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PERMANENT GAS GENERATOR SYSTEM

PRELIMINARY DESIGN

VOLUME I FINAL REPORT

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Report No. 2411

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November 1962

Report No. 2414

SECONDARY GAS GENERATOR SYSTEM
PRELIMINARY DESIGN

VOLUME I - FINAL REPORT

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TABLE OF CONTENTS

	<u>Page No.</u>
I. ABSTRACT	1
II. INTRODUCTION	2
III. TECHNICAL DISCUSSION	3
A. System Description	3
1. Purpose	3
2. Performance Requirements	3
a. Reliability	4
b. Operation	4
c. Conditions	5
d. Construction	6
3. Discussion	6
a. Description of REON Facility	6
b. Choice of System	8
c. Description of Equipment	10
d. Operation	12
B. Preliminary Design	13
1. System Process Design	13
a. Design Conditions at the Plenum Chamber	13
b. Summary of Combustion Chamber Conditions	13
c. Temperature	14
d. Mixture Ratio	14
e. Material Balance	14

TABLE OF CONTENTS (CONT'D)

	<u>Page No.</u>
2. Gas Generator Chamber Design	15
a. Design Considerations and Criteria	15
b. Design Description	16
c. Design Calculation Summary	17
3. Gas Generator Injector Design	19
a. Design Considerations	19
b. Injector Design Description	20
c. Design Calculation Summary	21
4. Gas Generator Igniter Design	22
a. Design Considerations	22
b. Design Description	22
c. Design Calculation Summary	23
5. Propellant and Purge Feed Systems	23
a. Introduction	23
b. Design and Development Problem Areas	24
c. Propellant Feed System	25
d. Purge System	26
6. Control System Design	27
a. Discussion of Open Loop System	27
b. Automatic Control	28
c. Malfunction Detection and Control	29

TABLE OF CONTENTS (CONT'D)

	<u>Page No.</u>
7. Thermal Analysis	31
a. Analysis Considerations	31
b. Analysis Summary	31
8. Stress Analysis	32
a. Analysis Considerations	32
b. Analysis Summary	32
9. Materials Evaluation	33
C. Reliability Analysis	35
1. Purpose	35
2. Reliability Analysis	35
a. Reliability Analysis to Determine Optimum System	35
b. Reliability Design Analysis	37
c. Malfunction Mode Review	38
d. System Analysis	38
3. Design Review and Reliability Control	39
a. Design Reliability	40
4. Reliability Test Program	40
a. Reliability Demonstration	41
b. Control System	41
5. Reliability Surveillance	42
a. Reliability Monitoring	42

TABLE OF CONTENTS (CONT'D)

	<u>Page No.</u>
6. Failure Evaluation	43
7. Quality Assurance	43
IV. PROGRAM DISCUSSION	45
A. Introduction	45
1. Purpose	45
2. Scope	45
B. Program Plan	46
1. Program Description	46
a. Azusa Development Program	47
b. Full-Scale Program	49
c. Reliability	52
2. Milestones	54
3. Schedule	54
4. PERT Network	54
C. Program Management	56
1. Program Organization	56
2. PERT	56
a. PERT Department Functioning	57
b. Implementation and Operational Phases	58
3. Documentation Requirements	58

TABLE OF CONTENTS (CONT'D)

	<u>Page No.</u>
a. Weekly Reports	58
b. Biweekly Reports	58
c. Monthly Progress Reports	58
d. Quarterly Progress Reports	59
e. Final Technical Report	59
D. Hardware	59
V. ROM COST ESTIMATE	61
A. Introduction	61
B. Basis of Estimation	61
C. Case I	62
D. Case II	63
E. Case III	63
F. Cost Summary and Comparison	64
G. Manpower	64

Tables

Figures

APPENDIX A - MODEL SPECIFICATIONS
APPENDIX B - PROCESS DESIGN CALCULATIONS
APPENDIX C - PROPELLANT AND PURGE-FEED SYSTEM DESIGN
APPENDIX D - CONTROL SYSTEM
APPENDIX E - THERMAL ANALYSIS
APPENDIX F - STRESS ANALYSIS
APPENDIX G - MATERIAL EVALUATION
APPENDIX H - RELIABILITY

TABLES

<u>Table No.</u>	<u>Title</u>
1	Engineering Cost Breakdown - Cases I and II
2	Design Cost Breakdown - Cases I and II
3	Fabrication Cost Breakdown - Case I
4	Fabrication Cost Breakdown - Case II
5	Testing Cost Breakdown - Cases I and II
6	One Extra System Cost Breakdown - Case III

FIGURES

<u>Figure No.</u>	<u>Title</u>
1.	Pipe Chase and Duct Vaults With Hot Gas Conduit
2.	Schematic Diagram of Secondary Gas Generator System
3.	Gas Generator Skid Package
4.	Injector Plate of Secondary Gas Generator
5.	Theoretical Properties of Combustion Gas
6.	Response Time Characteristics of Secondary Gas Generator
7.	Schematic Diagram of Propellant Feed System
8.	Secondary Gas Generator Control Instrumentation
9.	Block Diagram of Automatic Malfunction Detection System
10.	Summary Block Diagram of Automatic Malfunction Control System
11.	Secondary Gas Generator System Choice Based on Reliability
12.	Secondary Gas Generator Milestone Chart
13.	Secondary Gas Generator System Crash Program Schedule
14.	Secondary Gas Generator Program Evaluation Review Technique
15.	Program-Management Organization Chart
16.	Program Functional Flow Diagram
17.	Case I - Salaried Manpower
18.	Case I - Hourly Manpower
19.	Case II - Salaried Manpower
20.	Case II - Hourly Manpower
21.	Case III - Salaried Manpower
22.	Case III - Hourly Manpower

I. ABSTRACT

A preliminary design of a specific gas generator system, using LO_2/LH_2 as propellants, was made to demonstrate the feasibility of such a system and to approximate the costs. This system will use a feed mixture ratio of 1.14 and provide a full flow output of 210 lb/sec of combustion gas at a temperature of 1560°F , a pressure of 320 psia, and T/M value of 468°R lb-mol/lb. A duration of 1 hour per start at a specified duty cycle and a minimum of 200 starts were required.

The system chosen was for one generator, about 19-in. ID and 5-ft long, to provide the full gas production requirement while two identical redundant units operate on pilot flame standby. Each gas generator will be mounted on a separate skid with its associated valves, pipes, etc. Each generator is controlled by a separate control system rack mounted in a protected building. An executive switching function is used to change the units in case of a malfunction. A modified open-loop control system was chosen with flows controlled by REON Dewar pressurization systems and built-in pressure drops. All valves are of the "on-off" type and the instrumentation and controls are conventional.

The development program which is proposed includes a subscale firing program plus other investigation and testing programs required to provide detailed information for a full-scale design. A full-scale engineering development firing program of 40 firings and a full-scale reliability demonstration firing program of 44 firings are also included. By compressing the program schedule as much as possible and assuming no untoward troubles, a minimum time of 12 months is estimated for this crash program. As a normal program, it would take about 24 months.

Three cost estimate alternates are presented. The ROM cost estimate to deliver two gas generator systems (six generators) to the Nevada Test Site is \$4,372,886. To deliver one gas generator system, the ROM cost estimate is \$4,017,256; to deliver one additional gas generator system, ordered after the completion of either of these development programs, the ROM cost estimate is \$689,736. All of the above costs are based on government-furnished propellants and include general and administrative overhead.

II. INTRODUCTION

The objective of this study program was to procure a preliminary design of a gas generator system utilizing LO_2/LH_2 in accordance with agreed-upon ground rules. This gas generator system is to be used to provide the ejector-nozzle working fluid for the REON eductor tube which will maintain a vacuum during altitude simulation testing of the NERVA engine.

This report presents the results of the preliminary design program carried out between 14 August and 19 October 1962, and documents the information disclosed in the oral presentation to REON on 19 October 1962.

The report is divided into three main parts. First is the preliminary design technical discussion; second is the description of the proposed program, including the rough order of magnitude (ROM) cost estimate; and third is the collection of appendices.

It should be kept strongly in mind while considering this report that this is a preliminary design. The preliminary design program was intended to demonstrate the feasibility of building such a system and to obtain an estimate of the approximate total cost required for delivery of workable hardware to the Nevada Test Site. For this purpose, it was necessary to choose a specific example to demonstrate the feasibility and then to approximate the cost. Choices such as the number of generators and method of operation had to be made quickly at the beginning of the preliminary design program in order to provide the basis for design work. It was not possible, in the time available, to design more than one system so as to have a detailed basis of comparison. Therefore, the choices made and the designs based on such choices must be considered as tentative and subject to basic alteration upon more complete evaluation. The same applies to the details of the ROM cost estimate, although the total program cost (exclusive of propellant costs) will probably be comparable for all of the likely systems designs. Even if the basic "choice of system" decisions, as described in paragraph III.A.3.b., are later found to be optimum, the preliminary design still must be considered tentative. An adequate design is not likely to be completed without first obtaining the results of a preliminary development investigation, designing and building a full-scale generator based on those results, and then carrying out a full-scale development testing program. In brief, it is not possible simply to design a gas generator system and fabricate it with any firm guarantee that it will function as intended.

III. TECHNICAL DISCUSSION

A. SYSTEM DESCRIPTION

1. Purpose

The purpose of the secondary gas generator system is to provide the gas required by the ejector nozzle located in the REON bent-tube eductor. This eductor is used to create and to maintain a vacuum around the NERVA engine during testing so as to simulate altitude operation. At full-flow operation of the NERVA engine, the hot exhaust gas passing through the eductor is sufficient to maintain the vacuum. Unlike the usual chemical rocket, however, the startup and shutdown transients for the nuclear rocket are sufficiently long that an external or secondary gas source must be used during these transient periods. For operational safety during the lengthy cooling portion of the NERVA engine test duty cycle, it is desirable to have the secondary gas source available for instant use if a malfunction should occur.

NERVA engine hot exhaust gas is pure hydrogen traveling at a very high velocity. To be useful in providing the required aspirating action, the secondary gas must have an exit velocity from the ejector nozzle which at least approaches the hydrogen velocity. If the secondary gas velocity is too low, the slow secondary gas molecules get in the way of the fast moving hydrogen molecules and tend to "clog" the tube. Of the many pertinent variables, the two most important are molecular weight and temperature. In an earlier consideration of this problem, gaseous H_2O was investigated. As a result of experimentation performed by REON, this approach was discarded and the present approach taken. It was found that for reasonable temperatures, very low molecular weights were required. The secondary gas finally chosen was a hydrogen-rich mixture formed from the combustion of liquid hydrogen with just enough liquid oxygen to heat the resulting gas. It was established that the ratio of absolute temperature to molecular weight for this gas (a measure of acoustic velocity) must have a minimum value of $465^\circ R \text{ lb-mol/lb}$ for adequate performance of this system.

2. Performance Requirements

A variety of performance requirements, design limitations, assumptions, and other ground rules were specified both at the start and during the course of this program. The following list includes the more important requirements upon which the preliminary design is based. Some of these were specified by REON; others were developed as a result of calculations done on this program.

a. Reliability

(1) The gas generator system must have a facility reliability. The reliability requirement has not been numerically specified. The statement of reliability goal can be summarized as follows: a minimum of 200 starts is desired, but emergency repairs, substitutions, and maintenance may be made between starts if absolutely necessary. If the gas generator system fails to perform its function, there will be a loss of about \$18 million worth of equipment. The facility also will be lost and perhaps the contract, as well.

(2) A reliability demonstration test program for the full-scale gas generator should be specified.

b. Operation

(1) The gas generator system will operate on LH_2 as fuel and LO_2 as the oxidizer.

(2) Two-level throttle capability (step function) is required; full flow = 100% and idle flow = 1 to 10%.

(3) All generators of the gas generator system (two or more generators) must have the pilot injector burning at all times during operation of the system.

(4) All gas produced when the system is idling during full-throttle operation of the NERVA engine will be removed through the eductor, provided the mass flow rate is equal to or less than the gas generator system full-flow rate.

(5) The gas generator system will be designed for the following duty cycle:

(a) Purge the system; then ignite and stabilize flow at minimum flow conditions. Lapse time: 10 sec.

(b) Increase flow from minimum rate to maximum rate.
Transient time to pressurize the plenum chamber: 0.3 sec.

(c) Continue flow at maximum rate for 30 sec.

(d) Reduce flow from maximum rate to minimum rate.
Transient time: 10 sec maximum.

(e) Continue flow at minimum rate for 330 sec.

(f) Increase flow from minimum rate to maximum rate.
Transient time to pressurize the plenum chamber: 0.3 sec.

(g) Continue flow at maximum rate for 110 sec.

(h) Reduce flow from maximum rate to minimum rate.

Transient time: 110 sec maximum.

(i) Continue minimum flow rate for 3000 sec.

(j) Shut down gas generator. Transient time: 10 sec, or more, if required.

(6) The gas generator system must be provided with an automatic gaseous nitrogen purge of the propellant manifold each time an injector flow stops, and with a purge of the hot gas conduit and plenum chamber when the gas generator system is shutdown.

(7) The gas generator system will be designed for at least 200 starts after qualification.

(8) A pressurized propellant feed system will be used with a facility Dewar pressure limitation of 500 psig.

(9) The gas generator chamber can be uncooled. If cooling is used, the cooling fluid must be pressure fed.

(10) The control system can be either closed or open loop. Dynamic mixture ratio control is required for a closed-loop control system. Mixture ratio can be preset with a modified open-loop system in which the flow rates are set by the Dewar pressures and the preset control system pressure drops. Adjustments can be made either by changing flow-control orifices between runs or by adjusting the Dewar pressures.

(11) Failure of any component will call for a signal and automatic sequencing to bring the test to a safe shutdown.

(12) Provision must be included for manual override operation of the gas generator system.

c. Conditions

(1) Gas generator system full-flow rate in the range of 150 to 210 lb/sec.

(2) Plenum chamber minimum T/M = 465°R lb-mol/lb.

(3) Plenum chamber minimum pressure = 300 psia.

(4) Response time from idle flow to full-flow steady-state conditions in the plenum chamber = 0.3 sec (this could not be met without drastic changes - See Appendix E).

(5) Response time from idle flow to full flow through the gas generator injectors = 0.1 sec.

(6) The hot-gas conduit from the gas generator to the plenum chamber will be designed by REON in such a way that at full-flow the pressure drop will be not more than 15 psi and the temperature drop not more than 5°F.

(7) The gas generator system should be designed to minimize heat loss to the vault.

(8) The nuclear radiation environment corresponds to an integrated gamma dose rate = 5×10^5 rads.

d. Construction

(1) The gas generator system will be installed in the pipe chase vault which has dimensions as shown in Figure 1.

(2) Each gas generator, with its feed system, will be mounted on a separate skid so that it may be removed separately for repair or replacement.

(3) Skids will be designed for installation and removal by forklift or pallet-type operations.

(4) All instrumentation and control equipment not required to be placed elsewhere, will be mounted on racks in the Test Cell Building or in the Test Operation Console Building.

