NUCLEAR ROCKET OPERATIONS
SACRAMENTO PLANT

MASTER

Report No. RP-MR-0018
to
SPACE NUCLEAR PROPULSION OFFICE - CLEVELAND EXTENSION
PHOEBUS-2 MONTHLY PROGRESS REPORT
for the period 1 April through 30 April 1967

CONTRACT SNPC-35
MAY 1967

INCLUDING
REPORT NO. RP-TM-0014
COAXIAL INJECTOR DESIGN REPORT

NUCLEAR PRODUCTS AND SERVICES GROUP

AEROJET-GENERAL CORPORATION
SACRAMENTO, CALIFORNIA

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CLASSIFICATION CATEGORY

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5-18-67

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AEROJET - GENERAL CORPORATION
A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY

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Report No. RP-MR-0018

PHOEBUS-2 MONTHLY PROGRESS REPORT

for the period

1 April through 30 April 1967

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Project Manager – Phoebus
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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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Report No. RP-TM-001⁴ COAXIAL INJECTOR DESIGN REPORT

TASK H - STE AND FACILITIES

1. Work Performed in April

A re-evaluation of the convectively cooled nozzle modes-of-failure program was made. Additional fail-safe shutdown modes were determined to be necessary and will be installed for future tests of the convectively cooled nozzle.

The analog computer program was modified to include the additional fail-safe shutdown modes. A series of analog computer simulation runs were accomplished: (1) to investigate start-transient revisions necessary to accommodate a higher flow-rate in the nozzle pre-chill system; (2) to consider conditions existing during a variety of malfunction modes in the start-transient, steady-state, and shutdown portions of typical convectively cooled nozzle tests; and (3) to consider conditions created by the malfunction of test-facility systems.

Preparation of the test stand and control room for film-cooled nozzle testing was initiated. Separation of the instrumentation functions to isolate the data systems from the control systems was commenced.

2. Work Planned for May

Separation of the instrumentation functions (to isolate the data systems from the control systems) will be completed.

Review of the analog computer model runs and revision of modes-of-failure analysis for the convectively cooled nozzle will continue. Additional analog model runs, incorporating additional safety detection systems, will be made to define the start sequence.

On-stand activation efforts will continue, including pre-fabrication of facility lines for the film-cooled nozzle.

TASK I - REPORTS (CPFF)

1. Work Performed in April

Weekly highlights were submitted to SNPO-C each Friday (RP-TWX-0106 through 0109).

Ten copies of the Financial Management Report, NASA Form 533, for the period ending 26 March were submitted 17 April for the CPFF portion of the contract.

The Monthly Progress Report, RP-MR-0017, for the period 1 March through 31 March 1967 was submitted to SNPO-C 28 April and distributed as directed by the SNPO Technical Director. Accompanying this report, as an appendix, was Development Nozzle Design Report, RP-TM-0013.

2. Work Planned for May

Reports required by the work statement, and other contractually required or customer-requested reports, will be submitted to SNPO-C.

TASK J - DESIGN

1. Work Performed in April

a. Film-Cooled Nozzle

Redesign of the film-cooled nozzle was completed. A third film-coolant circuit was added and the existing two circuits were enlarged to reduce pressure drop.

b. Convectively Cooled Nozzle

A steady-state thermal analysis was performed for two design configurations of a thermocouple pass-through instrumentation boss assembly in the convergent section of the nozzle jacket. One design concept incorporates a countersunk installation in the jacket. The other is a flush-welded configuration. Emphasis was given to the flush-welded installation in the analysis. Mathematical models were analyzed with the IBM Program 278B and were run as two-dimensional steady-state conduction problems.

One case indicated the cooling effects of natural convection and radiation to the atmosphere (the external film coefficient assumed was $15 \text{ Btu/ft}^2 \text{ hr } ^\circ\text{R}$). Cases also were analyzed considering forced convection over the thermocouple boss assembly provided by a jet of ambient nitrogen. Maximum and minimum convective film coefficients, as suggested by LASL, of $500 \text{ Btu/ft}^2 \text{ hr } ^\circ\text{F}$ and $100 \text{ Btu/ft}^2 \text{ hr } ^\circ\text{R}$, respectively, were assumed. A factor of 1.25 was used, applied to the nominal nuclear heating rates.

Results of the analysis indicate that with natural convection, observed temperatures would be marginal. The minimum film coefficient value ($100 \text{ Btu/ft}^2 \text{ hr } ^\circ\text{R}$) provides adequate cooling throughout the assembly. The maximum value ($500 \text{ Btu/ft}^2 \text{ hr } ^\circ\text{R}$) reduces the extremity of the thermocouple

to almost ambient temperature. A nitrogen flow-rate equivalent to the convection film coefficient values specified should provide adequate cooling to the boss assembly. The two configurations, countersunk and flush-mounted, had no significant effect on thermal profiles.

2. Work Planned for May

All design activities in process will be completed.

TASK K - FABRICATION

1. Work Performed in April

a. Convectively Cooled Nozzle

S/N 880601 - The following operations were completed: X-ray of the coolant channels and main torus; polishing of 144 bolt-hole counter-bores; installation of accelerometer mounts; inspection of interface control dimensions; final cleaning; and addition of heat-indicating braze patches on coolant channels.

S/N 880604 - The following operations were completed: high-pressure proof and leak testing; backflushing and flushing of the coolant circuit; flowing for K values; and flow-symmetry testing.

S/N 880605 - The requisition to fabricate tooling for drilling thermocouple pass-through holes in the nozzle jacket was initiated. Tooling fabrication was initiated by the vendor.

b. Film-Cooled Nozzle

The following rework was completed: enlargement of existing feed holes; machining of a new cooling circuit just above the convergent knuckle; fabrication and installation of new coolant lips; penetrant inspection; and final cleaning.

c. Adapter Assembly

The adapter was backflushed, dehydrated, and cleaned. The adapter, adapter leg, and support were assembled for thrust-chamber assembly build-up.

d. Film-Cooled Thrust Chamber Assembly

The adapter assembly and film-cooled nozzle were assembled.

2. Work Planned for May

a. Convectively Cooled Nozzle

S/N 880604 - Fabrication will be completed.

S/N 880605 - Six thermocouple pass-through holes will be drilled in the jacket. The loading of jacket coolant-channels will continue.

b. Film-Cooled Thrust Chamber Assembly

The test assembly will be completed, including installation of the coaxial injector, helium leak checking, and delivery to the test area.

TASK L - RELIABILITY AND QUALITY ASSURANCE

1. Work Performed in April

A proposal was submitted to SNPO-C for ultrasonic inspection of Nozzles S/N 880604 and 880605.

Specification AGC-90180, governing procedure and acceptance levels for X-ray inspection of nozzle coolant channels and torus closure welds, was released and used as the basis for inspecting Nozzle S/N 880601.

The following integrated manufacturing and inspection planning for AGC fabrication was approved and released:

P/N 1118784-1	Throat Plug Assembly
P/N 1115202-9	Leg-Adapter
P/N 1118774-1	Seal and Closure Assembly Throat Plug
P/N 1115342-1	Boss, Thermocouple, Adapter Cooled
P/N 1115034-9	Nozzle Assembly, Test, Convectively Cooled
P/N 1115456-9	Line, Coolant, Nozzle Inlet
P/N 1115311-9	Injector Assembly
P/N 1118781-11	Plate Frame
P/N 1117091-9	Backflush of Adapter
P/N 1114830-49	Nozzle, Nuclear Rocket Engine, Braze Patch Installation
P/N 1115486-9	Adapter, Nozzle-to-Injector
P/N NAS 1351 C8H-36	Cap Screws
P/N 1115858-19	Nozzle Assembly, Test, Film-Cooled
P/N 1115485-1	Venturi Meter Tube
P/N HTIZ-1101/B	Hydrotest Instruction for P/N 1115344-9 Bolt Coolant Line
P/N HTIZ-1067/B	Hydrotest Instruction for P/N 1115858-19 Nozzle Assembly Test, Film-Cooled

The following drawings were reviewed and approved:

1114830J	Nozzle, Nuclear Rocket Engine
1115034C	Nozzle Assembly, Test
1114175B	Strainer Element
1115344A	Tube Assembly, Metal
1115485 NC	Venturi Meter
1118300G	Nozzle, Nuclear Rocket Engine
1118780B	Support, Throat Plug
1118781C	Frame, Support, Throat Plug
1118784B	Throat Plug Assembly
1134061 NC	Torus-Nozzle, Uncooled
1134067 NC	Boss Thermocouple, Adapter
1134129 NC	Plug-Transducer, Nozzle, Film-Cooled

2. Work Planned for May

Surveillance of AGC shopwork and vendor fabrication will continue.

Surveillance of nondestructive testing of components will continue.

TASK M - TESTING

1. Work Performed in April

A meeting was held 13 - 14 April with SNPO-W, SNPO-C, and LASL personnel to investigate Test 1.2-15-NNN-005.

Report RP-TR-0012, Phoebus-2 Test Failure Report, Test 1.2-15-NNN-005, was issued.

A preliminary test request was prepared for the film-cooled nozzle test series which will employ the coaxial injector.

2. Work Planned for May

The critical experiment review for the film-cooled nozzle test series will be held and the test request issued.

TASK N - REPORTS (CPIF)

1. Work Performed in April

Weekly highlights were submitted to SNPO-C each Friday (RP-TWX-0106 through -0109).

Bi-weekly PERT reports were submitted 7 and 21 April (RP-PR-046 through -047).

Ten copies of the Financial Management Report, NASA Form 533, for the period ending 26 March were submitted 17 April for the CPIF portion of the contract.

The Monthly Progress Report, RP-MR-0017, for the period 1 March through 31 March 1967 was submitted to SNPO-C 28 April and distributed as directed by the SNPO Technical Director. Accompanying this report, as an appendix, was Development Nozzle Design Report, RP-TM-0013.

2. Work Planned for May

Reports required by the work statement, and other contractually required or customer-requested reports, will be submitted to SNPO-C.

TASK Q - MISCELLANEOUS SUPPORT EQUIPMENT

1. Work Performed in April

Testing of the nozzle throat-plug in the simulated nozzle was initiated. The test assembly was pressurized in increments while recording deflection of the plug shaft. A leak developed at the bond between the seal and the aft-cone of the plug at approximately 50 psi. Deflection of the plug was between 0.30 and 0.35 inch when the leak occurred. The test was terminated and repairs made by injecting a two-part adhesive, EC 801, into the leak path.

The test has provided a good indication of the degree of load sharing between the plug support-framework and nozzle throat. The frame is designed to deflect less than 0.30 inch: therefore, the tubes at the nozzle throat will be exposed to an ejection load of less than that exerted by 50 psi, with the frame carrying the remainder.

It is believed that the test was more severe than that which will be conducted with the prototype nozzle. The plug was restrained only by the expanded seal at the forward end and, therefore, was relatively free to move. The outward movement removed the compressive load at the bond between the seal and the aft-cone and placed the interface in tension, allowing internal pressure to separate the bond.

2. Work Planned for May

The throat plug will be tested again. If successful, prototype nozzle testing will be initiated. If the seal-bond leaks again, the seal will be removed, another seal of 40 Durometer "A" hardness bonded in its place (the first seal tested was of 20 Durometer "A" hardness), and testing resumed.

Report No. RP-TM-0014

COAXIAL INJECTOR DESIGN REPORT

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COAXIAL INJECTOR DESIGN REPORT

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MAY 1967

Report No. RP-TM-0014

COAXIAL INJECTOR DESIGN REPORT

A handwritten signature in black ink, appearing to read 'R. L. Murray', with a stylized, flowing script.

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

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ABSTRACT

This report provides design information concerning the Phoebus coaxial injector. Design criteria are presented. Supporting documentation is provided in the areas of coolant flow, and structural analysis. A basic parts list is included.

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I. SUMMARY

The coaxial injector design was initiated as backup to the NERVA-type multiorifice injector. The interfaces, oxidizer tori, and inlets of the two injectors are identical. Injector design of the coaxial injector was based upon data from the M-1, J-2, and RL-10 injectors, and is conservative in regard to stress and combustion stability factors. The oxidizer tube can be replaced to change propellant, Δp , and/or velocity ratio. CRES 347 steel is the principal material. The elements were brazed into the plate with copper. Figures 1, 2, and 3 show the injector.

Figure 1 - Coaxial Injector

Figure 2 - Coaxial Injector

Figure 3 - Coaxial Injector

II. TECHNICAL DISCUSSION

A. GENERAL

Beginning with interfaces established for the design, work was initiated on the injector in June 1965. Table 1 presents the design criteria.

TABLE 1
PHOEBUS-2 COAXIAL INJECTOR

DESIGN CRITERIA

$\dot{w}_f$	= 114 lb/sec	T_f	= 120°R
$\dot{w}_o$	= 627 lb/sec	T_o	= 180°R
MR	= 5.5	γ_f	= 1.5 lb/ft ³
P_c	= 750 psia	γ_o	= 68.5 lb/ft ³
$\dot{w}/\text{element}$	= 3.06 lb/sec	P_f	= 150 psi
V_f/V_o	= 10	P_o	= 150 psi

REVISED DESIGN CRITERIA*

$\dot{w}_f$	= 114 lb/sec	T_f	= 90°R
$\dot{w}_o$	= 627 lb/sec	T_o	= 180°R
MR	= 5.5	γ_f	= 2.35 lb/ft ³
P_c	= 750 psia	γ_o	= 68.5 lb/ft ³
$\dot{w}/\text{element}$	= 3.06 lb/sec	ΔP_f	= 200 psi
V_f/V_o	= 15	ΔP_o	= 250 psi

A preliminary design review was held 10 June 1965 to present the design criteria and conceptual design sketches. The layout drawing of the plate dome and thrust structure was presented with sketches of element concepts. A compilation of coaxial elements considered by the M-1 program was reviewed.

*The criteria were revised after the preliminary design review.

The review resulted in a decision to increase velocity ratio, place a weld seal on the oxidizer element, and to initiate stress and stability analyses.

The velocity ratio of the element was increased to 15 by enlarging the inside diameter of the oxidizer tube and by reducing the fuel-annulus gap. This brought an increase in fuel-circuit pressure drop from 150 to 200 psi. The oxidizer circuit was increased to 250 psi to "stiffen" the circuit. A weld seal was added to the head of the oxidizer element to provide a positive lock as well as a seal.

The stress analysis was completed 14 March 1966 (see Appendix A).

A stability analysis was completed 22 June 1965 (see Appendix B).

An intermediate design review was held 1 October 1965, at which time design and analyses were approximately 90 percent complete. The final design review was held 17 November 1965. The report of this review is presented in Appendix C. Also presented at the final design review was the mode-of-failure analysis (see Appendix D).

B. COMPONENTS

The first design task was the preparation, review, and selection of conceptual design sketches. A flow-chart of drawings (see Figure 4) was prepared to schedule the release of drawings and to assist in the preparation of long lead-time fabrication orders.

Another scheduling tool used was the design PERT schedule illustrated in Figure 5. Fabrication was divided into definable operations and each operation, in turn, defined by a drawing. By adding dates and purchase-order numbers, PERT was used to follow injector components from

Figure 4 - Drawing Release Schedule

Figure 5 - Design PERT Schedule

forging order through final assembly. A basic parts list is contained as Appendix E.

1. Injector Plate, Machined, 1115314-19

The injector body was designed as a flat plate for simplicity of fabrication and to permit the use of identical injector elements throughout. All critical machine surfaces were straight cuts which could be made, in most cases, on a lathe.

Element attachment was accomplished by a threaded and brazed joint. The element holes in the plate were threaded to eliminate machined registers, to allow adjustment at braze assembly, and to provide maximum braze-surface contact.

Fuel enters the plate through an interface with the adapter. Figure 6 shows the interface. The fuel enters a plenum and moves radially inward toward the injector center flowing between and into the fuel elements. The spacing of the elements insures that radial velocity and the resultant fuel pressure-drop is low: therefore, element pressure-drop controls flow distribution.

An 0.875-inch-diameter high-strength bolt at the injector center supplements the sixty 0.375-inch studs at the flange to attach the plate to the dome. The attachment prevents deflection of the plate by the pressure differential between the propellant plenums, or from the propellant plenums to the combustion chamber.

The "spud" on the fuel side at the center of the plate accommodates maximum bolt thread engagement while allowing fuel flow between it and the plate for face cooling.

INJECTOR

Figure 6 - Adapter-to-Injector Interface

2. Support Assembly, 1115315-9

The support assembly was designed: (1) to support the test assembly in the test stand; and (2) to contain oxidizer manifolding.

Design criteria of the test assembly were changed to relocate the mounting point from the injector to the adapter support, thereby removing the thrust load from the injector-support assembly.

A Raco seal is used at the support flange while a Harrison K seal is used under the center bolt. Both seals have been proof-tested at 1375 psig and leak-tested at 1030 psig in accordance with AGC-STD-9008, Method 101. No permanent deformation or leakage have been noted.

Three major subassemblies are welded together to form the support assembly: (1) torus, 1115083-1; (2) dome, 1115087-3; and (3) support, 1115081-3. The torus was formed from 0.25-inch plate comprised of two pieces and welded to the support. The dome was machined from a conic-shaped forging. The support was machined from a ring forging. Automatic machine welding was employed to attach the dome to the support.

3. Element Assembly, 1115086 and 1115650

The element assembly was designed to produce the specified velocity ratio, pressure drop, flow pattern, and flexibility for modification. A departure from the M-1 and J-2 conventional designs was made in the location of the fuel sleeve attachment (see Figure 7). Note that the fuel sleeve, 1115086, is screwed into the plate and that the oxidizer element, 1115650, is screwed into the fuel sleeve.

PHOEBUS - 2

M-1

Figure 7 - Injector Element Comparison

Removal of the oxidizer element is accomplished by "machining-off" the welded heads and unscrewing the remaining shanks. The replacement elements may be modified to produce changes in velocity ratio, thrust level, or pressure drop. Up-rating capability is limited because the physical size of the injector limits the number of elements.

Fuel sleeves support the face plate. The plate is registered on the sleeves' hexagonal shoulders, and the sleeves' tips are swaged and fused to the plate. The original design specified a swage joint only: however, pull tests indicated that the joint strength for face support was marginal and the decision was made to fuse the swaged tips into the plate by TIG welding. Joint strength increased to approximately 1500 lb, or three times that of the non-fused joints.

Eight feed-holes in the fuel sleeve are used to pass fuel from the injector plenum to the element annulus. The holes are staggered and in two planes to provide even flow into the annulus and to minimize strength degradation.

Low-velocity and high-pressure drop were achieved in the oxidizer element by designing a sharp entrance orifice in the head which diverged into a tube. One significant point observed during element hydro-testing was the back pressure required to stabilize flow. Water weight-flow was maintained constant while back pressure was varied. Pressure drop was 371 psi at 125-psi back pressure, 272 psi at 200-psi back pressure, and 239 psi at 300-psi back pressure. Pressure drop remained nearly constant at back pressures above 300 psi.

Element installation procedures are shown in Figures 8, 9, and 10. Assembly was accomplished in a clean room with the parts ultrasonically cleaned in Freon.

INSTALLATION AND GAUGING OF ELEMENTS

COMPLETE INSTALLATION OF ELEMENTS WITH
BRAZE POWDER APPLIED AND WIRE IN PLACE

Figure 8 - Installation of Elements

COVER PLATE INSTALLED TO MAINTAIN LATERAL
POSITION OF ELEMENTS DURING BRAZING.

INJECTOR IN FURNACE WITH THERMOCOUPLES
AND HYDROGEN PURGE LINES INSTALLED. THE
FEED HOLES IN THE FLANGE HAVE BEEN
COVERED TO DIRECT FLOW OF HYDROGEN
THROUGH ELEMENTS.

Figure 9 - Furnace Preparation

FACE-SIDE JOINT SHOWING THE COMPLETE FLOW
OF THE BRAZE MATERIAL.

DOME SIDE SHOWING RUN-THROUGH OF BRAZE
MATERIAL.

Figure 10 - Post Braze

Two turns of OFHC 0.060-inch-diameter wire were wrapped around the shank and the ends twisted together and trimmed. After the elements had been screwed into the plate to a gauged height, they were staked with a center punch at the threaded interface to prevent further turning during the remainder of the assembly. Four drops of copper powder in suspension were placed at the threaded interface. The copper wire was then pushed down the element shank into the powder suspension.

A plate drilled to the injector hole-pattern was installed over the elements, resting both on the element shoulders and a register at the flange. The purpose of the plate was to give lateral support to the elements and to direct purge gas during brazing.

During brazing, dry hydrogen purge gas was introduced through four tubes into the fuel manifold. The gas was contained and directed by the cover plate and by shim stock tack-welded over the fuel slots.

4. Igniter

Ignition of the propellants is accomplished by four pyrotechnic igniters located near the flange. The igniters are placed so their hot-gas discharge blankets the injector face.

5. Rigimesh Face

Rigimesh* is used as the face-plate material. It has also been used for face-plate material on J-2, RL-10, and M-1 injectors.

Face-plate thickness is 0.200-inch with a rating of 200 SCFM. The standard method of specifying the degree of permeability is the amount of air at standard temperature that will pass through one-square-foot of Rigimesh at a ΔP of 20 psi.

*The trade name of a rigid, pervious stainless steel sheet material well suited for use in areas of severe heat flux.

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APPENDIX A

COAXIAL INJECTOR STRESS ANALYSIS REPORT

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REPORT NO.	PAGE 1a OF
	DATE 3-14-66
	WORK ORDER
BY D. Tow	CHK. BY
	DATE

AGC 2-843

SUBJECT

COAXIAL INJECTOR STRESS ANALYSIS REPORT

PRESENTED IN THE FOLLOWING IS THE STRESS ANALYSIS FOR THE
PHOEBUS-2 COAXIAL INJECTOR. A SUMMARY OF THE RESULTS FOR THE
CRITICAL STRUCTURAL COMPONENTS IS GIVEN IN PAGE 1b. THE
DESIGN LOADS AND ALLOWABLES ARE GIVEN ON PAGE 1c.

COAXIAL INJECTOR STRESS ANALYSIS

BY

D. Tow

CHK. BY

DATE

SUMMARY

COMPONENT	M.S.	PAGE
INJECTOR PLATE	0.15	76
RIGIMESH PLATE	7.39	6
INJECTOR DOME (CONICAL SHELL)	0.21	37
LOX INLET MANIFOLD	0.56	55a
¹ THRUST SUPPORT	0.22	—
CENTER BOLT	0.58	38
DOME/PLATE STUDS	0.05	47a
RIGIMESH FACE/PLATE JOINT UNDER THERMAL STRESS	0.55	44
INJECTOR-ADAPTER BOLT	0.33	64
DOME/PLATE INTERFACE SEAL SEPARATION	0.0013"	50
² INJECTOR/ADAPTER INTERFACE SEAL SEPARATION	0.0128"	81

¹ M.S. OF 0.22 WAS BASED ON THRUST BEING CARRIED BY THE INJECTOR. SINCE THE LOAD WILL BE CARRIED BY THE ADAPTER THE ACTUAL MARGIN OF SAFETY WILL BE MUCH GREATER. SEE PAGE 28 OF THE MULTI ORIFICE INJECTOR STRESS REPORT FOR CALCULATIONS

² 0.0128" IS BASED ON 900 P_c. THE SEPARATION OF THE FLANGE WHEN COUPLED TO THE HYDRO-TOOL WAS 0.038" AT THE PROOF PRESSURE OF 1375 PSIG (OR 0.033 AT 1175 PSIG).

COAXIAL INJECTOR STRESS ANALYSIS

DATE

6-17-65

WORK ORDER

0960-21-421

BY

D. Tow

CHK. BY

DATE

DESIGN DATA :

MATERIAL : 1. CRES 347 @ 70°F

$$F_{tu} = 75,000 \text{ psi}$$

$$F_{ty} = 30,000 \text{ psi}$$

$$F_{by} = 1.2 F_{ty} = 36,000 \text{ psi}$$

$$F_{sy} = 0.55 F_{ty} = 16,500 \text{ psi}$$

REF. REON REPORT 2275,
MATERIAL PROPERTIES DATA
BOOK, REVISED JULY 1964

2. RIGIMESH

$$F_{ty} = 0.8 \times 30,000 = 24,000 \text{ psi}$$

LOADS : CHAMBER PRESSURE = 900 psi

OTHERS AS SHOWN IN TEXT.

