet. Essentially the item is considered new as of the date entered in this box. Two of the three words, Received, Completed, Repaired, shall be crossed out so the remaining word identifies the entered date.

Example: Received 1/6/59
Completed
Repaired

(Need not be repeated on attached forms)

Box 5 Indicate the next assembly part number and serial number into which the component was integrated and the date. When the part is completely defective and scrapped or sent for repair enter "None" in this box. Completion of this box shall be considered the final entry on this form which will be subsequently removed and sent to —

Box 6 List the dates of all tests conducted on the item.

Box 7 Describe the test procedure, or reference, and the applicable test documents.
List the major test equipment items by name, serial number, and enter calibration due dates.
Example: Pressure Gage S/N A6377 (7/5/60) Procedure AGC 13786A
Volt Meter S/N 3547 (3/9/60) Para. 3.4
Potter Flow Meter S/N A-16 (4/27/60)

Box 8 The time at start, stop, and elapsed test time as measured or accurately estimated shall be listed here.

Box 9 Where an item is tested for a certain number of cycles or operations, that number shall be recorded here.

Box 10 Records of obvious conditions of defects such as burned, broken, contaminated, loose, sticking, shorted, etc., should be noted here. Where tests are performed tests effects should be recorded here. i.e., successful, failed linearity, valve closing or opening, pressure varies excessively, etc.

Box 11 List the AFTO 120 form number which was completed at the completion of each test.
Enter "X" if copy of log is made and sent in place of AFTO 120 forms.

Box 12 List all replaced or repaired parts required to correct the deficiencies noted in Column 10.
Example: Valve seat replaced, MFR #2215, Valve replaced 2-66586, Clean oxidizer tank pressurization system.

Box 13 The Quality Control Inspector shall reflect his approval of the recorded test results. Errors noted by inspector shall be corrected prior to approval here.

Box 14 Cross out "END" if additional forms required. Cross out "Continued" if additional form not required.

RELIABILITY LOG (SEE INSTRUCTIONS ON REVERSE SIDE)

LOG N^o 2441

10-052-101										(d) NO. OF	
(1) PART NO.			(2) SERIAL NO.			(3) ITEM DESCRIPTION					
(4) DATE: RECEIVED, COMPLETED, OR REPAIRED			(5) ASSEMBLED IN NEXT ASSEMBLY								
			ASSEMBLY PART NO.			SERIAL NO.			DATE		
(6) DATE OF TEST	(7) TEST PROCEDURE AND TEST EQUIPMENT USED	(8) TEST TIME	(9) CYCLES TESTED	(10) OBSERVATIONS OR TEST RESULTS	(11) AFTER 120 REPT. NO.	(12) REPLACED OR REPAIRED PARTS	(13) Q. C. STAMP				
		START HRS. MIN. SEC.									
		STOP HRS. MIN. SEC.									
		ELAPSED HRS. MIN. SEC.									
		START HRS. MIN. SEC.									
		STOP HRS. MIN. SEC.									
		ELAPSED HRS. MIN. SEC.									
		START HRS. MIN. SEC.									
		STOP HRS. MIN. SEC.									
		ELAPSED HRS. MIN. SEC.									
		START HRS. MIN. SEC.									
		STOP HRS. MIN. SEC.									
		ELAPSED HRS. MIN. SEC.									
		START HRS. MIN. SEC.									
		STOP HRS. MIN. SEC.									
		ELAPSED HRS. MIN. SEC.									

(14) CONTINUED - END