(5) Recommendation of the number of spares required must be included in the preliminary design.

(6) Metallic seals should be used because of the nuclear environment. No organic materials may be specified unless absolutely necessary and unless approved by REON.

3. Discussion

a. Description of REON Facility

A brief description of the associated REON facilities is made here to assist in a full understanding of the secondary gas generator system. Figure 2 is an overall schematic drawing of the gas generator system and indicates some of the relationships with the REON facilities.

The NERVA engine is contained in a housing on the test stand and its exhaust gas passes downward through the bent-tube eductor where it is exhausted to the atmosphere and burned. Directly below and in front of the test

stand in a northwesterly direction, is the duct vault through which the eductor tube passes. To the left of the duct vault looking toward the test stand, is the pipe chase vault in which the gas generator system will be installed. Both of these vaults are below grade, with heavy concrete roofs, and are installed in a large excavation. There is a large movable wall, the duct vault door, which is used for shielding. This wall door slides on tracks so that it covers the open end of the pipe chase vault during a firing and slides over to shield off the duct vault after a firing.

To the left of the pipe chase vault is an instrumentation tunnel which connects with the Test Cell Building and through which instrumentation cables, pipes, tubes, etc., pass to reach the pipe chase vault. Propellant storage facilities and the Test Cell Building are located about 300 ft behind the test stand. Propellant storage facilities include LO_2 and LH_2 pressurizing Dewars rated at 500 psig and a GN_2 storage bank at 3600 psig. The Test Cell Building is used for storage of a large part of the instrumentation and control equipment; it is not used by personnel during a test. Somewhat further back is an intermediate building, the Forward Control Room; in the rear is the Control Point Building from which the facility is monitored by the test personnel.

The engine housing is built in such a way that it will not allow air leakage into it when a vacuum is produced inside. However, the housing will not resist any appreciable internal pressure, but will pop open to relieve the pressure.

The eductor tube is used as an aspirator to maintain a vacuum in the engine housing during testing. At a downstream point in the duct, an annular type sonic nozzle is used to inject the secondary gas around the perimeter of the duct. This gas is injected into the duct at very high velocity, thereby evacuating the engine housing and the duct upstream of the ejector nozzle.

An annular plenum chamber, wrapped around the eductor tube, is used to supply gas to the ejector nozzle. A long hot-gas conduit is used to bring the secondary gas from the secondary gas generator to the plenum chamber. Gas from the gas generators is manifolded into a single conduit in the pipe chase vault; in the duct vault, the gas stream is split in half so as to supply the plenum chamber from two sides.

Propellants are pressure fed from the storage facilities to the gas generator system interface in the pipe chase vault. LH_2 and LO_2 Dewars are designed for 500 psig maximum and are maintained at specified pressures by a pressure-control system throughout each test. LH_2 is fed through a 12-in. vacuum-jacketed line whereas LO_2 is fed through an 8-in. line with conventional cryogenic insulation. This feed supply system will be operated so that both of these materials will be supplied to the gas generator system interface at 450 psig with specified densities. Gaseous nitrogen at 3600 psig will be supplied through a 6-in. line to a pressure reducer which will maintain a pressure of 400 psig through an 8-in. line to the gas generator system interface. Liquid nitrogen and water are also available but should be avoided unless required. The nuclear environment is a very important factor to be considered. Primary source of the radiation is the nuclear engine itself. As the test program proceeds however, additional sources such as plate-out on the interior surface of the eductor tube will have increasing importance. Highest levels of radiation will occur around the test stand and in the duct vault. The thick concrete barrier between the pipe chase and duct vaults and in the roof of the pipe chase vault will cut the radiation in the pipe chase vault to an integrated dosage of 5×10^5 rads. The additional barrier between the pipe chase vault and the instrumentation tunnel will cut the radiation in the tunnel to a level considered safe for installation of electrical relays. Radiation hazard in the Test Cell Building and Forward Control Room is considered negligible. The Control Point Building is considered safe, even for personnel.

b. Choice of System

The purpose of the secondary gas generator system can be accomplished in many different ways. Several of the more important choices were made by REON before the initiation of this preliminary design. For example, it was decided that the gas would be produced by a rocket-type gas generator using LO_2 and LH_2 . A number of the features of the system were left to be specified during the preliminary design program.

Before proceeding with any design work, it was first necessary to decide upon the number of combustion chambers and the method of operation. A variety of different approaches were considered, each of which had its own advantages and disadvantages. Preliminary screening reduced the number of approaches and a choice was then made primarily on the basis of reliability and simplicity as described in the section on reliability.

A system of three identical gas generator units was chosen in which one gas generator unit would produce the required gas flow while the two redundant units would operate on pilot standby.

Regenerative cooling and other types of cooling for the combustion chambers were considered but the complications were such that it was decided to base the design on an uncooled chamber.

After a lengthy study of control system possibilities, a modified open-loop system was chosen. This system is based on careful control of the propellant Dewar pressures. Pressure drops are built into the system and all valves are of the "on-off" type. In this way, the control of flow rate (at the specified Dewar pressures) is built into the equipment. Any necessary adjustments can be made between tests by changing orifice sizes or Dewar pressure control points. This is a simple effective type of system with which the Aerojet Liquid Rocket Plant Test Division is thoroughly familiar.

Conventional propellant injectors for combustion chambers become increasingly more difficult to design, build, and operate as the size of the chamber increases. For this reason, large-thrust-per-element injectors were selected for this application. A small pentad element (FF-O-FF) located in the middle of the injector plate face will be used to provide the pilot, or idle flow, flame. For full-flow operation, a single concentric-ring element (F-O-F) was chosen as the main injector. This element was chosen because of its geometrical symmetry and because the stream of liquid oxygen, injected as a cylindrical stream, is completely surrounded by the two streams of liquid hydrogen. Thus, the possibility of localized hot spots, with consequent chamber-wall erosion, is greatly reduced.

Electrical spark-type igniters are generally used where restart capability is required and the igniter cannot be replaced between starts. For single-start devices, it is more common to use pyrotechnic type igniters. Because of the effect of the nuclear environment on personnel, the spark-type igniter was chosen. A high-energy capacitor-discharge-ignition system, such as is currently in common usage, was selected. In this system, a high-energy sparkplug is recessed in a cavity between the streams of a doublet injection element (F-O) using the same propellants, LO_2/LH_2 .

c. Description of Equipment

Each gas generator with its associated piping, valves, etc., will be mounted on a separate skid as shown in Figure 3. In essence, the skid will be simply rolled structural steel sections - two parallel beams tied together by two cross beams.

The gas generator combustion chamber will be a piece of 24-in. Schedule-160 pipe (ID = 19.376 in.) with flanges attached to both ends to provide a total length of 5 ft. An injector plate 3-in. thick is sandwiched between the forward flange of the combustion chamber and the cryogenic feed flange. At the aft end of the combustion chamber, a gaseous-nitrogen purge-injection ring is inserted between the gas generator exit flange and the REON hot-gas conduit interface flange.

External insulation for the combustion chamber will be of a composite type consisting of two layers of quartz felt insulation, each covered with an aluminum foil reflector. These layers, in turn, will be covered by a suitable weathertight coating. Internally, the combustion chamber will be coated with a 0.06-in. Rokide-type insulation to minimize the effect of localized hot spots.

Figure 4 shows the injector plate with the injectors and the igniters. The injector plate is 3-in. thick and its combustion-chamber side is insulated with 0.2 in. of Rokide-type insulation. A small pentad element (FF-O-FF) located in the middle of the injector-plate face will be used as the pilot flame injector. This element has four 0.179-in. fuel tubes and one 0.170 in. oxidizer tube. The main injector is a large single-element concentric-ring-type injector with two annular fuel orifices impinging on one annular oxidizer orifice. Each fuel orifice has a cross-sectional area of 4.90 in.² and the oxidizer orifice has an area of 2.20 in.². As a backup for the pentad element, a coaxial element (an oxidizer tube inside of a hydrogen tube) will be considered. For backup of the concentric-ring element, a multi-element injector of pentads or coaxial elements will be considered.

Two high-energy sparkplug igniters will be used for redundancy. A small doublet element is used to impinge LH₂ on LO₂ just beyond the sparkplug in such a way as to prevent flooding and quenching the spark. Each stream will flash vaporize a small amount of gas upon entering the chamber and the spark will ignite this gas to start the igniter element flame.

Liquid hydrogen is supplied from a 12-in. flanged interface connection and liquid oxygen is supplied through an 8-in. flanged interface connection. Liquid hydrogen to the main injector passes through four parallel 3-in. ball valves is recombined into a 12-in. line and fed to the cryogenic feed flange. This feed flange is a conical expander section, internally insulated, which expands from the 12-in. line diameter to the combustion chamber diameter where it is flanged to mate with the combustion chamber flange and sandwich the injector plate between them. Liquid oxygen to the main injector passes through two parallel 3-in. ball valves, through two 3-in. lines to the opposite side of a half torus manifold welded to the outside of the cryogenic feed flange. Six 2-1/8-in. lines carry the oxygen from the external manifold through the expander wall to another half torus manifold welded to the back of the injector plate.

Each propellant fed to the idle-flow injector flows as a sidestream from the inlet propellant, passes through a special throttle valve and the bipropellant valve, through the cryogenic feed flange wall to the injector plate manifold for the pentad element. The purpose of the throttle valve is to compensate for the difference in combustion chamber back pressure between idle flow and full flow. Feed to the igniters is similar except there is no throttle valve.

Automatic gaseous nitrogen purge is required for each propellant manifold anytime the flow stops. Purge flow lines are therefore connected to each propellant line and located for most effective purge action. On startup, and again on shutdown, it is necessary to purge the gas generator, hot-gas conduit, and plenum chamber. This is done by means of an injection ring sandwiched between the gas generator exit flange and the hot-gas conduit interface flange. Gaseous nitrogen is supplied from an 8-in. flanged interface connection. All purge flow lines have a control valve followed by a check valve. Pressure in the nitrogen supply line back of the check valve is maintained at a pressure sufficiently lower than manifold pressure that the check valve stays closed under normal flow conditions. If the flow stops, however, the manifold pressure drops and the larger nitrogen pressure opens the check valve and purges the line.

A large amount of instrumentation will be used to evaluate the development generators but the deliverable system will not require much instrumentation. These sensors will be almost exclusively of three types: temperature transducers, pressure transducers, and valve-position sensors. Since operation of the system is

relatively simple, most of the instrumentation and control equipment is used for sequencing and malfunction detection. These are described in the Control System Design Section and in Appendix D. The three most important operation signals are all external signals from REON: (1) sequence signals - when to start, stop, etc., (2) plenum chamber temperature, and (3) plenum chamber pressure. The latter two will indicate proper operation with respect to flow rate, mixture ratio, and T/M, in addition to temperature and pressure.

d. Operation

The sequence of operations during startup is as follows: Upon receipt of the external startup signal, the entire system from propellant manifolds through the plenum chamber is purged with GN_2 .

Igniter sparking is commenced and propellants are fed to the igniters of all generators, using a fuel lead. Thermocouples in the injector-plate faces, but thermally insulated from the metal, indicate that the igniters are burning. Igniter spark is turned off.

Propellants are fed to the idle flow injectors of all generators, using a fuel lead. The thermocouples indicate that the pilot flames are lit. Igniter propellants are turned off.

Propellants are fed to the main injector of the combustion chamber which is to provide the full gas flow. A signal is sent to indicate satisfactory full-flow operation of the gas generator system so that the NERVA engine can start.

Upon receipt of a signal to go on idle standby, propellants to the main injector are turned off; this starts purge action to the main injector propellant manifolds.

Upon receipt of a signal to come to full flow, propellants to the main injector are turned on again with a fuel lead.

Upon receipt of a signal to shutdown the gas generator, all propellant streams are turned off and the entire system from propellant manifolds through the plenum chamber is purged with GN_2 .

B. PRELIMINARY DESIGN

1. System Process Design

a. Design Conditions at the Plenum Chamber

Performance required of the gas generator was specified by REON in terms of the annular plenum chamber which feeds the ejector nozzle rather than in terms of the gas generator outlet which would be more customary. Four primary full flow design conditions at the plenum chamber were specified:

- (1) $\dot{w} = 210 \text{ lb/sec}$
- (2) Pressure = 300 psia
- (3) $T/M \cong 465^\circ\text{R lb-mol/lb}$
- (4) Response time $\leq 0.3 \text{ sec}$ from minimum flow to full flow

These desired conditions were not rigid, but could be changed if the conditions could not be met.

b. Summary of Combustion Chamber Conditions

To determine combustion chamber conditions from plenum chamber conditions required a detailed knowledge, presently unavailable, of the physical configuration of each and of the connecting hot-gas conduit. On the basis of reasonable assumptions, however, fairly accurate values can be determined. Combustion-chamber conditions were then determined as described below and summarized here.

- (1) $\dot{w} = 210 \text{ lb/sec}$
- (2) Pressure = 320 psia
- (3) Mixture Ratio = 1.14 lb O_2 /lb H_2
- (4) Combustion Temperature = 1560°F

(5) Molecular Weight = 4.314

(6) $T/M = 468^{\circ}\text{R lb-mol/lb}$

(7) Allowable $\Delta T = 14^{\circ}\text{F}$

c. Temperature

On the basis of reasonable assumptions, it was determined by thermal analysis that the heat loss without insulation would be excessive and that an insulation of only 0.35 in. would keep the gas temperature from dropping more than 5°F .

d. Mixture Ratio

A mixture ratio for the gas generator was therefore chosen which would give a temperature allowing for at least a 5°F drop and still give a value of T/M greater than $465^{\circ}\text{R lb-mol/lb}$ at the plenum chamber.

The theoretical combustion temperature as a function of mixture ratio has been calculated previously as shown in Figure 5. Molecular weight of the combustion gas was calculated as a function of mixture ratio:

$$M = 2.016 (1 + \text{MR})$$

From these, T/M was calculated. The allowable temperature drop from the gas generator to the plenum chamber can then be calculated as:

$$\Delta T = T - 465M$$

Both T/M and ΔT are shown in Figure 5 as functions of mixture ratio. From the graph of ΔT , a design mixture ratio of 1.14 was chosen.

e. Material Balance

At this mixture ratio and temperature, the reaction is essentially complete with no dissociation.

<u>Comp.</u>	<u>Feed</u>		<u>Combustion Gas</u>	
	<u>Lb/Sec</u>	<u>Mol/Sec</u>	<u>Lb/Sec</u>	<u>Mol/Sec</u>
H ₂	98.13	48.676	84.03	41.684
O ₂	111.87	3.496	-	-
H ₂ O	-	-	125.97	6.992
Total	210.00	52.172	210.00	48.676

f. Pressure drop from the combustion chamber to the plenum chamber was calculated to be about 12 psi on the basis of simplifying assumptions as described in Appendix B. The design pressure in the combustion chamber was therefore set at 320 psia.

g. The response time was calculated to be 0.67 sec to reach steady state flow as described in Appendix E. Pressure in the plenum chamber and flow through the ejector nozzle were calculated as functions of time as shown in Figure 6. These calculations were based on simplifying assumptions using the preliminary dimensions for the hot-gas conduit furnished by REON. Accuracy of the response time calculation was estimated to be about ± 0.1 sec.