LOAD FACTOR : PRESSURE LOADS = 1.15

THRUST LOAD = 1.25

AOC 2-849
 SUBJECT

COAXIAL INJECTOR STRESS ANALYSIS

REPORT NO.

PAGE 1 OF

DATE

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WORK ORDER

0960-21-421

DATE

BY

D. Tow

CHK. BY

FIGURE 1 COAXIAL INJECTOR DOME CONFIGURATION

COAXIAL INJECTOR STRESS ANALYSIS

6-18-65

D. Tow

ELEMENT ②

FIXED PLATE WITH UNIFORM LOAD :

(TIMOSHENKO, THEORY OF PLATES AND SHELLS, pp 55)

$$M_r = \frac{q}{16} [a^2(1+\nu) - r^2(3+\nu)]$$

$$M_t = \frac{q}{16} [a^2(1+\nu) - r^2(1+3\nu)]$$

FIGURE 2

MAXIMUM M_r OCCURS AT THE BOUNDARY OF PLATE AND IS

$$(M_r)_{r=a} = -\frac{qa^2}{8}$$

MAXIMUM M_t OCCURS AT CENTER OF PLATE AND IS

$$(M_t)_{r=0} = \frac{qa^2}{16} (1+\nu)$$

$$\nu = 0.3$$

$$a \approx 11.53''$$

$$q = \Delta p = 300 \text{ psi}$$

$$(M_r)_{r=a} = -\frac{1.15(300)(11.53)^2}{8} = -5,730 \frac{\text{IN-LB}}{\text{IN}}$$

$$(M_t)_{r=0} = \frac{1.15(300)(11.53)^2}{16} (1+0.3) = 3,730 \frac{\text{IN-LB}}{\text{IN}}$$

MAXIMUM STRESS IS AT THE BOUNDARY OF THE PLATE WHERE

$$(f_r)_{\max} = -\frac{6M_r}{h^2} = \frac{6(5730)}{(1.0)^2} = 34,380 \text{ psi}$$

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REEVALUATE ELEMENT ② AS SIMPLY SUPPORTED PLATE

$$M_r = \frac{8}{16} (3+\nu) (a^2 - r^2)$$

(TIMOSHENKO, P & S., PP. 57)

$$M_t = \frac{8}{16} [a^2 (3+\nu) - r^2 (1+3\nu)]$$

MAXIMUM BENDING MOMENT IS AT THE CENTER OF THE PLATE WHERE

$$M_r = M_t = \frac{3+\nu}{16} 8 a^2$$

THE CORRESPONDING MAXIMUM STRESS IS

$$(f_r)_{\max} = (f_t)_{\max} = \frac{6M_r}{h^2} = \frac{3(3+\nu) 8 a^2}{8 h^2} = \frac{3(3+0.3)(1.15)(300)(11.53)^2}{8 (1)^2} = 56,800 \text{ psi}$$

$$F_{tb} = 1.2 F_{ty} = 36,000 \text{ psi}$$

$$\text{MINIMUM THICKNESS REQ'D} = \sqrt{\frac{3(3.3)(1.15)(300)(11.53)^2}{8 (36000)}} = \sqrt{1.58} = 1.256"$$

$\therefore$ USE $1\frac{1}{4}"$ THICK PLATE

ELEMENT ③

ELEMENT ③ IS A FLAT PLATE WITH ²⁴²~~250~~ FUEL SLEEVES. A TYPICAL PANEL, SHOWN IN DETAIL A IS ANALYZED UNDER THE FOLLOWING CONDITION

$\Delta p = 300 \text{ psi}$ (DIFFERENCE BETWEEN FUEL PRESSURE & CHAMBER PRESSURE)

F_{ty} OF MATERIAL (RIGIMESH) = $.80 F_{ty}$ FOR 347 SS = $24,000 \text{ psi}$

DETAIL A

⇒
APPROX. BY
RECT. PLATE
SUPPORTED AT
4 CORNERS

FIGURE 3a

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THE DANGEROUS SECTION OF THE PLATE IS APPROXIMATELY AT A DIAGONAL SECTION SUCH AS AC

THE BENDING MOMENT, ABOUT THE DIAGONAL AC, OF THE FORCES THAT LIE TO ONE SIDE OF THE DIAGONAL MAY BE FOUND AS FOLLOWS:

ΣM ABOUT AC

$$M = W\left(\frac{b}{3}\right) - Rh = \frac{Wh}{3} - \frac{Wh}{4} = \frac{Wh}{12}$$

BUT $W = qab$

THEN

$$M = \frac{1}{12} qab^2h$$

THE AVERAGE BENDING MOMENT PER UNIT WIDTH OF THE DIAGONAL IS

$$M_1 = \frac{1}{12} qab^2h / \bar{AC}$$

BUT $\bar{AC} = \sqrt{a^2 + b^2}$

$$h = \frac{ab}{\sqrt{a^2 + b^2}}$$

THEREFORE,

$$M_1 = \frac{qab}{12} \left(\frac{ab}{\sqrt{a^2 + b^2}} \right) \left(\frac{1}{\sqrt{a^2 + b^2}} \right) = \frac{1}{12} \left[\frac{a^2}{a^2 + b^2} \right] qb^2$$

THE AVERAGE BENDING STRESS AT THE SURFACE OF THE PLATE ACROSS THE DIAGONAL AC IS

$$f = \frac{M_1 c}{I} = \frac{6M_1}{t^2} = \frac{1}{2} \left[\frac{a^2}{a^2 + b^2} \right] \left[\frac{qb^2}{t^2} \right]$$

HERE

$$q = 300 \times 1.15 = 345 \text{ psi}$$

$$t = 0.20''$$

$$a = 1.4''$$

$$b = 1.0''$$

REF. SEELY & SMITH, "ADVANCED MECHANICS OF MATERIALS" PP. 231-232.

FIGURE 4

$$f = \frac{1}{2} \left[\frac{(1.4)^2}{(1.4)^2 + (1.0)^2} \right] \left[\frac{345(1.0)^2}{(0.2)^2} \right] = 2,860 \text{ psi}$$

THE ABOVE AVERAGE STRESS HAS BEEN USED WIDELY AS A BASIS OF DESIGN AND MAY BE JUSTIFIED BY THE FACT THAT THE HIGHER STRESSES AT THE CORNERS ARE LOCALIZED WHICH DO NOT AFFECT APPRECIABLY THE BEHAVIOR OF THE PLATE AS A WHOLE EVEN THOUGH THEY EXCEED THE ELASTIC STRENGTH OF THE MATERIAL, AND THAT WHEN THE MATERIAL BEGINS TO YIELD IN A PART OF THE DIAGONAL SECTION THE STRESSES ARE REDISTRIBUTED IN A MANNER SO THAT THEY BECOME MORE NEARLY UNIFORM ALONG THE DIAGONAL. BESIDES, IF A FACTOR OF 3 TO 4 IS INCLUDED IN THE ABOVE STRESS VALUE, THE PLATE IS STILL WELL BELOW THE MATERIAL YIELD OF 24,000 psi.

$$M.S. = \frac{24000}{2860} - 1 = \underline{7.39}$$

REEVALUATE ELEMENT ③ USING CONTINUOUS RECTANGULAR PLATE THEORY

FIGURE 5

REF.: TIMOSHENKO, "THEORY OF PLATES AND SHELLS", pp. 246-249

$$\frac{b}{a} = 1.4$$

MAXIMUM MOMENT AT CENTER OF A PANEL (TABLE 57, PP 249) IS

$$M_y = 0.0384 q b^2$$

$$f = \frac{6M_y}{t^2} = \frac{6(0.0384)qb^2}{t^2} = \frac{6(0.0384)(345)(1.4)^2}{(0.2)^2} = 3,900 \text{ psi}$$

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ELEMENT ①

ASSUME FREE CONICAL
SHELL (NO RESTRAINT AT EDGES)

$$p = 1350 \text{ psi} \times 1.15$$

$$R = 10.28''$$

$$t = 0.50''$$

$$\alpha = 60^\circ$$

Hoop STRESS :

$$\sigma_2 = \frac{pR}{t \cos \alpha} = \frac{1.15 (1350) (10.28)}{0.50 (\cos 60^\circ)} = 63,800 \text{ psi}$$

MERIDIONAL STRESS :

$$\sigma_1 = \frac{pR}{2t \cos \alpha} = 31,900 \text{ psi}$$

A MORE ELABORATE ANALYSIS IS GIVEN BELOW, WHICH TAKES INTO ACCOUNT
THE EDGE RESTRAINT.

FIGURE 6

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ELEMENT ① — ANALYSIS OF CONICAL SHELL

REF. HETENYI, "BEAMS ON
ELASTIC FOUNDATION," pp.
119-126

FIGURE 7a

$$p = 1 \text{ psi}$$

$$2\alpha = 120^\circ$$

$$2R = 20.56''$$

$$x_0 = 10.28 / (0.866) = 11.87''$$

$$t = 1.00'' \text{ (ASSUME FOR FIRST TRIAL)}$$

$$\nu = 0.30$$

FIGURE 7b

THE SHELL WILL BE CONSIDERED FIRST AS A MEMBRANE, WHEN THE CIRCUMFERENTIAL MEMBRANE FORCES N_m AND THE RADIAL MEMBRANE FORCES T_m DUE TO NORMAL LOADING $Z = p$ CAN BE OBTAINED BY

$$T_m = -\frac{1}{2} p x \tan \alpha \quad (1)$$

$$N_m = -p x \tan \alpha \quad (2)$$

THE MAXIMUM MEMBRANE FORCES OCCUR AT $x = x_0 = 11.87''$ WHERE WE HAVE

$$T_m = -\frac{1}{2} (1.00) (11.87) (1.7321) = -10.28 \text{ #/} \quad (3)$$

$$N_m = - (1.00) (11.87) (1.7321) = -20.56 \text{ #/} \quad (4)$$

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THE BENDING ANALYSIS OF A THIN-WALLED CONICAL SHELL BY FORCES OR MOMENTS UNIFORMLY DISTRIBUTED AROUND ANY HOOP CIRCLE OF THE SHELL GIVES THE FOLLOWING STRESS SYSTEM EQUATIONS (REF., PP. 121-122)

$$y_x = \sqrt{x} \left[C_1 z_1'(\xi) + C_2 z_2'(\xi) + C_3 z_3'(\xi) + C_4 z_4'(\xi) \right] \quad (5)$$

$$\theta_x = \lambda \left[C_1 z_2(\xi) - C_2 z_1(\xi) + C_3 z_4(\xi) - C_4 z_3(\xi) \right] \quad (6)$$

$$M_x = \frac{Et^3}{12} \frac{\lambda^2}{\sqrt{x}} \left[C_1 z_2'(\xi) - C_2 z_1'(\xi) + C_3 z_4'(\xi) - C_4 z_3'(\xi) \right] \quad (7)$$

$$Q_x = -\frac{Et^3}{12} \frac{\lambda^3}{x} \left\{ C_1 \left[z_1(\xi) + \frac{2}{\xi} z_2'(\xi) \right] + C_2 \left[z_2(\xi) - \frac{2}{\xi} z_1'(\xi) \right] + C_3 \left[z_3(\xi) + \frac{2}{\xi} z_4'(\xi) \right] + C_4 \left[z_4(\xi) - \frac{2}{\xi} z_3'(\xi) \right] \right\} \quad (8)$$

$$N_x = \frac{Et}{x \tan \alpha} y_x \quad (9)$$

$$T_x = Q_x \tan \alpha \quad (10)$$

WHERE THE ABOVE TERMS REPRESENT THE DEFLECTION (NORMAL TO THE GENERATOR OF THE CONE), ROTATION, BENDING MOMENT, SHEARING FORCE, HOOP FORCE, AND NORMAL FORCE.

FOR A CLOSED CONE, $C_3 = C_4 = 0$, AND THE TWO REMAINING CONSTANTS CAN BE FOUND FROM THE CONDITIONS PRESCRIBED AT THE BASE CIRCLE.

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FROM (3) & (4) THE HORIZONTAL DISPLACEMENT y_h ALONG THE BASE OF THE SHELL DUE TO THE MEMBRANE FORCES IS

$$y_h = \frac{R}{Et} (N_m - \nu T_m) = \frac{10.28}{E(1.0)} [-20.56 - 0.30(-10.28)] = -\frac{180}{E} \text{ IN.}$$

THE TWO BOUNDARY CONDITIONS AT THE BASE CIRCLE ARE

$$[y_x \cos \alpha]_{x=x_0} = -y_h$$

$$[\theta_x]_{x=x_0} = 0$$

BY MEANS OF EQS. (5) AND (6) THESE TWO BOUNDARY CONDITIONS CAN BE WRITTEN AS

$$\cos \alpha \sqrt{x_0} [C_1 Z'_1(\xi_0) + C_2 Z'_2(\xi_0)] = \frac{180}{E}$$

AND

$$C_1 Z_2(\xi_0) - C_2 Z_1(\xi_0) = 0$$

WHERE

$$\xi_0 = 2\lambda \sqrt{x_0} \quad \text{AND} \quad \lambda = \sqrt[4]{\frac{12}{t^2 \tan^2 \alpha}}$$

SUBSTITUTE HERE THE ASYMPTOTIC EXPRESSIONS OF Z_1 , Z_2 , Z'_1 AND Z'_2 FOR LARGE VALUES OF THE ARGUMENT (REF pp. 104-105), WE HAVE

$$C_1 \cos\left(\frac{\xi_0}{\sqrt{2}} + \frac{\pi}{8}\right) - C_2 \sin\left(\frac{\xi_0}{\sqrt{2}} + \frac{\pi}{8}\right) = \frac{180}{E} \frac{1}{\cos \alpha \sqrt{x_0}} \sqrt{2\pi\xi_0} e^{-\frac{\xi_0}{\sqrt{2}}} \quad (11)$$

$$C_1 \sin\left(\frac{\xi_0}{\sqrt{2}} - \frac{\pi}{8}\right) + C_2 \cos\left(\frac{\xi_0}{\sqrt{2}} - \frac{\pi}{8}\right) = 0 \quad (12)$$

CALCULATIONS OF PARAMETERS:

$$\lambda = \sqrt[4]{\frac{12}{1^2 \tan^2 60^\circ}} = \sqrt[4]{\frac{12}{(1.7321)^2}} = 1.414$$

$$\xi_0 = 2(1.414) \sqrt{11.87} = 9.742$$

$$\frac{\xi_0}{\sqrt{2}} + \frac{\pi}{8} = \frac{9.742}{1.414} + 0.3927 = 7.2824 \text{ rad.} = 2\pi + 0.9992 = 360^\circ + 57^\circ 15'$$

$$\frac{\xi_0}{\sqrt{2}} - \frac{\pi}{8} = 6.4970 \text{ rad.} = 2\pi + 0.2138 = 360^\circ + 12^\circ 15'$$

SUBSTITUTING THE ABOVE VALUES INTO EQS. (11) AND (12) TO OBTAIN

$$C_1 \cos 57^\circ 15' - C_2 \sin 57^\circ 15' = C$$

$$C_1 \sin 12^\circ 15' + C_2 \cos 12^\circ 15' = 0$$

THE SOLUTION OF THESE SIMULTANEOUS EQUATIONS GIVES

$$C_1 = 1.382 C$$

$$C_2 = -0.300 C$$

WHERE

$$C = \frac{180}{E} \frac{1}{\cos \alpha \sqrt{x_0}} \sqrt{2\pi \xi_0} e^{-\frac{\xi_0}{\sqrt{2}}}$$

SUBSTITUTING THESE VALUES TOGETHER WITH $C_3 = C_4 = 0$ IN EQUATIONS (5-10), WE HAVE THE FINAL RESULTS OF THE BENDING ANALYSIS. THIS GIVES THE FOLLOWING EXPRESSIONS (SEE PAGES 13 & 14) :

$$y_x = \frac{180 X}{E X_0 \cos \alpha} \sqrt{\left(\frac{\xi_0}{F}\right)^3} e^{-\frac{(\xi_0 - F)}{\sqrt{2}}} \left[1.382 \cos \left(\frac{F}{\sqrt{2}} + \frac{\pi}{8} \right) + 0.300 \sin \left(\frac{F}{\sqrt{2}} + \frac{\pi}{8} \right) \right] \quad (13)$$

$$\theta_x = \frac{180 \lambda \sqrt{x}}{E X_0 \cos \alpha} \sqrt{\left(\frac{\xi_0}{F}\right)^3} e^{-\frac{(\xi_0 - F)}{\sqrt{2}}} \left[-1.382 \sin \left(\frac{F}{\sqrt{2}} - \frac{\pi}{8} \right) + 0.300 \cos \left(\frac{F}{\sqrt{2}} - \frac{\pi}{8} \right) \right] \quad (14)$$

$$M_x = \frac{180 t^3 \lambda^2}{12 X_0 \cos \alpha} \sqrt{\left(\frac{\xi_0}{F}\right)^3} e^{-\frac{(\xi_0 - F)}{\sqrt{2}}} \left[-1.382 \sin \left(\frac{F}{\sqrt{2}} + \frac{\pi}{8} \right) + 0.300 \cos \left(\frac{F}{\sqrt{2}} + \frac{\pi}{8} \right) \right] \quad (15)$$

$$Q_x = - \frac{180 t^3 \lambda^3}{12 X_0 X^{\frac{1}{2}} \cos \alpha} \sqrt{\left(\frac{\xi_0}{F}\right)^3} e^{-\frac{(\xi_0 - F)}{\sqrt{2}}} \left\{ 1.382 \left[\cos \left(\frac{F}{\sqrt{2}} - \frac{\pi}{8} \right) - \frac{2}{F} \sin \left(\frac{F}{\sqrt{2}} + \frac{\pi}{8} \right) \right] + 0.300 \left[\sin \left(\frac{F}{\sqrt{2}} - \frac{\pi}{8} \right) + \frac{2}{F} \cos \left(\frac{F}{\sqrt{2}} + \frac{\pi}{8} \right) \right] \right\} \quad (16)$$

$$N_x = \frac{180 t}{X_0 \sin \alpha} \sqrt{\left(\frac{\xi_0}{F}\right)^3} e^{-\frac{(\xi_0 - F)}{\sqrt{2}}} \left[1.382 \cos \left(\frac{F}{\sqrt{2}} + \frac{\pi}{8} \right) + 0.300 \sin \left(\frac{F}{\sqrt{2}} + \frac{\pi}{8} \right) \right] \quad (17)$$

$$T_x = Q_x \tan \alpha \quad (18)$$

$$\begin{aligned}
 y_x &= \sqrt{x} \left[C_1 z_1'(\xi) + C_2 z_2'(\xi) \right] = \sqrt{x} C \left[1.382 z_1'(\xi) - 0.300 z_2'(\xi) \right] \\
 &= \sqrt{x} \frac{180}{E} \frac{1}{\cos \alpha \sqrt{x_0}} \sqrt{2\pi \xi_0} e^{-\frac{\xi_0}{\sqrt{x}}} \left[1.382 (\cos \sigma - \sin \sigma) + 0.300 (\cos \sigma + \sin \sigma) \right] \frac{\alpha}{\sqrt{x}} \\
 &= \sqrt{x} \frac{180}{E} \frac{1}{\cos \alpha \sqrt{x_0}} \sqrt{2\pi \xi_0} e^{-\frac{\xi_0}{\sqrt{x}}} \left(\frac{1}{\sqrt{2\pi \xi}} e^{\frac{\xi}{\sqrt{x}}} \right) \left[1.382 \cos \left(\frac{\xi}{\sqrt{x}} + \frac{\pi}{8} \right) + 0.300 \sin \left(\frac{\xi}{\sqrt{x}} + \frac{\pi}{8} \right) \right] \\
 &= \frac{180 \times}{E x_0 \cos \alpha} \sqrt{\left(\frac{\xi_0}{\xi} \right)^3} e^{-\frac{(\xi_0 - \xi)}{\sqrt{x}}} \left[1.382 \cos \left(\frac{\xi}{\sqrt{x}} + \frac{\pi}{8} \right) + 0.300 \sin \left(\frac{\xi}{\sqrt{x}} + \frac{\pi}{8} \right) \right]
 \end{aligned}$$

$$\begin{aligned}
 \theta_x &= \lambda \left[C_1 z_2(\xi) - C_2 z_1(\xi) \right] = \lambda C \left[1.382 z_2(\xi) + 0.300 z_1(\xi) \right] \\
 &= \lambda \frac{180}{E} \frac{1}{\sqrt{x_0} \cos \alpha} \sqrt{2\pi \xi_0} e^{-\frac{\xi_0}{\sqrt{x}}} \left(\frac{1}{\sqrt{2\pi \xi}} e^{\frac{\xi}{\sqrt{x}}} \right) \left[-1.382 \sin \left(\frac{\xi}{\sqrt{x}} - \frac{\pi}{8} \right) + 0.300 \cos \left(\frac{\xi}{\sqrt{x}} - \frac{\pi}{8} \right) \right] \\
 &= \frac{180 \lambda \sqrt{x}}{E x_0 \cos \alpha} \sqrt{\left(\frac{\xi_0}{\xi} \right)^3} e^{-\frac{(\xi_0 - \xi)}{\sqrt{x}}} \left[-1.382 \sin \left(\frac{\xi}{\sqrt{x}} - \frac{\pi}{8} \right) + 0.300 \cos \left(\frac{\xi}{\sqrt{x}} - \frac{\pi}{8} \right) \right]
 \end{aligned}$$

$$\begin{aligned}
 M_x &= \frac{Et^3}{12} \frac{\lambda^2}{\sqrt{x}} \left[C_1 z_2'(\xi) - C_2 z_1'(\xi) \right] = \frac{Et^3}{12} \frac{\lambda^2}{\sqrt{x}} C \left[1.382 z_2'(\xi) + 0.300 z_1'(\xi) \right] \\
 &= \frac{Et^3}{12} \frac{\lambda^2}{\sqrt{x}} \left(\frac{180}{E} \frac{1}{\sqrt{x_0} \cos \alpha} \sqrt{2\pi \xi_0} e^{-\frac{\xi_0}{\sqrt{x}}} \right) \left(\frac{1}{\sqrt{2\pi \xi}} e^{\frac{\xi}{\sqrt{x}}} \right) \left[-1.382 \sin \left(\frac{\xi}{\sqrt{x}} + \frac{\pi}{8} \right) \right. \\
 &\quad \left. + 0.300 \cos \left(\frac{\xi}{\sqrt{x}} + \frac{\pi}{8} \right) \right] \\
 &= \frac{180 t^3 \lambda^2}{12 x_0 \cos \alpha} \sqrt{\left(\frac{\xi_0}{\xi} \right)^3} e^{-\frac{(\xi_0 - \xi)}{\sqrt{x}}} \left[-1.382 \sin \left(\frac{\xi}{\sqrt{x}} + \frac{\pi}{8} \right) + 0.300 \cos \left(\frac{\xi}{\sqrt{x}} + \frac{\pi}{8} \right) \right]
 \end{aligned}$$

$$\begin{aligned}
 Q_x &= -\frac{Et^3}{12} \frac{\lambda^3}{x} \left\{ C_1 \left[z_1'(\xi) + \frac{2}{\xi} z_2'(\xi) \right] + C_2 \left[z_2(\xi) - \frac{2}{\xi} z_1'(\xi) \right] \right\} \\
 &= -\frac{Et^3}{12} \frac{\lambda^3}{x} \left(\frac{180}{E} \frac{1}{\sqrt{x_0} \cos \alpha} \sqrt{2\pi \xi_0} e^{-\frac{\xi_0}{\sqrt{x}}} \right) \left\{ 1.382 \left[\cos \left(\frac{\xi}{\sqrt{x}} - \frac{\pi}{8} \right) - \frac{2}{\xi} \sin \left(\frac{\xi}{\sqrt{x}} + \frac{\pi}{8} \right) \right] \right. \\
 &\quad \left. + 0.300 \left[\sin \left(\frac{\xi}{\sqrt{x}} - \frac{\pi}{8} \right) + \frac{2}{\xi} \cos \left(\frac{\xi}{\sqrt{x}} + \frac{\pi}{8} \right) \right] \right\} \left(\frac{1}{\sqrt{2\pi \xi}} e^{\frac{\xi}{\sqrt{x}}} \right) \\
 &= -\frac{180 t^3 \lambda^3}{12 x_0 \cos \alpha} \sqrt{\left(\frac{\xi_0}{\xi} \right)^3} e^{-\frac{(\xi_0 - \xi)}{\sqrt{x}}} \left\{ 1.382 \left[\cos \left(\frac{\xi}{\sqrt{x}} - \frac{\pi}{8} \right) - \frac{2}{\xi} \sin \left(\frac{\xi}{\sqrt{x}} + \frac{\pi}{8} \right) \right] + 0.300 \left[\sin \left(\frac{\xi}{\sqrt{x}} - \frac{\pi}{8} \right) \right. \right. \\
 &\quad \left. \left. + \frac{2}{\xi} \cos \left(\frac{\xi}{\sqrt{x}} + \frac{\pi}{8} \right) \right] \right\}
 \end{aligned}$$

$$N_x = \frac{180 t}{\lambda_0 \sin \alpha} \sqrt{\left(\frac{F_0}{F}\right)^3} e^{-(F_0 - F)/\sqrt{2}} \left[1.382 \cos\left(\frac{F}{\sqrt{2}} + \frac{\pi}{8}\right) + 0.300 \sin\left(\frac{F}{\sqrt{2}} + \frac{\pi}{8}\right) \right]$$

$$T_x = -\frac{180 t^3 \lambda^3 \tan \alpha}{12 \lambda_0 \sqrt{x} \cos \alpha} \sqrt{\left(\frac{F_0}{F}\right)^3} e^{-(F_0 - F)/\sqrt{2}} \left\{ 1.382 \left[\cos\left(\frac{F}{\sqrt{2}} - \frac{\pi}{8}\right) - \frac{2}{F} \sin\left(\frac{F}{\sqrt{2}} + \frac{\pi}{8}\right) \right] \right. \\ \left. + 0.300 \left[\sin\left(\frac{F}{\sqrt{2}} - \frac{\pi}{8}\right) + \frac{2}{F} \cos\left(\frac{F}{\sqrt{2}} + \frac{\pi}{8}\right) \right] \right\}$$

