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REPORT NO. RP-MR-0019
TO
SPACE NUCLEAR PROPULSION OFFICE - CLEVELAND EXTENSION

PHOEBUS-2 MONTHLY PROGRESS REPORT (U)
FOR THE PERIOD 1 JUNE THROUGH 30 JUNE 1967

CONTRACT SNPC-35
JULY 1967

MASTER

INCLUDING
REPORT NO. RP-TM-0015
NUCLEAR NOZZLE DESIGN REPORT (U)

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REPORT NO. RP-MR-0019

PHOEBUS-2 MONTHLY PROGRESS REPORT (U)
FOR THE PERIOD 1 JUNE THROUGH 30 JUNE 1967

R. L. Murray
Project Manager - Phoebus
Nuclear Rocket Operations

C. M. Rice
Program Manager
Nuclear Rocket Operations

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FOREWORD

This report is published in response to, and in partial fulfillment of, Item 4, Task I, Article I - Statement of Work of Contract SNPC-35, and Item 3, Task N, Article I - Statement of Work of Modification No. 1, Supplemental Agreement to Contract SNPC-35.

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TASK H - STE AND FACILITIES

1. Work Performed in June

The Hammel-Dahl flow-control-valve problem was resolved by a vendor modification and normal test preparations were resumed. Functional and sequence checks were completed and LO₂ pressurization and leak tests conducted. However, a further delay was encountered when the main GH₂ supply valve failed to close during an LH₂ pressurization test. Inspection of this 10-inch inline valve revealed that the actuator return-spring had taken a compressive set and would no longer function adequately. A new spring is being obtained from the vendor.

2. Work Planned for July

Repair of the GH₂ supply valve will be completed and film-cooled nozzle testing will begin.

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TASK I - REPORTS (CPFF)

1. Work Performed in June

Program-highlight TWX reports were transmitted weekly to SNPO-C (RP-TWX-0114 through RP-TWX-0118).

Ten copies of the Financial Management Report (NASA Form 533) for the CPFF portion of the contract were submitted 21 June to SNPO-C.

The Quarterly Report (RP-QR-0008) for the period 1 March through 31 May 1967 was submitted 28 June to SNPO-C and distributed as directed by the SNPO-C Technical Director.

2. Work Planned for July

Reports required by the work statement, as well as other reports required by the contract or requested by SNPO-C, will be submitted.

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TASK K - FABRICATION

1. Work Performed in June

a. Convectively Cooled Nozzle

S/N 880601 - Final cleaning was completed and the nozzle built-up into a test assembly less injector.

S/N 880604 - Final packaging was completed and the nozzle delivered to bonded stores.

S/N 880605 - The following operations were completed: end-cap welding; three furnace braze-cycles; removal of excess braze alloy; and installation of bolt coolant torus. Installation of the main fuel torus was initiated.

b. Adapter, S/N 880698

Adapter S/N 880698, damaged during Test No. 1.2-15-NNN-005, was successfully repaired.

Coolant-tube damage, which was most extensive within a 9- to 12-inch band extending forward from the core-support-flange interface, consisted of holes and roughened areas on the surface of the tubes caused by the splatter of molten metal from the eroded nozzle tubes (see Figure 1).

Tube surfaces which were to be repaired were first cleaned by wire brushing and then wiped with Freon solvent. Tube burn-through areas which were 1/8 inch in diameter or less were considered to be repairable by simple plug welds. Areas in excess of 1/8 inch in diameter were repaired by removing the damaged tube section and inserting a flush patch (see Figure 2).

Figure 1 - Adapter Leg and Adapter, Showing Coolant Tube Damage
From Molten Metal Splatter

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Figure 2 - Coolant Tube Cutout and Matching Flush Patches

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Patches to match the tube contour were fabricated from coolant tubes and welded in place with a plasma needle arc welder, specifically designed to weld thin materials and capable of maintaining a stable arc at settings from 1 to 10 amperes (see Figure 3). Practice welds were made on scrap tubes to develop a procedure and to establish amperage settings which would provide consistent penetration patterns.

Eleven flush patches and approximately 35 plug welds accomplished the repair (see Figure 4). All welds were blended flush with the tube surface.

A helium leak check at 100 psi revealed no leakage. A hydro-proof test at 1250 psig was subsequently accomplished successfully. The adapter was then delivered to the assembly shop for NTA buildup.

c. Nozzle Test Assembly

S/N 880003 (convectively cooled) - the assembly was built-up, using the repaired adapter and Convectively Cooled Nozzle S/N 880601, leak checked, and delivered to the test area less the injector.

2. Work Planned for July

a. Convectively Cooled Nozzle

S/N 880605 - installation of the main and bolt-coolant tori will be completed. Final machining of the interface control dimensions will be initiated.

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Figure 3 - Plasma Needle Arc Welder

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Figure 4 - Flush Patches and Plug Welds Prior to Blending

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TASK L - RELIABILITY AND QUALITY ASSURANCE

1. Work Performed in June

a. Nondestructive Testing

Nozzle S/N 880601 was X-rayed once again to assure tube and torus cleanliness between the throat and aft end. Fabrication of tooling for ultrasonic inspection of Nozzles S/N 880604 and 880605 was initiated.

2. Work Planned for July

Ultrasonic inspection of Nozzle S/N 880604 will begin.

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TASK M - TESTING

1. Work Performed in June

Test Request Supplements No. 1 and 2 for the film-cooled nozzle test series were released.

The Final Critical Experiment Review for Film-Cooled Nozzle Test Series 1.2-09-NNJ was held with representatives of SNPO, Phoebus engineering, NRO reliability and quality assurance, and test operations in attendance. Supplement No. 1 to the Test Request and the Film-Cooled Nozzle Test Assembly Addendum to the Modes of Failure Analysis were presented. The review board accepted the test procedures as presented.

2. Work Planned for July

The film-cooled nozzle test series for development testing of the coaxial injector will be conducted. The 75-second duration proof-test series of the convectively cooled nozzle will be initiated.

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TASK N - REPORTS (CPIF)

1. Work Performed in June

Program-highlight TWX reports were transmitted weekly to SNPO-C (RP-TWX-0114 through RP-TWX-0118).

Ten copies of the Financial Management Report (NASA Form 533) for the CPIF portion of the contract were submitted 21 June to SNPO-C. Three biweekly PERT reports were submitted to SNPO-C (RP-PR-0050 through RP-PR-0052).

The Quarterly Report (RP-QR-0008) for the period 1 March through 31 May 1967 was submitted 28 June to SNPO-C and distributed as directed by the SNPO-C Technical Director.

2. Worked Planned for July

Reports required by the work statement, as well as other reports required by the contract or requested by SNPO-C, will be submitted.

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REPORT NO. RP-TM-0015
TO
SPACE NUCLEAR PROPULSION OFFICE - CLEVELAND EXTENSION

NUCLEAR NOZZLE DESIGN REPORT (U)

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A handwritten signature in black ink, appearing to read 'R. L. Murray', with a long, sweeping horizontal stroke extending to the right.

R. L. Murray
Project Manager - Phoebus
Nuclear Rocket Operations

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ABSTRACT

This report provides design information concerning the Phoebus-2 nuclear nozzle. Design criteria and supporting documentation are provided in the areas of nuclear analysis, heat transfer, coolant flow, and nozzle shell structural analysis. A Basic Parts List is included. The LASL-AGC-ACFI four-part interface analysis is included as an appendix.

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I. INTRODUCTION

The Phoebus-2 nuclear nozzle is convectively cooled with 320 single-pass U-tubes. Hydrogen is fed to the channels (from a constant cross-section torus) through slots machined in the nozzle jacket. The hydrogen passes the entire length of nozzle and is discharged into the pressure vessel plenum. Figure 1 shows the nozzle.

The nozzle is a reactor development tool and is used to condition the hydrogen prior to entering the reactor and to control the flow and expansion of the hydrogen as it exits from the reactor. The nozzle is attached to the pressure vessel by 144 bolts to become an integral part of the reactor assembly.

Major nozzle components and their respective materials are: (1) nozzle jacket - Hastelloy X; (2) inlet and bolt coolant tori - Hastelloy X; (3) coolant channels and shims - nickel plated Hastelloy X; and (4) brazing material - gold base alloy.

II. TECHNICAL DISCUSSION

Nozzle design-criteria are presented in Table 1. NERVA nozzle design concepts were used, although deviations were made when design improvements could be achieved without sacrificing reliability. Hastelloy X was used throughout because of its improved strength-to-weight ratio over the temperature range predicted for the nuclear-nozzle application.

Material properties of Hastelloy X are discussed in Phoebus-2 Nozzle Materials Reports No. RP-DR-0001 thru 0004.

The nozzle U-tubes have individual end-caps welded directly to the nozzle jacket. The tubes have a constant wall-thickness of 0.012 inch $\pm$ 0.001 inch and are nickel plated to improve the brazing characteristics. The shims are Hastelloy X 0.008 inch $\pm$ 0.00025 inch in thickness and are also nickel plated.

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Figure 1 - Phoebus-2 Nuclear Nozzle

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TABLE 1

PHOEBUS-2 NOZZLE DESIGN CRITERIA

REQUIREMENTS:

Chamber Pressure	625 psia
Chamber Temperature	4500°R
Coolant Flow	245 lb/sec
Coolant Inlet Pressure	1240 psia
Coolant Inlet Temperature	57°R
Coolant Outlet Pressure	855 psia (Min)
Coolant Outlet Temperature	110/157°R (Min)
Operating Cycle	3 cycles of 30 min. duration at 100 power and cold flow and zero power.
Flow Symmetry	5% for any 15° sector

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The coolant inlet-torus (0.250 inch wall thickness) and the bolt coolant-torus (0.187 inch wall thickness) are constant cross-section tori to insure uniform flow distribution and to simplify fabrication. Flow symmetry flow-data is reported in Appendix B.

Coolant channels and shims are installed and brazed into the nozzle jacket employing procedures similar to NERVA nozzles. The resulting nozzle design has been analyzed for the following operating condition where: chamber pressure = 625 psia, chamber temperature = 4500°R, total gas flow = 285 lb/sec, total coolant flow = 250 lb/sec, coolant inlet pressure = 1251 psia, and coolant inlet temperature = 57°R. (Computer Job 8047, 13 April 1967).

Maximum predicted design gas-side wall temperature is 1588°F. Maximum coolant side-wall temperature is 852°F. The nozzle coolant pressure drop ΔP is 367 psia. Figure 2 shows coolant-velocity versus axial-distance. Figure 3 shows flow-area versus axial-distance. Figure 4 shows gas-side wall temperature versus axial-distance. Figure 5 shows coolant-side wall temperature versus axial-distance and Figure 6 shows coolant-pressure versus axial-distance.

1. $P_c = 625$
2. 320 TUBES
3. TUBE THICKNESS = .012 IN.

Figure 2 - Nozzle Coolant-Velocity Versus Axial-Distance

1. $P_c = 625$
2. 320 TUBES
3. TUBE THICKNESS = .012 IN.

Figure 3 - Nozzle Flow-Area Versus Axial-Distance

1. $P_c = 625$
2. 320 TUBES
3. TUBE WALL THICKNESS = .012 IN.

Figure 4 - Nozzle Gas-Side Wall Temperature Versus Axial-Distance

1. $P_c = 625$
2. 320 TUBES
3. TUBE WALL THICKNESS = .012 IN.

Figure 5 - Nozzle Coolant-Side Wall Temperature Versus Axial Temperature

1. $P_c = 625$
2. 320 TUBES
3. TUBE WALL THICKNESS = .012 IN.

Figure 6 - Nozzle Coolant-Pressure Versus Axial-Distance

III. APPENDICES

A. APPENDIX A

Phoebus-2 Pressure Vessel/Nozzle Interface Analysis

Part I - Load Analysis. Issued March 26, 1965, prepared by E. T. Kautt, AGC; J. L. Pickering, AGC; and C. W. Gay, ACF Industries.

Part II - Radiation Heating Calculations. Issued June 1, 1965, prepared by B. F. Williams and Martin Abrams, ACF Industries.

Part III - Heat Transfer Analysis. Issued July 7, 1966, prepared by E. A. Thomas, AGC.

Part IV - Stress Analysis. Issued July 15, 1965, prepared by J. W. Neudecker, Los Alamos Scientific Laboratory; C. W. Gay, D. N. Grimes, ACF Industries; E. T. Kautt and J. L. Pickering, AGC.

B. APPENDIX B

Flow Symmetry. Issued June 30, 1967, prepared by W. P. Pulliam, AGC.

C. APPENDIX C

Interface Control Drawing 43Y65194

D. APPENDIX D

Basic Parts List

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APPENDIX A

PRESSURE VESSEL/NOZZLE INTERFACE ANALYSIS

PART I - LOAD ANALYSIS

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PHOEBUS 2 PRESSURE VESSEL/NOZZLE
INTERFACE ANALYSIS *4/*

PART I - LOAD ANALYSIS

March 26, 1965
P2-65-6

REVISIONS		
Sym	Approved	Date
"A"	LASL	
	AGC	<i>Rev</i>
	ACF	
"B"	LASL <i>JWN</i>	2-1-66
	AGC	
	ACF <i>L. L.</i>	3-1-66
	LASL	
	AGC	
	ACF	

Prepared by: Phoebus 2 Task Force Group
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Rev. "B" 2-1-66

INTRODUCTION

This report presents the load analysis for the Phoebus-2 Pressure Vessel/Nozzle Interface Analysis. In the original version of the report two basic interface configurations, "Flat" and "Canted", were considered. Further study rejected the "Canted" configuration and selected the "Flat" configuration. The loads calculated in this report are based upon Revision "C" of the Phoebus 2 Interface Hydrodynamic State Diagram. The principal reasons for the necessity of this Revision "B" of the loads analysis are:

- a. The spring preload on the nozzle core support skirt has been eliminated.
- b. The flow separator pressure drop load is now carried by the dome of the pressure vessel rather than the nozzle core support skirt.

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NOMENCLATURE

PRESSURES (See Figure 1)

- P_a - Ambient Pressure (Atmospheric)
- P_1 - Nozzle Inlet
- P_2 - Reflector Inlet Plenum
- P_3 - Reflector Outlet
- P_4 - Core Inlet
- P_5 - Nozzle Chamber

FORCES (See Figure 1)

- F_{total} - Total Ejection Force at Bolt Q
- F_n - Ejection Force Due To Nozzle Chamber Pressure
- F_c - Ejection Force On Core Support
- F_p - Ejection Force Due to P_2
- F_s - *Pressure, core to nozzle support skirt*
- F_t - *Thrust load*

RADII (See Figure 1)

- R_{bc} - Bolt Circle Radius (At Which F_{total} Acts)
- R_n - Radius At Which F_n Acts
- R_c - Radius At Which F_c Acts (Also Core Seal Rad.)
- R_v - Radius To Pressure Vessel Wall
- R_s - Radius of Flange Seal

OPERATING CONDITIONS

- NSS - Nuclear Steady State
- CS - Chemical Simulation, Rated Power
- CSMSD - Chemical Simulation, Margin of Safety Demonstration
- HYDRO - Hydro Test
- PVPR - Pressure Vessel Proof Test
- TRAN - Reactor Startup Transient

CONFIGURATIONS

- Configuration 1 - Flat Type Flange
- Configuration 2 - Canted Flange

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CONDITIONS

The conditions considered and for which loads are presented in this report are as follows:

<u>Code</u>	<u>Description</u>
NSS	Full-Power Reactor Operating Condition (Nuclear Steady State). Figure 1, page 9, shows the flow rates, temperatures, and pressure distributions throughout the reactor for this condition.
HYDRO	Hydrostatic Test Condition. This condition is a test condition for verification of the structural analysis at the interface area. This test will also verify the structural compatibility between the pressure vessel and nozzle.
CS	Chemical Simulation. This is a nozzle test condition for chemical firing of the nozzle in simulation of coolant tube heat transfer behavior during reactor operation.
CSMSD	Chemical Simulation, Margin of Safety Demonstration. This is an overload chemical firing nozzle test condition for determination of coolant tube margins of safety of structural and heat transfer calculations.
PVPR	Pressure Vessel Proof Test. This is a hydrostatic pressure proof test to verify the structural integrity of each pressure vessel.

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<u>Code</u>	<u>Description</u>
PVPR (Con't.)	produced. The pressures for this condition have not been determined at the time of writing of this loads report. The loads induced by this condition will be analyzed in an appendix to this report which will be published at a later date.
TRAN	Reactor Transient Condition. This is the condition occurring during startup or shutdown of the reactor. The pressures, flow rates, and temperatures encountered during this condition had not been defined at the time this report was prepared. The load analysis for this condition will be added as an appendix at a later date.

Ambient temperature for all calculations is assumed to be 70°F. (530°R.).

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SUMMARY OF RESULTS

The summary of results is tabulated in Table 1, page 8, for all conditions except PVPR and TRAN which will be shown by appendices to this report. The load calculations are based upon the revised pressure distributions as shown on the Phoebus-2 Interface Hydrodynamic State Diagram, Revision "C" dated February 1, 1966, included herewith as page 9.

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TABLE 1
SUMMARY OF RESULTS

Configuration	Flat			
Load/Condition →	FSS	CS	CSMSD	HYDRO
P_a - psia	12.7	14.7	14.7	12.7
P_1 - psia	1240	1240	1240	855
P_2 - psia	855	1000	1000	855
P_3 - psia	795	----	----	855
P_4 - psia	775	----	----	855
P_5 - psia	625	750	900	625
F_n - lb.	1,511,608	1,615,202	2,165,573	----
F_c - lb.	354,019	0	0	354,019 *
F_p - lb.	406,450	475,309	475,309	----
F_{total} - lb.	2,232,077	2,293,571	2,660,882	2,232,100

$$R_{EC} = 32.00 \text{ in.}$$

$$R_V = 39.68 \text{ in.}$$

$$R_N = 30.45 \text{ in.}$$

$$R_s = 32.875 \text{ in.}$$

$$R_c = 30.45 \text{ in.}$$

* Both core load relief and thrust relief are provided,
see page 22.

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B₀ REFLECTOR LENGTH = 59.0 INCHES
 B₀ REFLECTOR O.D. = 78.36 INCHES
 B₀ REFLECTOR I.D. = 62.35 INCHES
 INTERFACE CYLINDER I.D. = 57.71 INCHES
 SLAT O.D. = 54.86 INCHES
 FUELED REGION DIA = 54.75 INCHES
 FUEL ELEMENT LENGTH = 53.375 INCHES
 SUPPORT BLOCK THICKNESS = 1.50 INCHES

PHOEBUS 2A STATE POINT SCHEMATIC

THIS DRAWING NOT TO SCALE
 DIMENSIONS ARE APPROXIMATE

LOS ALAMOS SCIENTIFIC LABORATORY

Refer to Page 9A for latest correct state point values.

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Major Performance Parameters

Reactor Power	5026 mw
Reactor Flow Rate	285 lb/sec
Station 20 Control Temperature	2960°R
Fuel Element Exit Gas Temperature	4543°R
Nozzle Chamber Temperature	4500°R

Plenum Conditions

	Temperature °R	Pressure psia	$\dot{w}$
Nozzle Inlet	57	1209	245
Reflector System Inlet	146	869	255
Reflector System Exit	204	809	255
Flow Separator Exit	204	789	255
Ave. Tie Tube Inlet Manifold	58	1050	30
Ave. Tie Tube Exit	516	789	30
Ave. Support Plate Inlet	236	789	285
Core Inlet	246	774	285
Core Exit	4543	625	281
Slat Exit	1200	625	2.0
Cavity Exit	450	625	2.0
Periphery Mixed Mean	821	625	4.0
Nozzle Chamber	4500	625	285

Reactor Component Pressure Drops

Core	149 psid
Flow Separator	20 psid
Reflector System	60 psid
Tie Tubes	261 psid
Nozzle Coolant Tubes	340 psid

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FIG. 2
PRESSURE DISTRIBUTIONS
NUCLEAR STEADY STATE
PHOEBUS NOZZLE
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CALCULATIONS

The following is a guide to the load calculations presented in this report:

<u>Section</u>	<u>Condition</u>	<u>Calculation</u>	<u>By:</u>
I	NSS	Core Load on Nozzle, F_c	C. Gay, ACFI
II	NSS	Pressure Load, F_p	C. Gay, ACFI
III	NSS	Nozzle Ejection Load, F_n	E. Kautt, AGC
IV	NSS	Total Ejection Force, F_{total}	J. Neudecker, LASL
V	CS, CSMSD	Nozzle Ejection Load, F_n	E. Kautt, AGC
VI	CS, CSMSD	Core Load, F_c ; Pressure Load, F_p	E. Kautt, AGC
VII	CS, CSMSD	Total Ejection Force, F_{total}	E. Kautt, AGC
VIII	HYDRO	Loads F_c and F_{total}	C. Gay, ACFI

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I. Core Load on Nozzle, F_c (Ref. Figure 1)

The core load, F_c , for condition HSS is composed of two basic components:

- 1 Pressure drop thru core, acting aft:

$$\Delta P = P_4 - P_5; \text{ acting on area } \pi r_c^2$$

- 2 Pressure drop thru reflector, acting forward:

$$\Delta P = P_2 - P_3; \text{ acting on area } \pi (r_v^2 - r_c^2)$$

In addition to these two components a preload is induced by a series of 18 bolts extending through the center of some of the regular interface bolts. The value of this preload is 40,000 lbs. This load replaces the preload formerly imposed by springs.

Note that the flow separator pressure drop, $\Delta P = P_3 - P_4$, is carried by the pressure vessel dome, hence does not contribute to core load, F_c .

$$P_s = 40,000 \text{ lbs (now bolts instead of springs)}$$

$$P_2 = 855 \text{ psia}$$

$$P_3 = 795 \text{ psia}$$

$$P_4 = 775 \text{ psia}$$

$$P_5 = 625 \text{ psia}$$

$$P_a = 12.7 \text{ psia (ambient pressure)}$$

$$r_c = 30.45" \text{ (core support seal radius)}$$

$$r_v = 39.74" \text{ (inside radius of pressure vessel)}$$

$$\begin{aligned} F_c &= P_s + (P_4 - P_5) \pi r_c^2 - (P_2 - P_3) \pi (r_v^2 - r_c^2) \\ &= 40,000 + 150 \pi (27.2 - 652.1) \\ &= 40,000 + 436,935 - 122,916 \end{aligned}$$

$$F_c = 354,019 \text{ lbs.}$$

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II PRESSURE LOAD ON NOZZLE, F_p (REF. FIG[#] 1)

THIS IS THE ANNULAR PRESSURE LOAD ON THE NOZZLE DUE TO THE REFLECTOR INLET PLENUM PRESSURE.

$$r_s = 32.875 \text{ IN.}$$

$$r_c = 30.45 \text{ IN.}$$

$$P_2 = 855 \text{ PSIA}$$

$$P_a = 12.7 \text{ PSIA}$$

$$\begin{aligned} F_p &= (r_s^2 - r_c^2) \pi (P_2 - P_a) \\ &= [(32.875)^2 - (30.45)^2] \pi (855 - 12.7) \\ &= 153.6 \pi 842.3 \end{aligned}$$

$$F_p = \underline{406450 \text{ LBS}}$$

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III NOZZLE EJECTION LOAD - F_n
CONDITION NSS $P_a = 12.7$ PSI

THE NOZZLE CHAMBER PRESSURE (P_5) IS SEPARATED FROM THE PRESSURE VESSEL PLENUM PRESSURE (P_2) BY A SEAL AT THE FORWARD END OF THE NOZZLE SKIRT AT A RADIUS OF 30.45". THE PRESSURE IS A CONSTANT 625 PSIA FROM THE REACTOR OUTLET TO POINT "A" (REF. FIG.) & IS ASSUMED TO VARY LINEARLY TO 568 PSIA AT POINT "B". AN AVERAGE PRESSURE OF $(568 + 340)/2 = 454$ PSIA IS CONSIDERED TO ACT ON THE ANNULUS BETWEEN POINT "B" & THE THROAT &. THE PRESSURE ACTING IN THE EXIT CONE RELIEVES F_n .

THE TOTAL EJECTION LOAD ACTING AT POINT "A" IS:

$$F_n = \oint P dA \quad \text{WHERE } dA = R dR d\theta$$

USING THE GEOMETRY OF FIGURE - , THE RADIUS CAN BE REPRESENTED BETWEEN POINTS "A" & "B" BY:

$$R = 1.88 - X$$

AND THE PRESSURE BY:

$$P = 529.17 - 2.9097X \quad \text{WHERE } P = \text{PSIA} - P_a = \text{PSIG}$$

THEN:

$$\begin{aligned} F_{N(A-B)} &= \int_0^{2\pi} \int_{-8.48}^{-28.57} (529.17 - 2.9097X)(X - 1.88) dX d\theta \\ &= \underline{\underline{1,495,753 \text{ *}}} \end{aligned}$$

THE LOAD BETWEEN POINTS "B" & "C" IS

$$\begin{aligned} F_{N(B-C)} &= \pi (R_B^2 - R_C^2) P_{A-B} = \pi [(10.60)^2 - (8.456)^2] (454 - 12.7) \\ &= \underline{\underline{59002 \text{ *}}} \end{aligned}$$

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FIGURE 3

BY E.T.K. DATE
CHKD. BY DATE

SUBJECT: LOAD ANALYSIS
NOZZLE GEOMETRY

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III (CONT)

THE EFFECT OF THE PRESSURE IN THE EXIT CONE IS TO ADD THRUST, THUS RELIEVING THE EJECTION LOAD AT THE NOZZLE - PRESSURE VESSEL JOINT.

THE NOZZLE EXIT CONE HAS A HALF ANGLE OF $17^{\circ}30'$. THE RADIUS AT THE EXIT PLANE IS 22.3725 (INSIDE). THE EQUATION:

$$R = .3153X + 8.337$$

CAN REPRESENT THE INTERIOR SURFACE OF THE EXIT CONE WHERE $X = 0$ AT THE THROAT. THIS RESULTS IN A NEGLIGIBLE ERROR OF $8.456 - 8.337 = .019$ " FOR THE THROAT RADIUS.

FOR A NOZZLE CHAMBER PRESSURE OF 625 PSIA, THE FOLLOWING EXIT CONE PRESSURES WERE OBTAINED FROM AGC SACRAMENTO.