2. Gas Generator Chamber Design

a. Design Considerations and Criteria

(1) Chamber Volume and Characteristic Length

The purpose of the chamber is to provide sufficient volume to complete combustion while still maintaining a reasonable size and configuration. The lower the combustion temperature and the lower the chamber pressure, the higher the volume required to complete combustion. A parameter L^* is in common usage to describe the volume. The advantage of defining chambers by L^* , which equals chamber volume divided by sonic throat area, is that the effect of chamber pressure is eliminated. Therefore, the choice of L^* can be

based primarily on combustion temperature. Rocket thrust chambers generally operate with combustion temperatures in the 5000 to 6500°F range with L* values in the 30 to 60-in. range. Gas generators operate with combustion temperatures in the 1000 to 2000°F range with L* values from the 100 to 200-in. range.

(2) Chamber Length-to-Diameter Ratio

Once L* or volume has been chosen for a system, the configuration can then be approximated. The chamber can be designed to have a short length-to-diameter ratio, as do most rocket thrust chambers, which has the advantage of providing combustion very near the injector face and the disadvantage of possible local hot spots. Or the chamber can be designed to a long length-to-diameter ratio, as do most gas generators, which has the advantage of continuing combustion and mixing as the gases proceed down the chamber. Since the proposed design is an uncooled chamber, every effort must be made to eliminate hot spots and provide a homogeneous temperature. Therefore, an L/D for the chamber in the range of 3 to 5 is recommended.

(3) Chamber Configuration

The choice of chamber shape from among spherical, conical, dual conical, and cylindrical configurations is based on packaging considerations and fabricability. Since space is not limited and standard piping is less expensive, the configuration choice is cylindrical.

b. Design Description

The gas generator chamber shown in Figure 3 consists of a cylindrical section to which flanges are welded on each end. To simplify construction and to minimize expense, standard Schedule 160 pipe and weld neck flanges were chosen. Of primary concern to this design are the stresses introduced by a temperature gradient across the chamber wall (see Appendix F) during operation. To minimize the temperature gradient across the metal wall, a ceramic type thermal insulation will be applied externally to the walls of the chamber. To minimize the effect on the metal of local hot spots, a thermal barrier coating such as Rokide "Z" will be applied to the internal surfaces.

c. Design Calculation Summary

(1) Chamber Diameter

Mach numbers for the gas velocity of rocket motor combustion chambers will usually be in the range of 0.2 to 0.5. The values for gas generators are usually lower. In the present case, with a relatively high temperature for an uncooled chamber of this size, the stress and thermal problems are critical, so that even though this is a facility installation, it will still be desirable to minimize the diameter of the chamber. Therefore, the combustion chamber will be designed for a gas velocity mach number of about 0.3. Gas velocity leaving the chamber and the chamber diameter can then be calculated as follows:

$$\begin{aligned}\text{Acoustic velocity} &= a = \sqrt{gkRT} = \sqrt{\frac{(32.17)(1.346)(1544)(2020)}{4.314}} \\ &= 5595 \text{ ft/sec}\end{aligned}$$

$$\text{Exit gas velocity} = V = 0.3 (5595) = 1679 \text{ ft/sec approx.}$$

$$\begin{aligned}\text{Required Cross-sectional area} &= A = \frac{\dot{w}}{\rho V} = \frac{210 (0.98)}{(0.0638) (1679)} \\ &= 1.92 \text{ ft}^2 \text{ approx.}\end{aligned}$$

$$\text{or Diameter} = 1.56 \text{ ft} = 18.75 \text{ in. approx.}$$

To approximate the ASME code, a 24-in. OD Schedule 160 tube was selected which has an internal diameter of 19.376 in. and a wall thickness of 2.312 in.

Summarizing the above values:

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

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

$$V = \frac{\dot{W}}{\rho A} = 1575 \text{ ft/sec}$$

(2) Chamber Length

Characteristic chamber length, L^* , for gas generators of this type will usually be in the range of 100 to 200 in. In the present case, the length of the chamber can be minimized because there is no exit nozzle and the entire hot-gas conduit leading to the plenum chamber can be considered as additional length. However, until the combustion is accomplished and the products reasonably well mixed, there can be local high temperatures, so precautions, such as providing internal insulation, must be taken. Therefore, the chamber will be designed for an L^* of about 125 in. Chamber volume can then be calculated as follows:

$$\begin{aligned} \text{Characteristic exhaust velocity} = C^* &= \frac{a}{k \sqrt{\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}} \\ &= \frac{5595}{1.346 \sqrt{\left(\frac{2}{2.346}\right)^{\frac{2.346}{0.346}}}} \\ &= 7140 \text{ ft/sec} \end{aligned}$$

$$\text{Equivalent throat area} = A_t = \frac{C^* \dot{W}}{P_o g} = \frac{7140 (210) (0.98)}{320 (32.17)} = 142.7 \text{ in.}^2$$

$$\text{Chamber volume} = V_c = L^* A_t = 125 (142.7) = 17,830 \text{ in.}^3 \text{ approx.}$$

$$\text{or Chamber Length} = L = \frac{V_c}{A_c} = \frac{17,830}{294.9} = 60.5 \text{ in. approximately}$$

Therefore, use: $L = 60 \text{ in.} = 5 \text{ ft}$

$$\text{and } \frac{L}{D} = \frac{60}{19.376} = 3.1$$

3. Gas Generator Injector Design

a. Design Considerations

The design of liquid-propellant injection systems is based on (1) a qualitative understanding of the injection-combustion process, (2) certain empirical relations determined from previous testing, and (3) basic hydraulic equations.

(1) Qualitative Considerations

To provide complete, high-performance combustion, the propellants must be broken into fine droplets, mixed to a semi-homogeneous state, vaporized, and finally allowed sufficient residual time in the chamber to complete combustion. The energy for breakup, mixing, and distribution is furnished by the kinetic energy and momentum of the injected liquid streams. In general, higher kinetic energy and momentum levels provide better mixing; however, a practical pressure-drop limit imposes a ceiling to energy levels. The geometry and location of the various injection orifices control the degree of efficient and effective use of the hydraulic energies. Vaporization is accomplished both by the passage of the mixed propellants into the hot-gas combustion zone and by the recirculation of hot gases back into the mixed propellants. Combustion proceeds in the gas phase; the gases expand and are accelerated down the length of the chamber.

(2) Empirical Relations

Logical interpretation of past test experience has provided an increasing backlog of empirical relations. These include, but are not limited to:

- (a) Injection pressure drops from 20 to 30% of operating chamber pressure
- (b) Orifice length-to-diameter ratios from 2.0 to 5.0
- (c) Injection impingement angles from 30 to 60°; i.e., the angle the impinging stream forms with the axis of the central stream.

(3) Implementation of Design

Once the basic configuration and allowable overall pressure drop are established, the design solution is simply a straightforward application of hydraulic pressure loss equations to various inlet and manifold designs. Since the energy level of injection should be of prime importance, the highest percentage of the allowable pressure drop is taken at the exit orifices. Therefore, the inlet lines and manifolds are accordingly designed with relatively small pressure drops. Pressure-drop calculations for both the pentad and concentric-ring injector are presented in Appendix B.

b. Injector Design Description

(1) Pentad Injector - Pilot Gas Generator Injector

The injector for the pilot flame of the gas generator, shown in Figure 4, is a single-element pentad; i.e., four fuel streams impinging on one oxidizer stream at a total impingement angle of 60°. The fuel tubes are inserted into a common annular manifold. Thin-walled (approximately 0.020 in.) tubes are used to permit proper cooling of the metal by the propellants. This particular type of element has been tested with excellent results using the LO_2/LH_2 propellant combination. Because of the simplicity of design, modifications to the element size and orientation can be achieved easily during a developmental test program, thereby reducing the cost of developing a prototype unit.

(2) Concentric-Ring Injector - Main Gas Generator Injector

The main injector for the gas generator shown in Figure 4, is a single-element concentric ring, i.e., one oxidizer slot-annulus bisects the

90° angle formed by the two fuel slot annuli. The exit orifice slots are fed by annular manifolds which evenly distribute the flows from the tubular inlet lines.

The primary advantage of a concentric ring type of injector is the inherent axial symmetry of the injected propellant streams and therefore of the flame front. This decreases the likelihood of localized "hot spots" on the chamber wall and injector face.

c. Design Calculation Summary

The detailed design calculations for both the pilot injector and the main injector are presented in Appendix B. A summary of the calculations is presented below:

(1) Pentad Injector

The approximate exit orifice velocities required were determined from previous programs as: $V_{\text{fuel}} = 350 \text{ ft/sec}$ and $V_{\text{oxid}} = 100 \text{ ft/sec}$. Using the basic continuity equation

$$\dot{w} = \rho VA,$$

the fuel and oxidizer tube diameters are calculated to be 0.179 inch ID and 0.170 inch ID, respectively.

The pressure drops were calculated by using the standard equation

$$\Delta P = \frac{K V^2 \rho}{2g}$$

where the flow coefficient (K) is found in appropriate tables in the Crane Hydraulics Handbook. The total pressure drops in the fuel and oxidizer circuits are 79 and 106 psi respectively.

(2) Concentric Ring Injector

The design exit velocities based on previous programs are: $V_{\text{fuel}} = 350 \text{ ft/sec}$ and $V_{\text{oxid}} = 100 \text{ ft/sec}$. The orifice areas to provide this velocity are 2.20 in.² for the central oxidizer annulus, and 4.90 in.² for each fuel annulus. The total pressure drops in the oxidizer and fuel circuits are 115 psi and 74 psi, respectively.

4. Gas Generator Igniter Design

a. Design Considerations

Ignition of hydrogen and oxygen can be accomplished with a minimum amount of energy, provided the energy source is above 1000°F. The extreme detonation hazards of the LO_2/H_2 system which can result from delayed ignition of large flow rates of propellants places a very great design importance on the igniter component. High-energy turbojet-type ignition systems are frequently utilized in cryogenic rocket engines where restart capabilities are required. The initial flow rate determines the magnitude of the starting combustion reaction. Therefore, separate igniter combustion assemblies are advantageous in order that preliminary ignition can be accomplished with small rates of propellant flow.

In order to assure a high degree of reliability to the restart capabilities, a redundant system is necessary. It is also required that maximum protection, in the form of cooling and choice of location, be afforded each spark plug assembly.

b. Design Description

Each igniter assembly, shown in Figure 4, consists of a high-energy spark plug recessed in a cavity between the streams of a doublet (one fuel on one oxidizer) injection element. The propellant streams impinge beyond the spark plug in such a way as to prevent any possibility of flooding and quenching the spark. High-energy capacitor discharge ignition systems, developed primarily for LO_2/LH_2 ignition, will be used in this application to initiate combustion in the two symmetrically located igniter assemblies. The spark plugs, cables and ignition exciters, which are commercially available items such as those furnished by General Laboratories Associates, Inc. of Norwich, New York, are described in Appendix B. Similar spark ignition systems are currently being successfully used with the following engines:

1. LO_2/LH_2 200K, Saturn J-2, Rocketdyne
2. LO_2/LH_2 15K, Centaur RL-10, Pratt & Whitney
3. $\text{LO}_2/\text{RD-1}$, 1500 K, Saturn F-1, Rocketdyne

The same type of ignition system is also included in the preliminary designs of the LO_2/LH_2 , Aerojet M-1, Gas Generator.

The combustion products of the two igniter assemblies will be directed toward the pilot pentad. Smooth ignition of the pentad will then be assured by these two burning propellant streams. The spark ignition system will therefore be required to ignite only a small flow of propellants, thus minimizing initial combustion hazards.

After ignition of the pilot pentad, the propellant flows to the combustion igniters will shut off. Cooling liquid will then be bled from the pilot pentad fuel supply line, circulated internally around the spark plug assemblies, and injected into the main combustion chamber to form a fuel cooling stream over the spark plugs.

c. Design Calculation Summary

The flow of each igniter will represent 10% of the design pilot flow. The 0.054-in.-dia oxidizer orifice will flow 0.112 lb/sec with a pressure drop of 108 psi. The 0.113-in.-dia fuel orifice will flow 0.098 lb/sec with a pressure drop of 81 psi. Details of these calculations are presented in Appendix B.

5. Propellant and Purge Feed Systems

a. Introduction

The propellant and purge feed systems described briefly in this section were designed to show the size and type of feed system required to service this gas generator. This preliminary design was not intended to arrive at an optimum arrangement, but to design a system which would work and would serve as a basis for design. Therefore, the valves are described in general terms, and the line sizes represent approximate sizes.

A schematic flow diagram of the feed system is presented in Figure 7. Calculations and equipment list are presented in Appendix C.

b. Design and Development Problem Areas

Problems in the design and development of the propellant and purge feed systems appear to lie in three general areas: insulation of the hydrogen feed line to minimize heat leakage and consequently boil off; bleed-off of the "chill-down" gas formed when the system is placed in operation; design and/or selection of the valves.

The problem of insulating the hydrogen feed line is a major design problem; it must be vacuum jacketed from the system interface to the gas generator manifold. This will require ingenuity both in joint designs and valve-vacuum jacketing since the heat leak through a joint or a valve can be more than 100 times the heat leak per foot of line. The envelope requirements for the main hydrogen valves due to this consideration are probably the limiting factors in the selection of the valves. The oxygen line and valve problems are similar but much less severe so that a vacuum jacket is not needed. The design engineer responsible for the piping design, layout, and fabrication is the key man in this area. Valve selection or design can be performed by a consultant or support group.

Bleed-off of the "chill-down" gas formed when the system is prepared for operation is a related problem. This vaporization results primarily from the mass of metal contacted which must be cooled down to cryogenic temperatures by the liquid hydrogen and oxygen. If the idle-flow injector could be arranged to operate on gaseous hydrogen and oxygen, this consumption of gas from the supply lines or manifolds would probably ensure delivery of liquid to the main valves after a reasonable length of time of idle operation. Alternately, it may be possible to allow the load-carrying gas generator to start on this gas, since the first start does not need to be within the 0.3 sec "idle-to-full-flow" response time restriction. Idle-flow consumption of gas in the other two generators would then prepare them for a liquid propellant start in case one of them is needed for emergency use. If neither of these possibilities is found to be acceptable, some provision for venting the gas must be designed into the propellant feed system. The system presently shown could be used for gaseous propellant flow in the idle-flow circuit by changing the valve and line sizes.

Design and/or selection of the valves in the propellant and purge systems will require the services of an engineer, or a support group, very familiar with Aerojet designs and with various supplier designs in these areas of application. The time schedule does not allow for an extensive valve development program. The valves in the propellant flow and the larger purge-flow lines are certainly within the present state-of-the-art of various valve suppliers, but it is doubtful that any existing designs can be used directly. Therefore, the vendor who can produce the required design with the least deviation from an existing proven design in an acceptable time should be selected.

c. Propellant Feed System

The propellant feed system consists of (1) the liquid-hydrogen and liquid-oxygen lines from the system interface to the gas generator, (2) the main propellant valves with their solenoid valves, (3) the idle-flow throttle valves, (4) the idle-flow bipropellant valve with its control solenoid valve, and (5) the igniter bipropellant valve with its control solenoid.