BY D. Tow

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FIGURE 8 CONICAL SHELL SECTIONS FOR STRESS
EVALUATION

$$R = 10.28$$

$$x_0 = 11.87$$

$$\alpha = 60^\circ$$

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①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬	⑭	⑮
SECTION	X	$\sqrt{X}$	F	$\frac{F_0}{F}$	$\left(\frac{F_0}{F}\right)^3$	$\sqrt{\left(\frac{F_0}{F}\right)^3}$	$F_0 - F$	$\frac{F_0 - F}{\sqrt{2}}$	$e^{-\left(\frac{F_0 - F}{\sqrt{2}}\right)}$	$\frac{F}{\sqrt{2}}$	$\frac{F}{\sqrt{2}} + \frac{\pi}{8}$	$\frac{F}{\sqrt{2}} - \frac{\pi}{8}$	$\frac{2}{F}$	$\cos ⑫$
1	2	1.414	4.000	2.436	14.455	3.802	5.742	4.061	0.0172	2.829	3.222 (184°36')	2.436 (139°34')	0.500	-0.9968
2	4	2.000	5.656	1.722	5.106	2.260	4.086	2.890	0.0556	4.000	4.393 (251°42')	3.607 (206°40')	0.354	-0.3140
3	6	2.449	6.926	1.407	2.785	1.669	2.816	1.992	0.1362	4.898	5.291 (303°9')	4.505 (258°7')	0.289	0.5468
4	8	2.828	8.000	1.218	1.807	1.344	1.742	1.232	0.2918	5.658	6.051 (346°42')	5.265 (301°40')	0.250	0.9732
5	10	3.162	8.942	1.089	1.291	1.136	0.800	0.566	0.5678	6.324	6.717 (384°51')	5.931 (339°49')	0.224	0.9074
6	11.87	3.445	9.742	1.000	1.000	1.000	0	0	1.0000	6.890	7.283 (417°17')	6.497 (372°15')	0.205	0.5405

$$\lambda = 1.414$$

$$\cos \alpha = 0.500$$

$$\sin \alpha = 0.866$$

$$\tan \alpha = 1.732$$

$$X_0 = 11.87$$

$$t = 1.00$$

$$\frac{F_0}{F} = 9.742$$

$$\frac{F_0}{F} = 2.828\sqrt{X}$$

$$\frac{\pi}{8} = 0.393$$

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MEMBRANE FORCES :

$$N_m = -p x \tan \alpha = -1.732 x$$

$$T_m = -\frac{1}{2} p x \tan \alpha = -0.866 x$$

(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
$\sin (12)$	$\cos (13)$	$\sin (13)$	y_x	M_x	Q_x	N_x	T_x	N_m	T_m	$N'_x = N_m + N_x$	$T'_x = T_m + T_x$
0.0802	-0.7612	0.6486	-0.192×10^{-6}	-0.095	0.315	-1.607	0.546	-3.464	-1.732	-5.071	-1.186
-0.9494	-0.8936	-0.4488	-0.378×10^{-6}	0.773	0.422	-1.582	0.731	-6.928	-3.464	-8.510	-2.733
-0.8372	-0.2059	-0.9786	0.720×10^{-6}	1.516	0.130	2.009	0.225	-10.392	-5.196	-8.383	-4.971
-0.2301	0.5250	-0.8511	4.187×10^{-6}	1.208	-0.617	8.763	-1.069	-13.856	-6.928	-5.093	-7.997
0.4202	0.9386	-0.3450	9.311×10^{-6}	-1.005	-1.640	15.590	-2.840	-17.32	-8.66	-1.730	-11.50
0.8414	0.9772	0.2122	12.408×10^{-6}	-5.053	-2.509	17.503	-4.346	-20.559	-10.279	-3.656	-14.625

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$$y_x = \frac{180}{29 \times 10^6 (11.87) (0.5)} \times (2) \times (7) \times (10) \left[1.382 \times (15) + 0.300 \times (16) \right]$$

$$= 1.046 \times 10^{-6} \times (2) \times (7) \times (10) \left[1.382 \times (15) + 0.300 \times (16) \right]$$

$$M_x = \frac{180 (1)^3 (1.414)^2}{12 (11.87) (0.50)} \times (7) \times (10) \left[-1.382 \times (16) + 0.300 \times (15) \right]$$

$$= 5.05 \times (7) \times (10) \left[-1.382 \times (16) + 0.300 \times (15) \right]$$

$$Q_x = -\frac{180 (1)^3 (1.414)^3}{12 (11.87) (0.50)} \times \frac{(7)}{(3)} \times (10) \left\{ 1.382 \left[(17) - (14) \times (16) \right] + 0.300 \left[(18) + (14) \times (15) \right] \right\}$$

$$= -7.15 \times \frac{(7)}{(3)} \times (10) \left\{ 1.382 \left[(17) - (14) \times (16) \right] + 0.300 \left[(18) + (14) \times (15) \right] \right\}$$

$$N_x = \frac{180 (1)}{(11.87) (0.866)} \times (7) \times (10) \left[1.382 \times (15) + 0.300 \times (16) \right] = 17.511 \times (7) \times (10) \left[1.382 \times (15) + 0.300 \times (16) \right]$$

$$T_x = 1.732 Q_x$$

THE VALUES OF y_x , M_x , Q_x , N_x , AND T_x DUE TO 1 PSI PRESSURE ARE TABULATED IN THE PRECEDING TABLE, COLUMNS 19 TO 23.

COLUMNS (24) AND (25) GIVE THE MEMBRANE FORCES. THE FINAL VALUES OF THE FORCES AND MOMENTS ARE TO BE OBTAINED AS THE ALGEBRAIC SUM OF THE SOLUTION FROM THE MEMBRANE ANALYSIS AND THE BENDING ANALYSIS, AND THESE ARE GIVEN BY COLUMNS (29), (31), (36) AND (37).

STRESSES ARE OBTAINED FROM THE FOLLOWING EQUATIONS:

MERIDIONAL STRESS

$$f_m = \pm \frac{6M_x}{t^2} + \frac{T_x'}{t} \quad (18)$$

HOOP STRESS

$$f_h = \pm \nu \frac{6M_x}{t^2} + \frac{N_x'}{t} \quad (19)$$

SECTION 1

$$f_m = \frac{6(0.095)}{1^2} + \frac{1.186}{1} = 1.756 \text{ PSI} / \text{PSI PRESSURE FOR 1" THICK SHELL}$$

$$f_H = 0.30(6)(0.095) + 5.071 = 5.242$$

SECTION 2

$$f_m = 6(0.773) + 2.733 = 7.371$$

$$f_H = 1.8(0.773) + 8.510 = 9.901$$

SECTION 3

$$f_m = 6(1.516) + 4.971 = 14.067$$

$$f_H = 1.8(1.516) + 8.383 = 11.112$$

SECTION 4

$$f_m = 6(1.208) + 7.997 = 15.245$$

$$f_H = 1.8(1.208) + 5.043 = 7.267$$

SECTION 5

$$f_m = 6(1.005) + 11.500 = 17.53$$

$$f_H = 1.8(1.005) + 1.730 = 3.539$$

SECTION 6

$$f_m = 6(5.053) + 14.625 = 44.943$$

$$f_H = 1.8(5.053) + 3.056 = 12.151$$

SUBJECT

DATE

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WORK ORDER

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MAXIMUM STRESSES OCCUR AT SECTION 6, WHERE FOR $p = 1350 \times 1.15$
 $= 1552.5$

$$f_m = 1350 \times 1.15 [6(5.053) + 14.625] = 47.069 + 22.705 = 69,77.4 \text{ psi}$$

$$f_H = 1350 \times 1.15 [1.8(5.053) + 3.056] = 14,121 + 4,744 = 18,865 \text{ psi}$$

FOR OTHER SECTIONS, THE STRESSES ARE

SECTION 1 :

$$f_m = 1.756(1552.5) = 2,726 \text{ psi}$$

$$f_H = 5.242(1552.5) = 8,138$$

SECTION 2 :

$$f_m = 7.371(1552.5) = 11,443$$

$$f_H = 9.901(1552.5) = 15,371$$

SECTION 3 :

$$f_m = 14.067(1552.5) = 21,839$$

$$f_H = 11.112(1552.5) = 17,251$$

SECTION 4 :

$$f_m = 15.245(1552.5) = 23,668$$

$$f_H = 7.267(1552.5) = 11,282$$

SECTION 5 :

$$f_m = 17.53(1552.5) = 27,215$$

$$f_H = 3.539(1552.5) = 5,494$$

BY
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FIGURE 9

THE CRITICAL STRESS OCCURS AT THE EDGE WHERE THE LARGE MAGNITUDE OF THIS STRESS IS ATTRIBUTED TO THE BENDING MOMENT AT THE BOUNDARY. THIS BENDING MOMENT IS LOCALIZED ONLY AND WILL DIMINISH RAPIDLY TOWARD THE VERTEX OF THE CONE (SEE FIGURE 9 ON PAGE 21). THEREFORE, TO DECREASE THE STRESSES AT THE EDGE, WE STIFFEN THE EDGE AS SHOWN IN FIGURE 10 (PAGE 24)

CHECK STRESSES AT VARIOUS SECTIONS NEAR THE EDGE USING PROPOSED CONFIGURATION GIVEN IN FIGURE 10.

AT $x = 11.87''$

$$f_m = \frac{6M_x}{t^2} + \frac{T_x'}{t} = \frac{6(5053)(1552.5)}{(2.0)^2} + \frac{14.62E(1552.5)}{2.0} = 23,120 \text{ psi}$$

AT $x = 11.20'$

$$t \approx 1.34'' \quad (\text{FIGURE 10})$$

$$\left. \begin{array}{l} M_x = -3.32 \\ T_x' = -13.6 \end{array} \right\} \quad (\text{FROM FIGURE 9})$$

$$f_m = \frac{6(3.32)(1552.5)}{(1.34)^2} + \frac{13.6(1552.5)}{1.34} = 17,223 + 15,757 = 32,980 \text{ psi}$$

$$M.S. = \frac{1}{\frac{17223}{36000} + \frac{15757}{36000}} - 1 = \frac{1}{0.478 + 0.525} - 1 = -0.003 \quad (\text{O.K., SINCE STRESS IS CONSERVATIVE})$$

AT $x = 10.70''$

$$t \approx 1.13''$$

$$M_x = -2.3$$

$$T_x' = -12.75$$

$$f_m = \frac{6(23)(1552.5)}{(1.13)^2} + \frac{12.75(1552.5)}{1.13} = 16,779 + 17,517 = 34,296 \text{ psi}$$

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$$M.S. = \frac{1}{\frac{16,779}{36,000} + \frac{17,517}{30,000}} - 1 = \frac{1}{0.466 + 0.584} - 1 = -0.048$$

(O.K. since stress is
conservative)

$$A_T \quad x = 10.20''$$

$$t \approx 1.02''$$

$$M_x = -1.32$$

$$T_x' = -11.8$$

$$f_m = \frac{6(1.32)(1552.5)}{(1.02)^2} + \frac{11.8(1552.5)}{1.02} = 11,818 + 17,960 = 29,778 \text{ psi}$$

$$M.S. = \frac{1}{\frac{11,818}{36,000} + \frac{17,960}{30,000}} - 1 = \frac{1}{0.328 + 0.599} - 1 = +0.079$$

BY D. Tow

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FIGURE 10 PROPOSED CONFIGURATION OF
CONICAL SHELL

COAXIAL INSPECTOR STRESS ANALYSIS

DATE

7-13-65

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BY

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DATE

MANIFOLD (TORUS) — ELEMENT ⑤

COAXIAL INJECTOR STRESS ANALYSIS

D. Tow

REGIONAL INPUT DATA

REGION ① — GEOMETRY 1

NSTATIONS = 3

ANGLE = 0.0

WRAP DISTANCE = 0.5"

$$\Delta \xi = \frac{0.5}{100} = 0.005$$

REGION ② — GEOMETRY 2

NSTATIONS = 3

PHI GOES FROM 0° TO 180°

RCURVE = 3.23"

OFFSET = 12.03"

WRAP DISTANCE = $\pi R = 3.23\pi = 10.15$ "

$$\frac{10.15}{100} = 0.1015$$

$\therefore \Delta \xi = 0.1$

REGION ③ — GEOMETRY 1

NSTATION = 3

ANGLE = 180°

WRAP DISTANCE = 0.5"

$$\Delta \xi = \frac{0.5}{100} = 0.005$$

SUBJECT

COAXIAL INJECTOR — TORUS

DATE

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RESULTS OF THE STRESS ANALYSIS BY THE 1040 COMPUTER PROGRAM ARE SUMMARIZED BELOW (SEE COMPUTER OUTPUT CASE 1.0 . DATE JULY 9, 1965)

REGION	DISTANCE Y (IN)	MERIDIONAL STRESS (σ_F) (PSI)		HOOP STRESS (σ_θ) (PSI)	
		OUTER SURFACE	INNER SURFACE	OUTER SURFACE	INNER SURFACE
1 (CYLINDER)	0.00	91,160	-41,735	27,348	-12,521
	0.10	89,873	-40,743	27,712	-12,505
	0.20	87,133	-38,290	27,627	-12,014
	0.30	82,960	-34,397	27,079	-11,054
	0.40	77,372	-29,080	26,031	-9,653
	0.50	70,343	-22,315	24,495	-7,765
2 (TORUS)	0.000	70,343	-22,315	24,530	-7,730
	1.006	16,888	30,028	6,798	4,820
	2.011	1,671	42,909	-6,671	2,821
	3.017	7,419	34,428	-10,803	-3,348
	4.023	16,593	23,368	-9,155	-7,156
	5.028	19,568	19,886	-8,111	-8,015
	6.034	14,239	26,153	-9,835	-6,367
	7.039	4,675	37,949	-10,475	-1,610
	8.045	3,149	42,238	-3,560	4,323
	9.051	28,333	19,046	11,995	2,893
	9.654	62,955	-14,983	22,701	-5,726
	9.755	70,341	-22,301	24,486	-7,762

NOTE: REGION 3 IS IDENTICAL WITH REGION 1

FROM THE RESULTS SHOWN ABOVE, EXTREMELY HIGH MERIDIONAL STRESS IS DEVELOPED AT THE CYLINDRICAL SECTION. THIS STRESS IS LARGELY DUE TO BENDING. IN ORDER TO ELIMINATE ^{MOST OF} THE BENDING STRESS, A DIFFERENT CONFIGURATION WHICH MAKES USE OF A CONTINUOUS TORUS IS NOW ANALYZED. THE ANALYSIS IS SHOWN IN THE NEXT FEW PAGES (SEE DWG NO SK 7520-2026 REV. A)

SUBJECT

COAXIAL INJECTOR — TORUS

DATE _____

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CASE 4.0 — DWG. No. SK 7520-2026 REV. A

REGION 1 - GEOMETRY 2

PHI GOES FROM 0° TO 184.26°

NOTATIONS = 3

RCURVE = 2.770"

OFFSET = 11.727'

$$\text{WRAP DISTANCE} = \frac{184.26}{180} \cdot (2.770) \cdot \pi$$

$$= 8.708''$$

$$\Delta \xi = \frac{8.30\%}{100} = 0.0831$$

USE 0.09

$$p = 1350 (1.15) = 1552.5 \text{ psi}$$

$$\theta = 180^\circ + \sin^{-1}\left(\frac{.197}{2.645}\right) = 184.26^\circ$$

COAXIAL INJECTOR — TORUS

7-18-65

D. Tow

RESULTS FROM THE 1040 COMPUTER PROGRAM, CASE 4.0 ARE SHOWN BELOW

DISTANCE ξ (IN)	MERIDIONAL STRESS (σ_{ξ}) (PSI)		HOOP STRESS (σ_{θ}) (PSI)	
	OUTER SURFACE	INNER SURFACE	OUTER SURFACE	INNER SURFACE
0.000	14,821	18,872*	4,446	5,662
0.905	15,059	17,007	5,555	6,335
1.810	15,738	15,162	6,915	6,918
2.715	15,855	14,343	7,961	7,583
3.620	15,651	14,222	8,477	8,059
4.525	15,597	14,251	8,538	8,138
5.429	15,780	14,333	8,181	7,796
6.334	15,838	14,836	7,335	7,190
7.239	15,422	16,348	6,105	6,580
8.144	15,100	18,177	4,951	5,961
8.416	15,318	18,487	4,703	5,676
8.506	15,452	18,536	4,636	5,561

* MAXIMUM STRESS

BOTH THE MERIDIONAL AND HOOP STRESSES ARE PRIMARILY DUE TO THE MEMBRANE FORCES.

$$MS = \frac{30,000}{18,872} - 1 = \underline{0.59}$$

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SUBJECT PHOEBUS 2 COAXIAL INJECTOR DOME ANALYSIS - CONICAL SHELL (COMPUTER SOLUTION)	
BY D. TOW	CHK. BY

REEVALUATION OF CONICAL SHELL USING PROPOSED CONFIGURATION (FIGURE 10) AND THE 1040 COMPUTER PROGRAM.

FIGURE 13

$$p = 1350 \times 1.15 = 1552.5 \text{ psi}$$

SUBJECT

CONICAL SHELL (COMPUTER SOLUTION)

DATE

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RESULTS OF THE STRESS ANALYSIS BY THE 1040 COMPUTER PROGRAM ARE
SUMMARIZED BELOW (REF. COMPUTER OUTPUT, PHOEBUS 2 COAXIAL INJECTOR DOME ANALYSIS
CONICAL SHELL - VARIABLE THICKNESS, CASE 1.20, DATE JULY 20, 1965)

REGION	DISTANCE ξ (IN)	MERIDIONAL STRESS σ_r (PSI)		HOOP STRESS σ_θ (PSI)	
		OUTER SURFACE	INNER SURFACE	OUTER SURFACE	INNER SURFACE
1	0.000	- 79	46	- 31	68
	1.006	6,445	- 8,198	5,042	- 9,635
	2.011	3,473	- 9,188	638	- 13,061
	3.017	- 1,025	- 8,500	- 4,281	- 15,202
	4.022	- 6,637	- 6,355	- 9,213	- 15,770
	5.028	- 12,606	- 3,323	- 13,534	- 14,724
	6.034	- 17,919	- 265	- 16,606	- 12,289
	7.039	- 21,401	1,743	- 17,363	- 8,965
	8.045	- 21,818	1,495	- 16,394	- 5,517
	9.050	- 18,007	- 2,224	- 13,509	- 2,954
	10.056	- 9,009	- 10,511	- 7,805	- 2,465
	10.357	- 5,196	- 14,021	- 5,698	- 2,916
	10.458	- 3,316	- 15,294	- 4,963	- 3,138
2	0.000	- 4,224	- 14,845	- 5,229	- 2,933
	0.141	- 1,470	- 17,328	- 4,016	- 3,450
	0.282	1,539	- 19,943	- 2,728	- 4,028
	0.423	4,533	- 22,430	- 1,531	- 4,765
	0.564	7,348	- 24,638	- 243	- 5,419
	0.705	9,841	- 26,441	844	- 6,010
	0.846	11,985	- 27,830	1,803	- 6,528
	0.987	13,750	- 28,792	2,629	- 6,969
	1.128	15,168	- 29,377	3,336	- 7,345
	1.269	16,324	- 29,686	3,950	- 7,578
	1.410	17,289	- 29,803	4,493	- 7,929
	1.551	18,133	- 29,811	4,990	- 8,296
	1.692	19,157	- 30,021	5,532	- 8,687
	1.804	20,527	- 30,761	6,133	- 9,191
	1.818	20,730	* - 30,887	6,219	- 9,266

AXIAL DEFLECTION (IN DIRECTION OF "Z" AXIS) OF THE VERTEX OF THE SHELL IS

$$W = +0.004133''$$

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CONICAL SHELL (COMPUTER SOLUTION)

DATE

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MAXIMUM STRESS OCCURS AT $\xi = 1.818''$ (FIXED END), REGION 2. AND THE MARGIN OF SAFETY IS CALCULATED AS FOLLOWS:

SINCE STRESS IS PRIMARILY DUE TO BENDING, USE $F_{ALLOW} = 36,000 \text{ psi}$

$$MS = \frac{36,000}{30,887} - 1 = \underline{\underline{0.17}}$$

SUBJECT

COAXIAL - INJECTOR ANALYSIS

DATE

7-26-65

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DATE

CIRCULAR PLATE DEFLECTION

FIGURE 14

VERTICAL DEFLECTION IN THE DIRECTION OF THE Φ DUE TO PRESSURE LOAD. $\dagger$ FOR THE CONICAL SHELL IS SMALL AND CAN BE NEGLECTED (SEE COMPUTER SOLUTION, CASE 1-20, JULY 20, 1965). FOR THE CIRCULAR PLATE ^{THE} VERTICAL DEFLECTION, W , AT THE CENTER FOR A SIMPLY-SUPPORTED PLATE IS GIVEN BY

$$W = \frac{(5+\nu) q a^4}{64(1+\nu) D} \quad (20)$$

WHERE $q = 300 \times 1.15 = 345$

$$D = \frac{E h^3}{12(1-\nu^2)} = \frac{29 \times 10^6 (1.25)^3}{12(1-0.3^2)} = 5.19 \times 10^6$$

THEN

$$W = \frac{(5+0.3) 345 (11.53)^4}{64(1+0.3) 5.19 \times 10^6} = 0.0748"$$

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COAXIAL INJECTOR ANALYSIS

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THE PREVIOUS CALCULATED DEFLECTION IS EXCESSIVE ; TO ELIMINATE THIS DEFLECTION! A BOLT IS INSERTED AT THE CENTER OF THE PLATE & SHELL. THE BOLT LOAD IS 'CALCULATED AS FOLLOWS:

FOR A SIMPLY SUPPORTED PLATE WITH A LOAD AT THE CENTER, THE CENTRAL DEFLECTION IS GIVEN BY.