X	PRESSURE (PSIA)	PRESSURE (PSIG)
0	340	327.3
5.18	125	112.3
11.68	62.5	49.8
20.55	31.3	18.6
27.00	20.8	8.1
36.51	12.5	-.2
45.42	8.3	-4.4

ASSUMING A LINEAR PRESSURE DROP BETWEEN VALUES OF X, THESE CAN BE EXPRESSED IN TERMS OF X AS:

FROM X =	TO X =	
0	5.18	$P = 327.3 - 41.506X$
5.18	11.68	$P = 162.106 - 9.615X$
11.68	20.55	$P = 90.879 - 3.517X$
20.55	27.00	$P = 52.055 - 1.628X$
27.00	36.51	$P = 31.671 - .873X$
36.51	44.51	$P = 18.968 - .525X$

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III (CONT.)

THE TOTAL FORCE W , DUE TO THE EXIT CONE PRESSURE IS:

$$F_{N(c-d)} = - \oint P dA$$

WHERE: $dA = R dR d\theta$, $P = f(x)$

$$R = .3153x + 8.337$$

$$dR = .3153 dx$$

$$dA = (.099414x + 2.628651) dx d\theta$$

$$F_{N(c-d)} = - \int_0^{2\pi} \int_{x_1}^{x_2} (.099414x + 2.628651) P dx d\theta$$

$$= -2\pi \sum_{n=1}^n \int_{x_{n-1}}^{x_n} (.099414x + 2.628651) P dx$$

FROM THE EQUATIONS FOR P , $F_{N(c-d)}$ IS CALCULATED AS:

$x =$	$TO x =$	$\Delta F_N / 2\pi$	$\Delta F_N =$
0	5.18	$-\int_0^{5.18} (860.357 - 76.565x - 4.1265x^2) dx$	-20647
5.18	11.68	$-\int_{5.18}^{11.68} (426.120 - 9.158x - .9559x^2) dx$	-11345
11.68	20.55	$-\int_{11.68}^{20.55} (238.889 - .210x - .3497x^2) dx$	-7935
20.55	27.00	$-\int_{20.55}^{27.00} (136.834 + .896x - .1619x^2) dx$	-2675
27.00	36.51	$-\int_{27.00}^{36.51} (83.252 + .853x - .0868x^2) dx$	-1330
36.51	44.51	$-\int_{36.51}^{44.51} (49.860 + .505x - .0522x^2) dx$	+785

$$F_{N(c-d)} = -43147$$

$$F_N = F_{N(A-B)} + F_{N(B-C)} + F_{N(C-D)}$$

$$= 1,495,753 + 59,002 - 43,147$$

$$\underline{\underline{F_N = 1,511,608 \#}}$$

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IV. Operating Condition, NSS

Calculation of Total Ejection Force, F_{total}

$$F_{total} = F_c + F_p + F_n - P_s \text{ (See Figure 1)}$$

For Condition NSS,

$$F_c = 354,019 \text{ lbs}$$

$$F_n = 1,511,603 \text{ lbs}$$

$$\text{"Flat" Configuration } F_p = 406,450 \text{ lbs}$$

Therefore:

$$\begin{aligned} \text{"Flat" Configuration } F_{total} &= 354,019 + 406,450 + 1,511,603 - 40,000 \\ &= 2,232,077 \text{ lbs.} \end{aligned}$$

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V NOZZLE EJECTION LOAD, F_N FOR CS & CSMSD
THE VALUE OF $F_N = 1,511,608^{\#}$ IS FOR NUCLEAR STEADY-STATE (COND NSS) OPERATING CONDITIONS. TWO OTHER CONDITIONS ARE CONSIDERED, CHEMICAL SIMULATION FIRING (COND. CS) AT RATED POWER, AND FOR MARGIN OF SAFETY DEMONSTRATION (COND. CSMSD).

THESE TWO CONDITIONS ARE TESTED AT SEA LEVEL, WHERE $P_a = 14.7$ PSI

THE NOZZLE CHAMBER PRESSURES ARE

CS - 750 PSIA = 735.3 PSIG
CSMSD - 900 PSIA 885.3 PSIG

ASSUMING THE PRESSURE DISTRIBUTION IN THE NOZZLE IS INDEPENDENT OF PRESSURE, THE VALUES OF F_N FOR THESE CONDITIONS WILL BE THAT FOR CONDITION NSS MULTIPLIED BY THE PRESSURE RATIOS.

CONDITION CS

$$F_N = 1,511,608 \times \frac{735.3}{612.3} = 1,815,262^{\#}$$

CONDITION CSMSD

$$F_N = 1,511,608 \times \frac{885.3}{612.3} = 2,185,573^{\#}$$

VI CORE LOAD F_c AND PRESSURE LOAD F_p FOR CONDITIONS CS AND CS13D

During chemical simulation firings, the core load F_c will be zero since the core and reflector are not used.

Condition CS

Flat Flame $F_c = 0$

$$F_p = \pi (R_s^2 - R_c^2) (P_2 - P_a)$$

$$R_s = 32.875''$$

$$R_c = 30.45''$$

$$P_2 = 1000 \text{ psia}$$

$$P_a = 14.7 \text{ psi}$$

$$F_p = \pi \left[(32.875)^2 - (30.45)^2 \right] \left[1000 - 14.7 \right]$$

$$\underline{\underline{F_p = 475,309 \#}}$$

Condition CS13D

During chemical simulation, the coolant and propellant circuits are independent, the plenum pressure, P_2 , will be maintained at 1000 psia. Therefore F_p will have the same value as for cond. CS.

VII TOTAL EJECTION FORCE, F_{TOTAL}

OPERATING CONDITIONS CS AND CSMSD

Calculation of total ejection force, F_{total}

$$F_{\text{total}} = F_c + F_p + F_n$$

Condition CS

$$F_c = 0 \qquad F_n = 1,815,262 \#$$

$$F_p = 475,309 \frac{\#}{\text{sec}} \text{ "FLAT" configuration}$$

$$\begin{aligned} F_{\text{total}} &= 0 + 1,815,262 + 475,309 \\ &= \underline{\underline{2,293,571 \frac{\#}{\text{sec}}}} \text{ "FLAT" configuration} \end{aligned}$$

Condition CSMSD

$$F_c = 0 \qquad F_n = 2,185,573 \frac{\#}{\text{sec}}$$

$$F_p = 475,309 \frac{\#}{\text{sec}} \text{ "FLAT"}$$

$$\begin{aligned} F_{\text{total}} &= 0 + 2,185,573 + 475,309 \\ &= \underline{\underline{2,660,882 \frac{\#}{\text{sec}}}} \text{ "FLAT"} \end{aligned}$$

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VIII. Calculation of Hyper Test Loads

The values of F_T (thrust load) and F_R (relieving load) will be calculated to produce load on core support skirt and load on nozzle attach bolts equal to loads for NSS condition as shown in loads report document.

Core load, $F_c = 354,019$ lbs

Bolt load, $F_{total} = 2,232,077$ lbs (see page 18)

NOTE: Auxiliary bolts contribute 40,000 lbs preload of F_c , hence

$$\begin{aligned} F_c &= 354,019 = 40,000 + \pi r_c^2 (P_2 - P_s) - F_R \\ &= 40,000 + \pi (30.45)^2 (855-625) - F_R \\ &= 40,000 + \pi (927.2)(230) - F_R \\ &= 40,000 + 669,965 - F_R \end{aligned}$$

$$\therefore F_R = 40,000 + 669,965 - 354,019 = 355,946 \approx \underline{356,000} \text{ lbs.}$$

$$F_{total} = \pi r_s^2 (P_2 - P_s) - F_R - F_T$$

$$F_{total} = 2,232,077 = \pi (32.875)^2 (855-12.7) - 355,946 - F_T$$

$$2,232,077 = \pi (1080.8)(842.3) - 355,946 - F_T$$

$$2,232,077 = 2,860,013 - 355,946 - F_T$$

$$\therefore F_T = 2,860,013 - 2,232,077 - 355,946 = 271,990 \approx \underline{272,000} \text{ lbs.}$$

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APPENDIX A

PRESSURE VESSEL/NOZZLE INTERFACE ANALYSIS

PART II - RADIATION HEATING CALCULATIONS

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PHOEBUS-2

PRESSURE VESSEL/NOZZLE

INTERFACE ANALYSIS (u)

PART II

RADIATION HEATING CALCULATIONS

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17 December 1965

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ABSTRACT

This addendum report provides updated nuclear heating rates for the final design configuration of the Phoebus-2 Pressure Vessel/Nozzle Interface Assembly. The heating rates provided in this addendum reflect the latest changes in configuration as well as improvements in source terms for both the primary and secondary gamma rays.

The QAD-P5 code was used to determine the heating rate contributions from primary and secondary gamma rays as well as from fast neutron scattering. The source terms for non-core secondary gamma rays were obtained from TDC neutron transport calculations.

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LIST OF FIGURES

<u>FIGURE NO.</u>	<u>TITLE</u>
1	Phoebus-2, Phase I Reference Design Nozzle
2	Phoebus-2, Phase II Reference Design Nozzle
3	Primary Gamma Source Axial Distribution
4	Nozzle Secondary Gamma Source Distribution
5	Interface Cylinder Secondary Source Axial Distribution
6	Interface Cylinder Secondary Gamma Source Radial Distribution
7	Detector Locations in Table II
8	Detector Locations in Table III

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LIST OF TABLES

<u>TABLE NO.</u>	<u>TITLE</u>
I	Radiation Source Spectra
II	Total Radiation Heating in the Reference Design Nozzle (AGC Detector Locations)
II-A	Total Radiation Heating in the Aluminum Pressure Vessel (AGC Detector Locations)
III	Total Radiation Heating in the Reference Design Nozzle (ACFI Detector Locations)

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I. INTRODUCTION

This addendum report provides nuclear heating rate data for use in temperature and stress analysis on the final design configuration of the Phoebus-2 pressure vessel/nozzle interface assembly. The original data are contained in Reference 1. In addition to configuration changes, these data reflect both a 16 percent increase in primary gamma source strength and inclusion of heating rate contributions from secondary gamma rays. Moreover, these data are based on 12-group calculations whereas the earlier work used a 9-group representation.

At a meeting held in Los Alamos (References 3 and 4) AGC agreed to provide nuclear heating data for use in temperature and stress analyses on the final design configuration. The analysis methods, models, and source terms used are given in this addendum along with the heating rate results at nominal values and at 25% above nominal values.

Nuclear heating analyses in support of the Phoebus-2 nozzle and pressure vessel design activities were performed by both AGC and ACFI. The preliminary nuclear heating analysis previously used by the Interface Task Force Group was principally an ACFI activity (Reference 1). The Phase I nuclear heating analysis performed by AGC is reported in Reference 2 as summarized below.

A. SUMMARY OF PHASE I RADIATION HEATING ACTIVITY

The Phase I portion of the Phoebus-2 nozzle design study by AGC included calculation of the nuclear heating rates in both the nozzle and pressure vessel for use in temperature and stress analyses. In the course of this design study, a number of candidate configurations were considered. These include a flat-flange model with a 45° nozzle jacket and with both 0.4" and 0.6" skirt thicknesses; a canted flange model with 45° nozzle jacket and 0.6" skirt; and a series of flat flange models with 0.6" skirts having nozzle jacket angles of 30°, 35°, and 40°. The heating rates due to primary gammas for these configurations are reported in Reference 2. - 1 -

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The flat flange, 45° nozzle jacket model with a 0.4" skirt, as shown in Figure 1, was the selected reference design for the Phase I study. This figure was drawn by a computer program using the input coefficients for the QAD program. For this configuration the contributions to nuclear heating due to nozzle secondaries, non-core reactor secondaries, clamshell secondaries, and fast neutrons were calculated and combined with the primary gamma heating rate to obtain the total nuclear heating rate. A detailed discussion of this activity and a tabulation of results are reported in Reference 2.

B. DEVELOPMENTS SINCE THE PHASE I STUDY

On the basis of the results from the Phase I study, the flat flange, 45° nozzle model but with the 0.6" skirt thickness (see Figure 2) was selected as the Phase II Reference design model. As noted above, only the primary gamma heating rates had been calculated for this model during the Phase I effort.

Also, since the end of the Phase I study, the primary gamma source power has been reported to be 86 megawatts per 1000 megawatts of reactor power (Reference 3). This corresponds to the gamma yield, including fission product decay gammas, after about 6 minutes of reactor operation at constant power. This new value represents a primary gamma source 6% greater than that used by AGC and 16% greater than that used by ACFI during the Phase I study.

The nozzle secondary gamma source terms used by AGC in the Phase I study were based on absorption of the unperturbed neutron flux. Further studies during Phase II with the TDC transport code, using a discrete representation of the nozzle, established the fact that the Phase I nozzle secondary gamma source terms were excessive and should be reduced by 50%.

A meeting was held between AGC and LASL personnel during Phase II for discussion of Phoebus-2 radiation heating calculations performed during Phase I (References 4 and 5). The preliminary radiation heating rates used by the Interface Task Force Group during Phase I was found to be low by as much as

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25 to 35 percent depending on location. Moreover, these rates were restricted to primary gamma sources only. It was decided that new radiation heating rates should be calculated at the detector locations used by ACFI (Reference 1) and at the detector locations used by AGC (Reference 2). Both of these sets of calculations would be performed by AGC, using the best current inputs, including the current reference nozzle configuration. With respect to the AGC Phase I calculations (Reference 2) this would include increasing the primary gamma source strength by 6% and decreasing the nozzle secondary source strength by 50%. These new total heating rates, as calculated and as increased by 25%, would then be used in temperature and thermal stress calculations to represent both the nominal and the "worst case" conditions.

Subsequent to this meeting with LASL personnel, the QAD mathematical model was compared with the current nozzle layout drawing and found to agree well in all significant details.

II. ANALYSIS

A. COMPUTER PROGRAMS

The TDC neutron transport computer program was used in determining the secondary source strength and its relative spatial distributions. The QAD-P5 point kernel radiation analysis program was used in computing the nuclear heating rates just as in the Phase I study (Reference 2).

B. ANALYTICAL MODEL

The current reference design of the nozzle differs from that used in the Phase I study principally in that the skirt thickness has been increased from 0.4" to 0.6". This model is shown in Figure 2 as drawn by the GECOP computer program (Reference 7). The QAD geometrical description is included as Appendix A to this document.

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C. SOURCE TERMS

The primary gamma source terms used are given in Table I (increased by the 6% discussed earlier). The primary gamma source distribution is unchanged from that used in the Phase I study. The axial distribution used is given in Figure 3 while the radial and azimuthal distributions were assumed to be flat. It is assumed that the 6% change in source strength results in negligible changes in its relative energy distribution.

The nozzle secondary source spectrum is included in Table I. This spectrum was obtained using the TDC transport code to determine the neutron absorption rates and distributions and by using the gamma yield per absorption from Reference 6. The secondary source spatial distribution, as shown in Figure 4, was input to QAD-P5 using the point source option.

The interface cylinder secondary gamma spatial distribution and spectrum were obtained in the same manner as the nozzle secondaries: i.e., using the TDC transport code and the data from Reference 6. The source terms are included in Table I and the axial and radial source distributions are given in Figures 5 and 6.

The fast neutron heating rates were obtained with the QAD-P5 program using moments method data. A more accurate value could be obtained with the use of the neutron transport code; but since the fast neutron contribute only about 1% to 5% of the total heating rate, use of a more complex routine could not be justified.

These represent all the secondary sources considered in heating rates calculated for the AGF detector locations. It was possible, for the AGC detector locations, to use heating rate data obtained during the Phase I study with suitable adjustments. This, in effect, considered several additional but small sources of nuclear heating such as the clamshell secondaries and other minor secondaries from non-core components of the reactor.

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TABLE I

Radiation Source Spectra

<u>Group No.</u>	<u>Group Energy Range (Mev)</u>	<u>Source Terms (Mev/sec)</u>		
		<u>Primary *</u>	<u>Nozzle Sec.</u>	<u>Interface Cyl. Sec.</u>
1	7.0 - 8.0	7.807×10^8	3.614×10^{18}	2.567×10^{19}
2	6.0 - 7.0	4.516×10^9	1.078×10^{18}	6.265×10^{18}
3	5.0 - 6.0	8.385×10^9	1.078×10^{18}	6.265×10^{18}
4	4.0 - 5.0	2.272×10^{10}	1.649×10^{18}	1.532×10^{19}
5	3.0 - 4.0	4.876×10^{10}	1.649×10^{18}	1.532×10^{19}
6.	2.6 - 3.0	2.83×10^{10}	9.254×10^{17}	5.172×10^{17}
7	2.2 - 2.6	3.795×10^{10}	9.254×10^{17}	5.172×10^{17}
8	1.8 - 2.2	4.83×10^{10}	1.218×10^{18}	5.172×10^{17}
9	1.35 - 1.8	6.678×10^{10}	1.7×10^{18}	5.818×10^{17}
10	0.9 - 1.35	9.13×10^{10}	1.48×10^{18}	4.526×10^{17}
11	0.4 - 0.9	1.217×10^{11}	8.225×10^{16}	0.0
12	0.26 - 0.4	5.68×10^{10}	2.205×10^{17}	0.0

* Units for this column are Mev/sec at power level of one watt. The QAD input for power must then be set equal to the reactor power in watts.

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D. DETECTOR LOCATIONS

The detector locations used are unchanged from Figure 6, Reference 1 and from Table 12, Reference 2. The Figure 6, Reference 1, data were originally calculated by ACFT and the Table 12, Reference 2, data by AGC during the Phase I study. The calculations reported herein use both of these sets of detector locations. The detector locations are given with the data in Table II and II-A. They are shown in Figure 7, for the detectors originally specified in Table 12, Reference 2; and in Table II and Figure 8 for the detectors initially designated in Figure 6, Reference 1.

E. CALCULATIONS

The basic heating rate calculations for the Phase II reference model existed in the Phase I report for those detector locations in Table II, i.e., in the nozzle itself. Thus, to obtain the updated heating rates at these locations, the primary gamma heating rates from Table 12, Reference 2, were increased by 6%. These were then combined with the heating rates due to the nozzle secondaries as decreased by 50%, the non-core reactor secondaries, the fast neutrons and the clamshell secondaries as obtained from Table 12, Reference 2.

The heating rates for those detectors in Table 12, Reference 2, located in the aluminum pressure vessel were obtained by calculating new data for interface cylinder secondaries and the nozzle secondaries. These heating rates were then combined with the fast neutron heating rates from the original QAD calculations and with the primary heating rates from Table 12 as increased by 6%. The total values are given in Table II-A.

The heating rates for the detector locations from Figure 6, Reference 1, were all new data calculated for this effort. The heating due to nozzle secondaries, interface cylinder secondaries, and fast neutrons was considered in addition to the primary heating rates.

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III. RESULTS

A. HEATING RATE TABLES

The heating rates at those detector locations used in Table 12, Reference 2, are given in detail in Table II. Because these numbers were obtained in two different ways, they are separated with the heating rates at the detector locations in the nozzle being in the main body of the Table and the heating rates at detector locations in the aluminum pressure vessel contained in its supplement, Table II-A.

The new heating rates of those detector locations from Figure 6, Reference 1, are given in Table III.

B. RESIDUAL DIFFERENCES IN TABULATED DATA

The total heating rates in Table II include several small sources of secondary gammas not included in Table II-A and in Table III. The contributions from these sources are generally negligible with respect to the total heating rate. The clamshell secondaries, for example, contribute about 0.2% at most nozzle locations. This contribution increases to 6% in out-board locations of the nozzle in the vicinity of detector 35 and 43 and where the total heating rate is relatively low.

The non-core reactor secondaries, additional to the interface cylinder secondaries, are the unfueled core tip secondaries, the graphite cookie secondaries, and the reflector secondaries. These contribute about 0.5% to the total nozzle heating with extreme values in the range of 1%.

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TABLE II

Total Radiation Heating in the Reference Design Nozzle
(AGC Detector Locations)

(Flat Flange, 0.6 in. Skirt, 45° Nozzle)*

<u>Detector Number</u>	<u>Detector R (in.)</u>	<u>Location Z (in.)</u>	<u>Nominal Heating Rate (Btu/in³-sec)</u>	<u>1.25 x Nominal Heating Rate (Btu/in³-sec)</u>
1	30.0	15.0	0.6659	0.8323
2	30.18	15.0	0.5976	0.7470
3	30.45	15.0	0.5385	0.6731
4	30.0	12.0	0.6826	0.8532
5	30.18	12.0	0.5425	0.6781
6	30.45	12.0	0.3958	0.4948
7	30.0	9.0	0.6031	0.7538
8	30.18	9.0	0.4744	0.5930
9	30.45	9.0	0.3434	0.4293
10	30.0	6.0	0.5812	0.7265
11	30.18	6.0	0.4577	0.5721
12	30.45	6.0	0.3319	0.4148
13	30.0	3.0	0.5658	0.7073
14	30.18	3.0	0.4428	0.5535
15	30.45	3.0	0.3209	0.4011
16	30.0	0.0	0.4425	0.5531
17	30.18	0.0	0.3984	0.4980
18**	30.45	0.0	0.2886	0.3608
30	31.15	-0.01	0.2393	0.2991
31	31.70	-0.01	0.1894	0.2367
32	32.37	-0.01	0.1619	0.2023
33	33.0	-0.01	0.1468	0.1835
34	33.62	-0.01	0.1336	0.1670
35	34.05	-0.01	0.1136	0.1420
36	34.45	-0.01	0.1084	0.1355

*These detector locations were initially specified in Table 12, Reference 2.

**Detectors 19 thru 29 are located in the aluminum pressure vessel and are included in Table II-A

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TABLE II (Contd)

<u>Detector Number</u>	<u>Detector R (in.)</u>	<u>Location Z (in.)</u>	<u>Nominal Heating Rate (Btu/in³-sec)</u>	<u>1.25 x Nominal Heating Rate (Btu/in³-sec)</u>
37	30.6	-0.62	0.2365	0.2956
38	31.15	-0.62	0.1596	0.1995
39	31.70	-0.62	0.1205	0.1506
40	32.37	-0.62	0.0957	0.1196
41	32.96	-0.62	0.0854	0.1067
42	33.62	-0.62	0.0771	0.0963
43	34.05	-0.62	0.0715	0.0894
44	34.45	-0.62	0.0665	0.0831
45	29.6	-1.18	0.5587	0.6984
46	30.0	-1.25	0.3544	0.4430
47	30.5	-1.30	0.1969	0.2461
48	31.1	-1.28	0.1119	0.1399
49	31.7	-1.25	0.0823	0.1028
50	32.37	-1.18	0.0651	0.0814
51	32.95	-1.13	0.0585	0.0731
52	33.5	-1.10	0.0553	0.0691
53	29.4	-1.65	0.5685	0.7231
54	29.75	-1.78	0.3878	0.4848
55	30.18	-1.95	0.2341	0.2926
56	30.65	-1.95	0.1458	0.1823
57	29.15	-2.12	0.5914	0.7393
58	29.45	-2.35	0.3665	0.4581
59	29.75	-2.60	0.2708	0.3385
60	29.95	-2.72	0.2171	0.2713
61	28.8	-2.78	0.5757	0.7196
62	29.0	-3.0	0.4254	0.5317
63	29.3	-3.28	0.2886	0.3608
64	26.6	-5.0	0.6680	0.8350
65	26.83	-5.2	0.4787	0.5983

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TABLE II (Contd)

<u>Detector Number</u>	<u>Detector R (in.)</u>	<u>Location Z (in.)</u>	<u>Nominal Heating Rate (Btu/in³-sec)</u>	<u>1.25 x Nominal Heating Rate (Btu/in³-sec)</u>
66	27.15	- 5.5	0.3304	0.4130
67	23.62	- 8.0	0.6891	0.8614
68	23.82	- 8.25	0.4372	0.5460
69	24.02	- 8.50	0.3682	0.4602
70	20.59	-11.0	0.6996	0.8745
71	20.83	-11.2	0.5062	0.6327
72	21.06	-11.4	0.3815	0.4769
73	17.56	-14.0	0.6710	0.8387
74	17.75	-14.2	0.5257	0.6571
75	17.95	-14.4	0.4029	0.5036
76	14.6	-17.0	0.6586	0.8232
77	14.76	-17.2	0.5065	0.6331
78	14.92	-17.4	0.4001	0.5001
79	11.55	-20.0	0.6387	0.7984
80	11.69	-20.16	0.5396	0.6745
81	11.85	-20.32	0.4313	0.5391

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TABLE II-A

Total Radiation Heating in Aluminum Pressure Vessel
(AGC Detector Locations)
(Flat Flange, 0.6 in. Skirt, 45° Nozzle)*

<u>Detector Number</u>	<u>Detector Location R (in.) Z (in.)</u>	<u>Nominal Heating Rate (Btu/in³-sec)</u>	<u>1.25 x Nominal Heating Rate (Btu/in³-sec)</u>
19	33.4 2.45	0.0963	0.1204
20	32.48 1.7	0.0972	0.1215
21	34.15 1.7	0.0698	0.0873
22	31.75 1.2	0.1001	0.1251
23	31.95 1.07	0.0914	0.1143
24	32.2 1.0	0.0849	0.1061
25	33.32 0.95	0.0679	0.0849
26	33.05 0.7	0.0670	0.0838
27	31.15 0.4	0.0963	0.1204
28	31.95 0.35	0.0750	0.0938
29	32.8 0.33	0.0633	0.0791

*These detector locations were initially specified in Table 12,
Reference 2.

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TABLE III

Total Radiation Heating in the Reference Design Nozzle
(ACFI Detector Locations)

(Flat Flange, 0.6 in. Skirt, 45° Nozzle)*

Detector Number	Detector Location		Nominal Heating ₃ Rate (Btu/in ³ -sec)	1.25 x Nominal Heating ₃ Rate (Btu/in ³ -sec)
	R (cm.)	Z (cm.)		
1	100.8	135.2	.0953	.1191
2	101.1	135.2	.0911	.1139
3	101.4	135.1	.0865	.1081
4	102.4	135.1	.0746	.0933
5	100.3	141.3	.1143	.1429
6	100.5	141.3	.1111	.1389
7	100.9	141.4	.1050	.1313
8	101.8	141.5	.0919	.1149
9	99.1	146.2	.1186	.1483
10	99.4	146.2	.1140	.1425
11	99.7	146.3	.1090	.1363
12	100.8	146.6	.0930	.1163
13	97.5	150.8	.1139	.1424
14	97.7	150.9	.1104	.1380
15	98.1	151.0	.1046	.1308
16	99.1	151.4	.0905	.1131
17**				
18	95.4	155.5	.1046	.1308
19	95.8	155.8	.0978	.1223
20	96.8	156.2	.0858	.1073
21	92.6	159.5	.1009	.1261
22	92.8	159.6	.0984	.1230
23	93.2	159.6	.0948	.1185
24	94.3	160.7	.0784	.0980
25	89.5	163.3	.0976	.1220
26	89.7	163.5	.0943	.1179
27	90.1	163.8	.0886	.1108

* These detector locations were initially specified in Table 6, Reference 1.

