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REPORT NO. RP-SR-0001

VOLUME I

TO

SPACE NUCLEAR PROPULSION OFFICE - CLEVELAND EXTENSION

PHOEBUS-2 NOZZLE DESIGN PROGRAM

PRELIMINARY DESIGN PHASE, SUMMARY REPORT (U)

AUGUST 1965

CONTRACT SNPC-35

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Space Nuclear Propulsion Office
Cleveland Extension
National Aeronautics and Space Administration
21000 Brookpark Road
Cleveland, Ohio 44135

Attention: A. A. Medeiros

Subject: Contract SNPC-35 Summary Report RP-SR-0001 (U)

Reference: (a) Letter 7120:1362L, H. E. Pharr to A. A. Medeiros
dated 27 August 1965, Subject: SNPC-35 Task I.7.
Summary Report

Gentlemen:

Reference (a) transmitted Volume 1 of the Phoebus-2 Nozzle Design Program, Preliminary Design Phase, Summary Report, RP-SR-0001 (U) dated August, 1965, which was classified CONFIDENTIAL RESTRICTED DATA. It has been determined that Figure Nos. 151 and 152, pages 285 and 287, respectively, should be classified CONFIDENTIAL.

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REPORT NO. RP-SR-0001
VOLUME I

PHOEBUS-2 NOZZLE DESIGN PROGRAM
PRELIMINARY DESIGN PHASE, SUMMARY REPORT (U)

ROCKET ENGINE OPERATIONS - NUCLEAR

AUGUST 1965

CONTRACT SNPC-35

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FOREWORD

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This Summary Report is published in fulfillment of Task I, Subsection F, of Contract SNPC-35 which states in part: "The Contractor shall submit summary reports which document and summarize results of the work performed under the study phase."

This Report consists of Volume I, the Preliminary Design Phase of the Phoebus-2 Nozzle Program and Volume II, Nuclear Analysis in support of this phase.

 J. J. Beereboom, Manager
 Phoebus Division
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Approved:

 W. D. Stinnett
 Program Manager
 REON

ABSTRACT

This Volume is a comprehensive summation of work accomplished in the Preliminary Design Phase of the Phoebus-2 Nozzle Development Program under Contract SNPC-35. Due to the complexity of the nuclear analysis portion a more detailed discussion of this section is presented as Volume II.

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I. INTRODUCTION

This summary report of the preliminary design study for the Phoebus-2 nozzle is submitted in partial compliance with Task I of the Statement of Work for Contract SNPC-35. The statement of work for the basic contract is included as Appendix A to this report.

This summary report documents and summarizes the results of the work performed under the study phase of the contract. Sections of the report also cover part of the final design of the special test equipment and the initial phases of the heat transfer experimental program for the liquid and gas side heat transfer coefficients. Also, based on the findings of the study phase, recommendations are made for further development work.

The nozzle design concept selected for study was the U-tube nozzle constructed of Hastelloy-X. The study program utilized a great deal of pertinent experience gained on the NERVA program.

The major portion of the nozzle design activity took place at the ACFI, Menaul Facility in Albuquerque, New Mexico. A joint design team made up of ACFI and AGC personnel under the direction of LASL established the nozzle/pressure vessel interface. This activity was pacing much of the preliminary design, especially that of the simulation test components. Because this interface was a pacing item certain key events were established so that the balance of the study program could proceed in an orderly fashion. These events were:

- (1) Establishment of interface task force start - 1 March 1965
- (2) Selection of interface - 13 April 1965
- (3) Oral review by SNPO - 11 and 12 May 1965

Although the primary effort was expended on the Phoebus-2 nozzle, some test component preliminary design was necessary. Test component preliminary design objectives were to: (1) provide information for sizing of S.T.E.; (2) establish potential

problem areas; (3) provide information required in completion of Task E, Instrumentation and Task F, Development, Proof and Acceptance Test Methods.

As a result of an oral review held at AGC on 11 and 12 May, at which the material in this report was presented to SNPO and LASL, AGC was **authorized to proceed** with the final design of the Phoebus-2 nozzle.

The material presented in the body of this report is presented by Work Statement Tasks, as listed below:

Task A	Preliminary Design
Task B	Heat Transfer and Coolant Pressure Drop
Task C	Stress and Vibration Analysis
Task D	Materials and Fabrication
Task E	Instrumentation
Task F	Development, Proof and Acceptance Test Methods
Task G	Reliability and Quality Assurance
Task H	Special Test Equipment (STE)
Task I	Reports

For a detailed description of these Tasks, the reader is referred to Appendix A.

II. CONCLUSIONS AND RECOMMENDATIONS

As a result of the preliminary design studies conducted, it is concluded that the design concept for the Phoebus-2 nozzle based on the U-tube is sound and it is recommended that the final design proceed based on this concept.

It is further concluded that potential major problem areas can be categorized as follows:

1. High heat flux - $20.0 \text{ BTU/in}^2 \text{ sec}$ at throat of nozzle
2. Hastelloy-X jacket welding
3. First development nozzle fabrication completion date
4. High heat flux - $24.0 \text{ BTU/in}^2 \text{ sec}$ at entrance to adapter

Recommendations of how to avoid program delays due to these potential problems are discussed in the succeeding paragraphs.

The nozzle high heat flux will be experimentally investigated in scale model testing as described in Task B. These experiments will be completed by September, in time to make trim changes in the U-tubes if changes are found to be necessary. The nozzle design will be further verified by chemical simulation testing and margin demonstration tests. No further action at this time is deemed necessary.

Welding of Hastelloy-X in thick sections duplicating the jacket forging must be demonstrated. The materials program discussed in Task D is designed to provide the necessary technology. Two alternate acceptable metals, Hastelloy-N and Inconel-625 are recommended as back-up materials. The weld program has begun and initial results will be available by the time the nozzle forging vendor is ready to forge. Results of welding additional heats of Hastelloy-X and the alternate materials are dependent upon material deliveries but should be available prior to welding the first jacket. The risk involved in proceeding with procurement of the Hastelloy-X forging is limited should the welding study indicate rejection of the prime material. As additional back-up, alternate welding sources are being investigated.

The first development nozzle fabrication completion date is critical because of the short time available from the start of testing to the delivery of the first deliverable nozzle. Because the chemical simulation testing constitutes verification of the suitability of the nozzle for a nuclear firing, it is most desirable to have sufficient time to make any changes indicated by the test program. The current estimated fabrication time is based upon NERVA experience, taking into account the larger size and tougher material of the Phoebus nozzle. Consideration of alternate fabrication methods for grooving and machining is recommended, and conventional methods should be expedited to make this first nozzle available at the earliest possible date.

The predicted high heat flux for the adapter is based on very conservative estimates. Further analysis is recommended and an investigation into NERVA adapter heat transfer should be started to establish a better basis for analysis. The adapter designer should also be allowed to consider additional aids such as: (a) fuel film cooling, (b) increased injector/adapter diameter, (c) coatings, and (d) ablative liners.

An additional area of concern, though not considered a major problem area, is the injector. So that no undue delay should occur in the test schedule in the event the planned injector (multiple orifice) should prove to be unstable (performance is not a consideration) it is recommended that a back-up design (coaxial) be undertaken.

III. TECHNICAL DISCUSSION

A. DESIGN - Task A

1. Objectives

The objectives of Task A of the Statement of Work were to perform a design evaluation of the nozzle concept to obtain engineering calculations, preliminary design layout and justify the design concept on the basis of:

- Stress analysis
- Heat transfer and fluid flow analysis
- Interface and interaction
- Testing problems
- Fabrication methods
- Inspection and special Quality Control problems
- Failure mode analysis
- Repairability
- Provision for instrumentation
- New technology requirements
- Growth capability in reactor discharge gas temperature

The results of this evaluation and justification are presented in the following sections under the appropriate headings (i.e., Heat Transfer; Stress, etc.).

2. Preliminary Design

a. Nozzle

(1) Operating Parameters: The following defines the nozzle parameters:

RP-SR-0001

(a) Chamber Temperature	4500°R
(b) Chamber Pressure	625 psia
(c) Nozzle Coolant Flow	250 lbs/sec
(d) Nozzle Chamber Propellant Flow	285 lbs/sec
(e) Reactor Core Exit Face Temperature	4550°R
(f) Reactor Core Exit Face Emissivity	0.55
(g) Axial Skirt Load	600,000 lbs
(h) Nozzle Maximum Total Length	110.0 in.
(i) Coolant Maximum Supply Condition	55°R, 1350 psia
(j) Minimum Coolant Discharge Pressure	880 psia
(k) Minimum Coolant Discharge Temperature	110°R
(l) Coolant Discharge Flow Symmetry of 5%
for any 15° Sector.	
(m) Nozzle must be capable of cold flow at
zero power.	
(n) Nozzle must be capable of three operating
cycles each of thirty minute duration.	

(2) "U" Tube Nozzle Concept Will Be Used

The "U" tube nozzle concept selected for the Phoebus-2 application consists of axial-flow "U" shaped channels brazed into a structural jacket, with the coolant inlet manifold located at the aft end. An integral flange at the core end mates with the pressure vessel flange.

Full length grooves are machined on the jacket inner surface for insertion of the "U" tube channels. The constant width of each groove is determined by the thickness of the pre-placed braze foil, tube wall and braze foil wrapped shim. The assembly of tubes and jacket is brazed in a hydrogen atmosphere furnace to form an integral structure. Passages are then machined in the pressure vessel flange region to allow coolant flow through the flange and attaching bolts. The "U" tube nozzle concept has the following significant features.

The jacketed chamber section that contains the high pressure gases and carries the high axial loads is convectively cooled by direct contact with the liquid hydrogen, thus, carrying away the gamma induced heat.

The full length jacket with integral flange precluded hot gas or coolant leakage while allowing reliable chamber and tube instrument penetration.

The full length jacket serves as a shield to protect the coolant tubes from external damage and, thus, facilitates the handling of the nozzle during fabrication, assembly, testing, and remote disassembly.

Flexibility is permitted in the selection of coolant passage flow area during nozzle development. This is made possible by varying the length of the "U" channel legs and machining the interior jacket contour proportionately larger or smaller, as required. This potential permits the optimization of design and modification of a given configuration in minimum time with virtually no change in tube and jacket tooling.

(a) Design Approach

The nozzle design can be divided into two basic problems: (1) the coolant tube design encompassing material selection, heat transfer, and stress considerations and (2) the nozzle jacket structure design encompassing material selection, nuclear heating, heat transfer, and stress considerations. The nozzle design evolution requires the definition of three basic aspects in the order: (1) nozzle coolant tube gas side contour vs. axial distance along the nozzle length; (2) nozzle coolant tube cross section flow area vs. distance along the nozzle contour; (3) nozzle jacket structure cross section thickness vs. distance along the nozzle contour.

1 Contour Selection

The elements of the nozzle gas side contour considered during contour selection are as follows:

<u>a</u>	Skirt length	<u>e</u>	Divergence angle
<u>b</u>	Convergence radius	<u>f</u>	Chamber diameter
<u>c</u>	Convergence angle	<u>g</u>	Throat diameter
<u>d</u>	Upstream and downstream throat radius	<u>h</u>	Expansion ratio

The "skirt length" is a variable dependent on the nozzle reactor, pressure-vessel interface geometry; and, for the configuration selected, is approximately 15.0-in. long. The "convergence radius" selected is 6.0 in., to provide a smooth transition for heat transfer and manufacturing considerations between the cylindrical skirt and convergence section. The "convergence angle"

selection is dependent upon heat transfer, stress, nozzle weight, and length considerations and is discussed in detail in later sections of this report. A 45° convergence angle was selected. An 8.0-in. "upstream" and 4.0-in. "downstream throat radius" was selected. This selection was based on heat transfer and manufacturing considerations to provide a gradual transition between the convergence and divergence sections of the nozzle. A "divergence angle" of 17.5° was selected, based on nozzle gas flow dynamics and related experience on the NERVA nozzle program. A conical contour was selected to provide ease of manufacturing. The "chamber diameter" selection was based on the core diameter (to provide adequate clearance during operation) and was established to be 59.00 in. The nozzle "throat diameter" is determined by the nozzle operating requirements of temperature, pressure and gas weight flow and was determined to be approximately 17.0 in.* The "expansion ratio" of 7.0:1 was selected, based on interface requirements associated with the Gamma shield, to permit clearance between the coolant inlet and the shield. This area ratio will require a chamber pressure of approximately 320 psia to produce a full flow condition in the nozzle. Figure 1 depicts the selected nozzle contour.

* The method employed for calculation of the throat diameter was to use the standard equation relating c^* , throat area, chamber pressure, and flow rate:

$$c^* = \frac{p_c A_t g}{\dot{w}}$$

and solve for throat area. For solution of this equation p_c and w were specified as 625 psia and 285 lb/sec, respectively, and g was taken as the standard 32.174 ft/sec². The value of c^* used was 15850 ft/sec, and was calculated using Aerojet Computer Program 166, for shifting equilibrium conditions. These figures result in a throat area of 224.641 in.² and a diameter of 16.912 in.

Program 166 uses an input of chamber pressure and temperature, and calculates the gas composition at several points through the nozzle. Assumptions are that chemical equilibrium is maintained throughout the rocket nozzle expansion, that the ideal gas law holds, that the flow of gases is adiabatic and reversible, and that the mixture of combustion products is homogeneous in the chamber and at any constant-velocity cross-section in the nozzle. The gas composition is then used to determine various physical properties of the mixture, and also performance properties of an ideal nozzle using this gas as propellant.

NOZZLE GAS LINE CONTOUR

Figure 1

2 Tube Design

The nozzle tube design is based on the constraints of tube wall temperature and the allowable coolant pressure drop available to convectively cool the tube wall. The working fluid temperature and pressure combine to define the hot gas side operating environment that the tube must survive. The parameter that may be selected in the design of the tube is the tube material, number of tubes, and tube wall thickness. Material selection is based on the material having high strength at elevated temperature, oxidation, resistance, and ease of fabrication. Manufacturing consideration dictates selecting the minimum number of tubes. Tube wall mechanical stress at the nozzle exit plane limits the minimum number of tubes for a given tube wall thickness and resultant tube wall temperature. Minimum tube wall thickness is desirable at the throat station where the heat transfer is most severe. The selected nozzle configuration incorporates 320 Hastelloy X tubes of 0.012 wall thickness. The maximum tube wall temperature is approximately 1600°F with a tube pressure drop of approximately 350 psi. A detailed discussion of the tube design is included in the heat transfer section of this report.

3 Jacket Design

The nozzle jacket structure design is based on the constraints of allowable material strength and interface geometry requirements. The nuclear radiation environment and the various fluid pressures combine to define the operating environment that the jacket structure must survive. The parameters that may be varied in the jacket structure designs are the material selection, the jacket section thickness, and the application of jacket cooling. The selected configuration incorporates Hastelloy X material based on its high temperature strength capability and compatibility with the tube material. The jacket thickness selection was the subject of detailed nuclear, thermal, and structural analysis and is discussed in later sections of this report. The selected jacket configuration incorporates a 0.6-in.-thick core support skirt section and a convergent section varying from 0.8-in. to 0.2-in.-thick at the throat station. The jacket incorporated a 1.5-in.-thick nozzle-to-pressure vessel flange with provisions for 144 attaching bolts. The divergent section is approximately 0.2-in.-thick with an 8.0-in.-dia torus and inlet attached. The jacket structure will be fabricated from three basic forgings with weld joints at the throat and approximately 3.0-in. above the pressure-vessel flange regions. Figure 2 is the design layout for the selected nozzle design.

b. Test Assembly

The requirements of chemical simulation testing of the nozzle design will necessitate the use of a chemical simulation test assembly. The function of the test assembly is to produce a thermal environment (by combustion of chemical propellants LO_2/LH_2) similar to that experienced during reactor testing. The primary components of the test assembly exclusive of the cooled nozzle are the injector, adapter (nozzle-to-injector), and film cooled nozzle. (See Figure 3) Figure 4 shows the test assembly with the cooled nozzle installed.

The selected test assembly design incorporates an independent nozzle coolant and combustion circuit. This feature has the following significant advantages:

- (1) Allows early injector and adapter development testing prior to the time a cooled nozzle would be available by use of a film cooled nozzle.
- (2) Allows test stand checkout prior to committing a cooled nozzle to test.
- (3) Allows varying the nozzle coolant flow while maintaining constant combustion conditions (chamber pressure and mixture ratio) and, conversely, varying combustion conditions while maintaining constant coolant flow.

The following describes the various test assembly components:

- (1) Igniter

The igniter selected to initiate combustion is a pyrotechnic end burning Alclo grain in a re-usable metal case. Four of these igniters will be mounted in a threaded adapter located in the 17th channel of the injector and will burn for two seconds duration. The use of this ignition technique will preclude tube damage (dents) experienced on the NERVA program because only the combustible igniter particles will be introduced into the combustion chamber. Figure 5 shows the proposed Phoebus-2 igniter and the current NERVA igniter.

FILM COOLED NOZZLE TEST ASSEMBLY

Figure 3

PHOEBUS-2 NOZZLE TEST ASSEMBLY

Figure 4

PHOEBUS VS. NERVA IGNITER COMPARISON

Figure 5

Figure 6 shows a plot of burning time vs igniter chamber pressure for two variations of the selected igniter.

Table 1 shows a summary of experience with the selected igniter.

(2) Injector

The function of the injector is to deliver the chemical propellants to the combustion zone in the proper proportion to promote and maintain stable combustion. The selected configuration is a concentric channel multi-orifice concave face design incorporating gas-side baffles. These baffles consist of a center hub and eight radially aligned legs, convectively and film cooled with hydrogen. The thrust support has been designed integral with the injector structure. (See Figure 7).

The injector is designed to operate at 750 psia chamber pressure, a total propellant flow of 744 lbs/sec and a mixture ratio of $5.5 \pm .25$. The injector face orifice pattern will be based on the KAMP 51-1 pattern developed and successfully tested on the NERVA program. The total injector pressure drop for both the fuel and oxidizer circuits will be approximately 250 psi. Approximately 150 psi will be allotted to the face orifice drop.

Detailed fluid, stress, heat transfer, and combustion stability analyses will be undertaken in the final design phase.

(3) Adapter

The function of the adapter is to accommodate assembly of the injector to the nozzle and condition the hydrogen fuel temperature prior to combustion. In serving this function, it is subjected to an environment (thermal and structural) similar to that of the nozzle with the absence of nuclear heating. The design of the adapter, therefore, is quite similar to that of the nozzle. The

PYROTECHNIC IGNITER 1 - 069300 - BURNING DURATION

Figure 6

NOTE:

THE PROPOSED IGNITER AGC MODEL # GGIG - 912 PN 1-069300 HAS BEEN USED ON THE FOLLOWING TEST PROGRAMS WITH BELOW STATED RESULTS:

PROGRAM	PROPELLANT	TESTS	IGNITERS PER TEST	FAILURES
MI GGA	LO ₂ /LH ₂	36	2	0
MI UNI-ELEMENT	LO ₂ /LH ₂	48	1	0
NASA 82644 STAGE COMBUSTION	LO ₂ /GH ₂	11	2	0
NASA 84008 EXPERIMENTAL COMB. STABILITY AT HIGH CHAMBER PRESSURE	LO ₂ /LH ₂	50	2	0
TITAN 1 - 3	LO ₂ /RP-1	~ 500	2	0

PHOEBUS - 2 IGNITER TEST EXPERIENCE

constraints are tube wall temperature and available pressure. The variables, as in the case of the nozzle, are material selection, tube wall thickness, and number of tubes. A detail heat transfer parametric study was conducted on the adapter and is presented in the heat transfer section of this report. This analysis resulted in the selection of an adapter incorporating 320 tubes of 0.014-in. wall thickness. The selected adapter concept is similar to that of the nozzle except that the material selection is type 347 stainless steel for the tube and jacket structure. The jacket is fabricated from a single piece forging. The tube forming and assembly brazing apply the same techniques developed for the NERVA nozzle. Figure 8 shows the details of the adapter configuration.

Concurrent with the design of this adapter, alternate concepts were investigated including an ablative liner and the application of thermal barrier coating. Both of these concepts appear feasible, although they constitute some development risk. Scale model testing of thermal barrier coating will be evaluated during the follow-on contract period.

(4) Film Cooled Nozzle

The function of the film cooled nozzle is to serve as a substitute for the cooled nozzle to permit early development of the injector and adapter and checkout of the test stand prior to committing the cooled nozzle to testing.

The selected configuration is a single piece type 347 stainless steel forging machined to the proper contour. Fuel film cooling is provided in the cylindrical skirt section and just upstream of the throat, as shown in Figure 9. Heat transfer analysis for the film cooled nozzle is presented in the heat transfer section of this report. This analysis indicates an operating duration capability of approximately 8.0 second, more than sufficient to obtain a steady thermal environment for evaluation of the injector and adapter.

FILM COOLED WORKHORSE NOZZLE

Figure 9

3. Interface Design

Scope: The Phoebus-2 Interface Task Force was convened March 1st, 1965 at ACF Industries facilities in Albuquerque, New Mexico. This group included representatives of IASL, ACF, and AGC and met for the purpose of designing the nozzle/pressure-vessel/reactor interfaces.

The results of this design effort are reported in detail in the Interface Analysis Report, which consists of the following four parts:

- Part I, Load Analysis
- Part II, Radiation Heating Calculation
- Part III, Heat Transfer Calculations
- Part IV, Stress Analysis

This report is included herein as Appendix B.

a. Analytical Tools

Analysis of the interface has been carried out with the aid of several computer programs as follows:

(1) QUAD Code

This computer program is a point **kernel** code used to **predict** the radiation heating on the pressure vessel and nozzle. This code makes use of an assumed source (reactor) mathematical model and an assumed pressure vessel/nozzle mathematical model. The results of these radiation heating calculations were used in the interface design effort.

(2) TANG Code

This code is a computer program developed by AGC and is a transient heat conduction code. The TANG Code was used to derive all temperatures in the pressure vessel and nozzle system.

(3) PETS Code

This program was developed by ACFT as a refinement to the LASL SAD Code for calculations of mechanical and thermal stresses in axisymmetric shells. This code was used to calculate the structural behavior of the pressure vessel and the nozzle including stresses, deflections, rotations, and load distributions at the interface.

b. Conditions and Assumptions

Conditions considered in the interface design effort include the full-power reactor condition (Nuclear Steady State), hydrostatic test condition, chemical simulation conditions, and reactor transient conditions. The reactor operating conditions and reactor transient conditions were based upon data furnished by LASL-N-Division.

c. Material Properties

A Materials Properties Data Book was prepared based upon the most reliable estimates of materials properties available at that time.

d. Identification Method

A configuration identification system was established for the various nozzle-pressure vessel interface configurations. These configurations were of two types, "Flat" and "Canted". Each configuration considered for analysis was identified by a title as follows:

Thus, the first configuration of each type studied is "FLAT - All" and "CANTED - All" respectively. The same basic design (such as sequence letter "A") with a minor change in the pressure vessel, such as a change of wall thickness (interfaced with the same nozzle), becomes "FLAT - A12".

If a nozzle modification is introduced in addition, such as an increased flange thickness, the designation becomes "FLAT-A22".

When it was necessary for a nozzle or pressure vessel to be identified by itself for any analysis not employing a specific mating number, a zero was used for the missing number. Example: "FLAT - A01" for a pressure vessel by itself or, "FLAT - A10" for a nozzle by itself.

e. Analytical Approach

The particular analytical approach used for the various analyses (i.e., nuclear, thermal and stress) are discussed under the applicable subject in the following report.

In addition to the interface structural analysis, several other areas of interface interest were investigated.

f. Interface Control Drawing

An interface control drawing was prepared and coordinated with LASL/ACF/AGC. This drawing shows the control dimension and other data necessary to define the critical dimensions of the interface. A procedure for controlling changes to this drawing was agreed upon and the drawing vellums were transmitted to LASL for release and control. This Interface Control Drawing No. 43Y-65194E (See Figure 10) defines the three primary interfaces: (1) Core Support Flange, (2) Pressure Vessel Flange and (3) Coolant Inlet. Primary effort was devoted to definitions of the Core Support and Pressure Vessel flange interface and these were satisfactorily resolved. Definition of the coolant inlet interface was limited to defining the radial and axial location of the interface and further analysis will be required to define the joint configuration. Three joint configurations were identified as feasible: (1) a welded connection, (2) a bolted joint interior to the gamma shield, and (3) a bolted joint exterior to the gamma shield. The advantages and disadvantages of these three joint configurations are presented below:

(1) Welded Connection

Advantage:	Simplicity, minimum mass; therefore, minimum Gamma heating.
Disadvantage:	Difficult cleanliness, difficult to inspect and test, must be a field weld connection.

(2) Bolted Flange Fitting (Located Inside the gamma shield)

Advantage:	Ease of assembly, short pipe to nozzle.
Disadvantage:	High Gamma heating; therefore, high fitting temperatures.

NOTES

- 1 THE LOCATION OF THESE HOLES TO BE VERIFIED USING A MASTER GAGE MUTUALLY AGREABLE TO AGC ACFT & LASL
- 2 ALL C & D DIMENSIONS TO BE INSPECTED AT ROOM TEMPERATURE OF TO F. ANY DEVIATION FROM 70°F MUST BE RECORDED
- 3 THESE REFERENCE DIMENSIONS ARE NOT CONTROLLED BY THIS INTERFACE CONTROL DRAWING NOR ARE THEY CURRENT
- 4 DATUM [A] IS DEFINED AS A LINE PERPENDICULAR TO [E] & PASSING THROUGH THE CENTER OF [D]
- 5 DIM A & C TO BE DETERMINED BY AGC. DIM B & D TO BE DETERMINED BY ACFT AND SUPPLIED TO AGC

INTERFACE CONTROL

Figure 10a

Figure 10b

DETAIL F

1	2
3	4

NOTE: THIS INTERFACE HAS
NOT BEEN DEFINED AT
THIS TIME (4-23-65).

SECTION C-C

SCALE: $\frac{1}{4}$

INTERFACE CONTROL

Figure 10c

(3) Bolted Flange Fitting (Located Outside the Gamma Shield)

Advantages: Low Gamma heating; therefore, low structural temperatures.

Disadvantage: Approximately 4-foot long pipe attached to nozzle inlet plenum.

g. Assembly and Disassembly Problems

Provision for vertical lifting of the nozzle was provided by the design of bolt-on handling lugs that attach to the nozzle exit flange in three places. See Figure 11.

A requirement for handling the nozzle in the horizontal position was identified and a clamping type fixture was proposed. Clearance provision will be provided for attachment of this fixture.

h. Manufacturing and Inspection Tooling

Manufacturing tooling is normally an "In-House" problem of the respective hardware manufacturers. However, it was considered essential that the nozzle attach bolt holes of the nozzle and pressure vessel coincide and that the shear lip of the nozzle fit the pressure vessel properly. Therefore, it was decided that a master drill jig be provided for both the pressure vessel and the nozzle. This drill jig will be designed by a team consisting of AGC and ACFI tool designers. The jig is to be manufactured by ACFI, and provided to AGC. In addition, an inspection gage will also be jointly designed and fabricated by ACFI and provided to AGC.

i. Results

The objectives of the Interface Design effort were successfully met, resulting in the design of a structurally sound and compatible interface as

HANDLING FIXTURE

Figure 11

supported by the Interface Analysis Report. The Interface Control Drawing was produced to document this design configuration and a procedure was established to control this drawing. The Interface tooling design effort was scheduled to be initiated on 1 June 1965 and interface tooling was scheduled to be available in December 1965.

4. Conclusion

Design schedules for the deliverable nozzles and major test assembly component to be produced in the follow-on effort are presented in Volume II of AGC Report RP-P-0001.

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B. HEAT TRANSFER AND NUCLEAR ANALYSIS - TASK B

1. Heat Transfer Analysis

The purpose of this heat transfer analysis was to provide temperature distributions for stress analysis. The thermal analysis was a joint effort by personnel from ACFI and AGC. It was agreed that the same computer code be used by both parties, the same boundary assumptions would be used and also the same nuclear heating rates. The nozzle jacket was analyzed by AGC personnel with the pressure vessel as a boundary condition, while the pressure vessel was analyzed by ACFI personnel with the nozzle as a boundary condition. Several combinations of nozzle and pressure vessel configurations were considered.

The results of all configurations considered are presented herein. The selected configuration is designated FLAT-C31, and the alternate design is designated FLAT-C11. The results of previous analyses are included as backup information.

During the Preliminary Design Study, several nozzle contours were analyzed for heat transfer and pressure drop of the coolant. Parametric studies were conducted to determine tube geometries.

One design has been selected for carryover to the final design; this design at present has a maximum wall temperature of 1580°R and coolant pressure drop of 350 psi. Computer runs have also been made to predict conditions at uprated reactor power levels. Results indicate that adequate margin exists in this design to permit future growth.

a. Nozzle

(1) Nozzle Jacket

(a) Summary

The thermal analyses supporting the design of the Phoebus-2 nozzle were performed in two phases. First, a preliminary design study was made on several FLAT flange configurations and one canted configuration in which the interface flange was canted at 45° . A final iteration was made during the second phase in which two versions of the flat flange were analysed with refined nuclear heating rates and boundary conditions. These two configurations are designated FLAT C11 and FLAT C31. The highest predicted temperature for these two configurations is 957°R which occurs on the outside of the jacket approximately 5-1/2 inches aft of the nozzle-pressure vessel interface. The maximum predicted temperature in the flange of configuration FLAT-C11 is approximately 100° cooler than for configuration FLAT-C31. The thicker core support skirt of FLAT-C11 provides additional shielding of nuclear radiation which results in cooler flange temperatures.

A study was made to determine the effect of interface contact conductance. Two-dimensional analyses were made for a completely adiabatic interface and one in which only the nozzle shear lip was in contact with the pressure vessel. The results show that there is little heat being conducted across the interface inside of the bolt circle because of the heat-sink provided by the nozzle coolant tubes and bolt coolant system. The analysis in which contact only at the shear lip was assumed shows nearly the same maximum flange temperature recorded for intimate contact. The assumption of contact at the interface is considered valid in view of the bolt preloads and forces which tend to maintain contact on the outer portion of the joint.

A transient analysis was performed for typical start-up and shutdown conditions. The results indicate the most severe thermal conditions are at full-power, steady-state conditions.

An analysis was performed to determine the operating temperature of the flange bolts under full-power, steady-state operating conditions for several total coolant flow-rates. It was determined that the minimum coolant flow is about 2 lb_m/sec for reliable operation.

(b) Method of Analysis

All thermal profiles were generated by AGC Computer Job 278-B (Thermal Analyzer and Network Generator) (Reference 1). This computer code utilized the IBM 7094 computer and uses the method of finite differences to solve the heat transfer partial differential equations. It provides transient or steady-state solutions for two-dimensional slab or cylindrical geometry with variable properties and boundary conditions.

The analytical models are generated by constructing a grid network on full-size layouts of the nozzle and pressure vessel. The temperature nodal points are assumed to be point masses connected by a network of resistors. The thermal resistance between temperature nodes is calculated by the computer program from the material thermal conductivity, which is programmed to vary with material temperature. Surfaces cooled by convection have resistors, evaluated from the convective film coefficients, connecting fluid nodes which are at the mean bulk temperature of the coolant fluid.

Nuclear heating is simulated by assigning a nuclear heating rate (q''') to each temperature node. Nuclear heating rates are calculated, using the QAD Code by both AGC and ACFI (Reference 2). A decision was made to use rates generated by ACFI as they would produce more conservative results in the stress calculations. In regions of the nozzle not covered by ACFI heating rates, values were extrapolated from AGC rates.

Film coefficients and coolant temperatures for the surfaces cooled by the nozzle coolant tubes were calculated using AGC Computer Job 8047, a program for analysis and design of regeneratively cooled thrust chambers. (see Reference 3). The coolant temperature for the pressure vessel inlet plenum was also

obtained from this computer job. Eighty-five percent of the Hess and Kunz correlation (see Reference 4) was selected for computing convective film coefficients in the coolant tubes for the nozzle convergent section, as this correlation best matches test data for straight asymmetrically heated tubes in the existing regime of coolant pressure, temperature, and heat flux. The full Hess and Kunz correlation was used in calculating the film coefficients in the bolt coolant circuit. This correlation is reasonably accurate but conservative for this coolant temperature regime, fluid flow, heat flux, and low wall-to-bulk temperature ratios.

Convective film coefficients along the pressure vessel aft closure, behind the flow liner, were obtained from OPTION runs used in conjunction with sizing the flow liner. (Reference 5)

The following set of assumptions were employed for the thermal analyses performed on the nozzle jacket and flange.

- 1 Two-dimensional thermal conduction
- 2 All materials homogeneous
- 3 Thermal conductivity of material varies with temperature
- 4 Intimate contact between nozzle and pressure vessel at interface (except where noted)
- 5 All external or ambient surfaces adiabatic
- 6 Cooling by forced convection with hydrogen
- 7 Nozzle coolant tube inlet temperature = 55°R
- 8 Nozzle coolant flow rate = $250 \text{ lb}_m/\text{sec}$

- 9 Bolt coolant temperature = 60°R
- 10 Bolt coolant flow rate = $10 \text{ lb}_m/\text{sec}$
- 11 Convective film coefficient along plenum side of nozzle core support skirt = $500 \text{ BTU}/\text{hr ft}^2 \text{ }^{\circ}\text{R}$
- 12 Convective film coefficient in stagnation region of nozzle-pressure interface = $100 \text{ BTU}/\text{hr ft}^2 \text{ }^{\circ}\text{R}$
- 13 A flow director adjacent to the pressure vessel aft closure diverts $42 \text{ lb}_m/\text{sec}$ of H_2 along pressure vessel wall.

NOMENCLATURE

<u>Symbol</u>	<u>Description</u>	<u>Units</u>
q'''	Nuclear Heating Rate	$\text{BTU}/\text{in.}^3\text{sec}$
h_c	Convective Film Coefficient	$\text{BTU}/\text{hr ft }^{\circ}\text{R}$
T	Absolute Temperature	$^{\circ}\text{R}$
T	Temperature Differential	$^{\circ}\text{R}$
$\dot{w}$	Coolant Flow Rate	lbm/sec

(c) Results

The thermal analyses supporting the design of the Phoebus-2 nozzle interface were performed in two phases. In Phase I the FLAT and CANTED "A" series configurations were analysed based upon preliminary values for nuclear heating rates and nozzle coolant tube design. These results, along with stress analyses, indicated that the FLAT flange was superior to the CANTED configuration. In Phase II of the study the FLAT-C30 and -C10 designs were selected as the most nearly optimum designs; and thermal analyses were performed using more refined values for nuclear heating rates and a more optimum coolant tube design. The results of the final (Phase II) study are discussed first, with the results of the preliminary study following as backup material.

1 Selected Design

The results of the full-power steady-state analysis of Configuration FLAT-C31, shown in Figures 12 and 13, are used in the thermal stress analysis. In this analysis, the maximum jacket temperature (957°R) and thermal differential (800°R) occur in the convergent section approximately 5-1/2 inches aft of the nozzle-pressure vessel interface. The maximum temperature in the nozzle flange is 943°R and occurs on the outer surface.

2 Alternate Design

The results of the full-power, steady-state, analysis of the alternate configuration FLAT-C11 are shown in Figure 14. The shielding effect to nuclear radiation of the thicker core support skirt of Configuration FLAT-C11 results in cooler temperatures in the interface-flange region of the nozzle and pressure vessel. The maximum temperatures in the outer part of the nozzle flange are approximately 100° cooler for Configuration FLAT-C11. The maximum temperature (365°R) in the core support skirt of FLAT-C11 is about 100° higher than the corresponding value of Configuration FLAT-C31 because of the thicker core support skirt of FLAT-C11. However, this is still very cold, and is of minor importance. It may be noted that the effect of the shielding provided by the thicker skirt is limited only to the flange and pressure vessel. The temperatures in the nozzle convergent sections of both configurations are identical aft of the bolt coolant manifold.

3 Interface Conductance

The results of a study to determine the effect of interface conductance between the nozzle and pressure vessel are shown as Figures 15 and 16. These steady-state nuclear cases are for the FLAT-C30 nozzle and are to be compared to Figure 12. The case in which an adiabatic boundary is assumed for the interface between the nozzle and pressure vessel is presented as Figure 15. The temperatures in the nozzle flange outboard of the bolt circle run as much as 450° hotter for the adiabatic interface than they do for

STEADY STATE THERMAL PROFILE
PHOEBUS-2 NOZZLE -
PRESSURE VESSEL INTERFACE
FLAT - C31

Figure 12

Figure 13a

Figure 13b

STEADY STATE THERMAL PROFILE
PHOEBUS-2 NOZZLE -
PRESSURE VESSEL INTERFACE
FLAT - C11

NOTES:
1. INTIMATE CONTACT AT INTERFACE
2. TEMP. °R

DISTANCE FROM AFT FACE OF OUTER REFLECTOR - IN.

1. INTIMATE CONTACT AT INTERFACE
2. TEMP. °R

DISTANCE FROM AFT FACE OF OUTER REFLECTOR - IN.

Figure 14

FLAT - C30

TEMPERATURES IN ° RANKINE

A horizontal axis with tick marks and numerical labels from 8.0 to 22.0 in increments of 1.0.

Figure 15

FLAT - C31

Figure 16

the case where intimate contact with the pressure vessel, is assumed. The temperatures in the nozzle flange region inboard of the bolt circle are only a few degrees warmer for the adiabatic case than for the case of intimate contact with the pressure vessel. This indicates that very little heat is conducted across the flange interface inboard of the bolt circle because this region is cooled from three sides: the nozzle tubes, bolt coolant, and bolt coolant manifold. The portion of the flange outboard of the bolt circle is more heavily dependent on conduction of heat into the pressure vessel. However, this case of no contact with the pressure vessel is the extreme case and not realistic, as some contact must exist between the mating parts. Stress analyses have predicted an interface moment which tends to close the joint as well as a shear force which tends to keep the pressure vessel and nozzle shear lip in contact. An analysis was made in which the mating surfaces of the nozzle and pressure vessel were assumed adiabatic but with intimate contact between the pressure vessel and nozzle shear lip. These results, shown in Figure 16, indicate that contact at the shear lip is only 15° warmer than for the case of total contact with the pressure vessel. Therefore, the assumption of contact at the flange is reasonable as the forces on the joint tend to maintain contact where it is needed, on the outer part of the joint.

4 Transient Analysis

A transient analysis was performed for typical startup and shutdown conditions. Figure 17 shows the time history of temperature at the inner and outer surfaces of the nozzle jacket at the point of most severe thermal gradient (approximately 5-1/2 inches aft of the nozzle-pressure vessel interface). It indicates the maximum temperature and thermal gradient occurring at steady-state conditions. The coolant flow and reactor power schedule for startup and shutdown is shown in Figure 18.

5 Bolt Coolant Analysis

A thermal analysis was performed for one of the flange bolts. The analysis was made in cylindrical coordinates and the section was sliced through the center of the bolt. The analysis shows that a total flow

MAXIMUM THERMAL GRADIENT
TYPICAL TRANSIENT CONDITIONS

Figure 17

TYPICAL TRANSIENT CONDITIONS

Figure 18

rate of 10 lbs/sec will cool the full 144 bolts adequately. Figure 19 shows the bolt temperature distribution for rated flow. Figures 20 and 21 show the bolt temperature distribution for total coolant flow rates of 5 lb/sec and 2 lb/sec, respectively. The results show that a total coolant flow rate of 2 lb/sec is adequate for bolt cooling, but a lower limit should be assumed as coolant density changes in the system become more significant and when lower coolant velocities make control of flow rate more difficult.

6 Analyses Based on Preliminary Heating Rates

The preliminary heating rates produce temperature predictions somewhat higher than those of the final iteration. However, the results of these analyses are valuable in comparing the various designs.

The basic difference between Configurations FLAT A11, (Figures 22 and 23) and FLAT A21 (Figures 24 and 25) is the thickness of the nozzle-flange shear lip. The additional material added in Configuration A21 increases the maximum temperature on the outside of the flange by approximately 300°R. The canted configuration, CANTED A11 (Figures 26 and 27) has a maximum jacket temperature of approximately 100° higher than Configurations FLAT A11 or FLAT A21. The canted configuration will not allow the bolt coolant manifold to be placed in a location which will provide effective jacket cooling, as does the flat configuration, because of interference with the flange bolt heads. In the canted configuration the flange is about one inch closer to the reactor core which increases nuclear heating slightly.

The effect of adding additional material to the jacket shell is shown in Figures 28 through 31. In Configuration FLAT A31 (Figure 28) the maximum temperature differential across the jacket is about 150° higher than for the nominal jacket thickness of FLAT A11 or FLAT A21. In configuration FLAT A41 (Figure 30) the maximum temperature differential is about 350° more than for the nominal case.

NOZZLE - PRESSURE VESSEL FLANGE BOLT, NOMINAL COOLANT FLOW

NOTES:

1. SCALE 2:1
2. TEMP °R

FIGURE 19

NOZZLE - PRESSURE VESSEL FLANGE BOLT,
50% OF NOMINAL COOLANT FLOW

FIGURE 20

THERMAL PROFILE - BOLT,
NOZZLE - PRESSURE VESSEL
FLANGE
20% RATED COOLANT FLOW

Figure 21

Figure 22

STEADY STATE THERMAL PROFILE

PHOEBUS-2 NOZZLE -

CONVERGENT SECTION

FLAT - A11

Figure 23a

STEADY STATE THERMAL PROFILE
 PHOEBUS-2 NOZZLE -
 CONVERGENT SECTION
 FLAT - All

Figure 23b

Figure 24

STEADY STATE THERMAL PROFILE
 PHOEBUS-2 NOZZLE -
 CONVERGENT SECTION
 FLAT - A21

NOTE:
 TEMPERATURES °R

Figure 25a

STEADY STATE THERMAL PROFILE
 PHOEBUS-2 NOZZLE -
 CONVERGENT SECTION
 FLAT - A21

NOTE:
 TEMPERATURES °R

Figure 25b

STEADY STATE THERMAL PROFILE
PHOEBUS-2 NOZZLE -
PRESSURE VESSEL INTERFACE
CANTED - A11

Figure 26

STEADY STATE THERMAL PROFILE
 PHOEBUS-2 NOZZLE -
 CONVERGENT SECTION
 CANTED - A11

NOTE:
 TEMPERATURES °R

Figure 27a

STEADY STATE THERMAL PROFILE
 PHOEBUS-2 NOZZLE -
 CONVERGENT SECTION
 CANTED - A11

NOTE:
 TEMPERATURES °R

Figure 27b

Figure 28

STEADY STATE THERMAL PROFILE
 PHOEBUS -2 NOZZLE -
 CONVERGENT SECTION
 FLAT - A31

NOTE:
 TEMPERATURES °R

FIGURE 18 a

DISTANCE FROM AFT FACE OF OUTER REFLECTOR - IN.

STEADY STATE THERMAL PROFILE
 PHOEBUS-2 NOZZLE -
 CONVERGENT SECTION
 FLAT - A31

NOTE:
 TEMPERATURES °R

Figure 29b

STEADY STATE THERMAL PROFILE
PHOEBUS-2 NOZZLE -
PRESSURE VESSEL INTERFACE
FLAT - A41

Figure 30

STEADY STATE THERMAL PROFILE
 PHOEBUS-2 NOZZLE -
 CONVERGENT SECTION
 FLAT - A41

NOTE:
 TEMPERATURES °R

Figure 31a

STEADY STATE THERMAL PROFILE
 PHOEBUS-2 NOZZLE -
 CONVERGENT SECTION
 FLAT - A41

NOTE:
 TEMPERATURES °R

Figure 31b

The temperatures in the flange region of Configurations FLAT A51 (Figures 32 and 33) and FLAT A61 (Figures 34 and 35) are somewhat misleading as the nuclear heating rates in the flange were not reduced to account for the shielding effect of the thicker core support. However, these results provide a qualitative answer and provided the basis for the more refined study made on the FLAT C series designs.