The liquid-oxygen line is an 8-in. line from the system interface to a manifold where the line branches into two 3-in. lines which supply the main injector, one 1/2-in. line which supplies the idle-flow injector, and one 3/8-in. line which supplies the igniters. The main oxygen valves are two 3-in. ball valves which are rotated by pneumatic actuators in both directions. Pneumatic gas (nitrogen) to the actuators is controlled by 3-way solenoid valves. The idle-flow throttle valve restricts flow in the normal position but allows free flow when actuated by the pneumatic signal which also opens the main valves. The purpose of the throttle valve is to compensate for the difference in combustion chamber back pressure between idle flow and full flow. A pneumatic actuator, controlled by a 3-way solenoid valve, is used to open the idle-flow bipropellant valve. The idle-flow bipropellant valve is closed by spring force and propellant pressure. The injector bipropellant valve operates similarly.

The liquid-hydrogen line is a 12-in. vacuum-jacketed line from the system interface to a manifold where the line branches into four 3-in. lines which supply the main hydrogen valves, one 1-in. line which supplies the idle-flow injector, and one 1/2-in. line which supplies the igniters.

The four main hydrogen valves are 3-in. ball valves which are the same model valve as the main oxygen valves. On the other side of the main hydrogen valves, the four 3-in. lines are recombined into a 12-in. header line which supplies the main injector. The idle-flow throttle valve is the same type of valve used in the oxygen idle-flow line and is controlled similarly by the signal which opens the main hydrogen valves.

To prepare the gas generator system for operation, the solenoid valves used for opening and closing the propellant valves are all energized, and the pneumatic gas supply to the solenoid valves is turned on (facility valve). This procedure closes all of the propellant valves. Propellant supply valves are then turned on (facility valves), and the system is then ready to operate. Igniter flame is initiated by de-energizing the solenoid valve which controls the igniter bipropellant valve by directing pressure to the valve actuator. The idle-flow phase of gas generator operation is initiated by de-energizing the solenoid valve which controls opening of the idle flow bipropellant valve by directing pressure to the valve actuator. The main flow phase of gas generator operation is initiated by de-energizing the solenoid valves which control opening and closing of the main valves. This vents the pneumatic pressures from the closing actuators of the main valves and directs pressure to the opening actuators. When the main valves are opened, pressure is also directed to the idle-flow throttling valves so as to switch these valves from restricted flow position to full-flow position.

d. Purge System

The purpose of the purge system is twofold: purge the gas generator chamber and hot-gas conduit prior to firing and during the shut-down procedure; and purge the injector manifolds any time propellant is not flowing. The gaseous-nitrogen purge line is an 8-in. line at the system interface. Chamber and propellant manifold purge are supplied by this line. The chamber purge supply line is an 8-in. line which is divided into four 4-in. supply lines to feed an injection ring. The four propellant injector manifolds are purged through separate lines, one each for the hydrogen and oxygen sides of the main and idle-flow injectors.

The 8-in. gas generator chamber purge line contains a solenoid-controlled shutoff valve, a check valve, and a flow-limiting orifice. The shutoff valve is normally closed and is energized to open when purge flow is required for start-up or shut-down.

Idle-flow injector manifolds are purged with gaseous nitrogen through 3/8-in. and 1/2-in. lines for the oxygen and hydrogen sides respectively. Igniter manifolds are similarly purged. Purge flows are controlled by solenoid valves and check valves. These solenoid valves are normally open so that they must be energized prior to a run and then de-energized when purge is required. The check valves automatically shut off the purge flow when manifold pressure builds up to normal operating pressure. If desired, the solenoids could then be energized for positive assurance that the purge is shut off. Purge is restored at shutdown by de-energizing the solenoids and/or the action of the check valves.

The main flow injector manifolds are purged with gaseous nitrogen through 2-in. and 4-in. lines for the oxygen and hydrogen, respectively; the valving in these lines consists of solenoid-controlled shutoff valves and check valves. The shutoff valves are normally open so that their control solenoids must be energized prior to a run and then de-energized when purge is required. Check valves stop the purge flow when manifold pressures build up to normal pressures. Depending upon the anticipated duration of the main flow, the shutoff valves may be left in the open position (unenergized) so that the purge will come back on automatically after a short main flow run, or the shutoff valves may be closed for positive assurance that the purge is shutoff.

If the quantity of gaseous N_2 through any purge line is found to be excessive, a flow-limiting orifice can be placed in the line to reduce the flow rate to an acceptable value.

6. Control System Design

a. Discussion of Open Loop System

The operating limits of the gas generator system are determined primarily from the minimum temperature and pressure consistent with correct duct evacuation, and maximum temperature and pressure consistent with

structural strength of the system walls. An additional restriction is the requirement that the gas be fuel-rich at all times. The range of these limits is such that a nominal operating range can be selected which will assure proper operation for a reasonable test duration. This is accomplished by calibrating the valves, pipes and injectors to give the desired full flow rates at specified Dewar and combustion chamber pressures. Calibration drift due to ejector and nozzle wear, or slow changes in ambient conditions, could be compensated for by small variations in the Dewar pressures. Thus, in a gross sense the system would then be closed loop while being open loop for a particular run. A closed-loop Dewar pressurization system will be required by REON regardless of gas generator requirements. It is, therefore, unnecessary to insert a redundant closed loop system on the gas generator. This approach is similar to the open loop techniques currently in use at the Aerojet test facilities in Sacramento.

In eliminating the hardware required for closed loop controls, one additional failure mode is eliminated.

b. Automatic Control

Transitional periods of the gas generator system's operation require automatic control. These periods include ignition, idle flow to full flow, shutdown to idle flow, and complete shutdown. Automatic control during these periods is required for the following reasons:

- (1) The programming of events requires swiftness and precision of timing beyond that of a human operator's capability.
- (2) In the event of malfunction, corrective action must be instantaneous to ensure a safe shutdown.
- (3) Since the system requires transfer of power from one gas generator to another, a simultaneous shutdown and start up must be perfectly synchronized to ensure an uninterrupted power level.

All of the required control functions are of the "on-off" type. All inputs are discrete signals which initiate various control programs. The control is performed by actuating valves to the open or closed positions, and controlling current to the ignition spark plugs. Details of the control sequencing, logic, and wiring are presented in Appendix D.

c. Malfunction Detection and Control

(1) Introduction

A malfunction in the gas generator system must not compromise the ability to safely shut down the NERVA engine. In addition to the redundant system of three gas generators, a system of malfunction detection and control is included for each gas generator. In general, malfunctions detected prior to NERVA engine firing result in immediate shutdown and purge. Malfunctions that are detected after the NERVA engine begins firing, result in the simultaneous shutdown of the faulty gas generator and the startup of a spare generator.

(2) Method of Detecting Malfunctions

(a) Critical gas generator parameters will be continuously monitored with appropriate transducers. A schematic diagram of the control instrumentation is presented in Figure 8. These signals will be quantized where required, compared to limit conditions references, and converted to "go, no-go" signals. These signals will be sampled on a time basis to determine whether or not corrective control actions should be taken. A block diagram of the automatic malfunction detection system is presented in Figure 9 and a summary block diagram of the automatic malfunction control system is presented in Figure 10.

(b) The following parameters and the corresponding limits are used as a basis for detecting malfunctions:

- 1 $1510 < T_p < 1595^{\circ}\text{F}$ (plenum chamber full-flow condition)
- 2 $300 < P_p < 350$ psia (plenum chamber full-flow condition)
- 3 $1000 < \frac{dP_c}{dt} < 1500$ psia (during full-flow startup)

- 4 T_1 (injector face) $> 200^{\circ}\text{F}$ (0.05 sec after ignition)
- 5 $T_1 > 500^{\circ}\text{F}$ (0.1 sec after idle startup)
- 6 $T_c - T_N \geq + \text{value (chamber)}$ (0.2 sec after return to idle from full flow)
- 7 T_{MH} (hydrogen manifold) $> -360^{\circ}\text{F}$ (0.05 sec after N_2 purge)
- 8 T_{MO} (oxygen manifold) $> -150^{\circ}\text{F}$ (0.05 sec after N_2 purge)
- 9 $P_{\text{purge}} > 350 \text{ psia}$ (0.05 sec after N_2 purge)

(3) Transducers

The T_1 transducer will measure temperature near the injector face. A thermocouple which is thermally insulated from the injector face will be used. In actual practice, several units will be installed so that a failure of one unit will not result in a loss of signal. Each thermocouple will have its output amplified. The amplified outputs will be electrically combined so that a single temperature value is obtained that represents the maximum of any thermocouple.

In a similar manner to T_1 above, T_c will measure chamber temperature. Again, redundant thermocouples will be used.

T_{MH} and T_{MO} measure hydrogen and oxygen manifold temperatures. Since the temperatures involved are at cryogenic levels, the transducers will be the platinum resistance-wire type. Redundant channels will not be used unless development tests show likelihood of failure.

P_c will be measured with a proportional pressure transducer such as a variable reluctance a-c carrier type. The demodulated output signal will be differentiated, with respect to time, in order to obtain the rate of pressure rise, dP_c/dt .

P_p will be a signal supplied from NERVA which indicates the plenum chamber pressure between the limits of 300 to 350 psia.

7. Thermal Analysis

a. Analysis Considerations

To provide the required acoustic velocity in the ejector, the parameter T/M must exceed $465^{\circ}\text{R lb-mol/lb}$. This requires the main gas generator to operate at a combustion temperature of approximately 1560°F . At this temperature, the design of uncooled hardware is critical since most of the acceptable metals are in the range of sharply decreasing strengths. In addition to the stresses set up by the working pressure, there are considerable stresses caused by the radial and axial thermal gradients. To establish basic design dimensions, a thermal analysis was completed and was incorporated in the basic stress analysis calculations. The thermal analysis is summarized below and presented in detail in Appendix E.

Only minimum heat losses can be tolerated from the combustion gases in order to maintain a T/M value of $465^{\circ}\text{R lb-mol/lb}$. Therefore, various insulation and thermal barrier materials were considered and the required thicknesses determined as summarized below.

b. Analysis Summary

Based on a preliminary estimate, the maximum axial temperature gradient in the cryogenic feed flange dome, with an insulation thickness in excess of 1 in. on the dome exterior surface, should be no greater than 100°F/ft .

For a 10°F radial temperature difference in the combustion chamber metal shell, the maximum shell temperature is 1555°F with an insulation thickness of 2.5 in.

The maximum allowable temperature difference in the axial direction across the injector plate is 1000°F . A temperature difference of 1000°F or less is obtainable by covering the chamber side of the injector plate with a 0.2 in. thickness of Rokide or equivalent insulation. An alternate means of controlling the temperature drop is to cool the plate internally with cryogenic propellant.

Two inches of insulation are required for the generator exit flange to limit the radial temperature drop to 100°F. An insulation thickness of 0.35 in. will limit the temperature drop of the gas flowing between the gas generator and the plenum to 5°F. The total heat-transfer rate from the gas generator and exhaust ducts to the pipe chase vault, with 0.35 in. of insulation on the exhaust ducts and the gas generator insulated as described above, is 6.8×10^6 Btu/hr for a vault temperature of 50°F.

The transient behavior of the gas flowing through the ejector nozzle upon changing from idle to full-flow operation has been determined from a simplified model of the gas generator and piping system. The time required for the flow, pressure, and density in the nozzle plenum to reach 98% of the steady-state values is approximately 0.67 sec.

8. Stress Analysis

a. Analysis Considerations

The gas generator system is to be used as standard facility hardware and, therefore, must have the reliability and factor of safety concomitant with safe facility operations. Therefore, the structural design and stress analysis are based on the conservative values and equations recommended by the ASME Code. The stress analysis provides the recommended wall, flange, and support dimensions based on loads and operating pressures, and also furnishes tolerance limits for the thermal gradients. These limiting thermal gradients are then utilized to determine the required thermal barrier and insulation thicknesses.

b. Analysis Summary

Low material values at high temperature and high thermal stresses due to temperature gradients will produce conservative initial design conditions. The test program will produce accurate data which can be used to modify, or structurally reduce the design.

The secondary gas generator consists of a combustion chamber, cryogenic feed flange, and an injector. The chamber and feed flange are assembled by using bolted flanges; the injector is sandwiched between these two flanges (see Figure 3).

Given below is a summary of the stress analysis with the recommended material thickness. A detailed analysis is presented in Appendix F.

<u>Item</u>	<u>Material</u>	<u>Size</u>	<u>Maximum Stress</u> (psi)
Cryogenic Feed Flange			
Dome	310 SS	1.218-in.thick	17,700
Flange	310 SS	ASA 24-in. 1500-lb standard flange	17,700
Combustion Chamber			
Aft Flange	Inconel	ASA 24-in. 1500-lb flange	1,560
Forward Flange	Inconel	1500-lb flange	1,560
Cylinder	Inconel	2.31-in. thick	1,560
Injector	310 SS	3.0-in. thick	17,605
Skid	Structural Steel	(6 E 18) Channels	20,000 to 30,000

9. Materials Evaluation

The major metallic component parts of the secondary gas generator system consist of the (a) combustion chamber -- hot side, (b) injector, (c) combustion chamber -- cold side, (d) propellant-feed piping, and (e) gaseous-nitrogen piping.

Material selections have been made for the various components based on the known or projected operating conditions, including design temperatures, pressures, and nuclear environment. Availability, weldability, and fabricability of the selected material were also considered.

Nuclear-grade Inconel material, in accordance with specification MIL-N-22987, has been selected for application in the combustion chamber and other adjacent equipment subject to the operating temperature of 1555°F. Type 310 stainless steel has been selected for application in the propellant feed piping, and the combustion chamber -- cold side. The injector will be constructed from Type 310 stainless steel or from the nuclear-grade Inconel material, depending on the final design which may permit either regenerative cooling or blanket insulation from the hot gases in the combustion chamber. Carbon steel piping has been selected for use in handling the gaseous nitrogen in areas removed from the combustion chamber. The skid upon which the gas generator and associated equipment is mounted will be constructed of common commercial structural steel.

The cyclic nature of projected operation of the gas generator system in a nuclear environment requires materials with low cobalt content and with favorable relaxation properties for the high temperature service. Nuclear-grade Inconel is considered to be the most favorable choice of materials for this application. Type 310 stainless steel, when insulated from the hot gases, is considered favorable for application in handling the cryogenic propellants due to the fact that the material retains fair ductility properties even at the liquid-hydrogen temperature. The gaseous-nitrogen piping is not considered to be critical from a materials standpoint, and carbon steel piping is considered to be satisfactory.

A detailed material evaluation is presented as Appendix G.

C. RELIABILITY ANALYSIS

1. Purpose

The purpose of the Reliability Program is to assure that contractual reliability requirements are met throughout the secondary gas generator system program. The Reliability Program assures that high levels of reliability will be designed into the system, verified by a sound test program, maintained through manufacture, transportation, storage, and operation, and improved through a closed-loop feedback program.