$$W = \frac{(3+\nu) Pa^2}{16\pi(1+\nu)D}$$

SOLVING FOR P

$$P = \frac{16\pi(1+\nu)DW}{(3+\nu)a^2}$$

(21)

FIGURE 15

SUBSTITUTING (20) INTO (21),

$$P = \frac{16\pi(1+\nu)D}{(3+\nu)a^2} \cdot \frac{(5+\nu)ga^4}{64(1+\nu)D} = \frac{5+\nu}{3+\nu} \frac{\pi}{4} \frac{g}{\delta} a^2$$

$$= \frac{5+0.3}{3+0.3} (0.785) (345) (11.53)^2 = \underline{57,850 \text{ Lbs}} \leftarrow \text{(BOLT LOAD)}$$

STRESS ANALYSIS OF THE CONICAL SHELL (FIGURE 13, PAGE 33) WITH AN ANGL. LOAD (BOLT LOAD) ACTING AT THE VERTEX CAN BE OBTAINED FROM THE 1941 COMPUTER SOLUTION.

$$(RVI)_1 = \frac{FV}{2\pi} = \frac{57,850}{2\pi} = 9207.09 \text{ Lbs}$$

CONICAL SHELL (BOLT LOAD INCLUDED) - COMPUTER SOLUTION
(INJECTOR DOME)

RESULTS OF STRESS ANALYSIS BY THE 1040 COMPUTER PROGRAM ARE SUMMARIZED BELOW (REF. COMPUTER RUN, PHOEBUS 2 COAXIAL INJECTOR ANALYSIS: CONICAL SHELL - BOLT LOAD INCLUDED, CASE 1.30, DATE 7-20-65)

REGION	DISTANCE ** Y (IN.)	MERIDIONAL STRESS σ_r (PSI)		HOOP STRESS σ_θ (PSI)	
		OUTER SURFACE	INNER SURFACE	OUTER SURFACE	INNER SURFACE
1	0.000	* -36,726	33,179	-11,000	9,972
	1.006	30,393	2,107	36,202	-21,052
	2.011	12,503	2,877	10,010	-15,919
	3.017	4,443	850	- 676	-16,466
	4.022	- 2,576	800	- 7,680	-16,499
	5.028	- 9,315	2,324	-12,844	-15,163
	6.034	-15,142	4,360	-16,270	-12,507
	7.039	-18,984	5,646	-17,655	- 8,989
	8.045	-19,633	4,843	-16,688	- 5,376
	9.050	-15,925	644	-13,224	- 2,685
	10.056	- 6,899	- 5,113	- 7,385	- 2,127
	10.357	- 3,051	-11,770	- 5,229	- 2,572
	10.458	- 1,653	-13,095	- 4,476	- 2,794
2	0.000	- 2,062	-12,650	- 4,747	- 2,600
	0.141	641	-15,134	- 3,528	- 3,096
	0.282	3,553	-17,730	- 2,248	- 3,706
	0.423	6,413	-20,182	- 929	- 4,350
	0.564	9,063	-22,346	185	- 4,968
	0.705	11,373	-24,103	1,233	- 5,522
	0.846	13,326	-25,452	2,149	- 6,003
	0.987	14,898	-26,382	2,930	- 6,410
	1.128	16,128	-26,948	3,593	- 6,755
	1.269	17,104	-27,250	4,162	- 7,059
	1.410	17,597	-27,369	4,662	- 7,343
	1.551	18,577	-27,386	5,116	- 7,624
	1.692	19,432	-27,596	5,612	- 7,986
	1.804	20,645	-28,311	6,168	- 8,459
	1.818	20,828	-28,433	6,248	- 8,530

* MAX. STRESS

** MEASURED ALONG ϕ

$$M.S. = \frac{36,000}{36,726} - 1 = -0.019 \quad (O.K.)$$

COAXIAL INJECTOR STRESS ANALYSIS

8-24-65

COVER, PROTECTIVE — INJECTOR PLATE (DWG No 1115320)

$$\Delta p = 300 \text{ psi}$$

$$t = 1.75''$$

$$a = 13.625''$$

$$F_{ty} = 35,000 \text{ psi}$$

$$E = 9.9 \times 10^6 \text{ psi}$$

$$G = 3.8 \times 10^6 \text{ psi}$$

$$\nu = \frac{E - 2G}{2G} = \frac{9.9 - 2 \times 3.8}{2 \times 3.8} = 0.303$$

ANALYZED AS SIMPLY SUPPORTED PLATE, MAXIMUM STRESS IS GIVEN BY

$$f_{max} = \frac{3(3+\nu)qa^2}{8t^2} = \frac{3(3+0.303)(300)(11.5)(13.625)^2}{8(1.75)^2} = 26,000 \text{ psi} < F_{ty} \text{ (O.K.)}$$

MAX DEFLECTION IS AT CENTER, WHERE

$$y_{max} = \frac{qa^4}{64D}$$

$$D = \frac{Et^3}{12(1-\nu^2)} = \frac{9.9 \times 10^6 (1.75)^3}{12(1-0.303^2)} = 4.86 \times 10^6$$

$$y_{max} = \frac{300(11.5)(13.625)^4}{64(4.86) \times 10^6} = 0.0383''$$

COAXIAL INJECTOR — CONICAL SHELL (BOLT LOAD INCLUDED)
STRESS SOLUTION

9-14-65

DRAWING NO. 1115474

RESULTS OF STRESS ANALYSIS USING THE COMPUTER PROGRAM ARE SUMMARIZED BELOW (SEE COMPUTER OUTPUT, CASE 1.50, SEPT. 14, 1965). THESE RESULTS REPLACE THOSE GIVEN ON PAGE 35

DISTANCE $\bar{x}$ (IN.)	MERIDIONAL STRESS $\sigma_{\bar{x}}$ (psi)		HOOP STRESS σ_{θ} (psi)	
	OUTER SURFACE	INNER SURFACE	OUTER SURFACE	INNER SURFACE
0.000	-16,846	15,382	- 5,054	4,615
1.006	23,681	- 8,031	* 28,889	- 20,297
2.012	8,018	- 1,304	9,292	- 13,034
3.018	740	542	835	- 10,941
4.024	- 4,497	2,061	- 4,302	- 9,159
5.030	- 8,453	3,435	- 7,552	- 7,132
6.036	- 11,031	4,295	- 9,296	- 4,937
7.042	- 11,928	4,170	- 9,646	- 2,849
8.047	- 10,817	2,597	- 8,667	- 1,231
9.053	- 7,415	- 829	- 6,455	- 496
10.059	- 1,530	- 6,433	- 3,169	- 1,074
11.065	6,913	- 14,428	954	- 3,396
11.769	14,315	- 21,500	4,168	- 6,277
11.870	15,467	- 22,608	4,640	- 6,782

* MAX. STRESS

$$MS = \frac{1}{\frac{24592}{36000} + \frac{4297}{30000}} - 1 = 0.21$$

SUBJECT

COAXIAL INJECTOR

DATE

9-17-65

WORK ORDER

BY

CHK. BY

DATE

CENTER BOLT (DWG. No. 1115084)

THD .875 - 14 UNF - 3B

$$F_u = 220,000 \text{ psi}$$

$$F_y = 180,000 \text{ psi}$$

$$\text{STRESS AREA} = 0.5088 \text{ IN}^2$$

$$\text{ALLOWABLE LOAD} = A_s \times F_y = 0.5088 (180,000) = 91,500^{\#} > 57,850^{\#}$$

$$\text{M.S.} = \frac{91500}{57850} - 1 = \underline{+0.58}$$

SUBJECT

INJECTOR PLATE STRESS ANALYSIS (BELT LOAD INCLUDED)

DATE

9-30-65

WORK ORDER

BY

D. Tow

CHK. BY

DATE

COMBINING SOLUTIONS GIVEN ON PAGES 3 AND 34 AND REEVALUATE INJECTOR PLATE STRESSES AS FOLLOWS.

FOR CASE ① — UNIFORM LOAD q

$$M_r = \frac{q}{16} (3 + \nu) (a^2 - r^2)$$

(TIMOSHENKO, R. & S.

$$M_t = \frac{q}{16} [a^2 (3 + \nu) - r^2 (1 + 3\nu)] \quad \text{PP. 57}$$

FOR CASE ② — CONCENTRATED LOAD P

$$M_r = -\frac{P}{4\pi} (1 + \nu) \log \frac{a}{r}$$

(TIMOSHENKO, R. & S.
PP. 68)

$$M_t = -\frac{P}{4\pi} \left[(1 + \nu) \log \frac{a}{r} + 1 - \nu \right]$$

SUPERPOSING THE TWO SOLUTIONS TO OBTAIN

$$M_r = \frac{q}{16} (3 + \nu) (a^2 - r^2) - \frac{P}{4\pi} (1 + \nu) \log \frac{a}{r} \quad (a)$$

$$M_t = \frac{q}{16} [a^2 (3 + \nu) - r^2 (1 + 3\nu)] - \frac{P}{4\pi} \left[(1 + \nu) \log \frac{a}{r} + 1 - \nu \right] \quad (b)$$

FROM PAGES 3 AND 34

$$q = 300(1.15) = 345 \text{ psi}$$

$$a = 11.53''$$

$$P = 57,850 \text{ #}$$

$$\nu = 0.3$$

NOTE: ALL LOGARITHMIC EXPRESSIONS ARE TO THE BASE e

SUBSTITUTING THE KNOWN VALUES AND SIMPLIFYING THE ABOVE EQUATIONS GIVE

$$M_r = 9460 - 71.15 r^2 - 5990 \log \frac{11.53}{r}$$

$$M_t = 6238 - 41.0 r^2 - 5990 \log \frac{11.53}{r}$$

SUBJECT

INJECTOR PLATE STRESS ANALYSIS

BY

D. Tow

CHK. BY

r (IN.)	M_r ($\frac{\text{IN-LB}}{\text{IN}}$)	M_t ($\frac{\text{IN-LB}}{\text{IN}}$)
1.5	-2920	-6074
2	-1111	-4303
3	759	-2191
5	2670	203
7	2979	1233
9	2212	1428
11	570	998
11.53	0	788

SUBJECT

INJECTOR PLATE STRESS ANALYSIS

DATE

9-30-65

WORK ORDER

BY

D. Tow

CHK. BY

DATE

MAXIMUM MOMENT OCCURS AT APPROXIMATELY $r = 1"$

$$M_{MAX} = M_L = 7600 \frac{in \cdot lb}{in}$$

$$f = \frac{6M_{MAX}}{h^2} = \frac{6(7600)}{1.25^2} = \underline{29,200 \text{ psi}}$$

$$M.S. = \frac{36000}{29200} - 1 = \underline{0.23}$$

CHECK STRESS AT CENTER OF PLATE :

EXPRESSIONS (a) AND (b) ARE NOT SUITABLE FOR CALCULATING THE BENDING MOMENTS SINCE THE EXPRESSIONS BECOME INFINITE AS r APPROACHES ZERO. THE ASSUMPTIONS ON WHICH THE ELEMENTARY THEORY OF BENDING OF CIRCULAR PLATES IS BASED DO NOT HOLD NEAR THE POINT OF APPLICATION OF A CONCENTRATED LOAD (SEE TIMOSHENKO, "PLATES AND SHELL," 2ND ED., p.69-71).

THE COMPRESSIVE STRESS AT THE BOTTOM OF THE PLATE DUE TO THE CONCENTRATED LOAD P ALTHOUGH MAY BE MANY TIMES AS LARGE AS THE TENSILE STRESS AT THE TOP, IT DOES NOT REPRESENT A DIRECT DANGER BECAUSE OF ITS HIGHLY LOCALIZED CHARACTER. THE LOCAL YIELDING IN THE PLATE WILL NOT AFFECT THE DEFORMATION IN GENERAL IF THE TENSILE STRESSES AT THE TOP OF THE PLATE REMAIN WITHIN SAFE LIMITS. THE TENSILE STRESS AT THE CENTER OF THE TOP SURFACE OF THE PLATE UNDER THE CONCENTRATED LOAD P IS GIVEN APPROXIMATELY BY

$$f_P = \frac{P}{h^2} \left[(1+\nu) \left(0.485 \log \frac{a}{h} + 0.52 \right) + 0.48 \right] \quad (\text{TIMOSHENKO, E \& S, p.70})$$

$$\text{FOR } h = 2.375"$$

$$f_P = \frac{57850}{(2.375)^2} \left[(1+0.3) \left(0.485 \log \frac{11.53}{2.375} + 0.52 \right) + 0.48 \right]$$

$$= 22,100 \text{ psi}$$

THIS STRESS HAS TO BE SUPERPOSED BY THE STRESS DUE TO THE UNIFORM LOAD, f_g , WHICH IS

$$f_g = \frac{-3(3+\nu)qa^2}{8h^2} = \frac{-3(3+0.3)(345)(11.53)^2}{8(2.375)^2} = -10,060 \text{ psi}$$

$$f = f_P + f_g = 12,040 \text{ psi}$$

COAXIAL INJECTOR — RIGIMESH PLATE THERMAL STRESS
(DWG. 1115474)

10-5-65

D. TOW

ASSUME FINAL TEMPERATURE UNDER MAXIMUM OPERATING CONDITION TO BE
-365°F (THIS VALUE IS OBTAINED FROM M. SMOOT
VERBALLY ON OCT. 5, 1965). MAXIMUM ΔT IS
THEN

$$\Delta T = -365 - 70 = -435^{\circ}\text{F}$$

THE STRESSES σ_r AND σ_{θ} OF A CIRCULAR DISK
UNDER CONDITIONS OF PLANE STRESS SATISFY

THE FOLLOWING EQUILIBRIUM EQUATION

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_{\theta}}{r} = 0$$

(a)

STRESS-STRAIN RELATIONS :

$$\epsilon_r = \frac{1}{E}(\sigma_r - \nu\sigma_{\theta}) + \alpha T$$

(b)

$$\epsilon_{\theta} = \frac{1}{E}(\sigma_{\theta} - \nu\sigma_r) + \alpha T$$

STRAIN-DISPLACEMENT RELATIONS :

$$\epsilon_r = \frac{du}{dr}$$

(c)

$$\epsilon_{\theta} = \frac{u}{r}$$

WHERE u DENOTES THE RADIAL DISPLACEMENT

SUBSTITUTING EQUATIONS (b) & (c) INTO (a) GIVES

$$\frac{d^2u}{dr^2} + \frac{1}{r} \frac{du}{dr} - \frac{u}{r^2} = (1+\nu)\alpha \frac{dT}{dr}$$

INTEGRATION OF THIS EQUATION YIELDS

$$u = (1+\nu)\alpha \frac{1}{r} \int^r T r dr + C_1 r + \frac{C_2}{r} \quad (d)$$

THE STRESS COMPONENTS ARE NOW FOUND BY USING SOLUTION (d) IN EQ. (c)
AND SUBSTITUTING THE RESULTS IN EQ. (b). THEN

$$\sigma_r = -\alpha E \frac{1}{r^2} \int_0^r T r dr + \frac{E}{1-\nu^2} \left[C_1 (1+\nu) - C_2 (1-\nu) \frac{1}{r^2} \right] \quad (e)$$

$$\sigma_\theta = \alpha E \frac{1}{r^2} \int_0^r T r dr - \alpha E T + \frac{E}{1-\nu^2} \left[C_1 (1+\nu) + C_2 (1-\nu) \frac{1}{r^2} \right] \quad (f)$$

THE CONSTANTS OF INTEGRATION C_1, C_2 ARE DETERMINED BY THE BOUNDARY CONDITIONS. FOR A CIRCULAR DISK RESTRAINED AT THE EDGE: THESE BOUNDARY CONDITIONS ARE

AT $r = 0$, C_2 MUST VANISH IN ORDER THAT u MAY BE ZERO

AT $r = r_0$, $u = 0$ AND THEREFORE FROM EQ. (d)

$$C_1 = -(1+\nu) \frac{\alpha}{r_0^2} \int_0^{r_0} T r dr$$

WITH THE TWO CONSTANTS BEING KNOWN, EQ. (d) BECOMES

$$u = (1+\nu) \frac{\alpha}{r} \int_0^r T r dr - (1+\nu) \frac{\alpha r}{r_0^2} \int_0^{r_0} T r dr \quad (g)$$

THE FINAL EXPRESSIONS FOR THE STRESSES ARE OBTAINED FROM EQS (e) AND (f)

$$\sigma_r = -\alpha E \left[\frac{1+\nu}{(1-\nu)r_0^2} \int_0^{r_0} T r dr + \frac{1}{r^2} \int_0^r T r dr \right] \quad (h)$$

$$\sigma_\theta = -\alpha E \left[T + \frac{1+\nu}{(1-\nu)r_0^2} \int_0^{r_0} T r dr - \frac{1}{r^2} \int_0^r T r dr \right] \quad (i)$$

IF $T = \text{CONSTANT}$, THEN EQS (h) & (i) BECOME

$$\sigma_r = \sigma_\theta = -\frac{\alpha E T}{1-\nu} \quad (j)$$

AGC 2-843

SUBJECT

BY

CHK. BY

FOR THE RIGIMESH PLATE

$$T = \Delta T = -435^{\circ}\text{F}$$

$$E = 15.7 \times 10^6$$

$$\alpha = 6.75 \times 10^{-6}$$

$$\nu = 0.3$$

} SEE REFERENCES 1-4 BELOW

$$\sigma_r = \sigma_{\theta} = - \frac{(6.75 \times 10^{-6})(15.7 \times 10^6)(-435)}{1 - 0.3} = \underline{65,900 \text{ psi}}$$

$$\text{ALLOWABLE } F_y = 51,000 \text{ psi @ } -365^{\circ}\text{F}$$

$$\text{M.S.} = \frac{2F_y}{\sigma_r} - 1 = \underline{+0.55}$$

NOTE:

NO KNOWN CASE OF RIGIMESH FAILURE EXISTS ON AGC M-1, J-2
RL-10, OR THE LERC INJECTORS.

REFERENCES:

- 1 "TRANSPIRATION COOLING THROUGH RIGIMESH SINTERED WOVEN WIRE SHEET
AIRCRAFT POROUS MEDIA, INC., APM-FSR-18A, MARCH 1, 1964
- 2 "POROUS METAL FOR INJECTOR USE", AGC FLASH REPORT NO. 62-107,
JANUARY 11, 1963.
- 3 "POROUS METAL FOR INJECTOR USE," AGC FLASH REPORT NO. 62-52,
SEPTEMBER 26, 1962.
- 4 REON "MATERIALS PROPERTIES DATA BOOK" REVISED JULY 1964.

COPING INJECTOR — FUEL & OXIDIZER ELEMENT SWAGE JOINT

DATE

10-12-65

WORK ORDER

0960-21-421

BY

D. Tow

CHK. BY

DATE

DWG. NO. 1115474 & 1115314

DESIGN ΔP ACROSS RIG MESH PLATE = 300 psi

$$\text{TOTAL LOAD} = (115)(300) \left(\frac{\pi}{4} \right) (21.360^2) = 123,600 \text{ \#}$$

$$\text{LOAD ON EACH ELEMENT, } P = \frac{123600}{242} = 516 \text{ \#}$$

MANY TESTS HAVE BEEN PERFORMED IN THE PAST TO DETERMINE THE FORCE REQUIRED TO PULL OUT THE ELEMENT FROM THE PLATE. THE FOLLOWING INFORMATION IS OBTAINED FROM D. VAN DYKE, K. NELSON AND H. INOUE

SERIAL NO INJECTOR TEST	WALL THICKNESS (IN.)	RANGE OF PULL OUT FORCE (#)	AVERAGE VALUE (#)
SNO 17	0.035	1250-1605 (9 TESTS)	1428
SNO 18	0.050	—	2400

THE FOLLOWING GRAPH IS PLOTTED AND BY EXTRAPOLATION THE REQUIRED PULLOUT FORCE FOR ANY WALL THICKNESS CAN BE FOUND.

AGC 2-843

REPORT NO.

SUBJECT

FUEL & OXIDIZER ELEMENT SWAGE JOINT

PAGE

DATE

WORK ORDER

BY

D. Tow

CHK. BY

DATE

REQ'D PULLOUT FORCE FOR 0.030 WALL THICKNESS = 1,100# > 516 #

SUBJECT

DATE

WORK ORDER

DATE

INJECTOR DOME BOLTS (DWG. No. 1115314)

10-12-65

BY D. Tow

CHK. BY

$$p = 1350 \text{ psi}$$

$$\text{TOTAL LOAD ON BOLTS} = (1.15)(1350) \left(\frac{\pi}{4} \right) (22.470^2) = 616,000 \text{ \#}$$

$$\text{LOAD PER BOLT} = \frac{616,000}{60} = 10,260 \text{ \#}$$

KNS 6245-18 STUD (KEENSERTS CATALOG D, REVISED FEBRUARY, 1963)

$$F_y = 125,000 - 140,000 \text{ psi}$$

$$A_s = 0.0876 \text{ IN}^2$$

$$\text{ALLOWABLE LOAD} = 125,000(0.0876) = 10,950 \text{ \#} > 10,260 \text{ \#}$$

$$\text{M.S.} = \frac{10950}{10260} - 1 = +0.07$$

SUBJECT

INJECTOR DOME BOLTS REVISED. (DWG. No. 1115314)

DATE

2-21-66

WORK ORDER

BY

D. Tow

CHK. BY

DATE

$$p = 1075 \pm 25 \text{ psi} \quad (\text{FROM M. H. SMOOT})$$

$$\text{TOTAL LOAD ON BOLTS} = 1.15 (1100) \left(\frac{\pi}{4}\right) (22.47^2) = 502,000 \text{ \#}$$

$$\text{LOAD PER BOLT} = \frac{502,000}{60} = 8370 \text{ \# / BOLT}$$

KNS 624S-18 STUD (KEENSERTS CATALOG D, REVISED FEBRUARY 1963)

$$F_y = 100,000 \text{ psi}$$

$$A_s = 0.0876 \text{ in}^2$$

$$\text{ALLOWABLE LOAD} = 100,000 (.0876) = 8,760 \text{ \#}$$

$$M.S. = \frac{8760}{8370} - 1 = \underline{+0.05}$$

NOTE: THIS PAGE WILL REPLACE PAGE 47

INJECTOR DOME JOINT SEPARATION (DWG. No. 1115474)

10-13-65

D. Tow

MAX. OPERATING CONDITION :

INJECTOR DOME PRESSURE = 1200 psia

FUEL PRESSURE = 1050 psia

Δp ACROSS INJECTOR PLATE = 150 psi

PRESSURE FACTOR = 1.15

REF. TIMOSHENKO, THEORY OF
PLATES AND SHELLS, 1959
PP. 65 - 68

SOLUTION WILL BE TWOFOLDS — PARTIALLY UNIFORM
LOADED PLATE PLUS CONCENTRATED LOAD PLATE.

THE DEFLECTION AT ANY POINT OF THE PLATE AT
A DISTANCE r FROM THE CENTER, IS

$$W_g = \frac{q c^2}{16D} \left\{ \frac{3+\nu}{1+\nu} (a^2 - r^2) + 2r^2 \log \frac{r}{a} + c^2 \left[\log \frac{r}{a} - \frac{1-\nu}{2(1+\nu)} \frac{a^2 - r^2}{a^2} \right] \right\}$$

FOR $a > r \geq c$

$$W_g = \frac{q c^2}{16D} \left\{ \left[\frac{3+\nu}{1+\nu} a^2 + c^2 \log \frac{c}{a} - \frac{7+3\nu}{4(1+\nu)} c^2 \right] + r^2 \left[2 \log \frac{c}{a} + \frac{(1-\nu)c^2}{2(1+\nu)a^2} - \frac{2}{1+\nu} \right] \right\}$$

FOR $c > r \geq 0$

$$W_p = \frac{-P}{16\pi D} \left[\frac{3+\nu}{1+\nu} (a^2 - r^2) + 2r^2 \log \frac{r}{a} \right]$$

THE CENTER DEFLECTIONS FOR BOTH CASES ARE

$$(W_g)_{r=0} = \frac{q c^2}{16D} \left[\frac{3+\nu}{1+\nu} a^2 + c^2 \log \frac{c}{a} - \frac{7+3\nu}{4(1+\nu)} c^2 \right]$$

$$(W_p)_{r=0} = - \frac{(3+\nu) P a^2}{16\pi D(1+\nu)}$$

NOTE: ALL LOGARITHMIC
EXPRESSIONS ARE TO THE
BASE e .