(d) Optimum Convergence Angle Study

A study to determine the effect of convergence angle on jacket temperatures is at this time incomplete. Nozzles with convergent angles of 30° , 35° and 40° are being analyzed. Preliminary analysis has indicated that very little reduction in jacket temperatures and temperature gradients will result from convergent angles greater than 45° .

(2) Tube Bundle Heat Transfer and Pressure Drop Analysis

(a) Summary

During the Preliminary Design Study portion of the contract, several nozzle contours and coolant tube geometries were studied for prediction of temperatures and pressure drops. This study resulted in selection of one design which was considered to be the most suitable for final optimization.

(b) Method of Analysis

The procedure for analyzing a tube bundle is highly computerized. The primary computer program used by Aerojet for prediction of temperatures and pressures is code 8047, programmed for the IBM 7094 computer. The program uses input in two blocks. The first of these defines conditions of the gas and coolant; that is chamber operating conditions, gas composition and flow rate, coolant inlet conditions, and coolant flow rate. (Gas and coolant transport properties are computed internally and do not have to be input.) The second block of input describes the chamber and tube geometry by dimensioning a series of stations progressing along the coolant passage.

STEADY STATE THERMAL PROFILE
PHOEBUS -2 NOZZLE -
PRESSURE VESSEL INTERFACE
FLAT - A51

Figure 32

STEADY STATE THERMAL PROFILE
PHOEBUS -2 NOZZLE -
CONVERGENT SECTION
FLAT - A51

Figure 33a

STEADY STATE THERMAL PROFILE
 PHOEBUS -2 NOZZLE -
 CONVERGENT SECTION
 FLAT -A51

Figure 33b

STEADY STATE THERMAL PROFILE
PHOEBUS -2 NOZZLE -
PRESSURE VESSEL INTERFACE
FLAT - A61

NOTES:
1. INTIMATE CONTACT AT INTERFACE
2. TEMPERATURES °R

DISTANCE FROM AFT FACE OF OUTER REFLECTOR - IN.

Figure 34

STEADY STATE THERMAL PROFILE
 PHOEBUS -2 NOZZLE -
 CONVERGENT SECTION
 FLAT - A61

NOTE:
 TEMPERATURES °R

Figure 35a

STEADY STATE THERMAL PROFILE
PHOEBUS-2 NOZZLE -
CONVERGENT SECTION
FLAT - A61

NOTE:
TEMPERATURES °R

Figure 35b

The program describes an iterative solution, working station-by-station; that is, gas and liquid tube wall temperatures at the first station are assumed and provide a basis for calculation of heat transfer coefficients and heat flux. Using this heat flux, and starting with coolant temperature, new gas and liquid side wall temperatures are calculated. If the assumed and calculated temperatures differ by more than one degree Fahrenheit, an adjustment is made and the procedure repeated.

Once the temperatures balance, a secondary loop begins in which coolant temperature rise and pressure drop are computed. The heat balance across the tube wall is then repeated until the system balance criteria are completely satisfied. The process is repeated at each station until the entire tube is traversed.

Output from the program is printed for each station, and includes coolant bulk temperature and pressure, gas and liquid side wall temperatures, heat transfer coefficients, heat flux, and heat input to coolant.

(c) Basis of Analysis

The thermal analyses are based on the correlations recommended in the proposal. The simplified Bartz equation (Reference 6):

$$Nu_f = C_g \left(\frac{\dot{w} d}{A_{t,f}} \right)^{0.8} Pr_f^{0.4} \left(\frac{\rho_f}{\rho_b} \right)^{0.8}$$

is used for the gas side. The values of the coefficient C_g (Figure 36) were derived for each nozzle contour by use of the program described in Reference 7, which solves the integral momentum and energy equations for boundary layers. Adjustment of the curve upward in the nozzle chamber region was made to allow for impingement effects of hot gases from the core. This adjustment was based on scale-model and NRX test data for the NERVA nozzle, and the same adjustment was applied to the Phoebus nozzle geometry pending substantiation by the Phoebus scale-model tests.

PRELIMINARY DESIGN - GAS-SIDE
EQUATION COEFFICIENT FOR PHOEBUS
NOZZLE

Figure 36

The liquid side correlation is based on 85% of the coefficient predicted by the Hess and Kunz equation (Reference 4):

$$\text{Nu}_f = (0.85) 0.0208 \text{Re}_f^{0.8} \text{Pr}_f^{0.4} \left(1 + 0.01457 \frac{\text{v}_w}{\text{v}_B}\right).$$

The factor of 85% is applied because it is believed to better correlate resistance-heated tube data. In the curved portion of the tube at the throat, however, where enhancement is expected, the factor applied is 100%. This is considered to conservatively describe the heat transfer in this area. The coolant side correlations will be substantiated by the resistance-heated tube tests.

In addition to the convective heat from the gases, thermal radiation from the core-face is also considered. Configuration factors are computed for each segment of the nozzle and used as input to the heat transfer program.

(d) Basis of Design

The basic geometrical factors upon which tube design was begun are shown in Figure 37. These are the dimensions dictated by performance, fabrication, and adjoining equipment. The design was carried through based on NERVA practice insofar as possible, to utilize the experience gained on that nozzle.

To alleviate the time consuming process of preparing new heat-transfer-program input decks for each change in nozzle contour, a computer program was written to compute all necessary chamber geometry at each station along the tubes. This permitted evaluation of several more contours than would have been possible without the program.

Technical drawing of a mechanical part, showing two views: a front view (top) and a side view (bottom).

Front View (Top):

- Overall width: 35.9"
- Top radius: 6.00" R
- Central vertical feature: 3.00" R
- Bottom radius: 9.00" R

Side View (Bottom):

- Overall height: 59.00"
- Top radius: 16.9/2"
- Central vertical feature: 17.5"
- Bottom radius: 9.5"

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(e) Design Procedure

Once a nozzle contour is established, the problem of determining the number and size of tubes is one of finding the best compromise between considerations of stress, temperature, pressure drop, and fabrication requirements. The Phoebus U-tubes were designed by running a parametric study to determine the effect of changes in number of tubes, wall thickness, and leg height. Initial design considerations are based on pressure stresses only, and so wall thickness becomes a function of number of tubes.

For any location along a coolant tube, a graph may be made of wall temperature-vs-leg height. Referring to Figure 38, a partial envelope is defined, shown by the unshaded area. It is bounded on the top by maximum allowable temperature and on the bottom by maximum allowable pressure drop. Also, as the number of tubes diminishes and their individual cross-sectional radii increase, the tube walls are subjected to greater hoop stresses. The design envelope of Figure 38 is therefore bounded on the left by the fewest number of tubes that may be used and still remain within stress limitations. It is desirable to work toward this limit for ease of fabrication. On the proposed design, 320 tubes having a wall thickness of 0.012 inches appeared to be close to optimum.

Once the number of tubes is fixed, the problem becomes one of altering tube leg height to find the least pressure drop commensurate with allowable wall temperatures. It will be noted that the lines of constant pressure are a function of the complete tube geometry and will, thus, be affected by a change in leg height at any point along the tube. What appears to be a sizeable task of studying the effect of various leg heights is simplified significantly by the fact that fabrication is considerably easier if the leg height is tapered uniformly. It is then a matter of adjusting leg height in only three or four critical locations and tapering the height between.

DESIGN LIMITS (1600 °F)

FIGURE 38

(f) Discussion of Design

The tube dimensions in the latest design appear to be close to optimum. Wall temperatures are shown in Figure 39. The discontinuities shown in the profile are the result of the sudden change from 85% to 100% of the Hess and Kunz equation used for the liquid-side heat transfer coefficient. The profile experienced in practice should show a smooth transition and decrease the axial temperature gradients shown.

The coolant pressure is plotted in Figure 40. On the same plot are shown the portions of the total pressure drop accounted for by friction and change of velocity.

Selected parameters of interest are shown in Table 2. The pressure drop of 335 psi is less than allowable to leave room for final design modifications. It is estimated that, when optimized, the drop will be close to the 375 psi allowable.

Coolant bulk temperatures are about 90°R at the throat, and 155°R at the outlet. Maximum coolant velocity is about 740 fps, equivalent to $M = 0.27$.

(g) Up-rated Conditions

Computer runs were made at chamber temperatures of 5000°R and 5500°R for up-rated power levels. Results of these runs are shown in Table 2 for comparison with nominal operating conditions. It appears feasible that the 5500°R level is within the nozzle capability; however, some decrease in wall temperature could be attained by decreasing tube leg height and taking a penalty in pressure drop, if such is considered advisable.

(h) Supplementary Studies

Supporting studies are being performed to determine effects of throat curvature variation and decrease of convergence angle. Results are not yet available.

NOZZLE TEMPERATURE PROFILE

Figure 39

NOZZLE PRESSURE DROP COOLANT TUBES

Figure 40
Page 84

TABLE 2

NOZZLE COOLING AT NOMINAL AND UPATED POWER LEVELS

<u>Chamber Temp. (°R)</u>	<u>Chamber Press. (psia)</u>	<u>Maximum Gas-Side Wall Temp. (°F)</u>	<u>Corresponding Liquid-side Wall Temp. (°F)</u>	<u>Maximum Heat Flux₂ (Btu/sec-in²)</u>	<u>Pressure Drop (psi)</u>	<u>Coolant Flow (lb/sec)</u>
Nominal:						
4500	625	1580	775	20.9	335	250
Upated:						
5000	570	1720	860	22.5	300	217
5500	521	1850	950	24.3	280	189

Also in progress is an alteration of the 8047 computer code described in Paragraph (a) to use hydrogen properties computed by the method of Farmer (LASL), Reference 8. This is considered advisable in order to make a comparison to the results given by the existing program, in light of the variation between some properties used by Aerojet and Farmer. An extreme example of this variation is thermal conductivity, which shows Farmer's data (supplied by ACF) to be some 50% higher than those of Aerojet.

(3) Phoebus "Workhorse" Nozzle

(a) Summary

Fuel film cooling requirements for the stainless-steel Phoebus "workhorse" nozzle (Figure 41) were determined for test durations up to 10 sec. This nozzle will be used for the development and checkout of the injector, adapter, and test facility prior to the completion and testing of the first U-tube nozzle.

The design criteria of this "workhorse" nozzle is the time required to heat the inside surface of the nozzle at the critical locations from 70 to 2000°F, and the controlling factor is the quantity of film cooling injected.

This analysis is the second conducted for this nozzle. (The results of the first analysis are reported in Reference 9). The chamber pressure decreased from 1000- to 900-psia and the mixture ratio from 6.5 to 5.5 for this reanalysis. A better definition of the nozzle contour is also now available.

(b) Method of Analysis

Analysis was conducted for a mixture ratio of 5.5 and for chamber pressures of 900- and 750-psia assuming 95% combustion efficiency. The final film cooling flow rates were determined first by calculating the required local

FILM COOLED WORKHORSE NOZZLE

Figure 41

driving temperature that would heat the nozzle surface at the throat, and at a point just upstream of the secondary injection point, from 70 to 2000°F for test durations up to 10 sec. Second, the local film temperature was determined along the nozzle wall for various film coolant flow rates and injection points. Matching the calculated required driving temperature to the film-cooling flow rate required to achieve this temperature determines the film-coolant flow rates.

(c) Analysis Program

1 Film Cooling

Local film temperatures were calculated using the computer program 8070 (a modified version of 8034 Reference 10) in which it was assumed that steady-state operating conditions existed instantaneously and that the fuel film coolant was injected axially along the wall at a velocity of 400 ft/sec at an initial temperature of 60°R. This film cooling model assumes no mixing of film coolant with main combustion gas stream and no heat transfer to or along the steel chamber wall. The simplified Bartz equation (Reference 6) was utilized for the hot gas heat transfer coefficient with design multiplying factors that are used in the U-tube nozzle simulation analysis.

2 Transient Heat Transfer to the Wall

The transient convection between the film and the chamber wall is a function of the driving temperature differential, that is, between the local film temperature and the instantaneous surface temperature of the nozzle. The heat transfer coefficient was calculated from the simplified Bartz equation with a multiplying factor of unity. Transient conduction within the wall was calculated by assuming the wall was an infinite flat plate at an initial temperature of 70°F; standard graphical differencing solution was used.

Since the ratio of the chamber wall thickness to the diameter is very small, little error is introduced by this conservative assumption. In using this graphical differencing solution it was necessary to assume constant physical properties of the 347 stainless steel. The following average value was used, based on a mean wall temperature of 1035°F: specific heats = 0.137 Btu/lb-°R, density = 0.287 lb/in.³, and thermal conductivity = 0.00029 Btu/in. sec °R. The value of the heat transfer coefficient between the film and the wall was also based on the constant mean film temperature which is a good assumption for this problem since the coefficient was found to vary only slightly between the initial and final values of the film temperature.

Radial wall temperature profiles at the throat and just upstream of the second injection point were calculated using the same assumptions and graphic methods as for the surface temperature, except that in this case the gas film temperatures were known and the local metal temperatures were calculated.

Figure 42 is the result of the study made to determine an optimum location of the second injection point in the converging section of the nozzle; (a two point film cooling injection always requires less coolant than a single point injection system). There is a slight variation of the coolant requirements as injection point is moved from 26- to 34-in. axial distance. The film coolant requirement decreases to cool the throat (45.1-in. axial distance) while film coolant requirement has to increase from the forward end to cool the increasing distance to this second injection point. The curve, therefore, indicates that the optimum location of this second point is approximately 30-in. axial distance.

Figure 43 is the curve indicating the film cooling requirements in relation to test duration. The total requirement varied from approximately 10- to 15% as the nozzle test duration requirement is varied from 3- to 10-sec. The anticipated test duration for this "workhorse" nozzle is from 5- to 10-sec; therefore, it is recommended that the nozzle be designed with

PHOEBUS WORKHORSE NOZZLE
FILM COOLING REQUIREMENT VARIATION
WITH LOCATION OF SECOND INJECTION POINT

Note:

1. $P_c = 750$ psia
2. $MR = 5.5$
3. Comb. Eff.: 95%

Figure 42

WORKHORSE CHAMBER FUEL FILM COOLANT REQUIREMENTS

Figure 43

a constant 15% fuel film coolant flow rate. Also shown in Figure 43 is the lower curve, labeled "throat", representing the coolant requirement from the second injection point. It indicates that a larger percentage is required from this point than the forward end.

Figures 44 and 45 present the predicted temperature profiles through the nozzle wall at 30-in. axial distance and at the throat respectively. The curves represent the temperature profile at various time intervals for the recommended film coolant flow rates.

(d) Recommendations

A film-cooling flow rate of 15% of the injector fuel flow is recommended for chamber pressures of 750- through 900-psia (approximately 17 and 22 lb/sec, respectively). Of this 15%, 10% will be injected from the second injection point. If the nozzle is to be tested at appreciably lower chamber pressures or higher mixture ratios, the film-coolant weight flow rate in lb/sec should not be decreased from these values obtained in the report, unless further analysis is conducted.

(4) Liquid-Side Test Program

(a) Summary

The liquid-side heat transfer and pressure drop test program was designed to obtain experimental test data applicable to the Phoebus-2 nozzle development. The experimental test program was initiated in April at the Von Karman Center (VKC) test facility while the Liquid Rocket Operation (LRO) heat transfer facility was being prepared for testing. The test program conducted at VKC was an evaluation of bulk temperature effects for liquid hydrogen under conditions to be achieved near the high heat flux region of the nozzle. Additional tests are to be conducted at the LRO facility in straight tubes at higher heat fluxes and correspondingly higher mass velocities. The test program to be conducted

PHOEBUS WORKHORSE NOZZLE TEMPERATURE PROFILE

Location: Just Upstream of Second Injection
Point, 30 in. Axial Distance

Figure 44

PHOEBUS WORKHORSE NOZZLE TEMPERATURE PROFILE

Location: Throat

Figure 45

at the LRO facility includes, in addition, a study of coolant passage curvature effects by performing tests in curved, asymmetrically heated, tube of both circular and non-circular, uniform, flow area. Tests of a full scale U-tube of the Probus-2 configuration, both with and without heat addition, will be conducted later in the program. This will permit an evaluation of the following combined effect:

- 1 Convergent-divergent flow rate.
- 2 A non-circular coolant passage cross section.
- 3 Asymmetric heat addition.
- 4 Varying heat flux along the length of the tube on both the heat transfer and the pressure drop.

(b) Experimental Methods

The tests to be conducted in this experimental program are designed to simulate coolant passage configuration and to obtain data in support of the development of the U-tube nozzle. The test sections will in each case be resistively heated with direct current. Tests will be conducted at the design coolant pressure level with instrumentation sufficient to the measurement of pressure drop across the test section, electrical power input, sensible energy rise, and wall temperature and heat flux at the test section - liquid interface. The test data will be analyzed using the IBM 7094 computer and the heat transfer analysis program 8061.

(c) Test Program

1 Straight-Tube Bulk Temperature Effects

Objective: Conduct tests in straight tubes to study the effects of bulk temperatures near the transposed critical temperature on the local heat transfer coefficient.

The conditions for the straight tube tests are tabulated in Table 3. A representative schematic of the instrumented test section for both these tests and the subsequent high heat flux tests is shown in Figure 46. Nine test conditions are outlined in this first series of tests. The local bulk temperature, wall temperature and heat flux will be achieved by varying the heated length and the mass velocity of the test fluid. Measurements made will include inlet and outlet coolant conditions of temperature and pressure, mass flow rate, total voltage and current flow, and local voltage drop. Pressure drop across the electrodes and local wall temperature measurements will be made in all cases.

The design equation currently used for predicting the coolant side heat transfer coefficient is based on a modified form of the Hess and Kunz film temperature correlation. However, a comparison of the available experimental data with the Hess and Kunz equation indicates that the predicted coefficients are somewhat higher than those determined experimentally, particularly in the coolant temperature regime predicted to occur in the maximum heat flux region of the nozzle. To better predict coolant-side heat transfer, the coefficient of the equation therefore was reduced to 85% of the nominal literature value for the straight tube portion of the nozzle.

Figure 47 is a comparison of the predicted and experimental heat transfer coefficient in which the heat flux parameter (local heat flux normalized by the diameter of the test section and the coolant mass velocity of the coolant) is plotted as a function of wall temperature for coolant temperatures between 80 and 100°R. Selected data from the current test program are shown for coolant temperatures between 80 and 100°R at local heat fluxes ranging from 6.7 to 14.6 Btu/in.² sec.

Status: The tests in straight tubes have been completed and the test data are currently being reduced and analyzed.

Table 3

TEST PARAMETERS

Coolant-Side Heat Transfer Study in Straight Tubes
at Coolant Temperatures Between 80 - 100°R

Inlet Temperature, 50°R

Inlet Pressure, 1200 psi

Outlet Temp °R	Mass Flow Rate lb/in ² sec	Heat Flux Btu/in ² sec	Wall Temp. °R	Heated Length in.
80	5.8	8.7	1300	3.0
80	7.3	11.6	1400	2.75
80	8.8	15.1	1500	2.75
90	5.8	10.5	1300	3.0
90	7.3	14.9	1400	2.75
90	8.8	18.1	1500	3.0
100	4.7	9.4	1300	3.0
100	7.0	14.5	1400	3.25
100	7.3	16.4	1500	3.0

STRAIGHT TUBE TEST SECTION

✓ Chromel-Alumel Thermocouples

* Voltage Taps

Test Section Hastelloy-X Tube

Nom Wall Thickness 0.015 in.

Inside Diameter 0.1475 in.

Test Section No.	L inches (Nom)
------------------	----------------

1	2.75
2	3.00
3	3.25

HEAT FLUX PARAMETER VS WALL TEMPERATURE

Figure 47

2 Straight Tube, High Heat Flux Tests

Objective: Conduct tests in straight tubes at heat fluxes in excess of 20 Btu/in.² sec at bulk temperatures near the transposed critical temperature.

The maximum heat flux predicted for the Phoebe-2 nozzle is between 20 and 25 Btu/in.² sec. The tests at heat fluxes greater than 20 in straight tubes are to be conducted at the LRO facility. The increased LH₂ capacity of the LRO facility high-pressure run tank will permit the attainment of higher mass velocities and consequently higher heat fluxes than can be achieved at the VKC facility. The attainment of the desired heat fluxes will be attempted while avoiding test section failure. Six tests will be conducted with the test parameters shown in Table 4. The measurements made will be the same as those made for the bulk temperature effects evaluation. Data at lower power levels will be compared with the VKC test data and serve as a check of the LRO equipment. The tests will be conducted in test sections of the same configuration as the initial straight tube tests..

The high heat flux tests will be made to ensure that the experimentally-obtained heat transfer coefficients are as high as those predicted by the design equations. All the tests in straight tubes will be performed in 3/16-in. diameter by 0.015 in. to 0.020 in. wall thickness Hastelloy-X tubing.

Status: Fabrication of one test section is complete. The experimental test facility is being readied for the testing. An 800-gallon liquid hydrogen storage vessel has been rented and is being located adjacent to the high pressure use tank. The tank insulation has been repaired, the tank fill line has been modified and a flow control valve is being purchased. Testing is scheduled to begin the week of 24 May.

Table 4

TEST PARAMETERS

Coolant-Side Heat Transfer Study in Straight Tubes at High Heat Fluxes

Inlet Temperature, 50°R

Inlet Pressure, 1200 psi

Outlet Temp. °R	Mass Flow Rate lb/in ² sec	Heat Flux Btu/in ² sec	Heated Length in.
95	7.0	25	1.8
95	11.7	25	2.8
95	23.4	25	5.87

3 Curved Tube, High Heat Flux

Objective: Conduct tests in curved asymmetrically-heated tubes of two different radii of curvature and two cross sectional configurations to determine the degree of enhancement due to tube curvature and to apply these data to design.

A significant enhancement or increase in the heat transfer coefficient on the "swept" side or the outside of a curved flow channel has been demonstrated for the Nerva nozzle geometry. The data obtained for the Nerva Program, however, are basically for only one tube diameter and one radius of curvature. Thus, no data are available for other ratios of tube diameter and test section radius of curvature. No sound criteria for extrapolation to non-Nerva specifications is known and therefore tests are planned in curved tubes. The objective of the test program will be to substantiate the choice of the design equation for predicting the heat transfer coefficient in the throat region of the nozzle.

The tests will be conducted in curved tube test sections fabricated from Hastelloy-X tubing. Two different radii of curvature, and both circular and non-circular cross sections, will be tested. The configuration of the test sections for the curved tube tests is illustrated in Figure 48. In his work with conventional fluids, Ito has developed an empirical equation for predicting the effect of curvature on the resistance to flow through the tube as compared to the resistance to flow through a straight tube. If Reynolds analogy holds, an increase in resistance should result in an increase in heat transfer. Based on the equation of Ito, increasing the radius of tube curvature should result in a decrease in the resistance to flow and a corresponding decrease in heat transfer. The prediction of the decrease in resistance for the upstream radius of curvature for the Nerva and Phoebus-2 nozzles for the same Reynolds number is illustrated in the following:

CURVED ASYMMETRICALLY-HEATED TEST SECTION

Figure 48

$$\frac{\lambda_{\text{Curved Tube}}}{\lambda_o \text{ Straight Tube}} = \left[\text{Re} \left(\frac{R}{r} \right)^2 \right]^{0.05} \quad \text{Ito's Eq.}$$

Where: Re = 10^6
 R = Tube Radius
 r = Radius of curvature

	$\frac{R}{r}$	$\frac{\lambda}{\lambda_o}$
Nerva Design	.0164	1.32
Phoebus Design	.0095	1.25

The resistance ratio based on the geometry and predicted Reynolds number for both the Nerva and Phoebus nozzles indicates about the same increase in resistance because of curvature in the upstream region of the throat. It is the intent of the test program to obtain data to permit a prediction of the enhancement caused by tube curvature in substantiation of the design equation, and the dependency of heat transfer on angular position around the curve. Possible effects of non-circular cross section on the heat transfer coefficient will be studied, since the equations for predicting the effect of curvature are all based on circular cross section tubes and the U-tube coolant passages are distinctly non-circular. Table 5 is a tabulation of the curved tube test parameters.

Status: The curved-tube test sections have been designed and fabrication has been initiated.

4 Full-Scale U-Tube Test Section

Objective: Conduct simulation tests in a full-scale, single, U-tube test section to better define the combined effects of geometry and fluid effects on both heat transfer and pressure drops.

Table 5

TEST PARAMETERS - CURVED TUBE

Test Section: Material, Hastelloy-X Tubing
 Inlet Temperature, 50°R
 Inlet Pressure, 1200 psi

Local Coolant Temperature °R	Wall Temperature °R	Mass Velocity lb/in ² sec	Predicted Maximum Heat Flux Btu/in ² sec
80	1300 - 1500	2.8 - 11	6 - 21
90	1300 - 1500	2.8 - 11	7 - 25
100	1300 - 1500	2.8 - 11	8 - 27

TEST SECTION GEOMETRY - CURVED TUBE

AGC Test Section Drawing Number	Tube Radius, R in.	Radius of Curvature, r in.	R/r	Cross Section
1114851-1	.107	4.00	.0268	Flattened
-3	.107	8.00	.0134	Circular
-5	.076	4.00	.0190	Flattened
-7	.076	8.00	.0095	Circular

The test section will be fabricated from either stainless steel or Hastelloy-X with a cladding of copper over the crown portion of the tube along the full length of the tube. The back side of the tube will be closed with a thin metal plate welded to the tube in place of the steel nozzle jacket.

The electrical heating current will be concentrated in the copper because of the difference in resistivity between the copper and the steel tube. The local heat input will vary as the crown radius of the tube varies, simulating the variable heat flux in both the circumferential and axial directions. The design of the full-scale U-tube test section is illustrated in Figure 49.

Test data from each test will include local static pressure, local wall temperature and voltage and current measurements, which in combination with the geometry, will permit the computation of power input local heat flux and local bulk temperature. The final design of the test section will be predicated on the results of a similar Nerva coolant passage U-tube test section currently being fabricated.

Status: The actual design of the test section will be initiated when the U-tube design has been established.

(5) Gas-Side Test Program

(a) Summary

The objective of the gas-side test program is to better characterize gas-side heat transfer coefficients of the Phoebus-2 nozzle through scale model experiments. Work accomplished includes:

- 1 Completion of detailed design of the full axisymmetric scale nozzle (1/9 scale size)
- 2 Final definition and placing of purchase orders for the required heat flux calorimeters.

SINGLE U-TUBE TEST SECTION

Figure 49

Future activities of the gas-side test program will include fabrication and testing of the full axisymmetric scale model nozzle. In addition, necessary modifications will be made to an existing Nerva wedge motor to permit gas-side testing with a significantly lower scale factor (1/2 scale size).

(b) Method of Analysis

A continuing evaluation of the available literature on gas-side heat transfer to nuclear nozzles indicates that there is such a scatter of data resulting from factors that are yet undetermined that it is not possible to obtain a correlating equation which relates the experimental data with sufficient precision to permit realistic design of nuclear nozzles without supporting studies on nozzle contours and flow conditions specific to the intended design. The region of primary interest for detailed heat transfer characterization lies between the core exit plane and the throat where the influence of nozzle convergence angle, core exit/nozzle convergence plane separation, core support structure, and core exit geometry on the gas-side heat transfer will predominate. The applicability of scale model heat transfer data derived from the proposed program to the Phoebus nozzle design will be considerably enhanced by the availability of full-scale Nerva nozzle data from both chemical simulation and nuclear NRX test firings.

There is supporting evidence from model studies conducted at Aerojet with the Nerva wedge motor and from data analysis of the recent NRX-A2 test that local heat transfer coefficients in the convergent section of the nozzle are higher than anticipated for normal turbulent flow conditions. This observation points to the need for experiments that will characterize gas-side heat transfer as a function of the following parameters:

1 Reactor core exit geometry - size and spacing of fuel element orifices.

2 Core support structure - configuration of the core support structure as it affects gas flow into the nozzle plenum.

3 Core exit/nozzle convergence plane separation - effect of gas flow development distance and impingement of discrete gas jets on the convergent section of the nozzle.

4 Nozzle convergence angle - a smaller convergence angle should moderate local gas impingement effects and result in improved boundary layer development (that is, less than the 45° angle in Nerva nozzle).

In the past, the use of film cooling in nozzles which have had marginal regenerative cooling have resulted in overall improvement of the engine system. The availability of the stated peripheral coolant for the Phoebus nozzle does not necessarily imply that a high margin of safety for the nozzle achieved by film cooling is desirable. To the contrary, indiscriminate use of the peripheral coolant for film cooling may actually be detrimental to the overall test objectives if it reduces the nozzle coolant temperature rise to prevent achievement of the minimum inlet temperature required for core reactivity purposes. Thus a necessary portion of the gas-side heat transfer program will be to determine the film cooling effectiveness of the peripheral coolant as effected by the gas impingement effects stated above.

(c) Test Program

The basic test model for gas-side heat transfer tests will employ uncooled subscale nozzle models shaped to the required contour with associated core exit simulators and instrumented with calorimeters at appropriate locations to obtain heat transfer data. The region of primary interest for detailed heat transfer characterization lies between the core exit plane and the throat where the influence of core exit/nozzle convergence plane separation and core exit geometry will predominate. Parametric variation from the nominal Phoebus-2 nozzle configuration for effects due to plane separation and core exit geometries will be conducted in the main with the 1/9-scale model since it facilitates planned changes in test condition and minimizes costs. As the program progresses and the nozzle details become more firm, it is planned to conduct a limited number of experiments with the 1/2-scale wedge motor to confirm findings with the 1/9-scale model and to better establish scaling parameters applicable to the full scale nozzle.

Both nitrogen and hydrogen at temperatures up to 1600°R will be employed as exhaust gases for this program in order to fully evaluate effects of transport properties on local heat transfer coefficients. A typical block of tests for a specific set of nozzle geometric parameters (nominal nozzle contour and core exit simulator plate at the nominal separation from nozzle convergence plane) is shown in Table 6. Other combinations of nozzle geometric parameters (that is, without core exit simulator plane) will be evaluated but on a more limited basis.

(d) Scale Model Nozzles

The initial scope of the gas-side test program was directed toward evaluating the effects of various nozzle geometric parameters cited in the previous section on the gas-side heat transfer coefficients under Phoebus-2 flow conditions. The characterization was to be accomplished through parametric experiments conducted with several scale model nozzles which would incorporate selected geometric factors that would have the greatest effect on the gas-side heat transfer coefficients. However, during the course of the program, it became more evident that the candidate Phoebus-2 nozzle contour would be very similar to existing Nerva nozzles. Thus the scope of the program was redirected toward evaluating in more detail gas-side heat transfer behavior with the single nozzle contour.

1 Full Axisymmetric Scale Nozzle

Final detailed design of the full axisymmetric scale nozzle (1/9 scale size) has been completed. This scale model nozzle (shown in Figure 50) will be tested at the hot-gas flow facility located at the Von Karman Center. The instrumentation bosses located on the nozzle contour (total of 19) have been designed to accept calorimeters with a circular sensing area of no larger than 0.125-in. diameter. A total of ten calorimeters have been ordered so that for any single test, up to ten stations will be monitored for heat transfer data, while the remaining nine stations will monitor local static pressure through the use of fittings which are identical in external geometry as the calorimeters. In this

Table 6

PHOEBUS-2 GAS-SIDE EXPERIMENTS						
RUN NO.	TIME	TYPE	FLUID	M _w	P _{pc} PSI	T _{pc} °R
1		PRESSURE PROFILE	N ₂	28	0-700 -0	1600
2		"	H ₂	2	0-700 -0	1600
3		HEAT TRANSFER	N ₂	28	650	1600
4		"	N ₂	28	"	1600
5		"	H ₂	2	"	1000
6		"	"	"	"	1000
7		"	"	"	"	1600
8		"	"	"	"	"
9		"	"	"	"	"
10		"	"	"	"	"

Figure 50
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SCALE MODEL PHOEBUS NOZZLE

manner, by relocating calorimeters with static pressure taps from one test to another, it will be possible to obtain heat transfer and pressure profile data at identical stations and provide a method for normalizing data resulting from minor changes in hot gas flow conditions. The core exit simulator plate has been designed to permit studies on core exit effects at four discrete separation distances from the nozzle convergent section.

2 Wedge Motor

Recognizing the rather large scale factor associated with the full axisymmetric scale model nozzle, an alternate scale model with a significantly lower scale factor will be employed. The basic concept is that of a wedge motor which is a representation of a longitudinal sector from a full axisymmetric nozzle. The main benefit of this model is that, by the use of a longitudinal sector of a nozzle in contrast to the full axisymmetric nozzle, it is possible to reduce the scale model factor significantly when the available flow rate of heated gas is limited. The 48° wedge motor designed and tested for Nerva hot bleed port studies was full scale with respect to the Nerva nozzle. With currently available heated hydrogen sources for this program, a scale factor of approximately $1/2$ is obtained, whereas a full axisymmetric nozzle results in scale factor of $1/9$. Since a significant area of study would be involved with gas flow impingement effects as affected by reactor core exit geometries and film cooling effect from peripheral coolant flows, it would be difficult at best to simulate the possible detailed fine structure of reactor core exit geometries and the distribution of peripheral coolant on a scale as small as $1/9$. Therefore, the conduct of meaningful experiments to investigate these effects dictate the need of a wedge motor model. The 48° wedge motor depicted in Figure 51 employed for Nerva hot bleed port studies is available for this program and can be used with minor modifications for a scale model nozzle with a 45° convergence angle.

(e) Instrumentation

The gas-side heat transfer coefficient, as currently predicted for the Phoebus-2 nozzle, is shown in Figure 52 as a plot of C_g -vs-area ratio,

HALF-SCALE WEDGE MOTOR

Figure 51

where C_g is the coefficient in the simplified Bartz equation (Reference 6). This C_g profile is based upon all applicable scale model data and analysis of the NRX-A2, EP-IV-A data. Additional experimental data specific to the Phoebus-2 contour will be obtained through this test program with emphasis at locations where effects caused by gas flow impingement and core exit geometry are considered to be significant but as yet uncharacterized. Test data will also be obtained at and near the nozzle throat where maximum wall temperatures and heat fluxes will occur. The selected area ratios where heat transfer data will be obtained are shown on the C_g profile in Figure 52. The corresponding locations of the heat flux calorimeters on the scale model nozzle are shown schematically in Figure 53. To minimize effects from possible flow perturbations on the heat transfer data, these calorimeter stations will be circumferentially displaced from each other.

Data sensing and subsequent recording and reduction method that will be employed on this program is shown in Figure 54. This setup is essentially the same as that currently employed on the scale model exhaust duct studies to take full advantage of a system that has been checked out and is currently operational.

b. Adapter

(1) Summary

The adapter is used in conjunction with the nozzle simulation testing; it connects the 59-in. I.D. nozzle to the 21-in. I.D. injector at a converging angle of 45 degrees. The coolant enters the large diameter end and exits into the injector; the coolant flow path is approximately 26-in long.

Preliminary heat transfer analysis of the U-tube adapter design resulted in the selection of a preliminary tube design consisting of 320 stainless-steel tubes of 0.014-in. wall thickness, and 0.090-in. constant leg height. Although this design is within the various design limitations, (discussed later in more detail), the predicted maximum gas-side wall temperature is 1980°F. However,

Figure 52

1/9 SCALE NOZZLE CALORIMETER STATIONS

Sensing and Conditioning System

Recording System

Playback and Data Reduction System

DATA RECORDING & ACQUISITION SYSTEM

this temperature is believed to be conservatively high because of the assumptions used for this preliminary design, and a more detailed investigation will be made to achieve a more realistic lower wall temperature prediction. The predicted pressure drop for the adapter is approximately 400 psi. The temperature and pressure drop noted are for a chamber pressure of 750 psia and mixture ratio of 5.5.

(c) Method of Analysis

The U-tube design analysis was conducted utilizing the 7001 IBM Computer Program 8047 (Reference 3). This program calculates various heat transfer parameters of regeneratively cooled nozzles and makes possible the rapid prediction and optimization of nozzle heat transfer.

The coolant-side heat transfer correlation used for this analysis was 85% of the Hess and Kunz (Reference 4) correlation which is the same correlation used for the nozzle analysis for straight tube sections.

The simplified Bartz correlation (Reference 5) was utilized for the hot gas heat transfer coefficient with design multiplying factors to account for uncertainties near the injector such as combustion turbulence, uneven mixture ratio and undeveloped boundary layer. The factor varied linearly from two at the injector end to 1.23 at the nozzle end of the adapter which coincides with the value used for the nozzle simulation analysis.

An extensive parametric study of the adapter, (Figure 55) was conducted where the chamber pressure, combustion efficiency, number of tubes, leg height, and tube radius were varied. However, this section will be limited to discussions at a chamber pressure of 750 psia, mixture ratio of 5.5, combustion efficiency of 95%, and a tube wall thickness of 0.014 in.

INJECTOR/NOZZLE ADAPTER

REGENERATIVELY COOLED

TYPICAL U-TUBE CROSS SECTION

Figure 55

(3) Results

The design summary results of the parametric study is shown in Figure 56, where the maximum gas-side wall temperature is plotted-vs-U-tube leg height for various number of tubes. This maximum temperature occurred at the forward end of the adapter adjacent to the injector. The curves indicate that varying the number of tubes does not appreciably decrease the wall temperature.

There are three design limits indicated on this figure. The minimum leg height limit (0.050 in.) and tube radius limit (0.080 in.) were limits selected for the convenience of fabrication. The maximum total pressure drop limit (500 psi) was determined by test facility limitations.

The design selected will have to be above the pressure drop limit, to the right of the leg height limit, and above-and to the left of-the tube radius limit. The recommended best design selected was 320 tubes and 0.090-in. leg height, which satisfied all the imposed limits.

The pressure profile of the selected design is shown in Figure 57 and it is typical for the adapter. The static pressure curve indicates that the majority of the pressure drop occurs at the forward end where the coolant velocities are high. The other two curves show the magnitudes of the frictional and velocity head losses; the latter is approximately four times the former. These pressure losses are the ones predicted in the U-tube only and do not include the entrance and exit losses. Calculations have indicated that approximately 250-psi exit losses will be experienced for the selected design; this is over 50% of the total adapter pressure drop of approximately 490 psi. This high exit loss is a result of the high coolant exit velocity - (890 ft/sec).

Figure 58 presents the tube wall and coolant bulk temperature profile for the recommended design, which is again typical for the adapter. There is an increasing gas-side to coolant-side wall temperature difference towards the forward end of the adapter caused by the increasing heat flux which for a

ADAPTER DESIGN SUMMARY

Figure 56

ADAPTER COOLANT PRESSURE PROFILE

FIGURE 57

ADAPTER TUBE TEMPERATURE PROFILE

Figure 58

constant tube wall thickness results in an increasing temperature drop across this wall. The bulk temperature curve increases almost linearly because of the increasing heat flux and decreasing heat transfer area as the adapter converges to the injector.

The predicted gas-side wall temperature of 1980°F is believed to be conservative. One of the reasons for this belief is the assumption of 95% combustion efficiency adjacent to the injector face. It is highly unlikely to have such a complete combustion within 2- to 3-in. of the injector face. Calculations have indicated that if 80% were assured in this region, the 1980°F temperature would decrease to less than 1600°F. Another reason is the factor of two applied to the gas-side heat transfer coefficient. This is believed to be conservative and an investigation will be made to determine if a more realistic value should be utilized.

(4) Alternate Design

In order to cover all aspects of an adapter design, various other design schemes were investigated in the preliminary design phase of the program.

(a) Thermal Barriers

Figure 58 indicates that if the gas-side temperatures were lowered in the region from 6- to 10-in. axial distance, this design selected would predict satisfactory wall temperatures. Heat transfer analysis was conducted to determine the effect of thermal barriers applied to this forward region. One of the thermal barriers considered is a composite consisting of 85W-12ZrO-3Si. Extensive laboratory tests indicated that these composites were very durable to thermal shocks. This particular thermal barrier was tested successfully on a full scale Titan II chamber with over 500 sec of duration in three tests under the Product Improvement Program. Figure 59 indicates the effect of the increasing thermal resistance (ratio of barrier thickness to thermal conductivity) on the wall temperatures. As the thermal resistance is increased from

THERMAL BARRIER DESIGN SUMMARY

Figure 59

50- to 250-in²sec°R/Btu, the gas-side barrier temperature increases from approximately 2500 to 3500°F and the tube temperature under the barrier decreases from approximately 1800 to 900°F. The composite considered has a thermal conductivity of 16×10^{-5} Btu/in.sec°R and, therefore, a 0.020-in. barrier thickness which results in a thermal resistance of 125 in²sec°R/Btu. The predicted barrier temperature would then be approximately 3000°F and the corresponding tube temperature would be 1200°F, both acceptable from a design standpoint. This barrier will decrease the bulk temperature rise by approximately 7°F and the pressure drop decrease by approximately 50 psi; however, extensive development work will have to be conducted to determine the effect of the Phoebus simulation condition (thermal cycling to cryogenic temperature) on the thermal barriers.

(b) Film Cooling

Film cooling the forward end would also decrease the gas-side wall temperatures. Preliminary calculations indicates that 2% of the full flow at 750 psia chamber pressure would decrease the wall temperature by approximately 10°F and 20 psi, respectively. These changes are small because the film is effective only in the forward end of the adapter.

(c) Ablative Material

The use of ablative material was also considered for the forward end of the adapter, the aft end remaining as a U-tube design. A study is currently being made to determine the selection of the proper ablative material and the estimation of the char, erosion, and gasifying rates.

2. Nuclear Analysis

The nuclear analysis results obtained during Phase I of the Phoebus-2 nozzle program are summarized in this section. These results include a detailed specification of the nuclear heating rate distributions within the nozzle jacket, interface flange, and support skirt for the reference configurations. In addition, data are provided which define the nozzle region radiation environment during

operation and the neutron induced activity in the nozzle as a function of time after a 20-minute full power firing.

Neutron induced activity as a function of time following a 20-minute full power firing is given in Figure 6 Page 12, Vol. II. Extrapolation to the reference condition of three 30-minute firings, or of any combination of firing durations, can be obtained by a linear superposition of dose rates beyond 10-days following each firing. These data were obtained from a series of calculations using the TDC code, the ACT-II code, and the QAD-P5 code. Activation of the cobalt content in Hastelloy X is the principal constituent of the 22 R/hr dose rate beyond 10 days following shutdown.

Table 7 provides the total nuclear heating rates at 81 point locations within the various nozzle components. The data in Figure 3 Page 6, Vol. II will help identify the receiver point locations on the nozzle. The total nuclear heating rates shown include the contributions from primary gamma rays produced in the reactor core; from secondary gamma rays produced by neutron absorption in the nozzle, in the clamshell side shield, and in non-core components of the reactor; and from energy deposition by elastic scattering of fast neutrons. Because of various computational uncertainties a design margin of 25% is recommended when using these results.

Contour maps of the full power gamma ray dose rates and fast neutron flux ($E_n < 0.9$ Mev) are given in Figures 23 (Page 75) and 24 (Page 76), Vol. II. The gamma ray data were generated with QAD-P5 point kernel code and the neutron flux data were generated with the TDC neutron transport code.