2. Reliability Analysis

a. Reliability Analysis to Determine Optimum System

The Reliability Department determined the most desirable number and arrangement of gas generators required to give a desired degree of reliability (.75). The optimum system was determined after the systems were reduced to two choices:

System "A" - One gas generator will carry most of the load with one or two additional gas generators on idle standby at 1% to 10% of maximum flow. In the event of failure of a load carrying generator, its partial load will be switched to a standby generator.

System "B" - Two gas generators will divide the load equally. One or two additional gas generators will be operating at 1 to 10% of maximum flow. In the event of a failure of one of the load-carrying generators, its partial load will be switched to a standby generator.

System "A" with two standby generators was compared with System "B" with two standby generators as described below.

Summarizing refer to Figure 11:

System A with 1 standby $>$ System B with 1 standby

System B with 2 standby $>$ System A with 1 standby

System A with 2 standby $>$ System B with 2 standby

(1) All corresponding components (i.e., valves, injectors, combustion chambers, controls, etc.) on each unit are assumed to have the same inherent reliability. Thus, all complete gas generator units are assumed to have the same reliability regardless of size, in the range of sizes being considered.

(2) In system "A", with two standbys, each of the three identical gas generators (including its valves, controls, etc.) would be operated as separate entities, each being capable of performing the full mission satisfactorily. They would, in this sense, be redundant units for the purpose of shutdown only. The only connection between units would be the sensing and switching devices and the REON hot gas manifold. The formula used in determining the reliability of this system is:

$$R_A = 1 - (1-R_1) (1-R_2r_e) (1-R_3r_e)$$

R_A = reliability of system A

R_1 = reliability of unit 1

R_2 = reliability of unit 2

R_3 = reliability of unit 3

R_e = executive function of reliability of switching device

(3) In system "B", with 2 standbys, the four identical gas generators (including the valves, controls, etc.) would be operated in sets of two to provide full loading by each carrying 50% of the required load. Any two generators would be capable of performing the mission satisfactorily. Each unit is effectively in series with its concomitant unit. In the event that one of the loaded units fails, its 50% load would be switched to one of the standby units. In the event of a second failure, the partial load would be switched to the fourth unit. A switching device will be used to switch from one unit to

another in the event of a failure. In this four generator system, it is possible that additional switching controls would be required, which would decrease the reliability. The formula used in determining the reliability of the system is:

$$R_B = 1 - (1-R_1R_2) (1-R_2R_3r_e) (1-R_3R_4r_e)$$

(a) The above formulas can best be compared and understood by assigning arbitrary reliability numbers for the R's and working through an example. An example of such a comparison follows:

System "A"

$$R_A = 1 - (1-R_1) (1-R_2r_e) (1-R_3r_e)$$

$$R_1 = R_2 = R_3 = 0.92$$

$$r_e = .999$$

$$\therefore R_A = 1 - (1-.92) (1-.92 \times .999) (1-.92 \times .999) = .99947$$

System "B"

$$R_B = 1 - (1-R_1R_2) (1-R_2R_3r_e) (1-R_3R_4r_e)$$

$$R_1 = R_2 = R_3 = R_4 = 0.92$$

$$r_e = .999$$

$$\therefore R_B = 1 - (1-0.92 \times 0.92) (1-0.92 \times 0.92 \times 0.999) (1-0.92 \times 0.92 \times 0.999)$$

$$R_B = 0.9966$$

One can readily see from the above illustration and the outlined criteria the reasons for selecting system "A" (three gas generators).

b. 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 for the secondary gas generator program will ensure that reliability becomes inherent in the design.

c. Malfunction Mode Review

A malfunction mode review will be performed by Reliability applying the results of the analysis of environments to the system functional breakdown. This type of review will successfully define salient reliability hazards, allowing corrective actions early in the design formulation phase.

The malfunction mode review will discuss each principle function of the secondary gas generator system, its possible modes of failure, the consequences of these failures, and proposed methods to eliminate their effect.

d. System Analysis

The reliability system analysis approach proposed for the secondary gas generator program will incorporate the results of the reliability design analysis and malfunction analysis to assess the reliability aspects of secondary gas generator configuration and lay the groundwork for making a system prediction and assigning reliability goals. Design will be analyzed to determine if reliability principles and techniques have been incorporated.

(1) Preliminary Reliability Estimates

The estimated projected reliability required of a gas generator unit consisting of concomitant controls and switching devices is:

0.9217

The estimated projected reliability of a control unit is:

0.99

The estimated projected reliability of the gas generator itself - - valves, injector, combustion chamber, etc., i.e., less control unit is:

0.931

(2) The system of three generators would effectively be in series for completion of a complete mission; hence, the reliability of 0.75, as determined from $R = 0.92 \times 0.92 \times 0.92$. The reason that they are considered to be in series arises out of the fact that any failure in any element at the system level will result in all equipments being shut down. In considering the equipment in this light, it can readily be seen that there are more pieces of equipment that would be subject to random failures. In shutdown, however, the equipments would be redundant.

The reasoning behind the redundancy in shutdown arises from the fact that after shutdown procedure is initiated, whether it be for emergency or normal, there may be three gas generators to perform this function. The shutdown procedures will continue through all three gas generators if required. Thus all three generator units must fail before there is a mission failure. The worst case that can be envisioned for the shutdown situation is that one gas generator fails and causes initiation of shutdown. In this case, there are only two gas generators left to safely shut the operation down. This shall be accomplished with a reliability of 0.995. The highest reliability situation would be where the rocket engine being tested initiated the shutdown. In this case, there would be three gas generators to safely shutdown. This shall be accomplished with a reliability of 0.9995.

3. Design Review and Reliability Control

A planned and carefully administered design review program will create high overall reliability during the development phase of the secondary gas generator program. The design review will assure that components and materials specialists 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.

a. Design Reliability

The following design criteria shall be considered.

- (1) Failsafe - Any failure shall occur in such a manner as not to cause complete loss of the system.
- (2) Design Margins - All equipment shall be designed to positive margins of safety.
- (3) Multiple Failure - The decisions to design for single or multiple failures shall be based upon the expected frequency of occurrence as it effects the equipment reliability and safety.
- (4) Repairs and Maintenance - No provisions shall be made for repairs and/or maintenance except in emergency conditions.
- (5) Design Life - The equipments shall be designed with a mean operating life of 200 hours before wearout point.
- (6) Component Reliability - Components shall be designed and tested to assure inherent reliability.

4. Reliability Test Program

An essential portion of the secondary gas generator reliability engineering program is a thorough statistical function. Statistical engineers will assist in mathematical reliability analyses and in 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.

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. The tests will be planned so that

mathematical confidence levels may be attached to the results and the maximum amount of information will be obtained. Every scientific investigator would like to conduct experimental tests that are informationally and economically optimum.

a. Reliability Demonstration

It shall be necessary to demonstrate a reliability of 0.92 with 90% confidence for an autonomous gas generator unit. The autonomous unit shall include concomitant controls and switching devices. Reliability demonstration tests will be made with qualified units or hardware which reflects the final design. The demonstration tests shall consist of a minimum of 28 one-hour tests at the duty cycle specified in Appendix A. If the equipment is operated for these 28 tests, without a failure, the gas generator unit will have a demonstrated reliability of 0.92 with 90% confidence level. If one failure occurs, the number of tests must be increased to 44.

b. Control System

The control system consists of the controls and instrumentation and the gas generator controls mounted in the test cell building and in the test operations console. Practical prediction of the overall reliability of the control system, necessitates the gathering of experimental component reliability data, followed by testing of subsystems for use in a thorough statistical analysis. After the control system design is fully determined, its complexity will require additional testing to determine system reliability. Since transportation could be a severe environmental condition for this equipment, full scale testing should be performed subsequent to exposure to this environment.

The control system circuitry, including switching element, will be sufficiently complex to warrant extensive developmental testing to allow "burn-in" of subsystems and to determine the maintenance requirement of each of the subsystems. This testing should consist principally of cycling and circuit loading. The data obtained will be used in prediction of system reliability from the subsystem level. Because of the brief program duration,

reliability demonstration tests will not be scheduled for subsystems unless there is a question relating to design development and reliability goals which indicates a need for additional testing before construction of the complete system.

The control system design reliability goal for all functions required in an on-site-test, i.e., the control sequence for "open-loop" system, is 0.99 with 90% confidence. This reliability can be demonstrated by using a "black box" (with back-up manual control at such specified points in the control sequence) to cycle the control system through the test control sequence, testing all decision and switching circuits on each cycle.

The number of tests required to demonstrate 200 hours of operation at the specified duty cycle at a 0.90 reliability with a 90% confidence level would require in excess of 4000 hours of operation without failure. This amount of testing is considered unreasonable economically and, unless more than three units are available, impossible in a one-year program. In addition, since gas generators can be replaced at the test site between tests, and since the true physical capability of the design will necessarily influence the frequency of replacements at the test site, there appears to be no need for such a stringent requirement. Also, it is apparent that until the physical capabilities of the gas generators are demonstrated in the one hour duty cycle, there is no need for proofing at a longer duration. It is much more economical to demonstrate reliability for shorter periods of time with a very high probability of succeeding in the demonstration, than to select a longer period and run the risk of failures and extended testing. The number of one-hour cycles these generators are capable of completing without failure should be a criterion for the number of generators to be built.

5. Reliability Surveillance

a. Reliability Monitoring

The reliability monitoring functions will require periodic adjustments in reliability apportionments among the subsystems and components of the secondary gas generator system during the design and manufacturing phases. The 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 surveillance at a series of predetermined monitoring points during the program which are coincidental with major development and production phases and the reliability growth cycle of the secondary gas.

6. Failure Evaluation

Proper evaluation and analysis of component failures during the development production of the secondary gas generator 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 evaluation program. All component failures recorded during the secondary gas generator 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 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.

7. Quality Assurance

Throughout the gas generator program an effective quality assurance program, beginning with receiving inspection and continuing through delivery of the complete system, will be conducted. To assure compliance with written procedures for inspection and testing, specific audits of these processes will be made periodically by quality assurance supervision and by audit personnel. In these audits, an investigation of the availability of current drawings and engineering documents to inspection and test personnel will be made and the adequacy of the associated quality assurance instructions and documentation will be evaluated. Periodic product audits shall be made by reinspecting accepted parts and assemblies under the surveillance of a quality assurance auditor.

Drawings and specifications for purchased parts shall receive the same treatment as design standards used for fabrication in the plant; this includes the establishment of reliability requirements, and the testing of the suppliers product for compliance with the reliability requirements stated in the purchase contract.

All incoming materials, materials in process, or final products which do not meet quality standards will be submitted to a material review board for disposition.

IV. PROGRAM DISCUSSION

A. INTRODUCTION

1. Purpose

The purpose of this program is to deliver one or more secondary gas generator systems to the REON Nevada Test Site (NTS). A choice has not yet been made as to the number of systems desired by REON. This makes no difference in the program description, but does in the cost estimate. For the cost estimate, three alternates are presented. One gas generator is composed of three gas generator units. One gas generator unit includes the gas generator assembly mounted on its skid with the associated valves, solenoids, inlet lines, instrumentation, and its rack-mounted control system. The performance requirements and design details are discussed in the Technical Discussion, Section III, of this report.

A further purpose of this program is to deliver a secondary gas generator system to NTS in time for it to be installed and tested before the NERVA engine tests using this equipment are scheduled to begin.

2. Scope

In order to deliver this secondary gas generator system on time, it was originally requested that a 12-month crash program be proposed if such a schedule were possible. If this were not possible, then the minimum time required should be specified - up to a maximum of 16 months.

As a normal development program, this secondary gas generator program should take 24 to 27 months to complete. On the basis of a conventional crash program, this time might be reduced to about 18 months. By collapsing the schedule to the extreme, it was found possible to compress the schedule to the requested 12 months. An example of the means by which this was accomplished is the scheduling of the first full-scale generator design concurrently with the preliminary investigations on which its design would normally be based.

The program schedule presented in this report (Figure 13) is therefore based on delivery of the finished hardware to NTS at the end of the twelfth month. It should be kept in mind, however, that there is no margin in this schedule for any unnecessary delays such as vendor delays in delivery of equipment, delays in receiving information or approvals from REON, cuts or delays in funding, or work stoppages.

The overall scope of this program is to develop, design, fabricate, test, and deliver a secondary gas generator system according to the System Development Specification AGC-14098 presented in Appendix A. To accomplish this purpose, subscale firings, component and material evaluations, and other preliminary investigations will be performed to obtain detailed information for use in full-scale designs. Three consecutive, but partially overlapping, gas generator designs will be made, fabricated, and tested. The third and final design will be used for the reliability demonstration testing. The deliverable hardware will be fabricated from this same design. A more complete description of the program is presented in the program plan that follows.

B. PROGRAM PLAN

1. Program Description

This program is divided into two major phases. The first phase includes a subscale development firing program, component and feed system evaluation and testing, component and control system evaluation and testing, and a materials and fabricability investigation. This phase will be referred to as the Azusa Development Program.

The second phase includes the design, fabrication, development testing, and reliability testing of the full-scale equipment and the delivery of the finished hardware. This phase will be referred to as the Full-Scale Program.

a. Azusa Development Program

(1) Subscale Firing

The subscale firing program will consist mainly of approximately 25 firings in subscale combustion chambers. Full-scale igniters will be evaluated for ignition characteristics and adequate thermal protection. A full-scale pilot pentad element will be evaluated for ignition and steady-state burning characteristics. For backup purposes, a full-scale pilot coaxial element will be similarly evaluated. A subscale concentric-ring element will then be used to evaluate the characteristics of this element and its effect on the centrally-located pentad. In particular, the effect of sudden flow and ignition of the longer element on the pilot flame will be examined. The effect on the pentad element of steady-state burning of the concentric-ring element and of the rapid loss of pressure when the concentric-ring is turned off, will also be examined.

In addition to the testing described above, the following experimentation will also be performed, perhaps as a part of the same tests. The response time of the insulated thermocouples, to be used for malfunction detection, will be evaluated and calibrated. Evaluation of proposed insulation materials will be made for both hot and cold applications. The operation of and the effect on combustion of an automatic manifold purge system, similar to that proposed for the full-scale system, will be evaluated. A malfunction detection and control system will also be evaluated.

(2) Feed System

There are no facets of the propellant and purge feed system development program that will require exotic design or radical departures from existing theory. Most of the valves, fittings, and test equipment are off-the-shelf-type items, necessitating only their selection from appropriate catalogs and the contacting of suppliers.

In addition to sizing the feed lines according to permissible pressure drop and the inertial effect of rapid acceleration to full flow, an analysis of the insulation requirement for the feed lines will

be made. The degree of heat leak into the lines, particularly at the joints, and the amount of boil-off of liquid propellant during chill-down must be determined. The feasibility of utilizing boil-off gases in the start-up and/or idle flow phase of gas generator operation will be considered. An automatic system must be devised during the development program to handle the boil-off gases.