** These points were not included in the original ACF data.

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TABLE III (Contd)

<u>Detector Number</u>	<u>Detector R (cm.)</u>	<u>Location Z (cm.)</u>	<u>Nominal Heating Rate (Btu/in³-sec)</u>	<u>1.25 x Nominal Heating Rate (Btu/in³-sec)</u>
28	91.2	164.7	.0751	.0939
29	85.3	167.2	.0974	.1218
30	85.5	167.4	.0937	.1171
31	86.0	167.8	.0865	.1081
32	87.2	169.0	.0712	.0890
33	82.5	169.3	.1005	.1256
34	82.7	169.5	.0961	.1201
35	83.3	170.0	.0860	.1075
36	84.6	171.0	.0712	.0890
37	81.1	170.1	.1020	.1275
38	81.5	170.4	.0975	.1219
39	82.4	170.4	.0889	.1111
40	84.1	171.6	.0696	.0870
41	79.7	171.4	.1006	.1258
42	80.3	171.7	.0931	.1164
43	81.5	171.8	.0827	.1034
44	83.6	172.3	.0675	.0844
45	79.1	173.3	.0948	.1185
46	79.9	173.2	.0829	.1036
47	81.3	173.2	.0725	.0906
48	83.6	173.3	.0593	.0741
49	86.6	173.3	.1355	.1694
50	76.8	168.5	.4971	.6214
51	76.7	174.2	.3755	.4694
52	79.1	174.3	.2117	.2646
53	79.7	174.2	.1890	.2363
54	81.4	174.3	.1445	.1806
55	83.7	174.3	.1218	.1522
56	86.7	174.3	.0802	.1003
57	76.5	175.5	.3759	.4699
58	78.3	175.4	.1826	.2282
59	79.1	175.5	.1527	.1909
60	79.9	175.4	.1305	.1631

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TABLE III (Contd)

<u>Detector Number</u>	<u>Detector Location R (cm.)</u>	<u>Z (cm.)</u>	<u>Nominal Heating Rate (Btu/in³-sec)</u>	<u>1.25 x Nominal Heating Rate (Btu/in³-sec)</u>
61	81.3	175.4	.1020	.1275
62	83.8	175.5	.0783	.0979
63	86.6	175.6	.0618	.0773
64	76.2	176.9	.3696	.4620
65	78.2	177.0	.1432	.1790
66	79.1	177.0	.1070	.1338
67	79.8	177.0	.0910	.1138
68	81.4	177.0	.0664	.0830
69	83.8	177.0	.0493	.0616
70	76.0	178.2	.3256	.4070
71	78.2	178.2	.1270	.1588
72	79.1	178.2	.0908	.1135
73	79.8	178.2	.0737	.0921
74	81.3	178.2	.0520	.0650
75	75.7	179.2	.3207	.4009
76	78.2	179.2	.1146	.1433
77	79.1	179.2	.0812	.1015
78**				
79	71.5	183.8	.4709	.5886
80	66.6	188.6	.5051	.6314

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APPENDIX

Analytical Description of the Reference Design Nozzle

The detailed description of the input data for the QAD-P5 code is given for the reference design. The zone description is given in Table A-1, the boundary description is given in Table A-2, and the material composition in Table A-3.

The boundaries are defined by the general quadratic expression $A(X-X_0)^2 + B(Y-Y_0)^2 + C(Z-Z_0)^2 = K^2$. The QAD-P5 code is programmed to recognize ~~six~~ specialized forms of this general equation. The three of these equation types that are used in the boundary description in Table A-2 are:

(2) $A(X-X_0)^2 + B(Y-Y_0)^2 + C(Z-Z)^2 = K$

(3) $X^2 + Y^2 = K$

(6) $Z = K$

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TABLE A-1

Referenced Design Model Zone Description

Zone No.	No. of Boundaries	Composition No.	Zone Boundaries with Crossing Sense ($\pm$ Bnd) and Probable Zone Entered (Pk)											
			Bnd #1	Pk	Bnd #2	Pk	Bnd #3	Pk	Bnd #4	Pk	Bnd #5	Pk	Bnd #6	Pk
1	1	1	-1	2										
2	3	2	1	1	5	6	-2	3						
3	3	12	2	2	5	6	-3	4						
4	3	4	3	3	5	6	-4	5						
5	3	11	4	4	15	17	-29	28						
6	4	3	1	1	8	9	-4	5	-5	2				
7	4	11	42	35	14	15	-26	21	-19	36				
8	4	13	34	29	36	43	-31	33	-35	37				
9	4	11	1	1	9	10	-4	5	-8	6				
10	4	9	1	1	10	11	-3	16	-9	9				
11	4	11	1	1	11	12	-3	18	-10	10				
12	4	7	1	1	12	13	-2	19	-11	11				
13	4	11	1	1	13	14	-2	19	-12	12				
14	4	9	1	1	14	15	-2	20	-13	13				
15	3	11	1	1	-31	33	-14	14						
16	4	11	3	10	15	17	-4	5	-9	9				
17	4	13	3	10	16	18	-28	27	-15	5				
18	4	11	3	10	18	19	-25	23	-16	17				
19	3	11	2	12	20	20	-18	18						
20	6	9	2	14	14	15	41	35	-42	34	-18	18	-20	19
21	4	13	26	45	40	39	-27	26	-19	22				
22	4	9	26	23	19	21	-27	26	-17	25				

TABLE A-1 (Contd)

Zone No.	No. of Boundaries	Composition No.	Zone Boundaries with Crossing Sense (+ Bnd) and Probable Zone Entered (pk)											
			Bnd #1	Pk	Bnd #2	Pk	Bnd #3	Pk	Bnd #4	Pk	Bnd #5	Pk	Bnd #6	Pk
23	5	9	25	18	18	34	-26	22	-17	25	-21	24		
24	3	11	25	18	21	23	-17	25						
25	4	11	25	18	17	23	-27	38	-16	17				
26	4	13	27	21	40	39	-28	27	-22	38				
27	5	13	28	17	40	39	39	40	-38	41	-15	28		
28	5	13	29	5	15	27	34	43	-30	29	-23	30		
29	4	13	30	28	34	43	-35	44	-24	31				
30	3	11	29	5	23	28	-30	31						
31	3	11	30	30	24	29	-35	44						
32	4	11	2	12	18	19	-3	18	-11	11				
33	1	11	31	15										
34	5	9	42	20	19	45	32	36	-26	22	-18	23		
35	3	11	-41	20	14	15	-42	45						
36	3	9	19	45	-26	22	-32	34						
37	3	11	33	44	35	46	-31	33						
38	4	11	27	25	22	26	-28	27	-16	17				
39	4	11	26	45	14	15	-31	33	-40	21				
40	3	11	40	39	-38	42	-39	27						
41	3	13	38	27	37	42	-15	28						
42	5	11	38	27	40	39	-31	33	-15	43	-37	41		
43	4	11	34	29	15	42	-31	33	-36	46				
44	3	11	30	30	35	31	-33	37						

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TABLE A-2

Reference Design Analytical Model Boundary Description

Boundary No.	Boundary Type	A	B	C	X _o	Y _o	Z _o	K
1	6							173.89
2	6							41.808
3	6							38.316
4	6							31.966
5	3							4861.3
6	3							4950.2
7	3							5040.0
8	3							5130.8
9	3							5295.5
10	3							6140.3
11	3							6200.0
12	3							9812.9
13	3							10161.0
14	3							10677.0
15	3							5767.8
16	3							6001.6
17	3							6240.0
18	3							6606.4
19	3							7294.4
20	2	1.0	1.0	2.4196	0.0	0.0	41.808	10161.0
21	2	1.0	1.0	-2.7312			-52.197	
22	2	1.0	1.0	-1.0163			-78.357	
23	2	1.0	1.0	4.9986			2.54	5767.8
24	2	1.0	1.0	-0.98599			- 8.0704	
25	6							3.3
26	6							0.79375
27	6							
28	6							0.9525
29	6							2.54
30	6							-8.255

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TABLE A-2 (Contd)

<u>Bnd. No.</u>	<u>Bnd. Type</u>	<u>A</u>	<u>B</u>	<u>C</u>	<u>X_o</u>	<u>Y_o</u>	<u>Z_o</u>	<u>K</u>
31	6							-70.66
32	2	1.0	1.0	-1.108			-79.629	
33	6							-62.852
34	2	1.0	1.0	-1.0555			-81.092	
35	3							447.23
36	3							503.69
37	2	1.0	1.0	-3.8025			-46.046	
38	6							-4.064
39	2	1.0	1.0	-2.8435			-53.925	
40	3							7723.6
41	2	1.0	1.0	2.1701			41.808	10816.0
42	6							1.6

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TABLE A-3

Composition	Material Composition							
	Material							
	H (g/cm ³)	H (g/cm ³)	Ni (g/cm ³)	Cr (g/cm ³)	Fe (g/cm ³)	Nb (g/cm ³)	C (g/cm ³)	Mn (g/cm ³)
1								
2	0.0001845	0.13833			0.08	0.153	1.192	
3							1.80	
4	0.000116				0.08	0.27	1.192	
5	0.00488		0.0634	0.0127	0.0476		1.22	0.00133
6	0.00479		0.0294	0.0589	0.222		1.51	0.00618
7	0.000938							
8	0.00985		0.0279	0.0075	0.00965	0.000359		0.00022
9								
10					7.6			
11								
12	0.00184				0.08	0.218	1.192	
13			3.984	1.769	1.623		0.008229	0.0535
14							0.00094	
15							0.00192	

	Material						
	Mo (g/cm ³)	Pb (g/cm ³)	Al (gm/cm ³)	Be (g/cm ³)	B (g/cm ³)	Cu (g/cm ³)	H ₂ O (g/cm ³)
1							
2							
3							
4							
5			0.112				
6			0.149				
7	0.0492		0.0434	1.695	0.00185		
8	0.380		0.0815	0.596	0.00058		
9			2.70				
10							
11							
12							
13	0.740						
14			1.0035		0.0034		0.6611
15			0.8795	- 21 -	0.0069		0.6866

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AEROJET GENERAL PHOEBUS II REACTOR MODEL 5/15/65

Figure 1

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Figure 2

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FIGURE 3
PRIMARY GAMMA AXIAL SOURCE DISTRIBUTION

NOTE: 1. POWER IN WATTS

2. THESE POINT SOURCES ARE INPUT WITH AZIMUTHAL ANGLES θ OF 22.5° , 67.5° , 112.5° AND 157.5° TO MAINTAIN A SEPARATION DISTANCE OF AT LEAST 10 CM FROM THE DETECTORS (INPUT AT $\theta = 0.0^\circ$)

FIGURE 4
NOZZLE SECONDARY GAMMA SOURCE DISTRIBUTION

FIGURE 5
INTERFACE CYLINDER SECONDARY GAMMA AXIAL SOURCE

FIGURE 6

INTERFACE CYLINDER SECONDARY GAMMA RADIAL SOURCE DISTRIBUTION

FIGURE 7

DETECTOR LOCATIONS IN TABLE II

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FIGURE 8
DETECTOR LOCATIONS IN TABLE III

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APPENDIX A
PRESSURE VESSEL/NOZZLE INTERFACE ANALYSIS
PART III - HEAT TRANSFER ANALYSIS

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DEPARTMENT OF ENERGY

PHOEBUS 2 PRESSURE VESSEL/NOZZLE
INTERFACE ANALYSIS (U)

PART III — HEAT TRANSFER ANALYSIS

July 7, 1966

P2-66-3

Prepared by: Phoebus 2 Task Force Group
E. A. Thomas, AGC

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Approved by: J.W. Neudecker
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ADDENDUM B To Part III — Heat Transfer Analysis

Introduction

The purpose of this revised heat transfer analysis is to determine the effect of additional jacket thicknesses on the steady-state temperature distribution of the Phoebus-2 nozzle jacket. Two separate analyses were actually performed: one, a complete two-dimensional analysis (similar to the one covered in Addendum "A" to Part III of the Phoebus-2 Pressure Vessel/Nozzle Interface Report) in which temperature distributions were generated for nominal and 125% of nominal nuclear heating rates; the second, a detailed two-dimensional analysis of part of the convergent section in which both the maximum temperature and stress occur. This second analysis was performed for the maximum and minimum limit on jacket thickness. The interface configuration analyzed is designated FLAT C-62.

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Assumptions

1. Two-dimensional conduction.
2. All materials homogeneous and isotropic.
3. Thermal conductivity of material varies with temperature.
4. 7039 aluminum pressure vessel material.
5. Hastelloy-X nozzle material.
6. Intimate contact between nozzle and pressure vessel at interface.
7. All external or ambient surfaces adiabatic.
8. End surfaces on models used for Figure 2 are adiabatic.
9. Cooling by forced convection with hydrogen.
10. Nozzle coolant tube inlet temperature = 57°R .
11. Nozzle coolant flow rate = 250 lbm/sec.
12. Bolt coolant temperature = 60°R .
13. Bolt coolant flow rate = 10 lbm/sec.
14. Convective film coefficient along plenum side of nozzle core support skirt = $500 \text{ Btu/hr-ft}^2 \text{ }^{\circ}\text{R}$.
15. Convective film coefficient in "Stagnant" region of nozzle-pressure interface = $200 \text{ Btu/hr-ft}^2 \text{ }^{\circ}\text{R}$.
16. A flow director adjacent to the pressure vessel aft closure diverts 42 lbm/sec of H_2 along pressure vessel wall.
17. Interface configuration — FLAT C-62.

NomenclatureSymbol

q'''	Nuclear heating rate, Btu/in ³ sec
h_c	Convective film coefficient, Btu/hr-ft ² -°R
T	Absolute temperature, °R
ΔT	Temperature differential, °R
$\dot{w}$	Coolant flow rate, lbm/sec

Method of Analysis

All thermal profiles were generated by AGC Computer Job 278B (Thermal Analyzer and Network Generator)¹. This computer code utilizes 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 calculated 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 Code². The heating rates used in this analysis are the revision of November, 1965 calculated by AGC. "Best estimate" (nominal computed) and 125% of "best estimate" rates were used as heating rate inputs.

Film coefficients and coolant temperatures for the surfaces cooled by the nozzle coolant tubes were calculated using AGC Computer Job 8047³, a program for analysis and design of regeneratively cooled thrust chambers. The coolant temperature for the pressure vessel inlet plenum was also obtained from this computer job. Eighty-five percent (85%) of the Hess and Kunz correlation 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 OPTION⁴ runs used in conjunction with sizing the flow liner.

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Results and Discussion

The model used in the two-dimensional analysis shown in Figures 1 and 3 is identical to that used in the analysis of the FLAT C-52 configuration described in Addendum "A" to Part III of the Phoebus-2 Interface Report, with the exception of the addition of 0.050 in. to the point of maximum thickness (making a total of 0.850 in). The jacket was assumed to taper linearly to its original dimension at the point of tangency with the throat upstream radius. These temperature predictions from this model are conservative, as computer program limitations necessitated a fairly coarse grid network.

While the above mentioned analysis provides an overall picture of the temperatures, it is somewhat misleading with respect to the effect of small changes in jacket thickness. The results shown in Figure 2 were generated with 2 models, one with the minimum print thickness, and one with the maximum print thickness. These models provide a more accurate picture of the temperatures in the most critical regions of the nozzle jacket as a finer grid network was used, and a more accurate means of inputting nuclear heating rates was used. Heating rates for this model were input in tabular form, varying with jacket thicknesses.

The results shown in Figures 1 and 2 used 125% of the nominal computed heating rates, while those of Figure 3 used the nominal values.

The maximum jacket temperature shown in Figure 3b is 1224°R compared to 1130°R, the corresponding value for the FLAT C-52 configuration. The maximum jacket temperature shown in Figure 1b is 1381°R compared to 1275°R, the corresponding value for the FLAT C-52 configuration. Figure 2 shows that the dimensional tolerance of 0.020 in. can cause a difference in maximum temperature of approximately 30°.

Summary and Conclusions

The results of this analysis show a jacket temperature increase of 106° for 125% of nominal heating rates, and 94° for nominal heating rates over configuration FLAT C-52. The maximum jacket temperature shown in Figure 1b is 1381°R. The temperature of the corresponding point from Figure 2 is 1303°R. The reason for this discrepancy is due to differences in the models. The lower value (Figure 2) is considered to be more realistic because that model is more accurate at that point.

The additional jacket thickness of configuration FLAT C-62 has no effect on flange temperatures. The temperatures on the flange region of Figures 1a and 3a are identical to the corresponding values of configuration FLAT C-52.

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References

1. "Network Generator and Thermal Analyzer", AGC Computer Job 278B, H. D. Sakakura, 27 August 1962.
2. QAD "Gamma Heating and Close Calculations", ACF Report No. 434-2, W. M. Burley and B. F. Williams, March 20, 1963.
3. "Heat Transfer (Cryogenic)", AGC Computer Job 8047, L. M. Nole, July 6, 1964.
4. "OPTION Program", LASL Memo N-3-1449, J. A. McClary, November 6, 1963.

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STEADY STATE THERMAL PROFILE
 PHOEBUS 2 NOZZLE - PRESSURE VESSEL INTERFACE
 FLAT C-62, 125% NOMINAL H. R.

STEADY STATE THERMAL PROFILE
 PHOEBUS 2 NOZZLE CONVERGENT SECTION
 FLAT C-62, 125 % NOMINAL H.R.

FIGURE 1.6

STEADY STATE THERMAL PROFILE
 PHOEBUS 2 NOZZLE CONVERGENT SECTION
 FLAT C-62, 125 % NOMINAL H.R.

FIGURE 1c

THERMAL PROFILE - PHOEBUS 2 NOZZLE JACKET
MAXIMUM AND MINIMUM THICKNESS TOLERANCE

- NOTE:
1. ALL TEMPS. °RANKINE
2. TIME = STEADY STATE
3. 125% NOMINAL HEATING RATES

FIGURE 2

STEADY STATE THERMAL PROFILE
 PHOEBUS 2 NOZZLE - PRESSURE VESSEL INTERFACE
 FLAT C-62, NOMINAL H. R.

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STEADY STATE THERMAL PROFILE
PHOEBUS 2 NOZZLE CONVERGENT SECTION
FLAT C-62, NOMINAL H.R.

FIGURE 36

STEADY STATE THERMAL PROFILE
PHOEBUS 2 NOZZLE CONVERGENT SECTION
FLAT C-62, NOMINAL H. R.

NOTE:
1. ALL TEMPS. °RANKINE
2. TIME = STEADY STATE
3. NOMINAL HEATING RATES

FIGURE 3c

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APPENDIX A
PRESSURE VESSEL/NOZZLE INTERFACE ANALYSIS
PART IV - STRESS ANALYSIS

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PHOEBUS 2 PRESSURE VESSEL/NOZZLE
INTERFACE ANALYSIS

PART IV — STRESS ANALYSIS

December 15, 1966

P2-66-4

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ABSTRACT

This Revision "A" to Part IV of the interface report presents the stress analysis of the Phoebus 2 Pressure Vessel/Nozzle Interface Design, revised to include the effects of:

- a. Changed reactor system pressures
- b. Enhanced nuclear heating rates
- c. Verified material properties of the nozzle material, Hastelloy-X, and the pressure vessel material, aluminum alloy 7039-T61.
- d. Revised design criteria
- e. Revised pressure vessel and nozzle configurations

The analysis includes the effects of both internal pressure and thermally induced loads. Design criteria are presented which establish the allowable limits of the primary and secondary stresses of the respective structural components. The stress analysis was carried out with the aid of the PETS digital computer program. The complete stress distributions for the nozzle and pressure vessel in the areas adjacent to the interface are presented. The loads at the interface are analyzed in considerable detail, and the interface rotation and radial deflection behavior is described. Margins of safety are calculated for all critical structural components. An appendix to this report contains complete computer program output data.

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I. INTRODUCTION

This report is Revision "A" to Part IV of the Phoebus-2 Pressure Vessel/Nozzle Interface Analysis. This revision became necessary because of changed conditions of the Phoebus-2 reactor design. These changes are, briefly, as follows:

- a. Revised pressure distributions throughout the reactor system.
- b. Nuclear heating rates enhanced over the rates assumed for the original analysis.
- c. Confirmed materials properties from testing programs.

The other parts of the Phoebus-2 Interface Analysis, which have also been revised to include these changed conditions, are:

PART I LOAD ANALYSIS, REVISION "B"

PART II RADIATION HEATING CALCULATIONS, ADDENDUM "A"

PART III HEAT TRANSFER ANALYSIS, ADDENDUMS "A" and "B"

This part of the revised interface analysis presents the revised stress analysis of the pressure vessel/nozzle interface design. This design has been only slightly revised over the basic configuration analyzed in the original stress analysis report. This current configuration is designated FLAT C62*.

The input data for the stress analysis comes primarily from Part I — Load Analysis, Revision B, and Part III — Heat Transfer Analysis, Addendums "A" and "B".

A complete stress analysis is presented for the current interface configuration, FLAT C62, for both pressure and thermal loads. Large amounts of structure either side of the actual interface are included in this report, since the interface behavior is influenced significantly by the adjacent structure.

* Note: The identification of pressure vessel and nozzle configurations employs a letter and two digits. The letter designates the basic interface design. The first digit designates the specific nozzle configuration and the second digit designates the specific pressure vessel. The configuration analyzed in this report is FLAT-C62 (.60" core support skirt).

Since the original stress analysis was published, significant changes have occurred in the nozzle attach bolt arrangement. At eighteen (18) equally spaced bolt positions, the center hole of each bolt is enlarged and auxiliary bolts are inserted for the purpose of positioning the inner reflector stiffener ring. A stress analysis of these auxiliary bolts is included in this report.

The material properties of the Hastelloy-X nozzle material have been determined by test data, and this stress analysis is based upon these revised material properties.

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II. NOMENCLATURE

The nomenclature used throughout this report is coordinated with the nomenclature used in Part I — Load Analysis (Reference 2).

Pressures (psia)

P_a	Ambient pressure (atmospheric)
P_1	Nozzle inlet
P_2	Reflector inlet
P_3	Reflector outlet
P_4	Core inlet
P_5	Nozzle chamber

Forces (lbs.)

F_{tot}	Total ejection force at interface
F_n	Ejection force due to nozzle chamber pressure
F_c	Ejection force on core support skirt of nozzle
F_p	Ejection force due to P_2
F	Preload, core to nozzle support skirt
F_t	Thrust load

Radii (inches)

$R_{bc} = 32.000$	Bolt circle radius
$R_c = 30.450$	Radius at which F_c acts (also core seal radius)
$R_s = 32.875$	Radius of flange seal
R	Radius to pressure vessel or nozzle wall (variable)

Operating Conditions

NSS	Nuclear steady-state
CS	Chemical simulation, rated power
CSMSD	Chemical simulation, margin of safety demonstration
HYDRO	Hydrostatic test
PVPR	Pressure vessel proof test
TRAN	Reactor transient, startup or shutdown
1.0 N.H.R.	Nominal nuclear heating rate
1.25 N.H.R.	125% nominal nuclear heating rate

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Shell Calculation Symbols

ξ, XI	Wrap distance, meridional direction (inches)
θ	Angle, hoop direction
β	Rotation (radians)
ζ	Distance from neutral surface (inches)
$N_{\xi} = \int_h \sigma_{\xi} d\zeta$	Membrane load, meridional direction (lbs/in.)
$N_{\theta} = \int_h \sigma_{\theta} d\zeta$	Membrane load, hoop direction (lbs/in.)
$M_{\xi} = \int_h \sigma_{\xi} \zeta d\zeta$	Moment, meridional direction (in-lbs/in.)
$M_{\theta} = \int_h \sigma_{\theta} \zeta d\zeta$	Moment, hoop direction (in-lbs/in.)
$Q = \int_h \tau_{\xi\zeta} d\zeta$	Shear (lbs/in.)
u	Radial deflection (inches)
H	Horizontal load (lbs/in.)
V	Vertical load (lbs/in.)
$C = \int_h E d\zeta$	Membrane elastic parameter (lbs/in.)
$D = \frac{1}{1-\nu} 2 \int_h E \zeta^2 d\zeta$	Bending elastic parameter (in-lbs.)
$\sigma_{\xi o.s.} \text{ or } \sigma_{\xi i.s.}$	Stress, meridional direction, outer or inner surface (psi)
$\sigma_{\theta o.s.} \text{ or } \sigma_{\theta i.s.}$	Stress, hoop direction, outer or inner surface (psi)
σ	Normal stress (psi)
τ	Shear stress (psi)
$\epsilon_{\xi}, \epsilon_{\theta}$	Strain, meridional or hoop direction (in/in.)
T	Temperature (°F or °R)

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Material Properties

E	Average modulus of elasticity (psi)
$\bar{\alpha}$	Average thermal expansion coefficient (in/in/°F)
F_y	Material yield stress, tension or compression (psi)
F_u	Material ultimate stress, tension or compression (psi)
F_{sy}	Material yield shear stress (psi)
F_{su}	Material ultimate shear stress (psi)
F_{bry}	Material yield bearing stress (psi)
F_{bru}	Material ultimate bearing stress (psi)
ν	Poisson's Ratio

Geometrical

A	Area (in ²)
d	Distance (inches)
I	Moment of inertia (in ⁴)
R,Z,	Coordinates (inches)
t,h	Thickness (inches)

Stress Categories (lbs/in²)

P_m	} For detailed definition of these stress categories, see Section III, <u>ASSUMPTIONS AND DESIGN CRITERIA</u>
P_L	
P_b	
Q	
F	
S_a	

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III ASSUMPTIONS AND DESIGN CRITERIA

The analyses of the pressure vessel and the nozzle presented in this report were carried out with the help of a computer machine program (called PETS) which makes use of the equations of axisymmetric thin elastic shells, as presented in Reference 1. The output derived from this PETS Computer Code consists of all pertinent stress and deflection elastic parameters of the shell such as radial deflections, rotations, stresses, strains, etc.

The use of the PETS Code has made possible the determination of the shell stresses in considerable detail. However, a calculated value of stress means little until it is associated with its location and distribution in the structure and with the loading which produced it. Different types of stresses have different degrees of significance and, therefore, must be assigned different allowable values. For example, the average hoop stress through the thickness of the wall of a vessel, due to internal pressure, must be held to a lower value than the stress at the root of a notch in the wall. Similarly, a thermal stress can be permitted to reach a higher value than one derived from internal pressure or dead weight.