The nuclear analysis work is described in detail in Volume II of this report, which deals solely with this subject.

TABLE 7

SUMMARY OF NUCLEAR HEATING IN THE PHOEBUS-2 NOZZLE
(Reference Configuration)

<u>Detector No.</u>	<u>R(in.) 1/</u>	<u>Z(in.) 2/</u>	<u>Nuclear Heating Rates (Btu/in³-sec) 3/</u>
1	30.0	15.0	0.6882
2	30.1	15.0	0.6338
3	30.2	15.0	0.5766
4	30.0	12.0	0.7270
5	30.1	12.0	0.6300
6	30.2	12.0	0.5438
7	30.0	9.0	0.6623
8	30.1	9.0	0.5702
9	30.2	9.0	0.4948
10	30.0	6.0	0.6461
11	30.1	6.0	0.5561
12	30.2	6.0	0.4861
13	30.0	3.0	0.6379
14	30.1	3.0	0.5473
15	30.2	3.0	0.4745
16	30.0	0.0	0.5112
17	30.1	0.0	0.4363
18	30.2	0.0	0.3796
30	31.15	-0.01	0.3188
31	31.70	-0.01	0.2467
32	32.37	-0.01	0.2084
33	33.0	-0.01	0.1888
34	33.62	-0.01	0.1720
35	34.05	-0.01	0.1433
36	34.45	-0.01	0.1358
37	29.86	-0.62	0.2548
38	31.15	-0.62	0.2085
39	31.70	-0.62	0.1538
40	32.37	-0.62	0.1227
41	32.95	-0.62	0.1092
42	33.62	-0.62	0.0982
43	34.05	-0.62	0.0906
44	34.45	-0.62	0.0842

TABLE 7 (cont.)

<u>Detector No.</u>	<u>R(in.) 1/</u>	<u>Z(in.) 2/</u>	<u>Nuclear Heating Rates (Btu/in³-sec) 3/</u>
45	29.6	-1.18	0.6237
46	30.0	-1.18	0.3876
47	30.5	-1.30	0.2126
48	31.1	-1.28	0.1354
49	31.7	-1.25	0.1046
50	32.37	-1.18	0.0834
51	32.95	-1.13	0.0748
52	33.5	-1.1	0.0711
53	29.4	-1.65	0.6436
54	29.75	-1.78	0.4209
55	30.18	-1.95	0.2486
56	30.65	-1.95	0.1544
57	29.15	-2.12	0.6580
58	29.45	-2.35	0.3922
59	29.75	-2.6	0.2854
60	29.95	-2.72	0.2282
61	28.8	-2.78	0.6360
62	29.0	-3.0	0.4540
63	29.3	-3.28	0.3030
64	26.6	-5.0	0.7526
65	26.85	-5.25	0.5111
66	27.15	-5.5	0.3477
67	23.62	-8.0	0.7884
68	23.82	-8.25	0.5294
69	24.02	-8.5	0.3693
70	20.59	-11.0	0.7948
71	21.83	-11.2	0.5313
72	21.06	-11.4	0.3713
73	17.56	-14.0	0.7585
74	17.75	-14.2	0.4418
75	17.95	-14.4	0.3796
76	14.6	-17.0	0.7515
77	14.76	-17.2	0.5162
78	14.92	-17.4	0.3737

TABLE 7 (cont.)

<u>Detector No.</u>	<u>R(in.) 1/</u>	<u>Z(in.) 2/</u>	<u>Nuclear Heating Rates (Btu/in³-sec) 3/</u>
79	11.55	-20.0	0.7407
80	11.69	-20.16	0.5408
81	11.85	-20.32	0.3881

1/ R is the radial distance from the centerline (axis) of the nozzle.
(See Figure 3 of Volume II)

2/ The coordinate origin (Z=0) is at the pressure vessel-nozzle flange interface with the positive sense forward.(See Figure 3 of Volume II)

3/ These are heating rates in Hastelloy-X for which a design margin of 25% is recommended.

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4. H. L. Hess and H. R. Kunz, "A Study of Forced Convection Heat Transfer to Supercritical Hydrogen" ASME Paper No. 63-WA-205, 1963.
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9. L. Schoenman, "Film Cooling Requirements for Phoebus Workhorse Chamber"; ETDR 9650:009, 27 August 1964.
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C. STRESS AND VIBRATION ANALYSIS - TASK C

1. Interface Task Force

a. Introduction

The Interface Task Force consisting of personnel from Aerojet-General, ACF Industries, and Los Alamos Scientific Laboratory met for the first time on 1 March in Albuquerque. At that time, nine preliminary nozzle-pressure vessel configurations which had been prepared by ACF Industries were evaluated (Figures 60 through 68). Configurations 6, 7, and 8 were eliminated from further consideration because of the large size forgings necessary. Configuration 4 was rejected because of the excessive discontinuity stresses which would be induced in the nozzle flange and pressure vessel, and because of a potential sealing problem. Configuration 3 was eliminated because of possible fabrication difficulties in making a "U" tube nozzle in a bell shaped convergent section. Configuration 9 was considered desirable because it would eliminate bolting problems. However, since the nozzle would have to be loaded through the forward end of the pressure vessel, it could not be removed or replaced without removing the reactor. Because of this undesirable feature, it too was rejected. Configurations 1 and 2 appeared to be quite similar. Notes on the original drawing of Configuration 1 indicated that no shear lip had been intended.

The final decision was to proceed with Configurations 2 and 5 (Figures 61 and 64). It was decided to perform a complete heat transfer analysis, pressure (mechanical) stress analysis, and thermal stress analysis on these two configurations to compare the merits of each. These two configurations were designated as "FLAT" (Figure 61) and "CANTED" (Figure 64).

These configurations are shown in cross section in Figure 69. Except for the flange area and length of the nozzle skirt the models are identical. The differences in the length of the nozzle skirts

are due to geometrical differences in the two pressure vessel configurations. Based on NERVA experience a 45° convergence angle was chosen. The FLAT model has an interface normal to the engine centerline while the CANTED interface is at 45° to the centerline. It can be seen that the offset in load line between the nozzle shell and pressure vessel in the CANTED model results in a discontinuity not present in the FLAT model. When a preliminary analysis of the CANTED nozzle showed large interface moments and discontinuity bending stresses, it was suggested that the offset could be reduced by inserting the bolts at an angle to the interface or by changing the interface angle. The first suggestion would impose additional fabrication and assembly problems and would mean redesigning the joint. The second suggestion would also require a redesign and as the interface angle was increased the joint would approach the FLAT model. Since the original intent was to determine the relative merits of two types of joints, it was decided to proceed with the model unchanged.

During March and April mechanical (pressure) and thermal stress analyses were performed on each model. In addition, a parametric study was conducted on the FLAT model to determine the effect of shell and skirt thicknesses in conjunction with two pressure vessel designs. Due to the geometry of the CANTED model, it was not feasible to conduct a similar study on this model. Since the inside surface dimensions were set by tube bundle design, adding thickness to the nozzle shell would require moving the bolt circle and would require redesign of the flange and pressure vessel.

During the basic and parametric study, the interface loads were determined for 21 nozzle-pressure vessel combinations. A complete thermal stress analysis was performed for 11 combinations, and final mechanical stresses for 10 combinations.

At the design review held in Albuquerque on 13 April, stress analyses of the FLAT-A21 and CANTED-A12 nozzles were presented. These analyses showed the FLAT configuration to have lower stress levels and interface loads than the CANTED configuration. On this basis, it was decided to abandon the CANTED configuration and complete a detailed analysis of the FLAT model.

Figure 60
CONVENTIONAL RN-6 TYPE NOZZLE END
CONFIGURATION #1

Figure 61
CYLINDRICAL FLANGE NOZZLE END WITH RN-6 TYPE NOZZLE
CONFIGURATION #2

Figure 62

CYLINDRICAL FLANGE NOZZLE END WITH MODIFIED NOZZLE
CONFIGURATION #3

Figure 63

CYLINDRICAL FLANGE NOZZLE END WITH MODIFIED NOZZLE AND CLAMPED JOINT
CONFIGURATION #4

Figure 64
CANTED FLANGE NOZZLE END
CONFIGURATION #5

Figure 65
LARGE DIAMETER NOZZLE WITH CLAMPED JOINT
CONFIGURATION #6

Figure 66
LARGE DIAMETER NOZZLE WITH BOLTED JOINT
CONFIGURATION #7

Figure 67
LARGE DIAMETER NOZZLE WITH CANTED BOLTED JOINT
CONFIGURATION #8

Figure 68
INTERNALLY SUPPORTED NOZZLE
CONFIGURATION #9

FLAT & CANTED JOINT DETAIL

FLAT
CONFIGURATION

CANTED
CONFIGURATION

Figure 69

After the design review the mechanical and thermal stress analyses proceeded on the FLAT-C model. Although basically similar to the "A" series, it was designated as "C" to prevent confusion with preceding analyses. A stress report on the FLAT-C11 configuration was prepared and is included in this document as Appendix B*.

In March a basic loads document, "Phoebus-2 Pressure Vessel/ Nozzle Interface Analysis, Part 1 - Load Analysis" (Ref. 1) was prepared. Loads were computed for both the FLAT and CANTED models.

b. Methods of Analysis

The method of analysis used for shell stresses is outlined in LAMS 3083, "A Digital Computer Method for Design and Analysis of Axisymmetric Thin Shells Subjected to Pressure and Thermal Environments," (Reference 2). This analysis method is incorporated in the "Plastic-Elastic Thin Shells of Revolution" (PETS) computer code, (Reference 3). The PETS code is an extension of the LASL Stress and Deflection (SAD) code. The basic computer solution is the same for both codes; however, the SAD code utilizes a least squares curve fitting technique using three input points at a time. The PETS code proved to be a more versatile code and the time saved in using this code was significant.

This code was used to determine influence coefficients, thermal stresses, and final mechanical stresses.

The method used to determine the loads at the nozzle-pressure vessel interface is based on ring analysis. The nozzle is mathematically "cut" at the flange (Figure 70) into three sections, shell, skirt and flange. Using the PETS code, the deflection and rotation of the nozzle shell at the junction with the flange due to pressure only is determined, considering the shell as a free body. The deflection and rotation due to a unit moment and a unit shear are then determined in a similar manner. From these influence coefficients the equations for the deflection and rotation of the nozzle shell can be written in terms of the

*ACF Industries Stress Report

NOZZLE PRESSURE VESSEL FREE BODY DIAGRAM

Figure 70

unknown moment (M_3), shear (H_3) and a constant (due to pressure P_2). Equations are written for the deflection and rotation of the nozzle skirt and pressure vessel in a similar manner. The nozzle flange is considered to be a rigid body (Figure 71). The equations of equilibrium are written in terms of the known loads V_1 , V_2 , V_3 and pressures P_1 and P_2 , and the unknown shears and moments, H_1 , H_2 , H_3 , M_1 , M_2 , and M_3 . The vertical loads V_1 and V_2 are obtained from the ejection load and nozzle skirt load (Reference III-C-4) and V_3 is calculated from the summation of vertical forces. The rotation of the ring and deflections at points 1, 2, and 3 are obtained as shown on Figure 71. These equations are combined with the previous equations to form a set of simultaneous equations which are solved by computer for the unknown shears, moments, rotations, and deflections. The moments and shears thus obtained are then entered in the PETS code as end boundary loads in place of the unit loads previously used. The output results in a complete stress and deflection survey of the components.

The thermal stress pattern is obtained in one computer run for the FLAT model. Since the thermal case is run without pressure, there is no resulting axial load and it is not necessary to ensure radial compatibility of the load line at regional junctions. It is only necessary to simulate the shell mass and temperatures. Each region is divided into a sufficient number of layers and stations to ensure an adequate thermal profile. The proper material mechanical properties and temperatures are used for each input point, and the computer output describes the thermal stress profile along the surface and at the layer interfaces, thus enabling a thermal stress profile across the vessel wall to be obtained.

c. Allowable Stresses

From NERVA program experience it was known that radial and meridional thermal gradients would produce stresses above the material yield point when calculated by an elastic analysis. Since an analytical method for determining stresses in the plastic region was not available, it

NOZZLE RING - FREE BODY DIAGRAM

The rotation of the ring in terms of forces acting on it, is;

$$\theta_{cg} = \frac{M_{cg} R_{cg}^2}{E I} \quad \text{and}$$

$$\theta_{cg} = \theta_{shell} = \theta_{skirt} = \theta_{p.v.}$$

The radial deflection of the ring is:

$$U_{cg} = \frac{H_{cg} R_{cg}^2}{E A}$$

The radial deflection of the skirt, shell, and pressure vessel are:

$$U_{skirt} = U_{cg} - d_2 \theta_{cg}$$

$$U_{shell} = U_{cg} + d_3 \theta_{cg}$$

$$U_{p.v.} = U_{cg} - d_1 \theta_{cg}$$

Figure 71

was decided that the methods outlined in the ASME Boiler Code (Reference 4) would be used to determine allowable stresses. The basic stress categories given in the ASME code are primary, secondary, and peak. These stresses are defined in Table 8, which is a reproduction from the ASME code of that portion of the stress categories encountered in the stress analysis of the Phoebus-2 nozzle. The secondary stress in the nozzle is bending, caused by changes of direction in load path and by changes in shell thickness. The stress due to a thermal gradient is a peak stress. These stress classifications are shown in Table 9, which is also reproduced from the ASME code. The allowable stress, S_m , to which primary stresses are compared was set by the task force at 80% of the material yield stress, at the temperature of the point being checked. The allowable secondary stress, $2.5 S_m$, is taken as twice the yield stress or the ultimate stress, whichever is lower, again considering temperature. The allowable Peak stress, S_a , is shown in Figure 72, which is reproduced from the ASME code. Although Hastelloy-X is not included in the materials here, it is expected that such a curve for Hastelloy-X will be quite similar. Until such a curve is obtained from the materials test program, the allowable peak stresses given in Figure 72.

The yield stress versus temperature used in the analyses and other material properties are shown in "Phoebus-2 Pressure Vessel/Nozzle Interface Analysis, Part IV-Stress Analysis" (Appendix B).

d. Analysis

During the basic and parametric study, twenty-one nozzle-pressure vessel combinations were investigated. These are shown in Table 10, which shows the amount of analysis performed on each model.

The preliminary shell was sized such that the thickness was 0.75" at the tangent to the outside flange blend radius. From this point the shell was tapered uniformly to 0.38" at the tangent to the throat radius.

STRESS CATEGORIES AND LIMITS OF STRESS INTENSITY
(FROM ASME BOILER CODE, SECTION 3, 1964)

STRESS CATEGORY	GENERAL MEMBRANE	SECONDARY MEMBRANE PLUS BENDING	PEAK
DESCRIPTION	AVERAGE PRIMARY STRESS ACROSS SOLID SECTION. EXCLUDES DISCONTINUITIES AND CONCENTRATIONS. PRODUCED ONLY BY MECHANICAL LOADS.	SELF-EQUILIBRATING STRESS NECESSARY TO SATISFY CONTINUITY OF STRUCTURE. OCCURS AT STRUCTURAL DISCONTINUITIES. CAN BE CAUSED BY MECHANICAL LOAD OR BY DIFFERENTIAL THERMAL EXPANSION. EXCLUDES LOCAL STRESS CONCENTRATIONS.	(1) INCREMENT ADDED TO PRIMARY OR SECONDARY STRESS BY A CONCENTRATION. (NOTCH) (2) CERTAIN THERMAL STRESSES WHICH MAY CAUSE FATIGUE BUT NOT DISTORTION OF VESSEL SHAPE.
	P_m	Q	F

F_y = YIELD STRESS

S_a = FATIGUE STRESS ALLOWABLE

TABLE 8

CLASSIFICATION OF STRESSES FOR SOME TYPICAL CASES

(FROM ASME BOILER CODE, SECTION 3, 1964)

VESSEL COMPONENT	LOCATION	ORIGIN OF STRESS	TYPE OF STRESS	CLASSIFICATION
NOZZLE	CROSS SECTION PERPENDICULAR TO NOZZLE AXIS	INTERNAL PRESSURE OR EXTERNAL LOAD OR MOMENT	GENERAL MEMBRANE AV. ACROSS FULL SECTION. STRESS COMPONENT PERPENDICULAR TO SECTION	P_m
		EXTERNAL LOAD OR MOMENT	BENDING ACROSS NOZZLE SECTION	P_m
	NOZZLE WALL	INTERNAL PRESSURE	GENERAL MEMBRANE LOCAL MEMBRANE BENDING PEAK	P_m P_L Q F
		DIFFERENTIAL EXPANSION	MEMBRANE BENDING PEAK	Q Q F
CLADDING	ANY	DIFFERENTIAL EXPANSION	MEMBRANE BENDING	F F
ANY	ANY	THERMAL GRADIENT THRU PLATE THICKNESS	BENDING	F
ANY	ANY	ANY	STRESS CONCENTRATION (NOTCH EFFECT)	F

ALLOWABLE AMPLITUDE OF ALTERNATING STRESS INTENSITY, S_a ,
FOR 18-8 STAINLESS STEELS AND NICKEL-CHROME-IRON ALLOY^a,
(FOR METAL TEMPERATURES NOT EXCEEDING 800°F).

Figure 72

TABLE 10
NOZZLE-PRESSURE VESSEL MODELS

CODE	Influence Coefficients			Matrix Solution	Thermal Stresses	Mechanical Stresses
	Shell	Skirt	P.V.			
Flat - A11	x	x	x	x		
Flat - A21	x	x		x	x	x
Flat - A22			x	x	x	x
Flat - A31				x	x	
Flat - A32	x			x		x
Flat - A41	x			x	x	x
Flat - A42				x		x
Flat - A51		x		x	x	
Flat - A52				x	x	x
Flat - A61				x	x	
Flat -(A20 + B01)			x	x		
Flat -(A50 + B01)				x		
Flat - C11	x	x	x	x	x	x
Flat - C31		x		x	x	x
Flat -(C10 + A01)				x		
Flat -(C10 + A02)				x		
Flat -(C30 + A01)				x		
Flat -(C30 + A02)				x		
Canted - A11	x	x	x	x		
Canted - A12			x	x	x	x
Canted - A14			x	x		

For the parametric study the thickness of 0.38" remained constant and the shell was uniformly tapered to the thickness indicated. Consideration was taken of the tube grooves based on NERVA experience and the chosen factor of safety. See Figure 73 for final flange dimensions.

As the parametric study proceeded it was evident that changing the shell or skirt thickness, or both, affected the interface loads (especially moment) significantly. This is shown in tabular form in Tables 11, and 12. Table 11 lists the moments and shears (from the matrix solution) due to mechanical loads at the interface, nozzle shell, and nozzle skirt. Table 12 lists the interface loads, rotations, and deflections for the thermal, mechanical, and combined cases.

Pertinent cases from these tables are shown graphically in Figures 74, 75, and 76. Figure 74 shows the effect of shell and skirt thickness on the interface moment for mechanical loads. Increasing the shell thickness decreases the mechanical moment, while increasing the nozzle skirt thickness increases the moment. From Table 11 it is seen that the interface mechanical moment is negative for all FLAT models. A negative moment tends to open a gap at the seal. Figure 75 shows thickness effect on the thermal moment. Here an increase in shell thickness increases the interface moment. This is due to the higher temperature gradients in the thicker shells. Increasing the skirt thickness reduces the moment due to the stiffening effect of the skirt. Figure 76 shows the combined thermal and mechanical moments versus thickness.

After the C model nozzle was designed it was decided to determine the effect of pressure vessel design on interface moment. The ring equation matrix was solved using influence coefficients from three pressure vessel designs. The results are shown in Figure 77. Only the mechanical moments were determined. This figure shows that pressure vessel design has a significant effect on the interface moment. Any changes in either nozzle or pressure vessel design must be closely coordinated by the two project groups.

MODEL DIMENSIONAL THICKNESS - FLAT - C30

Figure 73

TABLE 11
FLANGE RING LOAD SUMMARY - MECHANICAL

MODEL	INCH-LB/INCH			LB/INCH		
	M ₁	M ₂	M ₃	H ₁	H ₂	H ₃
Flat - A11	-2565	2285	2940	13296	1440	9520
Flat - A21	-2967	2135	2918	13197	1503	9013
Flat - A22	-2320	2263	2423	13303	1570	8884
Flat - A31	-3661	2186	3857	13067	1513	9025
Flat - A32	-2938	2310	3267	13183	1580	8893
Flat - A41	-4380	2235	4793	12938	1520	9069
Flat - A42	-3574	2355	4097	13065	1586	8938
Flat - A51	-1988	3268	2985	13490	2190	8952
Flat - A52	-1225	3601	2541	13634	2321	8833
Flat - A61	-3333	3622	5028	13251	2248	9013
Flat-(A20+B01)	-5167	2146	4011	13960	1530	9507
Flat-(A50+B01)	-3148	4186	4187	14528	2696	9439
Flat - C11	-62	3219	2266	13094	2160	8816
Flat - C31	-558	2465	2182	12998	1761	8877
Flat-(C10+A01)	-2116	3357	3420	13409	2271	9361
Flat-(C10+A02)	-1351	3699	2950	13554	2405	9251
Flat-(C30+A01)	-2813	2511	3349	13203	1814	9405
Flat-(C30+A02)	-2133	2699	2838	13319	1905	9288
Canted - A11	394	811	-9725	14165	0	-10845
Canted - A12	5558	-969	-7698	16596	1016	-10471
Canted - A14	5966	-1025	-7530	16519	1063	-10363

Refer to Figures 70 and 71 for sign convention.

TABLE 12
INTERFACE LOADS, DEFLECTIONS AND ROTATIONS

MODEL	FORCE	U(inches)	B(radians)	M ₁	H ₁
Flat - A21	Thermal	-.026639	.018262	3100	-2889
	Pressure	.022544	.001841	-2967	13197
	Net	-.004095	.020103	133	10308
Flat - A22	Thermal	-.026947	.018571	2462	-2770
	Pressure	.023426	.001237	-2320	13303
	Net	-.003521	.019808	142	10533
Flat - A31	Thermal	-.027573	.021671	7336	-2061
	Pressure	.021736	.001212	-3661	13067
	Net	-.005837	.022883	3675	11006
Flat - A41	Thermal	-.025204	.025913	12772	-965
	Pressure	.020780	.000538	-4380	12938
	Net	-.004424	.026451	8392	11973
Flat - A51	Thermal	-.015739	.016592	-2053	-4509
	Pressure	.021086	.002254	-1988	13490
	Net	.005347	.018846	-4041	8981
Flat - A52	Thermal	-.016100	.016906	-2782	-4458
	Pressure	.021822	.001725	-1225	13634
	Net	.005722	.018631	-4007	9176
Flat - A61	Thermal	-.011520	.023307	5632	-3138
	Pressure	.019211	.000977	-3332	13251
	Net	.007691	.024284	2300	10113
Flat - C11	Thermal	-.038835	.015916	136	-3648
	Pressure	.018538	.002109	-62	13094
	Net	-.020297	.018025	74	9446
Flat - C31	Thermal	-.035013	.017258	2031	-3051
	Pressure	.020145	.001721	-558	12998
	Net	-.014868	.018979	1473	9947
Canted - A12	Thermal	.022263	.029796	+1191	-5620
	Pressure	.029481	.009510	5558	16596
	Net	.052744	.039306	6749	10965

Refer to Figures 70 and 71 for sign convention.

EFFECT OF NOZZLE SHELL THICKNESS ON MECHANICAL INTERFACE MOMENT

Figure 74

EFFECT OF SHELL & SKIRT THICKNESS ON THERMAL INTERFACE MOMENT

Figure 75

EFFECT OF SHELL & SKIRT THICKNESS ON NET INTERFACE MOMENT

Figure 76
160

EFFECT OF PRESSURE VESSEL DESIGN ON INTERFACE MOMENT

Figure 77

After preliminary analysis of the C model analysis showed this design to be desirable, detailed analyses were performed. The mathematical model was prepared in greater detail to provide a fine grid. The mechanical model was prepared to reflect the value of Young's Modulus at the operating temperature of the shell. The resulting mechanical, thermal and net interface moments are shown in Figure 78.

The geometry plots and mechanical and thermal stress plots for the FLAT-C31 nozzle-pressure vessel model are shown in Figures 79 through 93. The regional numbers are shown by vertical lines. In all cases, region 1 starts on the left side of the plot. The stresses are plotted in regional numerical sequence. Note that the thermal stress plots show the nozzle skirt stresses (regions 9 through 12) between the nozzle shell and pressure vessel stresses. The mechanical stresses for the pressure vessel are not shown here, but are shown in Appendix B.

The geometry plots and mechanical and thermal stress plots for the CANTED-A12 nozzle-pressure vessel model are shown in Figures 94 through 107. These are included for comparison with the FLAT model. The computer output listing stresses versus wrap distance are not included, but all output for all models is available at Aerojet-General for examination.

The flange stresses due to interface loads are shown in Figure 108 for reference. The analysis is discussed in greater detail in Appendix B.

The stress distribution across the shell wall in the hoop direction at the maximum stress point is shown in Figure 109. Note that the mechanical stress is well below the yield point of the material. The yield stress curve is plotted versus temperature. Further discussion and margins of safety are contained in Appendix B.

MOMENT AT INTERFACE - C MODEL

Figure 78

NOZZLE SHELL GEOMETRY

FLAT C30-1 MECHANICAL STRESS FLAT C31

Figure 79

NOZZLE SHELL MERIDIONAL STRESS INSIDE

FLAT C30-1 MECHANICAL STRESS FLAT C31

Figure 80

NOZZLE SHELL HOOP STRESS INSIDE

Figure 8₁

NOZZLE SHELL MERIDIONAL STRESS OUTSIDE

Figure 82

FIGURE 83

NOZZLE SKIRT GEOMETRY

FLAT C30 - 2 MECHANICAL STRESS FLAT C31

FIGURE 84

NOZZLE SKIRT MERIDIONAL STRESS INSIDE

FLAT C30-2 MECHANICAL STRESS FLAT C31

FIGURE 85

FIGURE 86

NOZZLE SKIRT MERIDIONAL STRESS OUTSIDE

FIGURE 87

FLAT C30-2 MECHANICAL STRESS FLAT C31

FIGURE 88

THERMAL STRESS GEOMETRY

FIGURE 89

FIGURE 90

FIGURE 91

THERMAL STRESS - MERIDIONAL OUTSIDE

FIGURE 92

THERMAL STRESS - HOOP OUTSIDE

FIGURE 93

CANTED A - 12 - 1 NOZZLE SHELL GEOMETRY

FIGURE 94

NOZZLE SHELL MERIDIONAL STRESS INSIDE

FIGURE 95

FIGURE 96

NOZZLE SHELL HOOP STRESS OUTSIDE

FIGURE 97

FIGURE 98

FIGURE 99

CORE SUPPORT HOOP STRESS INSIDE

CANTED A - 12 CORE SUPPORT

FIGURE 100

CORE SUPPORT MERIDIONAL STRESS OUTSIDE

FIGURE 101

FIGURE 102

CANTED A - 12 - 1 THERMAL STRESS GEOMETRY

FIGURE 103

FIGURE 104

FIGURE 105

THERMAL STRESSES - MERIDIONAL OUTSIDE

FIGURE 106

THERMAL STRESSES - HOOP OUTSIDE

FIGURE 107

FLANGE STRESS - C30 - 0

SHEAR STRESS, SECTION A:

SHEAR $\approx$ 12500 PSI
M.S. ± 0.50

STRESS IN SECTION B:

BENDING $= 34780.$ PSI

SHEAR $= 4780.0$ PSI
M.S. $= +0.34$

STRESS IN SECTION C:

$\sigma_{NET} = 34000$ PSI (INCLUDING A STRESS
CONCENTRATION FACTOR
OF 1.5)

M.S. $= + 0.59$

FIGURE 108

HOOP STRESS (MAX) - FLAT C30 - 1

FIGURE 109
194

For preliminary analysis, it was necessary to choose a bolt in order to size the nozzle flange and the mating pressure vessel. A 5/8" diameter bolt was chosen based on experience and availability from the NERVA Program.

The bolt load consists of two components, that due to mechanical forces and that due to thermal forces. The mechanical load is caused by the ejection load and interface moment (See Appendix B, pp 99-105). This load is independent of the bolt material properties, but is dependent on the number of bolts. The load due to thermal forces is not as easily defined since it is affected by bolt and flange temperatures and coefficients of thermal expansion. It is independent of the number of bolts. Preliminary analysis of two bolt materials, Inconel 718 and A-286, in conjunction with the Hastelloy-X flange, showed the thermal load in the A-286 bolt to be approximately 1200 lbs. greater than for a bolt of Inconel 718. The mechanical load is approximately 19,000 lbs. per bolt, based on 144 bolts. The recommended bolt preload to insure sealing is 21,000 lbs. The thermal load for an Inconel 718 bolt is approximately 8700 lbs. and for an A-286 bolt, is approximately 9900 lbs. The 1200 lb. thermal load differential between the two bolts is seen to be about 6% of the recommended preload. Thus, there appears to be little difference between the two materials. The analysis for the two bolts is covered in greater detail in Appendix B.

The NERVA Program has accumulated considerable data on three heats of A-286 and one heat of Inconel 718. It is intended that these data be evaluated and that the final selection of bolt material be based on this evaluation.

INTERFACE TASK FORCE REFERENCES

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2. Parametric Structural Study, Nozzle Convergence Angle

a. Introduction

A parametric study using stress, weights and thermal analyses has been completed to determine the optimum convergence angle for the Phoebus nozzle. Thirty, 35, 40 and 45 degree convergence configurations were evaluated. Computer programs were utilized where applicable and advantageous.

This part of the report summarizes the preliminary analysis that was done to determine the optimum configuration while Part III-1 reports on the more detailed study of structures using the 45 degree convergence angle selected as optimum.

The basic structure and loading for the 45 degree design of this parametric study are basically similar to that of Part III-1 and are completely adequate for the comparative evaluation. However, all of the dimensions and load values are not precisely identical to those of Part III-1 and therefore some difference may be noted in the results.

The structural region considered in this study consists of the nozzle jacket, the aft end of the pressure vessel, and the bolted joint for attaching the nozzle to the pressure vessel. The subject structure is that illustrated in Figure 110, which shows which items were constant and which variable in the parametric study. Special emphasis was given to the bolted ring joint, a composite of which is illustrated for the four designs in Figure 112.

b. Summary and Conclusions

The 45 degree configuration was shown to be the most efficient structurally. The basic structure required between the nozzle exit plane and the pressure vessel dome-cylinder tangency plane weighs 3660 pounds in the 30 degree configuration compared with 3130 pounds for the 45 degree structure. This represents

SKETCH OF STRUCTURE EVALUATED

FIGURE 110

CONFIGURATIONS AT JOINT

FIGURE 111

a weight savings of 530 pounds or 14.5% for the 45 degree design. Figure 112 illustrates the variation of weight with convergence angle.

Maintaining the same bolt circle diameter and number of bolts, the total bolt load per bolt decreased from 32,900 pounds for the 30 degree configuration to 23,630 pounds for the 45 degree design because of decreasing bolt joint moment. Figure 113 illustrates this variation of bolt load as a function of the angle. Although there is no savings in flange or bolt weight for the 45 degree structure, the smaller bolt load is highly desirable. The achievement of precise, uniform pretension values in all the bolts by means of measured pretorque is extremely difficult under the best of conditions. Therefore, the $32,900/23,630$ or 1.39 times greater factor of safety for the 45 degree design increases the structural reliability considerably with greater assurance that preload, or preload plus external load, will never exceed the allowable.

From the standpoint of nozzle jacket heating, the shallower convergence angles were shown to have some advantage. However, the larger heat deposition for the 45 degree configuration is not a serious design problem since, in the bolting flange region, the heating rate is only 0.4075 - 0.3800 or 0.0275 Btu's per cu. in./sec (7.25%) greater than for the 30 degree configuration. Also, it should be emphasized that the thermal analysis was of a very preliminary nature and a more detailed study is currently being performed. The variation of heat deposition as a function of convergence angle is illustrated in Figure 114.

An incidental performance advantage is obtained with the 45 degree configuration because of the larger nozzle exit-to-throat area ratio associated with the geometry of the 45 degree convergence profile. The area increase ratio is 3.85 times greater than that of the 30 degree configuration, as illustrated in Figure 115.

In conclusion, since it yields best structural efficiency, best performance, and produces no significant increase in design problems, it is recommended that the 45 degree configuration be adopted for design.

TOTAL WEIGHT VS ANGLE

FIGURE 112

TOTAL JOINT BOLT LOAD VS NOZZLE ANGLE

FIGURE 113

HEATING RATES VS. CONV. ANGLE

VALUES EXPRESSED IN BTU/IN³ SEC

FIGURE 114

COMPARISON OF AREA RATIOS FOR VARIOUS NOZZLE ANGLES

FIGURE 115

c. Technical Discussion

(1) Description of Structure

The structure considered in this study consists of the nozzle jacket and aft portion of the 80-in.-dia pressure vessel of the Phoebus nuclear engine. The aluminum pressure vessel components include the cylinder, toroidal aft dome segment, and nozzle bolting flange. The Hastelloy X nozzle components include the mating flange, divergent and convergent cones, and the inner cylinder (skirt) for reactor core support. Figure 116 illustrates the structure.

(2) Method of Analysis

The structure was analyzed by a computer program, Reference 1, based on conventional thin shell and ring theory. The parts of the structure actually used in the analysis are the pressure vessel cylinder (considered infinitely long), the toroidal aft dome segment, the convergent nozzle cone (considered fixed at the throat radius), the core support cylinder, core support end ring, and the aft dome and nozzle cone bolting rings and bolts. The analytical model is illustrated in Figure 117.

The shell structures were divided into small segments whose identification, loads, material properties, and geometry were input to the computer program which then automatically generated rotation and deflection equations at each edge (cut) of each segment. Rotation and deflection equations were handwritten for each ring (bolting flange) at the points where the rings were cut from the adjacent shell segments (or mating ring). The matrix formed by these equations plus the foregoing shell equations were then solved by the computer for the four indeterminate quantities at each cut: meridional bending moment, radial shear, rotation, and deflection. The printouts of these indeterminates are enclosed as Figures 118 through 121. The variation of shear and moment at the ring cuts as functions of the convergence angles is illustrated in Figures 122 through 129.

STRUCTURAL SCHEMATIC

SHOWING LOADING ARRANGEMENT
INCLUDING BOUNDARY CONDITIONS

FIGURE 116

ONLY END CUTS OF SHELL SEGMENTS SHOWN & PRESSURE VECTORS OMITTED FOR CLARITY.

NOTE *** (W) AND (T) TERMS TO BE MULT. BY (10E-6) JOB 663											
M	1	810.7471237	Q	1	1093.7526245	M	2	273.9332581	Q	2	655.6162796
W	1	.0000000	W	2	-1658.4655151	T	1	.0000000	T	2	4189.4234619
M	3	-173.6039963	Q	3	7.7273405	W	3	-9704.9902344	T	3	3283.8865051
M	4	-87.5030346	Q	4	-65.4837313	W	4	-13317.0347900	T	4	907.8584595
M	5	-10.9414145	Q	5	-32.2146645	W	5	-14424.0946045	T	5	325.4580650
M	6	5.2672075	Q	6	-1.4916860	W	6	-15236.1633301	T	6	408.4752579
M	7	-2.3154981	Q	7	-.7225852	W	7	-16236.6347656	T	7	485.0262756
M	8	-6.6413436	Q	8	-3.5518214	W	8	-17308.2263164	T	8	494.8090706
M	9	-7.0219454	Q	9	-4.8787472	W	9	-18379.9026914	T	9	490.3131027
M	10	-5.6505699	Q	10	-5.2996564	W	10	-19451.2746582	T	10	495.3439407
M	11	-4.2680820	Q	11	-4.4377415	W	11	-20544.1350098	T	11	513.7976379
M	12	-4.1443701	Q	12	-3.2148552	W	12	-21676.8903809	T	12	538.2343674
M	13	-9.9122810	Q	13	2.9608488	W	13	-22847.3547363	T	13	552.1458054
M	14	-42.2295299	Q	14	16.4325898	W	14	-24267.4057617	T	14	470.6047478
M	15	-63.4876280	Q	15	23.9150953	W	15	-25149.2644043	T	15	260.3362007
M	16	-121.9876556	Q	16	11.0299919	W	16	-25552.9335938	T	16	-83.2864084
M	17	-122.2293024	Q	17	-11.1303974	W	17	-25516.6838379	T	17	-273.4629593
M	18	-97.1552867	Q	18	-48.3145080	W	18	-25328.7348633	T	18	-434.6969948
M	19	-33.4617453	Q	19	-101.7118950	W	19	-25033.2590332	T	19	-518.6584473
M	20	83.2928381	Q	20	-173.0775051	W	20	-24723.5473633	T	20	-463.9669914
M	21	267.3475342	Q	21	-260.2757988	W	21	-24550.5083008	T	21	-196.0667286
M	22	541.0359344	Q	22	-360.6244049	W	22	-24749.5209961	T	22	393.9587135
M	23	3239.5536194	Q	23	1509.0451355	M	24	1855.6153107	Q	24	1131.4253387
W	23	-28403.1926270	W	24	-31307.9643555	T	23	393.9587135	T	24	3523.0725708
M	25	875.9251938	Q	25	811.0007782	W	25	-36380.4599609	T	25	5097.3281860
M	26	197.4289894	Q	26	547.0083466	W	26	-42440.2143555	T	26	5667.7505493
M	27	-240.7117043	Q	27	340.1001472	W	27	-48661.5800781	T	27	5570.4937134
M	28	-498.8142453	Q	28	185.2948589	W	28	-54523.0283203	T	28	5077.5977173
M	29	-617.8492584	Q	29	74.8950081	W	29	-59729.4434477	T	29	4370.8627319
M	30	-638.9998245	Q	30	-26.0628366	W	30	-66049.5917969	T	30	3191.5924988
M	31	-553.2242431	Q	31	-73.3635988	W	31	-70564.5810547	T	31	2103.5418091
M	32	-378.0891457	Q	32	-90.3475761	W	32	-74293.8667188	T	32	986.0201721
M	33	-196.6906948	Q	33	-86.8041277	W	33	-76102.9726563	T	33	288.6743927
M	34	-27.2492974	Q	34	-82.4449272	W	34	-76856.9169922	T	34	3.2606314
M	35	137.8559837	Q	35	-84.0344915	W	35	-77331.4091797	T	35	82.6067505
M	36	308.9874916	Q	36	-88.0067692	W	36	-78266.3281250	T	36	542.2678986
M	37	480.0712891	Q	37	-81.6356068	W	37	-80410.7324219	T	37	1375.1232147
M	38	610.8144836	Q	38	-43.4391594	W	38	-84494.6835938	T	38	2542.2904663
M	39	610.0559998	Q	39	55.6761842	W	39	-91051.7695313	T	39	3870.6203003
M	40	514.7768707	Q	40	138.3229599	W	40	-95278.6650391	T	40	4476.0113525
M	41	323.7385292	Q	41	248.2198372	W	41	-100022.3818359	T	41	4922.9696045
M	42	183.3966351	Q	42	314.3466721	W	42	-102527.1865234	T	42	5054.5372314
M	43	8.0818247	Q	43	388.2590523	W	43	-105072.3652344	T	43	5101.5989380
M	44	-307.0539589	Q	44	247.2237606	W	44	-110114.5107422	T	44	4925.5270996
M	45	-496.5073953	Q	45	136.5576096	W	45	-114832.7968750	T	45	4476.7099609
M	46	-589.3967361	Q	46	53.5431199	W	46	-119017.6748047	T	46	3876.2478943
M	47	-611.5908127	Q	47	-5.4920944	W	47	-122565.3476563	T	47	3215.1313477
M	48	-585.0514221	Q	48	-44.6096559	W	48	-125449.5742188	T	48	2558.1994629
M	49	-2254.3580017	Q	49	-1622.8989410	M	50	-1745.9371490	Q	50	-1412.7930145
W	49	-25971.4580078	W	50	-25552.2329102	T	49	393.9587135	T	50	-2783.4577026

NOTE *** (W) AND (T) TERMS TO BE MULT. BY (10E-6) JOB 663											
M	51	-1113.0107727	Q	51	-1121.7391968	W	51	-23031.2175293	T	51	-6991.9022827
M	52	-618.4552612	Q	52	-861.0532990	W	52	-18721.2565912	T	52	-9964.3391113
M	53	-245.2572975	Q	53	-637.2291870	W	53	-13242.2460938	T	53	-11700.0006104
M	54	24.5678220	Q	54	-448.1596298	W	54	-7241.5483398	T	54	-12120.8686523
M	55	208.9366264	Q	55	-295.2051392	W	55	-1276.5144653	T	55	-11615.0524902
M	56	325.8825691	Q	56	-176.9284668	W	56	4271.1216431	T	56	-10496.9609375
M	57	391.1021576	Q	57	-90.0382204	W	57	9158.8964844	T	57	-9010.0931396
M	58	420.1193237	Q	58	-30.1207705	W	58	13249.6573877	T	58	-7333.6739502
M	59	424.8867569	Q	59	7.8199794	W	59	16481.7973633	T	59	-5591.6265259
M	60	415.0944977	Q	60	28.9883704	W	60	18843.7226563	T	60	-3862.7705994
M	61	397.8305664	Q	61	38.5579152	W	61	20354.3557129	T	61	-2191.4706116
M	62	377.6339455	Q	62	41.5355635	W	62	21048.3686523	T	62	-598.2389603
M	63	356.5562181	Q	63	42.6975818	W	63	20966.8813477	T	63	909.9908981
M	64	334.4838104	Q	64	46.5662770	W	64	20153.1452637	T	64	2330.0582581
M	65	308.8678322	Q	65	57.3981647	W	65	18652.9995117	T	65	3653.2885132
M	66	275.2627525	Q	66	79.1557379	W	66	16519.8374023	T	66	4856.7551270
M	67	227.2888546	Q	67	115.4366531	W	67	13823.7897949	T	67	5895.1531982
M	68	156.8857899	Q	68	169.3359966	W	68	10664.7917480	T	68	6693.4333496
M	69	54.6164241	Q	69	243.2196178	W	69	7189.0868530	T	69	7140.4833984
M	70	-89.8897743	Q	70	338.3896828	W	70	3608.5323486	T	70	7084.3262329
M	71	-287.2960815	Q	71	454.6282578	W	71	221.7893505	T	71	6329.5233154
M	72	-547.6574173	Q	72	589.6113205	W	72	-2563.9317322	T	72	4637.7227783
M	73	-879.1940460	Q	73	738.1952057	W	73	-4212.4316406	T	73	1732.5546265
M	74	-1286.6793518	Q	74	891.5905075	W	74	-4041.9179688	T	74	-2689.6626587
M	8	8285.7944336	Q	8	11422.0831299	T	8	393.9587135	W	8	-25971.4580078