ACC 2-843

SUBJECT

INJECTOR DOME JOINT SEPARATION

DATE

10-13-65

WORK ORDER

BY

D. Tow

CHK. BY

DATE

SINCE DEFLECTION AT CENTER OF PLATE MUST BE ZERO

$$(W_g)_{r=0} + (W_p)_{r=0} = 0$$

OR

$$\frac{g c^2}{160} \left[\frac{3+\nu}{1+\nu} a^2 + c^2 \log \frac{c}{a} - \frac{7+3\nu}{4(1+\nu)} c^2 \right] - \frac{(3+\nu) P a^2}{16\pi D(1+\nu)} = 0$$

SOLVING FOR P,

$$P = g \pi c^2 \left[1 + \frac{c^2}{a^2} \frac{1+\nu}{3+\nu} \log \frac{c}{a} - \frac{7+3\nu}{4(3+\nu)} \frac{c^2}{a^2} \right]$$

THE FINAL DEFLECTION AT ANY POINT OF THE PLATE AT A DISTANCE r FROM THE CENTER IS THE SUM OF THE DEFLECTIONS DUE TO g AND P . OF

$$W = W_g + W_p$$

FOR $a > r \geq c$, THIS GIVES

$$W = \frac{g c^2}{160} \left\{ \frac{3+\nu}{1+\nu} (a^2 - r^2) + 2r^2 \log \frac{r}{a} + c^2 \left[\log \frac{r}{a} - \frac{1-\nu}{2(1+\nu)} \frac{a^2 - r^2}{a^2} \right] \right\} - \frac{P}{16\pi D} \left[\frac{3+\nu}{1+\nu} (a^2 - r^2) + 2r^2 \log \frac{r}{a} \right]$$

$$\text{FOR } g = 150(1.15) = 172.5 \text{ psi}$$

$$a = 12.375''$$

$$(a^2 = 153.1)$$

$$c = 11.235''$$

$$(c^2 = 126.2)$$

$$E = 29 \times 10^6$$

$$\nu = 0.30$$

$$h = 1.25''$$

THUS

$$D = \frac{E h^3}{12(1-\nu^2)} = \frac{29 \times 10^6 (1.25)^3}{12(1-0.3^2)} = 5.19 \times 10^6$$

$$P = 172.5 (\pi) (11.235)^2 \left[1 + \frac{11.235^2}{12.375^2} \frac{1+0.3}{3+0.3} \log \frac{11.235}{12.375} - \frac{7+3(0.3)}{4(3+0.3)} \frac{11.235^2}{12.375^2} \right]$$

$$= 68400 [1 - 0.032 - 0.493] = 32,520$$

SUBJECT

INJECTOR DOME JOINT SEPARATION

DATE

10-13-65

WORK ORDER

BY

D. Tow

CHK. BY

DATE

AT THE SEAL JOINT, $r = c = .11.235"$

$$\log_e \frac{r}{a} = \log_e \frac{11.235}{12.375} = \log_e (0.90788) = -0.0968$$

THEN

$$W = \frac{172.5(126.2)}{16(5.19 \times 10^6)} \left\{ \frac{3.3}{1.3} (153.1 - 126.2) + 2(126.2)(-0.0968) + 126.2 \left[-0.0968 - \frac{0.7}{2(1.3)} \frac{153.1 - 126.2}{153.1} \right] \right. \\ \left. - \frac{32520}{16\pi(5.19 \times 10^6)} \left[\frac{3.3}{1.3} (153.1 - 126.2) + 2(126.2)(-0.0968) \right] \right\}$$

$$W = 2.622 \times 10^{-4} \{ 68.285 - 24.432 - 18.185 \} - 1.247 \times 10^{-4} \{ 68.285 - 24.432 \}$$

$$W = 67.3 \times 10^{-4} - 54.7 \times 10^{-4}$$

$$W = \underline{0.00126"} \quad \leftarrow \text{INJECTOR DOME SEAL JOINT DEFLECTION}$$

CHECK THIS DEFLECTION

FROM ROARK, "STRESS AND STRAIN"; TABLE X, CASE 2, pp. 194

$$W_g = \frac{3rc^2(m^2-1)}{16Em^2t^3} \left[4a^2 - 5c^2 + \frac{r^4}{c^2} - (8r^2 + 4c^2) \log \frac{a}{c} - \frac{2(m-1)c^2(a^2-r^2)}{(m+1)a^2} + \frac{8m(a^2-r^2)}{m+1} \right]$$

FOR $r \leq c$

$$\text{WHERE } m = \frac{1}{\nu} = 3.33$$

FOR $r = c = 11.235$

$$\log \frac{a}{c} = \log \frac{12.375}{11.235} = 0.0960$$

$$W_g = \frac{3(172.5)(126.2)(3.33^2-1)}{16(29 \times 10^6)(3.33^3)(1.25)^3} \left[4(153.1) - 5(126.2) + (126.2) - 12(126.2)(0.0960) - \frac{2(3.33-1)(126.2)(26.1)}{(3.33+1)(153.1)} \right. \\ \left. + \frac{8(3.33)(26.1)}{3.33+1} \right]$$

$$W_g = 6.56 \times 10^{-5} [612.4 - 631.0 + 126.2 - 145.3 - 23.9 + 165.5]$$

$$W_g = 68.2 \times 10^{-4} \approx 67.3 \times 10^{-4}$$

SUBJECT

INJECTOR DOME JOINT SEPARATION

DATE

10-13-65

WORK ORDER

BY

D. Tow

CHK. BY

DATE

THE THRUST SUPPORT WILL MOVE AWAY FROM THE PLATE WHILE UNDER DOME PRESSURE; BUT THIS MOVEMENT WILL BE MUCH SMALLER THAN THE PLATE DEFLECTION AND THEREFORE CAN BE NEGLECTED THE ALLOWABLE SEAL TOLERANCE IS 0.015" (OBTAINED FROM M. SMOOT 10-13-65) AND IS LARGER THAN THE PLATE DEFLECTION

THE INJECTOR DOME SEAL JOINT IS ADEQUATE

ADAPTER, INLET - TORUS, REVISED ANALYSIS

(SAME FOR BOTH
COAXIAL & MULTI-
ORIFICE INJECTORS)

2-21-66

D. Tow

DWG No. 1115201 AND 1115315

THE FOLLOWING ANALYSIS (PAGES 52a-55a) REPLACES THOSE GIVEN ON PAGES 52-57 OF THE COAXIAL INJECTOR REPORT. THIS ANALYSIS INCORPORATES THE LATEST PRESSURE SCHEDULE AS WELL AS THE LATEST EXTERNAL MOMENT AND LOADS IMPOSED FROM THE LOX FACILITY LINE.

THE FOLLOWING VALUES ARE OBTAINED FROM EMIL LUEDERS (2-7-66)

$$M = 65,002 \text{ IN-LB}$$

$$P = 9,557 \text{ LB}$$

$$V = 2,211 \text{ LB}$$

$$p = 1144 \text{ PSI (FROM M. H. SMOOT)}$$

(1) CONICAL SECTION

ASSUMED END FIXED - MAXIMUM STRESSES OCCURRED AT FIXED END. THE LONGITUDINAL AND HOOP STRESSES AT THIS END ARE GIVEN BY

$$f_{\text{Long}} = \frac{P}{A} + \frac{M_f C}{I} + \frac{pR}{2t \cos \alpha}$$

$$f_{\text{Hoop}} = \mu \left(\frac{P}{A} + \frac{M_f C}{I} \right) + \frac{pR}{t \cos \alpha}$$

(a)

(b)

FIGURE b

$$M_f = M - Vl = 65,002 - 2,211(3.23) = 57,860 \text{ IN-LB}$$

$$p = 115(1144) = 1316 \text{ PSI}$$

$$t = 0.25" \quad , \quad \mu = 0.30$$

$$R = 2.15 + .125 = 2.275"$$

$$A = 2\pi R t = 2\pi(2.275)(0.25) = 3.58 \text{ IN}^2$$

ADAPTER, INLET - TORUS

2-21-51

D. Tow

$$I = \pi R^3 t = \pi (2.275)^3 (0.25) = 9.26 \text{ in}^4$$

$$\alpha = 15^\circ$$

$$c = 2.15 + 0.25 = 2.40''$$

SUBSTITUTING THE ABOVE VALUES INTO EQUATIONS (a) & (b) YIELDS

$$f_L = \frac{9557}{3.58} + \frac{57860(2.40)}{9.26} + \frac{1316(2.275)}{2(0.25)(.966)} = 2,670 + 15,000 + 6,210 = \underline{23,880 \text{ psi}}$$

$$f_H = 0.3(2670 + 15000) + 2(6210) = 17,721 \text{ psi}$$

ALLOWABLE STRESS FOR S.S. 347 AT -280°F (Liquid O_2) = 45,000 psi

$$M.S. = \frac{1}{\frac{2670 + 6210}{45000} + \frac{15000}{1.2 \times 45000}} - 1 = \underline{\underline{+1.10}}$$

(2) TORUS ANALYSIS

$$\phi = 56.2^\circ$$

$$\theta = 18.8^\circ$$

$$\psi = 41^\circ$$

FIGURE C

THE EXTERNAL MOMENT (M_f) WILL CAUSE TENSION ON THE LONG SIDE (FIGURE C) AND COMPRESSION ON THE SHORT SIDE. THIS BENDING MOMENT IS RESOLVED INTO A COUPLE WITH MAGNITUDE

$$F = \sigma \cdot t = \frac{M_f c}{I} \cdot t = \frac{M_f \cdot R}{\pi R^3 t} \cdot t = \frac{M_f}{\pi R^2}$$

$$\text{OR } F = \frac{57860}{\pi (2.275)^2} = \pm 3,558 \text{ #/in} \quad (c)$$

THE TENSION FORCE (P) IS UNIFORMLY DISTRIBUTED AROUND THE CIRCUMFERENCE OF THE TORUS JUNCTION AND IS

ADAPTER, INLET — TORUS

$$P' = \frac{P}{\pi D} = \frac{9557}{\pi(4.55)} = +669 \text{ #/IN} \quad (d)$$

COMBINING EXPRESSIONS (c) AND (d), WE HAVE THE NET TOTAL FORCE ACTING AT THE TORUS JUNCTION (FIGURE c)

$$T = +3558 + 669 = +4,227 \text{ #/IN}$$

$$C = -3558 + 669 = -2,889 \text{ #/IN}$$

SHEARING FORCE PER UNIT LENGTH AT DISCONTINUITY JUNCTION IS

$$V' = \frac{V}{\pi D} = \frac{2211}{\pi(4.55)} = .154.7 \text{ #/IN}$$

FIGURE d SHOWS THE FORCES AS WELL AS THE PRESSURE LOADS ACTING AT THE TORUS.

$$b = 2.52 + .125 = 2.645$$

$$d_1 = b \sin 48.8^\circ = 1.99$$

$$d_2 = b \sin 18.8^\circ = 0.853$$

$$p = 1.15(1144) = 1316$$

$$t = 0.25$$

$$a = 11.53$$

FIGURE d

THE FOLLOWING APPROXIMATIONS ARE USED TO CALCULATE STRESSES AT THE TORUS JUNCTION (POINTS A & B, FIGURE d)

PRESSURE LOAD (ASSUME TORUS CONFIGURATION, ROARK, TABLE XIII, CASE 20, p.274)

$$f_L = \frac{pb}{t} \left(\frac{r+a}{2r} \right), \quad f_H = \frac{pb}{2t} \quad (\text{UNIFORM THROUGHOUT})$$

AT A

$$f_{LA} = \frac{1316(2.645)}{0.25} \left(\frac{11.53+1.99+11.53}{2 \times 11.53} \right) = 15,125 \text{ PSI}$$

AT B

$$f_{LB} = \frac{1316(2.645)}{0.25} \left(\frac{11.53+0.853+11.53}{2 \times 11.53} \right) = 14,438 \text{ PSI}$$

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DISCONTINUITY LOADS (T, C, V')AT A

$$f'_{LA} = \frac{T \cos 33.8^\circ - V' \sin 33.8^\circ}{t} = \frac{4227(.83) - 154.7(.557)}{0.25} = 13,700 \text{ psi}$$

AT B

$$f'_{LB} = -\frac{C \cos 33.8^\circ - V' \sin 33.8^\circ}{t} = -\frac{2889(.83) - 154.7(.557)}{0.25} = -9,250 \text{ psi}$$

FIGURE e

MAXIMUM COMBINED MERIDIONAL STRESSAT A

$$f_L = f_{LA} + f'_{LA} = 15,125 + 13,700 = 28,825 \text{ psi}$$

AT B

$$f_L = f_{LB} + f'_{LB} = 14,438 - 9,250 = 5,188 \text{ psi}$$

FIGURE f

ASSUME DISCONTINUITY LOADS HAVE LITTLE EFFECT ON THE BASE OF THE TORUS (D AND E IN FIGURE d) STRESSES IN THESE SECTIONS WERE PREVIOUSLY CALCULATED AND WERE GIVEN ON PAGE 29 OF THIS REPORT

$$M.S. = \frac{45,000}{28,825} - 1 = \underline{\underline{+0.56}}$$

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DWG. No. 1115201 AND 1115315

FIGURE a

EXTERNAL LOADS IMPOSED FROM THE LINE TO THE TORUS AFTER 20 SECONDS OF ENGINE OPERATING (NOTE: EXTERNAL LOADS AND MOMENT ARE FUNCTION OF TEMP)

$$M = 100,900 \text{ IN-LB}$$

$$P = 15,190 \text{ LB}$$

$$V = 22.8 \text{ LB}$$

THESE VALUES ARE OBTAINED FROM EMIL LUEREL.
VALUES DO NOT INCLUDE PRESSURE LOADS

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STRESS ANALYSIS OF THE SHORT CONICAL SECTION CONSISTS OF THE EVALUATION OF THE STRESSES DUE TO THE EXTERNAL LOADS AND MOMENT IMPOSED FROM THE LINE AND FROM THE INTERNAL PRESSURE.

ASSUME END FIXED AT THE TORUS JUNCTION

MAXIMUM STRESSES OCCURRED AT FIXED END.

FIGURE b

$$M_f = M + V \cdot l$$

STRESSES FROM EXTERNAL LOADS AND MOMENT :

LONGITUDINAL STRESS

$$f_{LE} = \frac{P}{A} + \frac{M_f C}{I}$$

HOOP STRESS

$$f_{HE} = \mu f_{LE}$$

STRESSES DUE TO PRESSURE

$$f_{LP} = \frac{PR}{2t \cos \alpha}$$

$$f_{HP} = \frac{PR}{t \cos \alpha}$$

COMBINED STRESSES AT THE FIXED END

$$f_L = f_{LE} + f_{LP} = \frac{P}{A} + \frac{M_f C}{I} + \frac{PR}{2t \cos \alpha} \quad (a)$$

$$f_H = f_{HE} + f_{HP} = \mu f_{LE} + \frac{PR}{t \cos \alpha} \quad (b)$$

$$P = 15,190^*$$

$$V = 238^*$$

$$M = 100,900^{**}$$

$$p = 1350 \times 1.15 = 1552.5 \text{ psi}$$

$$L = 3.23''$$

$$M_s = M + V \cdot L = 100,900 + 238 (3.23) = 101,670^{**}$$

$$t = 0.25'', \quad \mu = 0.30$$

$$R = 2.15 + 0.125 = 2.275''$$

$$A = 2\pi R t = 2\pi (2.275)(0.25) = 3.58 \text{ in}^2$$

$$I = \pi R^3 t = \pi (2.275)^3 (0.25) = 9.26 \text{ in}^4$$

$$\alpha = 15^\circ$$

$$C = 2.15 + 0.25 = 2.40''$$

SUBSTITUTING THE ABOVE VALUES INTO Eqs. (a) & (b), THE LONGITUDINAL AND HOOP STRESSES BECOME

$$f_L = \frac{15190}{3.58} + \frac{101,760(2.40)}{9.26} + \frac{1552.5(2.275)}{2(0.25)(0.966)} = 4,250 + 26,300 + 7310 = \underline{37,860 \text{ psi}}$$

$$f_H = 0.3(26300 + 4250) + 2(7310) = 23,790 \text{ psi}$$

ALLOWABLE STRESS FOR S.S. 347 AT -280°F (LIQUID O_2) = 45,000 psi

$$M.S. = \frac{1}{\frac{4250 + 7310}{45000} + \frac{26300}{1.2 \times 45000}} - 1 = \underline{+0.34}$$

RECOMMENDATION : IF STRENGTH IS A FACTOR, USE HASTELLOY C INSTEAD OF S.S. 347

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TORUS ANALYSIS FIGURE C

$$\phi = \tan^{-1} \frac{2.28}{1.53} = \tan^{-1} 1.492 = 56.2^\circ$$

$$\theta = 90 - 15 - 56.2 = 18.8^\circ$$

$$\psi \approx 41^\circ$$

THE EXTERNAL MOMENT (M_f) WILL CAUSE TENSION ON THE LONG SIDE (SEE FIGURE C). AND COMPRESSION ON THE SHORT SIDE. THIS BENDING MOMENT IS RESOLVED INTO A COUPLE WITH MAGNITUDE

$$F = \sigma t = \frac{M_f c}{I} \cdot t = \frac{M_f \cdot R}{\pi R^3 t} \cdot t = \frac{M_f}{\pi R^2}$$

$$\text{OR } F = \frac{101,670}{\pi (2.275)^2} = \pm 6,252 \text{ #/IN} \quad (c)$$

THE TENSION FORCE (P) IS UNIFORMLY DISTRIBUTED AROUND THE CIRCUMFERENCE OF THE TORUS JUNCTION AND IS

$$P' = \frac{P}{\pi D} = \frac{15190}{\pi (4.55)} = +1,062 \text{ #/IN} \quad (d)$$

COMBINING EXPRESSIONS (c) AND (d) WE HAVE THE NET TOTAL FORCE ACTING AT THE TORUS JUNCTION (SEE FIGURE C)

$$T = +6252 + 1062 = +7,314 \text{ #/IN}$$

$$C = -6252 + 1062 = -5,190 \text{ #/IN}$$

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SHEAR FORCE PER UNIT LENGTH AT DISCONTINUITY JUNCTION IS

$$V' = \frac{V}{\pi D} = \frac{238}{\pi(4.55)} = 16.7 \text{ } \mu\text{m}$$

FIGURE 4 SHOWS THE FORCES AS WELL AS THE PRESSURE LOADS ACTING AT THE TORUS

$$b = 2.52 + .125 = 2.645$$

$$d_1 = b \sin 48.8^\circ = 1.99$$

$$d_2 = b \sin 18.8^\circ = 0.853$$

$$a = 11.53$$

$$P = 1552.5$$

$$t = 0.25$$

FIGURE d

1. INJECTOR

THE FOLLOWING APPROXIMATIONS ARE USED TO CALCULATE STRESSES AT THE TORUS JUNCTION (POINTS A & B, FIGURE d).

PRESSURE LOAD (ASSUME TORUS CONFIGURATION, ROARK, TABLE XIII, CASE 20, p. 27)

$$f_L = \frac{pb}{t} \left(\frac{r+a}{2r} \right), \quad f_H = \frac{pb}{2t} \quad (\text{UNIFORM THROUGHOUT})$$

AT A

$$f_{LA} = \frac{1552.5(2.645)}{0.25} \left(\frac{11.53 + 1.99 + 11.53}{2 \times 11.53} \right) = 17,850 \text{ psi}$$

At B

$$f_{LB} = \frac{1552.5(2.645)}{0.25} \left(\frac{11.53 + 0.853 + 11.53}{2 \times 11.53} \right) = 17,040 \text{ psi}$$

DISCONTINUITY LOADS (i.e., T, C, V')

$$A_T \cdot A$$

$$f'_{LA} = \frac{T \cos 33.8^\circ + V' \sin 33.8^\circ}{t} = \frac{7314(.83) + 16.7(.557)}{0.25} = 24,320 \text{ psi}$$

FIGURE 2

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AT B

$$f'_{LB} = - \frac{C \cos 33.8^\circ + V' \sin 33.8^\circ}{t} = - \frac{5190(.83) + 16.7(.557)}{0.25}$$

$$= -17,300 \text{ psi}$$

MAXIMUM COMBINED MERIDIONAL STRESS :

FIGURE f

AT A

$$f_L = f_{LA} + f'_{LA} = 17,850 + 24,320 = \underline{42,170 \text{ psi}}$$

AT B

$$f_L = f_{LB} + f'_{LB} = 17,040 - 17,300 = \underline{-260 \text{ psi}}$$

ASSUME DISCONTINUITY LOADS HAVE LITTLE EFFECT ON THE BASE OF THE TORUS (D AND E IN FIGURE d) ; STRESSES IN THESE SECTIONS WERE PREVIOUSLY CALCULATED AND WERE GIVEN ON PAGE 29 OF THIS REPORT.

$$M. S. = \frac{45000}{42170} - 1 = \underline{+0.07}$$

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ADAPTER, INLET - TORUS

DEFLECTION INFLUENCE COEFFICIENT CALCULATIONS

BY

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$$\text{WIDTH OF ELEMENT, } b = \frac{\pi R}{2} = \frac{\pi (2.275)}{2} = 3.40''$$

ANALYSIS OF DEFLECTION INFLUENCE COEFFICIENTS DUE TO UNIT LOAD (SHORT E

$$a = R \sin (90^\circ - 15^\circ) = 2.70 (0.966) = 2.61$$

$$c = R \sin (90^\circ - 15^\circ - 18.8^\circ) = 2.70 (0.890) = 2.24$$

$$M_0 = P(a - c) = 1(2.61 - 2.24) = 0.37$$

$$d = a - R \sin (75^\circ - \theta) = 2.61 - 2.70 \sin (75^\circ - \theta)$$

THE MOMENT AT ANY ANGLE θ FROM THE VERTICAL AXIS IS GIVEN BY

$$M = M_0 - Pd$$

$$= 0.37 - 2.61 + 2.70 \sin (75^\circ - \theta)$$

$$= 2.70 [\sin 75^\circ \cos \theta - \cos 75^\circ \sin \theta] - 2.24$$

$$= 2.61 \cos \theta - 0.698 \sin \theta - 2.24$$

$$ds = R d\theta$$

THE DEFLECTION IN THE DIRECTION OF THE UNIT LOAD IS GIVEN BY

$$\delta_P = \int_0^{18.8} \frac{M^2}{EI} ds$$

$$= \frac{R}{EI} \int_0^{18.8} [2.61 \cos \theta - 0.698 \sin \theta - 2.24]^2 d\theta$$

$$= \frac{R}{EI} \int_0^{18.8} [(2.61)^2 \cos^2 \theta + (0.698)^2 \sin^2 \theta + (2.24)^2 - 2(2.61)(0.698) \cos \theta \sin \theta - 2(2.24)(2.61) \cos \theta + 2(0.698)(2.24) \sin \theta] d\theta$$

$$\begin{aligned}\delta_p &= \frac{R}{EI} \int_0^{18.8} \left[6.82 \left(\frac{1+\cos 2\theta}{2} \right) + 0.488 \left(\frac{1-\cos 2\theta}{2} \right) + 5.02 - 1.823 \sin 2\theta - 11.70 \cos \theta + 3.13 \sin \theta \right] d\theta \\ &= \frac{R}{EI} \left\{ 6.82 \left[\frac{\theta}{2} + \frac{\sin 2\theta}{4} \right] + 0.488 \left[\frac{\theta}{2} - \frac{\sin 2\theta}{4} \right] + 5.02 \theta + 0.9115 \cos 2\theta - 11.70 \sin \theta - 3.13 \cos \theta \right\}_0^{18.8} \\ &= \frac{R}{EI} \left\{ 6.82 [0.1641 + 0.1525] + 0.488 [0.1641 - 0.1525] + 1.6472 + 0.7222 - 3.7706 - 2.9630 \right. \\ &\quad \left. - 0.9115 + 3.13 \right\} \\ &= \frac{R}{EI} \left\{ 2.1592 + 0.0057 + 1.6472 + 0.7222 - 3.7706 - 2.9630 - 0.9115 + 3.13 \right\}\end{aligned}$$

$$\delta_p = 0.0192 \frac{R}{EI}$$

For $E = 29.0 \times 10^9$

$R = 2.70$, $b = 3.40$, $h = 0.25$

$$I = \frac{bh^3}{12} = \frac{3.40(0.25)^3}{12} = 4.427 \times 10^{-3}$$

$$\delta_p = (0.0192) \frac{2.70}{29 \times 10^6 (4.427 \times 10^{-3})} = 4.038 \times 10^{-7} \frac{\text{IN}}{\text{LB}}$$

SPRING CONSTANT, k , IS THEN

$$k = \frac{1}{\delta_p} = \frac{1}{4.038 \times 10^{-7}} = 2.476 \times 10^6 \frac{\text{LB}}{\text{IN}}$$

LONG END

$$a = R \cos(15 - 7.8^\circ) = 2.70(0.992) = 2.68''$$

$$c = R \sin 56.2^\circ = 2.70(0.830) = 2.24''$$

$$d = a - R \sin(105^\circ - 7.8^\circ - \theta) = 2.68 - 2.70 \sin(97.2^\circ - \theta)$$

$$M_0 = P(a - c) = 0.44$$

THE BENDING MOMENT AT ANY ANGLE

θ FROM THE FIXED END IS GIVEN BY

$$M = M_0 - P \cdot d$$

$$= 0.44 - 2.68 + 2.70 \sin(97.2^\circ - \theta)$$

$$= 2.70 [\sin 97.2^\circ \cos \theta - \cos 97.2^\circ \sin \theta] - 2.24$$

$$= 2.679 \cos \theta + 0.338 \sin \theta - 2.24$$

THE DEFLECTION IN THE DIRECTION OF THE UNIT LOAD IS GIVEN BY

$$\delta_P = \int_0^{41^\circ} \frac{M^2}{EI} ds$$

$$= \frac{R}{EI} \int_0^{41^\circ} [2.679 \cos \theta + 0.338 \sin \theta - 2.24]^2 d\theta$$

$$= \frac{R}{EI} \int_0^{41^\circ} [7.177 \cos^2 \theta + 0.114 \sin^2 \theta + 5.018 + 0.9055 \sin 2\theta - 12.002 \cos \theta - 1.514 \sin \theta] d\theta$$

$$= \frac{R}{EI} \left\{ 7.177 [0.3578 + 0.2476] + 0.114 [0.3578 - 0.2476] + 5.018 (0.7156) - 0.4528 (0.1392) - 12.002 (0.6561) + 1.514 (0.7547) + 0.4528 - 1.514 \right\}$$

$$\delta_P = \frac{R}{EI} \left\{ 4.3450 + 0.0126 + 3.5909 - 0.0630 - 7.8745 + 1.1426 + 0.4528 - 1.514 \right\} = \frac{0.0924R}{EI}$$

OR

$$\delta_p = \frac{0.0924(270)}{29 \times 10^6 (4.427 \times 10^{-3})} = 19.432 \times 10^{-7} \frac{\text{IN}}{\text{LB}}$$

SPRING CONSTANT, k , IS

$$k = \frac{1}{\delta_p} = 0.5146 \times 10^6 \frac{\text{LB}}{\text{IN}}$$

THE TWO SPRING CONSTANTS THUS FOUND WILL BE USED (BY THE LOX LINE ANALYST) TO FIND A MORE REALISTIC SOLUTION OF THE EXTERNAL FORCES AND MOMENT IMPOSED ONTO THE INJECTOR TORUS BY THE LOX INLET LINE.