Because of considerations such as the examples mentioned above, the original stress analysis of the Phoebus-2 Pressure Vessel/Nozzle Interface incorporated a design criteria based upon a recent revision of the ASME Boiler and Pressure Vessel Code for Nuclear Vessels. More recently Structural Design Specification Number SNPO-C-1 has been suggested by the Cleveland, Ohio office of Space Nuclear Propulsion Office. Accordingly, the design criteria presented below incorporates the pertinent provisions of this specification.

A. Primary Stresses

1. General Primary Membrane Stresses: P_m

This is the average primary stress across the solid section.

This stress is produced only by mechanical loads. Discontinuities and concentrations are excluded.

For Pressure Vessel: $P_m \leq .85 F_y$

For Nozzle: $P_m^* \leq .85 F_y^*$

Note: P_m^ and F_y^* are based upon biaxial gain, ref. (9).

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2. Local Primary Membrane Stresses: P_L

This is the average stress across any solid section. This stress is produced only by mechanical loads. Discontinuities and concentrations are included:

$$\text{For Pressure Vessel: } P_L \leq 1.0 F_y$$

$$\text{For Nozzle: } P_L \leq 1.0 F_y$$

3. Primary Bending Stresses: P_b

This is the component of primary stress, proportional to distance from centroid of solid section. Excludes discontinuities and concentrations. Produced only by mechanical loads.

$$\text{For Pressure Vessel: } P_m \text{ (or } P_L) + P_b \leq 1.2 F_y$$

$$\text{For Nozzle: } P_m \text{ (or } P_L) + P_b \leq 1.25 F_u$$

B. Secondary Stresses, Membrane + Bending: Q^*

This is the self-equilibrating stress necessary to satisfy continuity of structure. Can be caused by mechanical load or by differential thermal expansion. Includes effect of structure discontinuity, but excludes local stress concentrations.

$$\text{For Pressure Vessel: } P_m \text{ (or } P_L) + P_b + Q \leq 1.0 F_u$$

$$\text{For Nozzle: } P_m \text{ (or } P_L) + P_b + Q \leq 2 F_y$$

C. Peak Stresses: F

These stresses are produced by notches or by certain thermal stresses which may cause fatigue but not distortion of vessel shape.

$$\text{For Pressure Vessel and Nozzle: } P_m \text{ (or } P_L) + P_b + Q + F \leq 2.0 S_a$$

S_a is defined as the apparent fatigue stress allowable evaluated at 100 cycles. For the nozzle material, the S_a value will be verified by testing. In general, the pressure vessel and the nozzle will not be critical for the same types of stresses, for the following reasons:

1. Pressure vessel material, being 7039-T61 aluminum, has a ratio of $F_u/F_y \approx 1.4$ and an elongation of approximately 10%. Therefore, the value of F_y is the most significant strength parameter.

* Note: Not to be confused with shear force, also designated as Q in Nomenclature Section.

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2. The nozzle material, being Hastelloy-X (a nickel base alloy) has a ratio of $F_u/F_y \approx 3.0$ and an elongation of approximately 20% and, therefore, is capable of a relatively large amount of plastic deformation. Hence, the ultimate strength, F_u , is the most significant stress parameter, except for primary membrane stresses.

Application of design criteria is discussed in further detail in Section VII.C of this report.

IV. MATHEMATICAL MODELS

Figure 1 shows the configuration of the nozzle-pressure vessel joint and defines the nomenclature of the components.

Figures 2, 4, and 6 show the geometry and regional breakdown of the nozzle shell, nozzle skirt, and pressure vessel, respectively. Figures 3, 5, and 7 show the same geometry plotted by the plotter subroutine of the PETS Computer Code.

Figure 8 shows the geometry and regional breakdown for the thermal model of the nozzle-pressure vessel combined while Figure 9 represents the plotter output for the same model.

A. Nozzle Shell

The mathematical model of the nozzle shell (Figure 2) consists of twelve (12) regions and the number of layers in each region is as follows:

<u>Region Number</u>	<u>Number of Layers</u>	<u>Region Location</u>
1	2	Flange at end of nozzle divergent section
2	2	
3	2	
4	3	Divergent section
5	3	Throat
6	3	
7	7	Convergent section
8	7	
9	7	
10	6	
11	6	
12	6	

B. Nozzle Skirt

The mathematical model of the nozzle skirt (Figure 4) consists of four (4) regions. The first three regions consist of four (4) layers each, while the last region has six (6) layers. The axial loading on the skirt was obtained from Revision "B" of the "Phoebus-2 Pressure Vessel/Nozzle Interface Analysis, Part I — Load Analysis". (Reference 2.)

C. Pressure Vessel

The mathematical model of the pressure vessel (Figure 6) consists of four (4) regions. Regions 1 and 2 contain five (5) layers while regions 3 and 4 contain four (4) layers.

The outside surface is described using straight lines and arcs of circles, as defined on the geometric layout (Figure 6). The thickness of the pressure vessel normal to the outside surface is input at stations measured along the outside surface. The considerations in the choice of stations are: sufficient points for the computer code to fit the thickness of the shell and sufficient points to describe the temperature variation along the length of the shell. The layers are added across the thickness of the model to describe the temperature variation across the thickness of the shell. The math model was written to include operating condition temperatures, coefficients of expansion at these temperatures, and elastic moduli at these temperatures.

Region 2 has a very rapid change of both thickness and direction, and thus the geometry fit of this region shows the greatest deviation from actual geometry. The actual math model causes small perturbations of the behavior of region 2. The effects of these perturbations are small and localized. Region 2 is not a high-stress area and these local disturbances do not affect the over-all stress results.

D. Combined Nozzle/Pressure Vessel Thermal Model

The mathematical model of the nozzle-pressure vessel (Figure 8) for the thermal case consists of twenty (20) regions. The regions and layers correspond to the mechanical models, as given above, except that region one of the nozzle skirt is combined with the flange to form a region of ten layers.

Comparison between the actual geometry of the thermal model (Figure 8) and the plotter output (Figure 9) shows differences in the flange region. Since the thermal case does not involve mechanical loads, no axial loads are involved and it is not necessary to insure radial compatibility of the reference (or load) surface. Only the flange mass is simulated in this model.

E. Material Properties and Temperatures

Material properties and temperatures used in the models of both the nozzle and pressure vessel are shown in Section VIII of this report.

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JOINT CONFIGURATION
1/2 NOMENCLATURE
(REF. 6)

FIGURE 1

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STA 94.160

FIGURE 2(a)

STA 131.282

STA 139.421

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FIGURE 2(2)

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DATE 10.26.1966

CASE 600.11

FIGURE 3

AT C60-1

NOZZLE SHELL

MECH STRESS

N. S. 15

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FIG. 4, NOZZLE CORE SUPPORT SKIRT

CONFIGURATION: FLAT C-62 (.600 -INCH THICK)

REACTOR

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DATE 10.26.1966

CASE 600.22

FIGURE 5

1 FLAT CGO-2 CORE SUPPORT MECH STRESS N.S.S.

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FIGURE 6

PHOEBUS -2
PRESSURE VESSEL
MATH MODEL
4 REGIONS

SIGN
CONVENTION

(AT FLANGE END)

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DATE 10.25.1966

CASE 662.11

FIGURE 7

LAT C62-2 PRESSURE VESSEL MECHANICAL LOADS INP

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FIGURE 8

COMBINED NOZZLE/PRESSURE VESSEL THERMAL MODEL CONFIGURATION: FLAT - C62

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UNCLASSIFIED

REACTOR

UNCLASSIFIED

DATE 9.01.1966

CASE 1.25

FIGURE 9

1 FLAT C62

THERMAL

STRESS 1.25 X N. H. R.

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V. METHOD OF ANALYSIS

To determine the mechanical behavior and stresses in the components surrounding the Phoebus-2 interface, a mathematical model is derived for each shell component (nozzle shell, nozzle skirt, and pressure vessel) and each mathematical model is used as input separately into the PETS Computer Code with the known loads and behavior applied at the appropriate boundaries.

The next step is to determine influence coefficients for a Unit H and a Unit M_g on the deflection and rotation of each shell where it attaches to the nozzle flange. Then the deflection and rotation of each shell at its flange junction is written in terms of the initial behavior and unknown M_g and H loads.

The deflection and rotation of the flange, which is assumed to be a ring, are then written in terms of known loads and unknown loads at the three junctions with the shell components. The compatibility conditions of deflection and rotation and the equilibrium conditions of M_g and H at each junction provide the necessary and sufficient equations to solve for the values M_g , H, u, and β at each junction. This solution is obtained using the ACF M-201 Crout Reduction Computer Code (Ref. 8).

The mechanical behavior and stresses in each shell are computed by the PETS Computer Code by inputting the determined values of M_g and H (or u and β) as end conditions. The thermal behavior and stresses are obtained directly from the Combined Nozzle/Pressure Vessel Thermal Model computer run. The mechanical plus thermal behavior and stresses are obtained by superposition.

A complete list of the computer runs required, and a flow diagram of the above analytical procedure are shown on pages 30 and 31.

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V. METHOD OF ANALYSIS (Continued)

A. Nozzle

INFLUENCE COEFFICIENTS

The mechanical loads are resolved by equating the rotations and deflections of the shells to the rotation and deflection of the ring.

The unit rotations and deflections of the shells are termed influence coefficients and are determined by inputting the geometry of each shell into the PETS Code and regulating the boundary conditions at the end of the shell such that the rotation " β " and deflection " u " are determined for a unit M_x only, a unit H only, and the pressure applied over the surface. The resulting influence coefficients are combined to obtain equations describing " u " and " β " as follows:

MOMENT ONLY + RADIAL LOAD ONLY + PRESSURE ONLY = COMBINED

$$\begin{aligned}\beta, \text{ Nozzle Shell} &= c_1 (\text{Moment}) + c_2 (\text{Horizontal Load}) + \text{Pressure Constant} \\ u, \text{ Nozzle Shell} &= -c_3 (\text{Moment}) + c_4 (\text{Horizontal Load}) + \text{Pressure Constant}\end{aligned}$$

V. A. Nozzle (Continued)

The thermal stresses are analyzed for two temperature conditions, as follows:

- (1) 100% of nominal heat generation rates, hereafter designated 1.00 N.H.R.
- (2) 125% of nominal heat generation rates, hereafter designated 1.25 N.H.R.

The moduli of elasticity of both the nozzle material, Hastelloy-X, and the pressure vessel material vary as a function of temperature. However, the simplifying assumption is made in this analysis that the higher temperature (1.25 N.H.R.) modulus of elasticity values of both nozzle and pressure vessel are valid for calculation of mechanical loads for both 1.00 N.H.R. and 1.25 N.H.R. conditions.

B. Pressure Vessel

1. End Conditions

Cylinder (Region + 4):

The length of Region 4 is 20 inches. This length is sufficient for all junction effects to dampen out. This makes the moment and horizontal force in the cylinder the same as a semi-infinite cylinder.

$M_{\xi} = H = 0$ are the end conditions used.

Nozzle End (Region - 1):

The vertical load is the algebraic sum of the separating force from the loads document and the pressure force on the region end divided by the circumference generated by the P.V. neutral "axis".

$$V = \left\{ 2272077 - 842.3 \left[(32.875)^2 - (31.0625)^2 \right] \pi \right\} / (2\pi)(32.3334) = +9674.42 \text{ lbs/in.}$$

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B. Pressure Vessel (Continued)

The eccentricity of the vertical loads about the neutral axis causes a moment ($M_{O\xi}$) which is one end condition.

$$M_{O\xi} = \left\{ 2272077(32.3334 - 32) - 842.3 \pi \left[(32.875)^2 - (31.0625)^2 \right] \right.$$

$$\left. \left[32.3334 - (32.875 + 31.0625)/2 \right] \right\} / 2\pi \cdot 32.3334 = M_{O\xi} = + 3178.28 \text{ in-lbs/in.}$$

2. Influence Coefficients (Nozzle End)

Add $H = + 1000$ at $R = 32$. ($H = 1000 \times 32./32.3334 = 989.69$ at neutral axis) to otherwise identical problem to find influence of 1000 lbs/in of horizontal force on both u and β .

Add $M_{\xi} = + 1000$ at $R = 32$. ($M_{\xi} = 989.69$ at neutral axis) to otherwise identical problem to find influence of 1000 in-lbs of moment on both u and β .

Case 610.01 (P + V)

$$u_o = .21266$$

$$\beta_o = -.044702$$

$$M_o = 3178.3$$

$$= 212660 (10^{-6})$$

$$= - 44702 (10^{-6})$$

Case 610.02 (P + V + H = 1000 @ R = 32)

$$u = .19599$$

$$\beta = - .041140$$

$$(IC)u_{H=1} = \left[(.19599) - (.21266) \right] (10)^{-3} = - 16.670 (10)^{-6}$$

$$(IC)\beta_{H=1} = \left[(.041140) - (.044702) \right] (10)^{-3} = 3.562 (10)^{-6}$$

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Case 610.03 (P + V + M = 1000 @ R = 32.)

$$u = .21622$$

$$\beta = - .46088 (10)^{-1}$$

$$(IC)u_{M=1} = [(.21622) - (.21266)](10)^{-3} = 3.560 (10)^{-6}$$

$$(IC)\beta_{M=1} = [(.046088) - (.044702)](10)^{-3} = - 1.386 (10)^{-6}$$

Check Maxwell's Law

$$\beta_H = u_M$$

$$3.562 = 3.560$$

Error << 1%

INFLUENCE COEFFICIENTS:* NOZZLE SHELL C60-1
12 REGIONS

CASE	$\beta (+12)$	$u (+12)$	$V (+12)$	$H (+12)$	$M (+12)$	P	$V (-1)$	CASE
P Only	-.027773	-.070090	7435.1	0.	0.	-625.	0	601.00
Press + M	-.025959	-.066676	7435.1	0.	1000.	-625.	0	601.01
Press + H	-.024360	-.058636	7435.1	1000.	0.	-625.	0	601.02
Press + M	-.025959	-.066676	7435.1	0.	1000.	-625.	0	601.01
- P Only	-.027773	-.070090	-7435.1	0.	0	625.	0	601.00
M Only	.001814	.003414	0	0	+1000.	0	0	
Press + H	-.024360	-.058636	7435.1	1000.	0	-625.	0	601.02
-P Only	-.027773	-.070090	-7435.1	0	0	625.	0	601.00
H Only	.003413	.011434	0	+1000.	0	0	0	

* 1.25 x Nominal Heating Rates

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V METHOD OF ANALYSIS (Continued)

C. Nozzle Flange and Deformation Equations

RING EQUATIONS

The Nozzle Flange is treated as a ring; thus, the rotation of the ring, in terms of forces acting on it, is:

$$\beta_{cg} = \frac{M_{cg} R_{cg}^2}{E I}$$

and,

$$\beta_{cg} = \beta_{\text{Nozzle Shell}} = \beta_{\text{Skirt}} = \beta_{\text{Pressure Vessel}}$$

The radial deflection of the ring, in terms of forces acting on it, is:

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

and the relationship of the radial deflection, with respect to the ring, is:

$$\begin{aligned} u_{\text{Pressure Vessel}} &= u_{cg} - d_1 \beta_{cg} \\ u_{\text{Skirt}} &= u_{cg} - d_2 \beta_{cg} \\ u_{\text{Nozzle Shell}} &= u_{cg} + d_3 \beta_{cg} \end{aligned}$$

SIGN CONVENTION, RING EQUATIONS

INFLUENCE COEFFICIENTS:* CORE SUPPORT C60-2

4 REGIONS

CASE	<u>(-1)</u>	<u>u(-1)</u>	<u>V(-1)</u>	<u>H(-1)</u>	<u>M(-1)</u>	<u>P</u>	<u>V(+4)</u>	CASE
P+V	.00049716	-.010972	-2342.1	0.	0.	230.	0	602.00
P+V+M	-.0043103	-.0026206	-2342.1	0.	1000.	230.	0	602.01
P+V+H	.0088488	-.038971	-2342.1	1000.	0	230.	0	602.02
P+V_M	-.0043103	-.0026206	-2342.1	0	1000.	230.	0	602.01
-(P+V)	-.00049716	.010972	+2342.1	0	0	-230	0	602.00
M Only	-.00480746	.0083514	0	0	+1000.	0	0	
P+V+H	.0088488	-.038971	-2342.1	1000	0	230.	0	602.02
-(P+V)	-.00049716	+.010972	2342.1	0	0	-230	0	602.00
H Only	.0083516	-.027999	0	+1000.	0	0	C	

* 1.25 x Nominal Heating Rates

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TABLE OF COMPUTER RUNS

CASE NO.

601.00	NOZZLE SHELL	C60-1 PRESS	1.25xN.H.R.
601.01	NOZZLE SHELL	C60-1 PRESS + M	1.25xN.H.R.
601.02	NOZZLE SHELL	C60-1 PRESS + H	1.25xN.H.R.
602.00	CORE SUPPORT	C60-2 PRESS + V	1.25xN.H.R.
602.01	CORE SUPPORT	C60-2 PRESS + V + M	1.25xN.H.R.
602.02	CORE SUPPORT	C60-2 PRESS + V + H	1.25xN.H.R.
610.01	PRESSURE VESSEL	FLAT C02 P + V	1.25xN.H.R.
610.02	PRESSURE VESSEL	FLAT C02 P + V + UNIT H	1.25xN.H.R.
610.03	PRESSURE VESSEL	FLAT C02 P + V + UNIT M	1.25xN.H.R.
1.00	NOZZLE + PRESSURE VESSEL	C62 THERMAL STRESS	1.00xN.H.R.
1.25	NOZZLE + PRESSURE VESSEL	C62 THERMAL STRESS	1.25xN.H.R.
600.11	NOZZLE SHELL	C60-1 MECHANICAL LOADING	1.25xN.H.R.
600.22	CORE SUPPORT	C60-1 MECHANICAL LOADING	1.25xN.H.R.
662.11	PRESSURE VESSEL	FLAT C62 MECHANICAL LOADING	1.25xN.H.R.
662.12 ⁽²⁾	PRESSURE VESSEL	FLAT C62 MECH. LOADING(CHECK)	1.25xN.H.R.
662.13	PRESSURE VESSEL	FLAT C62 MECHANICAL+THERMAL	1.00xN.H.R.
662.14 ⁽²⁾	PRESSURE VESSEL	FLAT C62 MECH.+THERMAL(CHECK)	1.00xN.H.R.
662.23	PRESSURE VESSEL	FLAT C62 MECHANICAL+THERMAL	1.25xN.H.R.
662.24 ⁽²⁾	PRESSURE VESSEL	FLAT C62 MECH.+THERMAL(CHECK)	1.25xN.H.R.
30.10	NOZZLE SHELL	FLAT C62 MECHANICAL+THERMAL	1.00xN.H.R.
30.20	NOZZLE SHELL	FLAT C62 MECHANICAL+THERMAL	1.25xN.H.R.
40.10	CORE SUPPORT	FLAT C62 MECHANICAL+THERMAL	1.00xN.H.R.
40.20	CORE SUPPORT	FLAT C62 MECHANICAL+THERMAL	1.25xN.H.R.

(1) For model designations, see footnote in Introduction.

(2) These cases used as check only; no results will be included.

COMPUTER CASE FLOW DIAGRAM

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IC Dwg No. 1115209

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SECTION PROPERTIES.

$$\bar{X} = \frac{A\bar{x}}{A} = \frac{8.8253}{7.3361} = 1.203 \text{ IN.}$$

$$\bar{Y} = \frac{A\bar{y}}{A} = \frac{19.9103}{7.3361} = 2.714 \text{ IN.}$$

$$\begin{aligned} I_{Y-Y} &= \sum I_{O-Y} + \sum Ax^2 - \sum A(\bar{x})^2 \\ &= 0.79787 + 11.6539 - (7.3367)(1.203)^2 \\ &= 1.834 \text{ IN}^4 \end{aligned}$$

ITEM	(Y) BASE	(X) HEIGHT	AREA	X	Y	Ax	AY	Ax ²	I _{O-Y}
1	0.8725	0.430	0.3752	0.215	4.4981	0.0807	1.6877	0.0174	0.00578
2	0.9094	1.025	0.9321	0.9425	4.4797	0.8785	4.1755	0.8280	0.08161
3	0.9094	0.525	0.2387	1.630	4.3281	0.3891	1.0331	0.6342	0.00366
4	1.9850	1.550	3.0768	1.205	3.0325	3.7075	9.3304	4.4675	0.61599
5	1.5400	0.330	0.2541	2.090	2.5533	0.5311	0.6488	1.1100	0.00154
6	2.0400	0.775	0.7905	1.7933	1.3600	1.4176	1.0751	2.5422	0.02638
7	0.9100	0.725	0.6598	1.1725	1.5850	0.7736	1.0458	0.9070	0.02890
8	0.5300	0.380	0.2014	0.6200	1.7750	0.1249	0.3575	0.0774	0.00242
9	0.3800	0.380	0.0722	0.6833	1.3833	0.0493	0.0999	0.0337	0.00058
10	0.900	0.725	0.6525	1.1725	0.680	0.7651	0.4437	0.8970	0.02858
11	0.230	0.725	0.0834	1.2933	0.1533	0.1079	0.0128	0.1395	0.00243
Σ			7.3367			8.8253	19.9103	11.6539	0.79787

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SECTION PROPERTIES: (CONT.)

ASSUME:

AREA REMOVED FOR THE BOLT HOLES IS ONE HALF THAT OF THE ACTUAL BOLT HOLES TO MAKE A GENERAL CROSS-SECTION

ITEM	(Y) BASE	(X) HEIGHT	AREA	X	Y	AX	AY	AX ²	I _{O-Y}
1			7.3367			8.8253	19.9103	11.6539	0.79787
2	0.344	1.500	-.5160	1.180	2.434	-.6089	-1.2559	-0.7185	-.09675
3	0.672	0.250	-.1680	2.055	2.434	-.3452	-0.4089	-0.7094	-.000873
Σ			6.6527			7.8712	18.2455	10.2261	0.70027

$$\bar{X} = \frac{7.8712}{6.6527} = 1.183 \text{ IN}$$

$$\bar{Y} = \frac{18.2455}{6.6527} = 2.743 \text{ IN.}$$

$$\begin{aligned}
 I_{Y-Y} &= \Sigma I_{O-Y} + \Sigma Ax^2 - \Sigma A(\bar{x})^2 \\
 &= 0.70027 + 10.2261 - (6.6527)(\overset{9.3105}{1.183})^2 \\
 &= \underline{1.6159 \text{ IN}^4}
 \end{aligned}$$

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FREE - BODY DIAGRAM

$P_{atm.} = 12.7 \text{ PSI}$

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AXIAL FORCES:

N.S.S. COND.

$$P_c = 625.0$$

$$P_a = 12.7$$

$$P_{vc} = 855.0$$

PRESSURE ACTING ON FLANGE:

$$\begin{aligned} P_{V1} &= \frac{\pi (R_2^2 - R_1^2)}{2\pi R_3} \times P_{Pvc} \\ &= \frac{(32.875^2 - 30.535^2)}{2(31.705)} \times (855.0 - 12.7) \\ &= \underline{1970.98 \text{ LBS/IN @ 31.705 IN}} \end{aligned}$$

$$P_{V2} = 0.380 \times 842.3 = \underline{320.1 \text{ LBS/IN @ 30.964 IN}}$$

$$\begin{aligned} P_{H2} &= \frac{\pi (R_2^2 - R_1^2)}{2\pi R_3} \times P_c \\ &= \frac{(29.7956^2 - 29.5656^2)}{2(29.6806)} \times (625.0 - 12.7) \\ &= \underline{140.8 \text{ LBS/IN @ 29.6806 IN}} \end{aligned}$$

$$\begin{aligned} P_{H1} &= 0.700 \times 612.3 \\ &= \underline{428.6 \text{ LBS/IN @ 29.6806 IN}} \end{aligned}$$

AXIAL FORCES :

CORE LOADING

$$F_C = \text{CALCULATED LOAD} = 354019. \text{ LB.}$$

$$F_{CS} = (30.450^{\overset{39.425}{2}} - 29.7956^2) \pi \times 612.5 + (30.535^{\overset{5.184}{2}} - 30.450^2) \pi \times 842.3 + 354019.0$$

$$F_{CS} = 75799.4 + 13710.96 + 354019.0 \\ = 443529.4$$

$$V_{CS} = \frac{443529.4}{2\pi (30.155)}$$

$$= 2342.1 \text{ \#/IN @ } R=30.155 \text{ IN}$$

AXIAL FORCES:

$$F_{AD} = 2272077 \text{ LB (LOADS DOC.)}$$

$$V_{AD} = \frac{2272077}{2\pi (32.000)}$$

$$= 11306.1 \text{ \#/IN @ 32.000 IN}$$

$$\sum F_{\text{AXIAL DIRECTION}} = 0$$

$$RV_{NS} = RV_{AD} - RP_{V1} - RV_{CS} - RP_{H2}$$

$$RV_{NS} = \frac{(32.000)(11306.1) - (31.705)(1970.98) - (30.155)(2342.1) - (29.6806)(140.8)}{(30.561)}$$

$$V_{NS} = \frac{224500.3}{30.561}$$

$$= 7346. \text{ \#/IN @ 30.561 IN}$$

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HAST X NOZZLE NUCLEAR STEADY STATE

DEFORMATION EQUATIONS:

<u>ITEM</u>	<u>LOAD</u>	<u>R</u>	<u>d</u>	<u>$\bar{R}_M$</u>	<u>$\bar{R}_H$</u>
V_{PV}	11306.1	32.000	0.3086	111650.0	
V_{CS}	2342.1	30.155	2.1536	152100	
V_{NS}	7346.0	30.561	1.7476	- 392338.1	
M_{PV}	---	32.000	1.00	+ 32.000 MPV	
H_{PV}	---	32.000	.773	+ 32.192 HPV	+ 32.000 HPV
M_{CS}	---	30.155	1.00	+ 30.155 MCS	
H_{CS}	---	30.155	0.373	+ 11.2378 HCS	+ 30.155 HCS
M_{NS}	---	30.561	1.00	- 30.561 MNS	
H_{NS}	---	30.561	0.7895	+ 22.5999 HNS	- 30.561 HNS
P_{V1}	1970.98	31.705	0.6036	-37718.8	
P_{V2}	320.1	30.964	0.563	+ 5580.2	+ 9911.6
P_{H1}	428.6	29.6806	0.020	+ 254.4	+12721.1
P_{H2}	140.8	29.6806	2.628	-10982.5	
				-475654.8	+22632.7

① $32.3086 \text{ MCG} = 32.000 \text{ MPV} + 32.192 \text{ HPV} + 30.155 \text{ MCS} + 11.2478 \text{ HCS} -$
 $30.561 \text{ MNS} + 22.5999 \text{ HNS} - \underline{475654.8}$

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DEFORMATION EQUATIONS: (Con't)

$$(2) \quad 32.3086 \text{ HCG} = +32.000 \text{ HPV} + 30.155 \text{ HC} + 30.561 \text{ HNS} + 22632.7$$

$$(3)^* \quad +1.0 \beta_{CG} = \frac{M_{CG} R^2}{EI}$$

$$\text{Est. Mean Temp.} = 675 \text{ R} \quad = \frac{(32.3086)^2}{(29.377 \times 10^6)(1.6159) \times M_{CG}}$$

$$= 21.989 \times 10^{-6} M_{CG}$$

$$(4)^* \quad +1.0 u_{CG} = \frac{H_{CG} R^2}{EA}$$

$$= \frac{(32.3086)^2}{(29.377 \times 10^6)(6.6527) \times H_{CG}}$$

$$= 5.341 \times 10^{-6} H_{CG}$$

$$(5) \quad u_{PV} = u_{CG} + 0.753 \beta_{CG}$$

$$(6) \quad u_{CS} = u_{CG} + 0.383 \beta_{CG}$$

$$(7) \quad u_{NS} = u_{CG} - 0.7395 \beta_{CG}$$

PRESSURE VESSEL

$$(8) \quad \beta_{CG} = -1.386 \times 10^{-6} M_{PV} + 3.562 \times 10^{-6} H_{PV} - 0.044702$$

$$(9) \quad u_{PV} = +3.560 \times 10^{-6} M_{PV} - 16.670 \times 10^{-6} H_{PV} + 0.21266$$

CORE SUPPORT**

$$(10) \quad \beta_{CG} = -4.80746 \times 10^{-6} M_{CS} + 8.3516 \times 10^{-6} H_{CS} + 0.00049716$$

$$(11) \quad u_{CS} = +8.3514 \times 10^{-6} M_{CS} - 27.999 \times 10^{-6} H_{CS} - 0.010972$$

* NOTE: Young's modulus values are based on mean flange temperature at 1.25 x N.H.R.