Computer Printout of
Joint Indeterminates for 30° Configuration

FIGURE 118

NOTE *** (W) AND (T) TERMS TO BE MULT. BY (10E-6) JOB 663											
M	1	933.0203781	Q	1	1245.7298737	M	2	-19.0538576	Q	2	376.3735428
W	1	.0000000	W	2	-4669.8461304	T	1	.0000000	T	2	4945.9163208
M	3	-178.2092361	Q	3	106.3708525	W	3	-8135.4647217	T	3	4136.7666016
M	4	-160.6076393	Q	4	-68.9045105	W	4	-12584.1065674	T	4	1821.7154541
M	5	-64.7830381	Q	5	-56.9649348	W	5	-14466.1925049	T	5	709.5004196
M	6	-14.1097064	Q	6	-23.8128483	W	6	-15447.4251709	T	6	462.0544701
M	7	-1.6612430	Q	7	-5.5640457	W	7	-16322.9086914	T	7	490.7977142
M	8	-3.8810610	Q	8	-1.6295593	W	8	-17276.6079102	T	8	544.6625748
M	9	-7.1897303	Q	9	-2.6160337	W	9	-18294.7133789	T	9	576.5462646
M	10	-7.5526851	Q	10	-4.9058865	W	10	-19351.0571289	T	10	598.8600082
M	11	-4.8211849	Q	11	-6.3825347	W	11	-20444.4106445	T	11	629.2257538
M	12	-1.7742077	Q	12	-4.7859235	W	12	-21591.9909668	T	12	673.9918365
M	13	.4129443	Q	13	-3.1484440	W	13	-22191.7863770	T	13	700.8986588
M	14	-1.8563262	Q	14	3.9139435	W	14	-23128.3103027	T	14	741.3974838
M	15	-23.1516035	Q	15	20.8125119	W	15	-24425.9846191	T	15	758.5702438
M	16	-73.0077353	Q	16	44.9273496	W	16	-25684.1723633	T	16	672.7822189
M	17	-158.5893154	Q	17	71.5199833	W	17	-26708.6113281	T	17	416.0046692
M	18	-211.6396942	Q	18	80.9118462	W	18	-27046.4633789	T	18	208.1845207
M	19	-268.7185478	Q	19	83.9676752	W	19	-27218.3703613	T	19	-54.9208212
M	20	-324.0723639	Q	20	77.0783253	W	20	-27186.7900391	T	20	-369.1350136
M	21	-375.8790436	Q	21	48.7390118	W	21	-26836.7124023	T	21	-798.5182190
M	22	-392.3418427	Q	22	-.4526455	W	22	-26202.9875488	T	22	-1202.7923889
M	23	2619.9079895	Q	23	1149.5219574	M	24	1579.9917450	Q	24	882.2653275
W	23	-27043.9462891	W	24	-28145.4799805	T	23	-1202.7923889	T	24	1413.0923157
M	25	307.1245422	Q	25	643.0407104	W	25	-31182.5441895	T	25	2854.3961182
M	26	262.7986488	Q	26	442.0044746	W	26	-35156.3374023	T	26	3467.4975586
M	27	-95.7070618	Q	27	280.7258110	W	27	-39383.8925781	T	27	3531.5889587
M	28	-309.0617104	Q	28	156.0487270	W	28	-43429.0551758	T	28	3247.4574280
M	29	-429.7431755	Q	29	33.9783478	W	29	-48274.5073242	T	29	2593.9676208
M	30	-415.6808434	Q	30	-42.7568092	W	30	-51965.3374023	T	30	1897.0274506
M	31	-319.8523331	Q	31	-91.5170012	W	31	-54703.2280273	T	31	1302.0411377
M	32	-173.0218620	Q	32	-122.2714996	W	32	-56702.1430664	T	32	905.3325882
M	33	5.2882386	Q	33	-141.2816639	W	33	-58273.6250000	T	33	762.8935928
M	34	201.5638103	Q	34	-150.9949017	W	34	-59784.8330078	T	34	906.7339020
M	35	403.1651077	Q	35	-150.5151869	W	35	-61630.8564453	T	35	1349.0127716
M	36	593.4610367	Q	36	-133.9934807	W	36	-64209.9941406	T	36	2082.5012817
M	37	747.3100433	Q	37	-94.5735388	W	37	-67891.9267578	T	37	3070.2249146
M	38	827.0860901	Q	38	-21.2732525	W	38	-72969.7802734	T	38	4226.2834473
M	39	807.2567368	Q	39	62.8665442	W	39	-77763.3750000	T	39	5124.3484497
M	40	688.5656662	Q	40	178.1386185	W	40	-83394.7753906	T	40	5943.2446899
M	41	437.3904953	Q	41	329.5038261	W	41	-89731.5136719	T	41	6562.3724976
M	42	15.5374918	Q	42	520.8105927	W	42	-96497.0830078	T	42	6822.4270630
M	43	-407.3632355	Q	43	331.9623184	W	43	-103242.3076172	T	43	6591.3066406
M	44	-661.9585571	Q	44	183.7531815	W	44	-109558.0146484	T	44	5993.9672241
M	45	-787.2244720	Q	45	72.5669575	W	45	-115162.6201172	T	45	5192.5898438
M	46	-817.8053436	Q	46	-6.4973016	W	46	-119916.1689453	T	46	4309.0418701
M	47	-783.1274490	Q	47	-58.8676491	W	47	-123782.5830078	T	47	3430.1594543
M	48	-707.1589432	Q	48	-89.9583149	W	48	-126797.5458984	T	48	2613.6266174
M	49	-2148.5434407	Q	49	-1611.9756622	M	50	-1645.1189117	Q	50	-1394.3068848
W	49	-27797.9555664	W	50	-26871.6347656	T	49	-1202.7923889	T	50	-4215.2640381

NOTE *** (W) AND (T) TERMS TO BE MULT. BY (10E-6) JOB 663											
M	51	-1023.2617645	Q	51	-1096.6649780	W	51	-23707.0046387	T	51	-8139.9738159
M	52	-542.0312576	Q	52	-833.3551865	W	52	-18897.2421875	T	52	-10823.1346436
M	53	-182.7504902	Q	53	-609.6136017	W	53	-13062.5194092	T	53	-12273.4610596
M	54	73.6843262	Q	54	-422.3606606	W	54	-6834.5840454	T	54	-12465.4187012
M	55	245.8180428	Q	55	-272.2694473	W	55	-743.3624420	T	55	-11783.5030518
M	56	351.8287964	Q	56	-157.3731518	W	56	4854.4341431	T	56	-10536.3326416
M	57	408.4489746	Q	57	-73.9915237	W	57	9738.1594238	T	57	-8960.5300293
M	58	430.2949333	Q	58	-17.4424138	W	58	13788.9810791	T	58	-7228.1591797
M	59	429.5031548	Q	59	17.4398170	W	59	16959.9216309	T	59	-5456.2540894
M	60	415.5831223	Q	60	35.9506402	W	60	19250.9572754	T	60	-3717.3678894
M	61	395.4123917	Q	61	43.2950301	W	61	20689.4853516	T	61	-2050.4118652
M	62	373.3152046	Q	62	44.4680676	W	62	21316.1853027	T	62	-471.3260460
M	63	351.1822624	Q	63	44.2045383	W	63	21176.1157227	T	63	1016.6698761
M	64	328.6048775	Q	64	46.9668131	W	64	20314.8078613	T	64	2413.3534546
M	65	303.0117302	Q	65	56.9418588	W	65	18779.0812988	T	65	3712.3345032
M	66	269.8105888	Q	66	78.0198956	W	66	16622.3000488	T	66	4892.4588623
M	67	222.5506916	Q	67	113.7289343	W	67	13913.7779541	T	67	5909.8291626
M	68	153.1339169	Q	68	167.1013031	W	68	10751.9904785	T	68	6690.5814819
M	69	52.1142612	Q	69	240.4505577	W	69	7281.1564331	T	69	7124.6948853
M	70	-90.8648434	Q	70	335.0403519	W	70	3710.5640869	T	70	7061.2965088
M	71	-286.4375801	Q	71	450.6313362	W	71	335.7327957	T	71	6306.1433716
M	72	-544.6240921	Q	72	584.8987732	W	72	-2439.8991394	T	72	4622.2137451
M	73	-873.6154938	Q	73	732.7229843	W	73	-4084.6045532	T	73	1734.6034241
M	74	-1278.1751099	Q	74	885.3675995	W	74	-3921.8204956	T	74	-2658.8178406
M	8	6627.7873535	Q	B	12588.5461426	T	8	-1202.7923889	W	B	-27797.9555664

Computer Printout of
Joint Indeterminates for 35° Configuration

FIGURE 119

NOTE *** (W) AND (T) TERMS TO BE MULT. BY (10E-6) JOB 663									
M 1	1080.8252563	Q 1	1431.6435242	M 2	-148.0153103	Q 2	236.5662766		
W 1	.0000000	W 2	-6993.7897339	T 1	.0000000	T 2	4771.3505859		
M 3	-186.6986122	Q 3	-78.6758614	W 3	-13381.6217041	T 3	1904.9472198		
M 4	-62.8414731	Q 4	-57.6442413	W 4	-15810.3525391	T 4	696.8879623		
M 5	-19.4379759	Q 5	-24.6931992	W 5	-16736.0617676	T 5	559.6188507		
M 6	-5.6565335	Q 6	-9.2493836	W 6	-17623.2998047	T 6	587.9457855		
M 7	-1.6577018	Q 7	-7.2601844	W 7	-18577.7585449	T 7	653.8710556		
M 8	4.8564945	Q 8	-12.3050649	W 8	-19523.4091797	T 8	736.2705460		
M 9	18.3036723	Q 9	-18.0225184	W 9	-20785.7915039	T 9	850.5307159		
M 10	35.2399220	Q 10	-17.3818080	W 10	-22109.4968262	T 10	1008.2114487		
M 11	41.1079969	Q 11	1.8273362	W 11	-23647.0524902	T 11	1191.1238708		
M 12	33.7672553	Q 12	20.3065196	W 12	-24482.4560547	T 12	1272.8640442		
M 13	13.9742039	Q 13	44.8885098	W 13	-25359.9436035	T 13	1334.4113007		
M 14	-21.8320391	Q 14	75.9823818	W 14	-26263.2390137	T 14	1360.7332001		
M 15	-77.2815866	Q 15	113.5003462	W 15	-27166.7431641	T 15	1334.9073334		
M 16	-155.7370548	Q 16	155.6940517	W 16	-28034.6752930	T 16	1238.8751526		
M 17	-262.9893303	Q 17	208.4839543	W 17	-28829.3312988	T 17	1049.9953308		
M 18	-400.5274658	Q 18	261.9471664	W 18	-29478.7792969	T 18	749.2981262		
M 19	-567.9802628	Q 19	313.2667770	W 19	-29911.3679199	T 19	318.8636513		
M 20	-762.3538895	Q 20	357.3614426	W 20	-30046.2009277	T 20	-254.8634415		
M 21	-977.2887039	Q 21	387.8477211	W 21	-29796.3635254	T 21	-978.9831314		
M 22	-1190.3007660	Q 22	395.0855789	W 22	-29123.6335449	T 22	-1806.6937866		
M 23	1759.4699860	Q 23	740.0491409	M 24	1744.1936035	Q 24	736.5763474		
W 23	-19174.3254395	W 24	-19163.8710938	T 23	-1806.6937866	T 24	-1752.4279480		
M 25	1194.2944336	Q 25	600.5433995	W 25	-19247.1579590	T 25	-224.3545341		
M 26	732.9470825	Q 26	464.0433006	W 26	-20358.6616211	T 26	812.8712311		
M 27	369.5865631	Q 27	334.4842300	W 27	-22204.7749023	T 27	1427.0465088		
M 28	129.5280418	Q 28	228.3946419	W 28	-24245.6887207	T 28	1681.5303955		
M 29	-38.6743197	Q 29	128.4018116	W 29	-26599.5158691	T 29	1726.0095673		
M 30	-114.6219273	Q 30	54.1967621	W 30	-28627.3315430	T 30	1643.7618866		
M 31	-131.6043282	Q 31	-13.8294859	W 31	-30726.4619141	T 31	1501.6093140		
M 32	-87.2107801	Q 32	-70.9272261	W 32	-32734.1491699	T 32	1370.2322693		
M 33	7.2370403	Q 33	-115.3197813	W 33	-34591.0712891	T 33	1326.4708099		
M 34	125.0147829	Q 34	-145.5310059	W 34	-36225.0073242	T 34	1395.1193085		
M 35	298.8094063	Q 35	-170.1969604	W 35	-38340.4321289	T 35	1659.0952301		
M 36	350.0984192	Q 36	-174.4647312	W 36	-38968.0581055	T 36	1772.4210815		
M 37	650.0531616	Q 37	-175.2230225	W 37	-43271.4570313	T 37	2728.6865540		
M 38	813.2907181	Q 38	-152.6817856	W 38	-46658.1938477	T 38	3549.0812683		
M 39	1014.6546555	Q 39	-34.3715281	W 39	-56128.8886719	T 39	5608.8648071		
M 40	996.6286011	Q 40	73.2579908	W 40	-62426.3999023	T 40	6722.1662598		
M 41	851.8892639	Q 41	221.9385101	W 41	-69765.3867188	T 41	7747.9867554		
M 42	535.3186722	Q 42	417.9082642	W 42	-77984.7431641	T 42	8530.3193359		
M 43	-2.3117187	Q 43	666.1637955	W 43	-86738.1328125	T 43	8847.5157471		
M 44	-542.4194565	Q 44	423.0813065	W 44	-95474.8642578	T 44	8527.9738770		
M 45	-866.0340347	Q 45	232.5822334	W 45	-103638.9833984	T 45	7741.6192627		
M 46	-1023.5415336	Q 46	89.9034691	W 46	-110872.4941406	T 46	6696.9199829		
M 47	-1059.6578674	Q 47	-11.3452851	W 47	-116999.3125000	T 47	5550.2704468		
M 48	-1012.3119431	Q 48	-78.2092094	W 48	-121976.5400391	T 48	4412.8807373		
M 49	-1887.7207336	Q 49	-1443.0860443	M 50	-1437.5194550	Q 50	-1245.5439606		
W 49	-23703.5534668	W 50	-22639.2680664	T 49	-1806.6937866	T 50	-4446.8991699		

NOTE *** (W) AND (T) TERMS TO BE MULT. BY (10E-6) JOB 663											
M	51	-882.9476624	Q	51	-976.2615051	W	51	-19495.2795410	T	51	-7858.5980225
M	52	-455.3466454	Q	52	-738.9789276	W	52	-14931.6134033	T	52	-10150.8858643
M	53	-137.4955322	Q	53	-537.8595734	W	53	-9506.7816162	T	53	-11334.0948486
M	54	88.1492224	Q	54	-370.4492111	W	54	-3783.5357666	T	54	-11406.7910156
M	55	238.6351013	Q	55	-237.0529671	W	55	1771.6992493	T	55	-10712.7768555
M	56	330.5439262	Q	56	-135.6590481	W	56	6846.9531250	T	56	-9526.3874512
M	57	379.0483055	Q	57	-62.7624545	W	57	11250.8150635	T	57	-8056.4822998
M	58	397.3297386	Q	58	-13.9931458	W	58	14881.3713379	T	58	-6453.5360718
M	59	396.2662354	Q	59	15.4304448	W	59	17699.1843262	T	59	-4818.5374756
M	60	384.3084564	Q	60	30.3960717	W	60	19704.9721680	T	60	-3212.7580872
M	61	367.4775391	Q	61	35.7113910	W	61	20922.2502441	T	61	-1667.7594452
M	62	349.4325218	Q	62	36.0068111	W	62	21384.9536133	T	62	-195.2515717
M	63	331.5702324	Q	63	35.6979661	W	63	21129.9038086	T	63	1203.4030609
M	64	313.1349831	Q	64	38.9793324	W	64	20193.9206543	T	64	2528.1209412
M	65	291.3293953	Q	65	49.8217936	W	65	18615.3544922	T	65	3771.4826660
M	66	261.4308205	Q	66	71.9483271	W	66	16439.8132324	T	66	4910.5810547
M	67	216.9305439	Q	67	108.7633677	W	67	13729.8370361	T	67	5899.3863525
M	68	149.7246704	Q	68	163.2130051	W	68	10578.2341309	T	68	6661.7776489
M	69	50.3966007	Q	69	237.5551777	W	69	7124.6774292	T	69	7085.5308838
M	70	-91.3592882	Q	70	333.0219498	W	70	3574.9716187	T	70	7017.7391968
M	71	-286.1151733	Q	71	449.3603401	W	71	222.1129742	T	71	6262.3606567
M	72	-543.8257294	Q	72	584.2445450	W	72	-2532.1493530	T	72	4580.8385010
M	73	-872.5182251	Q	73	732.5617981	W	73	-4157.0768433	T	73	1697.0005714
M	74	-1277.1967773	Q	74	885.5867691	W	74	-3976.5255127	T	74	-2692.2977905
M	8	4393.1498413	Q	8	14277.4293213	T	8	-1806.6937866	W	8	-23703.5534666

Computer Printout of
Joint Indeterminates for 40° Configuration

FIGURE 120

NOTE *** (W) AND (T) TERMS TO BE MULT. BY (10E-6) JOB 663											
M	1	1283.2960968	Q	1	1698.2589111	M	2	-91.9324951	Q	2	433.0273857
W	1	.0000000	W	2	-5817.4021606	T	1	.0000000	T	2	5118.0065918
M	3	-284.8667984	Q	3	-42.9628682	W	3	-12362.2716064	T	3	2761.0303955
M	4	-162.0586853	Q	4	-90.9951248	W	4	-15464.5621338	T	4	1115.5298767
M	5	-78.3589172	Q	5	-76.7100544	W	5	-16550.5192871	T	5	704.5314484
M	6	-7.6401587	Q	6	-73.4650412	W	6	-17415.8515625	T	6	646.3600311
M	7	63.7639046	Q	7	-81.7567348	W	7	-18354.3613281	T	7	835.8913040
M	8	142.4515057	Q	8	-89.5141287	W	8	-19584.8259277	T	8	1226.2191620
M	9	217.4070988	Q	9	-74.4072094	W	9	-21282.6213379	T	9	1773.3768768
M	10	256.4410172	Q	10	-15.8338729	W	10	-23567.3723145	T	10	2399.8381958
M	11	247.7353687	Q	11	37.9706688	W	11	-24940.2478027	T	11	2699.9803467
M	12	207.6624432	Q	12	112.1396589	W	12	-26449.9296875	T	12	2959.0390320
M	13	126.0566138	Q	13	208.4078331	W	13	-28068.3337402	T	13	3146.7617188
M	14	-7.5210327	Q	14	326.5138969	W	14	-29751.9654824	T	14	3229.3235474
M	15	-203.2482872	Q	15	465.9545479	W	15	-31439.2050781	T	15	3168.6028748
M	16	-470.8553696	Q	16	625.7457047	W	16	-33049.0815430	T	16	2925.7929688
M	17	-818.5634842	Q	17	800.9848022	W	17	-34482.0302734	T	17	2460.3945923
M	18	-1252.1475830	Q	18	986.8711243	W	18	-35619.0239258	T	18	1736.9320374
M	19	-1773.9172058	Q	19	1174.2406311	W	19	-36324.1782227	T	19	718.5298920
M	20	-2381.3593750	Q	20	1352.6780548	W	20	-36445.2519531	T	20	-623.6568985
M	21	-3066.5281677	Q	21	1510.3546600	W	21	-35819.3798828	T	21	-2302.6652222
M	22	-3814.6416321	Q	22	1631.0681763	W	22	-34278.1386719	T	22	-4333.2012939
M	23	1255.9359131	Q	23	276.0797386	M	24	1109.2778320	Q	24	269.2623558
W	23	-10267.7971191	W	24	-8999.0423584	T	23	-4333.2012939	T	24	-3526.2834778
M	25	970.0952682	Q	25	253.6078758	W	25	-8072.3019409	T	25	-2834.4981384
M	26	727.1156006	Q	26	205.0334473	W	26	-7041.2025146	T	26	-1731.0366364
M	27	543.7953949	Q	27	144.2710381	W	27	-6833.0596924	T	27	-935.2958832
M	28	426.3081131	Q	28	79.6836739	W	28	-7200.7347412	T	28	-346.2602654
M	29	371.4633293	Q	29	1.1852706	W	29	-8245.8325195	T	29	244.2115288
M	30	396.1303215	Q	30	-55.8201828	W	30	-9483.2666016	T	30	689.4915466
M	31	474.0329819	Q	31	-104.8041277	W	31	-11102.2340088	T	31	1194.0811920
M	32	595.5359116	Q	32	-143.0089092	W	32	-13191.2268066	T	32	1805.0234985
M	33	748.1776428	Q	33	-167.1171227	W	33	-15886.1436768	T	33	2565.7384338
M	34	915.9235306	Q	34	-172.9698238	W	34	-19354.8557129	T	34	3505.8268738
M	35	1078.2084351	Q	35	-155.4153595	W	35	-23778.8601074	T	35	4615.2021484
M	36	1208.8748169	Q	36	-108.2665739	W	36	-29331.2595215	T	36	5895.1501465
M	37	1275.1327972	Q	37	-24.3948569	W	37	-36148.3881836	T	37	7265.4481812
M	38	1236.6802521	Q	38	104.0247650	W	38	-44296.0244141	T	38	8653.3167725
M	39	1045.1076202	Q	39	285.0776596	W	39	-53726.3710938	T	39	9925.4680176
M	40	874.5356369	Q	40	397.7677345	W	40	-58864.0131836	T	40	10449.1486816
M	41	643.2748245	Q	41	526.4050064	W	41	-64226.9526367	T	41	10863.5450439
M	42	344.9386406	Q	42	671.6517639	W	42	-69752.1718750	T	42	11138.7855225
M	43	-30.8462141	Q	43	834.1548309	W	43	-75359.7939453	T	43	11231.7174072
M	44	-706.1499863	Q	44	527.9017410	W	44	-86437.6240234	T	44	10801.4505615
M	45	-1108.8915558	Q	45	288.2547989	W	45	-96769.1533203	T	45	9788.6251221
M	46	-1302.8374329	Q	46	109.0759020	W	46	-105908.7529297	T	46	8455.5065918
M	47	-1344.4890137	Q	47	-17.7911134	W	47	-113639.4726563	T	47	6998.5100708
M	48	-1281.7069855	Q	48	-101.2992506	W	48	-119911.4619141	T	48	5556.9956665
M	49	-1470.1259308	Q	49	-1239.1335297	M	50	-1085.9904480	Q	50	-1055.6688690
W	49	-21172.0283203	W	50	-19366.3552246	T	49	-4333.2012939	T	50	-6361.3248901

NOTE *** (W) AND (T) TERMS TO BE MULT. BY (10E-6) JOB 663											
M	51	-620.4234161	Q	51	-810.9160614	W	51	-15503.1646729	T	51	-8864.4228516
M	52	-268.9579277	Q	52	-600.0945358	W	52	-10641.6621094	T	52	-10380.0970459
M	53	-14.1035712	Q	53	-424.7010651	W	53	-5270.8181152	T	53	-10931.4527588
M	54	161.1841965	Q	54	-281.8680229	W	54	142.8035927	T	54	-10604.9155273
M	55	273.0498924	Q	55	-170.6905212	W	55	5236.3662720	T	55	-9694.0141602
M	56	336.7107925	Q	56	-88.4947958	W	56	9777.4609375	T	56	-8427.5606689
M	57	365.7521515	Q	57	-31.5257602	W	57	13632.9725342	T	57	-6975.0245972
M	58	371.7210503	Q	58	4.5428314	W	58	16741.2470703	T	58	-5454.1588135
M	59	363.9355927	Q	59	24.2530112	W	59	19088.4074707	T	59	-3939.8241882
M	60	349.4384842	Q	60	32.1357393	W	60	20689.2226563	T	60	-2473.2801208
M	61	333.0377235	Q	61	32.5848169	W	61	21572.6342773	T	61	-1071.4694214
M	62	317.3909264	Q	62	29.8037899	W	62	21771.8681641	T	62	263.9660759
M	63	303.1035881	Q	63	27.7988377	W	63	21318.9565430	T	63	1538.0528717
M	64	288.8248367	Q	64	30.3917630	W	64	20243.4759805	T	64	2754.2549744
M	65	271.3368378	Q	65	41.2283883	W	65	18575.3247070	T	65	3906.6226501
M	66	245.6460762	Q	66	63.7588191	W	66	16351.2774658	T	66	4972.3073730
M	67	205.0962105	Q	67	101.1671257	W	67	13625.2611084	T	67	5904.4875488
M	68	141.5332165	Q	68	156.2292805	W	68	10481.9787598	T	68	6625.8528442
M	69	45.5635762	Q	69	231.0798721	W	69	7053.6168213	T	69	7022.9422607
M	70	-93.0445004	Q	70	326.8707428	W	70	3535.0692749	T	70	6941.8182983
M	71	-284.7593727	Q	71	443.3087578	W	71	224.8488026	T	71	6185.7802124
M	72	-539.4214020	Q	72	578.0660934	W	72	-2493.5614319	T	72	4516.0670166
M	73	-865.0519180	Q	73	726.0654449	W	73	-4091.7028809	T	73	1656.7611389
M	74	-1266.2763367	Q	74	878.6552277	W	74	-3899.9396973	T	74	-2694.6419983
M	8	1343.5415039	Q	8	16055.7496338	T	8	-4333.2012939	W	8	-21172.0283203

Computer Printout of
Joint Indeterminates for 45⁰ Configuration

FIGURE 121

NOZZLE SHELL TO FLANGE SHEAR VS. NOZZLE CONV. ANGLE

FIGURE 122

NOZZLE SHELL TO FLANGE MOMENT VS. NOZZLE CONV. ANGLE

FIGURE 123

CORE SUPPORT TO FLANGE SHEAR VS. NOZZLE CONV. ANGLE

FIGURE 12¹/₄

CORE SUPPORT TO FLANGE MOMENT VS. NOZZLE CONV. ANGLE

FIGURE 125

PRESSURE VESSEL TO FLANGE SHEAR VS. NOZZLE CONV. ANGLE

FIGURE 126

PRESSURE VESSEL TO FLANGE MOMENT VS NOZZLE CONV. ANGLE

FIGURE 127

JOINT SHEAR VS NOZZLE ANGLE

FIGURE 128

JOINT MOMENT VS NOZZLE ANGLE

FIGURE 129

Hoop and meridional stresses at inner and outer surfaces plus margins of safety based on the critical stresses at appropriate sections were also computed by the program. These margins of safety and critical stresses are enclosed as Figures 130 through 133. A printout example for one section showing how all the stresses are computed from the geometry, material properties and computed indeterminates is enclosed as Figure 134.

(3) Design Criteria

Hydrostatic pressure test was selected as the design condition for the parametric study since hydrotest is generally the critical condition for this type of joint. For the inner cylinder pressure, nozzle plenum pressure, and core support end load, the round figures of 650 psi, 950 psi, and 4500 lb/in., respectively, based roughly on Reference 2, were used.

Allowable stresses are based on the latest revisions of Reference 3. A safety factor of 1.0 on yield and a bending plasticity factor of 1.25 were used resulting in the following design stresses.

	<u>Direct (Axial) Stress</u>	<u>Bending</u>
Hastelloy X	51,000 psi	63,600 psi
7039-T61 Aluminum	50,000 psi	62,500 psi

The above factors are not considered final design values but merely reasonable values for the purposes of this preliminary, comparative evaluation.

In the final computer run for stress analysis of the four configurations, the only differences between the four designs, besides the profile, were the convergent shell thickness and bolting ring cross section properties. The shell thicknesses were based on preliminary runs and on consideration of the cone angles and radii as affecting the shell membrane force. Bolting ring sections were designed on the basis of geometric requirements and the desire to maintain a smooth load path through the joint.

LOAD DEFLECTION
IDENTIFICATION IDENTIFICATION

CRITICAL MARGIN OF SAFETY = -.3634 AT 49 49

SUMMARY OF MINIMUM MARGINS OF SAFETY AT EACH JOINT

LOAD IDENTIFICATION	DEFLECTION IDENTIFICATION	MAGNITUDE OF CRITICAL STRESS	TYPE OF CRITICAL STRESS	ALLOWABLE STRESS	MARGIN OF SAFETY
18	18	33558.62	HOOP OUTER	51000/ 63600	.5241
19	19	32440.55	HOOP OUTER	51000/ 63600	.5737
20	20	31892.85	HOOP INNER	51000/ 63600	.6030
21	21	31641.79	HOOP INNER	51000/ 63600	.6237
22	22	33559.04	HOOP INNER	51000/ 63600	.5420
23	23	37969.76	MERID INNER	50000/ 62500	.4670
24	24	29579.68	MERID INNER	50000/ 62500	.8280
25	25	23642.95	MERID INNER	50000/ 62500	1.2132
26	26	19541.09	MERID INNER	50000/ 62500	1.5901
27	27	19697.11	HOOP OUTER	50000/ 62500	1.5497
28	28	21661.55	HOOP OUTER	50000/ 62500	1.3274
38	38	27952.00	HOOP INNER	50000/ 62500	.8030
39	39	29522.79	HOOP INNER	50000/ 62500	.7063
40	40	30382.96	HOOP INNER	50000/ 62500	.6558
41	41	31206.63	HOOP INNER	50000/ 62500	.6082
42	42	31573.93	HOOP INNER	50000/ 62500	.5869
43	43	31890.61	HOOP INNER	50000/ 62500	.5680
44	44	33683.65	HOOP OUTER	50000/ 62500	.4893
45	45	35198.95	HOOP OUTER	50000/ 62500	.4277
46	46	36407.69	HOOP OUTER	50000/ 62500	.3814
47	47	37330.58	HOOP OUTER	50000/ 62500	.3473
48	48	38000.64	HOOP OUTER	50000/ 62500	.3231
49	49	-80119.31	MERID INNER	51000/ 63600	-.3634
50	50	-76750.77	MERID INNER	51000/ 63600	-.3355
51	51	-58118.70	MERID INNER	51000/ 63600	-.1225
52	52	-43180.97	MERID INNER	51000/ 63600	.1811
53	53	-24901.89	MERID INNER	51000/ 63600	1.0480
54	54	-14093.59	MERID OUTER	51000/ 63600	2.6187
55	55	-23122.92	MERID OUTER	51000/ 63600	1.2056
56	56	-28836.19	MERID OUTER	51000/ 63600	.7686
57	57	-32045.31	MERID OUTER	51000/ 63600	.5915
58	58	-33466.56	MERID OUTER	51000/ 63600	.5239
59	59	-33700.07	MERID OUTER	51000/ 63600	.5134
60	60	-33220.44	MERID OUTER	51000/ 63600	.5352
70	70	-17292.05	MERID INNER	51000/ 63600	1.9493
71	71	-26960.93	MERID INNER	51000/ 63600	.8916
72	72	-39713.32	MERID INNER	51000/ 63600	.2942
73	73	-55951.85	MERID INNER	51000/ 63600	-.0885
74	74	-75910.31	MERID INNER	51000/ 63600	-.3282

Computer Printout of
Critical Stresses & Margins of
Safety, 30° Configuration

FIGURE 130

LOAD DEFLECTION
IDENTIFICATION IDENTIFICATION

CRITICAL MARGIN OF SAFETY = $\sim$.3767 AT 42 42

SUMMARY OF MINIMUM MARGINS OF SAFETY AT EACH JOINT

LOAD IDENTIFICATION	DEFLECTION IDENTIFICATION	MAGNITUDE OF CRITICAL STRESS	TYPE OF CRITICAL STRESS	ALLOWABLE STRESS	MARGIN OF SAFETY
17	17	36382.43	HOOP OUTER	51000/ 63600	.4075
18	18	36442.10	HOOP OUTER	51000/ 63600	.4069
19	19	36329.20	HOOP OUTER	51000/ 63600	.4130
20	20	35988.33	HOOP OUTER	51000/ 63600	.4280
21	21	35207.14	HOOP OUTER	51000/ 63600	.4614
22	22	34061.96	HOOP OUTER	51000/ 63600	.5111
23	23	35246.98	HOOP INNER	50000/ 62500	.4576
24	24	33956.88	HOOP INNER	50000/ 62500	.4975
25	25	34877.85	HOOP INNER	50000/ 62500	.4456
26	26	36987.22	HOOP INNER	50000/ 62500	.3553
27	27	39934.23	HOOP OUTER	50000/ 62500	.2531
28	28	43352.46	HOOP OUTER	50000/ 62500	.1563
38	38	63899.32	HOOP INNER	50000/ 62500	-.2139
39	39	67438.31	HOOP INNER	50000/ 62500	-.2554
40	40	71464.79	HOOP INNER	50000/ 62500	-.2979
41	41	75818.95	HOOP INNER	50000/ 62500	-.3392
42	42	80224.15	HOOP INNER	50000/ 62500	-.3767
43	43	32153.85	HOOP OUTER	50000/ 62500	.5621
44	44	34183.98	HOOP OUTER	50000/ 62500	.4729
45	45	35804.33	HOOP OUTER	50000/ 62500	.4076
46	46	37042.44	HOOP OUTER	50000/ 62500	.3606
47	47	37942.29	HOOP OUTER	50000/ 62500	.3277
48	48	38555.91	HOOP OUTER	50000/ 62500	.3054
49	49	-76839.99	MERID INNER	51000/ 63600	-.3363
50	50	-72970.08	MERID INNER	51000/ 63600	-.3011
51	51	-54389.51	MERID INNER	51000/ 63600	-.0623
52	52	-39437.76	MERID INNER	51000/ 63600	.2932
53	53	-21840.33	MERID INNER	51000/ 63600	1.3351
54	54	-16498.31	MERID OUTER	51000/ 63600	2.0912
55	55	-24929.35	MERID OUTER	51000/ 63600	1.0458
56	56	-30121.72	MERID OUTER	51000/ 63600	.6931
57	57	-32894.95	MERID OUTER	51000/ 63600	.5504
58	58	-33964.96	MERID OUTER	51000/ 63600	.5015
59	59	-33926.17	MERID OUTER	51000/ 63600	.5033
60	60	-33244.38	MERID OUTER	51000/ 63600	.5341
70	70	-17339.81	MERID INNER	51000/ 63600	1.9412
71	71	-26918.88	MERID INNER	51000/ 63600	.8946
72	72	-39564.75	MERID INNER	51000/ 63600	.2890
73	73	-55678.62	MERID INNER	51000/ 63600	-.0840
74	74	-75493.78	MERID INNER	51000/ 63600	-.3244

Computer Printout of
Critical Stresses & Margins of Safety, 35° Configuration
FIGURE 131

LOAD DEFLECTION
IDENTIFICATION IDENTIFICATION

CRITICAL MARGIN OF SAFETY = -.3240 AT 74 74

SUMMARY OF MINIMUM MARGINS OF SAFETY AT EACH JOINT

LOAD IDENTIFICATION	DEFLECTION IDENTIFICATION	MAGNITUDE OF CRITICAL STRESS	TYPE OF CRITICAL STRESS	ALLOWABLE STRESS	MARGIN OF SAFETY
12	12	36402.54	HOOP INNER	51000/ 63600	.4023
13	13	36778.29	HOOP INNER	51000/ 63600	.3872
14	14	37313.04	HOOP OUTER	51000/ 63600	.3676
15	15	38044.59	HOOP OUTER	51000/ 63600	.3430
16	16	38755.58	HOOP OUTER	51000/ 63600	.3206
17	17	39515.89	HOOP OUTER	51000/ 63600	.2980
18	18	40186.94	HOOP OUTER	51000/ 63600	.2795
19	19	40712.36	HOOP OUTER	51000/ 63600	.2668
20	20	40968.77	HOOP OUTER	51000/ 63600	.2630
21	21	40903.39	HOOP OUTER	51000/ 63600	.2696
22	22	40365.92	HOOP OUTER	63600.00	.5756
23	23	30605.41	MERID INNER	50000/ 62500	.7547
24	24	30438.31	MERID INNER	50000/ 62500	.7640
25	25	27000.02	MERID INNER	50000/ 62500	.9557
26	26	24100.14	MERID INNER	50000/ 62500	1.1533
27	27	21799.70	MERID INNER	50000/ 62500	1.3412
28	28	20263.38	MERID INNER	50000/ 62500	1.4866
38	38	23976.38	MERID INNER	50000/ 62500	1.1739
39	39	25185.89	MERID INNER	50000/ 62500	1.0861
40	40	25080.74	MERID INNER	50000/ 62500	1.0934
41	41	24647.72	HOOP INNER	50000/ 62500	1.0541
42	42	26105.29	HOOP INNER	50000/ 62500	.9296
43	43	27317.20	HOOP OUTER	50000/ 62500	.8304
44	44	30463.79	HOOP OUTER	50000/ 62500	.6519
45	45	33078.19	HOOP OUTER	50000/ 62500	.5260
46	46	35161.98	HOOP OUTER	50000/ 62500	.4371
47	47	36751.83	HOOP OUTER	50000/ 62500	.3747
48	48	37905.34	HOOP OUTER	50000/ 62500	.3319
49	49	-68756.58	MERID INNER	51000/ 63600	-.2583
50	50	-65185.10	MERID INNER	51000/ 63600	-.2176
51	51	-48559.29	MERID INNER	51000/ 63600	.0503
52	52	-35191.98	MERID INNER	51000/ 63600	.4492
53	53	-19623.77	MERID INNER	51000/ 63600	1.5989
54	54	-17206.80	MERID OUTER	51000/ 63600	1.9639
55	55	-24577.54	MERID OUTER	51000/ 63600	1.0751
56	56	-29079.19	MERID OUTER	51000/ 63600	.7538
57	57	-31454.92	MERID OUTER	51000/ 63600	.6214
58	58	-32350.33	MERID OUTER	51000/ 63600	.5765
59	59	-32298.24	MERID OUTER	51000/ 63600	.5790
60	60	-31712.56	MERID OUTER	51000/ 63600	.6082
70	70	-17364.03	MERID INNER	51000/ 63600	1.9371
71	71	-26903.09	MERID INNER	51000/ 63600	.8957
72	72	-39525.65	MERID INNE	51000/ 63600	.2903
73	73	-55629.77	MERID INNER	51000/ 63600	-.0832
74	74	-75445.86	MERID INNER	51000/ 63600	-.3240

Computer Printout of
Critical Stresses & Margins of
Safety, 40° Configuration

FIGURE 132

LOAD DEFLECTION
IDENTIFICATION IDENTIFICATION

CRITICAL MARGIN OF SAFETY = -.3192 AT 74 74

SUMMARY OF MINIMUM MARGINS OF SAFETY AT EACH JOINT

LOAD IDENTIFICATION	DEFLECTION IDENTIFICATION	MAGNITUDE OF CRITICAL STRESS	TYPE OF CRITICAL STRESS	ALLOWABLE STRESS	MARGIN OF SAFETY
12	12	40236.88	HOOP INNER	51000/ 63600	.2732
13	13	41230.09	HOOP INNER	51000/ 63600	.2401
14	14	42122.55	HOOP OUTER	51000/ 63600	.2109
15	15	44232.19	HOOP OUTER	51000/ 63600	.1572
16	16	46431.66	HOOP OUTER	51000/ 63600	.1069
17	17	48596.61	HOOP OUTER	51000/ 63600	.0626
18	18	50630.55	HOOP OUTER	51000/ 63600	.0253
19	19	52373.16	HOOP OUTER	51000/ 63600	-.0030
20	20	53800.51	HOOP OUTER	51000/ 63600	-.0228
21	21	54455.64	HOOP OUTER	51000/ 63600	-.0275
22	22	59999.25	MERID OUTER	51000/ 63600	-.0181
23	23	28362.94	MERID INNER	50000/ 62500	.8618
24	24	27347.22	MERID INNER	50000/ 62500	.9219
25	25	26381.21	MERID INNER	50000/ 62500	.9828
26	26	24679.26	MERID INNER	50000/ 62500	1.1002
27	27	23361.45	MERID INNER	50000/ 62500	1.2018
40	40	24356.84	MERID INNER	50000/ 62500	1.1452
41	41	22875.99	HOOP INNER	50000/ 62500	1.2081
42	42	23706.99	HOOP INNER	50000/ 62500	1.1202
43	43	24536.72	HOOP OUTER	50000/ 62500	1.0387
44	44	28509.32	HOOP OUTER	50000/ 62500	.7696
45	45	31805.57	HOOP OUTER	50000/ 62500	.5920
46	46	34429.33	HOOP OUTER	50000/ 62500	.4723
47	47	36428.33	HOOP OUTER	50000/ 62500	.3910
48	48	37876.29	HOOP OUTER	50000/ 62500	.3364
49	49	-55814.59	MERID INNER	51000/ 63600	-.0863
50	50	-52002.77	MERID INNER	51000/ 63600	-.0193
51	51	-37651.08	MERID INNER	51000/ 63600	.3545
52	52	-26062.73	MERID INNER	51000/ 63600	.9568
53	53	-13580.07	MERID INNER	51000/ 63600	2.7555
54	54	-20784.02	MERID OUTER	51000/ 63600	1.4538
55	55	-26263.16	MERID OUTER	51000/ 63600	.9419
56	56	-29381.24	MERID OUTER	51000/ 63600	.7358
57	57	-30803.68	MERID OUTER	51000/ 63600	.6556
58	58	-31096.03	MERID OUTER	51000/ 63600	.6401
59	59	-30714.70	MERID OUTER	51000/ 63600	.6604
60	60	-30326.94	HOOP OUTER	51000/ 63600	.6817
70	70	-17446.57	MERID INNER	51000/ 63600	1.9232
71	71	-26836.68	MERID INNER	51000/ 63600	.9004
72	72	-39309.93	MERID INNER	51000/ 63600	.2974
73	73	-55259.18	MERID INNER	51000/ 63600	-.0771
74	74	-74910.98	MERID INNER	51000/ 63600	-.3192

Computer Printout of Critical Stresses
& Margins of Safety, 45° Configuration

FIGURE 133

STRUCTURAL ANALYSIS AT JOINT				LOAD IDENTIFICATION	DEFLECTION IDENTIFICATION
				12	12
LOADS AND GEOMETRY				STRESSES	
MOMENT	M	12	196.85814	MEMBRANE +STRESS FM	+Q COS(PHI)/T BENDING TOTAL
SHFAR	Q	12	122.58827	MERID OUTER = 17209.94	135.23 -2874.67 = 14469.40
DEFLECTION	W	12	-26553.24585(10E-6)		
THICKNESS OF LEFT CONE			.64100	MEMBRANE +STRESS FM	+Q COS(PHI)/T BENDING TOTAL
RADIUS OF POINT			24.00000	MERID INNER = 17209.94	135.23 2874.67 = 20218.74
L SIN(PHI)			.50000	.3(MERID. MEMBRANE)	.3(MERID. OUTER -F(W-T-WF)/R BENDING) TOTAL
R (OTHER)			24.50000		
YOUNGS MODULUS			31.00000(10E6)	HOOP OUTER = 5162.65	-862.40 34297.94 = 38598.19
THERMAL COEFFICIENT			.00000(10E-6)		
TEMPERATURE INCREMENT			.00000	.3(MERID. MEMBRANE)	.3(MERID. INNER -E(W-T-WF)/R BENDING) TOTAL
PRESSURE			650.00000	HOOP INNER = 5162.65	862.40 34297.94 = 40323.00
AXIAL AND NEGATIVE BENDING STRESS ALLOWABLE			51000.00000		
POSITIVE BENDING STRESS ALLOWABLE			63600.00000	MINIMUM MARGIN OF SAFETY	TYPE OF STRESS
UNITS - LBS - INCHES - DEG. FAHRENHEIT				.2702	HOOP INNER

Sample of Computer Stresses and
Margin of Safety Calculation for One Cut
FIGURE 134

(4) Assumptions Used in the Analysis

The following assumptions were made to complete the analytical model and provide a reliable method of analysis:

(a) The pressure vessel cylinder beyond the last section cut for analysis was considered infinitely long.