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$$\theta = \frac{(1.9432 - 0.4038) \times 10^{-6}}{2(2.275)} = 0.3383 \times 10^{-6}$$

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SUBJECT

INJECTOR - ADAPTER, BOLT

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$$\begin{aligned} \text{TOTAL INJECTOR BOLT LOAD} &= 1.15 \left[885.3 \left(\frac{\pi}{4} \right) (22.10)^2 + 1235.3 \left(\frac{\pi}{4} \right) (24.15^2 - 22.65^2) \right] \\ &= 1.15 [340,000 + 68,100] = 470,000 \# \end{aligned}$$

$$\text{OR } \frac{470,000}{60} = 7,840 \#/\text{BOLT}$$

BOLT MATERIAL - MS 21291-23 ($\frac{3}{8}$ ")

$$\text{MIN. } F_y = 85,000 \text{ psi}$$

$$A_s = 0.0773 \text{ IN}^2$$

$$f = \frac{7840}{0.0773} = 101,400 \text{ psi}$$

MS 21291-23 BOLTS NO GOOD

USE AS 4099-06-016 BOLT (12-14-65)

$$\text{MIN } F_y = 160,000 \text{ psi}$$

$$\text{MIN. } A = \frac{\pi}{4} (0.3239)^2 = 0.0825 \text{ IN}^2$$

$$f = \frac{7840}{0.0825} = 95,000 \text{ psi} < 160,000 \times 0.75 = 120,000 \text{ psi}^*$$

$$\text{M.S.} = \frac{120,000}{95,000} - 1 = 0.26 \quad (\text{M.S. FOR JOINT SEPARATION})$$

$$\text{M.S.} = \frac{160,000}{120,000} - 1 = 0.33 \quad (\text{M.S. FOR BOLT})$$

* REFERENCE TO MEMORANDUM 7510:012 (E.T. KAUTT TO C.W. KAWASHIGE),
"TORQUE VALUES FOR PHOEBUS-2 TEST ASSEMBLY COMPONENTS," 10 DECEMBER 1965

SUBJECT

COAXIAL INJECTOR PLATE STRESS ANALYSIS

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THE COAXIAL INJECTOR PLATE IS A PERFORATED PLATE TYPE DESIGN, CONSISTING OF 242 FUEL AND OXIDIZER ELEMENTS, WHICH BRINGS THE TWO PROPELLANTS TOGETHER FOR A GOOD COMBUSTION HOT GAS PRODUCT.

THE ARRANGEMENT OF THE ELEMENTS IS SHOWN IN FIGURES 1 AND 2. DESIGN CRITERIA USED IN THIS ANALYSIS IS GIVEN ON PAGE 66.

THE STRESS ANALYSIS IS BASED ON O'DONNELL AND HORVAY'S METHOD (REFERENCES 1 AND 2) WHICH CONSISTS OF THE FOLLOWING STEPS:

STEP 1. CALCULATE THE NOMINAL BENDING AND MEMBRANE STRESSES AND DEFLECTIONS OF AN EQUIVALENT SOLID PLATE HAVING THE EFFECTIVE MODIFIED ELASTIC CONSTANTS E^* AND μ^* AND THE SAME DIMENSIONS AS THE PERFORATED PLATE.

STEP 2. CALCULATE PHYSICALLY MEANINGFUL PERFORATED PLATE STRESS VALUES FROM THE NOMINAL VALUES IN THE EQUIVALENT SOLID PLATE FROM STEP 1

STEP 3. CALCULATE ALLOWABLE STRESS VALUE AND COMPARE WITH THE PERFORATED PLATE STRESS VALUES OBTAINED FROM STEP 2 TO OBTAIN MARGIN OF SAFETY.

COAXIAL INJECTOR PLATE STRESS ANALYSIS

11-19-65

D. Tow

FIGURE 1

MAX OPERATING CONDITION : (OBTAINED FROM M. SMOOT, DATED 11-19-65)

CHAMBER PRESSURE = 900 psia

INJECTOR DOME PRESSURE = 1075 psia

FUEL PRESSURE = 1200 psia

Δp ACROSS INJECTOR PLATE = 175 psi

PRESSURE SAFETY FACTOR = 1.15

MATERIAL : 347 STAINLESS STEEL

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COAXIAL INJECTOR PLATE STRESS ANALYSIS

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FIGURE 2

ELEMENTS ARRANGEMENT

ELEMENT ROW NO.	BASIC RADIUS	NO. HOLES EQUALLY SPACED
1	1.625	8
2	2.750	18
3	4.125	26
4	5.500	36
5	6.875	44
6	8.250	54
7	9.625	56

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COAXIAL INJECTOR PLATE STRESS ANALYSIS

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RADIAL DIRECTION

$$2R = 1.375$$

$$2h = 0.75$$

$$\text{LIGAMENT EFFICIENCY, } \epsilon = \frac{h}{R} = \frac{0.375}{0.6875} = 0.545$$

CIRCUMFERENTIAL DIRECTION

$$2R = 0.982$$

$$2h = 0.357$$

$$\text{LIGAMENT EFFICIENCY, } \epsilon = \frac{h}{R} = \frac{0.1785}{0.491} = 0.364$$

FROM REF. 2, FIGURE 4

$$\epsilon = 0.545$$

$$\frac{E^*}{E} = 0.46 \quad \longrightarrow \quad E^* = 0.46 E$$

$$\mu^* = 0.37$$

$$\epsilon = 0.364$$

$$\frac{E^*}{E} = 0.26 \quad \longrightarrow \quad E^* = 0.26 E$$

$$\mu^* = 0.45$$

AVERAGE EFFECTIVE MODIFIED ELASTIC YOUNG'S MODULUS AND POISSON'S RATIO :

$$E^* = \left(\frac{0.46 + 0.26}{2} \right) E = 0.36 E$$

$$\mu^* = \frac{0.37 + 0.45}{2} = 0.41$$

COAXIAL INJECTOR PLATE STRESS ANALYSIS

11-19-65

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THE PERFORATED PLATE IS NOW ANALYZED AS AN EQUIVALENT SOLID PLATE HAVING THE EFFECTIVE MODIFIED ELASTIC CONSTANTS E^* AND μ^* AND THE SAME DIMENSIONS AS THE PERFORATED PLATE.

SOLUTION WILL BE TWO-FOLD — PARTIALLY UNIFORM LOADED PLATE PLUS CONCENTRATED LOADED PLATE

THE CENTER DEFLECTIONS FOR BOTH CASES

(a) & (b) ARE

$$(W_q)_{r=0} = \frac{q c^2}{16 D^*} \left[\frac{3+\mu^*}{1+\mu^*} a^2 + c^2 \log_e \frac{c}{a} - \frac{7+3\mu^*}{4(1+\mu^*)} c^2 \right]$$

$$(W_p)_{r=0} = - \frac{(3+\mu^*) P a^2}{16 \pi D^* (1+\mu^*)}$$

(a)

FIGURE
3a

(b)

3b

WHERE D^* IS THE MODIFIED FLEXURAL RIGIDITY OF THE PLATE BASED ON E^* AND μ^*

DEFLECTION AT CENTER OF PLATE MUST BE ZERO:

$$(W_q)_{r=0} + (W_p)_{r=0} = 0$$

OR

$$\frac{q c^2}{16 D^*} \left[\frac{3+\mu^*}{1+\mu^*} a^2 + c^2 \log_e \frac{c}{a} - \frac{7+3\mu^*}{4(1+\mu^*)} c^2 \right] - \frac{(3+\mu^*) P a^2}{16 \pi D^* (1+\mu^*)} = 0$$

SOLVING FOR P,

$$P = q \pi c^2 \left[1 + \frac{c^2}{a^2} \frac{1+\mu^*}{3+\mu^*} \log_e \frac{c}{a} - \frac{7+3\mu^*}{4(3+\mu^*)} \frac{c^2}{a^2} \right] \quad (c)$$

STRESSES DUE TO CONCENTRATED LOAD P (REF. 5, PP. 68)

$$\sigma_r = \frac{G M r}{t^2} = - \frac{3 P}{2 \pi t^2} (1+\mu^*) \log_e \frac{a}{r} \quad (d)$$

$$\sigma_t = \frac{G M t}{t^2} = - \frac{3 P}{2 \pi t^2} \left[(1+\mu^*) \log_e \frac{a}{r} + 1 - \mu^* \right] \quad (e)$$

COAXIAL INJECTOR PLATE STRESS ANALYSIS

11-19-65

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STRESSES DUE TO UNIFORM LOAD (REF. 6, TABLE X, CASE 2, PP. 194)

$$\underline{r < c}, \quad \sigma_r = \frac{3W}{2\pi m t^2} \left[m + (m+1) \log_e \frac{a}{c} - (m-1) \frac{c^2}{4a^2} - (3m+1) \frac{r^2}{4c^2} \right] \quad (f)$$

$$\sigma_t = \frac{3W}{2\pi m t^2} \left[m + (m+1) \log_e \frac{a}{c} - (m-1) \frac{c^2}{4a^2} - (m+3) \frac{r^2}{4c^2} \right] \quad (g)$$

$$\underline{r > c}, \quad \sigma_r = \frac{3W}{2\pi m t^2} \left[(m+1) \log_e \frac{a}{r} - (m-1) \frac{c^2}{4a^2} + (m-1) \frac{c^2}{4r^2} \right] \quad (h)$$

$$\sigma_t = \frac{3W}{2\pi m t^2} \left[(m-1) + (m+1) \log_e \frac{a}{r} - (m-1) \frac{c^2}{4a^2} - (m-1) \frac{c^2}{4r^2} \right] \quad (i)$$

WHERE $W = g \pi c^2$

$$m = \frac{1}{\mu^*}$$

t = THICKNESS OF PLATE

$$\text{FOR } g = \Delta p = 175 \times 1.15 = 201 \text{ psi}$$

$$a = 12.375''$$

$$c = 11.235''$$

EQ. (c) BECOMES

$$P = (201)(3.14)(11.235)^2 \left[1 + \frac{11.235^2}{12.375^2} \frac{1+0.41}{3+0.41} \log_e \frac{11.235}{12.375} - \frac{7+3(0.41)}{4(3+0.41)} \frac{11.235^2}{12.375^2} \right]$$

$$P = 37,500 \text{ #}$$

SUBSTITUTING THE ABOVE VALUES INTO EQS. (d) TO (e) AND SIMPLIFYING, YIELDS

DUE TO P :

$$\sigma_r = -16,150 \log_e \frac{a}{r} \quad (d')$$

$$\sigma_t = \sigma_r - 6,750 \quad (e')$$

DUE TO g :

$$r < c$$

$$\sigma_r = 24,690 - 164.54 r^2 \quad (f')$$

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COAXIAL INJECTOR PLATE STRESS ANALYSIS

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$$\sigma_t = 24,690 - 107.573 r^2$$

(g')

$$r > c$$

$$\sigma_r = 9,984 \left[3.439 \log_e \frac{a}{r} - 0.297 + \frac{45.4}{r^2} \right]$$

(h')

$$\sigma_t = 9,984 \left[1.439 + 3.439 \log_e \frac{a}{r} - 0.297 - \frac{45.4}{r^2} \right]$$

(i')

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① r (IN.)	② r ²	③ $\frac{a}{r}$	④ $\log_e \frac{a}{r}$	⑤ STRESSES DUE TO P		⑦ STRESSES DUE TO q		⑨ = ⑤ + ⑦ TOTAL STRESSES	
				σ_r (psi)	σ_t (psi)	σ_r (psi)	σ_t (psi)	σ_r (psi)	σ_t (psi)
1.0	1.00	12.375	2.516	-40,700	-47,450	24,525	24,582	-16,175	-22,868
1.5	2.25	8.250	2.110	-34,100	-40,850	24,320	24,448	-9,780	-16,402
2.0	4.00	6.190	1.822	-29,430	-36,180	24,032	24,260	-5,398	-11,920
3.0	9.00	4.125	1.417	-22,900	-29,650	23,209	23,722	309	-5,928
4.0	16.00	3.096	1.130	-18,250	-25,000	22,057	22,969	3,807	-2,031
5.0	25.00	2.475	0.906	-14,640	-21,390	20,576	22,001	5,936	611
6.0	36.00	2.064	0.725	-11,710	-18,460	18,767	20,817	7,057	2,357
7.0	49.00	1.768	0.570	-9,210	-15,960	16,628	19,419	7,418	3,459
8.0	64.00	1.547	0.436	-7,030	-13,780	14,159	17,805	7,129	4,025
9.0	81.00	1.375	0.318	-5,140	-11,890	11,362	15,977	6,222	4,087
10.0	100.00	1.238	0.213	-3,444	-10,194	8,236	13,933	4,792	3,739
11.235	126.2	1.101	0.0961	-1,552	-8,302	3,925	11,114	2,373	2,812
12.0	144.0	1.031	0.0305	-493	-7,243	1,230	9,301	737	2,058

STRESSES ARE GIVEN FOR THE BOTTOM SURFACE OF THE PLATE, NEGATIVE DENOTES COMPRESSION. FOR THE TOP SURFACE OF THE PLATE, STRESS VALUES ARE THE SAME EXCEPT WITH REVERSED SIGN.

COAXIAL INJECTOR PLATE STRESS ANALYSIS

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FIGURE 4

COAXIAL INJECTOR PLATE STRESS ANALYSIS

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HAVING THE PRINCIPAL STRESSES σ_r AND σ_t AT EITHER SURFACE OF THE EQUIVALENT SOLID PLATE, THE AVERAGE LIGAMENT STRESS INTENSITY OF THE PERFORATED PLATE CAN BE EVALUATED USING THE FOLLOWING SOLUTION (REF. 1)

$$\sigma_{\text{EFF}} = K \frac{R}{h} |\sigma_1| \quad (j)$$

WHERE

σ_{EFF} = LIGAMENT STRESS INTENSITY BASED ON STRESSES AVERAGED ACROSS MINIMUM LIGAMENT SECTION AT EITHER PLATE SURFACE.

K = VALUE GIVEN IN FIGURE 10, REF. 1

$\frac{R}{h}$ = RECIPROCAL OF LIGAMENT EFFICIENCY

$\sigma_1 = \sigma_r$ OR σ_t , WHICHEVER HAS THE LARGEST ABSOLUTE VALUE

σ_r, σ_t = STRESSES AT EITHER SURFACE OF EQUIVALENT SOLID PLATE OBTAINED IN THE FOREGOING ANALYSIS

THE K -VALUES IN EQUATION (j) DEPEND ON THE BIAXIALITY OF THE STRESS FIELD AND VARY WITH RADIAL LOCATION IN THE PLATE. THE BIAXIALITY RATIO, β , IS GIVEN BY

$$\beta = \frac{\sigma_r}{\sigma_t} \text{ OR } \frac{\sigma_t}{\sigma_r}, \text{ WHICHEVER GIVES } -1 \leq \beta \leq 1$$

THE ALLOWABLE STRESS VALUE, BASED ON SECTION III OF THE ASME PRESSURE VESSEL CODE, IS GIVEN BY

$$\sigma_{\text{ALLOW}} = 1.5 S_m$$

WHERE THE BASIC STRESS INTENSITY ALLOWANCE $S_m = \frac{2}{3} \sigma_y$

THEREFORE, $\sigma_{\text{ALLOW}} = 1.5 \left(\frac{2}{3} \sigma_y \right) = \sigma_y = 30,000 \text{ psi}$

COAXIAL INJECTOR PLATE STRESS ANALYSIS

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FIGURE 5

FIGURE 6

STRESS IN A TYPICAL LIGAMENT

$$\sigma_{\text{Allow}} = 30,000 \text{ psi}$$

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(1) LIGAMENT SECTION	(2) r (IN)	(3) FROM FIGURE 4		(5) $\beta = \frac{\sigma_r}{\sigma_t} \text{ OR } \frac{\sigma_t}{\sigma_r}$	(6) K	(7) R (IN)	(8) h (IN)	(9) $\frac{R}{h}$	(10) σ_1 (PSI)	(11) = (6) x (9) x (10) σ_{EFF} (PSI)	(12) M. S.
		σ_r (PSI)	σ_t (PSI)								
1	2.16	-4,250	-10,800	0.394	1.03	0.565	0.240	2.354	10,800	26,200	0.15
2	3.34	1,700	-4,400	-0.387	1.44	0.688	0.375	1.835	4,400	11,620	1.58
3	4.80	5,600	200	0.036	1.15	0.688	0.375	1.835	5,600	11,820	1.54
4	6.16	7,200	2,700	0.375	1.03	0.688	0.375	1.835	7,200	13,600	1.21
5	7.54	7,350	3,800	0.517	1.02	0.688	0.375	1.835	7,350	13,750	1.18
6	8.91	6,300	4,100	0.651	1.01	0.688	0.375	1.835	6,300	11,670	1.57
7	10.27	4,300	3,600	0.837	1.005	0.688	0.375	1.835	4,300	7,930	2.78

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COAXIAL INJECTOR PLATE STRESS ANALYSIS

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CHECK STRESS AT CENTER OF PLATE :

THE TENSILE STRESS AT THE CENTER OF THE TOP SURFACE OF THE PLATE UNDER THE CONCENTRATED LOAD P IS GIVEN BY (REF. 5, pp. 70)

$$\begin{aligned}\sigma_p &= \frac{P}{t^2} \left[(1 + \mu^*) \left(0.485 \log_e \frac{a}{t} + 0.52 \right) + 0.48 \right] \\ &= \frac{37500}{(2.375)^2} \left[(1 + 0.41) \left(0.485 \log_e \frac{12.375}{2.375} + 0.52 \right) + 0.48 \right]\end{aligned}$$

$$\sigma_p = 15,520 \text{ psi}$$

FOR THE UNIFORM LOAD q , THE STRESS IS

$$\sigma_g = \frac{-3(3 + \mu^*) q a^2}{8 t^2} = \frac{-3(3 + 0.41)(201)(12.375)^2}{8 (2.375)^2} = -6,980 \text{ psi}$$

$$\sigma = \sigma_p + \sigma_g = \underline{8,540 \text{ psi}}$$

SUMMARY

MAXIMUM STRESS IN THE INJECTOR PLATE OCCURS MIDWAY BETWEEN THE FIRST AND SECOND ROW ELEMENTS. ITS MAGNITUDE AND MARGIN OF SAFETY ARE

$$\sigma_{\text{MAX}} = 26,200 \text{ psi}$$

$$M.S. = 0.15$$

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COAXIAL INJECTOR PLATE STRESS ANALYSIS

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INJECTOR INTERFACE LOAD DISTRIBUTION

12-22-65

D. Tow

SECTION THROUGH 1 BOLT OF INJECTOR FACE

$$l = \text{BOLT SPACING} = \frac{\pi (27.25)}{60} = 1.427$$

$$W_1 = 14.6185 - 10.915 = 3.7035$$

$$W_3 = 0.182$$

$$W_4 = 0.750$$

$$W_5 = 0.182$$

$$l_3 = l_5 = l = 1.427$$

$$l_4 = (1.427)(0.375) \frac{1}{\frac{2\pi(11.71)}{120}} = 0.873$$

ITEM	W	l	A	x	Ax	Ax ²	I ₀
1	3.7035	1.427	5.284895	1.85175	9.786304	18.121788	6.040595
2	—	—	-0.150399	2.710	-0.407581	-1.104545	-0.001800
3	0.182	1.427	-0.259714	1.3665	-0.354899	-0.484969	-0.000717
4	0.750	0.873	-0.654750	0.795	-0.520526	-0.413818	-0.030691
5	0.182	1.427	-0.259714	0.2235	-0.058046	-0.012973	-0.000717
Σ	—	1.427	3.960318	—	8.445252	16.105483	6.006670

$$\bar{x} = \frac{\sum Ax}{\sum A} = \frac{8.445252}{3.960318} = 2.132468$$

$$I = \sum Ax^2 + I_0 - (\sum A) \bar{x}^2 = 16.105483 + 6.006670 - 3.960318 (2.132468)^2 = 4.102924$$

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INJECTOR INTERFACE LOAD DISTRIBUTION

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AREA OF ONE BOLT (MINIMUM) — AS 4099-06-016 BOLT

$$A = \frac{\pi}{4} (0.3239)^2 = 0.0825 \text{ IN}^2$$

PRELOAD ON BOLT

ASSUME = 0.75 F_y OF BOLT.