** NOTE: Influence coefficients based on wall temperature (Young's modulus) values.

NOZZLE SHELL*

$$(12) \quad \beta_{CG} = + 1.814 \times 10^{-6} M_{NS} + 3.413 \times 10^{-6} H_{NS} - 0.027773$$

$$(13) \quad u_{NS} = + 3.414 \times 10^{-6} M_{NS} + 11.454 \times 10^{-6} H_{NS} - 0.07009$$

* Ibid, pg. 40

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FLAT-C62 SIMULTANEOUS EQUATION SOLUTION*

M_{CG}	= - 95.70	IN-LB/IN
β_{CG}	= -.00210	RADIANS
U_{CG}	= .0169	IN
H_{CG}	= 3160.7	LBS/IN
U_{PV}	= .0153	IN
U_{CS}	= .0161	IN
U_{NS}	= .0184	IN
M_{PV}	= -680.5	IN-LB/IN
H_{PV}	= 11694.1	LBS/IN
M_{CS}	= -2362.5	IN-LBS/IN
H_{CS}	= -1671.4	LBS/IN
M_{NS}	= - 891.5	IN-LB/IN
H_{NS}	= 7994.7	LBS/IN

*NOTE:

THE INFLUENCE COEFFICIENTS USED IN THIS ANALYSIS WERE BASED ON THE 1.25 X NOMINAL HEATING RATE VALUES, AND THE FORCES DEVELOPED ARE TO BE USED TO REPRESENT THE FORCES DEVELOPED IN THE PRESSURE ONLY CASE FOR ALL HEATING RATE VALUES.

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D. Nozzle Shell Thermal Gradients

The temperature gradients through the nozzle shell wall are plotted on Figures 10 through 45. These gradients are derived from the temperature distributions shown in Reference 4.

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FIG. 10

TEMPERATURE GRADIENT THRU WALL

1.00 x N.H.R.

STA. 28.224

$t = 0.425$

REGION 7

JLP 6/20/66

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FIG. 11

TEMPERATURE GRADIENT THRU WALL
1.00 x N.H.R.

STA 84.5055

$t = 0.53062$

REGION 7

UNCLASSIFIED

FIG. 12

TEMPERATURE GRADIENT THRU WALL
1.00 x N.H.R.

STA 80.2628

t = 0.6384

REGION 7 (END)

JLP 6/23/66

46

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FIG. 13

TEMPERATURE GRADIENT THRU WALL
1.00 x N. H. R.

STA 76.0201

$t = 0.74419$

REGION 8 (END)

JLP 6/28/66

47

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FIG. 14

TEMPERATURE GRADIENT THRU WALL
1.00 X N.H.R.

STA. 73.8938

t = 0.79708

REGION 9

UNCLASSIFIED

FIG. 15

TEMPERATURE GRADIENT THRU WALL
1.00 x N H R

STA 71.7775

t = 0.850

REGION 9 (END)

JLP 6/23/66

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FIG. 16

TEMPERATURE GRADIENT THRU WALL
1.00 x N.H.R.

REGION 10

(MIDDLE OF REGION)

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FIG. 17

TEMPERATURE GRADIENT THRU WALL
1.00 x N.H.R.

REGION 10 (END)

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FIG. 18

TEMPERATURE GRADIENT THRU WALL
 $1.0 \times \text{N.H.R.}$

REGION 11

(MIDDLE OF REGION)

UNCLASSIFIED

FIG. 19TEMPERATURE GRADIENT THRU WALL
 $1.00 \times \text{N.H.R.}$

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FIG. 20

TEMPERATURE GRADIENT THRU WALL
1.00 x NHR.

REGION 12

UNCLASSIFIED

FIG. 21TEMPERATURE GRADIENT THRU WALL
1.00x NHR

REGION 12 (END)

FIG. 22 - TEMPERATURE AT MATH MODEL SURFACES

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F/G. 23 - TEMPERATURE AT MATH MODEL SURFACES

1.00 x N.H.R

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FIG. 24 - TEMPERATURE AT MATH MODEL SURFACES

1.00 x N.H.R.

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FIG. 25

REGION 10

 $1.00 \times \text{N.H.R.}$

FIG. 26

REGION 11

1.00 x N.H.R

FIG. 27

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FIG. 28

TEMPERATURE GRADIENT THRU WALL
1.25 x N. H. R

STA 83.3224

$t = 0.425$

REGION 7

x -- FROM TEMP PROFILE, NSS 6/16/66

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FIG. 29

TEMPERATURE GRADIENT THRU WALL
1.25 x N. H. R.

STA 84.5055

 $t = 0.53263$

REGION 7

FIG. 30

TEMPERATURE GRADIENT THRU WALL
1.25 × N.H.R.

STA 80.2628

 $t = 0.6584$

REGION 17 (END)

FIG. 31

TEMPERATURE GRADIENT THRU WALL
1.25 X N. H. R.

STA 16.0203

 $t = 0.74119$

REG ON 3 (END)

FIG. 32

TEMPERATURE GRADIENT THRU WALL
 $1.25 \times \text{N.H.R}$

STA 73.8983

$t = .79708$

REGION 9

x--- FROM TEMP PLOT II, N.E.S. 5/15/66

FIG. 33

TEMPERATURE GRADIENT THRU WALL
 $1.25 \times \text{N.H.R}$

STA 71.7775

$t = 0.350$

REGION 9 (END)

FIG. 34

TEMPERATURE GRADIENT THRU WALL
 $1.25 \times N.H.R.$

REGION 10

(MIDDLE OF REGION)

FIG. 35TEMPERATURE GRADIENT THRU WALL
 $1.25 \times \text{N.H.R.}$

REGION 10 (END)

FIG. 36TEMPERATURE GRADIENT THRU WALL
 $1.25 \times \text{N.H.R.}$ REGION 11
(MIDDLE OF REGION)

FIG. 37TEMPERATURE GRADIENT THRU WALL
 $1.25 \times \text{N.H.R.}$

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FIG. 33

TEMPERATURE GRADIENT THRU WALL
 $1.25 \times \text{N.H.R.}$

REGION 12

(MIDDLE OF REGION)

UNCLASSIFIED

FIG. 39

TEMPERATURE GRADIENT THRU WALL
 $1.25 \times N.H.R.$

REGION 12 (END)

FIG. 40

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UNCLASSIFIED

UNCLASSIFIED

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UNCLASSIFIED

UNCLASSIFIED

76

1.25 x N.H.R.

UNCLASSIFIED

FIG. 43

UNCLASSIFIED

FIG. 44

WRAP LENGTH

REGION 11

1.25 x N.H.R.

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UNCLASSIFIED

WRAP LENGTH

REGION 12

1.25 x N. H. R.

UNCLASSIFIED

VI. RESULTSA. General Summary

The table presented below shows the derivation of the stress categories from the analytical results of the PETS Computer Program. The stress categories are defined and discussed in in Section III, ASSUMPTIONS AND DESIGN CRITERIA. The terms $\sigma_{o.s.}$ and $\sigma_{i.s.}$ refer to the PETS Code output stresses on the outer surface and inner surface, respectively. Subscript M refers to mechanical stresses only, and subscript T refers to thermal stresses only.

The combinations of PETS Code output stresses resulting in the stress categories of P_m , P_b , Q , and F for both the pressure vessel and the nozzle are shown in this table, together with the allowable stress parameters from which margins of safety have been calculated.

The table on page 81 shows a general summary of these stress category values and their associated margins of safety.

	P_m	$P_m + P_b$	$P_m + P_b + Q$	F	$P_m + P_b + Q + F$
Nozzle	$\frac{\sigma_{o.s.M} + \sigma_{i.s.M}}{2}$		$\sigma_{o.s.M}$ or $\sigma_{i.s.M}$	$\sigma_{o.s.T}$ or $\sigma_{i.s.T}$	$\sigma_{o.s.M}$ or $\sigma_{i.s.M}$ + $\sigma_{o.s.T}$ or $\sigma_{i.s.T}$ (Manual Superposition)
Allowable	$.85 F_y^*$	$1.25 F_y$	$2 F_y$		$2.0 S_a$
Pressure Vessel	$\frac{\sigma_{os.M} + \sigma_{i.s.M}}{2}$	$\sigma_{o.s.M}$ or $\sigma_{i.s.M}$	$\sigma_{o.s.M+T}$ or $\sigma_{i.s.M+T}$		
Allowable	$.85 F_y$	$1.2 F_y$	$1.0 F_u$		$2.0 S_a$

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A. General Summary (Continued)

STRESSES AND MARGINS OF SAFETY

COMPONENT	STRESS INTENSITIES* (PSI)					MINIMUM MARGINS OF SAFETY*			
Stress Direction	P_m	$P_m + P_b$	$P_m + P_b + Q$	F	$P_m + P_b + Q + F$	P_m	$P_m + P_b$	$P_m + P_b + Q$	$P_m + P_b + Q + F$
<u>NOZZLE SHELL</u>									(100 cycles)
Hoop (Inner)	31,100	---	32,140	245,190	277,330	.00	---	High	.73
Hoop (Outer)	31,100	---	28,100	---	---	.00	---	High	---
Meridional (Inner)	12,800	---	10,980	---	---	High	---	High	---
Meridional (Outer)	12,800	---	18,180	---	---	High	---	High	---
(See Pages 87 thru 90)									
<u>NOZZLE SKIRT</u>									
Hoop (Inner)	17,920	---	4,708	58,200	62,900	High	---	High	2.82
Hoop (Outer)	17,920	---	31,140	-4,101	27,040	High	---	High	7.88
Meridional (Inner)	-6,127	---	-48,130	63,220	15,090	High	---	High	High
Meridional (Outer)	-6,127	---	35,880	-21,630	14,250	High	---	High	High
<u>P.V. SHELL</u>									
Hoop	36,200	37,180	40,260	---	---	.26	.74	.83	---
Meridional	14,770	27,540	51,120	---	---	High	High	High	---
(See Pages 106, 107)									
<u>NOZZLE FLANGE</u>	Bending	Shear	Tension						Bend + Shr. + Tension
(See Page 138)	30,200	4,210	7,300	---	---	---	---	---	.08
<u>SHEAR LIP</u>									
(See Page 140)	25,400	12,750	---	---	---	---	---	---	.72
<u>P.V. FLANGE</u>	Shear (Due to Shear-Up)	Bearing	Tension (Horiz. Bolt Pull-Out)	Shear	---	Shear (Due to Shear Lip)	Bearing	Tension (Horiz. Bolt Pull-Out)	Shear
Radial	12,160	26,000	45,730	16,750	---	.90	High	.00	.37
(See Page 128)						(All Based On Yield Strength)			

*For definition of Stress Intensity Categories and Allowables, see Section III, ASSUMPTIONS AND DESIGN CRITERIA.

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VI. RESULTS (Continued)B. Nozzle (other than flange)

The primary hoop membrane stress caused by mechanical loading was the main consideration in sizing the nozzle shell. The design criteria dictates that this stress, P_m , shall be no more than .85 times the yield stress of the material (F_y). The mean wall temperature of the shell during the 1.25 N.H.R. steady-state operating condition was selected as the temperature at which the yield strength is to be evaluated. The yield stress of the nozzle shell material has been determined from a materials testing program and has been adjusted to a higher value than would normally be used. The basis for "upgrading" the value of F_y for the Hastelloy-X nozzle shell material is as follows:

1. An "offset" value of .004 in./in. on the stress-strain curve has been selected as the "yield point" of the material.
2. The state of stress on the nozzle shell is biaxial tension. Hence, a "biaxial gain" factor enhances the yield strength of the material. This factor has been calculated to be 8% of the uniaxial yield strength.

The minimum margins of safety for primary hoop membrane stress occur at the intersection of regions 8 and 9 (see Figure 2b). Tabulations of nozzle shell primary and secondary stresses and calculated margins of safety are presented on pages 84 thru 90.

The core support portion of the nozzle is not critical and has high margins of safety for all stress categories.

The mechanical stresses are shown in Figures 48 thru 59, and were obtained by inputting the calculated load values on the mathematical computer models of both the shell and core support skirt. Values used are:

Nozzle Shell

$$\begin{aligned} M_{\xi} &= -891.5 \text{ in-lbs./in.} \\ H &= +7994.7 \text{ lbs./in.} \\ \text{Pressure} &= -612.3 \text{ psi} \end{aligned}$$

Skirt

$$\begin{aligned} M_{\xi} &= -2362.5 \text{ in-lbs.} \\ H &= -1671.4 \text{ lbs./in.} \\ \text{Pressure} &= +230.0 \text{ psi} \end{aligned}$$

For values, and sign conventions, refer to the simultaneous equation solution of the nozzle flange, page 42.

The thermal stresses for both 1.0 N.H.R. and 1.25 N.H.R. conditions are shown in Figures 68 thru 79 and were obtained directly from the Combined Nozzle/Pressure Vessel Thermal Model Output. The combined mechanical plus thermal parameters were obtained by superposition, and combined stresses are tabulated on page 90.

The radial deflection and rotation behavior of the nozzle shell and core support skirt was obtained by superposition, and these parameters are plotted on Figures 46 thru 47.

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VI. B. (Continued)

Allowable Stress:

Point of minimum margin of safety

Ref: Nozzle Shell Hoop Membrane Stress

Station 76.0201

@t = 0.7442

1.25 x N.H.R.

Temperature

Thru Wall

% t	T °R	T — °F	YIELD STRENGTH (KSI)		
			0.2%	0.3%	0.4%
5	360	-100	48.7	51.0	52.6
15	610	150	35.8	37.8	39.2
25	805	345	31.0	33.0	34.4
35	945	485	29.0	31.0	32.5
45	1035	575	28.0	30.0	31.5
55	1110	650	27.4	29.0	30.7
65	1170	710	26.9	28.5	30.0
75	1225	765	26.4	28.0	29.6
85	1275	815	26.0	27.5	29.1
95	1315	855	25.6	27.1	28.9
AVERAGE	985	525	30.48	32.29	33.85

$$F_y^* = (0.85 \times 1.08) F_{Ty} = 0.918 F_{Ty}$$

where: 0.85 is from SDS No. SNPO-C-1, Rev. O, Dec.

1.08 is biaxial gain factor from MIL-HDBK-5

$$@0.2\% \quad F_y^* = (.918)(30.48) = 27,981 \text{ psi}$$

$$@0.3\% \quad F_y^* = (.918)(32.29) = 29,642 \text{ psi}$$

$$@0.4\% \quad F_y^* = (.918)(33.85) = 31,100 \text{ psi}$$

VI. B. (Continued)

Allowable Stress (Continued)

Minimum margin of safety location:

Station 76.0201 @t = 0.7442

$$\sigma_{pm} = 29,050 \text{ psi}$$

This stress value, from the computer printout Case 600.11 Mechanical Stress, does not include the tube grooves.

The stress developed when assuming that the tube grooves are 50% effective is:

$$29,050 \times \frac{.7442}{.6942} = 31,100 \text{ psi} \\ (\text{M.S.} = -0.13)$$

A negative margin of safety is a result when a 0.4% offset is used for the yield allowable (nozzle shell hoop membrane stress table). But considering the stress field in which the part is acting and adjusting, the yield condition for that distribution by means of the biaxial gain effect, a positive margin of safety can be obtained.

Thus:

@0.4% offset & a 1.08% increase due to biaxial gain

$$F_y^* = 31,074$$

$$\text{M.S.} = \frac{31,100}{31,100} - 1 \\ = \underline{\underline{+0.0}}$$

∴ Assume all negative M.S. values on the hoop membrane table can be made positive by using the biaxial gain effect.

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NOZZLE SHELL MERIDIONAL MEMBRANE STRESS (PRIMARY)

Region	Station	XI	Thickness	N_{ξ}	$\sigma_{pm} = \frac{N_{\xi}}{t}$	σ_{pm}' Tube Grooves	MWT °F		.85 F_y @ MWT		M. S.	
	(inches)	(inches)	(inches)	(kips)	(psi)	50% Eff.	1.0	1.25	1.00	1.25	1.0	1.25
1 - 5	DIVERGENT PORTION OF NOZZLE SHELL IS LOW STRESS AREA											
6	94.160	0.0	.425	-1.01	-2380	-2690	-150	-100	47,500	44,795	↑ HIGH ↓	↑ HIGH ↓
	88.822	5.78	.425	0.22	520	590	25	90	38,590	35,700		
7	84.5055	6.11	.5326	3.2	6,000	6,600	150	235	33,320	31,280		
	80.263	12.10	.6384	5.69	8,900	9,670	312	410	29,835	28,390		
8	78.85	2.00	.6737	6.5	9,650	10,400	345	445	29,325	28,050		
	77.43	4.00	.7089	7.3	10,300	11,050	375	485	28,900	27,625		
	76.02	6.00	.7442	8.09	10,870	11,700	412	525	28,390	27,200		
9	74.61	2.00	.7795	8.85	11,350	12,110	435	550	28,050	27,030		
	73.19	4.00	.8147	9.58	11,750	12,530	390	495	28,730	27,540		
	71.78	6.00	.850	10.21	12,020	12,800	275	366	30,345	28,900		
10	71.44	0.48	.88	10.35	11,760	12,500	140	220	33,660	31,450		
	71.11	0.93	.94	10.43	11,100	11,800	127	254	33,915	30,770		
11	70.75	0.48	1.10	10.69	9,720	10,180	195	302	32,215	30,005		
	70.40	0.947	1.295	10.88	8,400	8,530	310	400	29,750	28,560		
12	70.01	0.50	1.674	11.64	6,950	7,100	335	463	29,410	27,800		
	69.62	0.99	2.16	12.54	5,820	5,960	290	397	30,090	28,645		

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NOZZLE SHELL MERIDIONAL STRESS (SECONDARY)

Region	Inner Surface					M.S.	Outer Surface			
	Station	XI	Stress	Temp. °F	2 F _y		Stress	Temp., °F	2 F _y	M.S.
	(inches)	(inches)	(psi)	@ 1.25 N.S.S.	(ksi)		(psi)	@ 1.25 N.S.S.	(ksi)	
1 - 5	DIVERGENT PORTION OF NOZZLE SHELL IS LOW STRESS AREA									
6	94.160	0.0	1,400	-300	135	↑ HIGH ↓	-6453	280	70	↑ HIGH ↓
	88.822	5.78	-400	-300	135		1,370	280	70	
7	84.5055	6.11	6,180	-300	135		5,740	480	65	
	80.263	12.10	10,400	-290	134		7,970	710	60	
8	78.85	2.00	10,980	-280	132		8,900	760	58	
	77.43	4.00	10,750	-270	130		10,400	840	57	
	76.02	6.00	9,790	-270	130		12,410	880	56	
9	74.61	2.00	8,300	-270	130		14,700	900	55	
	73.19	4.00	6,950	-270	130		16,750	810	58	
	71.78	6.00	6,380	-280	132		17,780	610	61	
10	71.44	0.48	6,100	-280	132		17,680	170	76	
	71.11	0.93	4,810	-280	132		18,180	-130	108	
11	70.75	0.48	4,780	-280	132		15,490	-310	137	
	70.40	0.947	4,310	-280	132		13,750	-330	142	
12	70.01	0.50	4,880	-280	132		9,760	-370	160	
	69.62	0.99	5,030	-300	135		7,283	-370	160	

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NOZZLE SHELL HOOP STRESSES, COMBINED MECHANICAL AND THERMAL LOADING, 1.25 N.H.R.

INNER SURFACE⁽²⁾: $\sigma_{M+T} = P_m + P_b + Q + F$

Region	Station	Xl	σ_M	σ_T	σ_{M+T}	Temp.	2 Sa ⁽¹⁾	M. S.
	(inches)	(inches)	(psi)	(psi)	(psi)	°F		
6	94.160	0.0	5,122	71,149	76,271	-300	480,000	High
	88.8224	5.7813	19,986	110,500	130,486	-300	480,000	High
7	84.5055	6.11	27,100	140,000	167,100	-300	480,000	High
	80.2628	12.105	30,460	211,200	241,660	-290	480,000	0.99
8	78.85	2.00	31,500	228,000	259,500	-280	480,000	0.85
	77.43	4.00	32,140	241,000	273,140	-270	480,000	0.75
	76.02	6.00	32,140	245,190	277,330	-270	480,000	0.73
9	74.61	2.00	31,200	238,000	269,200	-270	280,000	0.78
	73.19	4.00	29,400	216,000	245,400	-270	480,000	0.95
	71.78	6.00	26,440	175,590	202,030	-280	480,000	High
10	71.44	0.48	25,300	168,000	193,300	-280	480,000	High
	71.11	0.93	23,790	165,800	189,590	-280	480,000	High
11	70.75	0.48	22,500	166,680	189,470	-280	480,000	High
	70.40	0.947	21,030	160,920	181,950	-280	480,000	High
12	70.01	0.50	19,600	150,000	169,600	-280	480,000	High
	69.62	0.99	17,940	121,110	139,050	-300	480,000	High

(1) Value for 2 Sa, 480 ksi, was selected on basis of low-cycle fatigue testing conducted at AGC, Sacramento. Complete test results will be published at a future date.

(2) Meridional stresses and outer surface hoop stresses are not critical for combined mechanical and thermal loads.

FIG. 46

NOZZLE ROTATION, MECHANICAL AND THERMAL LOADS

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CASE 600.11

FIGURE 48

1FLAT C60-1

NOZZLE SHELL

MECH STRESS

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CASE 600.11

FIGURE 50

1FLAT C60-1

NOZZLE SHELL

XI (WRAP LENGTH)

MECH STRESS

N. S. S

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CASE 600.11

FIGURE 51

1FLAT C60-1

NOZZLE SHELL

XI (WRAP LENGTH)

MECH STRESS

N. S. S

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DATE 10.26.1966

CASE 600.11

FIGURE 52

1FLAT C60-1

NOZZLE

SHELL

XI (WRAP LENGTH)

MECH STRESS

N. S. S

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DATE 10.26.1966

CASE 600.11

FIGURE 53

1FLAT C60-1

NOZZLE SHELL

XI (WRAP LENGTH)

MECH STRESS

N. S. S

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DATE 10.26.1966

CASE 600.23

FIGURE 54

1 FLAT C60-2 CORE SUPPORT MECH STRESS N.S.S.

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FIGURE 55

LAT C60-2 CORE SUPPORT MECH STRESS N.S.S.

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CASE 600.23

FIGURE 56

1 FLAT C60-2 CORE SUPPORT MECH ^{XI} (WRAP LENGTH) STRESS N.S.S.

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CASE 600.23

FIGURE 57

1 FLAT CGO-2 CORE SUPPORT MECH STRESS N.S.S.

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FIGURE 58

1 FLAT CGO-2 CORE SUPPORT MECH STRESS N.S.S.

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FIGURE 59

1 FLAT C60-2 CORE SUPPORT MECH STRESS N.S.S

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VI. RESULTS (Continued)C. Pressure Vessel

The three design stress intensity parameters and their permissible values are:

1. Primary membrane stress, $P_m \leq .85 F_y$.
2. Primary membrane + primary bending, $P_m + P_b \leq 1.2 F_y$.
3. Primary membrane + primary bending + secondary (thermal)
 $P_m + P_b + Q \leq 2.0 F_y \leq 1.0 F_u$.

Tables I, II, III, and IV on pages 106 thru 107 show the maximum values of stress intensity in the hoop and meridional directions. The plots of these stresses are shown in Figures 60 thru 65, taken directly from the PETS Code output of the pressure vessel model. The correct interface values of moment and horizontal force were used as input for the end conditions.

In addition to the stress results obtained from the PETS Computer Code, four areas of local stress were investigated. The stresses in these local areas are tabulated in Table V, page 128. The stress calculations immediately follow.