(b) The nozzle convergent cone was considered fixed against rotation and deflection at the nozzle throat radius.

(c) The core support end flange was considered free ended.

(d) The bolting flanges of the pressure vessel and nozzle jacket were considered rigid rings rotating and deflecting equally at their interface.

(e) Conventional thin shell theory was assumed to apply for the shell segments.

d. Results

The results of the parametric study are presented as follows:

Graphs of total weight, total bolt moment, nozzle heating rate and exit-throat area ratio as functions of convergence angle in Figures 112, 113, 114, and 115, respectively.

Computer printout of the indeterminates (rotation, radial deflection, discontinuity shear and moment) for all the cuts of the 30, 35, 40, and 45 degree configurations in Figures 118, 119, 120, and 121, respectively.

Graphs of discontinuity shear and moment as functions of convergence angle for the following joints: Nozzle shell to flange, Figures 122, and 123; Reactor core support to flange, Figures 124 and 125; Pressure vessel to flange, Figures 126 and 127; Nozzle flange to pressure vessel flange (bolting interface), Figures 128 and 129.

Computer printout of critical stresses and margins of safety for the 30, 35, 40, and 45 degree configurations in Figures 130, 131, 132, and 133, respectively.

The first group of illustrations listed above has been discussed under b, "Summary and Conclusions."

For the second group of illustrations the legend is as follows:

M = Bending moment in inch-lbs/in.

Q = Shear in lbs/in.

W = Radial deflection in inches $\times (10)^{-6}$

T = Rotation in radians $\times (10)^{-6}$

The cuts at the sections considered critical; that is, at the bolting flange to adjacent shell (or mating flange) joints, are underlined and are identified as follows:

Nozzle shell to flange, No. 22

Core support to flange, No. 49

Pressure vessel to flange, No. 23

Flange to Flange, No. B

The third listed group above represents the graphical illustration of the critical shears and moments, which are the underlined items in the second group. Note that in all cases the shear increases going from 30 to 45 degree convergence while the moment decreases, except that in the case of the pressure vessel dome to flange, the shear decreases also. These parameters of

discontinuity shear and moment, and in particular the moment, at the critical cuts are of prime importance in this study since they have greatest influence in determining shell and ring weight and bolt strength requirement. All of the moment graphs point to decreasing weight requirement in going from the shallower to the 45 degree convergence angle.

In the fourth group of illustrations, (the computer printout of critical stresses and margins of safety), the data for the critical sections has been underlined. There are several small negative margins of safety but, since this is a parametric study, they are of no concern. In the 45 degree design shown to be optimum there are small negative margins only in the vicinity of the nozzle shell to flange joints. This situation can easily be remedied in detail design by slightly more generous filleting between rings and shells. If the structures for the other convergence designs were revised to eliminate their negative margins, an even greater weight savings advantage would be shown for 45 degree convergence.

NOZZLE CONVERGENCE ANGLE PARAMETRIC STUDY REFERENCES

1. AGC Program No. 663 for Elastic, Axisymmetric Shells of Revolution - for IBM 7094 Computer
2. "Phoebus-2 Pressure Vessel Nozzle Interface Analysis, Part I - Loads Analysis" March 26, 1965, D2-65-6 (Appendix B)
3. AGC REON Report No. 2275 to AEC-NASA SNPO, "Materials Properties Data Book," July 1964

3. Preliminary Vibration Analysis

a. Introduction

As a part of the preliminary design effort a preliminary vibration parametric analysis of the nozzle exit cone was prepared. The primary purposes of this analysis were to determine the fundamental frequencies of the nozzle exit section as a function of the exit section wall thickness and to determine if the range of thicknesses being considered for the exit section would result in a serious degradation of the nozzle fundamental frequencies.

b. Discussion

It was found during NRX-A testing that the NERVA U-tube nozzle $n = 2$ bell mode frequency is in the range of 235 to 240 cps and that this mode is easily excited during periods of low power operation when the nozzle is not flowing full, and that the ratio of stress to g loading is approximately 3000 psi per 100 g's at 235 cps. This is not a significant stress level and has no detrimental effects on the nozzle structure. In the final design of the Phoebus-2 nozzle jacket the exit cone and propellant inlet torus design will be appropriately stiffened such that the fundamental frequencies are within the tolerable range that have been shown to be acceptable for the NERVA U-tube nozzle.

Consideration in subsequent analyses will be given to the inlet line, the inlet torus configuration and the Phoebus test assembly foundation, as well as propellant flow effects and material property variation with temperature.

c. Summary

The enclosed graph (Figure 135) shows the results of a bell mode analysis of three variations of the Phoebus regeneratively cooled nozzle. The nozzle is constructed of a truncated conical shell in which coolant U-tubes are imbedded. A large torus is attached at the exit plane. For the analysis the nozzle was assumed to be at room temperature and dry.

FIGURE 135

A parametric study was made of the nozzle structural dynamic characteristics for shell thicknesses of 0.25, 0.35 and 0.45-in. The fundamental frequencies for all three cases occurred in the bending mode ($n = 1$)*and were 170, 176, and 193 cps, respectively. The differences in the frequency vs n plots become greater for n values greater than 2.

In determining the anisotropic stiffness properties of the nozzle structure, the U-tubes and the material between them were found to provide great longitudinal stiffening because of the large cross-sectional inertia. In the bending mode ($n = 1$), the results indicate that the effect of shell thickness on frequency has been minimized by the dominant stiffness contribution of the U-tubes.

However, in the circumferential direction, the stiffness contribution of the U-tubes to the shell was negligible. This was due to the large bending compliance at the top of the U-tubes. The torus also contributed significant stiffness (and mass) to the structure. It tends to fix the nozzle at the exit for n values greater than 2 and dominates the dynamic behavior of the nozzle at $n = 2$.

d. Limitations of the Analytical Method

Assumptions and idealizations which must be made in reducing the physical nozzle to its analytical model are listed below.

(1) The analysis is based on ideal fixed-free boundary conditions at the "throat" (fixed) and exit (free). The fixed condition is much less than ideal in most rocket nozzle hardware, the effect of which is to lower the frequencies associated with low values of n (this effect is quite pronounced for the $n = 1$ frequency). In the case of the Phoebus nozzle analysis, the "fixed" boundary is taken at the throat.

* n represents the number of complete deflection sine waves occurring around the circumference of the shell and is illustrated for several values in Figure 136.

ILLUSTRATIONS OF SEVERAL VALUES OF THE MODESHAPE PARAMETER n
(BELL MODES)

FIGURE 136

(2) The anisotropic conical shells program accounts for properties which vary in the R direction. However, it does not account for nozzle properties which vary circumferentially. Therefore, concentrated masses (such as the manifold inlet) must be distributed around the circumference.

(3) The nozzle contour must be replaced by an equivalent truncated cone.

(4) The analysis is developed in such a manner that the "cosine n" type of circumferential deflection occurs uniformly over the nozzle. Vibration modes have been excited during testing of tubular nozzles in which the manifold and coolant tube portions of the structure oscillate with different n values. The analytical method is not capable of predicting this type of motion.

(5) A six-term summation of assumed displacement functions (in the R-direction) is used in the computer program. While producing good results for the fundamental frequency vs n curve, this technique produces less reliable answers for harmonic modes.

(6) There are other simplifications employed in the development of the shell equations, discussion of which is beyond the scope of this report.

In summary, there are a number of factors which might influence the analytical results given in Figure 137. Assumptions made with regard to these factors are such that the calculated bell mode frequencies would tend to be greater than measured values.

e. Method of Analysis

A detailed report on the anisotropic conical shell vibration analysis has not been published. The method is a rather straightforward extension of the isotropic version presented in Ref. 1, the difference being in the form of the stress-strain relationships. A brief statement of the approach follows. The

EXPERIMENTAL ANALYTICAL CORRELATION
AJ10-137 (APOLLO) SUBSCALE EXTENSION SKIRT
BELL MODE VIBRATION FREQUENCIES

FIGURE 137

stress-strain, strain-displacement, strain energy, and kinetic energy equations of shell theory are formulated for a conical shell. The energy expressions involve integration over the shell surface; the portions of these integrals dealing with the R-direction are left in a general form such that structural nonuniformity can be accounted for. Displacement functions are assumed for the three orthogonal directions of motion. The normal displacement, for instance, has the form

$$\omega(R, \phi, t) = \cos n \phi \sum_{i=1}^n \omega_i(t) \left(\frac{R - R_1}{R_2 - R_1} \right)^{i+1}$$

The "cos n" term accounts for the classical bell mode patterns shown in Figure 136, while the summation on R defines the meridional components. The dependent variables of the problem are the $\omega_i(t)$ terms and their meridional and circumferential counterparts. The energy integrals are then formed using these assumed displacement functions. Lagrange's equation is used to develop the equations of motion which may be written in matrix form such that they resemble the equation of a spring mass system in simply harmonic motion:

$$-\omega^2 MX + CX = 0$$

where

ω = circular frequency

M = mass matrix

C = stiffness matrix

X = matrix of dependent variables

For nontrivial solutions of these homogenous equations, the determinant of the matrix $-\omega^2 K + C$ must vanish. Values of ω which satisfy this condition are the desired vibration frequencies. Mode shapes corresponding to each frequency are easily found from the equations of motion.

Input to the computer program consists of structural and mass characteristics, shell geometry, internal pressure (if required), and a list of n values. Input data for the Phoebus nozzle was prepared by dividing it into structurally similar zones cut by planes perpendicular to the thrust axis. Shell elements for each zone were analyzed in detail and equivalent anisotropic elastic

constants derived. Thus, the differences in deflection due to loads applied parallel to the tubes and perpendicular to the tubes may be included in the simulation. Output includes natural frequency, mode shape, and generalized mass for each value of n .

The special capabilities of the conical shell vibration program are: (1) handles shells with structural nonuniformity in the R-direction; (2) will account for anisotropic structures (such as regeneratively cooled nozzles); (3) can include the effects of nonuniform internal pressure.

The isotropic conical shell vibration program has been checked by comparing analytical and experimental bell mode frequencies for the Apollo subscale nozzle (see Ref. 1). The correlation is quite good, as illustrated in Figure 137. The analytical results have been repeated by using the anisotropic program, for which the Apollo subscale nozzle is a degenerate case.

VIBRATION ANALYSIS REFERENCES

1. Free Vibrations of Conical Shells, Aerojet-General Report 9620:D0006R, 29 August 1963.

4. Vibrations Testing

a. Test Description

(1) Part I

The nozzle will be bolted to a rigid mass such as the concrete floor of the testing laboratory, with the manifold end up. The nozzle will then be excited by a small shaker which imparts a sinusoidal forcing function radially at the manifold. A frequency sweep from 5 to 2000 cps will be conducted to determine all possible resonant frequencies. The response of the nozzle will be measured, at each resonant frequency, by a hand-held accelerometer probe circumferentially at several stations and longitudinally at several values. This 'mapping' technique* will enable the determination of the complex bell mode deflections of the nozzle. Additional tests will be conducted with the input tangentially and longitudinally at the manifold.

(2) Part II

The nozzle will be mounted on a standard vibration slipper table with the manifold end up. A forcing function will be applied at the nozzle-pressure vessel interface. The response of the nozzle will again be measured by hand probes. This particular test setup will very closely simulate the nozzle's reaction to reactor induced vibrations.

b. Test Objectives

The objectives of this vibration survey test are to:

- (1) Provide a check on the analytical results.
- (2) Determine the resonant frequencies of the nozzle.

* "Vibration test of the KIWI nozzle", Rocketdyne RN-2, No. 11, Los Alamos Scientific Laboratory, 5 January 1965.

- (3) Define the resonant mode shapes.
- (4) Measure the amplification factors associated with each resonance.
- (5) Determine the transmissibility of the nozzle.

c. Responsibilities

The vibrations test will be performed by Department 4640, Dynamics Programs, SRO. They will also provide all the equipment necessary to conduct the test with the exception of the nozzle itself. Department 7510, Phoebus-2 Nozzle Analysis, will provide the coordination and technical support required. Department 7520, Phoebus-2 Nozzle Design and Analysis will provide the nozzle.

d. Results

The results of the vibration tests will be compared to the analytical findings and the degree of correlation will indicate the predictability of the vibration behavior of the nozzle. The amplification factors and transmissibility will provide an indication of the accelerations to be expected during the reactor tests. If the predicted accelerations are found to be too severe, design modifications will be made to add damping. These modifications may be done without changing the mechanical structure of the nozzle.

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D. MATERIALS AND FABRICATION - TASK D

1. Materials List

The materials under consideration for the Phoebus-2 nozzle are listed on Table 13. Hastelloy X was selected as the reference structural material and Hastelloy N and Inconel 625, are included in the test program as back-up jacket and cooling channel materials. The weld and braze filler materials are also listed. The properties data are discussed in detail in subsequent paragraph 3.

2. Material Specifications

The policy adopted in writing the materials specifications has been to incorporate the most recent technical advances which have an application to the materials and procedures indicated for the Phoebus-2 nozzle. While any departure from current industrial or government specifications may incur delays or problems, the anticipated results of using the select quality, vacuum melted, materials and minimizing undesirable elements such as phosphorus and boron were considered as ample justification for such changes.

Five materials procurement specifications were generated for nickel-chromium-molybdenum alloys applicable to the materials evaluation program. The initial issue of these specifications was based on ORNL documents. The Aerojet documents cover the alloys designated as Hastelloy X, Hastelloy N, INOR-8 and Inconel 625. The chemistry and tensile properties were presented as jointly approved by SNPO and Aerojet. Aerojet non-destructive testing requirements were incorporated. The latest issues of referenced ASTM specifications were shown.

A summary of the work done on these five specifications is as follows:

a. Forgings - AGC-90056 B was based on ORNL Specification MET-RM-2. The initial issue date was 31 March 1965 with the "A" and "B" revisions issued on 9 April 1965 and 14 May 1965, respectively.

TABLE 13

MATERIALS LIST

NOZZLE

JACKET	HASTELLOY X INCONEL 625 HASTELLOY N	REFERENCE A ALTERNATE ALTERNATE	AVAILABLE LARGE SIZE INGOT AND FORGING EXPERIENCE
CHANNEL	HASTELLOY X INCONEL 625 HASTELLOY N	REFERENCE ALTERNATE ALTERNATE	
WELD FILLER	HASTELLOY X HASTELLOY N INCONEL 625	UNDER STUDY OF COMPOSITIONS AND MERITS	
BRAZE ALLOY	82 Au-18 Ni 70 Au-8Pd-22 Ni 81.5 Au-16.5 Cu- 2 Ni		

INJECTOR

PLATE	347 SS		
RING & BAFFLES	COPPER - (OFHC)		
BRAZE ALLOYS	65 Cu 35 Au-3 Ni - (1925°F)		
1ST REBRAZE ALLOY	50 W/O (82 Au-18 Ni); 50 W/O (65 Cu 35 Au-3 Ni) (1850°F)		

b. Plate, Sheet and Strip - AGC 90057A - Amendment 1 was based on ORNL Specification MET-RM-B334. The initial issue date was 31 March 1965. The "A" revision was issued on 9 April 1965 with Amendment 1 issued on 14 May 1965.

c. Welding wire - AGC-90058A - Amendment 1 was based on ORNL Specification MET-RM-B304. The initial issue date was 31 March 1965. The "A" revision was issued on 9 April 1965 with Amendment 1 issued on 14 May 1965.

d. Weldability test - AGC-90059B was based on ORNL Specification MET-WR-4. The initial issue date was 31 March 1965 with the "A" and "B" revisions issued on 9 April 1965 and 14 May 1965, respectively.

e. Bar - AGC-90060 was based on ORNL Specification MET-RM-B336. The initial issue date was 9 April 1965. This specification is currently being revised to reflect the changes already incorporated into the other specifications

3. Properties Data

a. Jacket Forgings

The materials selected for the nozzle jacket are all solid solution strengthened nickel base alloys to assure good yield strength and ductility over the entire temperature range from -423° to 1200°F. While some other alloys may offer adequate strength and ductility in this temperature range, the service temperature requirement for nickel-base alloy channels and the attendant joining problems eliminated other alloys for candidate jacket materials.

The material design requirement of the nozzle jacket are summarized as follows:

(1) Cryogenic ductility over 10% elongation and the best tensile yield, shear and compressive strength and the modulus of elasticity for the temperature range minus 423 to 1200°F.

(2) Physical properties relative to thermal stress, α , K_t , E_{dynamic} , μ and plastic strain effects.

The data obtained from industrial and government sources are useful to the ambient and elevated temperature design requirements, but are very limited in sub-zero properties. The actual properties to be obtained from the heavy section forging may differ from the tabulated values. The available data are taken from sheet, bar, and plate but no data are available from heavy section forgings. The majority of the reported data are for air melted grades containing the commercial range of alloy constituents including the interstitial elements H, O, N, and normal levels of boron, phosphorus and sulphur. It is apparent that all of these elements will be significantly lower in the vacuum melted jacket forgings. The effect of the metallurgical thermal history including the brazing cycle on the mechanical properties can contribute a minor change which is not defined by any of the available references. The published values properties for the three jacket alloys for the 0.2% yield strength are shown in Figure 138. The figure includes weld metal properties and a design allowable curve (solid line) based on 80% of values for the 0.5 in bar stock data. Figure 139 presents the ultimate strength data corresponding to the above yield data. The values for the elongation of the same materials are shown in Figure 140 (Revised). The solid line represents the design allowable values based on 80% of values for Hastelloy X bar. The dashed lines in Figures 138, 139, and 140 present the first Aerojet samples (tested at LASL) of vacuum-melted Hastelloy X. The improved elongation values of the consumable electrode vacuum melted (CEVM) material compared with air melted heats illustrate the advantages of the vacuum approach.

Efforts to evaluate the full range of variation of tensile properties is shown by the vertical bands shown in Figures 138, 139, and 140. The data provided by Union Carbide, Stellite Division represents a large number of tests (over 100) at room temperature, of which 1% to 99% of the data fall within the bands shown. Values for the modulus of elasticity, the thermal expansion and the thermal conductivity are shown on Figures 141, 142, and 143, respectively.

0.2 % YIELD STRENGTH VS TEMPERATURE - PHOEBUS - 2 JACKET DESIGN ALLOWABLES

FIGURE 138

FIGURE 139
246

ELONGATION VS TEMPERATURE PHOEBUS - 2 JACKET DESIGN ALLOWABLES

FIGURE 140

MODULUS OF ELASTICITY VS TEMPERATURE PHOEBUS-2 JACKET DESIGN

FIGURE 14.1

THERMAL EXPANSION VS TEMPERATURE PHOEBUS - 2 JACKET DESIGN

FIGURE 142

THERMAL CONDUCTIVITY VS TEMPERATURE PHOEBUS - 2 JACKET DESIGN

FIGURE 143
250

b. Channel Strip Materials

The requirements for the channel wall material are very stringent as a result of the surface temperature of 1800°F (maximum) and the high heat flux which imposes severe temperature gradients in the channel wall. Hastelloy X is the reference alloy for this application as a result of extensive use at high temperature. The alternate materials are of interest because of higher yield strength values above 1600°F.

The properties required by the design are the same as listed for the jacket forgings, with the addition of a higher temperature up to 1800°F. Since the channels are to be furnace-brazed, there is no need of evaluating welded material, however the thermal expansion must be matched with that of the jacket material. The data shown for the three nickel-base alloys for the jacket will be used until more representative data for the thin channel strip is available.

c. Additional Properties

The service conditions for the Phoebus-2 nozzle have indicated that the performance of materials in the region of plastic strain is a serious consideration. The stresses computed from the large temperature gradients superimposed upon the mechanical stresses exceed the normal stress allowances in the jacket, and thus present a special case. The use of a controlled strain produced by bending a specimen while under a tensile load was proposed as a means of determining the effects of the service conditions on the candidate alloys.

While the similar nickel-alloy compositions demonstrate comparable short time tensile properties, the performance and relative plastic-strain endurance properties are unknown (such as those resulting from testing by repeated straining in the elastic and plastic regions). Such severe tests are believed to demonstrate more decisively the performance variation of the reference alloys in the temperature range of interest, namely room temperature to 1200°F. The proposed approach for such testing is shown in Figure 144.

TECHNIQUE FOR PLASTIC STRAIN TESTING

FIGURE 144

d. Radiation Effects on the Properties of Hastelloy X,
Hastelloy N and Inco 625

Hastelloy X and Hastelloy N have been used in reactor service and benefit from sufficient radiation exposure to demonstrate their performance under varying conditions. Nuclear facilities which have reported irradiation testing or reactor applications include: Aerojet General Nucleonics, San Ramon, California; BMI, Columbus, Ohio; General Atomics, San Diego, General Electric, Cincinnati, Ohio; ORNL, Oak Ridge, Tennessee and Philips Petroleum, Idaho Falls, Idaho.

No work has been reported on Inconel 625 irradiation as a result of its recent development. It should be pointed out, however that the 625 alloy benefits from a similarity to Hastelloy X and other solid solution strengthened nickel base alloys, at least as far as understanding or predicting its metallurgical behavior in service.

The effects of radiation can best be treated in two regions, low temperature and elevated temperature, although no sharp line of distinction is intended.

(1) Exposures at Temperatures Less Than 1000°F

The performance of Hastelloy X and similar ductile alloys when exposed to reactor neutron doses in excess of 1×10^{19} nvt ($E \geq 0.1\text{MEV}$) was consistently satisfactory. The yield strength increased by factor of two after 5×10^{19} nvt with very little change in ductility as shown on Table 14. The threshold dose for the indicated hardening effect of fast neutrons is approximately 2×10^{17} nvt, but substantial changes are not generally observed below 10^{19} nvt which is approximately the fast neutron dose anticipated at the throat of the Phoebus-2 nozzle after firing. Since the nozzle jacket wall will be at low temperature, below 600°F, the yield and tensile strength will improve progressively as shown in Figure 145. The hardening of Hastelloy N or Inconel 625 would presumably be very similar, however, the changes in % elongation tend to differ between alloys depending upon the micro-structure of each alloy and the heat treatment.

EFFECTS OF IRRADIATION OF THE PROPERTIES OF HASTELLOY -X (ANNEALED)

PROPERTIES	UNITS	PRE-IRRADIATION VALUE	(*) AFTER IRRADIATION, AT INTEGRATED NEUTRON FLUX, IN n/cm^2					
			5×10^{19}		1.8×10^{20}		2.5×10^{20}	
			VALUE	CHANGE, %	VALUE	CHANGE, %	VALUE	CHANGE, %
1. ULTIMATE TENSILE STRENGTH	1000 psi	112.5	129.3	+15.0	130.7	+16.2	131.0	+17.3
2. YIELD STRENGTH 0.2% OFFSET	1000 psi	49.4	100.2	+103	104.0	+110	106.3	+115
3. ELONGATION	%	52.0	50.0	-3.8	43.0	-17.3	42.0	-19.2
4. REDUCTION IN AREA	%	52.0	62.0	+19.3	64.0	+23.1	59.0	+13.5

(*) Irradiated at $120^{\circ}F$, tested at R. T.

Refs: Bartz, M. H., "Performance of Metals During Six Year Service in the MTR." Peaceful uses of Atomic Energy, Geneva, (1958) 5 P. 1878

HASTELLOY-X IRRADIATION

MECHANICAL PROPERTIES DEPENDENCE ON INTEGRATED
FAST NEUTRON FLUX FOR HASTELLOY-X ANNEALED

FIGURE 145

In general, it is concluded that the low temperature effects are not deleterious to the material performance of Hastelloy X.

(2) Elevated Temperature Radiation Effects

Neutron exposures at elevated temperatures results in progressively less hardening and strength changes as the temperatures are increased. At temperatures about 1000°F the exposure to 10^{19} nvt would cause the material to suffer only a 5 or 15% loss in strength and ductility.

At higher temperatures, 1200°F and above, a number of nickel-base alloys and stainless steels have demonstrated a loss of ductility, primarily noted during stress rupture testing, after irradiation. Most nickel base alloys which have been exposed to thermal neutrons at about 10^{16} nvt or more will show a decrease in the rupture life and elongation when tested at 1200°F and above as shown for Hastelloy X in Figure 146. The elongation measured by short time tensile testing was less affected than stress rupture elongation values after low neutron doses, but the former was reduced progressively above 10^{17} nvt (thermal). Low strain rates show greater losses than high strain rates.

Short time tensile test data on Hastelloy N has been obtained at ORNL (see Reference 1) for temperatures ranging from room temperature to 1650°F after irradiation at 1300°F to doses of 8×10^{20} . The extent of the changes in properties are shown in Figure 147. The uniform elongation values were found to fall more seriously than the total or true fracture strain which had a value of 4.9% at 800°C as compared to 1.8% for the uniform strain values. It was observed (Reference 2) that the loss of ductility was affected by strain rate at the higher temperatures. At a strain rate of 0.2 in/in min. the uniform elongation at 700° (1292°F) was 13.5% as compared with a value of 5.6% at the low strain rate 0.002 in/in min. The corresponding unirradiated values were 32% and 20% respectively. Although the above ORNL data represents a case where the neutron exposure is about 40 times as great as Phoebus-2, it does contribute to evaluating the problem.

HASTELLOY X IRRADIATION AT 1200° F

NOTE: NO EFFECT BELOW 1000° F - SHORT TIME TENSILE ELONGATION NOT AFFECTED UP TO 10^{17} BUT SOME CORRELATION ABOVE 10^{17} DATA FROM GE, NMPO, RPT. GE-MP-177-A SECOND ANNUAL REPORT ON HIGH TEMPERATURE MATERIALS (1963)

FIGURE 146

PHOEBUS - 2 THERMAL NEUTRON EFFECTS ON HASTELLOY N

STRAIN RATE - 0.002 IN/IN MIN

REF: MARTIN & WEIR, ORNL

———— UNIRRADIATED
 - - - - - IRRADIATED

(9×10^{20} nvt (THERMAL) AT 700°C)

FIGURE 14-7

The generally accepted cause of the severe loss of ductility, and stress rupture life for nickel-base alloys as well as stainless steels when stressed at 1200°F or above is the formation of helium by the reaction $B^{10}(n, \alpha) Li^7$, and to a lesser extent by other gas forming reactions. The boron content of the Hastelloy N tested at ORNL was listed as 40 ppm, and that for the Hastelloy X was 5-ppm for data shown in Figure 146.

Martin, W. R. and Weir, J. R. (Reference 2) indicate further evidence that boron is involved by comparing cadmium shielded and unshielded exposures which show that thermal neutron reactions are the principal cause of the ductility loss.

A systematic evaluation (Reference 3) made with varying amounts of boron in the alloy was performed with Inconel 600 but not with the Hastelloys as yet. The question of what the allowable concentration of boron in the alloy should be cannot be established without further work, because of the many factors which affect the results. The following are major influencing factors:

- (a) Temperature of exposure
- (b) Time of exposure
- (c) Temperature during applied stress
- (d) Boron content
- (e) Metallurgical history of alloy
- (f) Grain size
- (g) Strain rate

While all similar boron-containing alloys have shown neutron induced changes when tested at elevated temperatures, the extent of damage cannot be predicted from the boron analysis above. Stress rupture tests (Reference 4) on A-286 heats having 8.5-ppm and 100-ppm boron contents demonstrated that irradiation of 5×10^{19} nvt (fast) was more damaging to the low boron than to the high boron analysis. The stress rupture life and elongation at 1200°F of the high boron heat was substantially better than those properties of the low boron analysis under the

same test conditions. While the effects on A-286 are not applicable to other alloys they serve to illustrate the complex nature of the problem which is primarily dependent upon the microstructure, grain size and grain boundary conditions.

No quantitative relationship for the influence of boron on Hastelloy X is apparent at this time since the only data relating to high temperature testing was performed on heats containing less than 10-ppm boron. The 40-ppm Boron contained in Hastelloy N was apparently too high for Phoebus applications, but data was not available on low boron containing heats as yet.

It is important to note that all tangible evidence of serious ductility losses as a result of neutron doses less than 10^{20} nvt were at temperatures above 100°F where grain boundary fracture was evident. Lower temperature exposures and stressing irradiated material at lower temperatures will allow the use of established data with normal safety factors.

At least two approaches are under consideration as a means of reducing the degree of degradation of ductility and strength. They are the reduction of the boron content in the original melt, and the controlling boron in stable precipitates not primarily at the grain boundaries. A fine grain size is also desirable, and may be helpful in the channel strip, but is not considered feasible in heavy forgings for the jacket.

4. Welding Development

a. Objectives

The fabricating of the Phoebus-2 jacket in three segments will require definition of the welding process to provide optimum and reproducible joint quality.

The objective of the welding program is to establish the weldability of Hastelloy X and two alternate heat resistant nickel base alloys, in

thick-section sizes (in excess of 1-1/2-in.). Current literature and industrial experience with regard to welding of these candidate jacket materials is limited to smaller section sizes.

The welding is to be performed on three vacuum-melted heats of Hastelloy X and Hastelloy N in forgings and plate form and in three vacuum-melted heats of Inconel 625 in plate form. Additional welding requirements are that three vacuum-melted heats of filler wire are to be employed in the welding of each of three candidate materials in forgings and plate form.

(1) Forging Joints

The initial weld joint is located in the cylindrical section approximately 2-in. forward of the pressure vessel flange on a 59-in. diameter. The section thickness in this area is approximately 1.375 in. as seen in Figure 148. The proposed weld joint preparation is also shown. A double "U" joint preparation having a root radius of 0.180 in., a 45° included angle, and a .125-in. abutting land was selected to accomplish a balance of the welding shrinkage stresses. Approximately 40 automatic weld passes will be required to complete this weld.

(2) Development Plan

The welding evaluation program plan is illustrated in Table 15. The first task was to establish the initial welding parameters which were formulated into a preliminary welding procedure. The weld quality would be monitored by non-destructive tests and metallography. It is currently planned to evaluate the TIG process on Hastelloy X plate material. Plate material was selected primarily because of lower costs involved. These plate weldments would be submitted for non-destructive engineering evaluation and would be correlated with metallographic examination.

JACKET WELDMENT

FIGURE 148

WELDING EVALUATION PROGRAM PLAN

Table 15

The weldability of forgings will be established by welding ring rolled forgings simulating the jacket throat diameter. The degree of restraint which will be encountered in the automatic welding of these ring forgings will approximate that which will be encountered in jacket fabrication. The extent of the distortion throughout the welding operation will be closely monitored. In addition to in-process weld inspection, the rings will be submitted for NDT engineering evaluation. Limited weld-process qualification tests will be performed to verify the application of sound welding techniques. The applicable filler wire will be selected and plates will be welded by the automatic process. The plates will be submitted to NDT engineering evaluations. Weld qualification tests will be performed as in the two previous studies. Qualified weldments will be submitted for the design materials test program.

The Hastelloy N welding evaluation will likewise be performed on plate and ring rolled forgings. The flow diagram is essentially the same as that of the Hastelloy X. It is assumed that weld process can be completely defined in the Hastelloy X evaluation.

The Inconel 625 welding evaluation will be confined to plate material. This is because of the small size and weight of forgings produced in this alloy.

Completion of the projected program will have established suitable welding procedures to be applied to the jacket fabrication.

The type and quantity of weldments which will be fabricated during the course of the development program are summarized in Table 16. On the left, Table 16, are types and heats of each filler wire to be employed. Type 347SS listed was welded with Hastelloy X filler wire to establish the initial welding parameters. The vertical column of figures illustrate the number of weldments to be fabricated during the course of the test program in the three heats of each material in forging and plate forms. A total of 19 weldments will be produced during the course of this program.

WELD TEST PROGRAM - SUBTASK D-2

<u>FILLER WIRE</u>	<u>PARENT METAL</u>					
	<u>347 SS</u> <u>PLATE</u>	<u>HASTELLOY X</u> <u>FORGED RINGS</u> <u>(3 HEATS)</u>	<u>PLATE</u> <u>(3 HEATS)</u>	<u>HASTELLOY N</u> <u>FORGED RINGS</u> <u>(3 HEATS)</u>	<u>PLATE</u> <u>(3 HEATS)</u>	<u>INCONEL 625</u> <u>PLATE</u> <u>(3 HEATS)</u>
AMS 5798						
HEAT A (AIR MELT)	3	1				
AGC 90058A						
HEAT A (CEVM)		1	1	1	1	1
HEAT B (CEVM)		1	1	1	1	1
HEAT C (CEVM)	<u> </u>	<u>1</u>	<u>1</u>	<u>1</u>	<u>1</u>	<u>1</u>
SUB-TOTAL WELDMENTS	3	4	3	3	3	3
TOTAL WELDMENTS -	19					

The minimum weld process qualification tests which will be required to develop quality weldments are illustrated in Table 17. It is planned to obtain the weld chemistry, perform limited tensile tests at room temperature in both the axial and transverse directions. Metallographic samples which encompass the weld, heat affected zone and parent metal will be sectioned for examination. These sections will be utilized for hardness transverses. The vertical columns of Table 17 illustrate the minimum number of tests planned on each heat of material. The total number of 144 tests are planned.

(3) Procedure

A preliminary welding specification* was initiated and the weldability program was started with the procurement of commercially available Hastelloy X forging stock. This first heat of CEVM ring forgings meets the AGC 90056 specification with the exception of the boron content. Air melt Hastelloy X filler wire was procured to AMS 5798 specification. These ring forgings, 17-in. ID x 23-in. OD x 5.25-in. thick were machined and subjected to engineering ultra-sonic inspection and were established to be sound.

Two of the rings intended for the welding studies were machined with the joint preparation shown in Figure 149, while the third ring forging was parted into two rings each measuring 2.5-in. thick. The details of the third ring forging likewise received the weld joint preparation shown in Figure 149. The rings were tack welded together in eight places on the OD each tack being approximately 2-in. long. The assembled rings were mounted on a weld positioner dimensional measurements were recorded to evaluate distortion.

Six type 347 stainless steel plates were also machined with the double "U" groove joint preparation. These 1.5-in. x 6-in. x 24-in. plates were used to provide the welding parameters for the forged rings. Weld parameters for semiautomatic TIG welding were established on these plates using Hastelloy X filler wire as follows:

* See page 271, Proposed Preliminary Welding Specification for Phoebus-2 Jacket

WELD TEST PROGRAM - SUBTASK D-2

	PARENT METAL				
	HASTELLOY X		HASTELLOY N		INCONEL 625
	<u>FORGED RINGS</u> <u>(3 HEATS)</u>	<u>PLATE</u> <u>(3 HEATS)</u>	<u>FORGED RINGS</u> <u>(3 HEATS)</u>	<u>PLATE</u> <u>(3 HEATS)</u>	<u>PLATE</u> <u>(3 HEATS)</u>
<u>WELD QUALIFICATION</u> <u>TESTS PER WELDMENT</u>					
WELD CHEMISTRY	1	1	1	1	1
TENSILE SPECIMENS					
(AXIAL)	3		3		3
(TRANSVERSE)	3		3		3
METALLOGRAPHIC	4	4	4	4	4
HARDNESS TRAVERSE	<u>1</u>	<u>1</u>	<u>1</u>	<u>1</u>	<u>1</u>
SUBTOTAL TEST SAMPLES (3 HEATS)	36	18	36	18	36

TOTAL TEST SAMPLES - 144

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Table 17

RP-SR-0001

DETAIL OF WELD JOINT PREPARATION RING FORGING

Figure 149

Amperage	Voltage	Wire Dia.	Wire Feed	Travel
180	10	.045	58 IPM	6 IPM

Using these parameters, a root pass was successfully deposited on the ID of the ring assembly. The weld was using 18,000 joules-per-in. of travel with a ratio of filler wire deposition rate of linear travel rate of 6:1. A grinding operation was then performed on the OD to remove the tack-welds and lack of complete penetration.

The results of the weld penetration achieved on the first root pass in the ring weldment indicate that it may be desirable to reduce the joint land thickness of the jacket from the present 0.135 dimension to .075 so full penetration of the joint may be achieved on the initial ID root pass. Full penetration of the joint during the first root pass presents several advantages, foremost of which would be the elimination of the back-machining operation on the OD which is required if full penetration is not obtained eliminating an in process jacket machining and handling problem.

Two additional root passes were deposited on the joint OD. Inert gas back-up was employed for all root passes. These root passes were inspected by radiographic and penetrant techniques and were established to be found free of internal or external defects.

The Hastelloy X ring forging set on the rotating positioner for welding is shown in Figure 150. The weld preparation on the ID is identical with that of the OD but is somewhat covered by the penetrant developer.

The tungsten inert gas automatic head is shown repositioned on the ID joint for illustration purposes. The torch, electrical and inert gas supply lines, push-type wire feed unit and cable, and torch extension arm are shown here. The torch extension arm and wire feed cable will have to be extended an additional 36-in. to accomplish the ID throat weld of the jacket. Procurement of these items are presently being initiated.

AUTOMATIC WELDING OF HASTELLOY X RING FORGINGS

FIGURE 150

Fourteen additional passes were made alternately on the ID and OD of the ring forging in an effort to assess the problems that may arise in joining the more massive rings.

The restricted access to the ID of the rings, requires a change in the method of filler wire deposition, from the conventional "push"-type of feed to a "pull"-type mechanism. This change is presently being incorporated.

The experience gained on this first ring weldment also indicates that it would probably be desirable to have access to both ends of the nozzle during welding. The limited space on the small ID of the nozzle, after the welding head and wire feed unit are in place, makes it extremely difficult for a welding operator to observe the weld melt if access to the opposite end of the nozzle is denied because of fixturing.

b. Proposed Preliminary Welding Specification for Phoebus-2 Jacket

(1) Scope

This specification establishes the requirements for welding the Phoebus-2 jacket and includes the welding conditions, weld operator qualifications, inspection methods and rework requirements.

(2) Applicable Documents

The following documents, of the issue in effect on date of invitation for bids, form a part of this specification to the extent specified herein:

Military

MIL-T-5021 Tests: Aircraft and Missile Welding Operator's
Qualification

MIL-STD-20 Welding Terms and Definitions

Non-Military

ASA Y 32.3 - 1959 Graphical Symbols for Welding

Aerojet-General Corporation

AGC-90056 Material Specification, Nickel - Molybdenum - Chromium Wrought Alloy Forgings (U)

AGC-90058 Material Specification, Nickel and Nickel-Base Alloy Bare Welding Filler Wire (U)

AGC-46350 Process Specification, Levels of Cleanliness, Description of

AGC-36163 Process Specification Metals; Ultrasonic Inspection of

Standards

AGC-STD-3010 Standard Inspection, Penetrant

AGC-STD-1151 Standard Inspection, Radiographic Materials Procedure for

AGC-STD-4005 Standard Engineering Acceptance Criteria for Welds

Manufacturing Process Instruction (MPI)

MPI 7-2 Welding Wire and Electrodes, Identification, Handling, Cleaning and Storage of

(3) Applicable Definitions

Welding definitions and symbols shall be in accordance with MIL-STD-20, ASA Y32.3 1959, and the following:

- (a) TIC (WELDING): Inert gas shielded, nonconsumable electrode
- (b) Manual Welding: Welding wherein the entire welding operation is performed and controlled by hand.
- (c) Machine Welding: Welding with equipment which performs the welding operation under the observation and control of an operator.

(4) General Requirements

The welding facility shall record, retain, and upon request, make available to authorized REON personnel, historical data pertaining to weldments and welding operator's as noted below.

(a) Welding Procedure Records

Welding procedure data, including inspection and rework records of each part welded, shall be recorded on forms which shall be provided by REON. The records shall identify the weldment by the applicable part number, serial number, and material heat numbers of each section of the assembly. The identification, by name and stamp number, of the weldor or weldors who performed the welding shall be included as an integral part of such records.

(b) Qualification Test Records

A file of the test results of each welding operator's certification and machine welding qualifications shall be maintained.

(5) Welding Operator Qualifications

All welding shall be performed by weldors currently certified in accordance with the requirements of MIL-T-5021 for Group III alloys. Weldors who will perform machine welding shall be required to successfully pass a machine welding certification test which shall typify the production weldment, (Joint No. 7) of MIL-T-5021, Reference Paragraph 3.6.3.5.

(a) Qualification Test Requirements

1 General. The requirements for the certification test shall be per MIL-T-5021 and as noted below.

2 Material. The test plate material shall conform to the applicable material specification for the Phoebus-2 jacket. Weld filler wire shall conform to the applicable material specification and shall be of the same diameter as that used in welding the Phoebus jacket.

3 Size. The test plates shall be of the same section thickness as the thickest joint section of the Phoebus jacket, plus or minus three-eighths of an inch, and shall be four inches wide and twenty-four inches long. Two test plates shall constitute one test weldment. One weldment will be required for each machine weld or certification.

4 Weld Joint. A double "U" joint incorporating the groove dimensions of the Phoebus jacket weldment (as shown in the applicable AGC REON drawing) shall be machined in the test plates.

5 Welding Requirements. The welding procedures and conditions for the machine weld certification test shall be the same as prescribed for the Phoebus jacket in this specification.

6 Inspection and Acceptance Criteria. The certification welds shall be subject to the same non-destructive test inspection methods, sequence, and acceptance criteria during and after completion of welding, as that prescribed for the jacket weldment, as noted in this specification.

7 Weld Testing. The welds shall be tested as required by MIL-T-5021 (Reference Paragraph 4.2.3.3).

8 Certification. Certification of the welder shall be per MIL-T-5021. Successful completion of the machine welding test shall be cause for the issuance of a certification of machine welding proficiency by the welding facility to the welder applicant.

9 Recertification. Recertification requirements shall be as noted in MIL-T-5021 and the following:

a All certified machine welders shall be recertified prior to expiration of valid certification.

b Recertification tests shall require the welding of one test plate conforming to all requirements of the original test as stated in this specification.

c An individual record of satisfactory workmanship, as evidenced by N.D.T. inspection records may, at the discretion of the cognizant Phoebus Q. C. representative, be accepted in lieu of a recertification test.

(b) Machine Welding Certification Test Waiver

At the discretion of the cognizant Phoebus quality engineering representative the requirements for a machine-weld certification test for a welder may be waived providing, (a) the welder is currently certified for the applicable welding process in Group III alloys per the requirements of MIL-T-5021, (b) the welding facility can produce proof, as evidenced by N.D.T. inspection records, that the welder has a recent (last six months) machine welding record of satisfactory workmanship in material of the same composition and comparable section thickness as that of the Phoebus jacket.

(6) Welding Inspectors Qualification

Inspectors employed by the facility in the various N.D.T. inspection categories shall be properly qualified and/or certified as required by the applicable specifications governing such qualifications for specific inspection methods and processes.

(7) Material and Process Requirements

The Phoebus jacket material shall conform to the requirements of AGC-90056 for the designated alloy, and to the applicable Aerojet General, REON Divisions drawing.

(a) Weld Filler Material

The weld filler material shall conform to the applicable requirements of AGC 90058 and shall be of the diameter prescribed by this specification.

(b) Weld Joint Configuration

The weld joint configuration shall conform to the requirements of the applicable Aerojet-General Corporation REON drawing.

(c) Welding Equipment

Welding equipment such as machines, torches, regulators, wire feeds and heads shall be capable of making satisfactory welds when operated by a certified welder.

The welding controls shall consist of a direct current (dc) power supply, an automatic arc voltage controlled head, a welding sequence timing control to initiate and terminate sequentially, welding current, wire feed, positioner or rolls rotation, gas pre-flow, and gas post-flow. The equipment shall have suitable current sloping controls and a means of accomplishing automatic arc ignition.

(d) Welding Process

The welding process shall be machine TIG. Manual TIG welding shall be used for tack welding and in making weld repairs.