$$\text{MIN. } F_y = 160,000 \frac{\text{LBS}}{\text{IN}^2}$$

$$\text{PRELOAD } \frac{\text{LBS}}{\text{BOLT}} = 0.75 (160,000) (0.0825)$$

$$F_{PL} = 9,900 \frac{\text{LBS}}{\text{BOLT}}$$

EJECTION LOAD ON BOLT

$$F_{\text{TOTAL}} = \left[885.3 \times \frac{\pi}{4} \times 22.10^2 + 1235.3 \times \frac{\pi}{4} \times (24.15^2 - 22.65^2) \right] 1.15 = 470,000 \text{ LBS}$$

$$F_E = \frac{470,000}{60} = 7,833 \frac{\text{LBS}}{\text{BOLT}}$$

NET LOAD ON INJECTOR FACE

$$F_I = -9900 + 7833 = -2067 \frac{\text{LBS}}{\text{BOLT}}$$

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NET LOAD (F_I) ON INJECTOR FACE IS DISTRIBUTED OVER ENTIRE SECTION

$$d = 2.1325 - 1.85175 = 0.2807 \text{ IN.}$$

$$C_o = 1.5710 \text{ IN.}$$

$$C_i = 2.1325 \text{ IN.}$$

STRESSES ON INJECTOR FACE DUE TO NET LOAD F_I

$$\sigma_{o.s.I} = \frac{F_I}{A} - \frac{F_I \times d \times C_o}{I} = \frac{-2067}{3.960318} - \frac{(-2067)(0.2807)(1.5710)}{4.102924} = -522 + 222$$

$$\sigma_{o.s.I} = -300 \frac{\text{LBS}}{\text{IN}^2}$$

$$\sigma_{i.s.I} = \frac{F_I}{A} + \frac{F_I \times d \times C_i}{I} = \frac{-2067}{3.960318} + \frac{(-2067)(0.2807)(2.1325)}{4.102924} = -522 - 302$$

$$\sigma_{i.s.I} = -824 \frac{\text{LBS}}{\text{IN}^2}$$

STRESSES DUE TO INTERFACE MOMENTINTERFACE MOMENT DUE TO MECHANICAL LOADS = $-4,000 \frac{\text{IN-LBS}}{\text{IN}}$ AT $R = 13.07 \text{ IN.}$

$$\sigma_{o.s.M} = \frac{M C_o}{I} = \frac{(-4000)(2\pi)(13.07)}{60} \times \frac{1.5710}{4.102924} = (-5474.7441)(0.382897) = -2,096 \frac{\text{LBS}}{\text{IN}^2}$$

$$\sigma_{i.s.M} = -\frac{M C_i}{I} = -(-5474.7441) \times \frac{2.1325}{4.102924} = (5474.7441)(0.519751) = +2,846 \frac{\text{LBS}}{\text{IN}^2}$$

STRESSES ON INJECTOR FACE

$$\sigma_{o.s.} = \sigma_{o.s.I} + \sigma_{o.s.M} = -300 - 2,096 = -2,396 \frac{\text{LBS}}{\text{IN}^2}$$

$$\sigma_{i.s.} = \sigma_{i.s.I} + \sigma_{i.s.M} = -824 + 2,846 = +2,022 \frac{\text{LBS}}{\text{IN}^2}$$

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INJECTOR INTERFACE LOAD DISTRIBUTION

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RESOLVE INTERFACE MOMENT INTO A COUPLE

$$F_M = \frac{M}{d_m} = \frac{420(25)(13.07)}{60(0.9935)} = 5511 \frac{\text{lbs}}{\text{BOLT}}$$

INJECTOR FLANGE

ADAPTER

BOLT

TOTAL LOAD ON INJECTOR FACE

$$F_T = F_I + F_M = 2067 + 5511 = 7,578 \frac{\text{lbs}}{\text{BOLT}}$$

$$d_m = 14.6185 - 13.625 = 0.9935$$

EFFECTIVE LENGTH OF BOLT

$$L = 1.0 + \frac{1}{3} \left(\frac{3}{8} \right) = 1.125 \text{ IN.}$$

CHANGE IN LENGTH DUE TO F_T

$$\delta_{\text{BOLT}} = \frac{F_T L}{AE} = \frac{7578 (1.125)}{0.0825 \times 29 \times 10^6} = 0.00356 \text{ IN}$$

SEAL SEPARATION

$$\delta_{\text{SEAL}} = \frac{3.5710}{0.9935} (0.00356) = 0.0128 \text{ IN.}$$

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COAXIAL INJECTOR

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2-24-66

INJECTOR, TORUS - THERMAL + MECHANICAL STRESSES

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THE THERMAL STRESS ANALYSIS FOR THE INJECTOR LOX INLET TORUS IS ANALYZED FOR THE 750 PC (OPERATING CONDITION) ONLY. FROM A CONVERSATION WITH THE HEAT TRANSFER GROUP (O.D. VICK) IT WAS FOUND THAT THE THERMAL PROFILES FOR BOTH THE 750 AND 900 PC CASES ARE VERY MUCH ALIKE. MECHANICAL STRESSES WERE CALCULATED FOR THE 900 PC CASE AND WILL BE COMBINED WITH THE 750 PC THERMAL STRESS CASE WHEN CALCULATED THE COMBINED MARGIN OF SAFETY.

THE FOLLOWING TABLE, EXTRACTED FROM SNPO-C STRUCTURAL DESIGN SPECIFICATION, DEC. 1965, SHOWS THE DIFFERENT KINDS OF STRESS CATEGORIES OF P_m , P_L , P_b , Q , AND F , TOGETHER WITH THE ALLOWABLE STRESS PARAMETERS FROM WHICH MARGINS OF SAFETY HAVE BEEN CALCULATED

FOR GROUP SUPPORT AND TEST EQUIPMENT STRESS INTENSITY LIMITS

STRESS CATEGORIES	STRESS INTENSITY LIMITS	
	YIELD STRENGTH (f_y)	ULTIMATE STRENGTH (f_u)
GENERAL PRIMARY MEMBRANE (P_m)	$\frac{2}{3} f_y$	$\frac{1}{3} f_u$
LOCAL PRIMARY MEMBRANE (P_L)	f_y	$\frac{1}{2} f_u$
PRIMARY MEMBRANE PLUS BENDING P_m (OR P_L) + P_b	f_y	$\frac{1}{2} f_u$
SECONDARY + PRIMARY STRESS INTENSITY * P_m (OR P_L) + P_b + Q	$2 f_y$	f_u
PEAK STRESS INTENSITY P_m (OR P_L) + P_b + Q + F	—	(.9) (ACTUAL LIFE CYCLE)

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INJECTOR, TORUS

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DWG. No. 1115083 - TORUS CONFIGURATION

$$\theta = 184.26^\circ$$

$$\text{WRAP DISTANCE} = \frac{184.26}{180} \times (3.142)(2.645) = 8.506''$$

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INJECTOR, TORUS — THERMAL + MECHANICAL STRESSES

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MECHANICAL STRESSES (SEE PAGES 28-29, OR COMPUTER RUN, CASE 4.0, 7-14-65,
PHOENUS-2 COAXIAL INJECTOR ANALYSIS (MANIFOLD - .250 THICKNESS))

* MERIDIONAL STRESS (σ_x)

STATION, ξ (IN.)	MEAN TEMP. (°F)	MERIDIONAL STRESS (PSI)	STRESS CATEGORY	ALLOW STRESS @ MEAN TEMP.	M. S.
0.00	-55	16,847	P _L	33,500	0.99
0.91	-252	16,033	P _L	42,600	1.66
1.81	-272	15,450	P _L	43,700	1.83
2.72	-266	15,099	P _m	29,000	0.92
3.62	-260	14,937	P _m	28,670	0.92
4.53	-260	14,924	P _m	28,670	0.92
5.43	-261	15,057	P _m	28,730	0.91
6.33	-271	15,362	P _m	29,130	0.90
7.24	-271	15,885	P _m	29,130	0.83
8.14	-235	16,639	P _m	27,730	0.67
8.42	-197	16,903	P _L	39,200	1.32
8.51	-186	16,994	P _L	38,500	1.27

* HOOP STRESS IS NOT CRITICAL

SUBJECT

INJECTOR, TORUS — THERMAL + MECHANICAL STRESSES

BY

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MECHANICAL + THERMAL STRESSES

REFERENCES: (1) PHOENUS-2 COAXIAL INJECTOR — TORUS THERMAL STRESS:

COMPUTER RUN, CASE 1-10 1-12-66

(2) PHOENUS COAXIAL INJECTOR TRANSIENT TEMPERATURE FILL:

(750 P_c, 20 SECONDS), 11-17-65MERIDIONAL STRESSES (σ_F)(STRESS CATEGORY — P_m (OR P_L) + P_b + Q + F)

STATION Z (IN)	MECHANICAL STRESS P_m (OR P_L) + P_b + Q (PSI)		THERMAL STRESS F (PSI)		MAX. THERMAL + MECHANICAL STRESSES * P_m (OR P_L) + P_b + Q + F	CYCLIC FATIGUE (BASED ON 100 CYCLES) ALLOWABLE STRESS, $0.9 S_a$ **	MINIMUM M.S.
	INNER	OUTER	INNER	OUTER			
0.00	18,872	14,821	-96,919	21,436	-78,047	216,000 ↑ ↓ 216,000	1.77
0.91	17,007	15,055	-28,316	48,944	64,053		
1.81	15,162	15,738	13,419	1,813	28,581		
2.72	14,343	15,855	35,760	-32,435	50,103		
3.62	14,222	15,651	39,458	-46,423	53,680		
4.53	14,251	15,597	38,851	-49,854	53,102		
5.43	14,333	15,780	36,281	-46,694	50,614		
6.33	14,886	15,838	16,461	-21,693	31,847		
7.24	16,348	15,422	-26,411	25,202	40,624		
8.14	18,177	15,100	-66,019	58,528	73,628		
8.42	18,487	15,318	-66,009	42,121	57,439		
8.51	18,536	15,452	-63,966	32,895	48,347		

* — DENOTES COMPRESSIVE STRESS, AND " + " DENOTES TENSILE STRESS

** $S_a = 240,000$ PSI (OBTAINED FROM SNPO-C STRUCTURAL DESIGN SPEC., TABLE 1)

INJECTOR, TORUS — THERMAL + MECHANICAL STRESSES

2-24-66

D. Tow

HOOP STRESSES (σ_{θ})

(STRESS CATEGORY — $P_m(OR P_L) + P_b + Q + F$)

STATION $\bar{x}$, (IN)	MECHANICAL STRESS $P_m(OR P_L) + Q$ (PSI)		THERMAL STRESS F (PSI)		MAX. THERMAL + MECHANICAL STRESSES $P_m(OR P_L) + P_b + Q + F$	CYCLIC FATIGUE (BASED ON 100 CYCLES) ALLOWABLE STRESS, 0.9 S _a	MINIMUM M.S.
	INNER	OUTER	INNER	OUTER			
0.00	5,662	4,446	17,334	26,422	30,868	<div style="text-align: center;"> 216,000 ↑ ↓ 216,000 </div>	1.44
0.91	6,335	5,555	57,188	80,052	85,607		
1.81	6,918	6,915	47,362	49,534	56,449		
2.72	7,583	7,961	30,509	9,453	38,092		
3.62	8,059	8,477	15,617	-15,977	23,676		
4.53	8,138	8,538	12,596	-20,205	20,734		
5.43	7,796	8,181	23,450	-4,942	31,246		
6.33	7,190	7,335	39,196	32,191	46,386		
7.24	6,580	6,105	49,625	72,279	78,384		
8.14	5,961	4,951	54,964	83,441	88,392		
8.42	5,676	4,703	59,430	63,992	68,695		
8.51	5,561	4,636	61,570	54,851	67,131

PROOF & LEAK FIXTURE INJECTOR (DWG No. 1015207)

12-16-65

D. Tow

SUBJECT

PROOF & LEAK FIXTURE INJECTOR

REPORT NO.

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OF

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PROOF CONDITION

$p = 1375 \text{ psig}$

MATERIAL

BOLT STRENGTH, MIN. $F_y = 168,000 \text{ psi}$

END PLATE = HEAT TREAT 4130

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$$p = 1375 \text{ psig}$$

PLATE ANALYSIS

ASSUME CLAMPED EDGES.

$$M_1 = \frac{pa^2}{8} = \frac{1375(11.375)^2}{8} = 22,240 \frac{\text{IN-LB}}{\text{IN}}$$

$$V_1 = \frac{p(\pi r^2)}{2\pi r} = \frac{pr}{2} = \frac{1375(11.375)}{2}$$

MAX. STRESS IS AT EDGE ($h=2.5$)

$$V_1 = 7820 \frac{\text{LB}}{\text{IN}} \quad @ \quad R=11.375$$

$$\sigma_{\text{MAX}} = \frac{6M_1}{h^2} = \frac{6(22,240)}{(2.5)^2} = 21,400 \text{ psi}$$

MAX. DEFLECTION IS AT THE CENTER

$$W_{\text{MAX}} = \frac{pa^4}{64D}$$

$$D = \frac{Eh^3}{12(1-\nu^2)} = \frac{29 \times 10^6 (2.75)^3}{12(1-0.3^2)} = 55.3 \times 10^6$$

$$W_{\text{MAX}} = \frac{1375(11.375)^4}{64(55.3 \times 10^6)} = 0.0065"$$

CHECK SIMPLY SUPPORTED PLATE:

MAX. STRESS IS AT CENTER ($h=2.75$)

$$\sigma_{\text{MAX}} = \frac{3(3+\nu)pa^2}{8h^2} = \frac{3(3+0.3)(1375)(11.375)^2}{8(2.75)^2} = 29,100 \text{ psi}$$

MAX DEFLECTION IS ALSO AT CENTER

$$W_{\text{MAX}} = \frac{(5+\nu)pa^4}{64(1+\nu)D} = \frac{(5+0.3)1375(11.375)^4}{64(1+0.3)55.3 \times 10^6} = 0.0265" \quad \leftarrow$$

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PLATE MATERIAL — HEAT TREAT 4130

$$F_u = 166,000 \text{ psi}$$

$$F_y = 149,000 \text{ psi}$$

$$F_s = 102,500 \text{ psi}$$

$$F_u (\text{ksi}) \quad 180 \quad 150 \quad 166$$

$$F_y (\text{ksi}) \quad 163 \quad 132 \quad ?$$

$$F_s (\text{ksi}) \quad 109 \quad 95 \quad ?$$

PREDICTED MAXIMUM DEFLECTION AND STRESS OF THE PLATE ARE

$$W_{MAX} = 0.0265''$$

$$\sigma_{MAX} = 29,100 \text{ psi}$$

$$M.S. = \frac{149,000}{29,100} - 1 = \underline{4.12}$$

RING SECTION PROPERTIES

ITEM	BASE	HEIGHT	AREA	X	Y	AX	AY	AX ²	I _{cy}
1	5.90	1.975	11.6525	2.95	0.9875	34.3749	11.5068	101.4060	33.8020
2	1.38	1.275	1.7595	5.21	2.6125	9.1670	4.5967	47.7601	0.2792
				13.4120		43.5419	16.1035	149.1661	34.0812

$$\bar{x} = \frac{43.5419}{13.4120} = 3.2465 \text{ IN.}$$

$$\bar{y} = \frac{16.1035}{13.4120} = 1.2007 \text{ IN.}$$

$$A\bar{x}^2 = 13.4120 (3.2465)^2 = 141.3593$$

$$I_{yy} = I_{oy} + A\bar{x}^2 - A\bar{x}^2 = 34.0812 + 149.1661 - 141.3593 = 41.8880 \text{ IN}^4$$

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RING ANALYSIS

$$P_H = 1375 \times 3.40 = 4675.0 \frac{\text{LBS}}{\text{IN}} @ R = 11.375$$

$$M_1 = 22,240.0 \frac{\text{IN-LBS}}{\text{IN}} @ R = 11.375$$

$$V_1 = 7.820.0 \frac{\text{LBS}}{\text{IN}} @ R = 11.375$$

$$V_2 = \frac{1375 \times \frac{\pi}{4} \times 22.75^2}{2\pi \times 13.625} = 6528.88 \frac{\text{LBS}}{\text{IN}} @ R = 13.625$$

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DEFLECTION EQUATIONS:

ITEM	LOAD	R	d	$\bar{R}M$	$\bar{R}H$
V_1	7820.0	11.375	1.2007	-106805.27	—
V_2	6528.88	13.625	1.0493	-93341.52	—
P_H	4675.0	11.375	0.9535	+50705.34	+53178.125
M_1	22240.0	11.375	—	-252980.00	—
M_2	M_2	13.625	—	-13.625 M_2	—
H_2	H_2	13.625	2.6535	-36.1539 H_2	-13.625 H_2
				-402421.45	

$$12.5757 M_{CG} = -402421.45 - 13.625 M_2 - 36.1539 H_2 \quad (1)$$

$$12.5757 H_{CG} = 53178.125 - 13.625 H_2 \quad (2)$$

$$\beta_{CG} = \frac{M_{CG} R^2}{EI} = \frac{(12.5757)^2}{29.0 \times 10^6 (41.888)} M_{CG} = 0.1302 \times 10^{-6} M_{CG} \quad (3)$$

$$u_{CG} = \frac{H_{CG} R^2}{EA} = \frac{(12.5757)^2}{(29 \times 10^6)(13.412)} H_{CG} = 0.4066 \times 10^{-6} H_{CG} \quad (4)$$

COAXIAL
FROM AN INJECTOR INFLUENCE COEFFICIENTS CALCULATION (SEE CASES 12.10,
12.11, & 12.12, FREE END 9-30-65 & 10-4-65 COMPUTER RUNS)

LOAD IS CONDITION	u	β
(MOMENT) $M_2 = 1.0$	-0.256×10^{-6}	$+0.1519 \times 10^{-6}$
(HORIZ. LOAD) $H_2 = 1.0$	$+0.6528 \times 10^{-6}$	-0.256×10^{-6}
PRESSURE LOAD	-0.1425×10^{-2}	$+0.9991 \times 10^{-3}$

$$u_z = u_{c.g.} + d_z \beta_{c.g.} = u_{c.g.} + 2.6535 \beta_{c.g.} \quad (5)$$

$$\beta_z = \beta_{c.g.} \quad (6)$$

INJECTOR

$$u_z = -0.256 \times 10^{-6} M_z + 0.6528 \times 10^{-6} H_z - 0.1425 \times 10^{-2} \quad (7)$$

$$\beta_z = +0.1519 \times 10^{-6} M_z - 0.256 \times 10^{-6} H_z + 0.9991 \times 10^{-3} \quad (8)$$

THE FOLLOWING IS THE SOLUTION OF THE UNKNOWN: $M_{c.g.}$, $H_{c.g.}$, M_z , H_z , β_z , u_z , $u_{c.g.}$; β_c

SUBSTITUTING EQ (1) INTO (3) AND (2) INTO (4) YIELDS

$$\beta_{c.g.} = 0.1302 \times 10^{-6} \left[\frac{1}{12.5757} (-402421.45 - 13.625 M_z - 36.1539 H_z) \right]$$

$$\beta_{c.g.} = -0.416639 \times 10^{-2} - 0.141064 \times 10^{-6} M_z - 0.374312 \times 10^{-6} H_z \quad (9)$$

$$u_{c.g.} = 0.4066 \times 10^{-6} \left[\frac{1}{12.5757} (53178.125 - 13.625 H_z) \right]$$

$$u_{c.g.} = 0.171937 \times 10^{-2} - 0.440526 \times 10^{-6} H_z \quad (10)$$

SUBSTITUTING (9) & (10) INTO (5) AND SIMPLIFYING

$$u_z = 0.171937 \times 10^{-2} - 0.440526 \times 10^{-6} H_z + 2.6535 \left[-0.416639 \times 10^{-2} - 0.141064 \times 10^{-6} M_z - 0.374312 \times 10^{-6} H_z \right]$$

$$u_z = -0.933615 \times 10^{-2} - 0.374313 \times 10^{-6} M_z - 1.433763 \times 10^{-6} H_z \quad (11)$$

EQUATING EQS. (7) & (11) YIELDS

$$+0.118313 \times 10^{-6} M_z + 2.086563 \times 10^{-6} H_z + 0.791115 \times 10^{-2} = 0 \quad (12)$$

EQUATING EQS. (8) & (9) YIELDS

$$+0.292964 \times 10^{-6} M_z + 0.118312 \times 10^{-6} H_z + 0.516549 \times 10^{-2} = 0 \quad (13)$$

SOLVING Eqs. (12) AND (13) TO OBTAIN

$$H_2 = -2,857 \frac{\text{LBS.}}{\text{IN}}$$

$$M_2 = -16,478 \frac{\text{IN-LBS.}}{\text{IN}}$$

FROM (9),

$$\beta_{CG} = \beta_2 = -0.416639 \times 10^{-2} - 0.141064 \times 10^{-6} (-16,478) - 0.374312 \times 10^{-6} (-2857)$$

$$\beta_{CG} = -0.077253 \times 10^{-2}$$

FROM (10),

$$u_{CG} = 0.171937 \times 10^{-2} - 0.440526 \times 10^{-6} (-2857) = +0.297795 \times 10^{-2}$$

FROM (5)

$$u_2 = +0.297795 \times 10^{-2} + 2.6535 (-0.077253 \times 10^{-2}) = +0.092804 \times 10^{-2}$$

FROM (4)

$$H_{CG} = \frac{+0.297795 \times 10^{-2}}{0.4066 \times 10^{-6}} = +7,324 \frac{\text{LBS.}}{\text{IN}}$$

FROM (5)

$$M_{CG} = \frac{-0.077253 \times 10^{-2}}{0.1302 \times 10^{-6}} = -5,933 \frac{\text{IN-LBS.}}{\text{IN}}$$

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SIMULTANEOUS EQUATION SOLUTION

$$M_{CG} = -5,933 \text{ IN-LBS/IN}$$

$$H_{CG} = +7,324 \text{ LBS/IN}$$

$$\beta_{CG} = -0.077253 \times 10^{-2}$$

$$u_{CG} = +0.297795 \times 10^{-2}$$

$$M_2 = -16,478 \text{ IN-LBS/IN}$$

$$H_2 = -2,857 \text{ LBS/IN}$$

$$\beta_2 = -0.077253 \times 10^{-2}$$

$$u_2 = +0.092804 \times 10^{-2}$$

NOTE: THIS SET OF VALUES IS FOR THE COAXIAL INJECTOR CASE

SECTION A-A

$$A = 1.975 \times 4.52 = 8.927 \text{ IN}^2$$

$$I_{yy} = \frac{1.975 \times 4.52^3}{12} = 15.198515 \text{ IN}^4$$

RING EQUATIONS:

$$\beta = \frac{MR^2}{EI} \quad (\text{ROTATION})$$

$$u = \frac{HR^2}{EA} \quad (\text{RADIAL DEFLECTION})$$

RESULTS FROM PAGE 10

$$\beta_{CG} = -0.077253 \times 10^{-2} \text{ RAD}$$

$$u_{CG} = +0.297795 \times 10^{-2} \text{ IN}$$

$$\Sigma M = \frac{\beta EI}{R^2} = - \frac{(-0.077253 \times 10^{-2})(27 \times 10^6)(15.198515)}{(12.3625)^2} = +2223.0 \frac{\text{IN-LBS}}{\text{IN}}$$

$$\Sigma H = \frac{uEA}{R^2} = - \frac{(0.297795 \times 10^{-2})(27 \times 10^6)(8.927)}{(12.3625)^2} = -5044.4 \frac{\text{LBS}}{\text{IN}} \quad \left. \vphantom{\Sigma H} \right\} @ R = 12.3625$$

$$\Sigma F_{\text{VERTICAL}} = 0$$

$$V_A = -P_H' - \Sigma H = - \frac{11.375}{12.3625} (2777.5) + 5044.4 = 2488.8 \frac{\text{LBS}}{\text{IN}}$$

$$\Sigma F_{\text{HORIZ.}} = 0$$

$$T_A = V_1 = \frac{11.375}{12.3625} (7820.0) = 7195.3 \frac{\text{LBS}}{\text{IN}}$$

$$\Sigma M_{CG} = 0$$

$$M_A = -(2.26) V_A - \Sigma M + \frac{11.375}{12.3625} [M_1 + V_1 (0.9875) - P_H' (1.25)] = 16,521.7 \frac{\text{IN-LBS}}{\text{IN}}$$