TABLES OF PRESSURE VESSEL RESULTS

TABLE I: MAXIMUM HOOP STRESSES, 1.00 NHR CONDITION

Nom.	Category	Max. Value (KSI)	Location	Temp. °F	F _y (KSI)	F _u (KSI)	Allowable (KSI)	Margin of Safety
P _m	Prin. Memb.	36.2	Region 4, XI = 12.0	-275	53.8	74.0	45.7	.26
P _m + P _b	Prin. Memb. + Prin. Bending	37.18	Region 4, XI = 9.0 Outside Surface	-275	53.8	74.0	64.6	.74
P _m + P _b + Q	Prin. Memb. + Prin. Bending + Secondary (Thermal)	38.53	Region 4, XI = 13.0 Inside Surface	-275	53.5	74.0	74.0	.92

TABLE II: MAXIMUM MERIDIONAL STRESSES, 1.00 NHR CONDITION

Nom.	Category	Max. Value (KSI)	Location	Temp. °F	F _y (KSI)	F _u (KSI)	Allowable (KSI)	Margin of Safety
P _m	Prin. Memb.	14.77	Junction Regions 3 & 4	-278	54.0	74.0	45.9	High
P _m + P _b	Prin. Memb. + Prin. Bending	27.54	Region 3, XI = 12.339 Inside Surface	-269	53.5	73.0	64.6	High
P _m + P _b + Q	Prin. Memb. + Prin. Bending + Secondary (Thermal)	41.26	Region 3, XI = 7.403 Inside Surface	-261	52.5	71.6	71.6	.74

TABLES OF PRESSURE VESSEL RESULTS (Continued)

TABLE III: MAXIMUM HOOP STRESS, 1.25 NHR CONDITION

Nom.	Category	Max. Value (KSI)	Location	Temp. °F	F _y (KSI)	F _u (KSI)	Allowable (KSI)	Margin of Safety
P _m	Prin. Memb.	36.2	Region 4 XI = 12.0	-269	53.5	73.5	45.5	.25
P _m + P _b	Prin. Memb. + Prin. Bending	37.18	Region 4, XI = 9.0 Outside Surface	-269	53.5	73.5	64.5	.73
P _m + P _b + Q	Prin. Memb. + Prin. Bending + Secondary (Thermal)	40.26	Region 4, XI = 9.0 Outside Surface	-269	53.5	73.5	73.5	.83

TABLE IV: MAXIMUM MERIDIONAL STRESSES, 1.25 NHR CONDITION

Nom.	Category	Max. Value (KSI)	Location	Temp. °F	F _y (KSI)	F _u (KSI)	Allowable (KSI)	Margin of Safety
P _m	Prin. Memb.	14.77	Junction Regions 3 & 4	-269	52.5	73.6	44.6	High
P _m + P _b	Prin. Memb. + Prin. Bending	27.54	Region 3, XI = 12339 Inside Surface	-260	52.5	71.6	63.	High
P _m + P _b + Q	Prin. Memb. + Prin. Bending + Secondary (Thermal)	51.12	Region 3 XI = 9.049 Inside Surface	-250	52.2	71.4	71.4	.38

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CASE 662.11

FIGURE 50

FLAT C62-2 PRESSURE VESSEL MECHANICAL LOADS INP

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FIGURE 61

FLAT C62-2 PRESSURE VESSEL MECHANICAL LOADS IN PSI

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FIGURE 62

1 FLAT C62-2 PRESSURE VESSEL MECHANICAL LOADS

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FIGURE 63

FLAT C62-2 PRESSURE VESSEL MECHANICAL LOADS I:

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CASE 362.11

FIGURE 34

FLAT C62-2 PRESSURE VESSEL MECHANICAL LOADS I:

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DATE 10.25.1966

CASE 662.11

FIGURE 65

1 FLAT C62-2 PRESSURE VESSEL MECHANICAL LOADS I

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UNCLASSIFIED

DATE 9.01.1966

CASE

1.00

FIGURE 68

IFLAT C62

THERMAL

XI (LAP LENGTH)
STRESS

1.00 X N.

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DATE 9.01.1966

CASE 1.00

FIGURE 69

IFLAT 062

XI (WRAP LENGTH)
THERMAL STRESS 1.00 X N.

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UNCLASSIFIED

DATE 9.01.1966

CASE

1.00

FIGURE 70

FLAT C62

THERMAL

STRESS

1.00 X

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UNCLASSIFIED

UNCLASSIFIED

DATE 9.01.1966

CASE

1.00

FIGURE 72

1 FLAT C62

THERMAL

STRESS

1.00 X 1

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UNCLASSIFIED

DATE 9.01.1966

CASE

1.00

FIGURE 73

1FLAT C62

THERMAL

XI (RAP LENGTH)
STRESS 1.00

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DATE 9.01.1966

CASE 1.25

FIGURE 74

1 FLAT C62 THERMAL XI (WRAP LENGTH) STRESS 1.25 X N.

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DATE 9.01.1966

CASE 1.25

FIGURE 75

FLAT C62

THERMAL

XI (WRAP LENGTH)
STRESS

1.25 X N. H. R.

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UNCLASSIFIED

DATE 9.01.1966

CASE 1.25

FIGURE 76

FLAT C62

THERMAL

XI (WRAP LENGTH)

STRESS

1.25 X

N. H. R.

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DATE 9.01.1966

CASE 1.25

FIGURE 77

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CASE 1.25

FIGURE 78

FLAT C62

THERMAL

XI (WRAP LENGTH)
STRESS

1.25 X N.

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TABLE V
Local Stresses (Hand Calculations)

ITEM	LOCATION (See Sketch)	NHR	VALUE (ksi)	TEMP. (°F)	YIELD (ksi)	MARGIN OF SAFETY	ULT. (ksi)	MARGIN OF SAFETY
Bearing, due to Shear Lip	1	1.00	52.0	-100	91.	.75	120.	1.31
		1.25	49.7	-60	91.	0.83	120.	1.41
Shear, due to Shear Lip	2	1.00	12.16	-60	23.15	.90	30.9	1.54
		1.25	11.65	0	23.	.97	30.	1.57
Tension, due to Bolt	3	1.00	45.73	-140	46.2	.02	66.0	.44
		1.25	45.73	-105	46.8	.00	63.	.37
Shear, due to Bolt	4	1.00	18.75	-140	23.1	.38	33.	.97
		1.25	16.75	-105	22.9	.37	31.5	.88

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Bearing Area

$$= 2\pi \times 33.625 [(.430 - .015) - (.060 + .015) - (+.040 + .010)]$$

$$= 61.27 \text{ in}^2$$

$$F_{\text{bry}} = 91,000 \text{ psi}$$

$$F_{\text{bru}} = 120,000 \text{ psi}$$

Assume: H is triangularly distributed over bearing area.

Case I - Mechanical Loads Only

$$H = 11,694 \text{ at } R = 32.0$$

$$\sigma_B = 12,073 \times 4\pi \times 32/61.27 = 76,600 \text{ psi}$$

$$MS_{(y)} = 91,000/76,600 - 1 = 0.19$$

$$MS_{(u)} = 120,000/76,600 - 1 = 1.57$$

Case II - Operating Conditions (1.00 NHR)

$$H = 7919. \text{ at } R = 32.0$$

$$\sigma_B = 4\pi \times 7919. \times 32.0/61.27 = 52,000 \text{ psi}$$

$$MS_{(y)} = 91,000/\sigma_B - 1 = .75$$

$$MS_{(u)} = 120,000/\sigma_B - 1 = 1.31$$

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Case III — Operating Conditions (1.25 NHR)

$$H = 7579. \text{ at } R = 32.0$$

$$\sigma_B = 4\pi R H / 61.27 = 49700. \text{ psi}$$

$$MS_{(y)} = 91,000 / \sigma_B - 1 = .83$$

$$MS_{(u)} = 120,000 / \sigma_B - 1 = 1.41$$

Assume all H load acts above seal groove depth

$$\text{Shear Area} = [(33.625)^2 - (33.0)^2]\pi = 130.82 \text{ in}^2$$

Case I - Mechanical Loads

$$H = 11,694 \text{ at } R = 32$$

$$\tau = 11,694 \times 2\pi \times 32/A = 17,950 \text{ psi}$$

$$T(^{\circ}\text{F}) = \text{along plane a-b} = -60^{\circ}$$

$$F_y(T=-60^{\circ}) = 46,300 \text{ psi} \therefore F_{sy} \approx \frac{46,300}{2} \approx 23,150 \text{ psi}$$

$$F_u(T=-60^{\circ}) = 61,800 \text{ psi} \therefore F_{su} \approx \frac{61,800}{2} \approx 30,900 \text{ psi}$$

$$MS_{(y)} = F_{sy}/\tau - 1 = .29 \text{ shear, yield}$$

$$MS_{(u)} = F_{su}/\tau - 1 = .72 \text{ shear, ultimate}$$

Case II - Operating Conditions (1.00 NHR)

$$H = 7919. \text{ at } R = 32.0$$

$$\tau = 2\pi R H/A = 12,160$$

$$MS_{(y)} = 23,150/\tau - 1 = .90$$

$$MS_{(u)} = 30,900/\tau - 1 = 1.54$$

Case III - Operating Conditions (1.25 NHR)

$$H = 7579 \text{ at } R = 32.0$$

$$\tau = 2\pi R H/A = 11,650 \text{ psi}$$

$$MS_{(y)} = 23,000/\tau - 1 = .97$$

$$MS_{(u)} = 30,000/\tau - 1 = 1.57$$

Differential Movement

The pressure vessel at the interface may move outward possibly as much as .020 inches before it contacts the nozzle shear lip. If the worst case is assumed, friction at the bolt head and no friction at the interface, the bolt will (1) move .020 in. with respect to the bolt threads in the PV, or (2) a maximum frictional force will be developed at the bolt head.

Case I

Assume friction at the bolt head develops enough force to move head of bolt .020 in. with respect to bolt threads.

Assume bolt fixed WRT rotation at each end

$$\text{Bolt OD} = .552" \quad \text{ID} = .125"$$

$$A = \frac{\pi}{4} [(.552)^2 - (.125)^2] = .7854 (.289079) = .227043 \text{ in.}^2$$

$$I = \frac{\pi}{64} [(.552)^4 - (.125)^4] = .0490875 (.092845 - .000244) = .004546 \text{ in.}^4$$

Deflection due to shear

$$\Delta_v = \frac{F\ell}{AE}$$

Deflection due to moment

$$\Delta_M = \frac{1}{2} \left(-\frac{M}{EI} \right) \frac{\ell}{2} \times \frac{1}{3} \frac{\ell}{2} + \frac{1}{2} \left(+\frac{M}{EI} \right) \frac{\ell}{2} \left(\frac{\ell}{2} + \frac{2}{3} \frac{\ell}{2} \right) = \frac{M\ell^2}{6EI}$$

$$M = F \times \frac{\ell}{2} \quad \therefore \Delta_M = \frac{F\ell^3}{12EI}$$

$$\Delta = .020 = \frac{F\ell}{AE} + \frac{F\ell^3}{12EI}$$

$$E = 30 \times 10^6$$

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$$F \left(\frac{1.56}{.227043} + \frac{(1.56)^3}{2} \times .004546 \right) = .020 \times 30 \times 10^6$$

$$F (6.870945 + 69.592609) = .020 \times 30 \times 10^6$$

$$F = \frac{.6 \times 10^6}{76.463554} = \frac{60 \times 10^4}{76.463554} = 7850 \text{ lbs.}$$

CASE II:

Find Maximum F Due to Friction:

Assume coefficient of friction between bolt head and nozzle = .15.

Assume coefficient of friction between nozzle and pressure vessel = 0.

Assume axial load on bolt = 32,000 lbs (see page /52)

then, $F = .15 \times 32,000 = \underline{4800 \text{ lbs/bolt}}$

∴ F due to friction is largest horizontal load on bolt.

Check pressure vessel for stress due to bolt load: (Next page)

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Check tension on Section AA top of PV.

$$\sigma_{AA} = \frac{E}{A} + \frac{M_c}{I}$$

$$F = 4800 \text{ lbs.}$$

$$A = (1.396 - .750)(1.6) = .646 \times 1.6 = 1.0336 \text{ in.}^2$$

$$C = 1.6/2 = 0.80 \text{ in.}$$

$$I = \frac{.646}{12} (1.6)^3 = .2205 \text{ in.}^4$$

$$M = 4800 \times (1.56 + \frac{1.6}{2}) = 11,320 \text{ in-lbs.}$$

$$\sigma_{AA} = 4800/1.0336 + 11,320 (1.6/2) / .2205 = 45,730 \text{ psi (tension)}$$

Temperature at top A-A 1.00 NHR - 140°F

 1.25 NHR - 105°F

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$F_y(-140) = 46,200 \text{ psi}$	$F_u(-140) = 66,000 \text{ psi}$
$F_y(-105) = 45,800 \text{ psi}$	$F_u(-105) = 63,000 \text{ psi}$
$F_y(\text{RM T}) = 45,000 \text{ psi}$	$F_u(\text{RM T}) = 55,000 \text{ psi}$
$FS_y(-140) = 46,200/45,730 = 1.02$	$FS_u(-140) = 66,000/45,730 = 1.44$
$FS_y(-105) = 45,800/45,730 = 1.00$	$FS_u(-105) = 63,000/45,730 = 1.37$
$FS_y(\text{RM T}) = 45,000/45,730 = 0.98$	$FS_u(\text{RM T}) = 55,000/45,730 = 1.20$

Check shear pullout at top of Section AB; due to bearing of bolts.

$P = \text{load rate (lbs./in.) at top of Section AA}$

$$P = \sigma_{AA} \times .646 = 45,730 \times .646 = 29,600 \text{ lbs./in.}$$

Applying this load at the top of (2) Section AB gives

$$\tau_{AB} = 29,600/2 \times (.8825) = 16,750 \text{ psi}$$

$$\text{Since: } F_{sy} \approx F_y/2; F_{su} \approx F_u/2 ;$$

then, for shear

$FS_y(-140) = 46,200/2\tau = 1.38$	$FS_u(-140) = 66,000/2\tau = 1.97$
$FS_y(-105) = 45,800/2\tau = 1.37$	$FS_u(-105) = 63,000/2\tau = 1.88$
$FS_y(\text{RM T}) = 45,000/2\tau = 1.34$	$FS_u(\text{RM T}) = 55,000/2\tau = 1.61$

VI. RESULTS (Continued)

D. Interface

1. Interface Behavior and Nozzle Flange Analysis:

The tables on page 42 shows the simultaneous equations solutions, FLAT-C62 configuration, mechanical loads only. The net loads and deflections for both mechanical and thermal loads at both 1.00 NHR and 1.25 NHR conditions are shown on the following pages. An examination of the interface loads and deflections shows that the interface behavior is expected to be satisfactory in all respects.

VI. D. 1. (Continued)

(1) Positive directions are shown.

(2) Values at $R = 32.0$ in.

INTERFACE LOAD COMBINATIONS

UNITS →	V	M_{pv}	H_{pv}	u	β
CASE	lbs./in.	in-lbs./in.	lbs./in.	inches	radians
Mechanical Loads Only	11,306	-680.5	11,694	.0153	-.00210
Thermal Loads, 1.0 N.H.R.	0	1,870	-3,775	-.0184	-.01848
Thermal Loads, 1.25 N.H.R.	0	2,070	-4,115	-.0035	-.02066
Mechanical + Thermal, 1.0 N.S.S.	11,306	1,190	7,919	-.0031	-.02058
Mechanical + Thermal, 1.25 N.S.S.	11,306	1,390	7,579	.0118	-.02276

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VI. D. 1. (Continued)

Summary:

SECTION	STRESS	M. S.	
		1.0 x N.H.R.	1.25 x N.H.R.
A - A	$\sigma_b = 25,400$ $\tau = 12,750$	.81	.72
B - B	$\sigma_b = 30,200$ $\sigma_T = 7,300$	.14	.08
C - C	$\sigma_b = 45,660$ $\sigma_T = 13,450$	.04*	

* $\approx$ SAME MEAN TEMPERATURE

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VI. D. 1. (Continued)

Shear Lip.

The force values are taken from the simultaneous equation solution of the FLAT-C62.

$$H_{pV} = 11694 \text{ lbs./in. at } 32.000 \text{ in. } R$$

Transfer H_{pV} at 32.000 to 33.625 for H'_{pV}

$$\begin{aligned} \therefore H'_{pV} &= 11694 \times \frac{32.000}{33.6275} \\ &= 11129 \text{ lbs./in. at } 33.625 \text{ in.} \end{aligned}$$

Bending Stress:

$$M = (.29)(11129)$$

$$= 3227 \text{ in-lbs/in.}$$

$$\sigma = \frac{6M}{t^2} = \frac{6(3227)}{(.8725)^2} = 25450 \text{ psi}$$

Shear Stress:

$$\tau = \frac{11129}{0.8725} = 12780 \text{ psi}$$

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SHEAR LIP

(CONT.)

MARGIN OF SAFETY

1.00 x NHR

1.25 x NHR

BENDING STRESS IS TENSION ON THE INSIDE SURFACE.

$$\therefore T_{AVE} = 422 + 9/2 = 215^{\circ}F$$

$$T_{AVE} = 541 + 75/2 = 298^{\circ}F$$

$$F_{Ty@215} = 37200 \text{ PSI}$$

[20% WELD @ 0.4% OFFSET]

$$F_{Ty@298} = 35300 \text{ PSI}$$

[30% WELD @ 0.4% OFFSET]

BENDING MODULUS:

$$F_{By} = (1.24) (37200) \\ = 46128$$

$$F_{By} = (1.21) (35300) \\ = 43772$$

$$M.S. = \frac{46128}{25450} - 1 = +0.81$$

$$M.S. = \frac{43772}{25450} - 1 = +0.72$$

NOTE: SHEAR STRESS IS MAXIMUM AT THE NEUTRAL AXIS OF THE PIECE WHERE THE BENDING STRESS IS ZERO, THEREFORE IT WILL BE NEGLECTED IN THE DETERMINATION OF MARGIN OF SAFETY FOR THE SHEAR STRESS.

SECTION B-B

$$d = 0.66 + (\cos 30) (0.86603) (0.9)$$

$$H_{pv}' = 11129 \text{ #} @ R = 33.627$$

$$\begin{aligned} \text{MOMENT} &= H_{pv}' \cos 30 \times d \\ &= (11129) (0.86603) (0.911) \\ &= 8770 \text{ #-LB} \end{aligned}$$

$$F_{\text{SHEAR}} = H_{pv}' \sin 30^\circ = (11129) (0.5) = 5565 \text{ #}$$

$$F_{\text{TENSION}} = H_{pv}' \cos 30^\circ = (11129) (0.86603) = 9620 \text{ #}$$

BENDING STRESS:

$$\sigma_B = \frac{6M}{t^2} = \frac{6(8770)}{(1.32)^2} = 30200 \text{ PSI}$$

TENSION STRESS

$$\sigma_T = \frac{9620}{1.32} = 7290 \text{ PSI}$$

SHEAR STRESS

$$\tau = \frac{5565}{1.32} = 4220 \text{ PSI}$$

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SECTION B-B

(CONT.)

1.00 x NHR

1.25 x NHR

BENDING AND TENSION STRESS ARE ADDITIVE
AT THE INSIDE SURFACE OF THE FLANGE

$$T_{AVE} = 500 + 9/2 = 254^{\circ}\text{F}$$

$$T_{AVE} = 635 + 75/2 = 355^{\circ}\text{F}$$

$$F_{Ty @ 254} = 36100.$$

[3 SIGMA VALUE = 0.4% OFFSET]

$$F_{Ty @ 355} = 34200.$$

[3 SIGMA VALUE = 0.4% OFFSET]

$$F_{by} = (1.24)(36100) = 44764.$$

$$F_{by} = (1.24)(34200) = 42408.$$

MARGIN OF SAFETY:

$$M.S. = \frac{1}{\frac{F_{by}}{\sigma_b} + \frac{F_{Ty}}{\sigma_T}} - 1$$

$$M.S. (1.00) = \frac{1}{\frac{30200}{44764} + \frac{7290}{36100}} - 1 = +0.14$$

$$M.S. (1.25) = \frac{1}{\frac{30200}{42408} + \frac{7290}{34200}} - 1 = +0.08$$

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SECTION PROPERTIES:

ITEM	(Y) EAST	(X) HEIGHT	AREA	X	Y	AX	AY	AX ²	I _{o-y}
1.	0.8725	0.430	0.5752	0.415	2.7325	0.3007	.7745	.0175	0.005
2.	0.9094	1.025	0.9521	0.9425	2.0447	.3730	1.9007	.3730	0.000
3.	0.9094	0.525	0.2387	1.630	.8710	.3491	.450	.5642	0.000
4.	1.590	1.550	2.4645	1.205	0.125	1.510	1.2500	6.210	0.000
			4.0105			4.213	5.0014	5.23	0.584

$$\bar{X} = \frac{4.213}{4.0105} = 1.0767$$

$$\bar{Y} = \frac{5.0014}{4.0105} = 1.2500$$

$$I_{Y-Y} = \sum I_{o-y} + \sum A \bar{x}^2 - \sum A (\bar{x})^2$$

$$= 0.58414 + 5.23 - (4.0105)(1.0767)^2$$

$$= 0.775 \text{ IN}^4$$

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STRESS AT BOLT SECTION C-C

RING EQUATIONS

$$\beta = \frac{MR^2}{EI}$$

$$u = \frac{HR^2}{EA}$$

WHERE FOR PRESSURE ONLY CONDITION, FLAT C 62

$$\beta_{c.g.} = - .00210 \text{ Radian}$$

$$u_{c.g.} = + .0153 \text{ IN.}$$

$$E = 27.62 \times 10^6$$

$$\therefore \sum M_{c.g.} = \frac{(.0021)(27.62 \times 10^6)(.993)}{(33.2692)^2} = 52.0 \frac{\text{IN-LB}}{\text{IN}}$$

$$\sum H'_{c.g.} = \frac{(.0153)(27.62 \times 10^6)(4.0105)}{(33.2692)^2} = 1533 \frac{\#}{\text{IN}}$$

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BOLTS

144 BOLTS @ AN ANGLE OF 2.50° , 0.043625 IN.

1.312 COUNTER BORE

0.680 BORE

RADIUS @ 30.000 IN

$$\begin{aligned} \text{ARC LENGTH BETWEEN BOLTS} &= SR \\ &= (0.043625)(30.000) \\ &= 1.309 \text{ IN} \end{aligned}$$

$$\begin{aligned} \text{LAND BETWEEN BOLTS} &= 1.309 - 0.680 \\ &= 0.629 \end{aligned}$$

LAND BETWEEN C.B. = 0.032 IN.

PERCENT OF AREA REMOVED

$$\begin{aligned} \text{NET AREA} &= \frac{1.309 - 0.629}{1.309} \\ &= 0.519 \approx 52\% \end{aligned}$$

ASSUME A $K = 1.5$

TO COMPENSATE FOR
AREA REMOVED

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STRESS AT BOLT SECTION (CONT.)

$$\sum F_{RADIAL} = 0 = Q + H'_{C.G.} - H'_{PV}$$

$$@ R = 33.627 \quad Q \approx H'_{PV} - H'_{C.G.} = 11129 - 1533 = 9596$$

$$\text{CORRECTING TO } R = 32.0 \quad Q \approx \left(\frac{33.627}{32} \right) (9596) = 10080 \text{ LB/IN}$$

$$\sum M = 0 \quad \therefore M \approx \left[(.6467) H'_{PV} + M'_{C.G.} + (9596)(.1033) \right] \frac{33.27}{32}$$

$$M \approx [7200 + 52 + 990] \frac{33.27}{32} = 8560 \frac{\text{IN-LB}}{\text{IN}}$$

$$\sigma_b = \frac{6M}{t^2} = \frac{(6)(8560)}{(1.5)^2} = 22830 \text{ psi}$$

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BENDING STRENGTH IN THE PLASTIC RANGE:

HASTELLOY X

MECHANICAL PROPERTIES (30 VALUES)

[0.4% OFFSET] $F_{Ty @ RT} = 43000 \text{ PSI}$

$F_{tu @ RT} = 93900 \text{ PSI}$

METHOD REF. APPENDIX II - STRUCTURAL DESIGN
SPECIFICATION (SNPO-C-1)

A FICTITIOUS ULTIMATE BENDING STRESS, CALLED THE BENDING MODULUS OF RUPTURE, B CAN BE USED FOR ESTABLISHING THE BENDING STRENGTH OF A MATERIAL.

FOR A RECTANGULAR CROSS SECTION,
 $K=1.5$ AND THE ULTIMATE BENDING
MODULUS IS:

$$B_{u,1.5} = F_u + 1.5 f_{ou}$$

AND THE YIELD BENDING MODULUS IS:

$$B_{y,1.5} = F_{Ty} + 1.5 f_{oy}$$

WHERE:

$$\left. \begin{array}{l} f_{ou} = 35000 \\ f_{oy} = 21000 \end{array} \right\} \begin{array}{l} \text{BASED ON THE} \\ \text{AVERAGE CURVE} \end{array}$$

$$\& B_{y,1.5} = 43000 + (1.5)(21000)$$

$$= 53500 \text{ PSI}$$

THIS IS A 24% INCREASE OVER THE
ROOM TEMPERATURE TENSILE YIELD STRENGTH.
NOTING THAT THE YIELDING POINT IS STABLE
THROUGHOUT THE OPERATION TEMPERATURE
RANGE.

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STRESS AT BOLT SECTION: (CONT.)

BENDING STRESS: (CONT.)

THE BOLT HOLES REMOVE ABOUT 50 PERCENT OF THE MATERIAL, THEREFORE A STRESS CONCENTRATION OF "2" SHALL BE APPLIED TO ALL STRESSES ACTING IN THIS AREA.

$$\begin{aligned}\sigma_b &= (2)(22830) \\ &= 45660 \text{ PSI}\end{aligned}$$

TENSION STRESS:

$$\begin{aligned}\sigma_t &= \frac{10080}{1.5} \times 2 \\ &= 13450. \text{ PSI}\end{aligned}$$

THE BENDING AND TENSION STRESSES ARE ADDITIVE AT THE FRONT OF THE FLANGE.

APPROX TEMP $\approx 1200^\circ\text{F}$

$$F_{ty} = 52600$$

$$F_{uy} = (1.24)(52600) = 65224.$$

[3 SIGMA VALUE @ 0.4% OFFSET]

MARGIN OF SAFETY

$$\begin{aligned}\text{M.S.} &= \frac{1}{\frac{45660}{65224} + \frac{13450}{52600}} - 1 \\ &= \underline{\underline{+0.04}}\end{aligned}$$

VI. D. Interface (Continued)

2. Interface Load Distributions

The problem of determining the load distributions at the pressure vessel/nozzle interface is complicated by many factors. Notwithstanding these difficulties it is possible, by making overlapping assumptions, to analyze certain aspects of interface load distributions. These analyses are presented on the following pages.

Note that two types of interface bolts are used to join the nozzle to the pressure vessel. The standard bolt has a .557-inch outside diameter shank and a .125 diameter cooling hole drilled through the center. There are 18 non-standard bolts (of a total of 144 bolts) which have the center hole enlarged to .314-inch diameter. Both bolt configurations are analyzed in the following pages.