The testing of components will be undertaken at both Azusa and Sacramento with the latter tests being of greater scope. Azusa tests will primarily be concerned with checkout testing to verify the performance characteristics of the individual components. In addition, the feed system will be hydraulic flow tested over the range of operating conditions to determine, and eliminate if necessary, any excessive pressure drops, cavitation sections, and "water hammer" characteristics. The feed lines will be filled with liquid nitrogen to establish the effects of cryogenic temperatures on material embrittlement, weldment distortion, and seal leakage. The Sacramento tests will include the determination of the rate of boil-off of propellant liquids, the optimum point in the feed lines from which to remove boil-off gases, the actual pressure drops in the respective feed lines, and the satisfactory performance of the feed system as a whole.

Equipment required for the above tests must be determined, specified, and procured. It will include propellant supply and receiving tanks, pressure gages, timers, temperature measuring devices, pressure source and regulators, and flow-rate measuring devices.

(3) Control System

The control system electrical design is straightforward. All of the required techniques are well known and represent no challenge to the state-of-the-art.

Development effort will be required in the areas of investigating modes of failure and modifying the basic design to increase reliability. Additionally, methods of increasing flexibility will be analyzed to enhance modifying the controller for changed requirements.

Special test schedules will be implemented to assure reliability of any components for which inadequate life test data exists. The assembled control system will be utilized in hydraulic flow tests in conjunction with the feed system. Initial start transient, shutdown transient, and malfunction detection sequencing conditions will be established in these flow tests.

(4) Materials

Various investigations and tests, as well as coordination efforts, will be required in the way of Materials Support over the program cycle. It is anticipated that the maximum effort will be required in the initial four months of the program. Areas to be investigated include the development of suitable weld procedures and standards for heavy-wall Inconel sections, including the adequacy of presently-available weld wire and methods, the development of sealing techniques to effectively retain cryogenics and hot gases at the injector faces, the investigation of castings for possible use of a regeneratively-cooled injector, and a series of low-temperature tensile tests to determine the adequacy of Type 310 Stainless Steel for service at -423°F.

b. Full-Scale Program

(1) Design and Fabrication - Azusa

The first full-scale development gas generator unit design will begin at the go-ahead. This design will take four months and will be running concurrently with the Azusa Development Program so that only a portion of the investigation results will be available for the gas generator design. However, the development models of both the feed and control systems will be used in testing this unit. Prerelease of some materials and fabrication will begin after one month. Fabrication, delivery to the Sacramento LRP Test Area, and installation on the test stand will be completed by the end of the sixth month.

Upon completion of the control system investigation and material evaluation portions of the Azusa Development Program (at the end of the fourth month), the prerelease of materials and fabrication of the second development generator will begin. Design will continue at least through the fifth month. Fabrication, delivery to the Sacramento LRP Test Area, and installation will be completed by the end of the eighth month. Most of the preliminary investigation results will therefore be available for inclusion in the design of this second generator.

The same skid used for the first development generator will also be used for the second and third development generators. Both the feed system and control system will be used for all three development generators and will be modified as necessary, or desirable, during the course of testing.

Upon completion of the preliminary investigation portion of the Azusa Development Program (at the end of the sixth month), the prerelease of materials and fabrication of the third development generator will begin. Design will continue at least through the seventh month. Fabrication, delivery to the Sacramento LRP Test Area, and installation will be completed by the end of the tenth month. All of the results from the first generator development firings and most of the results from the second will be available for consideration in the design of the third generator. Results from any trouble-shooting tests by the subscale firing program, during the seventh and eighth months, will also be available.

Release of materials for fabrication of the deliverable hardware will begin as soon as the design of the third development generator is sufficiently complete to render feasible their release. Fabrication of the deliverable hardware will be completed by the end of the eleventh month. Packaging, crating, and delivery of the finished hardware to NTS will take place during the twelfth month.

During the thirteenth month the secondary gas generator system will be installed at the Nevada Test Site. Program personnel will be furnished to supervise installation of the system and to instruct

resident REON personnel on proper operation of the system.

(2) Testing - Sacramento

After test installation in the Sacramento LRP Test Area is complete, full-scale unit testing can begin. The full-scale firing program for the development series of secondary gas generator units is divided into three phases corresponding to the three development generators.

(a) Test Installation - Sacramento

A variety of activities will be included under the heading of test installation. The normal plumbing, wiring, instrumentation, etc., will still be required to some extent. But it will also be necessary to design, fabricate, and install a hot-exhaust-gas conduit system that is dynamically equivalent to the REON hot-gas conduit. This is required in order to simulate the response-time characteristics of the gas generator-REON system. Another major item to be needed is a high-flow-rate liquid-hydrogen pump, which also must be fabricated for this full-scale program.

It was estimated by Sacramento Test Area personnel that the whole test installation could be completed in time for full-scale unit testing at the beginning of the seventh month.

(b) Short-Duration Development Testing

The first development generator will be a workhorse model. A total of twenty firings will be made at durations varying from about 1 sec to 100 sec. These tests will be used to investigate ignition and start-transient characteristics, performance, combustion stability, re-start capability, and material resistance to erosion and failure. In general, these tests will be used to confirm the applicability to full-scale operation of the results obtained from the Azusa Development Program. During this test series, modifications will be made in various parameters such as injection velocities, propellant lead times, and insulation thicknesses in order to make corrections for deficiencies or to make improvements in the performance.

In addition to testing for normal operating characteristics, it will be necessary to determine the effect of variation of the control parameters such as mixture ratio, chamber pressure, and fuel lead time.

(c) Prototype Development Testing

The second development generator will be a prototype model that will be designed to conform to all of the requirements as closely as possible. A total of twenty firings will be made at durations starting at a few seconds and eventually reaching the full one-hour duty cycle specified in the model specifications in Appendix A. The measured parameters and test conditions will be essentially the same as those in the first generator test series. Results from the testing of this second generator should be sufficient to permit a firm final design for use in the fabrication of the third development generator and the deliverable generators.

(d) Reliability Demonstration Testing

The third development generator will be the final design. After several short-duration firings to check out functionability, the Reliability Demonstration Tests will be conducted. These tests will be used to demonstrate a reliability of 0.92 for the gas generator unit with a 90% confidence level. The duty cycle required for these tests is specified in Appendix A. To demonstrate the required reliability, twenty-eight one-hour tests, with the specified duty cycle, must be conducted without a failure. If one failure occurs, the number of tests must be increased to forty-four.

c. Reliability

The reliability program will be used to assure that the required reliability levels are designed into the system, maintained in the course of fabrication, transportation, storage, and operation.

A comprehensive reliability design analysis will be performed by the program reliability engineers. This will be followed by an analysis of environments and a malfunction mode review. These will then be included in the reliability system analysis.

Design review and reliability control will be exercised to create high overall reliability during the development phase of the program. The reliability monitoring functions will require predetermined periodic adjustments in reliability apportionments among the subsystems and components of the secondary gas generator system during the design and manufacturing phases. The 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 the secondary gas generator.

An essential portion of the secondary gas generator reliability engineering program is a thorough statistical function. Statistical engineers will assist in mathematical reliability analyses and in 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.

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. The tests will be planned so that mathematical confidence levels may be attached to the results and the maximum amount of information is obtained.

2. Milestones

A series of significant points in the progress of the program have been chosen as milestones. These milestones can serve as an overall indication of accomplishment as compared to scheduled progress. The milestone chart for this crash program is presented in Figure 12.

3. Schedule

The twelve-month crash program schedule is presented in Figure 13. This figure is a graphical type presentation of the schedule for the detailed program discussion of Section IV.B.1.

4. PERT Network

a. The following is a brief glossary of commonly used PERT terms. Reference thereto may prove helpful in a study of the management network which is included in Figure 14.

(1) Network. A graphic representation utilizing events and activities to illustrate sequences, dependencies, and constraints inherent in the program.

(2) Event. An event is a status point discreet in time, and usually represents either the start or completion of an activity. An event is represented by a circle on the network.

(3) Activity. An activity represents the work required to attain the status of the succeeding event. Resources (facilities, money, manpower, etc.) are expended in activities. Activities are shown by arrow-tipped lines which interconnect events. The flow of activities is generally from left to right.

(4) Time Estimates (t_e). The symbol t_e is used to designate the estimated duration of a specific activity. It is an estimate, or a weighted average of three estimates, made by an experienced and capable member of Project Management. A time estimate is expressed in weeks and tenths of weeks.

(5) Expected Time (T_E). This is the summation of the entries, t_e , from program start to a given event as computed along the longest time path to that event.

(6) Event Dependency. The sequence of events which must be completed successfully before initiating another event. For example, if event "B" is contingent upon completion of event "A", then "B" is said to be dependent upon "A". Time may or may not be related to event dependency.

(7) Constraint. The restraint on an activity caused by an incomplete preceding activity or activities.

(8) Dummy Activity. A constraint between activities; it is not associated with any identifiable work. It is indicated by a broken line with a zero time estimate.

(9) Latest Time (T_L). T_L is the latest point in time at which a given event can occur without causing the entire program to slip.

(10) Slack Time (S). Slack time can be either positive or negative. It is the difference between the time expected (T_E) and the latest time (T_L). It is the amount of time by which an event or activity can slip without affecting the final program completion date. Negative slack appears only when an arbitrarily scheduled completion date is imposed on an event. For example, completion time for an event may be arbitrarily set at an earlier date than is shown to be logical by PERT. The difference in time then, is expressed as negative slack. Conversely, if the arbitrarily scheduled completion date is established at a later date than is shown to be feasible by PERT, the difference is expressed as positive slack.

(11) Critical Path. This is the path through the program with the least slack time or the longest sequence of activity times (t_e 's) through the network. Any event on this path that falls behind T_L , will extend the terminal date of the program on a day-for-day basis.

b. The Summary Network

A 54-event Summary Network has been prepared as shown in Figure 14. It is of the PERT time-type and therefore does not depict both a start and a completion for every activity. Many of the activities are not fully described by the events with which they are associated because the events on a summary network are restricted to project milestones. The necessity of such a restriction eliminates many events that would be included on a more comprehensive network and which would normally be used to describe these long activities more fully.

Realistic time estimates were supplied by gas generator program personnel and predicted event dates were computed. The network supports the program schedules.

c. PROGRAM MANAGEMENT

1. Program Organization

The secondary gas generator development program will be conducted under the technical cognizance of the Space Propulsion Division of the Liquid Rocket Plant. An organization plan has been developed based on a project type of control. Specialists from various departments will be assigned to the project and will report directly to the program manager during the period their services are required. This system provides the benefits of the advanced technical skills of various support departments and still allows direct control of schedules and costs. Figure 15 is the program-management organization chart of the secondary gas generator program. In order to facilitate communications, key personnel will be grouped in a separate location. This centralization of the organization will aid in obtaining decisions and result in a short, well-organized development program.

2. PERT

Program Evaluation Review Technique (PERT) was evolved, and is still being developed, as a natural result of the immense complexity of modern weapon, defense, or space systems. The complexity is evidenced by the fact that although no mass production is considered, typical space projects

receive significant contributions from major contractors operating major facilities in virtually every section of the country. With such diversification of effort, it becomes imperative that an efficient and effective management device be utilized both in the interest of economy, and to meet stringent scheduling requirements. PERT was first devised for the Polaris Project and was brought into use in 1959. Since that introduction, PERT programming techniques have been continuously under development and are now in use throughout industry.

PERT is a tool used by management to help remove guesswork from program planning and to give a firm basis for management decisions. PERT illustrates graphically the chronological courses that a complex project, and the elements of which it is composed, are mathematically most likely to follow in arriving at a stated objective. PERT shows the relationships and interdependencies of the program elements (activities and events) and further exposes probable future problem areas so that early corrective action can be taken.

A completely staffed PERT Department has been established within the Space Propulsion Division. This department is now aiding the 706 System Program, the 624A System Program, and the Apollo Service Module Program by the PERT System. The various systems applied include the NASA, Navy, and Air Force Systems.

a. PERT Department Functioning

The responsibility for PERT networks, documentation, and analysis will be assigned to the PERT Department of the Space Propulsion Division. The direct responsibility of the PERT portion of the subject program will be assigned by the PERT Department Manager to a PERT Coordinator who will devote full time to the conduct of this specific project. A formally trained and active PERT staff of approximately 20 coordinators, analysts, and technicians are assigned to the department.

b. Implementation and Operational Phases

The implementation phase of PERT will consist of the establishment of the necessary networks, the completion of the glossary or dictionary report, the submittal of material to REON for approval, and the incorporation of requested changes resulting from the review of the material by REON.

The operational phase will consist of monitoring the developing program by means of the foregoing PERT data at the direction of Program Management. Reporting on the summary network will be done on a routine biweekly cycle. See Figure 14 for the preliminary PERT network chart.

3. Documentation Requirements

The proposed reporting requirements are discussed below. These reports will be submitted during the tenure of the contract.

a. Weekly Reports

The brief weekly status reports will be in memo format and will cover only that work which was accomplished during the report period.

b. Biweekly Reports

A biweekly PERT report will be submitted which will indicate any changes in the critical paths, danger areas which require attention, and potential changes to the final program completion date.

c. Monthly Progress Reports

Informal monthly progress reports will be submitted within ten (10) working days following the end of the report period. When a monthly progress report and a quarterly progress report are due at the same time, only the quarterly will be submitted, thereby avoiding duplication of effort.

d. Quarterly Progress Reports

A quarterly progress report shall be submitted within twenty (20) working days following the end of the report period. These progress reports shall describe in detail all work accomplished during the report period, including design drawings, test data, summarization, and recommendations.

e. Final Technical Report

A preliminary draft of the final report shall be submitted for approval to the procuring agency within thirty (30) working days following the completion of the work. The final report, in distribution form, will be submitted to the procuring agency twenty (20) working days after receipt by the contractor of the approved preliminary draft. This report shall summarize results of the entire program, including any recommendations and conclusions.

D. HARDWARE

1. Non-Deliverable

Non-deliverable hardware will comprise all materials, purchased parts, and fabricated parts which will be used in the Azusa test program (subscale) and the Sacramento full-scale test program. It will include valves, piping, controls, generators, etc. This material and hardware will not necessarily be according to Military Specifications, but will be of a quality and functionability such that the results obtained from tests conducted using it will not conflict with any results that might have been derived from Mil-Spec materials. The reliability demonstration tests will be conducted using equipment which corresponds to the Model Specification.

2. Deliverable

Deliverable hardware will comprise the one or two (depending on the scope of the program) complete full-scale gas generator systems, including valves, controls, gas generators, and skids, plus spare parts as determined to be necessary during the developmental and testing phases of the program. All deliverable materials and hardware will conform to the appropriate specifications as required by the Model Specification presented in Appendix A.

V. ROM COST ESTIMATE

A. INTRODUCTION

A rough order of magnitude (ROM) cost estimate was requested by REON for the program described in Section IV. To assist in a consideration of various means of financing, three alternates were requested. These three cases are defined and described below. Details of the ROM cost estimates are presented in Tables 1 through 6.