(e) Shielding Gases

Inert gases used in the welding process shall be in accordance with the following.

<u>Gas</u>	<u>Specification</u>
Argon	MIL-A-4144
Helium	Bulletin 585, Grade A

1 Adequate shielding of the molten weld puddle and underside of the joint being welded is required. The adequacy of the inert shielding shall be determined by visual examination. The finished weld and joint underside shall present a clean, and relatively shiny surface, which shall be free of oxide discoloration.

2 The moisture content of inert gases used during the welding process shall be checked at the welding outlets (torch and back-up) per the requirements of the applicable specification as designated by Phoebus quality control.

(f) Weld Filler Wire

The welding facility shall identify, handle, clean and store all weld filler material per the requirements of MPI 7-2.

(g) Fit-Up of Jacket Sections

1 Mismatch of abutting joint lands shall not exceed .030 in., or the applicable drawing requirements whichever is the least.

2 Gap between joint land faces shall not exceed .030 in., or the applicable drawing requirements whichever is the least.

(h) Tack Welding

Where tack welds are employed in the assembly of the jacket sections the following procedure shall be employed.

1 Tack welds shall be made by the TIG process incorporating a suitable inert gas back-up.

2 Tack welds shall be made on the OD of the joint.

3 Each tack weld shall be approximately one inch in length and spaced twelve to eighteen inches apart around the circumference of the joint.

(i) Welding Position

The welding will be accomplished in the down hand position, the jacket assembly being rotated beneath a stationary TIG welding head.

(j) Welding Schedule

The weld procedure, such as sequence and operating conditions, which shall apply for each joint in the jacket assembly shall be determined as a result of the weld development program. When this data is available it shall be incorporated as an appendix to this specification.

(k) Interpass Temperature and Control

Interpass temperature in a circumferential zone six inches each side of the weld joint shall not exceed 175°F. The temperature shall be checked using a contact pyrometer. Temperature indicating sticks shall not be used to check temperature.

(8) Inspection and Acceptance Criteria

Inspection methods, and acceptance criteria shall be per the requirements of AGC-STD-3010 Penetrant, AGC-STD-1151 Radiographic, AGC-36163, Ultrasonic, and AGC-STD-4005 Acceptance Criteria.

(9) Cleaning

Each jacket section shall be cleaned to Level H per AGC-46350 after machining the weld joints and prior to assembly on the weld fixture. Such cleanliness shall mean freedom from water and soils such as grease, cutting oils, and carbon on hardware which would interfere with further processing on fabricating operations.

(a) Spool Wire

Spool wire shall be inspected for cleanliness prior to use. Contaminated wire shall be cleaned according to the prescribed specification as designed by Phoebus quality control and then re-wound per applicable specification. Prior to installation of spool wire in the weld equipment, the reel case and wire feed lines of the equipment shall be cleaned.

(b) Tooling

All tooling employed during the welding and assembly of the jacket shall be cleaned prior to use to Level H per AGC-46350 and maintained at that level of cleanliness during the assembly and welding operations.

(c) Weld Joint

The weld joints and adjacent areas shall be thoroughly cleaned after assembly on the weld fixture by wiping with lint free clean cloths saturated with acetone, alcohol or other solvents as designed by the cognizant Phoebus welding engineer. After cleaning the joint shall be checked for cleanliness by wiping with a clean, dry, white, lint free cloth. If scale is present in areas directly adjacent to the machined joint it shall be removed by grinding with a rotary file to bright metal and wiping clean with solvent as described above.

(d) Inter Pass

The weld joint and weld deposit shall be cleaned after each pass by brushing with a clean stainless steel brush to remove all dirt and

foreign materials. The weld deposit shall be closely inspected after each weld pass for oxide deposits in the surface of the weld bead or along the edges of the deposited welds. Such deposits shall be removed prior to making the next weld pass by grinding with a rotary file and wire brushing. Wipe clean with solvent after grinding.

(e) After Penetrant Inspection

Immediately after penetrant inspection of the weld the penetrant solution shall be adequately removed.

(10) Tooling

(a) Internal

Welding of the Phoebus jacket will require the use of internal tooling for alignment and tack welding of jacket sections and for support in positioning jacket assembly on turning rolls.

(b) External

External tooling will be required to position, support, and rotate the jacket assembly beneath a stationary TIG machine welding head.

(c) Rotation Drive

The mechanism used to rotate the jacket assembly shall have variable speed with vernier controls.

(d) Back-Up-Gas

Design of the tooling shall include a provision for incorporating back-up gas rings as an integral, or auxiliary part of the tooling.

(11) Back-Machining

Joints which have inadequate root penetration after ID root weld shall be back-machined on OD. Back-machining shall intersect the root weld penetration. Joints shall be dye penetrant inspected and cleaned as described previously after the back machining operation.

(12) Weld Repairs

Weld defects in excess of the acceptable limits* shall be repaired under the cognizance of the responsible REON weld engineer.

The same weld process and filler material as specified for the original weldment shall be used in making the repair.

The number of times a defective weld may be repaired and the extent of repair shall be determined by the cognizant Phoebus Welding Engineer.

Complete records shall be maintained for each weld repair and shall include the following information:

- (a) Part number and serial number
- (b) Inspection process
- (c) Inspectors name
- (d) Identification of defect (type) and size
- (e) Area of repair
- (f) Number of times repaired in any given area
- (g) Results of inspection of repair
- (h) Name and identification of welder making repair

* AGC-STD-3010 and 4005

5. Brazing Evaluation Program

a. Objectives

The objectives of the brazing program are to develop technology and establish brazing procedures for the solution strengthened nickel-base alloys for the Phoebus-2 nozzle. The experience developed in the fabrication of Nerva 347 stainless steel nozzles indicates that major assembling and brazing problems can be resolved by fabricating straight and contoured nozzle sectors.

The scope of the brazing program, as applied to the nickel-base alloys, will include development of applicable braze alloy systems and associated braze joint shear strength. Straight and contoured nozzle sectors will be fabricated to define the assembling and brazing parameters, to establish the effects of differential coefficients of expansion and to develop thermal fatigue data. Brazed sectors will be subjected to destructive testing to evaluate the joint design. Additional testing of sectors will include hydro-testing to proof pressures and metallographic joint coverage.

A concurrent NDT engineering program will be initiated to insure braze joint quality and reliability. It is planned that the NDT test program be correlated with metallographic examination.

Additional samples of brazed sectors will be employed to develop non-destructive testing techniques and procedures which will establish quality brazed joints.

The Phoebus-2 brazing development program is shown in Table 18. The first task will be to establish the brazing process parameters which can be formulated into a tentative brazing procedure for Hastelloy X; Hastelloy N and Inconel 625. The initial braze alloy evaluations will be performed on .75-in. x 4-in. x 10-in. flat sectors containing .012-in. U-tubes. These sectors will be utilized for destructive tests to evaluate the brazed joint and in the thermal fatigue study phase.

BRAZING DEVELOPMENT PROGRAM PLAN

Table 18

Shear specimens will be prepared and brazed to evaluate brazed joint shear strength. Braze alloys development work is currently planned for all three nickel-base alloy combinations. The program plan, Table 18, illustrates that .75-in. x 4-in. x 60-in. flat specimens having six 0.12-in. formed U-tubes will be prepared and fabricated to establish the assembling and brazing parameters.

Full length contoured sectors which simulate the nozzle configuration will establish the final brazing parameters to be applied to nozzle fabrication. With these contoured sectors we should be able to establish braze alloy placement, establish braze alloy coverage and eliminate excessive run off and finalize the brazing specification.

The leak population of straight and contoured sectors will be measured under leak and proof pressures. Applicable repair techniques for joint leaks will be devised.

In the case of Hastelloy X jacket to Inconel 625 tube evaluation, it will be necessary to determine the effects of the differential coefficients of expansion on straight sectors and establish the possibilities of overcoming this problem.

Schematic views of present assembly techniques applied in the fabrication of Nerva nozzles and which are currently planned for Phoebus-2 nozzles are shown in Figure 151. View 1 illustrates the preplacement of .001-in., preformed Nicro brazing foil in the jacket groove, which is positioned by a di-electric spacer for tack-welding.

View 2 shows the installation of .020-in. diameter Nicro braze alloy wires along the entire joint length. The Di-electric spacer provides the required spacing for channel installation during the probe tacking operation. View 3 illustrates probe tack welding of the "U" channel to the jacket wall. A thinner spacer which is employed to maintain the joint spacing and to hold the channel against the groove wall. The probe electrode is inserted into the jacket scallop and a spot weld is performed joining the channel to the jacket groove

BRAZE JOINT DESIGN COMPARISON

FIGURE 151

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wall for brazing fixturing purposes only. View 4 illustrates the insertion of the adjacent channel. A similar technique is applied to the opposite channel leg. This operation is repeated until all "U" channels are assembled. View 5 illustrated insertion of .001-in. thick Nicro preformed brazing foil and a 0.005-in. full hard (RC 35+) parent metal shim with the aid of a specially designed driving tool. The shim and braze alloy is driven completely to the base of the joint interface to ensure tight joint clearances. The assembly is furnace brazed in dry hydrogen at 1850°F with a controlled heating and cooling cycle. Views 6 and 7 illustrate the technique of sealing the shim butt ends with the application of a duplex alloy composed of 50% Palnicro 7 and 50% Nicro braze alloy powders. A second furnace brazing operation in hydrogen is then performed at 1800°F as a final operation precise amounts of Nicoro 80 is then applied to all faying channel surfaces and a final furnace brazing operation in hydrogen is performed at 1750°F.

The full length contoured nozzle sector design which is currently planned in the brazing program is shown in Figure 152. Straight and contoured sectors provide a method of establishing process control of assembly; and furnace brazing operations. This schematic view depicts the location of the braze joint shims and the method of sealing the shim butt ends. This brazing approach is currently being employed in the fabrication of NERVA nozzles.

A straight, U-tube, Hastelloy X brazed sector which is approximately 60-in. long is shown in Figure 153. This sector was prepared for the initial proposal effort. The sector is composed of a grooved Hastelloy X base and six .023-in. thick Hastelloy X formed U channels. The sector was brazed using the braze alloys and procedures previously described and which are identical to those presently being employed on Nerva nozzles. This sector was hydro-tested to 3100 psi which is in excess of the design requirements. Deformation and fracture of the channel side wall discontinued higher pressure hydro tests. The tube fracture resulted from inadequate external channel side wall support by the side rails.

FIGURE 152

FULL LENGTH CONTOURED SECTORS

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~~CONFIDENTIAL~~

60-IN. HASTELLOY X-TO-HASTELLOY X, STRAIGHT U-TUBE SECTOR

FIGURE 153

b. Recommendations

Successful experience by Aerojet-General in brazing U-tube nozzles for the Nerva program has lead us to recommend the same or equivalent processes for the nickel base alloys of the Phoebus-2 system. The validity of this has been successfully demonstrated on a preliminary basis on the 60-in. sector as previously shown. The selection of solutioned hardened Ni base alloys has circumvented potential problems of required surface preparation which are characteristic to the precipitation hardening alloys systems.

Work to be accomplished is to scale up experimental samples to full scale contoured hardware, evaluate the braze alloy diffusion problem, and overcome the minor differential expansion mismatch in the event that channel material must be a different alloy than that employed for the Phoebus-2 jacket.

6. Nozzle Grooving Development

The nozzle jacket materials requiring grooving will be Hastelloy X, which has a machineability rating of 30 as compared to a rating of 50 for 347 stainless steel, based on 100 for mild machining steel. It is apparent the 40% decrease of the Hastelloy X suggests that special attention is required to reduce this predicted increase in grooving time by conventional methods. However, the jacket grooving cannot realistically be considered conventional machining simply because standard tools are used. The arm length or reach needed to machine a groove places the slitting saw in a precarious position to hold close tolerances notwithstanding the fact the saw has not any side cutting teeth to recover alignment in the event of true position run out during the cut. Aerojet-General has considerable experience grooving nozzle jackets of 347 Stainless Steel for the NERVA program. This background will be upgraded to the Phoebus nozzles through a development program, to optimize machine feeds, speeds, alignment control and slitting saw materials. An alternate parallel nozzle grooving development process is also currently in effect to use an electrical discharge machining process. An initial attempt to elox a full length groove all at once in a 60-in. long plate will be attempted. Electrical

discharge machining (E.D.M.) has the advantage over conventional machining leaving no burrs. Assembly and brazing requires scrutiny of the groove corner radii and the groove surface finish and contamination.

The cleaning requirements for an E.D.M. groove will be evaluated to assure a non-contaminated joint for brazing. Specific recommendations will be made to be incorporated into an A.G.C. process specification.

7. Channel Forming Methods

There are currently two methods under consideration to form channels for the Phoebus nozzles. Aerojet-General's present experience in forming U-tube coolant channels is to form strip stock around the punch by wiping the material across the face of a die. An alternate method to channel forming is the stretch-form process. All stretch-forming methods employ constant longitudinal tension on the strip stock to alleviate unwanted compressional forces that tend to wrinkle the material.

Both approaches could satisfy design requirements in view of the larger throat radii of Phoebus nozzles; however, less spring-back, and the longer leg length of these channels, tends to favor the stretch-form method. The forming wrinkle problem occurs in the throat radii which places the channel leg in compression and the cylindrical to convergent section radii which places the crown in compression. Design requirements will need process development to justify the ultimate process selection. Development in this area has already started and Figure 155 shows initial Hastelloy X tubes formed by the stretch form method. These tubes have a designed crown thickness taper which was a requirement when this development phase was started. Future tubes will not have the thin crown requirement although some areas of crown and leg will thin within print tolerances. The illustrated tubes were not stress-relieved during or after the forming process. The NERVA tube was formed from hardenable 347 austenetic stainless steel channels with several interstage anneals between the forming or deep drawing operation, but final draw of 15% cold work was not annealed. Aerojet plans to optimize the channel form annealing during the forming development program.

STRETCH-FORMED U-TUBES FOR PHOEBUS-2

FIGURE 154

After forming, the channels have a trim edge that must be removed to match the tube leg contour to the contour of the bottom of the groove in the nozzle jacket. A close fit-up of these parts is essential to maintain print tolerances and braze joint efficiency. The trim edge is removed on NERVA channels by clamping the channel on its side after filling the interior with a plaster and milling the trim edges to the correct contour, utilizing a tracer attachment and contour template. Aerojet plans to remove Phoebus channel trim edges either with a pinch off die or by Eloxing. The Elox process is most desirable in view of very little restraint necessary to hold the channel in place and a requirement that trim edges be free from all burrs.

The equipment required to form channels by the deep draw process will be a conventional die with a male punch and female wiping die. The forming operation necessitates over-riding the room temperature yield strength material properties, therefore, the die and press will need greater capacity than that required for NERVA nozzles. This requirement for greater capacity also applies to the stretch forming methods where only the male punch is used for final form after the strip has been formed in the cross sectional configuration. The longitudinal tension is usually adjustable on most stretch forming machines.

Aerojet is presently exploring the capabilities of several vendors that could supply channels to our requirements. The development program, in addition to evaluating vendor capabilities, will include refinement of existing specifications, inspection and quality control criteria and N.D.T. practices.

8. Forging Development

Four concepts of forging requirements were originally envisioned as useable to produce a Phoebus-2 nozzle jacket. A monolithic forging concept shown at the top of Figure 155, which is similar to those presently in use for NERVA nozzles would avoid joining development. However, a one or even a two-piece forging had to be discarded because of existing melting and forging capacity limitations.

FORGING CONCEPTS

FIGURE 155

Two of the country's leading producers of forgings were requested to propose on the ingot size limitations of the Union Carbide (Haynes Stellite) Company and existing weldability and forgeability specifications. Stellite, had melted two, 24-in. diameter 10,000 pound, Hastelloy X Consumable Arc Vacuum melted ingots and expressed confidence they could melt 28- or 30-in. diameter Hastelloy X ingots up to 32,000 pounds. However, new larger copper molds would be required to make this melt. In addition, Stellite lacked equipment for handling and forging this large ingot, therefore, the responsibility for the billet would be shifted to the forger. The original request for proposals stipulated omission of weld joints forward of the throat.

One company chose to stay with the present forging state-of-the-art and actually offered a feasible approach with the maximum possibility of making the part satisfactory at this time. Their facilities consist of a 23,000-ton press with 16 feet between platens, and a 200-in. stroke. Counter-blow hammers are available for the fabrication of 24-in. ingots. They had experience working Hastelloy X in 24-in. ingots and had completed 60-in. dia. rolled ring forgings. This large ingot size needs full work to effectively utilize the ring rolling process which removes centerline effects of the ingot. Extrusion would precede the ring rolling and align defects in the circumferential direction corresponding with the hoop stress. The proposal involved four separate forgings. Figure 155, lower view, was to contour a rolled ring of the 20-in. billet of 3,500 pound capacity for the aft divergent section; a 20-in. billet of 2000 pound capacity for the forward divergent section; a proposed 24-in. ingot of 6000 pounds, contour extruded, rolled center and closed-die forged for the convergent section; a 16-in., 1500 pound, forged ring for the cylindrical section. Separation of the cylindrical section from the convergent section with the resultant unwanted weld joint at the time reduced the demand for the untried 30-in. ingot and made it possible to use a 10,000 pound ingot of 24-in. in diameter.

The second company took no exceptions to Aerojet-General's request and initially-proposed a three forging concept utilizing the 30-in. untried ingot. Handling and processing an ingot of this size was outside the capabilities of this

vendor, therefore, sub-contracting was included in their proposal. A 28-in. billet with a wrought structure weight of 10,200 pounds was proposed to make the convergent and cylindrical section in one piece. A 22-in. diameter, 4,200 pound, billet was proposed for the forward divergent section and a 9,900 pound billet would be required for the aft ring.

A design review indicated a weld would be acceptable in the cylindrical section forward of the flange. Vendors were requested to re-submit a new proposal based on the new design weld. The new proposal from the second forger employed only three ingots of 24-in. diameter derived from one, 30,000 pound, air melt broken down into the cylindrical section which is a rolled-ring weighing 2450 pounds; the convergent section and the divergent section each weighing 6700 pounds, as shown in Figure 155, center view. The convergent and divergent sections ingots of 55-in. will be upset, drawn out, and re-upset to put the work in prior to going into a blocker die. Final forge configuration is established in a closed-finish die. The forging is then solution-heat treated, tested and rough machined. In the interest of expediency, the weld groove may be machined at this time while the forgings are chucked up in the machine.

There is an approximate 10 week delivery advantage in the second company's proposal. Further material work on nozzle forgings will pertain to print refinement. Approximately 500,000 pounds of tooling steel needs to be ordered.

9. Procurement

The procurement activities for the Phoebus Materials Evaluation Program has progressed to the point where the latest required amendments have been made to existing specifications and all Hastelloy X and N materials are being placed on purchase orders. The latest changes to the specifications reflect agreement between SNPO, ORNL and Aerojet-General. These changes are as follows:

- a. All Hastelloy X, Hastelloy N and Inconel 625 Aerojet-General specifications shall limit boron content to ten parts-per-million.
- b. Phosphorous shall be limited to 200 parts-per-million in Hastelloy X.
- c. Plate, sheet, strip and bar room temperature ultimate tensile strength changed to 40,000 psi.
- d. Cross head strain rate above yield shall be modified to 0.5-in.-per-minute and the die-penetrant requirements on the AGC weldability specification will be changed to three applications only: one on the root pass, one on the midway cover passes, and one on the final cover passes comparable to the previous requirement that each layer of passes be penetrant-inspected.

Aerojet-General will allow exceptions to the specifications on their purchase orders for plate and forgings of Hastelloy X and waive the ten parts-per-million boron requirement in favor of 50 parts-per-million to expedite procurement for program needs.

The information currently being reviewed from the Allvac Company indicates availability of an Allvac 625 material very similar to Inconel 625 except that the molybdenum range is 7.5 to 8.5 and this exception has been approved by SNPO.

A review of the materials procurement status is shown in Tables 19 through 21. All of the Hastelloy X material requirements (Table 19) are being placed on purchase orders. The material forms requiring the AMS specifications

PHOEBUS-2 TEST PROGRAM MATERIAL - HASTELLOY X

<u>MATERIAL FORM</u>	<u>MELT</u>	<u>SIZE</u>	<u>QTY</u>	<u>NO. OF HEATS</u>	<u>SPECIFICATION</u>	<u>REQ.</u>	<u>DATE</u>
WELD WIRE	AIR	.045 DIAMETER	50 LBS	1	AMS 5798	475409-1	4-1-65
WELD WIRE	CEVM	.045 DIAMETER	50 LBS	1	AMS 5798	475409-1	4-1-65
WELD WIRE	AIR	.062 DIAMETER	25 LBS	1	AGC 90058A	479487	4-6-65
WELD WIRE	CEVM	.062 DIAMETER	25 LBS	1	AGC 90058A	459487	4-6-65
WELD WIRE	CEVM	.062 DIAMETER	100 LBS	2	AGC 90058A	459495	4-10-65
FORGED RINGS	CEVM	23"ODx17"IDx6"	4	1	AMS 5754	478292-1	4-1-65
FORGED RINGS	CEVM	23"ODx17"IDx6"	6	2	AGC 90056A	468135	4-10-65
PLATE	CEVM	1.5"x4"x12"	6	1	AMS 5536	475410-1	4-1-65
PLATE	CEVM	1.5x6"x12"	4	2	AGC 90057A	468136	4-10-65
BAR	CEVM	.750 DIAMETER	150 FT	1	AGC 90060	459483	4-7-65
SHEET	CEVM	12"x48"x.050"	1	1	AGC 90057A	459493	4-7-65
STRIP	CEVM	8"x90"x.012 $\pm .001$	12	3	AGC 90057A	459493	4-7-65

LEAD TIME	RING FORGINGS - - -	MATERIAL - STOCK
		FORGING - 4-6 WEEKS
		AIR MELT - (.045 - 2-3 WEEKS
	WELD WIRE - - - -	(.062 - 8-10 WEEKS
		CEVM (.045 - 8-10 WEEKS
		(.002 - 8-10 WEEKS
	PLATE - - - - -	8-10 WEEKS
	BAR - - - - -	8-10 WEEKS
	SHEET/STRIP - - -	10-12 WEEKS

Table 19

PHOEBUS-2 TEST PROGRAM MATERIAL - HASTELLOY N

<u>MATERIAL FORM</u>	<u>MELT</u>	<u>SIZE</u>	<u>QTY</u>	<u>NO.OF HEATS</u>	<u>SPEC.</u>	<u>REQ.</u>	<u>DATE</u>
WELD WIRE	AIR	.045 DIAMETER	50 LBS	1	CONTR. CHEM.	475414-1	4-1-65
WELD WIRE	CEVM	.045 DIAMETER	50 LBS	1	CONTR. CHEM.	475414-1	4-1-65
WELD WIRE	CEVM	.062 DIAMETER	25 LBS	1	AGC 90058A	479722	4-6-65
WELD WIRE	CEVM	.062 DIAMETER	100 LBS	2	AGC 90058A	459496	4-10-65
FORGED RINGS	CEVM	23"ODx17"IDx6"	9	3	AGC 90056A	459480	4-6-65
PLATE	CEVM	1.5"x4"x12"	6	1	CONTR. CHEM.	475408-1	4-1-65
PLATE	CEVM	1.5"x6"x12"	4	2	AGC 90057A	479725	4-10-65
BAR	CEVM	.750 DIAMETER	150 FT	1	AGC 90060	479723	4-7-65
SHEET	CEVM	12"x48"x.050	1	1	AGC 90057A	459493	4-7-65
STRIP	CEVM	8"x90"x.012 $\pm .001$	12	3	AGC 90057A	479717	4-7-65

LEAD TIME	RING FORGINGS - -	MATERIAL - 8-10 WEEKS
		FORGING - 4-6 WEEKS
		AIR MELT (.045 - 12 WEEKS
	WELD WIRE - - - -	(.062 - 11-12 WEEKS
		CEVM (.045 - 15 WEEKS
		(.062 - 15-16 WEEKS
	PLATE - - - - -	10 WEEKS
	BAR - - - - -	12 WEEKS
	SHEET - - - - -	20 WEEKS
	STRIP - - - - -	20 WEEKS

Table 21.

PHOEBUS-2 TEST PROGRAM MATERIAL - INCONEL 625

<u>MATERIAL FORM</u>	<u>MELT</u>	<u>SIZE</u>	<u>QTY</u>	<u>NO.OF HEATS</u>	<u>SPEC</u>	<u>REQ</u>	<u>DATE</u>
WELD WIRE	CEVM	.062 DIAMETER	75 LBS	3	AGC 90058A	468157	4-10-65
PLATE	CEVM	1.5"x36"x12"	9	3	AGC 90057A	459492	4-7-65
BAR	CEVM	.750 DIAMETER	150 FT	1	AGC 90060	459490	4-7-65
SHEET	CEVM	12:x48"x.050"	1	1	AGC 90057A	459494	4-8-65
STRIP	CEFM	8"x90"x.012 ⁺ .001	12	3	AGC 90057A	459494	4-8-65

LEAD TIME	WELD WIRE	10-15 WEEKS
	PLATE	10-15 WEEKS
	BAR	10-15 WEEKS
	SHEET	10-15 WEEKS
	STRIP	10-15 WEEKS

were ordered some time ago, all of these, except for the 0.045 diameter CEVM weld wire are presently at AGC and in use. Three different heats of ring-forgings, plate, strip and weld wire will be ordered. The tentative quoted lead times required to get this material are listed below Table 19; however, every effort shall be expended to shorten these periods whenever possible.

Table 20 reveals Hastelloy N material requirements closely resembling those of Hastelloy X. The controlled chemistry items are those presently on order and the AGC specification items are being placed on purchase orders. The material forms being ordered in three heats are identical to those of Hastelloy X. The lead times quoted for Hastelloy N are from Haynes Stellite due to input lacking from Allvac at this writing. Present comparison indicates Hastelloy N will take from two to six weeks longer to procure depending on which material form is selected.

Table 21 displays the Inconel 625 requirements to be purchased. These quotes reflect the shortest lead times comparing Allvac to Huntington Alloys. Three heats will be ordered of the same material forms as Hastelloy X and N with the exception of the ring forgings which will not be procured for this alloy.

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E. INSTRUMENTATION - TASK E

1. Objectives

Instrumentation on the Phoebus-2 nozzle is designed to monitor performance and to verify adequacy of the hardware design. Major emphasis is placed on utilizing reliable and accurate instrumentation. Phoebus-2 will rely heavily on the development experience gained in the NERVA program since the operating environments are similar.

2. Discussion

Instrumentation plans were made for the three major types of test: chemical simulation, pressure, and nuclear.

Chemical simulation tests will be conducted using the LO_2/LH_2 injector, adapter, and nozzle assembly. Initially, the nozzle will be a film-cooled "workhorse" type designed for short duration tests; it will be used to check out the test facility and verify the injector and adapter designs. Subsequently, the development cooled nozzle will be test fired, using the available 177 channels of millisadc, 54 channels of oscillograph, 24 channels of Brown recorders, and 54 channels of Ampex tape. The Phoebus-2 nozzle will be one of the most extensively instrumented assemblies so far tested by Aerojet. See Figure 156 for a layout of the chemical simulation testing instrumentation and Table .22 for the instrumentation planned for the nozzle development and component development test series.

During pressure test of the nozzle, instrumentation will determine stresses and deflections throughout the nozzle pressure vessel assembly to verify the analytical structural analysis. Typical pressure test instrumentation is shown in Figure 157.

Nuclear nozzle test instrumentation will consist of temperature and pressure instruments to determine the properties of the hydrogen from the time it enters the inlet torus until it enters the pressure vessel plenum.

PROPOSED INSTRUMENTATION LOCATIONS FOR PHOEBUS - 2 NOZZLE TEST ASSY

FIGURE 156

TABLE 22
CHEMICAL SIMULATION INSTRUMENTATION

No.	Parameter	Transducer Type	Range	Readout Type							Description
				Visual	DCS (Millisec)	Brown	Oscillo	Tape	Noz Proof	Comp Dev.	
1	PoT	Pressure	0-2000 PSIA		L	x	x		x	x	Oxidizer Tank
2	PfT	Pressure	0-2000 PSIA		L	x	x		x	x	Fuel Tank
3	PoTCV	Pressure	0-2000 PSIA	x	L		x		x	x	Oxidizer Thrust Chamber Valve
4	PfTCV	Pressure	0-2000 PSIA	x	L		x		x	x	Fuel Thrust Chamber Valve
5	PCV	Pressure	0-2000 PSIA	X	L		x		x		Coolant Valve
6	PoI	Pressure	0-2000 PSIA		H				x	x	Oxidizer Inlet to Injector
7	PfI-A	Pressure	0-2000 PSIA		H		x	x	x	x	Fuel Inlet to Adapter
8	PfI-B	Pressure	0-2000 PSIA		H				x	x	Fuel Inlet to Adapter
9	PfI-C	Pressure	0-2000 PSIA		H			x		x	Fuel Inlet to Adapter
10	PfI-D	Pressure	0-2000 PSIA		H					x	Fuel Inlet to Adapter
11	PcI-1	Pressure	0-1500 PSIA		M		x	x			Coolant Inlet to Nozzle Torus
12	PcI-2A	Pressure	0-1500 PSIA		M			x	x		Coolant Inlet to Nozzle Torus
13	PcI-2B	Pressure	0-1500 PSIA		M				x		Coolant Inlet to Nozzle Torus
14	PcI-2C	Pressure	0-1500 PSIA		M		x	x	x		Coolant Inlet to Nozzle Torus
15	PcI-2D	Pressure	0-1500 PSIA		M				x		Coolant Inlet to Nozzle Torus
16	PcI-2E	Pressure	0-1500 PSIA		M				x		Coolant Inlet to Nozzle Torus
17	PcI-2F	Pressure	0-1500 PSIA		M				x		Coolant Inlet to Nozzle Torus
18	PfO-A	Pressure	0-1500 PSIA		H			x	x	x	Fuel Outlet From Adapter

TABLE 22 (cont.)

No.	Parameter	Transducer Type	Range	Readout Type						Description	
				Visual	DCS (Millisec)	Brown	Oscillo	Tape	Noz Proof		Comp Dev.
19	PfO-B	Pressure	0-1500 PSIA		H		x	x	x	x	Fuel Outlet From Adapter
20	PfO-C	Pressure	0-1500 PSIA		H					x	Fuel Outlet From Adapter
21	PfO-D	Pressure	0-1500 PSIA		H					x	Fuel Outlet From Adapter
22	PcO-A	Pressure	0-1500 PSIA		M	x	x	x	x		Coolant Outlet From Nozzle
23	PcO-B	Pressure	0-1500 PSIA		M				x		Coolant Outlet From Nozzle
24	PcO-C	Pressure	0-1500 PSIA		M		x	x	x		Coolant Outlet From Nozzle
25	PcO-D	Pressure	0-1500 PSIA		M						Coolant Outlet From Nozzle
26	PcO-E	Pressure	0-1500 PSIA		M						Coolant Outlet From Nozzle
27	PcO-F	Pressure	0-1500 PSIA		M						Coolant Outlet From Nozzle
28	PoJ-A	Pressure	0-1500 PSIA	x	H		x	x	x	x	Oxidizer Injector Manifold - LIMP
29	PoJ-B	Pressure	0-1500 PSIA		H			x	x	x	Oxidizer Injector Manifold
30	PoJ-C	Pressure	0-1500 PSIA		H					x	Oxidizer Injector Manifold
31	PfJ-A	Pressure	0-1500 PSIA	x	H		x	x	x	x	Fuel Injector Manifold - FIMP
32	PfJ-B	Pressure	0-1500 PSIA		H			x	x	x	Fuel Injector Manifold
33	PfJ-C	Pressure	0-1500 PSIA		H					x	Fuel Injector Manifold
34	PcE-1	Pressure	0-1500 PSIA		M		x	x	x		Coolant Exit - Dump Line
35	PcE-2	Pressure	0-1500 PSIA		M		x		x		Coolant Exit - Dump Line
36	PcE-3	Pressure	0-1000 PSIA		L			x	x		Coolant Exit - Dump Line

TABLE 22 (cont.)

No.	Parameter	Transducer Type	Range	Readout Type						Description
				Visual	DCS (Millisec)	Brown	Oscillo	Tape	Noz Proof	
37	Pc-2A	Pressure	0-1000 PSIA	H	x	x	x	x	x	Chamber-Nozzle Passthroughs
39	Pc-2C	Pressure	0-1000 PSIA	H					x	Chamber-Nozzle Passthroughs
40	Pc-2D	Pressure	0-1000 PSIA	H		x				Chamber-Nozzle Passthroughs
41	Pc-2E	Pressure	0-1000 PSIA	H		x				Chamber-Nozzle Passthroughs
42	Pc-2F	Pressure	0-1000 PSIA	H		x				Chamber-Nozzle Passthroughs
43	Pc-3A	Pressure	0-1000 PSIA	H		x	x	x	x	Chamber Injector to Adapter Interface
44	Pc-3B	Pressure	0-1000 PSIA	H					x	Chamber Injector to Adapter Interface
45	Pc-5A	Pressure	0-1000 PSIA	H					x	Chamber Adapter to Nozzle Interface
46	Pc-5B	Pressure	0-1000 PSIA	H					x	Chamber Adapter to Nozzle Interface
47	Pc-6A	Pressure	0-1000 PSIA	H	x	x			x	Chamber Injector Face
48	Pc-6B	Pressure	0-1000 PSIA	x	H			x	x	Chamber Injector Face - CSM
49	PaTCoV	Pressure	0-5000 PSIA	L		x			x	Oxidizer Valve Actuator
50	PaTCfV	Pressure	0-5000 PSIA	L		x			x	Fuel Valve Actuator
51	PaCV	Pressure	0-5000 PSIA	L		x			x	Coolant Valve Actuator
52	PcT-1A	Pressure	0-1500 PSIA	M				x	x	Nozzle Coolant Tube Divergent Section
53	PcT-1B	Pressure	0-1500 PSIA	M					x	Nozzle Coolant Tube Divergent Section
54	PcT-1C	Pressure	0-1500 PSIA	M					x	Nozzle Coolant Tube Divergent Section
55	PcT-2A	Pressure	0-1500 PSIA	M			x			Nozzle Coolant Tube Convergent Section

TABLE 22 (cont.)

No.	Parameter	Transducer Type	Range	Readout Type						Description
				Visual	DCS (Millisec)	Brown	Oscillo	Tape	Noz Proof	
56	PcT-2B	Pressure	0-1500 PSIA	M						Nozzle Coolant Tube Convergent Section
57	PcT-2C	Pressure	0-1500 PSIA	M						Nozzle Coolant Tube Convergent Section
58	PcBC-1	Pressure	0-1500 PSIA	M					x	Bolt Coolant Line
59	PNFC-1	Pressure	0-1500 PSIA	M		x	x		x	Workhorse Nozzle Film Coolant Line
60	PNFC-2	Pressure	0-1500 PSIA	M		x			x	Workhorse Nozzle Film Coolant Line
61	Δ PcBC	Δ Pressure	0-50 PSIA	H		x			x	Bolt Coolant Line Venturi
62	Δ PNFC-1	Δ Pressure	0-50 PSIA	H		x			x	Film Coolant Line Venturi
63	Δ PNFC-2	Δ Pressure	0-50 PSIA	H		x			x	Film Coolant Line Venturi
64	Δ PcO-Pc3	Δ Pressure	0-1000 PSIA	H	x	x	x	x		Chamber to Coolant Outlet
65	Δ PcI-PcT	Δ Pressure	0-100 PSIA	L					x	Nozzle Coolant Tube Inlet
66	Δ PcI-Pct	Δ Pressure	0-100 PSIA	L					x	Nozzle Coolant Tube Inlet
67	Δ PcI-PcT	Δ Pressure	0-100 PSIA	L					x	Nozzle Coolant Tube Inlet
68	Δ PcI-PcT	Δ Pressure	0-100 PSIA	L						Nozzle Coolant Tube Inlet
69	Δ PcI-PcT	Δ Pressure	0-100 PSIA	L						Nozzle Coolant Tube Inlet
70	Δ PcI-PcT	Δ Pressure	0-100 PSIA	L						Nozzle Coolant Tube Inlet
71	Δ PcT	Δ Pressure	0-100 PSIA	L					x	Nozzle Coolant Tube
72	Δ PcT	Δ Pressure	0-100 PSIA	L					x	Nozzle Coolant Tube
73	Δ PcT	Δ Pressure	0-100 PSIA	L					x	Nozzle Coolant Tube

TABLE 22 (cont.)

No.	Parameter	Transducer Type	Range	Readout Type						Description	
				Visual	DCS (Millisadic)	Brown	Oscillo	Tape	Noz Proof		Comp Dev.
74	Δ PcT	Δ Pressure	0-100 PSIA	L							Nozzle Coolant Tube -
75	Δ PcT	Δ Pressure	0-100 PSIA	L							Nozzle Coolant Tube -
76	Δ PcT	Δ Pressure	0-100 PSIA	L							Nozzle Coolant Tube -
77	Δ PcT-PcO	Δ Pressure	0-100 PSIA	L					x		Nozzle Coolant Tube - Exit
78	Δ PcT-PcO	Δ Pressure	0-100 PSIA	L					x		Nozzle Coolant Tube - Exit
79	Δ PcT-PcO	Δ Pressure	0-100 PSIA	L					x		Nozzle Coolant Tube - Exit
80	Δ PcT-PcO	Δ Pressure	0-100 PSIA	L							Nozzle Coolant Tube - Exit
81	Δ PcT-PcO	Δ Pressure	0-100 PSIA	L							Nozzle Coolant Tube - Exit
82	Δ PcT-PcO	Δ Pressure	0-100 PSIA	L							Nozzle Coolant Tube - Exit
83	Δ PcI-PcO	Δ Pressure	0-500 PSIA	M				x	x		Nozzle Coolant Tube - Exit
84	Δ PcI-PcO	Δ Pressure	0-500 PSIA	M				x	x		Nozzle Coolant Tube - Exit
85	Δ PcI-PcO	Δ Pressure	0-500 PSIA	M				x	x		Nozzle Coolant Tube - Exit
86	Δ PcI-PcO	Δ Pressure	0-500 PSIA	M				x			Nozzle Coolant Tube - Exit
87	FMo ¹	Flowmeter	0-800 lb/Sec	H	x	x			x	x	Oxidizer
88	FMf	Flowmeter	0-200 lb/Sec	H	x	x			x	x	Fuel
89	FMc	Flowmeter	0-300 lb/Sec	H	x	x			x		Nozzle Coolant
90	ToFM	RTT	-200 to -300°F	M	x				x	x	Oxidizer Flowmeter
91	TfFM	RTT	-375 to -425°F	M	x				x	x	Fuel Flowmeter
92	TcFM	RTT	-375 to -425°F	M	x				x		Nozzle Coolant Flowmeter

TABLE 22 (cont.)

No.	Parameter	Transducer Type	Range	Readout Type							Description
				Visual	DCS (millisec)	Brown	Oscillo	Tape	Noz Proof	Comp Dev.	
93	ToTcV	RTT	-200 to -300°F	L	x				x	x	Oxidizer Thrust Chamber Valve
94	TfTcV	RTT	-375 to -425°F	x	L	x			x	x	Fuel Thrust Chamber Valve
95	TcV	RTT	-375 to -425°F	x	L	x			x		Nozzle Coolant Valve
96	ToI-A	RTT	-375 to -425°F	M	x			x	x	x	Oxidizer Inlet To Injector
97	ToI-B	RTT	-375 to -425°F	M						x	Oxidizer Inlet To Injector
98	TfI-A	RTT	-375 to -425°F	H	x			x	x	x	Fuel Inlet To Adapter
99	TfI-B	RTT	-375 to -425°F	L					x	x	Fuel Inlet To Adapter
100	TfI-C	RTT	-375 to -425°F	L				x	x	x	Fuel Inlet To Adapter
101	TfI-D	RTT	-375 to -425°F	L							Fuel Inlet To Adapter
102	TcI-1	RTT	-375 to -425°F	M	x			x			Coolant Inlet To Nozzle Torus
103	TcI-2A	RTT	-375 to -425°F	L	x			x	x		Coolant Inlet To Nozzle Torus
104	TcI-2B	RTT	-375 to -425°F	L					x		Coolant Inlet To Nozzle Torus
105	TcI-2C	RTT	-375 to -425°F	L					x		Coolant Inlet To Nozzle Torus
106	TcI-2D	RTT	-375 to -425°F	L							Coolant Inlet To Nozzle Torus
107	TcI-2E	RTT	-375 to -425°F	L							Coolant Inlet To Nozzle Torus
108	TcI-2F	RTT	-375 to -425°F	L							Coolant Inlet To Nozzle Torus
109	TfO-A	RTT	+75 to -425°F	M	x	x	x	x	x	x	Fuel Outlet From Adapter
110	TfO-B	RTT	+75 to -425°F	M					x	x	Fuel Outlet From Adapter
111	TfO-C	RTT	+75 to -425°F	M				x	x	x	Fuel Outlet From Adapter

TABLE 22 (cont.)

No.	Parameter	Transducer Type	Range	Readout Type						Description	
				Visual	DCS (Millisec)	Brown	Oscillo	Tape	Noz Proof		Comp Dev
112	TfO-D	RTT	+75 to -425°F	M					x	x	Fuel Outlet From Adapter
113	TcO-A	RTT	+75 to -425°F	M	x		x	x			Coolant Outlet From Nozzle
114	TcO-B	RTT	+75 to -425°F	M		x		x			Coolant Outlet From Nozzle
115	TcO-C	RTT	+75 to -425°F	M			x	x			Coolant Outlet From Nozzle
116	TcO-D	RTT	+75 to -425°F	M		x		x			Coolant Outlet From Nozzle
117	TcO-E	RTT	+75 to -425°F	M				x			Coolant Outlet From Nozzle
118	TcO-F	RTT	+75 to -425°F	M		x		x			Coolant Outlet From Nozzle
119	ToJ-A	RTT	-200 to -300°F	L			x	x	x		Oxidizer Injector Manifold
120	ToJ-B	RTT	-200 to -300°F	L				x	x		Oxidizer Injector Manifold
121	ToJ-C	RTT	-200 to -300°F	L			x		x		Oxidizer Injector Manifold
122	TfJ-A	RTT	-75 to -425°F	M	x	x	x	x	x		Fuel Injector Manifold
123	TfJ-B	RTT	-75 to -425°F	M				x	x		Fuel Injector Manifold
124	TfJ-C	RTT	-75 to -425°F	M			x		x		Fuel Injector Manifold
125	TcE-1	RTT	+75 to -425°F	M		x	x	x			Nozzle Coolant - Dump Line
126	TcE-2	RTT	+75 to -425°F	M				x			Nozzle Coolant - Dump Line
127	TcE-3	RTT	+75 to -425°F	M			x	x			Nozzle Coolant - Dump Line
128	TcT-1A	RTT	-300 to -425°F	L			x	x			Nozzle Coolant - Divergent Section
129	TcT-1B	RTT	-300 to -425°F	L				x			Nozzle Coolant - Divergent Section
130	TcT-1C	RTT	-300 to -425°F	L			x	x			Nozzle Coolant - Divergent Section

TABLE 22 (cont.)