Extensive testing has been carried out on a 2-dimensional cross-section model of the interface. This model was wide enough to include three bolts (two standard and one non-standard). Photo-stress, strain-gage, and deflection gage data was collected during this testing. In general, this test corroborated the analysis presented herewith.

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VI. D. 2. (Continued)

Nozzle Attach Bolt Analysis

A total of 144 bolts are used to attach the nozzle to the pressure vessel. At 18 locations, the standard bolts (AGC Dwg. No. 1115487) are replaced by special bolts in which the outer hole is enlarged from nominal 0.125-inch diameter to 0.314-inch diameter.

The bolts (both standard and special) are made of A-286 alloy having a minimum yield strength at 70°F of 180,000 psi.

The loading conditions on the bolt are as follows:

- (1) Bolt preload
- (2) N.S.S., Nuclear Steady-State operating condition
- (3) Transient startup loads

Each of these loading conditions will be discussed.

Bolt Preload:

A high bolt preload is desirable to insure that the flanges of the nozzle and pressure vessel remain securely clamped together. Calibrated bolts are used during nozzle installation to measure the value of bolt axial load induced by the torquing procedure. During hydrostatic testing, a value of bolt preload of 34,000 lbs. was found to be satisfactory.

Nuclear Steady-State Operating Condition:

The 1.25 N.H.R. condition has the most critical temperature distribution:

Average bolt temperature = -380°F (Ref. Fig. 8, P2-65-31)

Effective bolt length = 1.708 inches

Flange expansion across 1.5-inch thickness = +.00105 inches.

VI. D. 2. (Continued)

Nuclear Steady-State Operating Condition (Continued)

$$\bar{\alpha} \text{ of A-286 at } -380^{\circ}\text{F} = 6.8 \times 10^{-6} \text{ in./in. } ^{\circ}\text{F}$$

$$\xi \text{ of Bolt} = L \bar{\alpha} \Delta T = (1.708)(6.8 \times 10^{-6})(-450) = -.00523 \text{ in.}$$

$$\xi \text{ of Flange} = +.00105 \text{ inches}$$

$$\text{Strain of Bolt} = \epsilon = -(\xi_{\text{Bolt}} - \xi_{\text{Flange}}) \div L_{\text{Bolt}}$$

$$\epsilon = \frac{-(-.00523 - .00105)}{1.708} = \frac{.00608}{1.708}$$

$$\epsilon = .00356 \text{ in./in.}$$

$$\text{Bolt stress} = E \epsilon = (29 \times 10^6)(.00356) = 103,100 \text{ psi}$$

Since bolt thermal stress is independent of bolt type, bolt thermal loads are as follows:

$$\begin{aligned} \text{Standard Bolt, } P_{\text{thermal}} &= \sigma A = (103,100)(.226) \\ &= 23,300 \text{ lbs.} \end{aligned}$$

$$\text{Special Bolt, } P_{\text{thermal}} = (103,100)(.1614) = 16,650 \text{ lbs.}$$

Figure 176 shows the variation of A-286 yield stress as a function of temperature. At -380°F , the yield stress, $F_{Ty} = 220 \text{ ksi}$; hence, the yield loads are:

$$\text{Standard Bolt, } P_y = (220,000)(.226) = 49,700 \text{ lbs.}$$

$$\text{Special Bolt, } P_y = (220,000)(.1614) = 35,500 \text{ lbs.}$$

Assume that preload applied by bolt torquing is the difference between P_y and P_{thermal} ; then,

$$\text{Standard Bolt, Preload} = 49,700 - 23,300 = 26,400 \text{ lbs.}$$

$$\text{Special Bolt, Preload} = 35,500 - 16,650 = 18,850 \text{ lbs.}$$

Since the thermal load is probably conservatively high and slight yielding under thermal loads is in any event permissible, the recommended preload values are:

VI. D. 2. (Continued)

Nuclear Steady-State Operating Condition (Continued)

Standard Bolts: 30,000 lbs.

Special Bolts: 20,000 lbs.

Therefore, total bolt loads (preload + thermal) are:

Standard Bolt: $30,000 + 23,300 = 53,300$ lbs.

Special Bolt: $20,000 + 16,650 = 36,650$ lbs.

VI. D. 2. (Continued)

Transient Startup Bolt Loads:

During the reactor startup transient, the nozzle attach bolts are subjected to a flow of LH_2 coolant which quickly lowers the bolt temperature while, at the same time, the nozzle and pressure vessel flanges have not cooled down from ambient temperature. This transient bolt cooldown induces an axial load in the bolts which is superimposed on the bolt preload.

$$\text{Bolt Temperature} = -423^\circ\text{F}$$

$$\text{Flange Temperature} = 77^\circ\text{F}$$

$$\Delta T = -500^\circ\text{F}$$

$$\text{Bolt Length} = 1.708 \text{ inches}$$

$$\sigma_{\text{thermal}} = E \alpha \Delta T = (29 \times 10^6)(-500)(6.8 \times 10^{-6}) = 98,600 \text{ psi}$$

Since this transient cooldown results in thermal stresses less severe than the 1.25 N.H.R. operating condition analyzed above, the 1.25 N.H.R. operating condition determines the bolt preload value.

Based on C62 interface loads at $R = 32.0$ (Ref. page /37):

$$\text{Axial load, } V, = 11,306 \text{ lbs./in.}$$

$$M = 1,190 \text{ in-lbs./in. for 1.0 N.S.S. Condition}$$

$$M = 1,390 \text{ in-lbs./in. for 1.25 N.S.S. Condition}$$

VI. D. 2. (Continued)

Section Thru Bolt Pattern of Interface

Ref: Pg. 106 of Part IV—Stress Analysis, P2-65-32.

$$\text{Area, } A = 2.458 \text{ in.}^2$$

$$\bar{X} = 1.237$$

$$I = 1.49 \text{ in.}^4$$

$$\text{Ejection Load/Bolt} = 1.396 V = 15,780 \text{ lbs./Bolt}$$

VI. D. 2. (Continued)

Stress on Pressure Vessel Face

Assume total bolt preload (torque + thermal) loads P.V. face uniformly in compression, and ejection force loads P.V. face uniformly in tension, leaving a net uniform compression load on P.V. face.

$$\text{For Standard Bolt } P.V. = \frac{-53,300 + 15,778}{2.458} = -15,400 \text{ psi}$$

$$\text{For Modified Bolt } P.V. = \frac{-36,650 + 15,778}{2.458} = -8,520 \text{ psi}$$

Find moment in each direction such that P.V. stress tends to zero.

(+) Moment value is defined as adding compression to outside surface of P.V.

Consider only vicinity of modified bolt.

CASE OF $+M_E$

CASE OF $-M_E$

VI. D. 2. (Continued)

Stress on P.V. Face (Continued)

$$\sigma_{M\xi} = \sigma_{\text{Preload}} = -8,520 \text{ psi}$$

$$\sigma_{M\xi} = \frac{M C}{I} = \frac{M_1 C_1}{I} = \frac{M_2 C_2}{I}$$

$$\text{where: } C_1 = -1.276 \text{ in.}$$

$$C_2 = +1.177 \text{ in.}$$

$$I = 1.49 \text{ in.}^4$$

$$\text{therefore, } M_1 = \frac{(-8,520)(1.49)}{-1.276} = -9,970 \text{ in-lbs./Bolt}$$

$$\therefore -M_{\xi \text{ max.}} = \frac{M_1}{1.396} = -7,140 \text{ in-lbs./in.}$$

$$M_2 = \frac{(8,520)(1.49)}{1.177} = -10,790 \text{ in-lbs./Bolt}$$

$$\therefore +M_{\xi \text{ max.}} = \frac{M_2}{1.396} = +7,720 \text{ in-lbs./in.}$$

This analysis shows that, at a standard bolt preload of 30,000 lbs., the interface moment can vary from values of -7,140 to +7,720 in-lbs./in. without encountering "liftoff".

The maximum range of values of the interface moment is expected to be:

$$M = -680.5 \text{ (Mechanical Loads Only)}$$

$$M = +1390 \text{ (Mechanical + Thermal, 1.25 N.S.S.);}$$

hence, "liftoff" will not occur.

VII. DISCUSSION AND CONCLUSIONSA. Nozzle

Since the publication of the original stress analysis report, two factors have emerged to influence the stress analysis of the nozzle as follows:

1. Recently acquired test data of the Hastelloy-X nozzle shell material shows that the yield and ultimate strength of the Hastelloy-X is considerably below the estimated strength values that were assumed for the original structural analysis. These strength values, shown plotted vs. temperature are presented by Figures 80 and 81.
2. The nuclear heating rates have been re-analyzed since the original interface analysis was published and the revised heating rates are considerably higher than was originally assumed.

Both of these factors have tended to reduce the margins of safety calculated for the nozzle shell. The analysis presented in the previous sections shows negative margins of safety over a considerable portion of the shell for primary hoop tension loading P_m , when the "3-sigma" value of material yield stress is used to calculate the relationship of:

$$P_m \leq 0.85 F_y .$$

In order to not further aggravate the thermal stress situation, the decision was made to not increase the thickness of the nozzle shell (permissible tolerances on thickness variation were reduced), but instead, to consider the analysis for P_m rationally, as follows:

1. Permit slight local permanent set to occur by redefining a yield stress value at 0.004 inch/inch permanent deformation.
2. Take advantage of the fact that in a bi-axial stress field, the effective yield stress is increased by approximately 8% (Ref.

3. Integrate the strength capability of the nozzle shell material across the thickness, to take advantage of the increased strength at lower temperatures.

When all of these factors are included in the analysis of the most critical point on the nozzle shell, the margin of safety is calculated to be 0.00. While this concept of "margin of safety" is based upon a series of strictly arbitrary standards, each of which is designed to introduce "conservatism", the strong implication remains that the nozzle shell is operating at its maximum or near maximum capability for the combined environment of internal pressure and severe nuclear heating.

The calculated values of thermal stress are high, well above the elastic limit, thus placing them in the plastic range or above the yield point of the material. Although the stress values shown for the thermal conditions 1.00 N.H.R. and 1.25 N.H.R. have the units of psi, they are not true stresses because they were calculated on the basis of the structure being an elastic material. But to change these stress values to a more realistic value would require re-distribution of forces due to the plastic flow of the material; i.e., an "elastic-plastic" analysis, which would be difficult and cumbersome to accomplish. The structural design criteria permits comparison of allowable thermal stresses based upon an elastic analysis, and the calculated values of secondary (mechanical and thermal) stresses are well below allowable values.

B. Pressure Vessel

Four design criteria were established early in the Phoebus-2 joint task force effort which greatly affected the design of the pressure vessel. The first criterion was that the interface shear would be taken by a shear lip on the nozzle rather than by the nozzle attaching bolts. This requires a bearing area on the outside surface of the pressure vessel near the interface.

VII. B. (Continued)

The second criterion was that the groove for the main gas seal would be in the pressure vessel. This required the interface area of the pressure vessel to be wide enough to accept this groove and for the width outside of the groove to have a large enough shear area to transfer the shear to the entire pressure vessel.

The third criterion was that the interface moment needed to be small enough to allow the available bolt pre-load to override the tension effect of the moment and keep the entire interface area in compression. It is also desirable to have the direction of the net interface moment (mechanical + thermal) such that it will tend to retain compression at the main gas seal.

The fourth criterion was that the design operate satisfactorily at all transients and at nuclear steady-state operating conditions.

The design of the pressure vessel is also predicated on the load line of the pressure vessel being vectorally coincident with the 45° load line of the nozzle at the bolt circle. This 45° load line is then curved on a generous radius to an axial load line in the cylindrical portion of the pressure vessel. The thickness of the pressure vessel around the theoretical load line should be minimum to make the vessel flexible and thus reduce the interface shear and reduce the value of any moment that is induced by the actual and theoretical load lines not being coincident. The minimum sections are determined on the basis of stress and thickness requirements for bolt inserts and seal groove area requirements.

The configuration chosen meets all four design criteria. The mechanical interface moment tends to open a gap at the gas seal, but the thermal moment overrides the mechanical moment and the net interface moment causes additional compression of flange surfaces at the gas seal. The in-lbs./in. magnitude of the net interface moment (at the neutral surface) is such that an assumed realistic bolt pre-load will cause compression over the entire interface area.

VII. B. (Continued)

The horizontal shear at the interface is 11,694 lbs./in. (at the neutral surface) for the mechanical load only, and 7,919 lbs./in. (max. @ 1.00 N.H.R.) when thermal effects are considered. The area outside of the gas seal is sufficient to transfer this shear to the entire vessel without causing a local failure.

The thickness of the vessel in the cylindrical section is very nearly optimum from the primary membrane stress consideration. In this area, the bending and thermal stresses do not nearly approach their allowable stresses. However, no further reduction in thickness is feasible since thinning the vessel would cause the membrane stress to exceed the allowable stress. All margins of safety are greater in the remainder of the vessel and this would indicate that the sections are too thick. But the thickness requirements at the interface for bolt inserts and the seal groove are nearly minimum, and the realistic necessity to reduce thicknesses gradually results in a nearly optimum over-all configuration.

Friction under the bolt heads, together with clearance between the shear lip and pressure vessel, might cause some of the horizontal shear to be taken by the nozzle attach bolts rather than the shear lip. A severe assumption of this condition was made and an analysis of local areas in the pressure vessel shows that there is a positive margin of safety over yield for this severe condition.

C. GeneralMargins of Safety:

The margins of safety for the pressure vessel are considered optimum from the standpoint of the applicable design criteria and the use of 7039-T61 aluminum alloy for the pressure vessel material. The margins of safety for the nozzle have a different connotation since plastic behavior is permitted. The method in which the plastic analysis is carried out is considered reasonable; hence, one can be confident that the nozzle is structurally adequate. However, careful interpretation of margin of safety numbers pertaining to the nozzle analysis is necessary to the understanding of the nozzle structural behavior.

VIII. MATERIALS PROPERTIES DATA

Mechanical and thermal properties data for the nozzle material (Hastelloy-X), the pressure vessel material (Aluminum Alloy 7039-T61), and the attach bolt material (A-286 Alloy) are presented in the following figures. All parameters are presented as a function of temperature.

Nozzle — Hastelloy-X

Figure 80	Yield Strength
Figure 81	Ultimate Strength
Figure 82	Elongation
Figure 83	Modulus of Elasticity
Figure 84	Dynamic Modulus of Elasticity
Figure 85	Coefficient of Thermal Expansion
Figure 86	Thermal Conductivity

Pressure Vessel — Aluminum 7039-T61

Figure 87	Yield Strength
Figure 88	Ultimate Strength
Figure 89	Notched Tensile Strength
Figure 90	Elongation
Figure 91	Modulus of Elasticity
Figure 92	Coefficient of Thermal Expansion

Bolt Material — A-286 Alloy

Figure 93	Yield and Ultimate Strength
Figure 94	Elongation
Figure 95	Modulus of Elasticity
Figure 96	Coefficient of Thermal Expansion

FIGURE 80

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FIGURE 82

FIGURE 83

AVERAGE TANGENT MODULUS OF ELASTICITY OF HASTELLOY X FORGINGS

○ - Heat 261-5-4000 Average Values

□ - Heat 261-5-4001 Average Values

Values at 0.2% Offset

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TANGENT MODULUS OF ELASTICITY - PSI X 10⁻⁶

TEMPERATURE (100°F)

166

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FIGURE 84

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FIGURE 85

MEAN COEFFICIENT OF THERMAL EXPANSION OF HASTELLOY X FORGINGS
RET. RPT. RP-DR-004, SIX MONTH MATERIALS REPORT, FEBRUARY-AUGUST 1966

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FIGURE 86

THERMAL CONDUCTIVITY OF HASTELLOY X

12

10

8

6

4

2

0

$\frac{BTU \cdot FT}{HR \cdot FT^2 \cdot ^\circ F}$

TEMPERATURE ($100^\circ F$)

-4

-2

0

2

4

6

8

10

12

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FIGURE 89

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FIG. 90. ELONGATION vs TEMPERATURE, ALUMINUM ALLOY 7039-T61

REFERENCE: AFPA REPORT NO. AFPA-412-262 DATED OCT. 8, 1965

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MODULUS OF ELASTICITY OF 7039-T61 ALUMINUM

Note: Above data taken from Martin Co. report CR-64-74, Figure 5/

7039-T61
2-12-64

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FIG. 94 ALLOY A-286
ELONGATION VS TEMPERATURE

REF: AEC. REPORT 2275 "MATERIALS PROPERTIES DATA BOOK"

NOTE: 50% OF VALUES WERE SELECTED TO COMPENSATE FOR FACT THAT
BOLT MATERIAL IS COLD WORKED.

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Interface Control Drawing".
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8. Crout Reduction Code, M-201 —an ACFI Computer Code for the IBM-1620—
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APPENDIX B
FLOW SYMMETRY

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I. DESCRIPTION

Flow symmetry testing is performed on each nozzle as a part of hydro-testing. This test is performed to ensure that each nozzle meets the requirements for flow symmetry of 5% for any 15° sector.

The test is comprised of setting the nozzle over the hydraulics laboratory water sump with the individual tube flow tooling installed on the core-support flange (see Figure 1). Water is introduced into the nozzle at the inlet torus as shown in Figure 2.

The complete nozzle is flowed although flow from one tube only is measured; water from the remaining 319 tubes flows directly into the sump.

The tube flow rate is determined by measuring the time required to collect 100 pounds of water.

The test requirement is to substantiate that the flow rate through any 15° sector of the nozzle does not vary more than 5% from any other sector. Table 1 presents the results of an individual tube-flow hydrotest analysis. There are 320 sectors. Once a maximum and a minimum flow sector are determined, the other sectors are compared to the two to obtain the percent deviation (maximum and minimum) as follows:

$$\% \text{ Deviation to Maximum} = \frac{\text{High Sector (Max)} - (\text{Any of 320 Sectors})}{\text{High Sector (Max)}}$$

$$\% \text{ Deviation to Minimum} = \frac{(\text{Any of 320 Sectors}) - \text{Low Sector (Min)}}{\text{Low Sector (Min)}}$$

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Figure 1 - Nozzle With Individual Tube Flow Tooling

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Figure 2 - Individual Tube Flow Using Time-Weight Method

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TABLE 1 (1 OF 6)

PHOEBUS-2 NOZZLE INDIVIDUAL TUBE FLOW HYDROTEST ANALYSIS

NOZZLE S/N 880603 NOZZLE P/N 1118300- 9 DATE OF TEST 2 22 67

TOTAL MEASURED FLOW RATE IS 608.00 LB/SEC SUM TOTAL OF INDIVIDUAL TUBE FLOW IS 607.047 LB/SEC

MAXIMUM 15 DEGREE SECTOR FLOW IS 25.414 MINIMUM 15 DEGREE SECTOR FLOW IS 24.259

TUBE NO	TUBE FLOW	PCNT OF WT	15 DEG SEC FLOW	PCNT DEV MAXFD	PCNT DEV MINFD
1	1.95	3.2154	25.139	1.093	3.500
2	1.96	3.2319	25.089	1.295	3.308
3	1.95	3.2072	24.989	1.700	2.921
4	1.95	3.2072	24.924	1.965	2.668
5	1.94	3.1907	24.869	2.191	2.452
6	1.94	3.1990	24.844	2.294	2.354
7	1.91	3.1496	24.774	2.583	2.078
8	1.89	3.1085	24.714	2.832	1.840
9	1.92	3.1661	24.699	2.894	1.781
10	1.96	3.2319	24.664	3.040	1.642
11	1.94	3.1907	24.564	3.460	1.241
12	1.89	3.1085	24.494	3.755	0.959
13	1.91	3.1414	24.469	3.861	0.858
14	1.90	3.1332	24.439	3.989	0.736
15	1.86	3.0674	24.414	4.095	0.634
16	1.88	3.1003	24.424	4.053	0.675
17	1.89	3.1167	24.399	4.159	0.573
18	1.91	3.1496	24.349	4.373	0.369
19	1.87	3.0838	24.314	4.523	0.226
20	1.85	3.0509	24.309	4.545	0.205
21	1.87	3.0838	24.324	4.480	0.267
22	1.89	3.1085	24.349	4.373	0.369
23	1.86	3.0674	24.349	4.373	0.369
24	1.87	3.0756	24.354	4.352	0.390
25	1.86	3.0674	24.359	4.330	0.410
26	1.88	3.0921	24.394	4.181	0.553
27	1.88	3.0921	24.419	4.074	0.655
28	1.87	3.0838	24.434	4.010	0.716
29	1.86	3.0592	24.454	3.925	0.797
30	1.84	3.0345	24.484	3.798	0.918
31	1.88	3.0921	24.494	3.755	0.959
32	1.87	3.0756	24.489	3.777	0.939
33	1.87	3.0756	24.509	3.692	1.020
34	1.90	3.1250	24.524	3.628	1.080
35	1.89	3.1085	24.519	3.650	1.060
36	1.87	3.0756	24.449	3.946	0.777
37	1.87	3.0838	24.479	3.819	0.898
38	1.90	3.1250	24.499	3.734	0.979
39	1.90	3.1332	24.514	3.671	1.040
40	1.89	3.1167	24.564	3.460	1.241
41	1.89	3.1167	24.549	3.523	1.181
42	1.89	3.1085	24.489	3.777	0.939
43	1.85	3.0509	24.504	3.713	0.999
44	1.87	3.0838	24.529	3.607	1.100
45	1.89	3.1085	24.579	3.397	1.301
46	1.88	3.1003	24.629	3.187	1.502
47	1.89	3.1167	24.624	3.208	1.482

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TABLE 1 (2 OF 6)

PHOEBUS-2 NOZZLE INDIVIDUAL TUBE FLOW HYDROTEST ANALYSIS

NOZZLE S/N 880603 NOZZLE P/N 1118300- 9 DATE OF TEST 2 22 67

TOTAL MEASURED FLOW RATE IS 608.00 LB/SEC SUM TOTAL OF INDIVIDUAL TUBE FLOW IS 607.047 LB/SEC

MAXIMUM 15 DEGREE SECTOR FLOW IS 25.414 MINIMUM 15 DEGREE SECTOR FLOW IS 24.259

TUBE NO	TUBE FLOW	PCNT OF WT	15 DEG SEC FLOW	PCNT DEV MAXFD	PCNT DEV MINFD
48	1.82	2.9934	24.594	2.333	1.362
49	1.90	3.1250	24.679	2.978	1.701
50	1.89	3.1167	24.674	2.998	1.681
51	1.91	3.1496	24.674	2.998	1.681
52	1.95	3.2154	24.679	2.978	1.701
53	1.88	3.0921	24.624	3.208	1.482
54	1.83	3.0180	24.674	2.998	1.681
55	1.90	3.1332	24.769	2.603	2.058
56	1.88	3.0921	24.764	2.624	2.039
57	1.92	3.1661	24.814	2.417	2.236
58	1.94	3.1907	24.814	2.417	2.236
59	1.88	3.0921	24.769	2.603	2.058
60	1.86	3.0674	24.804	2.459	2.197
61	1.90	3.1332	24.854	2.253	2.393
62	1.89	3.1167	24.869	2.191	2.452
63	1.89	3.1167	24.889	2.109	2.531
64	1.92	3.1578	24.899	2.068	2.570
65	1.90	3.1250	24.869	2.191	2.452
66	1.93	3.1743	24.879	2.150	2.491
67	1.93	3.1743	24.884	2.129	2.511
68	1.90	3.1250	24.844	2.294	2.354
69	1.93	3.1743	24.864	2.211	2.433
70	1.92	3.1661	24.834	2.335	2.315
71	1.89	3.1167	24.804	2.459	2.197
72	1.91	3.1496	24.789	2.521	2.137
73	1.91	3.1496	24.784	2.541	2.118
74	1.92	3.1578	24.789	2.521	2.137
75	1.91	3.1496	24.794	2.500	2.157
76	1.90	3.1332	24.804	2.459	2.197
77	1.89	3.1085	24.804	2.459	2.197
78	1.91	3.1414	24.819	2.397	2.256
79	1.93	3.1825	24.804	2.459	2.197
80	1.89	3.1085	24.744	2.707	1.960
81	1.92	3.1578	24.759	2.645	2.019
82	1.90	3.1250	24.729	2.769	1.900
83	1.89	3.1167	24.754	2.666	1.999
84	1.88	3.0921	24.764	2.624	2.039
85	1.91	3.1414	24.774	2.583	2.078
86	1.92	3.1578	24.774	2.583	2.078
87	1.92	3.1661	24.724	2.790	1.880
88	1.92	3.1661	24.699	2.894	1.781
89	1.90	3.1332	24.714	2.832	1.841
90	1.90	3.1332	24.714	2.832	1.841
91	1.89	3.1167	24.729	2.769	1.900
92	1.87	3.0838	24.759	2.645	2.019
93	1.90	3.1332	24.794	2.500	2.157
94	1.89	3.1085	24.804	2.459	2.197
95	1.92	3.1661	24.854	2.253	2.393
96	1.90	3.1332	24.834	2.335	2.315
97	1.89	3.1085	24.859	2.232	2.413
98	1.91	3.1414	24.884	2.129	2.511
99	1.87	3.0756	24.854	2.253	2.393
100	1.90	3.1250	24.889	2.109	2.531
101	1.94	3.1907	24.994	2.088	2.550
102	1.90	3.1332	24.874	2.170	2.472
103	1.92	3.1578	24.844	2.294	2.354
104	1.92	3.1661	24.839	2.314	2.334
105	1.91	3.1414	24.834	2.335	2.315
106	1.91	3.1496	24.824	2.376	2.275
107	1.94	3.1907	24.819	2.397	2.256
108	1.90	3.1332	24.744	2.707	1.960
109	1.93	3.1743	24.724	2.790	1.880

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TABLE 1 (3 OF 6)