B. BASIS OF ESTIMATION

It should be emphasized that the costs included in this ROM cost estimate are preliminary. These costs were compiled by experienced design and manufacturing engineers and are based on their best judgement but are not backed up by detailed cost analyses. In several cases vendors were informally contacted for supplemental cost backup for outside production (OP) parts. This ROM cost estimate has been prepared in sufficient depth to preclude any order of magnitude errors, subject to the assumptions listed below.

In planning the program schedule and estimating the costs a number of assumptions were made which are not otherwise stated. It should be kept in mind, however, that if the program is delayed, the total cost will increase. The more important of these assumptions were:

1. Notification of intent will be given in sufficient time to obtain personnel (4 to 6 weeks before go-ahead).
2. Project will have adequate priority and authority to obtain people and technical services.
3. There will be no cuts or delays in funding.
4. There will be no delays for security reasons - i.e., to get secret clearances for personnel, or because of new stringent security requirements.

5. No major design or requirement changes will be specified by REON.
6. There will be no delays in obtaining design approval or drawing sign-off.
7. There will be no major unforeseen problems in meeting reliability requirements.
8. There will be no delays due to transportation or delivery difficulties.
9. Raw materials will be available on the West Coast.
10. There will be no delays in obtaining Azusa Proving Grounds personnel and facilities.
11. Sacramento personnel and facilities will be available as scheduled.
12. There will be no catastrophic failures - i.e., only minor damage subject to repair by reworking equipment, no excessive damage to test facilities.
13. There will be no work stoppage.
14. No provision has been included in the costs for extended work week although it must be realized that extended work week will be required of some personnel, especially during the Sacramento testing phase.

C. CASE I

Case I is based on delivery of one complete secondary gas generator system to the Nevada Test Site following the development program described in Section IV. The ROM estimate of the cost for this alternate is \$4,017,256, including direct labor overhead (DLO) and general and administrative overhead (G&A). Details of this estimate are presented in Tables 1, 2, 3 and 5.

One gas generator system is made of three gas generator units. One gas generator unit includes the gas generator assembly mounted on a skid with the associated valves, piping, instrumentation, etc., and the rack mounted controls. An allowance of 20% is included for control system spare parts.

Note that the equipment described above is the deliverable hardware and should not be confused with the development hardware. For full scale development testing, three gas generator assemblies will be fabricated but only one feed system, one control system, and one skid will be utilized. An allowance of 30% was made for rework of each of the three development gas generator assemblies, the skid, and the feed system. An allowance of 50% was made for modifications to the development control system and 20% for spare parts.

In addition, costs are included for the design, fabrication, and testing performed in the Azusa Development Program. An allowance of 30% is included for rework of the subscale models.

D. CASE II

Case II is based on delivery of two complete secondary gas generator systems (i.e., 6 gas generator units) to the Nevada Test Site following the development program described in Section IV. The ROM estimate of the cost for this alternate is \$4,372,886, including DLO and G&A. Details of this estimate are presented in Tables 1, 2, 4, and 5. Except for the extra deliverable gas generator system, this case is identical to Case I.

E. CASE III

Case III is based on fabrication and delivery to the Nevada Test Site of one additional secondary gas generator system (i.e., 3 gas generator units) within a reasonable time after completion of either Case I or Case II. The ROM estimate of the cost for this alternate is \$689,736, including DLO and G&A. Details of this estimate are presented in Table 6.

F. COST SUMMARY AND COMPARISON

	<u>CASE I</u>	<u>CASE II</u>	<u>CASE III</u>
Engineering	\$ 979,884	\$ 979,884	\$ 62,760
Design	254,380	254,380	---
Fabrication	1,364,626	1,720,256	626,976
Test	1,418,366	1,418,366	---
	<hr/>	<hr/>	<hr/>
TOTAL	\$4,017,256	\$4,372,886	\$ 689,736

It should be noted that a program involving the combination of Case I and Case III results in a total cost which is greater than Case II, although the amount of hardware delivered is the same. The difference in cost would approximately pay for one additional gas generator system, if it were fabricated at the same time as the other deliverable hardware during the development program.

Details of these ROM cost estimates are presented in Tables I through 6.

G. MANPOWER

Estimates of the manpower requirements have been made for the three cases previously described. These are included in the details of the ROM cost estimates presented in Tables 1 through 6. The manpower information is summarized in bar-chart form with separate charts for salaried and hourly manpower requirements. Each chart shows the breakdown into engineering, design, fabrication, and testing. All administrative and related personnel are included under engineering.

The bar-chart manpower values reflect the total number of hours to be expended, not necessarily the actual number of persons working on the project. For some items the cost estimate was supplied as a total dollar cost without a manpower estimate. This was true of the modification of the

Sacramento test stand, the LH_2 pump, the regular installation at Sacramento, and the technical publication costs. For Case III, the liaison for the gas generator phase and the fabrication of the skid were also available only as a dollar estimate.

The manpower bar-charts for Case I are presented in Figure 17 and 18; for Case II in Figure 19 and 20; and for Case III in Figures 21 and 22.

CASE I AND II

SHEET 1 OF 4-

TABLE 1 ENGINEERING COST BREAKDOWN
PRELIMINARY PROGRAM BUDGET

PROPOSAL NO. _____

DATE _____

SALARY HRS.	HOURLY HRS.	MAT'L \$
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10-014-002 1

		MONTH/YEAR		1	2	3	4	5	6	7	8	9							
SALARY HOURS	SALARY DOLLARS	HOURLY HOURS	HOURLY DOLLARS										TOTAL HRS						
													TOTAL \$						
HOURLY HOURS	HOURLY DOLLARS	MAT'L \$	TOTAL \$										TOTAL HRS						
													TOTAL \$						
MAT'L \$		TOTAL \$										TOTAL MATERIALS							
TOTAL \$		TOTAL \$											TOTAL DOLLARS						
CUMULATIVE TOTAL		TOTAL \$											(Labor and Mat'l)						
				1	2	3	4	5	6	7	8	9	TOTALS						
ITEM	DESCRIPTION	DEPT	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	SAL HRS	HRLY HRS	MAT \$
ORGANIZATION PLAN & SUPERVISION																			
	PROGRAM MANAGER	SAL.	173		173		173		173		173		173		173				
	ASSISTANT PROGRAM MGR.	SAL.	173		173		173		173		173		173		173				
	ENGINEERING ADMINISTRATION	SAL.	519		346		346		346		346		346		346				
	ENGINEERING ADMINISTRATION	HLV	173		173		173		173		173		173		173				
	SECRETARY & CLERICAL	HLV	346		346		346		346		346		346		346				
	ADMIN. & BUDGET CONTROL	SAL.	260		260		260		260		260		260		260				
	ADMIN. & BUDGET CONTROL	HLV	173		173		173		173		173		173		173				
	REPORT GROUP	SAL	346		346		346		346		346		346		346				
	REPORT GROUP	HLV	173		173		173		173		173		173		173				
AZUSA DEVELOPMENT PROGRAM																			
	PG COORDINATOR - AZUSA	SAL.			173		173		173		173		173						
	SYSTEMS ANALYSIS	SAL.	48		48		48		48		48		48		48				
	SYSTEMS ANALYSIS	HLV.	48		48		48		48		48		48		48				
	MISC. SPECIALISTS & SERV. GROUP	SAL.	100		100		100		100		100		100		100				
	MISC. SPECIALISTS & SERV. GROUP	HLV.	100		100		100		100		100		100		100				
	THERMAL ANALYSIS - 704 COMPUTER	SAL.				180		100	180	100	180								
	THERMAL ANALYSIS - 704 COMPUTER	HLV.					100	20	100	20									
	SUB-SCALE FIRING PROGRAM	SAL.	173		260		260		260		260		260		260		173		173
	FEED SYSTEM EVALUATION	SAL.			173		173		173		173								
	MATERIALS EVALUATION	SAL.	173		173		173		173		173								
	MATERIALS EVALUATION	HLV	191		191		191		191		191		173		173				

TABLE 1 ENGINEERING COST BREAKDOWN

PRELIMINARY PROGRAM BUDGET

PROPOSAL NO. _____

DATE _____

MONTH/YEAR	10	11	12	13							TOTAL HRS	
SALARY HOURS	/	/	/	/	/	/	/	/	/	/	/	/
SALARY DOLLARS	/	/	/	/	/	/	/	/	/	/	/	/
HOURLY HOURS	/	/	/	/	/	/	/	/	/	/	/	/
HOURLY DOLLARS	/	/	/	/	/	/	/	/	/	/	/	/
MAT'L \$											TOTAL MATERIALS	
TOTAL \$											TOTAL DOLLARS	
CUMULATIVE TOTAL											(Labor and Mat'l)	

SALARY HRS	HOURLY HRS	MAT'L \$
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10-014-002-1

ITEM	DESCRIPTION	DEPT	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	SAL HRS	HRLY HRS	MAT \$
	ORGANIZATION, PLANNING & SUPERVISION																		
	PROGRAM MANAGER	SAL	173		173		173		173								2249		
	ASSISTANT PROGRAM MANAGER	SAL	173		173		173		173								2249		
	ENGINEERING ADMINISTRATION	SAL	346		346		346		173								4498		
	" "	HLY	173		173		173		173									2249	
	SECRETARY & CLERICAL	HLY	346		346		346		346									4498	
	ADMINISTRATION & BUDGET CONTROL	SAL	260		260		260		260								3380		
	" " " "	HLY	173		173		173		173									2249	
	REPORT GROUP	SAL	346		346		346		346								4498		
	" "	HLY	173		173		173		173									2249	
	AZUSA DEVELOPMENT PROGRAM																		
	P.G. COORDINATOR - AZUSA																1038		
	SYSTEM ANALYSIS																384	384	
	MISC SPECIALISTS & SERVICE GROUP	SAL	100		100		100		100								1300		
	" " " " "	HLY	100		100		100		100									1300	
	THERMAL ANALYSIS- 704 COMPUTER																540	40	\$ 200
	SUBSCALE FIRING PROGRAM																2079		
	FEED SYSTEM EVALUATION																865		
	MATERIAL EVALUATION																1038	1472	

CASE I AND II
TABLE 1 ENGINEERING COST BREAKDOWN
PRELIMINARY PROGRAM BUDGET

PROPOSAL NO. _____

DATE _____

SALARY HRS	HOURLY HRS	MAT'L \$
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10 014-002 1

MONTH/YEAR	1	2	3	4	5	6	7	8	9	
SALARY HOURS	4494	5230	6156	6076	5473	5446	5100	4034	3564	TOTAL HRS
SALARY DOLLARS	\$53,928	\$62,760	\$73,872	\$72,912	\$65,676	\$65,352	\$61,200	\$48,408	\$42,768	TOTAL \$
HOURLY HOURS	2519	2559	2632	2479	2359	2512	2494	2321	2023	TOTAL HRS
HOURLY DOLLARS	\$20,152	\$20,472	\$21,056	\$19,832	\$18,872	\$20,096	\$19,952	\$18,568	\$16,184	TOTAL \$
MAT'L \$	2100	1300	300	1300	150	9918	8868	8868	8868	TOTAL MATERIALS
TOTAL \$	\$76,180	\$84,532	\$95,228	\$94,044	\$84,698	\$95,366	\$90,020	\$75,844	\$67,820	TOTAL DOLLARS (Labor and Mat'l)
CUMULATIVE TOTAL	\$76,180	\$160,712	\$255,940	\$349,984	\$434,682	\$530,048	\$620,068	\$695,912	\$763,732	

ITEM	DESCRIPTION	DEPT	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	SAL HRS	HRLY HRS	MAT \$
	FULL SCALE PROGRAM																				
1	GAS GENERATOR	SAL	346		346		346		346		346		346		432		432				
2	SKID	SAL					173		173		173		173		173						
3	FEED SYSTEM	SAL	346		432		432		432		605		605		432		432		260		
4	CONTROL SYSTEM	SAL	86		86		86		173		173		173		173						
	" "	HLY	173		173		173		173		173		173		173						
5	THERMAL ANALYSIS	SAL	550	\$100	940	\$300	1080	\$300	1000	\$300	310	\$150	290	\$50	290		90		90		
	" "	HLY	200		240		140		140		20		20		20		20		20		
6	PERT	SAL	173		173		173		173		173		173		173		173		173		
	" "	HLY	519		519		519		346		346		346		346		346		346		
7	STRESS ANALYSIS - 704 COMPUTER	SAL	519		519	\$1000	519		519	\$1000	346		346	\$1000	519		173		173		
8	WEIGHTS ANALYSIS	SAL					173		173		173		173		173		173				
9	QUALITY CONTROL	SAL					173		173		173		173		173		173		173		
	" "	HLY					173		173		173		173		173		173		173		
10	FULL SCALE FIRING PROGRAM	SAL									173		173		173		173		173		
	" " " "	HLY									173		173		173		173		173		
11	PG. COORDINATION-SACTO	SAL	86		86		173		173		173		173		173		173		173		
12	SYSTEM ANALYSIS	SAL	77		77		77		77		77		77		77		77				
	" "	HLY	77		77		77		77		77		77		77		77				
13	TECHNICAL PUB	SAL											\$8868		\$8868		\$8868		\$8868		
	" "	HLY																			
14	MISC SPECIALISTS & SERVICE GROUP	SAL	346	\$2000	346		346		346		346		346		346		346		346		
	" " " " "	HLY	346		346		346		346		346		346		346		346		346		
	TOTAL ENGINEERING																				

DATE _____

10-014-002 1

Table 1 of 4

CASE I AND II

TABLE 2 DESIGN COST BREAKDOWN

PRELIMINARY PROGRAM BUDGET

DATE _____

MONTH/YEAR	1	2	3	4	5	6	7	8	9		
SALARY HOURS	1909	2070	2466	1951	1373	1597	1022	537	558	TOTAL HRS	
SALARY DOLLARS	22,908	24,840	29,592	23,412	16,476	19,164	12,264	6,424	6,696	TOTAL \$	
HOURLY HOURS	1101	1361	1707	1578	1210	1383	1015	209	209	TOTAL HRS	
HOURLY DOLLARS	8808	10,888	13,656	12,624	9680	11,064	8120	1,672	1,672	TOTAL \$	
MAT'L \$										TOTAL MATERIALS	
TOTAL \$	31,716	35,728	43,248	36,036	26,156	30,228	20,384	8116	8,368	TOTAL DOLLARS	
CUMULATIVE TOTAL	31,716	67,444	110,692	146,728	172,884	203,112	223,496	231,612	239,980	(Labor and Mat'l)	

10-014 002 1

[illegible]

TABLE 2 DESIGN COST BREAKDOWN
PRELIMINARY PROGRAM BUDGET

DATE _____

SALARY HRS	HOURLY HRS	MAT L \$
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[illegible]

CASE I
TABLE 3 FABRICATION COST BREAKDOWN
PRELIMINARY PROGRAM BUDGET

PROPOSAL NO. _____

DATE _____

SALARY HRS	HOURLY HRS	MAT'L \$
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10-014-0021