No.	Parameter	Transducer Type	Range	Readout Type						Description
				Visual	DCS (Millisadic)	Brown	Oscillo	Tape	Noz Proof	
131	TcT-1D	RTT	-300 to -425°F	L						Nozzle Coolant - Divergent Section
132	TcT-1E	RTT	-300 to -425°F	L				x		Nozzle Coolant - Divergent Section
133	TcT-1F	RTT	-300 to -425°F	L						Nozzle Coolant - Divergent Section
134	TcT-3D	RTT	-300 to -425°F	L				x	x	Nozzle Coolant - Convergent Section
135	TcT-3B	RTT	-300 to -425°F	L					x	Nozzle Coolant - Convergent Section
136	TcT-3C	RTT	-300 to -425°F	L				x	x	Nozzle Coolant - Convergent Section
137	TcT-3D	RTT	-300 to -425°F	L						Nozzle Coolant - Convergent Section
138	TcT-3E	RTT	-300 to -425°F	L						Nozzle Coolant - Convergent Section
139	TcT-2A	RTT	-300 to -425°F	L						Nozzle Coolant - Convergent Section
140	TcT-2A	C/C TC	-300 to -425°F	L				x	x	Nozzle Coolant - Throat
141	TcT-2B	C/C TC	-300 to -425°F	L					x	Nozzle Coolant - Throat
142	TcT-2C	C/C TC	-300 to -425°F	L				x	x	Nozzle Coolant - Throat
143	TcT-2D	C/C TC	-300 to -425°F	L						Nozzle Coolant - Throat
144	TcT-2E	C/C TC	-300 to -425°F	L				x		Nozzle Coolant - Throat
145	TcT-2F	C/C TC	-300 to -425°F	L						Nozzle Coolant - Throat
146	TN-1A	C/A TC	+100 to -350°F	x	L					Nozzle Jacket
147	TN-1B	C/A TC	+100 to -350°F	x	L					Nozzle Jacket
148	TN-2A	C/A TC	+100 to -350°F		L					Nozzle Jacket
149	TN-2B	C/A TC	+100 to -350°F		L					Nozzle Jacket

TABLE 22 (cont.)

No.	Parameter	Transducer Type	Range	Readout Type						Description
				Visual	DCS (Millisadic)	Brown	Oscillo	Tape	Noz Proof	
150	TN-3A	C/A TC	+100 to -350°F	L						Nozzle Jacket
151	TN-3B	C/A TC	+100 to -350°F	L						Nozzle Jacket
152	TN-4A	C/A TC	+100 to -350°F	L						Nozzle Jacket
153	TN-4B	C/A TC	+100 to -350°F	L						Nozzle Jacket
154	TN-5A	C/A TC	+100 to -350°F	L						Nozzle Jacket
155	TN-5B	C/A TC	+100 to -350°F	L						Nozzle Jacket
156	TN-6A	C/A TC	+100 to -350°F	L						Nozzle Jacket
157	TN-6B	C/A TC	+100 to -350°F	L						Nozzle Jacket
158	TN-7A	C/A TC	+100 to -350°F	L						Nozzle Jacket
159	TN-7B	C/A TC	+100 to -350°F	L						Nozzle Jacket
160	TN-8A	C/A TC	+100 to -350°F	x L						Nozzle Jacket
161	TN-8B	C/A TC	+100 to -350°F	x L						Nozzle Jacket
162	TN-9A	C/A TC	+100 to -350°F	X						Nozzle Jacket
163	TN-9B	C/A TC	+100 to -350°F	L						Nozzle Jacket
164	TN-10A	C/A TC	+100 to -350°F	L						Nozzle Jacket
165	TN-10B	C/A TC	+100 to -350°F	L						Nozzle Jacket
166	TA-1A	C/A TC	+100 to -350°F	L	x					Nozzle-to-Injector Adapter Jacket
167	TA-1B	C/A TC	+100 to -350°F	L						Nozzle-to-Injector Adapter Jacket
168	TA-2A	C/A TC	+100 to -350°F	L						Nozzle-to-Injector Adapter Jacket

TABLE 22 (cont.)

No.	Parameter	Transducer Type	Range	Readout Type							Description
				Visual	DCS (Millisadic)	Brown	Oscillo	Tape	Noz Proof	Comp Dev.	
169	TA-2B	C/A TC	+100 to -350°F	L							Nozzle-to-Injector Adapter Jacket
170	TA-3A	C/A TC	+100 to -350°F	x	L	x					Nozzle-to-Injector Adapter Jacket
171	TA-3B	C/A TC	+100 to -350°F	x	L						Nozzle-to-Injector Adapter Jacket
172	TA-4A	C/A TC	+100 to -350°F	L							Nozzle-to-Injector Adapter Jacket
173	TA-4B	C/A TC	+100 to -350°F	L							Nozzle-to-Injector Adapter Jacket
174	TA-5A	C/A TC	+100 to -350°F	L							Nozzle-to-Injector Adapter Jacket
175	TA-5B	C/A TC	+100 to -350°F	L							Nozzle-to-Injector Adapter Jacket
176	TA-6A	C/A TC	+100 to -350°F	L							Nozzle-to-Injector Adapter Jacket
177	TA-6B	C/A TC	+100 to -350°F	L							Nozzle-to-Injector Adapter Jacket
178	GN-1X	Accelerometer					x	x	x	x	Nozzle
179	GN-1Y	Accelerometer					x	x	x	x	Nozzle
180	GN-1Z	Accelerometer					x	x	x	x	Nozzle
181	GN-2X	Accelerometer					x		x		Nozzle
182	GN-2Y	Accelerometer					x		x		Nozzle
183	GN-2Z	Accelerometer					x		x		Nozzle
184	GA-1X	Accelerometer					x		x	x	Adapter
185	GA-1Y	Accelerometer					x		x	x	Adapter
186	GA-1Z	Accelerometer					x		x	x	Adapter
187	GA-2X	Accelerometer					x				Adapter

TABLE 22 (cont.)

No.	Parameter	Transducer Type	Range	Readout Type							Description
				Visual	DCS (Millisadic)	Brown	Oscillo	Tape	Noz Proof	Comp Dev	
188	GA-2Y	Accelerometer					x				Adapter
189	GA-2Z	Accelerometer					x				Adapter
190	SN	Strain Patch			x						Nozzle
191	SN	Strain Patch			x						Nozzle
192	SN	Strain Patch			x						Nozzle
193	SN	Strain Patch			x						Nozzle
194	SN	Strain Patch			x						Nozzle
195	SN	Strain Patch			x						Nozzle
196	SA	Strain Patch			x						Adapter
197	SA	Strain Patch			x						Adapter
198	SA	Strain Patch			x						Adapter
199	SA	Strain Patch			x						Adapter
200	SA	Strain Patch			x						Adapter
201	SA	Strain Patch			x						Adapter
202	TCoVPV	Switch Trace					x		x	x	Thrust Chamber Ox Valve Pilot Valve
203	TCfVPV	Switch Trace					x		x	x	Thrust Chamber Fuel Valve Pilot Valve
204	TCcVPV	Switch Trace					x		x		Thrust Chamber Coolant Valve Pilot Valve
205	CSM	Switch Trace					x	x	x	x	Combustion Stability Monitor

TABLE 22 (cont.)

No.	Parameter	Transducer Type	Range	Readout Type							Description
				Visual	DCS (Millisadic)	Brown	Oscillo	Tape	Noz Proof	Comp Dev	
206	Ignition	Switch Trace					x		x	x	
207	FS	Switch Trace					x	x	x	x	Fire Switch
208	LTCoV	Switch Trace					x		x	x	Ox Valve position
209	LTCfV	Switch Trace					x		x	x	Fuel Valve position
210	LTCcV	Switch Trace					x		x		Coolant Valve position
211	PcOPS	Switch Trace					x		x		PcO pressure switch
212	FIMP	Switch Trace					x		x	x	Fuel Manifold purge
213	LIMP	Switch Trace					x		x	x	Oxidizer Manifold purge
214	CMP	Switch Trace					x		x		Nozzle coolant manifold purge

PRESSURE TEST NOZZLE INSTRUMENTATION

LOCATION OF NOZZLE
SIMULATOR STRAIN GAGES

O - BIAXIAL STRAIN GAGES

- NOTE 1. INSIDE GAGES ARE DIRECTLY
OPPOSITE OUTSIDE GAGES
2. GAGES ARE AT 0° MERIDIONAL
LOCATION

Pass-throughs (or bosses) that extend between the coolant tubes are provided, as required, to measure chamber pressure and chamber temperature. The exterior jacket structure and attaching bolts will be instrumented with thermocouples and strain gages. Accelerometers will measure vibration and a venturi in the bolt coolant line will monitor hydrogen flow to the cooled bolts. Typical nuclear nozzle instrumentation is shown in Figure 158. Also shown are the parameter designation, instrument location (axial, radial and angular) instrument range requirement, accuracy range requirement and proposed instrumentation boss interface configuration.

NOZZLE NUCLEAR INSTRUMENTATION LOCATION (PRELIMINARY)

NOZZLE, NUCLEAR INSTRUMENTATION-PRELIMINARY													
PRESSURE	STATION	LOCATION	RANGE	PSI	PROPOSED	INTERFACE							
COOLANT	STATION	LOCATION	RANGE	PSI	PROPOSED	INTERFACE							
P1	31.20	0°	127.80	0.1500	1550±200	438 20 UNF 38 THREAD							
P2	24.30	30°	129.70	0.1500	1550±200								
P3	15.0°	129.70	0.1500	1550±200									
P4	210°	129.70	0.1500	1550±200									
P5	270°	129.70	0.1500	1550±200									
P6	24.30	330°	129.70	0.1500	500±200	438 20 UNF 38 THREAD							
ΔPac	36.00	180°	81.84	0.200	100±50	438 20 UNF 38 THREAD							
GAS													
P7	15.0°	90°	0.800	RATED 100	875 20 UNF 24 THREAD								
P8	270°	0.800	RATED 100	875 20 UNF 24 THREAD									
P9	270°	0.400	200±200	875 20 UNF 24 THREAD									
TEMP													
TEMP SENSORS													
T1	31.20	0°	128.20	35.50	300±100	438 20 UNF 38 THREAD							
T2	27.10	30°	129.70	35.75	35±5								
T3	150°												
T4	210°												
T5	270°												
T6	27.10	330°	129.70	35.75	35±5	438 20 UNF 38 THREAD							
TEMP GAS													
P10	150°												
P11	270°												
P12	270°												
TEMP SENSORS													
T7	34.48	0°	69.00	300	1000±250	875 20 UNF 24 THREAD							
T8	150°												
T9	210°												
T10	330°												
TEMP SENSORS													
T11	34.48	90°	69.00	300	1000±250	875 20 UNF 24 THREAD							
T12	33.00	0°	69.90	300	1000±250								
T13	33.00	90°	69.90	300	1000±250								
T14	28.10	0°	75.00	300	1500±250								
T15	28.10	90°	75.00										
T16	26.60	0°	76.50										
T17	26.60	90°	76.50										
T18	25.60	0°	75.50										
T19	25.60	90°	75.50	300	1500±250								
TEMP SENSORS													
T20	32.00	0°	70.70	200	500±250								
T21	32.00	90°	70.70	200	500±250								
T22	32.00	180°	70.70	200	500±250								
TEMP SENSORS													
T23	27.10	0	71.20	TO BE DETERMINED									
T24	27.10	90	71.20										
T25	26.00	0	75.00										
T26	26.00	90°	75.00										
T27	25.00	0	76.00										
T28	25.00	90	76.00										
ACCELEROMETER													
A1	34.48	45°	69.00	TO BE DETERMINED									
A2	34.48	135°	69.00										
A3	28.60	45°	132.00										
A4	28.60	135°	132.00										

Figure 158
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F. DEVELOPMENT, PROOF, AND ACCEPTANCE TEST METHOD - TASK F

1. Introduction

The test methods selected for the development, proof, and acceptance testing for the Phoebus-2 nozzle are presented. A description of tests necessary for the development of chemical simulation components is also included.

2. Development Tests

Development tests are defined as those necessary to determine fabrication feasibility and improve manufacturing techniques such as the forging fabricability study and the welding, brazing, and machining sample work. Tests that provide information to verify and improve the analytical design of the nozzle such as the subscale gas-side and coolant-side heat transfer studies and the nozzle vibration tests are also categorized as development tests.

These tests are required to provide data necessary to finalize the nozzle design. The description, objectives, methods, and use of the results of these development tests are covered in the preliminary design section of this report.

3. Phoebus-2 Nozzle Acceptance Testing

a. Tests to be Conducted

Acceptance tests are defined as nondestructive tests which will be conducted to ensure proper nozzle design and fabrication techniques. The following acceptance tests will be conducted:

- (1) Radiographic Tests
- (2) Ultrasonic Tests
- (3) Penetrant Tests

- (4) Low Pressure Leak Check
- (5) Hydrostatic Proof and Leak Tests
- (6) Coolant Tube Flow Area Check (Titration Test)
- (7) Coolant Flow Symmetry Test
- (8) Cleaning Tests

b. Objectives

The objectives of these acceptance tests are:

- (1) To ensure acceptability of the end product.
- (2) To provide an accept/reject criteria for each fabrication operation to qualify the nozzle for subsequent operations.

c. Description of Tests

(1) Radiographic Tests

(a) Welds. To verify the integrity of critical welds, radiographic tests will be conducted per AGC-STD-1151 and accepted to AGC-STD-9005.

(b) Coolant Passages. A radiographic test will be conducted to verify that the coolant passages in the nozzle are free of obstructions.

(2) Ultrasonic Tests

(a) Forging - Individual forged nozzle sections will be ultrasonically tested per AGC-36163A to verify the absence of internal flaws.

(b) U-Tubes - Testing of U-Tubes during fabrication by ultrasonic techniques for laminar type defects is presently being investigated and will be incorporated as an acceptance test if the need is indicated.

(3) Penetrant Tests

(a) Forging Sections - All surfaces of the individual sections will be penetrant inspected per AGC-STD-3010A prior to welding.

(b) Welds - All welding performed on the nozzle not otherwise tested will be penetrant inspected per AGC-STD-3010A to check for propagating type surface defects.

(c) Machined Surfaces - The final machined surfaces of the nozzle jacket will be penetrant inspected per AGC-STD-3010A.

(4) Low Pressure Leak Check

A low pressure leak check will be conducted on the coolant tubes with gaseous nitrogen per AGC-90064. This test is conducted prior to the hydrostatic proof and leak test to locate or repair obvious leaks.

(5) Hydrostatic Proof and Leak Test

A high pressure hydrostatic proof and leak test of the nozzle coolant tubes will be conducted. A proof pressure of 1420 psig and a leak check at 1065 psig will be applied to the nozzle per AGC-90064 to demonstrate braze joint and tube wall integrity.

(6) Coolant Tube Flow Area Test (Titration Test)

A volumetric check of the coolant tube will be made by the "Titration Method" where a differential volume of water in an increment of vertical height is used to compute an average flow area in the increment. A plot of the measured flow areas can be compared to the design flow areas and the actual flow area used in the heat transfer analysis. The test apparatus presently used on Nerva nozzles is shown in Figure 159.

(7) Coolant Flow Symmetry Test

Water flow rate of each coolant tube will be measured at a constant total flow rate to determine if the nozzle meets the acceptable limit of 5% deviation in flow in any 15° sector.

"TITRATION" TEST FOR DETERMINING TUBE FLOW AREAS

Figure 159

The design of the nozzle coolant passage is such that the flow from each individual tube can be trapped and measured. The determination of the flow rate in each individual coolant tube relative to the flow rate in all other tubes will verify the flow symmetry of the nozzle.

The titration test and the coolant flow symmetry test together determine:

- (a) The actual total flow area in the coolant tubes.
- (b) The symmetry of flow in the coolant tubes.
- (c) That no tubes are plugged or restricted.

(8) Cleaning Tests

The cleaning and cleaning inspection required during fabrication is documented in AGC-STD-9001. This standard was prepared from the processes developed during Nerva nozzle fabrication. The tests to determine jacket and U-Tube cleanliness before brazing and also the final cleaning operation are of sufficient importance to be included in this discussion of acceptance test methods.

d. Nozzle Acceptance Testing Sequence

In order to obtain a general idea of when each test is conducted, the proposed sequence of the acceptance tests to be conducted during fabrication of the Phoebus-2 nozzle is shown in Figure 160.

(1) Jacket Forging

(a) Rough machining of the individual forged sections is accomplished and the entire surface penetrant tested for propagating type surface defects. Then the longitudinal ultrasonic test is performed. These tests are performed to the following specifications:

1 Penetrant inspect per AGC-STD-3010A,
Method B.

Figure 160

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2 Ultrasonic (Longitudinal Wave) to be inspected per AGC-26163.

(b) Welding of the separate forgings is accomplished and the welds tested by a series of penetrant and radiographic tests. The sequence of these test operations will be established upon review of the welding development program results. The tests will be performed to the following specifications:

1 Penetrant inspect per AGC-STD-3010A, Method C.

2 Radiographic inspect per AGC-STD-1151 and accept per AGC-STD-9005.

(c) Welding - Final Inspection

Welds will be radiographed per AGC-STD-1151 and accepted per AGC-STD-9005.

(2) In-house Jacket Machining and Grooving

The final inside surfaces of the nozzle jacket will be penetrant tested. The nozzle will then be grooved, cleaned, and tested for cleanliness. These tests will be performed to the following specifications:

(a) Penetrant inspect all surfaces to AGC-STD-3010A, Method B.

(b) Test jacket for cleanliness to AGC-STD-9001, Method No. 1.

(3) U-Tube Fabrication

Ultrasonic and/or penetrant tests for defects are to be conducted. The procedure is currently under investigation and the recommended test method will be submitted for review. After fabrication the U-Tube will be cleaned and tested for cleanliness. These tests will be performed to the following specifications:

(a) Ultrasonic inspect for internal defects according to procedure and acceptance criteria determined by the need for test.

(b) Penetrant inspect for surface defects per AGC-STD-3010A, Method B.

(c) Test tube for cleanliness per AGC-STD-9001, Method No. 2.

(4) Tube Installation and Brazing

After tube installation and brazing, the torus will be welded to the nozzle and the torus welds penetrant tested. The installation of the torus is necessary to conduct the low pressure GN_2 leak check of the braze joints and the high pressure hydrostatic proof and leak test of the tubes and braze joints. These tests will be performed to the following specifications:

(a) Conduct low pressure GN_2 leak checks of the nozzle coolant passages per AGC-90064, Type I.

(b) Conduct high pressure hydrostatic test of the nozzle coolant passages per AGC-90064, Type I.

(5) Final Machining of the Nozzle

The nozzle then goes through a series of machining operations and when it has completed the final machining operation, the low pressure GN_2 and the high pressure proof and leak tests are again applied. The nozzle is then backflushed and flowed, after which the "Titration" and the "Flow Symmetry Test" will be conducted. A radiograph inspection for tube obstructions follows. These tests are performed to the following specifications:

(a) Hydrotest - In Process

Low pressure leak test of coolant tubes after final braze cycle per AGC-90064, Type I, with GN_2 .

(b) Hydrotest - Final Assembly

1 Proof and leak test nozzle with water at 1420 and 1065 psig, respectively, per AGC-90064, Type I.

2 Backflush and flow nozzle coolant tubes and bolt coolant circuit with water per AGC 90064, Type I. Nozzle water flow coefficient (K_w) will be determined where:

$$K_w = \frac{\dot{w}}{\sqrt{\Delta P \cdot SG}} \quad \text{and}$$

SG = Specific gravity

$\dot{w}$ = Weight flow in lbs/sec

ΔP = Pressure drop in lbs/ in²

3 Perform coolant tube flow area "Titration Test" per AGC-90064, Type I.

4 Perform coolant flow symmetry test per AGC-90064, Type I.

(c) Radiographic Inspect - Final

Radiographic inspect all nozzle coolant passages to ensure that all passages are free of obstructions.

(6) Final Inspection

The nozzle is final inspected, cleaned, and tested for cleanliness per drawing requirements.

4. Chemical Simulation Component Development Testing

The major components necessary to test the Phoebus-2 nozzle with LO₂/LH₂ are the injector, nozzle-to-injector adapter, and the igniter.

In order to allow early development of the components, a film-cooled workhorse nozzle will be used to chemically proof test the assembly. Fifteen (15) percent of the fuel necessary for combustion will be used to film cool the workhorse nozzle allowing testing durations of 8-10 seconds.

a. Test Objectives

The objectives of the chemical simulation component development testing program are to:

- (1) Activate test stand H-4B.
- (2) Provide test stand checkout.
- (3) Demonstrate igniter capabilities.
- (4) Refine start and shutdown valve sequencing.
- (5) Develop a suitable injector for Phoebus-2 nozzle testing.
- (6) Develop a suitable Nozzle-To-Injector Adapter.
- (7) Define steady state parameters.

The accomplishment of the objectives will determine the suitability of the system required for chemical simulation testing and will ensure the timely completion of the first series of Phoebus-2 nozzle tests.

b. Acceptance Tests

During the fabrication of these test components, the customary radiographic, penetrant, pressure, and other NDT testing will be accomplished per the applicable specification, similar to those planned for the Phoebus-2 nozzle. The acceptance test plan for each component is under investigation and will be available for review at a later date.

The critical or unique acceptance tests to be performed on the test components are:

(1) Injector

A visual orifice pattern check will be made with water per AGC-90064, Type III, to ensure that no plugged or partially plugged, oversized, or maldirected orifices are present.

(2) Nozzle-To-Injector Adapter

A "Titration Test" similar to that planned for the nozzles will be performed per AGC-90064, Type II, to determine the coolant flow area in the adapter tubes. This test will provide flow area data necessary for the heat transfer analysis of this component.

(3) Igniters

A sample of each lot of igniters fabricated at Aerojet's Von Karman Center is fired as part of its acceptance test; therefore, only a short series of qualification tests are planned at the Sacramento test facility, mainly to check out the test stand controls system.

(4) Film-Cooled Workhorse Nozzle

A water flow test of the film coolant circuit of the workhorse nozzle will be performed per AGC-90064, Type IV, to visually check the distribution pattern in the chamber. This test will isolate any problem areas caused by maldistribution in the manifolds or improperly placed orifices.

c. Chemical Testing of Components

A series of eight (8) LO_2/LH_2 chemical tests are planned for the development of Phoebus-2 nozzle test components. The test assembly will

consist of the injector, nozzle-to-injector adapter, film-cooled workhorse nozzle and all applicable propellant lines. The liquid hydrogen required for combustion passes from the fuel tank into the nozzle-to-injector adapter where it regeneratively cools the adapter tubes; the hydrogen then flows through the injector and into the combustion chamber. This system will be referred to as the "fuel" system, Figure 161. In the "oxidizer" system liquid oxygen flows from the oxidizer tank through the injector and into the chamber. In the film-cooled nozzle tests the liquid hydrogen required for film cooling will be taken from the system designed to provide liquid hydrogen, referred to as the "coolant", to the nozzle as shown or from a bypass taken off the "fuel" system.

The first two (2) tests in this series will be checkout tests of 2 and 3 second duration to activate test stand H-4B, to verify start sequences, and to allow visual examination of the hardware before steady state tests are conducted. All test duration times discussed here will be times from fire switch one to fire switch two unless otherwise noted. Firing sequence will be covered in the discussion on Phoebus-2 nozzle proof tests. In the 2.0 second test, all valves will be fully opened and in the 3.0 second test, steady state operation will be attained. Any test duration in excess of 3.0 seconds is "steady state" time. The third test, as shown in Test Plan A, Table 23, is a milestone demonstration of 8 seconds duration or 5 seconds steady state operation at chamber pressure higher than 675 psia. Test number 4 is a test of Phoebus-2 reactor simulation P_c and MR. Tests 5-8 will verify previous test data and extend confidence in the injector and test controls system.

5. Phoebus-2 Nozzle Proof Tests

a. Nozzle Proof Tests

Proof tests of the Phoebus-2 nozzle will be conducted using the LO_2/LH_2 combustion system chemically tested in the film-cooled nozzle series. The coolant flows to the nozzle in a circuit parallel to the fuel circuit and will be controlled independent of the propellant flow into the combustion chamber, Figure 162. A maximum of fourteen (14)

FILM COOLED NOZZLE TEST ASSEMBLY

TEST PLAN A

CHEMICAL TEST HARDWARE DEVELOPMENT TESTING - UNCOOLED NOZZLE

TEST	DURATION sec	MR	P _c psia	% NOZZLE FILM COOLING	DESCRIPTION
1	2.0	5.5	700	15.0	Stand Checkout- Valves fully opened
2	3.0	5.5	700	15.0	Steady State Attained
3	8.0	5.5	700	15.0	Milepost Demonstration
4	8.0	5.5	750	15.0	Reactor Simula- tion Conditions
5	8.0	5.5	750	15.0	Verification Tests to Extend Confidence in Injector and Test Control System
6	8.0	5.5	750	15.0	
7	8.0	5.5	750	15.0	
8	8.0	5.5	750	15.0	

Table 23

NOZZLE TEST ASSEMBLY

tests are planned to demonstrate the capability of the nozzle to operate at reactor design conditions.

(1) Test Objectives

The objectives of this test series is to qualify the nozzle for reactor tests. Reactor simulation tests have been defined as tests conducted at 750 psia chamber pressure, 5.5 to 1 mixture ratio and design coolant flow rate of 250 lb LH_2 /sec. A total cumulative duration of 75.0 seconds in a minimum of four (4) tests is necessary for proof testing. These tests will be conducted according to Test Plan B, Table 24.

(2) Controls

The proposed control concept for the chemical test series consists of a closed loop system which will simultaneously maintain LH_2 and LO_2 tank pressures, control chamber pressure and mixture ratio to any independently specified value, and allow coolant flow rate to vary in desired steps or remain constant as dictated by the test requirements. The oxidizer flow rate is regulated by the preset chamber pressure and the fuel flow is controlled by the preset mixture ratio. The control of chamber pressure and mixture ratio is also applied during transient conditions allowing close control of the test during start and shutdown as well as during steady state operation. This control system is described in greater detail in the STE portion of this report.

(3) Start and Shutdown Chemical Test Sequence

(a) Start Sequence

In a typical Nerva oxidizer lead start transient, propellant valves are fully opened at $\text{FS}_1 + 2.0$ seconds, as shown in Figure 163. Steady state is achieved by $\text{FS}_1 + 3.0$ seconds. Phoebus start transients will

TEST PLAN B

PHOEBUS-2 NOZZLE PROOF TESTING PLAN

TEST	DURATION sec	MR	P _c psia	$\dot{W}_c$ lb/sec	DESCRIPTION
1	3.0	5.5	750	250	Test Stand Checkout
2	4.0	5.5	750	250	Check out Test-Nozzle One Second Steady State
3	15.0 ^a	5.5	750	250	Proof Test
4	20.0 ^b	5.5	750	250	Proof Test
5	20.0 ^b	5.5	750	250	Proof Test
6	20.0 ^b	5.5	750	250	Proof Test
Total	75.0 seconds cumulative duration				
7-14	20.0 ^b	5.5	750	250	Contingency tests to be run if necessary for proof demonstration

- * a. or 3/4 tank capacity
b. or maximum allowable duration

NERVA START TRANSIENT

TEST 1.2-09-NNN-013
S/N 13 NOZZLE

Figure 163

utilize the same valve opening times, as shown in Figure 164. The nozzle coolant valve will be opened at a faster rate than the propellant valves to ensure that coolant flow leads chamber pressure during the start transient. The coolant valve opening time may be altered after flow tests of the test assembly and the test system to prevent excessive pressure loads on the nozzle coolant passages. Under consideration is a plan to have partial coolant flow before FS_1 to ensure proper burn pond ignition and to have some coolant flow through the nozzle before chamber ignition is initiated.

(b) Shutdown Sequence

In a typical Nerva shutdown, the oxidizer valve receives its closing signal at FS_2 and it is fully closed in 0.7 seconds. When the oxidizer valve is 85% open, a signal is given to close the fuel valve. The fuel valve closes in 0.8 seconds, as shown in Figure 165.

This same fuel and oxidizer valve shutdown is planned for Phoebus. The coolant valve will receive its closing signal with the fuel valve, and will close in approximately 1.25 seconds. Another possible coolant valve shutdown sequence is under investigation in which the coolant valve will be closed to some preset value (100-150 lb/sec) and will receive its final closing signal at some low chamber pressure. This step function closing sequence is shown as dotted line in Figure 166. This again ensures that some coolant is flowing in the nozzle when combustion is occurring in the chamber.

b. Operating Limit Determination

A series of eight (8) chemical tests are planned to demonstrate the operating capability of the Phoebus-2 nozzle at reduced coolant flow. Nozzle coolant flow will be decreased at simulation chamber pressure and mixture ratio as shown in Test Plan C, Table 25, until 55% of design coolant flow (137 lb/sec) is achieved. These tests will provide data necessary to predict the operating limits of the nozzle.

PHOEBUS START - OXIDIZER LEAD

Figure 164

NERVA SHUTDOWN TRANSIENT

TEST 1.2-09-NNN-013
S/N 13 NOZZLE

Figure 165

PHOEBUS SHUTDOWN TRANSIENT

Figure 166

TEST PLAN C

PHOEBUS-2 NOZZLE OPERATING LIMIT DETERMINATION

TEST	DURATION	P _c psia	MR	W _c LB/SEC	COMMENTS
1	3.0	750	5.5	250	Checkout test
2	20.0 +	750	5.5	249	Design Coolant Flow
3	20.0 +	750	5.5	225	Coolant reduced
4	20.0 +	750	5.5	200	
5	20.0 +	750	5.5	175	
6	20.0 +	750	5.5	160	
7	20.0 +	750	5.5	145	
8	20.0 +	750	5.5	137	.55 W _c Milepost

* or maximum allowable test duration

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G. RELIABILITY AND QUALITY ASSURANCE - TASK G

1. Reliability and Quality Assurance Program Plans

The Intermediate Reliability and Tentative Final Quality Assurance Program Plans required by the statement of work were completed 3 May 1965 and submitted to SNPO-C for review and approval. The Final Reliability and Quality Assurance Program Plans incorporating the SNPO-C comments will be submitted to SNPO-C by 18 June 1965. The scope of these program plans describes the Phoebus-2 Nozzle Program approach for controlling design, procurement, fabrication, and testing of the Phoebus-2 nozzle developed under NASA Contract SNPC-35. Implementation of the program scope during the preliminary design study period is described in the following sections.

2. Reliability Assurance

a. Design Review

The preliminary Phoebus-2 Nozzle designs are being reviewed to ensure that specifications are used to control the quality necessary to achieve design requirements. The modes of failure analysis (MOFA) is used by the Reliability Engineer to ensure that the possible causes of nozzle failure are prevented by design specifications and manufacturing processing procedures. Design configuration control is established during drawing review to ensure that purchase requisitions and fabrication planning incorporate the latest drawing revisions.

b. Modes of Failure Analysis (MOFA)

The preliminary Phoebus-2 Nozzle MOFA has been revised using applicable historical data of the NERVA Program to itemize the preventive design features that will be used by the designers to ensure a highly inherent Phoebus-2 nozzle reliability. This revision has incorporated the logic diagrams in Figures 167 thru 171 to define the critical and major modes of failure.

NOZZLE ASSEMBLY LOGIC DIAGRAM

Figure 167
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BOLT (NOZZLE TO PV CYLINDER) LOGIC DIAGRAM

Figure 168

JOINT (NOZZLE TO CYLINDER) LOGIC DIAGRAM

Figure 169

JOINT (NOZZLE TO PFL) LOGIC DIAGRAM

Figure 170
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JOINT (NOZZLE TO REFLECTOR) LOGIC DIAGRAM

Figure 171

The modes of failure in the logic diagrams are used as the basis for the MOFA to develop the cause of failure, its effects on the system, and specify preventive design features (see Figure 172 for an example). The MOFA will be used in the reliability review of designs and test plans and will be periodically revised to reflect the Phoebus-2 Nozzle design control approach.

3. Quality Assurance

a. Interface Control System

An interface control procedure was prepared for control of dimensional characteristics affecting the interface of deliverable nozzles with the pressure vessel and reactor and submitted to the interface task team. This procedure, revised by LASL and approved by the SNPO-C Technical Director, was incorporated into the Tentative Final Phoebus-2 Quality Program Plan. Inspection and recording requirements for interface dimensions will be incorporated into integrated planning documents in accordance with the guidelines established by the interface task team and will be included in the narrative end-item reports for deliverable nozzles.

b. Drawing Review

Internal procedures for quality review of drawings were established which include the use of a check list (see Figure 173, Sheets 1 and 2). Drawings will also be reviewed for configuration control and interface control dimension requirements. The following drawings were reviewed and approved after incorporation of comments:

- (1) Material Evaluation Program:
 - (a) SK 2001 - ring, test, machining
 - (b) SK 2002 - ring, test, weldment
- (2) Hardware Development Program:
 - (a) 1013602 - jacket, forging - film cooled
 - (b) 1114738 - forging, adapter
 - (c) 1114856 - forging, nozzle

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(Con't over)

Figure 172 (cont.)

<div> <div>MODES OF FAILURE ANALYSIS</div> <div>PHOEBUS 2 NOZZLE</div> <div> <div>PAGE 3 OF 9</div> <div>DATE May 1965</div> </div> </div>				
MODE OF FAILURE	CAUSE OF FAILURE	EFFECTS ON ENGINE SYSTEM	PREVENTIVE DESIGN FEATURES	REMARKS
I External Propellant Leakage A. Structural Jacket and Coolant Manifold Failures	I.A.1C Corrosion during chemical simulation testing of development nozzles. a. Start b. Operation c. Shutdown	I.A. Critical - Explosion Major - Fire Damage to Nozzle Exterior	IA10 b. Injector pattern to be checked on work-horse nozzle. c. Test stand has nitrogen available if flushing is necessary to prevent air back-flow	

Figure 172 (cont.)

MODES OF FAILURE ANALYSIS PHOEBUS 2 NOZZLE				
			PAGE <u>4 OF 9</u>	
			DATE <u>May 1965</u>	
MODE OF FAILURE	CAUSE OF FAILURE	EFFECTS ON SYSTEM	PREVENTIVE DESIGN FEATURES	REMARKS
I.B. Structural Weld Failure	IB 1. Poor Weld a. Porosity b. Inclusions c. Lack of Penetrations. d. Undercut of base material IB 2. Incorrect weld material IB 3. Weld embrittlement	IB Critical - Explosion Major - Fire Damage to Nozzle Exteriors	IB1 a. Material program will investigate: 1 Weld joint Design 2 Welding process 3 Physical properties of weld joint design and welding process b. Certification of welders for selected weld process c. Welding instructions or procedure in fabrication planning d. Penetrant and radiographic interpass inspection e. Ultrasonic weld inspection f. Fabrication surveillance by Phoebus weld engineer	IB1 The material program is establishing the engineering welding requirements of the Phoebus program. This information is being recorded in the welding engineer's log book. A specimen identification procedure has been established to ensure the physical properties of test specimens and can be correlated with welding procedures and material chemistry. IB3 Experiments with radiation effects on welds are being considered.

Figure 172 (cont.)

MODES OF FAILURE ANALYSIS PHOEBUS 2 NOZZLE				
			PAGE 5 OF 9 DATE May 1965	
MODE OF FAILURE	CAUSE OF FAILURE	EFFECTS ON SYSTEM	PREVENTIVE DESIGN FEATURES	REMARKS
II Internal Propellant Leakage A. Structural Jacket Failure	IIA Same as IA	IIA Major - Test abort Minor - Fire	IIA Same as IA	IIA The Hastelloy X jacket nozzle is designed to allow cold propellant to enter hot exhaust stream in case of internal structural failure. Hot exhaust gas is contained by structural steel jacket and prevented from damaging test facility instrumentation on surface of engine envelope.
II B. Structural Tube Failure	IIB <ol style="list-style-type: none"> 1. Tears in forming 2. Laps and laminations in strip stock 3. Inclusions 4. Improper Chemistry 5. Enlarged material grain size 6. Over pressure and temperature 7. Thermal and Mechanical fatigue. 8. Design inadequacies 9. Fabrication <ol style="list-style-type: none"> a. Dents & gouges b. Burns c. Foreign material or braze runoff in coolant passages 	IIB <ol style="list-style-type: none"> 1. Major - Test abort from unbalanced flow distribution in the coolant circuit. 2. Minor - Fire 	IIB.1-2 Penetrant inspect tubes for laps and tears. 3,5 Metallographic inspection 4. Chemical Certifications 6. Pressure kill limits for development testing. 7. Thermal fatigue program will be conducted. 8.a. Structural analysis b. Verification of design analysis with development testing. c. Ultrasonic check tube crown thickness. d. Minimize pockets in coolant channels where material could collect during flushing and cleaning. 9.a. Limits for depth of dents and gouges are to be specified on nozzle assembly drawing. b. Deburr internal drilled passages prior to cleaning. c. 1. Provide protective closures to prevent foreign materials from entering coolant passages during fabrication. 2. Flush nozzle cleaning hydraulic system prior to installing nozzle for cleaning. 3. Radiographic inspection of nozzle coolant passages after flushing. 4. 1/2 Segment flow symmetry test	IIB Extra tubes are ordered so that any damaged tubes can be rejected without jeopardizing nozzle reliability or schedules and material specifications will be used to control quality of tubes. IIB 6. Appropriate pressure kill limits will be needed for reactor tests. 9. Protective padding or closure will be used.

Figure 172 (cont.)

<div> <div>MODES OF FAILURE ANALYSIS</div> <div>PHOEBUS 2 NOZZLE</div> </div>				
			<div> <div>PAGE 6 OF 9</div> <div>DATE May 1965</div> </div>	
MODE OF FAILURE	CAUSE OF FAILURE	EFFECTS ON SYSTEM	PREVENTIVE DESIGN FEATURES	REMARKS
C. Structural Braze Failure	IIC 1. Rapture at or adjacent to braze joint 2. Too many braze cycles 3. Braze Joint design	IIC 1. Major - Test abort from unbalanced flow distribution in the coolant circuit. 2. Minor - Fire	IIC 1. Testing: a. Chemical firing of development nozzle b. Thermal fatigue tests. c. Hydrostatic acceptance test. 2. Brazing requirements to be specified in procedure, and on drawing. 3. a. Design points to minimize braze drop-through during brazing and temperature cycle nozzle during brazing to allow excess braze material to run off. b. Material evaluation program including destructive analysis. c. Dimensional inspection of jacket, tubes and shims. d. Hydro-testing e. Use leak test to locate leaks prior to rebrazing.	IIC 1. Ultrasonic immersion testing of tube to jacket braze bond will be investigated in nondestructive testing program. 3. The braze joint design under consideration has been proven successful on the NEVA Program. Test sample work is to be performed to establish optimum braze cycle, type of purge and temperature control. Radiation effects experiments on the braze joints are being considered.

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MODES OF FAILURE ANALYSIS PHOEBUS 2 NOZZLE				PAGE 7 OF 9 DATE May 1965
MODE OF FAILURE	CAUSE OF FAILURE	EFFECTS ON SYSTEM	PREVENTIVE DESIGN FEATURES	REMARKS
I. External Propellant Leakage a. Structural Failure of bolt	IA11. Rupture of bolt from stress induced by: a. Overtorque b. Areas of stress concentration. c. Fatigue 22. Reduction of allowable stress capability of bolt material from: a. Radiation effects b. Corrosion c. Fatigue 3. Brittle failure due to loss of ductility of material from: a. Cryogenic fluid b. Radiation effects 4. Handling damage 5. Shearing of bolt 6. Foreign material blocking coolant passages a. Overheating	IA 1. Major - Fire damage to nozzle exterior 2. Minor - Fire	IA1. a. ACF Industries to investigate nozzle to bolt interface load-carrying capability. b. Bolt assembly will be qualified during chemical simulation testing of development nozzles. c. Bolts destructively tested and physical properties determined. 2. a. Structural analysis of bolt. b. Corrosion has not been a problem. c. Elongation to be defined in material specification. 3. Same as 2.c. 4. Shipping and packing requirements are to be specified on drawing. 5. Shear lip is being designed into nozzle flange to relieve bolt of shear load. 6. Cleaning specification will be incorporated to remove foreign material introduced during fabrication.	IA1 c. Ultrasonic inspection of bolt stock, penetrant inspection of finished bolt being considered. IA6 Review bolt design to determine if visual or radiographic inspections of coolant passage is necessary.

Figure 172 (cont.)

<div> <div>BOLT ASSEMBLY</div> <div> <div>MODES OF FAILURE ANALYSIS</div> <div>PHOEBUS 2 NOZZLE</div> </div> <div>PAGE 8 OF 9</div> <div>DATE May 1965</div> </div>				
MODE OF FAILURE	CAUSE OF FAILURE	EFFECTS ON SYSTEM	PREVENTIVE DESIGN FEATURES	REMARKS
I.B Structural failure of Bolt Seals	I.B. 1. Incorrect seal dimensions, tolerances or finish. 2. Damaged seal. 3. Hydrogen permeability 4. Cryogenic temperature effects. 5. Abrading of seal surfaces during assembly		I.B. 1. Seal dimensions, tolerances and finish specified on drawing. 2. Special packing to be specified. 3. Metal seals minimize hydrogen permeation. 4. Harrison "K" seals have been successfully used on NERVA Program 5. Plating on seal surface to be investigated.	I.B. 1 Seal material and design under investigation.

Figure 172, (cont.)

<div> <div>FLANGE SURFACES AND JOINTS</div> <div> <div>MODES OF FAILURE ANALYSIS</div> <div>PHOEBUS 2 NOZZLE</div> </div> <div>PAGE <u>9</u> OF <u>9</u> DATE <u>May 1965</u></div> </div>				
MODE OF FAILURE	CAUSE OF FAILURE	EFFECTS ON SYSTEM	PREVENTIVE DESIGN FEATURES	REMARKS
I. Propellant Leakage A. Nozzle to PV Joint B. Nozzle to Propellant Feed-line Joint C. Nozzle to Reflector Joint	I. A.B.&C. Flange Surfaces and Joints 1. Incorrect seat dimensions, tolerances or finish. 2. Damaged seal surface during assembly 3. Foreign material on sealing surface. 4. Bolt torquing sequence.	I.A. 1. Major-Fire damage and test abort 2. Minor - Fire I B. 1. Critical - Explosion 2. Major - Fire damage and test abort. 3. Minor - Fire I C. 1. Critical-Reactor overheating 2. Major -Reactor cooling limited.	I A.B &C. 1. Dimensions, tolerances and finish are specified on nozzle drawing. 2. Seal plating can act as lubricant 3. Joint assembly cleaned per cleaning specifications. 4. To be specified in joint assembly procedure.