PHOEBUS-2 NOZZLE INDIVIDUAL TUBE FLOW HYDROTEST ANALYSIS

NOZZLE S/N 880603 NOZZLE P/N 1118300- 9 DATE OF TEST 2 22 67

TOTAL MEASURED FLOW RATE IS 608.00 LB/SEC SUM TOTAL OF INDIVIDUAL TUBE FLOW IS 607.047 LB/SEC

MAXIMUM 15 DEGREE SECTOR FLOW IS 25.414 MINIMUM 15 DEGREE SECTOR FLOW IS 24.259

TUBE NO	TUBE FLOW	PCNT OF WT	15 DEG SEC FLOW	PCNT DEV MAXFD	PCNT DEV MINFD
110	1.91	3.1496	24.709	2.853	1.821
111	1.88	3.0921	24.709	2.853	1.821
112	1.90	3.1332	24.714	2.832	1.840
113	1.90	3.1332	24.699	2.894	1.781
114	1.92	3.1578	24.689	2.936	1.741
115	1.87	3.0838	24.694	2.915	1.761
116	1.91	3.1496	24.759	2.645	2.019
117	1.92	3.1578	24.794	2.500	2.157
118	1.90	3.1250	24.749	2.686	1.979
119	1.91	3.1414	24.744	2.707	1.959
120	1.86	3.0674	24.759	2.645	2.019
121	1.88	3.1003	24.829	2.356	2.295
122	1.91	3.1496	24.849	2.273	2.374
123	1.91	3.1496	24.854	2.253	2.393
124	1.88	3.1003	24.864	2.211	2.433
125	1.89	3.1085	24.864	2.211	2.433
126	1.89	3.1167	24.899	2.068	2.570
127	1.92	3.1661	24.924	1.965	2.668
128	1.94	3.1907	24.869	2.191	2.452
129	1.95	3.2072	24.804	2.459	2.197
130	1.87	3.0838	24.719	2.811	1.860
131	1.89	3.1167	24.739	2.728	1.940
132	1.92	3.1661	24.759	2.645	2.019
133	1.93	3.1825	24.719	2.811	1.860
134	1.90	3.1332	24.664	3.040	1.641
135	1.92	3.1578	24.654	3.082	1.602
136	1.92	3.1661	24.654	3.082	1.602
137	1.88	3.1003	24.619	3.229	1.462
138	1.92	3.1661	24.664	3.040	1.641
139	1.92	3.1578	24.664	3.040	1.642
140	1.87	3.0756	24.629	3.187	1.502
141	1.87	3.0838	24.649	3.103	1.582
142	1.86	3.0674	24.679	2.978	1.701
143	1.89	3.1167	24.724	2.790	1.880
144	1.91	3.1496	24.739	2.728	1.940
145	1.88	3.1003	24.739	2.728	1.940
146	1.88	3.0921	24.749	2.686	1.979
147	1.89	3.1167	24.764	2.624	2.039
148	1.92	3.1578	24.754	2.666	1.999
149	1.89	3.1085	24.729	2.769	1.900
150	1.93	3.1743	24.729	2.769	1.900
151	1.92	3.1661	24.689	2.936	1.741
152	1.88	3.1003	24.659	3.061	1.622
153	1.89	3.1085	24.649	3.103	1.582
154	1.90	3.1332	24.659	3.061	1.622
155	1.91	3.1414	24.659	3.061	1.622
156	1.91	3.1414	24.624	3.208	1.482
157	1.91	3.1496	24.579	3.397	1.301
158	1.89	3.1167	24.554	3.502	1.201
159	1.89	3.1167	24.544	3.544	1.161
160	1.89	3.1003	24.509	3.692	1.020
161	1.89	3.1167	24.494	3.755	0.959
162	1.89	3.1085	24.449	3.946	0.777
163	1.89	3.1085	24.469	3.861	0.858
164	1.89	3.1167	24.469	3.861	0.858
165	1.87	3.0838	24.459	3.904	0.817
166	1.90	3.1250	24.524	3.628	1.080
167	1.90	3.1332	24.534	3.586	1.120
168	1.87	3.0838	24.509	3.692	1.020
169	1.86	3.0674	24.549	3.523	1.181
170	1.89	3.1085	24.534	3.586	1.120
171	1.89	3.1003	24.509	3.692	1.019

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TABLE 1 (4 OF 6)

PHOEBUS-2 NOZZLE INDIVIDUAL TUBE FLOW HYDROTEST ANALYSIS

NOZZLE S/N 880603 NOZZLE P/N 1118300- 9 DATE OF TEST 2 22 67

TOTAL MEASURED FLOW RATE IS 608.00 LB/SEC SUM TOTAL OF INDIVIDUAL TUBE FLOW IS 607.047 LB/SEC

MAXIMUM 15 DEGREE SECTOR FLOW IS 25.414 MINIMUM 15 DEGREE SECTOR FLOW IS 24.259

TUBE NO	TUBE FLOW	PCNT OF WT	15 DEG SEC FLOW	PCNT DEV MAXFD	PCNT DEV MINFD
172	1.86	3.0592	24.524	3.628	1.080
173	1.87	3.0756	24.574	3.418	1.281
174	1.85	3.0427	24.604	3.291	1.402
175	1.91	3.1414	24.664	3.040	1.642
176	1.89	3.1085	24.629	3.187	1.502
177	1.88	3.1003	24.639	3.145	1.542
178	1.94	3.1907	24.649	3.103	1.582
179	1.91	3.1414	24.67	3.166	1.522
180	1.88	3.0921	24.	3.250	1.442
181	1.91	3.1496	24.	3.145	1.542
182	1.85	3.0427	24.634	3.166	1.522
183	1.86	3.0674	24.659	3.061	1.622
184	1.90	3.1250	24.719	2.811	1.860
185	1.91	3.1414	24.714	2.832	1.841
186	1.90	3.1250	24.769	2.603	2.098
187	1.91	3.1414	24.729	2.769	1.900
188	1.87	3.0838	24.709	2.853	1.821
189	1.90	3.1250	24.704	2.873	1.801
190	1.89	3.1167	24.654	3.082	1.602
191	1.92	3.1661	24.634	3.166	1.522
192	1.89	3.1085	24.639	3.145	1.542
193	1.90	3.1332	24.629	3.187	1.502
194	1.91	3.1414	24.604	3.292	1.402
195	1.87	3.0838	24.564	3.460	1.241
196	1.92	3.1661	24.544	3.544	1.161
197	1.89	3.1167	24.504	3.713	0.999
198	1.96	3.2319	24.524	3.628	1.080
199	1.86	3.0592	24.494	3.755	0.959
200	1.89	3.1085	24.544	3.544	1.161
201	1.87	3.0756	24.524	3.628	1.080
202	1.85	3.0427	24.534	3.586	1.120
203	1.87	3.0838	24.564	3.460	1.241
204	1.93	3.1743	24.564	3.460	1.241
205	1.88	3.0921	24.539	3.565	1.141
206	1.88	3.0921	24.544	3.544	1.161
207	1.87	3.0756	24.534	3.586	1.120
208	1.85	3.0509	24.559	3.481	1.221
209	1.88	3.1003	24.594	3.333	1.362
210	1.91	3.1496	24.564	3.460	1.241
211	1.93	3.1825	24.539	3.565	1.141
212	1.91	3.1414	24.494	3.755	0.959
213	1.87	3.0756	24.484	3.798	0.918
214	1.88	3.0921	24.509	3.692	1.020
215	1.88	3.0921	24.534	3.586	1.120
216	1.87	3.0838	24.509	3.692	1.020
217	1.90	3.1332	24.489	3.777	0.939
218	1.88	3.1003	24.444	3.968	0.756
219	1.87	3.0756	24.444	3.968	0.756
220	1.89	3.1167	24.484	3.798	0.918
221	1.89	3.1085	24.479	3.819	0.898
222	1.85	3.0509	24.514	3.671	1.040
223	1.89	3.1085	24.534	3.586	1.120
224	1.89	3.1085	24.524	3.628	1.080
225	1.90	3.1250	24.569	3.439	1.261
226	1.89	3.1167	24.569	3.439	1.261
227	1.90	3.1332	24.579	3.397	1.301
228	1.85	3.0509	24.614	3.250	1.442
229	1.85	3.0509	24.689	2.936	1.741
230	1.86	3.0592	24.744	2.707	1.960
231	1.88	3.1003	24.814	2.417	2.236
232	1.91	3.1414	24.789	2.521	2.137
233	1.89	3.1085	24.779	2.562	2.098

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TABLE 1 (5 OF 6)

PHOEBUS-2 NOZZLE INDIVIDUAL TUBE FLOW HYDROTEST ANALYSIS

NOZZLE S/N 880603 NOZZLE P/N 1118300- 9 DATE OF TEST 2 22 67

TOTAL MEASURED FLOW RATE IS 608.00 LB/SEC SUM TOTAL OF INDIVIDUAL TUBE FLOW IS 607.047 LB/SEC

MAXIMUM 15 DEGREE SECTOR FLOW IS 25.414 MINIMUM 15 DEGREE SECTOR FLOW IS 24.259

TUBE NO	TUBE FLOW	PCNT OF WT	15 DEG SEC FLOW	PCNT DEV MAXFD	PCNT DEV MINFD
234	1.92	3.1661	24.759	2.645	2.019
235	1.87	3.0838	24.739	2.728	1.940
236	1.88	3.0921	24.799	2.479	2.177
237	1.93	3.1825	24.824	2.376	2.275
238	1.90	3.1250	24.789	2.521	2.137
239	1.90	3.1332	24.789	2.521	2.137
240	1.94	3.1907	24.764	2.624	2.039
241	1.93	3.1743	24.724	2.790	1.880
242	1.91	3.1414	24.694	2.915	1.761
243	1.93	3.1743	24.704	2.873	1.801
244	1.86	3.0592	24.669	3.019	1.661
245	1.90	3.1250	24.694	2.915	1.761
246	1.87	3.0756	24.764	2.624	2.039
247	1.90	3.1332	24.804	2.459	2.197
248	1.93	3.1825	24.819	2.397	2.256
249	1.90	3.1332	24.799	2.479	2.177
250	1.90	3.1250	24.789	2.521	2.137
251	1.90	3.1250	24.824	2.376	2.275
252	1.88	3.0921	24.829	2.356	2.295
253	1.90	3.1250	24.839	2.314	2.334
254	1.90	3.1250	24.779	2.562	2.098
255	1.92	3.1578	24.729	2.769	1.900
256	1.89	3.1167	24.679	2.978	1.701
257	1.88	3.1003	24.644	3.124	1.562
258	1.97	3.2401	24.679	2.978	1.701
259	1.91	3.1414	24.539	3.565	1.140
260	1.92	3.1578	24.494	3.755	0.959
261	1.91	3.1496	24.444	3.968	0.756
262	1.89	3.1167	24.404	4.138	0.594
263	1.93	3.1825	24.434	4.010	0.716
264	1.90	3.1332	24.389	4.202	0.533
265	1.89	3.1085	24.344	4.395	0.349
266	1.84	3.0263	24.314	4.523	0.226
267	1.85	3.0427	24.349	4.373	0.369
268	1.87	3.0756	24.379	4.245	0.492
269	1.86	3.0592	24.404	4.138	0.594
270	1.92	3.1578	24.399	4.159	0.573
271	1.83	3.0098	24.374	4.266	0.471
272	1.86	3.0674	24.424	4.053	0.675
273	1.87	3.0756	24.464	3.883	0.837
274	1.87	3.0838	24.439	3.989	0.736
275	1.92	3.1661	24.449	3.946	0.777
276	1.89	3.1085	24.429	4.031	0.695
277	1.86	3.0592	24.409	4.117	0.614
278	1.86	3.0592	24.414	4.095	0.634
279	1.87	3.0839	24.414	4.095	0.634
280	1.88	3.0921	24.394	4.181	0.553
281	1.89	3.1167	24.379	4.245	0.492
282	1.85	3.0509	24.319	4.502	0.246
283	1.89	3.1167	24.324	4.480	0.267
284	1.88	3.0921	24.289	4.631	0.123
285	1.90	3.1332	24.289	4.631	0.123
286	1.84	3.0345	24.259	4.760	0.000
287	1.88	3.1003	24.299	4.588	0.164
288	1.90	3.1332	24.294	4.609	0.144
289	1.87	3.0756	24.269	4.717	0.041
290	1.86	3.0674	24.259	4.760	0.000
291	1.86	3.0592	24.279	4.674	0.082
292	1.85	3.0509	24.329	4.459	0.287
293	1.86	3.0674	24.314	4.523	0.226
294	1.83	3.0180	24.299	4.588	0.164
295	1.86	3.0592	24.364	4.309	0.430

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TABLE 1 (6 OF 6)

PHOEBUS-2 NOZZLE INDIVIDUAL TUBE FLOW HYDROTEST ANALYSIS

NOZZLE S/N 880603 NOZZLE P/N 1118300- 9 DATE OF TEST 2 22 67

TOTAL MEASURED FLOW RATE IS 608.00 LB/SEC SUM TOTAL OF INDIVIDUAL TUBE FLOW IS 607.047 LB/SEC

MAXIMUM 15 DEGREE SECTOR FLOW IS 25.414 MINIMUM 15 DEGREE SECTOR FLOW IS 24.259

TUBE NO	TUBE FLOW	PCNT OF WT	15 DEG SEC FLOW	PCNT DEV MAXFD	PCNT DEV MINFD
296	1.86	3.0592	24.389	4.202	0.533
297	1.88	3.0921	24.429	4.031	0.695
298	1.87	3.0838	24.434	4.010	0.716
299	1.88	3.1003	24.469	3.861	0.858
300	1.88	3.0921	24.534	3.586	1.120
301	1.88	3.0921	24.619	3.229	1.462
302	1.86	3.0592	24.669	3.019	1.661
303	1.88	3.1003	24.739	2.728	1.940
304	1.91	3.1414	24.799	2.479	2.177
305	1.84	3.0263	24.869	2.191	2.452
306	1.85	3.0427	24.994	1.680	2.940
307	1.90	3.1250	25.124	1.154	3.442
308	1.88	3.1003	25.174	0.953	3.634
309	1.90	3.1250	25.244	0.673	3.901
310	1.88	3.1003	25.309	0.414	4.148
311	1.91	3.1414	25.374	0.157	4.394
312	1.95	3.2072	25.414	0.000	4.544
313	1.96	3.2319	25.404	0.039	4.506
314	1.93	3.1743	25.384	0.118	4.431
315	1.93	3.1743	25.369	0.177	4.375
316	1.94	3.1990	25.329	0.335	4.224
317	1.98	3.2565	25.309	0.414	4.148
318	1.96	3.2319	25.294	0.474	4.091
319	1.98	3.2565	25.269	0.573	3.996
320	1.95	3.2072	25.179	0.933	3.653

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APPENDIX C

INTERFACE CONTROL DRAWING

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5. THESE REFERENCE DIMENSIONS
ARE CONTROLLED BY THIS
INTERFACE CONTROL DRAWING NOR
ARE THEY CURRENT.

6. INTERFERT DRAWING PER M-57C-BC.

Phoebus-2 Nozzle Pressure Vessel Reactor Interface Control Drawing (U)
(Sheet 1 of 3)

[REDACTED]

[REDACTED] b6
[REDACTED] b7C

[REDACTED] 1054

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APPENDIX D
BASIC PARTS LIST

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BASIC PARTS LIST										3/N 880605	
										DRAWING NO.	
										1118300-29, H	
										SHEET 1 OF 8	
LET.	DATE	REVISION	BY	CKD	TITLE						
					NOZZLE, NUCLEAR ROCKET ENGINE
					AEROJET GENERAL CORPORATION					DRAWN	DATE
										CHECKED	
										APPROVED	
										6-1-67	
SIZE	DWG. NO.	REV.	1	2	3	4	5	6	PART NAME	NO. REQ'D.	
	1118300-29	H	x						Nozzle, Nuclear Rocket Engine		
	1115860-1	E		x					Jacket, Tube Coolant	1	
	1114857-1	B			x				Nozzle Weldment	1	
	1114856-7	G				x			Convergent Section	1	
	1114856-1	G					x		Forging	1	
	1114856-11	G				x			Aft Section	1	
	1114856-3	G					x		Forging	1	
	1114856-13	G					x		Fwd Section	1	
	1114856-5	G						x	Forging	1	
	Weld Rod							x	Hastelloy X - AGC-90058B	AR	
	1118578-1	NC	x						Shim Plated	320	
	1115035-7	B		x					Shim	320	
	1118578-3	NC	x						Shim Plated	320	
	1115035-11	B		x					Shim	320	
	1118578-5	NC	x						Shim Plated	320	
	1115035-13	B		x					Shim	320	
	1115035-1	B				x			Shim	--	
	1118578-7	NC	x						Shim Plated	320	
	1115035-15	B		x					Shim	320	
	1115035-1	B				x			Shim	--	
	1118578-11	NC	x						Shim Plated	320	
	1115035-17	B		x					Shim	320	
	1115035-1	B					x		Shim	320	
	1118578-13	NC	x						Shim Plated	320	

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BASIC PARTS LIST										DRAWING NO. 1118300-29		
										SHEET 2 OF 8		
LET.	DATE	REVISION	BY	CKD	TITLE							
					NOZZLE, NUCLEAR ROCKET ENGINE
					AEROJET-GENERAL CORPORATION <small>INCORPORATED IN CALIFORNIA</small>					DRAWN	DATE	
										CHECKED		
										APPROVED		
SIZE	DWG. NO.	REV.	1	2	3	4	5	6	PART NAME	NO. REQ'D		
	1115035-21	B			x				Shim	320		
	1115035-1	B				x			Shim	--		
	1118578-15	NC	x						Shim Plated	320		
	1115035-23	B			x				Shim	320		
	1115035-1	B				x			Shim	--		
	1118578-17	NC	x						Shim Plated	320		
	1115035-25	B			x				Shim	320		
	1115035-1	B				x			Shim	--		
	1118578-21	NC	x						Shim Plated	320		
	1115035-27	B			x				Shim	320		
	1115035-1	B				x			Shim	--		
	1118578-23	NC	x						Shim Plated	320		
	1115035-31	B			x				Shim	320		
	1115035-1	B				x			Shim	--		
	1118578-25	NC	x						Shim Plated	320		
	1115035-33	B			x				Shim	320		
	1115035-1	B				x			Shim	--		
	1118578-27	NC	x						Shim Plated	320		
	1115035-35	B			x				Shim	320		
	1115035-1	B				x			Shim	--		
	1118578-31	NC	x						Shim Plated	320		
	1115035-37	B			x				Shim	320		
	1115035-1	B				x			Shim	320		
	1118578-33	NC	x						Shim Plated	320		

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BASIC PARTS LIST										DRAWING NO. 1118300-29		
										SHEET 3	OF 8	
LET.	DATE	REVISION	BY	CK.D	TITLE							
					NOZZLE, NUCLEAR ROCKET ENGINE
					AEROJET-GENERAL CORPORATION <small>EST. 1945</small>					DRAWN	DATE	
										CHECKED		
										APPROVED		
SIZE	DWG. NO.	REV.	1	2	3	4	5	6	PART NAME	NO. REQ'D.		
	1115035-41	B			x				Shim	320		
	1115035-3	B				x			Shim	--		
	1118578-35	NC		x					Shim Plated	320		
	1115035-43	B			x				Shim	320		
	1115035-3	B				x			Shim	--		
	1118578-37	NC		x					Shim Plated	320		
	1115035-45	B			x				Shim	320		
	1115035-3	B				x			Shim	--		
	1118578-41	NC		x					Shim Plated	320		
	1115035-47	B			x				Shim	320		
	1115035-3	B				x			Shim	--		
	1118578-43	NC		x					Shim Plated	320		
	1115035-51	B			x				Shim	320		
	1115035-3	B				x			Shim	--		
	1118578-45	NC		x					Shim Plated	320		
	1115035-53	B			x				Shim	320		
	1115035-3	B				x			Shim	--		
	1118578-47	NC		x					Shim Plated	320		
	1115035-55	B			x				Shim	320		
	1115035-5	B				x			Shim	--		
	1118578-51	NC		x					Shim Plated	320		
	1115035-57	B			x				Shim	320		
	1115035-5	B				x			Shim	--		
	1118578-53	NC		x					Shim Plated	320		

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BASIC PARTS LIST										DRAWING NO. 1118300-29		
										SHEET 4	OF 8	
LET.	DATE	REVISION	BY	CKD	TITLE NOZZLE, NUCLEAR ROCKET ENGINE
					AEROJET-GENERAL CORPORATION AEROSPACE DIVISION P.O. BOX 1080 Azusa, California 91701						DRAWN	DATE
											CHECKED	
											APPROVED	
SIZE	DWG. NO.	REV.	1	2	3	4	5	6	PART NAME	NO. REQ'D.		
	1115035-61	B			x				Shim	320		
	1115035-5	B				x			Shim	--		
	1118579-1	N/C		x					Channel Plated	308		
	1115058-9	D			x				Channel	308		
	1115058-1	D				x			Channel	1		
	1115058-5	D				x			End Cap	1		
	1115058-7	D				x			End Cap	1		
	Weld Rod					x			Hastelloy X AGC-90058B	AR		
	1118579-3	N/C		x					Channel Plated	6		
	1115058-19	D			x				Channel	6		
	1115058-3	D				x			Channel	1		
	1115058-5	D				x			End Cap	1		
	1115058-7	D				x			End Cap	1		
	Weld Rod					x			Hastelloy X AGC-90058B	AR		
	1118579-5	N/C		x					Channel Plated	6		
	1115058-29	D			x				Channel	6		
	1115058-4	D				x			Channel	1		
	1115058-5	D				x			End Cap	1		
	1115058-7	D				x			End Cap	1		
	Weld Rod					x			Hastelloy X AGC-90058B	AR		
	1115205-5	C		x					Torus Bolt Coolant Line	1		
	1115205-1	C			x				Elbow	1		
	1115205-11	C				x			Elbow Half	1		
	1115205-13	C				x			Elbow Half	1		

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BASIC PARTS LIST										DRAWING NO. 1118300-29		
										SHEET 5	OF 8	
LET.	DATE	REVISION	BY	CK'D	TITLE NOZZLE, NUCLEAR ROCKET ENGINE
					AEROJET-GENERAL CORPORATION					DRAWN	DATE	
										CHECKED		
										APPROVED		
SIZE	DWG. NO.	REV.	1	2	3	4	5	6	PART NAME	NO. REQ'D		
	Weld Rod					x			Hastelloy X AGC-90058B	AR		
	1115205-3	C			x				Adapter	1		
	1115205-7	C				x			Adapter Half	2		
	Weld Rod					x			Hastelloy X AGC-90058B	AR		
	1115805-1	NC			x				Adapter	1		
	Weld Rod					x			Hastelloy X AGC-90058B	AR		
	1115270-1	NC	x						Brazing Alloy	320		
	1115270-3	NC	x						Brazing Alloy	320		
	1115270-5	NC	x						Brazing Alloy	480		
	1115271-1	A	x						Brazing Alloy	3200		
	1115271-3	A	x						Brazing Alloy	320		
	1115271-5	A	x						Brazing Alloy	320		
	1115271-7	A	x						Brazing Alloy	1600		
	1115271-9	A	x						Brazing Alloy	960		
	1115271-11	A	x						Brazing Alloy	320		
	1115271-13	A	x						Brazing Alloy	320		
	1115344-9	A	x						Tube Assembly	1		
	1115344-11	A			x				Tube	1		
	1115344-5	A			x				Tube	1		
	1115344-7	A			x				Adapter	2		
	1115347-5	NC				x			Adapter	1		
	1115485-1	NC			x				Venturi Meter	1		
	AN818-32C				x				Nut	2		
	MS20819-32C				x				Sleeve	2		

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BASIC PARTS LIST										DRAWING NO. 1118300-29		
										SHEET 6 OF 8		
LET.	DATE	REVISION	BY	CKD	TITLE NOZZLE, NUCLEAR ROCKET ENGINE
					AEROJET-GENERAL CORPORATION <small>• AERONAUTICS •</small>					DRAWN		DATE
										CHECKED		
										APPROVED		
SIZE	DWG. NO.	REV.	1	2	3	4	5	6	PART NAME	NO. REQ'D		
	AS1425-103				x				Tape	AR		
	AS1425-234				x				Tape	AR		
	AS1425-376				x				Tape	AR		
	AS1425-481				x				Tape	AR		
	Weld Rod				x				AISI 349 - MIL-R-5031B, Amd. I, Class 5A	AR		
	1115380-1	NC	x						Adapter Torus	1		
	1115382-49	E	x						Torus Assembly	1		
	1115349-21	E		x					Torus-Adapter Assembly	1		
	1115349-17	E			x				Adapter - Assembly	1		
	1115349-19	E				x			Pipe	1		
	1115349-15	E				x			Splitter	1		
	1115349-11	E				x			Ring Flange	1		
	1115349-9	E				x			Ring Adapter	1		
	1115349-1	E				x			Adapter	1		
	1115349-7	E					x		Adapter Half	2		
	1115349-13	E			x				Torus Segment	1		
	Weld Rod							x	Hastelloy X AGC-90058B	AR		
	1115335-1	C		x					Torus Nozzle Coolant	1		
	1115335-2	C			x				Torus	1		
	1115335-3	C			x				Torus	1		
	1115335-6	C			x				Torus	1		
	1115335-7	C			x				Torus	1		
	1115352-1	A			x				Adapter	8		
	1115352-3	A			x				Adapter	1		

ACC 2-327 CC 87540-00661

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BASIC PARTS LIST										DRAWING NO. 1118300-29		
										SHEET 7	OF 8	
LET.	DATE	REVISION	BY	CKD	TITLE NOZZLE, NUCLEAR ROCKET ENGINE
					AEROJET-GENERAL CORPORATION <small>1118300-29</small>					DRAWN	DATE	
										CHECKED		
										APPROVED		
SIZE	DWG. NO.	REV.	1	2	3	4	5	6	PART NAME	NO. REQ'D.		
	Weld Rod					x			Hastelloy X AGC-90058B	AR		
	1117092-9	NC	x						Torus	2		
	1115352-1	A		x					Adapter	3		
	Weld Rod			x					Hastelloy X AGC-90058B	AR		
	1116049-1	A	x						Gusset	1		
	1116049-2	A	x						Gusset	1		
	1116088-1	NC	x						Boss	1		
	AS1149-32		x						Restrictor	1		
	AN742F32		x						Clamp	1		
	AN3CH3A		x						Bolt	1		
	AN960C10L		x						Washer	1		
	MS20995C41		x						Lockwire	AR		
	MS24391S4L		x						Plug	16		
	MS24391S12L		x						Plug	1		
	12100CL4		x						Seal	16		
	12100CL12		x						Seal	1		
	1118382-1		x						Mount, Accelerometer	4		
	1118706-1		x						Stud, Mounting - Neutron Detector	8		
	Neo Lube		x						Thread Lubricant	AR		
	Weld Rod		x						Hastelloy X AGC-90058B	AR		
	Brazing Alloy		x						Powder AGC-44079, Amend. I	AR		
	Brazing Alloy		x						Powder AGC-44148A	AR		
	Brazing Alloy		x						Wire AGC-44148A	AR		
	Brazing Alloy		x						Powder AGC-90022A, Type III	AR		

AGC 2-327 CC 87540-00661

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THE FIELD

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