MONTH/YEAR	1	2	3	4	5	6	7	8	9	
SALARY HOURS		56	240	240	240	240	260	240	176	TOTAL HRS
SALARY DOLLARS		672	2880	2880	2880	2880	3120	2880	2112	TOTAL \$
HOURLY HOURS	173	202	940	940	940	940	964	940	924	TOTAL HRS
HOURLY DOLLARS	1384	1616	7520	7520	7520	7520	7712	7520	7392	TOTAL \$
MAT'L \$	21,927	35,154	132,787	132,787	131,787	119,560	119,160	220,870	132,668	TOTAL MATERIALS
TOTAL \$	23,311	57,442	143,187	143,187	142,187	129,960	129,992	231,270	142,172	TOTAL DOLLARS (Labor and Mat'l)
CUMULATIVE TOTAL	23,311	60,753	203,940	347,127	489,314	619,274	749,266	980,536	1,122,708	

ITEM	DESCRIPTION	DEPT	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	TOTALS	SAL HRS	HRLY HRS	MAT \$
	AZUSA DEVELOPMENT PROGRAM																					
	SUBSCALE FIRING PROGRAM	SAL			43	\$10,175	43	\$10,175	43	\$10,175	43	\$10,175	43		43		43					
	"	HLY			22		22		22		22		22		22		22					
	REWORKS (30%)	SAL			13	\$3,052	13	\$3,052	13	\$3,052	13	\$3,052	13		13		13					
	"	HLY			7		7		7		7		7		7		7					
	FULL SCALE PROGRAM																					
	FEED SYSTEM - (2 SYSTEM)	HLY	173	\$21,927	173	\$21,927	173	\$21,927	173	\$21,927	173	\$21,927	173	\$21,927	173	\$21,927	173	\$21,927				
	CONTROL SYSTEM - (4 UNITS)	SAL			60	\$6,927	60	\$6,927	60	\$6,927	60	\$6,927	60	\$6,927	60	\$6,927	60	\$6,927				
	"	HLY					545		545		545		545		545		545					
	SPARE PARTS (20% CONTROL SYSTEM)							\$1,038		\$1,038		\$1,038		\$1,038		\$1,038		\$1,038				
	MODIFICATION (50% CONTROL SYSTEM)	SAL			10	\$866	10	\$866	10	\$866	10	\$866	10	\$866	10	\$866	10	\$866				
	"	HLY					136		136		136		136		136		136					
	GAS GENERATOR																					
	FAB OF 1 SYSTEM (SACTO)	SAL			86	\$7,540	86	\$7,540	86	\$7,540	86	\$7,540	86	\$7,540	86	\$7,540	86	\$7,540				
	"	HLY					43		43		43		43		43		43					
	REWORKS	SAL			28	\$20,262	28	\$20,262	28	\$20,262	28	\$20,262	28	\$20,262	28	\$20,262	28	\$20,262				
	"	HLY					14		14		14		14		14		14					
	FAB OF 1 SYSTEM NTS																\$101,310					
	DELIVERABLE	SAL																	86			
	"	HLY																	46			
	SKID						\$1,000		\$1,000				\$1,000				\$1,000					
	DELIVERY TO SACTO	SAL													20	\$600			20	\$600		
	"	HLY													24				24			
	DELIVERY TO NTS																					

TABLE 3

FABRICATION C
PRELIMINARY PROGRAM BUDGET

DATE _____

SALARY HRS	HOURLY HRS	MAT'L \$
---------------	---------------	-------------

10

TOTALS

CASE II

TABLE 1 FABRICATION COST BREAKDOWN
PRELIMINARY PROGRAM BUDGET

PROPOSAL NO. _____

DATE _____

SALARY HRS	HOURLY HRS	MAT'L \$
---------------	---------------	-------------

10 014 002 1

MONTH/YEAR	1	2	3	4	5	6	7	8	9	
SALARY HOURS		56	463	463	463	463	483	463	399	TOTAL HRS
SALARY DOLLARS		672	5556	5556	5556	5556	5796	5556	4788	TOTAL \$
HOURLY HOURS	173	202	1208	1208	1208	1208	1232	1208	1192	TOTAL HRS
HOURLY DOLLARS	1384	1616	9664	9664	9664	9664	9776	9664	9456	TOTAL \$
MAT'L \$	31,240	44,467	133,354	133,354	133,354	120,127	120,727	285,117	212,392	TOTAL MATERIALS
TOTAL \$	32,624	46,355	148,574	148,574	148,574	135,347	136,299	300,337	226,636	TOTAL DOLLARS (Labor and Mat'l)
CUMULATIVE TOTAL	32,624	79,379	227,953	376,527	525,101	660,448	796,747	1,097,084	1,323,720	

ITEM	DESCRIPTION	DEPT	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	TOTALS	SAL HRS	HRLY HRS	MAT \$
	AZUSA DEVELOPMENT PROGRAM																					
	SUB SCALE FIRING PROGRAM	SAL.			43	10,175	43	10,175	43	10,175	43	10,175	43		43							
	SUB SCALE FIRING PROGRAM	HLV.			22		22		22		22		22		22							
	REWORKS	SAL.			13	3052	13	3052	13	3052	13	3052	13		13							
	REWORKS	HLV.			7		7		7		7		7		7							
	FULL SCALE PROGRAM																					
	CONTROL SYSTEM SHOP LIAISON	SAL.			173		173		173		173		173		173							
	FEED SYSTEM (3 SYSTEM)	HLV.	173	31,240	173	31,240	173	31,240	173	31,240	173	31,240	173	31,240	173	31,240	173	31,240				
	CONTROL SYSTEM (7 UNITS)	SAL.			100	10,837	100	10,837	100	10,837	100	10,837	100	10,837	100	10,837	100	10,837				
	CONTROL SYSTEM (7 UNITS)	HLV.			878		878		878		878		878		878		878					
	SPARE PARTS 20 %					2167		2167		2167		2167		2167		2167		2167				
	MOD. CONTROL SYSTEM 50%	SAL.			20	1548	20	1548	20	1548	20	1548	20	1548	20	1548	20	1548				
	MOD. CONTROL SYSTEM 50%	HLV.			71		71		71		71		71		71		71					
	GAS GENERATOR																					
	FAB. OF 1-SACTO.	SAL.			86	55,000	86	55,000	86	55,000	86	55,000	86	55,000	86	55,000	86	55,000				
	FAB. OF 1-SACTO.	HLV.			43		43		43		43		43		43		43					
	REWORKS	SAL.			28	18,335	28	18,335	28	18,335	28	18,335	28	18,335	28	18,335	28	18,335				
	REWORKS	HLV.			14		14		14		14		14		14		14					
	FAB. OF 2 DELIVERABLE															165,000		165,000				
	DELIVERABLE	SAL.															86					
	DELIVERABLE	HLV.															46					
	SKID.					1000		1000		1000		1000		1000		1000		1000				
	DELIVERY TO SACTO.	SAL.												20	600		20	600				
	DELIVERY TO SACTO.	HLV.												24			24					

CASE I AND II
TABLE 5. TESTING COST BREAKDOWN

PRELIMINARY PROGRAM BUDGET

PROPOSAL NO. _____

DATE _____

SALARY HRS	HOURLY HRS	MAT'L \$
---------------	---------------	-------------

10-014-002 1

MONTH/YEAR	1	2	3	4	5	6	7	8	9	
SALARY HOURS	778	1383	2297	2547	1855	1855	4094	4094	2671	TOTAL HRS
SALARY DOLLARS	9,336	16,596	27,584	30,564	22,260	22,260	49,128	49,128	32,052	TOTAL \$
HOURLY HOURS	259	259	559	509	336	336	12,096	12,096	11,846	TOTAL HRS
HOURLY DOLLARS	2,072	2,072	4,472	4,072	2,688	2,688	96,768	96,768	94,768	TOTAL \$
MAT'L \$	11,762	63,686	88,348	65,198	62,312	62,312	21,128	21,128	19,194	TOTAL MATERIALS
TOTAL \$	23,170	82,354	120,384	99,834	87,260	87,260	167,024	167,024	146,014	TOTAL DOLLARS (Labor and Mat'l)
CUMULATIVE TOTAL	23,170	105,524	225,908	325,742	413,002	500,262	667,286	834,310	980,324	

ITEM	DESCRIPTION	DEPT	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	TOTALS	SAL HRS	HRLY HRS	MAT \$
	AZUSA DEVELOPMENT PROGRAM																							
	SUB SCALE FIRING PROGRAM																							
	TEST INSTALLATION (PG)	SAL.				1000	5500																	
	TEST INSTALLATION (PG)	HLV.				300																		
	TESTING (PG)	SAL.						1250	550	1250	550	1250	550	1250	550	1250	550							
	TESTING (PG)	HLV.						250		250		250		250		250								
	RENTALS						5000																	
	S.T.E.						13200																	
	FEED SYSTEM EVALUATION				346	1924	519	2886	519	2886														
	CONTROL SYSTEM INVESTIGATION	SAL.	86		86		86		86															
	CONTROL SYSTEM INVESTIGATION	HLV.	173		173		173		173															
	FULL SCALE PROGRAM																							
	TEST INSTALLATION																							
	MOD. OF TEST STAND					50,000		50,000		50,000		50,000		50,000										
	LH ₂ PUMP			10,000		10,000		10,000		10,000														
	REGULAR INSTALLATION											10,000												
	TESTING (GFP)																							
	COST OF 40 DEVELOPMENT TEST	SAL.												1066	8960	1066	8960	1066	8960					
	COST OF 40 DEVELOPMENT TEST	HLV.												5600		5600		5600						
	COST OF 44 RELIABILITY TEST	SAL.												1173	9856	1173	9856	1173	9856					
	COST OF 44 RELIABILITY TEST	HLV.												6160		6160		6160						

CASE III

PRELIMINARY PROGRAM BUDGET

PROPOSAL NO. _____

TABLE 6 ONE EXTRA SYSTEM COST BREAKDOWN

DATE _____

SALARY HRS	HOURLY HRS	MAT'L \$
---------------	---------------	-------------

10-014-0021

MONTH/YEAR	1	2	3	4	5	6						
SALARY HOURS	803	803	803	803	803	903						
SALARY DOLLARS	9636	9636	9636	9636	9636	10,836						
HOURLY HOURS	1173	1173	1173	1173	1173	433						
HOURLY DOLLARS	9384	9384	9384	9384	9384	3464						
MAT'L \$	144,084	144,084	144,084	144,084	19,020	4000						
TOTAL \$	163,104	163,104	163,104	163,104	19,020	18,300						
CUMULATIVE TOTAL	163,104	326,208	489,312	652,416	671,436	689,736						

TOTAL HRS	4918
TOTAL \$	\$ 59,016
TOTAL HRS	6298
TOTAL \$	\$ 50,384
TOTAL MATERIALS	\$ 580,336
TOTAL DOLLARS (Labor and Mat'l)	\$ 689,736

ITEM	DESCRIPTION	DEPT	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	HOURS	MAT'L	SAL HRS	HRLY HRS	MAT \$
ENGINEERING																					
	PROGRAM MANAGER	SAL	173		173		173		173		173		173						1038		
	ASSISTANT PROGRAM MANAGER	SAL	173		173		173		173		173		173						1038		
	SECRETARY & CLERICAL	HLV	173		173		173		173		173		173							1038	
	ADMINISTRATION & BUDGET CONTROL	SAL	100		100		100		100		100		100						600		
	BUDGET CONTROL ASSISTANT	HLV	50		50		50		50		50		50							300	
	SUPPORT GROUP	SAL	277		277		277		277		277		277						1662		
FABRICATION - FULL SCALE PROGRAM																					
	GAS GENERATOR & SKID			\$101,310		\$101,310		\$101,310		\$101,310											\$405,240
	FEED SYSTEM	HLV	173	\$25,905	173	\$25,905	173	\$25,905	173	\$25,905	173	\$25,905	173	\$25,905						865	\$103,620
	CONTROL SYSTEM	SAL	80	\$11,688	80	\$11,688	80	\$11,688	80	\$11,688	80	\$11,688	80	\$11,688					400		\$46,752
	" "	HLV	777		777		777		777		777		777							3885	
	SPARE PARTS (20%)			\$5,181		\$5,181		\$5,181		\$5,181											\$20,724
	DELIVERY OF 1 SYSTEM TO NTS	SAL											180	\$4,000					180		\$4,000
	" " "	HLV											210							210	
PRICE BASED ON NO HOT TEST OF EQUIPMENT

Pipe Chase and Duct Vaults with Hot Gas Conduit

Figure 1

SCHEMATIC DIAGRAM OF SECONDARY GAS GENERATOR SYSTEM

Figure 2

Figure 3

Figure 4

* REPORT NO. TTF-PN-61-8-2, AGC, LRP, SACTO, CALIF.
"PROPELLANT PERFORMANCE AND PROPERTIES —
PROJECT NIMBUS"

RESPONSE TIME CHARACTERISTICS
SECONDARY GAS GENERATOR

10-067-116-1

SCHEMATIC DIAGRAM OF PROPELLANT FEED SYSTEM

Figure 9

SUMMARY
BLOCK DIAGRAM
AUTOMATIC MALFUNCTION CONTROL SYSTEM

BASED ON ASSUMPTIONS

- A. ALL SIMILAR COMPONENTS HAVE THE SAME INHERENT RELIABILITY
- B. ALL GAS GENERATORS WILL PERFORM THE SAME DUTY CYCLE
- C. FAILURE OF ONE UNIT WOULD NOT AFFECT THE OPERATION OF ANOTHER UNIT

SECONDARY GAS GENERATOR SYSTEM CHOICE
BASED ON RELIABILITY

FIGURE 12

10-067-116-1

Figure 13

Figure 14

PROGRAM-MANAGEMENT ORANIZATION CHART

FIGURE 15

PROGRAM FUNCTIONAL FLOW DIAGRAM

□ ENGINEERING* ▨ FABRICATION
 ▩ DESIGN ▤ TESTING

LEGEND

* INCLUDES ADMINISTRATIVE AND RELATED PERSONNEL

CASE I SALARIED MANPOWER

FIGURE 17

ENGINEERING * FABRICATION
 DESIGN TESTING

LEGEND

* INCLUDES ADMINISTRATIVE AND RELATED PERSONNEL

CASE I HOURLY MANPOWER

FIGURE 13

— ENGINEERING* / FABRICATION
 \ DESIGN = TESTING

* INCLUDES ADMINISTRATIVE AND RELATED PERSONNEL

CASE II SALARIED MANPOWER

FIGURE 19

[] ENGINEERING* [] FABRICATION
 [] DESIGN [] TESTING

LEGEND

* INCLUDES ADMINISTRATIVE AND RELATED PERSONNEL

CASE II HOURLY MANPOWER

FIGURE 20

□ ENGINEERING *

▨ FABRICATION

LEGEND

* INCLUDES ADMINISTRATIVE AND RELATED PERSONNEL

CASE III SALARIED MANPOWER

FIGURE 21

☐ ENGINEERING *
☐ FABRICATION
LEGEND

* INCLUDES ADMINISTRATIVE AND RELATED PERSONNEL

CASE III HOURLY MANPOWER

FIGURE 22.