AEROJET-GENERAL CORPORATION

DRAWING QUALITY REVIEW

DRAWING NO.	DRAWING LEVEL	PROGRAM	MODEL	REVIEWER	DEPT/BLOG/EXT	DATE		
						YES	NO	N/A
1. <u>ACCEPTANCE CRITERIA</u> : ARE ACCEPTANCE LIMITS OF QUALIFICATION AND/OR ACCEPTANCE TEST CRITERIA SPECIFIED?								
2. <u>ASSEMBLY AND INSTALLATION</u> : CAN PARTS BE ASSEMBLED AND/OR DISASSEMBLED WITHOUT UNREASONABLE COMPLICATIONS FOR INSPECTION? IS INSTALLATION SEQUENCE DESCRIBED WHEN NECESSARY?								
3. <u>BALANCE</u> : ARE STATIC OR DYNAMIC BALANCE LIMITS INCLUDED?								
4. <u>CLASSIFICATION OF CHARACTERISTICS</u> : IS THE SELECTION AND CODING OF CHARACTERISTICS ADEQUATE FOR INSPECTION TO PLACE THE PROPER EMPHASIS ON THEM?								
5. <u>CLEANLINESS</u> : ARE THE CLEANLINESS REQUIREMENTS AND ACCEPTANCE LIMITS SPECIFIED?								
6. <u>DIMENSIONS</u> : IS THE PART DIMENSIONED TO AVOID UNNECESSARY CALCULATIONS BY INSPECTION?								
7. <u>GRAIN FLOW</u> : IF THE PART IS MADE FROM A FORGING OR FROM SHEET METAL, IS THE DESCRIPTION OF GRAIN FLOW INDICATED, WHEN REQUIRED?								
8. <u>LOCKING FEATURE</u> : ARE FEATURES FOR ASSURING RETENTION OF PARTS SPECIFIED, WHEN REQUIRED? (WIRE HOLE, KEY WASHER SLOTS, OR SIMILAR FEATURES.)								
9. <u>MATERIAL</u> : ARE PHYSICAL AND MECHANICAL PROPERTIES, APPLICABLE TEST REQUIREMENTS, AND CONTROLLING SPECIFICATIONS NOTED? ARE HEAT TREATING REQUIREMENTS STATED? ARE ACCEPTANCE LIMITS FOR THE ABOVE SPECIFIED?								
10. <u>METAL JOINING (WELDING, BRAZING, AND SOLDERING)</u> : ARE THE PROCESSES AND THEIR APPLICATIONS CLEARLY DEFINED? ARE ACCEPTANCE STANDARDS STATED? ARE METAL JOINING SYMBOLS IDENTIFIED?								
11. <u>NON-DESTRUCTIVE TEST PROCESSES</u> : ARE THE REQUIREMENTS FOR PENETRANT, MAGNETIC PARTICLE, RADIOGRAPHIC, ULTRASONIC, OR SIMILAR INSPECTION PROCESSES SPECIFIED, WHEN REQUIRED? ARE ACCEPTANCE CRITERIA SPECIFIED? ARE THE SEQUENCE OF INSPECTION AND AREA OF COVERAGE PROPERLY INDICATED, WHEN REQUIRED?								
12. <u>PART IDENTIFICATION</u> : IS THE METHOD AND LOCATION OF MARKING CONSISTENT WITH ACHIEVING A QUALITY PRODUCT?								
13. <u>PRESERVATION AND PACKAGING</u> : ARE APPROPRIATE METHODS AND LEVELS SPECIFIED TO ASSURE RECEIPT STORAGE OR DELIVERY OF THE PRODUCT IN SATISFACTORY CONDITION?								
14. <u>RELIABILITY</u> : CAN THE PART BE PRODUCED WITH THE REQUIRED ASSURANCE OF QUALITY?								
15. <u>PROTECTIVE FINISH</u> : ARE PROTECTIVE FINISH NOTES, ACCEPTANCE LIMITS, AND CONTROLLING SPECIFICATIONS ADEQUATELY DESCRIBED?								
16. <u>SERIALIZATION AND/OR LOT CONTROL</u> : ARE THE METHOD, LOCATION, AND SEQUENCE REQUIREMENTS NOTED, WHEN REQUIRED?								

c. Procurement Document Review

Procurement packages for material ordered to the AGC-90000 series specifications for the material evaluation program were reviewed for inclusion of adequate definition of quality engineering requirements. These quality requirements were incorporated into the purchase order by Sacramento procurement quality control standard clauses. The procurement clauses provide process and facility approval, receiving inspection, source surveillance, physical and chemical data, identification and certification, and other requirements as needed for nozzle components.

d. Integrated Planning

Recommended guidelines to incorporate quality inspection requirements in integrated fabrication planning by the Phoebus Reliability and Quality Assurance Department were prepared. These guidelines are intended to amplify the REON quality procedure for integrated planning now being coordinated.

e. Fabrication Surveillance

Quality surveillance of fabrication was provided to assure adequate documentation of efforts on the forged ring weld evaluation samples. The integrated shop planning for this work was reviewed and approved. Procedures were established to provide sample identification and recording of welding program results by the Phoebus Materials Group.

4. Nondestructive Testing

a. Inspection

The roll-ring forgings of Hastelloy X were ultrasonically inspected with both longitudinal and shear wave modes. The longitudinal mode was calibrated to a 3/64" flat bottom hole and then scanned in a radial direction.

Only one detectable indication was located with the signal being smaller than the reference hole. The shear wave inspection was calibrated on 3/64" diameter holes drilled 1/2" on the inner and outer surface of the ring. The only indications detected were traceable to the steel-stamped identification numbers. The ultrasonic properties were uniform around each ring and there was no detectable difference from ring to ring.

Penetrant and radiography have been used for in-process inspection during the welding of the rings. Defects revealed by the nondestructive tests were removed prior to re-welding.

Radiographic facility time in the energy range up to 300 kv is available for the duration of the Phoebus-2 Program. This energy range is adequate for good radiographic inspection of welds in high nickel alloys up to 1.0-in. thick. For thicker sections, AGC planning had assumed that the 2 mev Van de Graff generator of the M-1 program would be available. Funding has not as yet been furnished to install this unit. The 10 mev linear accelerators at AGC Sacramento can be used for radiographic inspection, but the energy range is too high for sensitive examination of one to two-in.-thick sections. Also, the facility availability is limited to the extent that the Phoebus welding development program is expected to experience extensive schedule delays if we are limited to this facility. Subcontractors for radiography of heavy sections will be investigated.

b. Specifications and Planning

The existing AGC specification for nondestructive testing (NDT) requirements were reviewed and specifications for penetrant, radiographic, and ultrasonic testing of Phoebus materials and components were selected. This review revealed a need for additional specifications to cover special Phoebus applications. Radiographic Acceptance Criteria, AGC-90005, is currently in coordination and a specification to cover angle-beam ultrasonic testing of plate and forgings has been drafted. Procedural specifications for the inspection of strip and for the U-tube-to-nozzle joints will be prepared following laboratory study.

The Material and Process Development Plan has been reviewed and the NDT plans incorporated. The NDT data will provide information to evaluate the control of the processes and to qualify the processes and the operators.

The PERT fabrication planning has been reviewed and the NDT requirements are incorporated at the proper inspection control points. The fabrication plan calls for both in-process and final item inspection and will provide inspection for material and fabrication to assist in evaluation of process control.

Process Inspection Procedures will be generated as required to give detailed coverage of non-standard inspections. These procedures will be generated either by the Phoebus NDT personnel or by the vendor subject to Phoebus Reliability and Quality Assurance review and approval.

c. Ultrasonic Development

The ultrasonic method used to inspect the NERVA U-tube-to-jacket braze joint can be extended to evaluate the processes and controls for the Phoebus braze joint development program and to provide engineering data for the Phoebus nozzle fabrication. Development studies to date show a correlation of the ultrasonic signals with the observed unbonds at either the tube/jacket or the tube/shim interface. The variables effecting calibration for quantitative measurement are being analysed and studied for transducer type, control of beam width, refracted angle, dynamic range, and attenuation correction. The transducer must inspect the total depth of joint, but be limited so that reflections from the bottoms of adjacent joints will not affect the inspection. Both focused and collimated transducers have been studied. The results indicate that further investigation is required.

Currently, test parameters are being selected to provide a measuring range from 0.005 to 0.100 inch unbond. The data collected during the NERVA braze development program will indicate criteria that will permit less rigorous calibration on the Phoebus-2 Program. Present data indicates that the smallest refracted angle that provides a simple calibration is 35°.

Test parameter optimization studies are expected to be complete on the NERVA program in time to provide inspection procedures for the Phoebus braze development studies. The data gathered on the NERVA program and the correlation studies now under way on NERVA Nozzle S/N 008 is expected to provide criteria for the evaluation and process control for inspecting the braze joint of the Phoebus nozzles.

5. Special Test Equipment

a. Drawings

Approximately fifty Special Test Equipment (STE) construction drawings are being reviewed to ensure that AETRON specifications appropriate standard code requirements are incorporated. The code requirements are selected on basis of best commercial practice for the particular activity. Structural steel erection is based on AISC and AWS standards. Process piping installations is based on the ASME code, the ASA standard code for pressure piping, and AETRON specifications which have been developed for this purpose. NDT requirements are set forth in the drawings and specifications. Welding, materials and NDT specialists are consulted as needed. Approval of drawings is shown by Phoebus Reliability and Quality Assurance signature in the Product Assurance signature block.

b. Specifications

The "Phoebus Standard Component and Equipment Notes" were developed by the Phoebus STE and Facilities and Reliability and Quality Assurance Departments. These notes incorporate the quality control requirements into the Phoebus STE specifications, where the exact wording can be made specific to each procurement. The notes are not repeated as standard clauses on the face of the purchase order, since differences in wording may offer the vendor the opportunity to choose between two versions of the requirements.

The following specifications have been reviewed and approved:

- (1) Phoebus 2-101 - flow control valves
- (2) Phoebus 2-102 - high pressure universal gimbal joints
- (3) Phoebus 2-103 - high pressure gas filters
- (4) Phoebus 2-104 - high pressure remote shutoff valve
- (5) Phoebus 2-105 - vacuum jacketed run line spools
- (6) Phoebus 2-106 - remote shutoff valves, incline
- (7) Phoebus 2-107 - high pressure remote shutoff valves
- (8) Phoebus 2-108 - check valves
- (9) Phoebus 2-109 - flow control valve
- (10) Phoebus 2-110 - globe valves

c. Purchase Requisitions

Requisitions covered by specifications with Phoebus Standard Component Equipment Notes have quality control requirements defined. Requisitions for items not having Phoebus-2 specifications are reviewed and quality control requirements are incorporated on the requisition by standard clauses or special clauses developed for the particular need. STL and Facilities requisitions procured through the AETRON-Sacramento organization are reviewed and approved by the Phoebus Reliability and Quality Assurance Department. Other AETRON requisitions processed through the Sacramento Plant are reviewed and approved by Product Assurance Procurement. All AETRON procurement packages transmitted to SNPO-C for prior approval are reviewed by the Product Assurance Procurement Department.

d. Procurements

Meetings were conducted between prospective vendors, the purchasing agent, pertinent technical personnel, and the Phoebus Reliability and Quality Assurance Department to resolve vendor problems of meeting the quality control or technical requirements of procurements.

e. Surveillance

The AETRON-Sacramento Quality Assurance Department is responsible for the planned, detailed, on site inspection and documentation for all process piping installations. Phoebus Reliability and Quality Assurance personnel will monitor the performance and effectiveness of this function and will participate in periodic progress meetings with the erection subcontractors.

The supplier discrepancy action request has been included in the Phoebus-2 Specifications Standard Notes to incorporate engineering review board action into the dispositioning of STE discrepancies.

H. SPECIAL TEST EQUIPMENT - TASK H

1. Introduction

As originally proposed, special test equipment and facility requirements for this program were presented in two phases. The first phase, a study program, was for the purpose of selecting a test facility within the Liquid Rocket Operations which would meet the technical requirements of this program with minimum modifications, time, cost, and testing interference with other test programs. The second phase included the necessary design, fabrication, and installation associated with the test facility selected at the conclusion of this study.

Following the proposal submittal and subsequent to the contract award, SNPO-AGC mutually agreed that based on a previous AGC review of facilities and due to the urgency of providing test facility consistent with the proposed nozzle development program scheduling, the STE and facilities study program could be eliminated. On 15 February, test stand H-4B was selected for this program based upon the information presented in the Proposal.

2. Technical Discussion

Within the Liquid Rocket Operations test area, Figure 174, three test stands were considered for this program: Test Stand C-9; Test Stand H-4B (located within the NERVA test complex H-4, -5, and -6); and Test Stand H-8.

Test Stands C-9 and H-8, both M-1 owned test facilities, were presented as an alternative combination.

Test Stand C-9, Figure 175, was activated in 1963 to serve the requirements of the M-1 nozzle and gas generator development programs. This test position was selected as a candidate for the Phoebus program on the basis of its existing capability to conduct nozzle testing requiring propellant flows

TEST AREA - LIQUID ROCKET OPERATIONS

Figure 174

TESTING COMPLEX C-9

Figure 175

at high pressures. This facility became available for other test programs in 1964, following a test malfunction and subsequent program redirection. This stand could provide the capability for conducting short duration nozzle development testing and would be used in conjunction with Test Stand H-8, where nozzle test system acceptance testing could be performed at longer durations.

The Phoebus nozzle test installation in Test Stand C-9 is shown in Figure 176. In addition to modifications necessary to adapt this position for the Phoebus nozzle installation, replacement of specific test equipment damaged following the M-1 test malfunction will be required to allow shared non-interference usage with the M-1 program in the event future testing is necessary.

The primary on-stand special test equipment serving both programs are as shown in Figure 176. Liquid hydrogen is supplied from an existing high pressure 6,000 gallon vacuum jacketed supply vessel through a propellant piping system into the injector and nozzle. The nozzle coolant discharge gasses are disposed of in a hydrogen disposal area. Liquid oxygen is supplied from a 2,000 gallon supply vessel through a similar system to the injector.

Pressurants for both the liquid hydrogen and liquid oxygen, are supplied from a gas storage area where gas is stored at 3,500 psig. At nominal flow, durations of up to 8 seconds can be obtained with this test system. Also, serving this position are liquid hydrogen, nitrogen, and oxygen, storage facilities. The data acquisition and recording capability is located in Control Room D-2. This control room is utilized on a shared non-interference basis with the components development test programs located in D-3, A and B bays.

Test Stand H-8, shown in Figure 177, was activated in 1965 to serve the extended test duration requirements of the M-1 program.

As mentioned previously this test position could be used in conjunction with Test Stand C-9 and could provide Phoebus nozzle acceptance test durations of approximately 20 seconds.

PHOEBUS-2 NOZZLE INSTALLATION - TEST STAND C-9

Figure 176

TESTING COMPLEX H-8

Figure 177

Test Stand H-8 could be modified as shown in Figure 178 to allow interchangeability between the M-1 and Phoebus programs.

Propellant and other support systems to the test hardware are similar to systems shown for Test Stand C-9.

Test Stand H-4B, located within the NERVA test complex H-4, -5, and -6, shown in Figure 179, would be created to serve this program. Located adjacent to the existing NERVA nozzle test system, Test Stand H-4, this test position would utilize existing special test equipment and facilities as provided by the NERVA development program over the past 3 years. Based upon the current NERVA nozzle test program plan and the projected testing program for the Phoebus nozzle, Figure 180, co-utilization of common special test equipment and facilities serving both programs presents no significant problem.

Test Stand H-4B Figure 181, is shown as originally proposed. Modifications to existing on-stand special test equipment, specifically the high pressure propellant supply vessels discharge systems and pressurization systems, will be required. In addition, new systems such as liquid hydrogen and oxygen propellant supply piping systems, test hardware work platforms, handling system, a nozzle structural supporting system capable of withstanding a 330,000 lbs thrust load, and a gaseous hydrogen disposal system will be necessary.

Liquid hydrogen, will be supplied from the existing high pressure 14,000 gallon, 1800 psig supply vessel through appropriate valving and flowmeters to the nozzle and injector. The nozzle coolant discharge will be carried to a hydrogen disposal area. The liquid oxygen will be supplied from the existing high pressure 5,000 gallon, 1800 psig supply vessel through a similar system to the injector.

Pressurants (gaseous hydrogen and gaseous nitrogen) are supplied from a gas storage facility where nitrogen is stored at 5,000 psig and hydrogen is stored at both 5,000 and 3,500 psig levels dependent upon cascade pressure limitations.

SUGGESTED TEST STAND H-8 MODIFICATION

Figure 178

TESTING COMPLEX H-4, H-4A, H-5 AND H-6

Figure 179

NERVA/PHOEBUS TEST STAND UTILIZATION

TEST DESCRIPTION	TEST STAND	1966												1967											
		J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
PHOEBUS Nozzle	H-4B		3	2	1	2	6	6	3	2					2	1				1	1				
NERVA Nozzle	H-4																								
Turbine Power Control Valve	H-4A	2				10	5							1	2										
Cold Flow Development Test System	H-5																								
Turbopump Assembly	H-6		4	8	2				1						1										
	TOTAL	2	7	10	3	12	11	6	3	3				1	2	4				1	1				

PHOEBUS-2 NOZZLE INSTALLATION, TEST STAND H-4B

Figure 181

At nominal flows test durations of approximately 18 seconds can be obtained with this system. Data acquisition and recording capability is located in control room H-2. This control room specifically constructed for the NERVA test complex will be utilized on a shared non-interference basis.

Primary support facilities currently available to serve this program are shown in Figure 182. Gaseous hydrogen and nitrogen storage facilities shown in the upper left provide pressurant to the NERVA and M-1 test programs on a shared non-interference basis. This facility is currently being modified to provide additional gaseous hydrogen storage capacity. Specifically, to accommodate the increased requirements of the Phoebus program, a new 10" gaseous hydrogen and 8" gaseous nitrogen system to the test stand will be installed. The other facilities include liquid hydrogen, nitrogen and oxygen storage facilities and other support facilities currently available within zone H.

In summary, Test Stand H-4B was selected on the following basis:

- (1) Ownership by SNPO eliminating the need for non-interference co-utilization of facilities agreement with other government agencies.
- (2) Most complete instrumentation acquisition and data processing system available to existing facilities.
- (3) Shared utilization of zone H NERVA trained test personnel which will result in a more efficient and effective operation.
- (4) The lowest cost for test stand modification/augmentation of the alternates presented.

On 15 February 1965 design activity associated with Test Stand H-4B was initiated. To date, 65% of the design and STE procurement effort has been completed.

FACILITY PLOT PLAN - TEST ZONE H

Figure 182

Test Stand H-4B shown in Figure 183, reflects the most current concept for the Phoebus nozzle test installation.

This concept differs from the proposed installation shown in Figure 181. The position of the test hardware was altered to provide better accessibility to the serviceable special test equipment within the test bay, blast screens have been provided directly over the test hardware to preclude damage to the adjacent special test equipment on Test Stand H-4, 5, and 6 in the event of a test malfunction.

The mechanical special test equipment and facilities serving test stand H-4B are shown schematically in Figure 184. Liquid hydrogen, is supplied from a high pressure vacuum jacketed spherical run vessel through a 12-in.-dia piping system to the nozzle for nozzle coolant and in turn through a 10-in.-dia piping system to the injector. Liquid oxygen is supplied from a similar system to the injector. Propellant flow rates are controlled by fast response (200 millisecond), servo controlled, hydraulically operated, flow control valves. Depending upon the flow characteristics desired, this system will provide the capability of pre-programming changes in liquid hydrogen and oxygen flow rates during the test. To dispose of the nozzle coolant gases discharging from the nozzle, a hydrogen burn pond approximately 80 Ft. x 40 Ft. will be constructed 400 Ft. away from the test stand. This system will be designed to dispose of 250 lb/sec of gaseous hydrogen. Systems similar to this, but smaller, are currently in operation at Cape Kennedy and the Sacramento Douglas Testing Facilities. Pressurants are supplied from a gas farm where gaseous hydrogen and nitrogen is stored at 5000 psig and 3500 psig. Both pressurant supply systems have filters and servo controlled hydraulically actuated flow control valves to regulate the gas for specific test conditions. Some typical system pressure drops are shown in the upper right.

PHOEBUS-2 NOZZLE INSTALLATION, TEST STAND H-4B

Figure 183

FLOW DIAGRAM - TEST STAND H-4B

Figure 184

The Phoebus-2 program will use the existing H-2 control room for data acquisition and controls as shown in Figure 185. The use of this control room has substantially reduced both cost and schedule for the Phoebus program. There is presently 1.3 million dollars of instrumentation and control equipment installed in this control room, all of which is available to the Phoebus-2 program on a no-cost basis.

From left to right are the common, facility, H-6, H-5, and H-4 consoles. The Phoebus program will share this console by means of the interchangeable lid assembly.

At the opposite end of this control room are two analog-to-digital converters. The Beckman 210 analog-to-digital converter is presently programmed to take 3,750 samples per second; these samples are divided among 185 data channels. Signals from the A-D converters are transmitted to a remote central data recording center via land cables. This recording center processes the data and provides a raw data print-out in engineering units within 30 minutes after the test has been conducted.

The H-2 control room plan, as shown in Figure 186, encompasses all of the instrumentation and controls necessary to conduct the testing planned for the NERVA and Phoebus H-Zone complex.

Specific equipment by individual bay designation is shown at the bottom of the chart.

The H-4B test stand data acquisition system was integrated into the existing data acquisition systems for Test Stands H-4, -5, and -6. Standardized Acrojet system were used, permitting the H-4B data to be transmitted to the control room over existing land line channels. Prepatched patch boards, located in a common terminal room provide ease of stand selection with maximum channel flexibility.

H 2 CONTROL ROOM

Figure 185

H2 CONTROL ROOM PLAN

2 NOV 64

Figure 187 shows the fixed wiring of the patch system and the number of channels for each data system between the stands, master patch, and control room. This master patch provides the basic stand and data channel selection. Presently, some of the existing data channels are relocated to provide the space required by the H-4B position.

Figure 188 compares the number of data acquisition channels provided for NERVA nozzle testing on test stand H-4, and Phoebus-2 nozzle testing on test stand H-4B. Note that the six channels of Micro systems high frequency pressure and 18 channels of CU/CN thermocouples are omitted.

The CU/CN channels were eliminated in favor of installing a standard 48 channel C/A thermocouple system. A review of the Phoebus data requirement indicates these 48 channels will meet all of the requirements.

The closed loop servo control systems for Test Stand H-4B are shown in Figure 189. They have demonstrated their reliability and performance while being successfully utilized previously on the M-1, Gemsip, and NERVA test programs.

These systems are designed specifically to control large mass flows with precision under rapidly changing conditions. Application of these systems has provided effective controls for tank pressurization, turbine speed control, turbopump backpressure, and thrust chamber control - including start transients, chamber pressure, and mixture ratio. In these applications, tank pressures were controlled to ± 0.5 psi of the set point. Both steady state turbopump speed and pump flow rates were maintained in accordance with set-point values within an error band of $\pm 0.2\%$. Through the use of integral or proportional-plus integral compensation, the steady-state control error has been reduced to approximately that of the feedback transducer.

PATCH SYSTEM BLOCK DIAGRAM - TEST STANDS H-4B, H-4, H-5 AND H-6

Figure 187

NERVA/PHOEBUS NOZZLE TEST STAND INSTRUMENTATION CAPABILITY COMPARISON

SYSTEM	TEST STAND	
	H-4	H-4B
Strain Gage (Pressure)	108	108
Micro Systems (High Frequency)	6	
Accelerometer (High Frequency)	12	12 *
Thermocouples		
Cu/Con	18	
Cr/Al	42	48
RTT	36	36
Flow and Speed	12	12
Valve Trace	24	24
Switch Trace	60	60

* Common with Test Stand H-4

Figure 1.88

PHOEBUS-2 SERVO CONTROL SYSTEM - TEST STAND H-4B

Figure 189

Figure 189 shows the five separate closed loop servo control systems provided for the control of the Phoebus-2 nozzle, two control tank pressures, one nozzle coolant flow, one fuel flow, and one oxidizer flow. These systems provide both transient control of start-up and shut-down as well as steady state control to preset combustion requirements.

Steady state conditions will be controlled to provide fixed parameters of chamber pressure and mixture ratio. Control is initiated by sensing chamber pressure, which modulates the lox flow proportionally. Fuel flow is then modulated to maintain a constant mixture ratio. Note that a small analog computer is required here to process the individual propellant flow signals and provide an output signal to the electronic servo controller proportional to the flow ratio.

Coolant flow control is also maintained by a closed loop servo control which will maintain a preset steady state flow value. The analog computer has been provided to shift the coolant flow rate to a new value during any one test firing. This computer-controller will function after a preset time to establish the rate of change in coolant flow to a new present coolant flow rate. A flow sensor in the discharge line is being considered to provide an emergency shut-down in case of inadequate coolant flow.

Servo control of propellant tank pressurization is also provided by standard closed loop systems. Each senses tank pressure and admits pressurant gasses as required to ensure system pressures and resultant propellant flows to permit proper performance of the nozzle servo controls.

During both start and stop transient periods propellant flows will be totally computer controlled to provide specific flow rate changes and mixture ratios.

Coolant flow control is also maintained by a closed loop servo control which will maintain a preset steady state flow value. The analog computer was provided to shift the coolant flow rate to a new value during any one test firing. This computer-controller will function after a preset time to establish the rate of change in coolant flow to a new preset coolant flow rate. A flow sensor in the discharge line is being installed to provide an emergency shut-down in case of inadequate coolant flow.

Servo control of propellant tank pressurization is also provided by standard closed loop systems. Each senses tank pressure and admits pressurant gasses as required to maintain a constant tank pressure. These systems were provided to ensure system pressures and resultant propellant flows to permit proper performance of the nozzle servo controls.

During both start and stop transient periods propellant flows will be totally computer controlled to provide specific flow rate changes and mixture ratios.

The facility construction schedule, Figure 190 describes the current scheduled completion dates for all major categories of procurement, design, and construction associated with this facility. Aerojet funded civil construction activity shown above was awarded on 12 April 1965, and is scheduled for completion on 7 June. Preprocurement of critical long lead special test equipment is 65% complete with a scheduled completion date of 1 November 1965.

The design effort associated with mechanical instrumentation and controls system is currently 65% complete. Contractor fabrication and installation of these systems is scheduled for 15 February 1966 with the first nozzle test scheduled for 15 February.

PHOEBUS-2 FACILITY CONSTRUCTION SCHEDULE

Figure 190

A plan view of the work associated with the civil construction effort is shown in Figure 191. This includes the test hardware access road, the concrete apron, and the burn pond previously described.

Test stand site preparation currently in progress is shown in Figures 192, 193, and 194.

CIVIL CONSTRUCTION PLOT PLAN - TEST STAND H-4B

Figure 191

SITE PREPARATION FOR TEST STAND H-4B

Figure 192

CIVIL CONSTRUCTION - TEST STAND H-4B

Figure 193

CIVIL CONSTRUCTION - TEST STAND H - 4B

Figure 194

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ARTICLE I - STATEMENT OF WORK

The objective of effort herein described is to perform a design evaluation of a nozzle concept to obtain engineering calculations, preliminary design layouts, and a model specification. A selection of fabrication and inspection methods for the nozzle shall be made and fabrication and installation of STE for nozzle testing shall be completed.

Task A - Preliminary Design

1. The Contractor shall study the design concept to meet the design requirements. The concept, including the nozzle contour in both the convergent and divergent sections, shall be selected with consideration to heat transfer, fabrication, repair, inspection and testing of the nozzles. By utilizing the findings and requirements of the tasks which follow, the design concept will be justified on the basis of:
 - a. Stress analysis.
 - b. Heat transfer and fluid flow analysis - tube and structure.
 - c. Interface and Interactions.
 - d. Testing problems.
 - e. Fabrication methods.
 - f. Inspection and/or special quality control problems.
 - g. Failure mode analysis.
 - h. Repairability.
 - i. Provision for instrumentation.
 - j. New technology required.
 - k. Growth capability in reactor discharge gas temperature.
2. Based on the selected concept a preliminary design shall be prepared. This shall include layout drawings, model specification, materials list, and fabrication and inspection methods.
3. Areas of uncertainty in the design, fabrication, inspection, and testing shall be identified and the methods of resolving these uncertainties shall be proposed.
4. A failure mode analysis under all test conditions of the selected concept shall be conducted.

Task B - Heat Transfer and Coolant Pressure Drop

A heat transfer and pressure drop analysis shall be made using the nozzle design parameters as specified in Appendix C. The heat transfer analysis shall include thermal radiation from the reactor core exit face, convection heat transfer from the hot propellant and internal heat generation from neutron and gamma heating. All equations and computer codes used for

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ARTICLE I - STATEMENT OF WORK (Cont'd)

both heat transfer and pressure drop calculations for use in this design study shall be supplied to the SNPO Technical Director for review and evaluation. The results of all calculations and associated input parameters shall also be supplied to permit a further evaluation of the analytical methods. Information regarding coolant discharge temperature and coolant pressure drop as related to the nozzle coolant passage design shall be submitted to the SNPO Technical Director for review and evaluation for subsequent use by LASL for reactor design. This shall include a map of temperature rise and pressure drop for the operating range of the reactor.

Conduct scale model and cryogenic test programs as necessary to verify the heat transfer correlations used in the Phoebus-2 nozzle design.

Task C - Stress and Vibration Analysis

1. Stress Analysis

A complete stress analysis of the nozzle, including nozzle pressure vessel interface, shall be conducted. "Complete" shall be construed to include an evaluation of the stresses, strains, deflections (both axially and radially) and rotational displacements that the nozzle will experience during its history and shall include mechanical loads and the effects of the thermal environments. The mechanical and the thermal environments effects shall be stress analyzed both separately and in correct combinations so that differentiation of structural effects can be evaluated. Separated flow conditions will exist while the engine is being accelerated through the low pressure regime in being brought up to rated power. The effects of these conditions shall also be analyzed.

The criteria for satisfactory structural behavior of the nozzle shall include the following considerations:

- a. All components of the nozzle structure shall be free of buckling instability throughout the loading envelope.
- b. It is evident that the nozzle and reactor pressure vessel must be entirely compatible with each other. Compatibility implies that the pressure vessel and nozzle under all loading conditions rotate and deflect in unison, without introducing excessive stresses each in the other and without detrimental separation or discontinuities in behavior at the interface area. This problem is more completely described in LASL report LAMS 3083 entitled "A Digital Computer Method for Design and Analysis of Axisymmetric Thin Shells Subjected to Pressure and Thermal Environments". Analysis may be accomplished

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ARTICLE I - STATEMENT OF WORK (Cont'd)

by the use of the existing computational programs currently in use at LASL. Substitute computational programs shall be submitted to the SNPO Technical Director for review and approval before use in the nozzle design.

- c. The allowable working stress must be established on the basis of the cyclic nature of the imposed load, the properties of the material, the operating temperature, and other factors. Combinations of steady state and cyclic loading shall be considered on the basis of Soderberg or modified Goodman diagrams, as applicable. Should the materials be operated in the creep range, creep and stress rupture characteristics of the materials shall be considered. The effects of stress raisers, notches, discontinuities, etc., shall be considered in relating the calculated stresses to the known material properties.
- d. Particular attention should be paid to the loads in the nozzle attachment bolts or other connection scheme to determine margins of safety in the attachments.
- e. Mechanical and thermal loads on the nozzle resulting from the fact that the nozzle is an integral component of a larger pressure containment and propellant feed system shall be analyzed.

2. Vibration Analysis

The Contractor shall analytically determine the natural frequencies and modes of the following types of nozzle vibrations:

- a. Lateral
- b. Longitudinal
- c. Radial
- d. Torsional

The natural frequencies of the individual components in the nozzle assembly shall also be determined in the applicable directions (lateral, longitudinal, etc.) with the boundary restraints as used in the design.

All equation and computer codes used for stress and vibration calculations in the design study shall be supplied to the SNPO Technical Director for information. The results of calculations and associated input parameters shall also be supplied to permit an evaluation of the analytical methods.

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ARTICLE I - STATEMENT OF WORK (Cont'd)

Task D - Materials and Fabrication

The Contractor shall select and submit for review and approval by the SNPO Technical Director a materials list for every item or part of the nozzle, including joining materials for the concept.

This list shall include properties of each material pertinent to its application(s).

The Contractor shall determine and submit fabrication methods for review and approval by the SNPO Technical Director. Inspection and repair between and after all stages of the fabrication is a desirable feature of the nozzle design and fabrication method.

Task E - Instrumentation

The Contractor shall determine and submit for information to the SNPO Technical Director the instrumentation for the concept, required to evaluate the nozzle for development testing. A minimum of three instrumentation pass-throughs shall be required in the nozzle convergent region for reactor testing. The installation of instrumentation including, but not limited to, thermocouples, platinum resistance temperature sensors, pressure taps, accelerometers and strain gages shall be determined and shown on the preliminary design layout.

Task F - Development, Proof and Acceptance Test Methods

The Contractor shall prepare and submit to the SNPO Technical Director for review and approval, three types of test methods for the concept. These are development test methods, proof test methods, and acceptance test methods.

The development test methods shall be fully defined. The objective of each test, the method of achieving the objective, and the use of the results shall be described.

Proof test methods shall be developed in which chemical test firings shall be used to demonstrate the capability of the nozzle to operate at reactor design conditions. The Contractor shall also plan a series of chemical tests to demonstrate the limit of the capability of the nozzle to operate at increased reactor chamber gas temperatures at specified reactor power.

Acceptance test method developed by the Contractor shall be nondestructive in nature. They shall include pressure testing, X-ray, ultrasonics, etc.

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ARTICLE I - STATEMENT OF WORK (Cont'd)

In addition, the Contractor shall define tests as required to develop injectors, nozzle-to-injector adapters and other associated hardware for chemical testing.

Task G - Reliability and Quality Assurance

As a part of the planning effort, the Contractor shall prepare a reliability program plan and a quality program plan for the subsequent development fabrication and testing effort. These plans shall conform with the requirements of NPC-250-1 and NPC-200-2, respectively, except that the requirements of NPC-250-1 (July 1963) shall be modified as stated in paragraphs 1, 2 and 3 below and the Contractor will implement and use applicable sections of the NERVA Quality Assurance Program Plan (AGC Report 2469, Volume II, Revision B) to interpret the initial requirements of NPC-200-2 and SNPC-35. These applicable sections of the NERVA Quality Assurance Program Plan will be replaced by appropriate sections of the Phoebus Tentative Final Quality Assurance Program Plan.

Prior to the initiation of the subsequent development effort, the Contractor shall submit an Intermediate Reliability Program Plan as prescribed in paragraph 2.2.3 of NPC 250-1, and a tentative Final Quality Program Plan for the subsequent development effort as prescribed in paragraph 3 of NPC 200-2. Reliability and Quality Assurance Program Plans shall be submitted to the SNPO Technical Director for approval.

The requirements of NPC-250-1 are modified as follows:

1. General Comments

- a. The intent of NPC-250-1 as applied to the nozzle program is more readily apparent if the words, "parts and materials," is substituted for the word, "components," and "assembly, subassembly, parts and materials," are used as applicable in place of terms such as "space system" and "system, subsystem and component level."
- b. Reference to "mission profile" or "mission success" shall be interpreted as "reactor/nozzle field test."

2. Deletions

Delete the following: Paragraph 2.7; paragraph 3.2.2 after the second sentence; paragraph 3.3; paragraph 3.5; paragraph 3.8.d and e; paragraphs 4.2, 4.3.1, 4.3.4, 4.5; reference in paragraph 4.4 to the Reliability Evaluation Plan and to reliability models; Appendix C, 2e and i, 3c data in second parenthesis; Appendix F, items 2, 3, 13, 14, 16 and 20.

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ARTICLE I - STATEMENT OF WORK (Cont'd)

3. Modifications

Paragraph 3.9.1, modify the first sentence; change "establish" to "have and utilize"; change "to conduct the parts program" to "process control (reference paragraph 7.5.4 of NPC 200-2)".

Task H - Special Test Equipment (STE)

The Contractor shall determine the detailed requirements for STE necessary to perform the test programs as described in Task F and for the subsequent development program.

The Contractor shall provide the following STE effort for Test Zone H-4B.

1. Mechanical

- a. Procure, fabricate and install LH₂ and LO₂ propellant piping systems (including flow control) from vessels VH-12 and VH-13 to the nozzle interface.
- b. Procure, fabricate and install high pressure GH₂ and GN₂ pressurization piping systems.
- c. Procure, fabricate and install nozzle LN₂ prechill system.
- d. Procure, fabricate and install H₂ exhaust and disposal system.
- e. Fabricate and install shields for diffuser and diffuser drive system, nozzle thrust frame and handling system, and work platforms.
- f. Activate TS H-4B systems for nozzle testing.
- g. Provide continuing test setup modifications to accommodate test hardware configuration changes.

2. Instrumentation and Controls

- a. Procure and install data acquisition equipment and/or systems, i.e., drop boxes, switching modules, ref. junctions, transducers.
- b. Procure and install control equipment and/or systems, i.e., amp patch systems, servo controllers, console, relay modules and timers.

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ARTICLE I - STATEMENT OF WORK (Cont'd)

- c. Procure and install lighting and power equipment and/or systems.
- d. Procure and install stand ancillary systems required for safety and/or test performance, i.e., TV systems, H₂ detectors, flame detectors, area warning, etc..
- e. Activate TS H-4B systems for nozzle testing.
- f. Provide continuing test setup modifications to accommodate test hardware configuration changes.

In support of the STE effort, the Contractor will supply the following reliability and quality assurance functions:

- a. Review and approve designs, drawings, specifications and procurement documents.
- b. Review fabrication planning for non-destructive inspection requirements.
- c. Provide quality assurance surveillance and engineering review board review action.

Task I - Reports

1. Planning Report

Within 15 calendar days after contract authorization, the Contractor shall submit a plan for realizing the objective of this study phase. The plan shall include:

- a. Important milestones.
- b. Schedule of performance to attain these milestones.
- c. A graphical presentation of the proposed estimated spending schedule.

2. Weekly TWX

The Contractor shall send a weekly TWX to highlight progress as well as delays on the contract. Engineering, material, scheduling, and other problems that might delay the contract shall be noted and anticipated corrective action defined. A maximum of ten (10) copies shall be distributed in accordance with a distribution list to be furnished by the SNPO Technical Director.

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ARTICLE I - STATEMENT OF WORK (Cont'd)

3. Oral Review

Oral reviews suggested by the Contractor or requested by the SNPO Technical Director shall be conducted on appropriate subjects covered by the contract.

4. Monthly Progress Reports

a. The Contractor shall submit monthly progress reports of all work accomplished during each month of contract performance. Reports shall be in narrative form and shall include:

- (1) A quantitative description of overall progress.
- (2) An indication of any current problems which may impede performance, and proposed corrective action.
- (3) A discussion of the work to be performed during the next monthly reporting period.
- (4) Test results obtained during the reporting period.
- (5) Pertinent data, calculation methods, calculation results, and graphs in sufficient detail to explain the results achieved.

b. Monthly progress reports shall be submitted in twenty-five (25) copies, no later than twenty (20) working days after the reporting period. Such reporting period shall be of a thirty (30) day duration and dating from date of the contract and monthly thereafter. The monthly progress report may be omitted when the quarterly or final reports are due.

5. Quarterly Reports

The Contractor shall submit separate quarterly reports of all work accomplished during each three (3) month period of contract performance. In addition to factual data, these reports shall include a separate analysis section which interprets the results obtained, recommends further action, and relates occurrences to the ultimate objective of the contract work. Sufficient diagrams, sketches, curves, photographs, and engineering drawings shall be included to convey the intended meaning.

A preliminary copy of the quarterly report shall be submitted within twenty (20) working days following the end of the reporting period to the assigned SNPO Technical Director. The quarterly reports shall be distributed in a maximum of one hundred (100) copies, plus one (1)

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reproducible copy, in accordance with a distribution list to be furnished by the SNPO Technical Director. The reporting period shall start three (3) months from the date of contract. The quarterly reports shall be omitted when the final report is due.

6. Financial Management Report

Pursuant to Clause 55 of the General Provisions, NASA Financial Management Reporting Form 533, segregating the CPFF costs from CPIF costs, is required monthly for this procurement. The report will contain one subdivision of work and the following elements of cost: labor engineering hours, labor engineering dollars, labor manufacturing hours, labor manufacturing dollars, material dollars, subcontract dollars, overhead dollars, general and administrative dollars, and reliability program control data. (Ref. NPC 250-1 paragraph 5.2.3). Form 533 shall be furnished in ten (10) copies on or before the twenty second (22nd) calendar day of the month following the reporting period.

7. Summary Reports

The Contractor shall submit summary reports which document and summarize results of the work performed under the study phase. Recommendations and conclusions based on the experience and the results obtained shall be included. The summary reports shall also include, as applicable, tables, drafts, diagrams, curves, sketches, photographs and engineering drawings, to permit complete understanding of any equipment, processes, concepts, analyses or other items developed under this investigation.

Four (4) preliminary copies of the summary reports shall be submitted to the SNPO Technical Director for review and approval within thirty (30) calendar days after the critical design review described in paragraph 8 below. Within ten (10) working days after approval, the summary report shall be distributed in a maximum of one hundred (100) copies, plus one (1) reproducible copy, in accordance with a distribution list to be furnished by the SNPO Technical Director.

The following summary reports shall be submitted:

a. Preliminary design report including

- (1) Evaluation of concept.
- (2) Preliminary design layouts.
- (3) Failure mode analysis for the concept.
- (4) Preliminary fabrication plan.

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ARTICLE I - STATEMENT OF WORK (Cont'd)

- b. Model specification for Phoebus-2 nozzle.
- c. Materials list and material properties data.
- d. Development, proof, and acceptance test methods.
- e. Program plan, PERT network and major milestones for all activities in the subsequent development phase.
- f. Preliminary design and construction schedule for necessary STE.
- g. A graphical presentation of the proposed estimated spending schedule.
- h. An engineering release plan of action.

8. Critical Design Review

An oral presentation covering the material specified to be submitted in the Summary Report (paragraph a above) shall be made by the Contractor on or before May 11, 1965.

9. Final Report - Required at completion of the contract.

The Contractor shall submit a final report which documents and summarizes results of the work performed under the completed phase. This shall include recommendations and conclusions based on the experience and diagrams, curves, sketches, photographs and engineering drawings, in complete detail, to enable complete understanding of any equipment, processes, concepts, analyses or other items developed under the investigation. A reproducible set of drawings in sufficient detail to enable manufacture of any equipment or items developed under this investigation shall be submitted with this report. Four (4) preliminary copies of the final report shall be submitted by the Contractor within 45 calendar days after completion of all work performed, to the assigned SNPO Technical Director, for review and approval. Within 30 calendar days after approval, the final report shall be distributed in a maximum of one hundred (100) copies, plus one (1) reproducible copy, in accordance with a distribution list to be furnished by the Technical Director.

10. Topical Reports

Topical Reports suggested by the Contractor or requested by the SNPO Technical Director shall be prepared on appropriate subjects covered by the contract.

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ARTICLE I - STATEMENT OF WORK (Cont'd)

11. Other Miscellaneous Reports

a. Incurred Cost Estimate

The Contractor shall prepare and submit on the fourth working day of the month, an incurred cost estimate for the preceding month by NASA system number(s).

b. Report on International Transactions

The Contractor shall prepare and submit a report on international transactions as required by NASA Management Manual, Volume 7, Chapter 6, paragraph 76001-76050.

c. ADP Reports

The Contractor shall prepare and submit applicable ADP reports as required by BOB A-55 and NASA Management Manual 3-6-1.

ARTICLE II - PERIOD OF PERFORMANCE

All work set forth in Article I, Contract SNPC-35, chargeable to the CPFF portion, shall be completed on or before May 18, 1965 with the following exceptions:

- (a) Completion of the Summary Report as set forth in Task I shall be accomplished on or before July 31, 1965, or ten (10) days after SNPO Technical Director's approval of the preliminary summary report, whichever is later.
- (b) Completion of all STE work as set forth in Task H shall be accomplished on or before February 1, 1968.
- (c) Completion of all Quality Control work as set forth in Task G applicable to STE, shall be accomplished on or before February 1, 1968.
- (d) Completion of all heat transfer work as set forth in Task B shall be accomplished on or before October 31, 1965.
- (e) Completion of procurement of Hastelloy X material in support of Task D, shall be accomplished on or before July 20, 1965.