BENDING STRESS

$$\sigma_b = \frac{6M_A}{t^2} = \frac{6(16521.7)}{1.975^2} = 25,414 \text{ PSI}$$

$$\begin{aligned} P_H' &= 1375 \times 2.02 = 2777.5 \frac{\text{LBS}}{\text{IN}} \\ V_1 &= 7820.0 \frac{\text{LBS}}{\text{IN}} \\ M_1 &= 22,240.0 \frac{\text{IN-LBS}}{\text{IN}} \end{aligned} \quad \left. \vphantom{\begin{aligned} P_H' \\ V_1 \\ M_1 \end{aligned}} \right\} @ R = 11.375$$

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TENSILE STRESS :

$$\sigma_t = \frac{T_A}{t} = \frac{7195.3}{1.975} = 3643 \text{ psi}$$

SHEAR STRESS :

$$\sigma_s = \frac{3}{2} \frac{V_A}{t} = 1.5 \frac{2488.8}{1.975} = 1890 \text{ psi}$$

ALLOWABLE MATERIAL STRESSES :

$$F_y = 149,000 \text{ psi}$$

$$F_s = 102,500 \text{ psi}$$

$$\text{BENDING MODULUS, } F_B = 1.20 F_y = 178,800 \text{ psi}$$

MARGIN OF SAFETY :

COMBINED BENDING & TENSILE :

$$M.S. = \frac{1}{\frac{3643}{149000} + \frac{25419}{178800}} - 1 = \underline{5.01}$$

SHEAR :

$$M.S. = \frac{102,500}{1890} - 1 = \underline{\text{Exc.}}$$

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SECTION B-B

60 BOLTS AT DIAMETER 27.25" , 0.4375" BORE

$$\text{ARC LENGTH BETWEEN BOLTS} = \frac{\pi(27.25)}{60} = 1.4268 \text{ IN}$$

$$\text{SPACE BETWEEN BOLTS} = 1.4268 - 0.4375 = 0.9893 \text{ IN}$$

PERCENT OF AREA REMOVED :

$$\text{NET AREA REMOVED} = \frac{0.4375}{1.4268} = 0.3066 \approx 30\%$$

USE A $K = 1.30$ TO COMPENSATE FOR AREA REMOVED

ITEM	BASE	HEIGHT	AREA	X	Y	Ax	Ay	Ax ²	I _{cy}
1	4.52	1.975	8.927	2.26	0.9875	20.17502	8.815413	45.595545	15.198515
2	1.38	2.25	3.105	5.21	1.125	16.17705	3.493125	84.282431	0.492763
			12.032			36.35207	12.308538	129.877976	15.691278

$$\bar{X} = \frac{\sum AX}{\sum A} = \frac{36.35207}{12.032} = 3.021282$$

$$\bar{Y} = \frac{\sum AY}{\sum A} = \frac{12.308538}{12.032} = 1.022983$$

$$A\bar{X}^2 = 12.032(3.021282)^2 = 109.829841$$

$$I_{yy} = A\bar{X}^2 + I_{cy} - A\bar{X}^2 = 35.739413 \text{ IN}^4$$

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$$\begin{aligned}\Sigma M_{CG} &= \frac{\beta EI}{R^2} = - \frac{(-0.077253 \times 10^{-2})(29 \times 10^6)(35.739413)}{(12.398)^2} = +5,209 \frac{\text{IN-LBS}}{\text{IN}} \\ \Sigma H_{CG} &= \frac{UEA}{R^2} = - \frac{(40.297795 \times 10^{-2})(29 \times 10^6)(12.032)}{(12.398)^2} = -6,760 \frac{\text{LBS}}{\text{IN}}\end{aligned} \quad \left. \vphantom{\begin{aligned}\Sigma M_{CG} \\ \Sigma H_{CG}\end{aligned}} \right\} @ R = 12.398$$

$$\begin{aligned}P_H &= 4,675.0 \frac{\text{LBS}}{\text{IN}} \\ V_1 &= 7,820.0 \frac{\text{LBS}}{\text{IN}} \\ M_1 &= 22,240.0 \frac{\text{IN-LBS}}{\text{IN}}\end{aligned}$$

$$\Sigma F_{\text{VERTICAL}} = 0 = \Sigma H_{CG} + P_H + T_B$$

$$\therefore T_B = +6,760 \left(\frac{12.398}{13.625} \right) - 4,675 \left(\frac{11.375}{13.625} \right) = 2,248 \frac{\text{LBS}}{\text{IN}}$$

$$\Sigma F_{\text{HORIZ.}} = 0 = V_1 - V_B$$

$$\therefore V_B = 7,820.0 \left(\frac{11.375}{13.625} \right) = 6,529 \frac{\text{LBS}}{\text{IN}}$$

$$\Sigma M = 0 = \left[1.1787 P_H - M_1 - 1.0230 V_1 \right] \frac{11.375}{13.625} + \Sigma M_{CG} \left(\frac{12.398}{13.625} \right) + 2.1887 T_B - 1.227 V_B + M_B$$

$$0 = \left[1.1787 (4,675.0) - 22,240.0 - 1.0230 (7,820.0) \right] \frac{11.375}{13.625} + 5,209 \left(\frac{12.398}{13.625} \right) + 2.1887 (2,248) - 1.227 (6,529) + M_B$$

$$0 = -20,646 + 4,740 + 4,920 - 8,011 + M_B$$

$$M_B = 18,997 \frac{\text{IN-LBS}}{\text{IN}}$$

D. Tow

STRESSES AT SECTION B-B :BENDING STRESS

$$\sigma_b = K \frac{6M_B}{t^2} = 1.30 \left(\frac{6 \times 18997}{1.38^2} \right) = 77,807 \text{ psi}$$

TENSILE STRESS

$$\sigma_t = K \frac{T_B}{t} = 1.30 \left(\frac{2248}{1.38} \right) = 2,118 \text{ psi}$$

SHEAR STRESS

$$\sigma_s = K \frac{3}{2} \frac{V_B}{t} = 1.30 \left(\frac{3}{2} \right) \left(\frac{6529}{1.38} \right) = 9,226 \text{ psi}$$

MARGIN OF SAFETY :COMBINED BENDING & TENSILE

$$M.S. = \frac{1}{\frac{2118}{149000} + \frac{77807}{178800}} - 1 = 1.23$$

SHEAR

$$M.S. = \frac{102,500}{92} - 1 = \text{Exc.}$$

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COAXIAL INJECTOR SEAL JOINT INVESTIGATIONINTERFACE MOMENT DUE TO PROOF PRESSURE = $-16,478 \frac{\text{IN-LBS}}{\text{IN}}$ AT $R = 13.625$ PRELOAD ON BOLT

$$\frac{2}{3} F_y \text{ OF BOLT}$$

$$\text{MIN. } F_y = 168,000 \frac{\text{LBS}}{\text{IN}^2}$$

$$\text{PRELOAD } \frac{\text{LBS}}{\text{BOLT}} = \frac{2}{3} (168,000) (0.0876) = 9,811 \frac{\text{LBS}}{\text{BOLT}}$$

EJECTION LOAD ON BOLT

$$F_{\text{TOTAL}} = 1375 \times \frac{\pi}{4} \times 22.75^2 = 558,927 \text{ LBS}$$

$$F_E = \frac{558,927}{60} = 9,315 \frac{\text{LBS}}{\text{BOLT}}$$

NET LOAD ON INJECTOR FACE

$$F_I = -9811 + 9315 = -496 \frac{\text{LBS}}{\text{BOLT}}$$

RESOLVE INTERFACE MOMENT INTO A COUPLE:

$$F_M = \frac{M}{d_m} = \frac{16478 (2\pi) (13.625)}{60 (0.9935)} = 23,665 \frac{\text{LBS}}{\text{BOLT}}$$

TOTAL LOAD ON INJECTOR FACE

$$F_T = F_I + F_M = 496 + 23665 = 24161 \frac{\text{LBS}}{\text{BOLT}}$$

EFFECTIVE LENGTH OF BOLT

$$L = 1.0 + \frac{1}{3} D = 1.0 + \frac{1}{3} \left(\frac{3}{8} \right) = 1.125 \text{ IN.}$$

CHANGE IN LENGTH DUE TO F_T

$$\delta_{\text{BOLT}} = \frac{F_T L}{AE} = \frac{24161 (1.125)}{(0.0876) (29 \times 10^6)} = 0.01068 \text{ IN}$$

SEAL SEPARATION

$$\delta_{\text{SEAL}} = \frac{3.5710}{0.9935} (0.01068) = \underline{\underline{0.0384 \text{ IN.}}} \quad 130$$

$$d_m = 14.6185 - 13.625 = 0.9935 \text{ IN}$$

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PROOF AND LEAK FIXTURE INJECTOR

RING ANALYSIS (BASED ON NEW CONFIGURATION)

ITEM	BASE	HEIGHT	AREA	X	Y	AX	AY	AX ²	I _{oy}
1	5.90	2.100	12.39	2.95	1.05	36.5505	13.0095	107.82315	35.941325
2	1.505	1.15	1.73075	5.1475	2.675	8.909036	4.629756	45.859238	0.326683
14.12075				45.459536 17.639256 153.683238 36.268008					

$$\bar{X} = \frac{45.459536}{14.12075} = 3.2193 \text{ IN.}$$

$$\bar{Y} = \frac{17.639256}{14.12075} = 1.2492 \text{ IN}$$

$$A\bar{X}^2 = 14.12075 (3.2193)^2 = 146.345928$$

$$I_{yy} = I_{oy} + AX^2 - A\bar{X}^2 = 36.268008 + 153.683238 - 146.345928 = 43.605318 \text{ IN}^4$$

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DEFORMATION EQUATIONS :

ITEM	LOAD	R	d	$\bar{R}M$	$\bar{R}H$
V_1	7820.0	11.375	1.2492	-111119.46	—
V_2	6528.88	13.625	1.0008	-89027.15	—
P_H	4675.0	11.375	0.9807	+52151.79	+53178.125
M_1	22240.0	11.375	—	-252980.00	—
M_2	M_2	13.625	—	-13.025 M_2	—
H_2	H_2	13.625	2.6807	-36.5245 H_2	-13.625 H_2
				-400974.82

$$12.6242 M_{CG} = -400974.82 - 13.625 M_2 - 36.5245 H_2 \quad (1')$$

$$12.6242 H_{CG} = +53178.125 - 13.625 H_2 \quad (2')$$

$$\beta_{CG} = \frac{M_{CG} R^2}{EI} = \frac{(12.6242)^2}{29.0 \times 10^6 (43.605318)} M_{CG} = 0.1260 \times 10^{-6} M_{CG} \quad (3')$$

$$u_{CG} = \frac{H_{CG} R^2}{EA} = \frac{(12.6242)^2}{29 \times 10^6 (14.12075)} H_{CG} = 0.3892 \times 10^{-6} H_{CG} \quad (4')$$

$$u_2 = u_{CG} + d_2 \beta_{CG} = u_{CG} + 2.6807 \beta_{CG} \quad (5')$$

$$\beta_2 = \beta_{CG} \quad (6)$$

FROM COAXIAL INJECTOR INFLUENCE COEFFICIENTS :

$$u_2 = -0.256 \times 10^{-6} M_2 + 0.6528 \times 10^{-6} H_2 - 0.1425 \times 10^{-2} \quad (7)$$

$$\beta_2 = +0.1519 \times 10^{-6} M_2 - 0.256 \times 10^{-6} H_2 + 0.9991 \times 10^{-3} \quad (8)$$

SUBSTITUTING EQ. (1') INTO (3') AND EQ. (2') INTO (4') YIELDS

$$\beta_{CG} = 0.1260 \times 10^{-6} \left[\frac{1}{12.6242} (-400974.82 - 13.625 M_2 - 36.5245 H_2) \right]$$

$$\beta_{CG} = -0.400205 \times 10^{-2} - 0.135988 \times 10^{-6} M_2 - 0.364544 \times 10^{-6} H_2 \quad (9')$$

$$u_{CG} = 0.3892 \times 10^{-6} \left[\frac{1}{12.6242} (+53178.125 - 13.625 H_2) \right]$$

$$u_{CG} = 0.163946 \times 10^{-2} - 0.420053 \times 10^{-6} H_2 \quad (10')$$

SUBSTITUTING (9') AND (10') INTO (5') AND SIMPLIFYING

$$u_2 = 0.163946 \times 10^{-2} - 0.420053 \times 10^{-6} H_2 + 2.6807 \left[-0.400205 \times 10^{-2} - 0.135988 \times 10^{-6} M_2 - 0.364544 \times 10^{-6} H_2 \right]$$

$$u_2 = -0.908884 \times 10^{-2} - 0.364543 \times 10^{-6} M_2 - 1.397286 \times 10^{-6} H_2 \quad (11')$$

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EQUATING Eqs. (7) AND (11') YIELDS

$$+ 0.108543 \times 10^{-6} M_2 + 2.050086 \times 10^{-6} H_2 + 0.766384 \times 10^{-2} = 0 \quad (12')$$

EQUATING Eqs. (8) AND (9') YIELDS

$$+ 0.287888 \times 10^{-6} M_2 + 0.108544 \times 10^{-6} H_2 + 0.500115 \times 10^{-2} = 0 \quad (13')$$

SOLVING EQUATIONS (12') AND (13') TO OBTAIN

$$H_2 = -2,876 \frac{\text{LBS}}{\text{IN}}$$

$$M_2 = -16,288 \frac{\text{IN-LBS}}{\text{IN}}$$

FROM (9')

$$\beta_{CG} = \beta_2 = -0.400705 \times 10^{-2} - 0.135988 \times 10^{-6} (-16288) - 0.364544 \times 10^{-6} (-2876)$$

$$\beta_{CG} = -0.073865 \times 10^{-2}$$

FROM (10')

$$u_{CG} = 0.163946 \times 10^{-2} - 0.420053 \times 10^{-6} (-2876) = +0.284753 \times 10^{-2}$$

FROM (5')

$$u_2 = +0.284753 \times 10^{-2} + 2.6807 (-0.073865 \times 10^{-2}) = +0.086743 \times 10^{-2}$$

FROM (4')

$$H_{CG} = \frac{+0.284753 \times 10^{-2}}{0.3892 \times 10^{-6}} = +7,316 \frac{\text{LBS}}{\text{IN}}$$

FROM (3')

$$M_{CG} = \frac{-0.073865 \times 10^{-2}}{0.1260 \times 10^{-6}} = -5,862 \frac{\text{IN-LBS}}{\text{IN}}$$

COAXIAL INJECTOR SEAL JOINT INVESTIGATION

RESOLVE INTERFACE MOMENT INTO A COUPLE

$$F_M = \frac{M_z}{d_m} = \frac{16288(2\pi)(13.625)}{60(0.9935)} = 23,392 \frac{\text{LBS}}{\text{BOLT}}$$

TOTAL LOAD ON INJECTOR FACE (BASED ON $\frac{2}{3}$ F_y PRELOAD)

$$F_T = 496 + 23392 = 23,888 \frac{\text{LBS}}{\text{BOLT}}$$

CHANGE IN BOLT LENGTH

$$\delta_{\text{BOLT}} = \frac{F_T L}{AE} = \frac{23888(1.125)}{(0.0876)(29 \times 10^6)} = 0.01058 \text{ IN}$$

APPROX. SEAL SEPARATION

$$\delta_{\text{SEAL}} = \frac{3.571^\circ}{0.9935} (0.01058) = \underline{0.0380 \text{ IN}}$$

RING ANALYSIS (MULTIORIFICE INJECTOR) — NEW CONFIGURATION

THE ONLY DIFFERENCE IN THIS ANALYSIS FROM THE PREVIOUS ONE LIES IN EQUATIONS (7) AND (8) WHERE THEY ARE TAKEN FROM THE MULTIORIFICE INJECTOR INFLUENCE COEFFICIENTS CALCULATION (SEE CASES 10.00, 10.10, 10.20, FREE END, 10-8-65 COMPUTER RUNS)

LOADING CONDITION	u	β
(MOMENT) $M_2 = 1.0$	-0.615×10^{-6}	$+0.3207 \times 10^{-6}$
(HORIZ. LOAD) $H_2 = 1.0$	$+2.0297 \times 10^{-6}$	-0.616×10^{-6}
PRESSURE LOAD	-0.2981×10^{-2}	$+0.06853 \times 10^{-2}$

EQUATIONS (7) & (8) BECOME

$$u_2 = -0.615 \times 10^{-6} M_2 + 2.0297 \times 10^{-6} H_2 - 0.2981 \times 10^{-2} \quad (7')$$

$$\beta_2 = +0.3207 \times 10^{-6} M_2 - 0.616 \times 10^{-6} H_2 + 0.06853 \times 10^{-2} \quad (8')$$

EQUATING EQS (7') AND (11') YIELDS

$$+0.250457 \times 10^{-6} M_2 - 3.426986 \times 10^{-6} H_2 - 0.610784 \times 10^{-2} = 0 \quad (14)$$

EQUATING EQS. (8') AND (9') YIELDS

$$+0.456698 \times 10^{-6} M_2 - 0.251456 \times 10^{-6} H_2 + 0.468735 \times 10^{-2} = 0 \quad (15)$$

SOLVING EQS. (14) & (15) TO OBTAIN

$$H_2 = -3639 \frac{\text{LBS}}{\text{IN}}$$

$$M_2 = -11,716 \frac{\text{IN-LBS}}{\text{IN}}$$

FROM (9')

$$\beta_{CG} = \beta_z = -0.400205 \times 10^{-2} - 0.135988 \times 10^{-6} (-11,716) - 0.364544 \times 10^{-6} (-2639)$$

$$\beta_{CG} = -0.144678 \times 10^{-2}$$

FROM (10')

$$U_{CG} = 0.163946 \times 10^{-2} - 0.420053 \times 10^{-6} (-2639) = +0.274798 \times 10^{-2}$$

FROM (5')

$$U_z = +0.274798 \times 10^{-2} + 2.6807 (-0.144678 \times 10^{-2}) = -0.113040 \times 10^{-2}$$

FROM (4')

$$H_{CG} = \frac{+0.274798 \times 10^{-2}}{0.3892 \times 10^{-6}} = +7,061 \frac{\text{LBS}}{\text{IN}}$$

FROM (3')

$$M_{CG} = \frac{-0.144678 \times 10^{-2}}{0.1260 \times 10^{-6}} = -11,482 \frac{\text{IN-LBS}}{\text{IN}}$$

MULTIORIFICE INJECTOR SEAL JOINT INVESTIGATION

$$F_M = \frac{M_L}{d_m} = \frac{11716(2\pi)(13.625)}{60(.9935)} = 16,889 \frac{\text{LBS}}{\text{BOLT}}$$

TOTAL LOAD ON INJECTOR FACE (BASED ON $\frac{2}{3} F_y$ PRELOAD)

$$F_T = 496 + 16889 = 17,385 \frac{\text{LBS}}{\text{BOLT}}$$

CHANGE IN BOLT LENGTH

$$\delta_{BOLT} = \frac{F_T L}{AE} = \frac{17,385(1.125)}{(0.0876)(29 \times 10^6)} = 0.0076988 \text{ IN}$$

APPROX. SEAL SEPARATION

$$\delta_{SEAL} = \frac{3.5710}{0.9935} (0.0076988) = 0.0277 \text{ IN}$$

SUBJECT

INJECTOR FACE STRESSES

~~INJECTOR INTERFACE LOAD DISTRIBUTION~~

DATE _____

12-22-65

WORK ORDER

BY

D. Tow

CHK. BY

DATE

SECTION THROUGH 1 BOLT OF INJECTOR FACE

$$l = \text{BOLT SPACING} = \frac{\pi (27.25)}{60} = 1.427$$

$$W_1 = 14.6185 - 10.915 = 3.7035$$

$$W_3 = 0.182$$

$$W_4 = 0.750$$

$$W_c = 0.182$$

$$l_3 = l_5 = l = 1.427$$

$$l_4 = (1.427)(0.375) \frac{1}{\frac{24(11.71)}{12.9}} = 0.873$$

ITEM	W	L	A	x	Ax	Ax ²	I ₀
1	3.7035	1.427	5.284895	1.85175	9.786304	18.121788	6.040595
2	—	—	-0.150399	2.710	-0.407581	-1.104545	-0.001800
3	0.182	1.427	-0.259714	1.3665	-0.354899	-0.484969	-0.000717
4	0.750	0.873	-0.654750	0.795	-0.520526	-0.413818	-0.030691
5	0.182	1.427	-0.259714	0.2235	-0.058046	-0.012973	-0.000717
Σ	—	1.427	3.960318	—	8.445252	16.105483	6.006670

$$\bar{x} = \frac{\sum Ax}{\sum A} = \frac{8.445252}{3.960318} = 2.132468$$

$$I = \sum Ax^2 + I_0 - (\sum A) \bar{x}^2 = 16.105483 + 6.006670 - 3.960318 (2.132468)^2 = 4.102924$$

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NET LOAD ON INJECTOR FACE (P.16)

$$F_I = -496 \frac{\text{LBS}}{\text{BOLT}}$$

ASSUME THIS NET LOAD IS DISTRIBUTED OVER THE ENTIRE SECTION OF INJECTOR FACE.

$$d = 2.1325 - 1.85175 = 0.2807 \text{ IN}$$

$$C_o = 1.5710 \text{ IN}$$

$$C_i = 2.1325 \text{ IN}$$

STRESSES ON INJECTOR FACE DUE TO NET LOAD F_I

$$\sigma_{o.s.i} = \frac{F_I}{A} - \frac{F_I \times d \times C_o}{I} = \frac{-496}{3.960318} - \frac{(-496)(0.2807)(1.5710)}{4.102924} = -125 + 53$$

$$\sigma_{o.s.i} = -72 \text{ psi}$$

$$\sigma_{i.s.i} = \frac{F_I}{A} + \frac{F_I \times d \times C_i}{I} = \frac{-496}{3.960318} + \frac{(-496)(0.2807)(2.1325)}{4.102924} = -125 - 72$$

$$\sigma_{i.s.i} = -197 \text{ psi}$$

STRESSES DUE TO INTERFACE MOMENT :COAXIAL INJECTOR :

$$M_z = -16,288 \frac{\text{IN-LBS}}{\text{IN}} \quad (\text{P.20})$$

$$\sigma_{o.s.M} = \frac{M_z C_o}{I} = \frac{-16,288(2\pi)(13.625)}{60} \frac{1.5710}{4.102924} = (-23239.81)(0.382897) = -8,898 \text{ psi}$$

$$\sigma_{i.s.M} = -\frac{M_z C_i}{I} = -(-23239.81) \frac{2.1325}{4.102924} = -(-23239.81)(0.519751) = +12,079 \text{ psi}$$

MULTIORIFICE INJECTOR

$$M_z = -11,716 \frac{\text{IN-LBS}}{\text{IN}} \quad (\text{P.22})$$

$$\sigma_{o.s.M} = \frac{M_z C_o}{I} = \frac{-11,716(2\pi)(13.625)}{60} (0.382897) = -6,401 \text{ psi}$$

$$\sigma_{i.s.M} = -\frac{M_z C_i}{I} = -(-11,716.45)(0.519751) = +8,688 \text{ psi}$$

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STRESSES ON INJECTOR FACE :

$$\sigma_{o.s.} = \sigma_{o.s.I} + \sigma_{o.s.M}$$

$$\sigma_{i.s.} = \sigma_{i.s.I} + \sigma_{i.s.M}$$

COAXIAL INJECTOR

$$\sigma_{o.s.} = -72 - 8,898 = \underline{-8,970 \text{ psi}}$$

$$\sigma_{i.s.} = -197 + 12,079 = \underline{+11,882 \text{ psi}}$$

$$M.S. = \frac{36000}{11882} - 1 = \underline{2.03}$$

MULTIORIFICE INJECTOR

$$\sigma_{o.s.} = -72 - 6,401 = \underline{-6,473 \text{ psi}}$$

$$\sigma_{i.s.} = -197 + 8,688 = \underline{+8,491 \text{ psi}}$$

$$M.S. = \frac{36000}{8491} - 1 = \underline{3.24}$$

APPENDIX B

COMBUSTION STABILITY ANALYSIS OF PHOEBUS-2

INJECTOR

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I. INTRODUCTION AND SUMMARY

A high-frequency combustion stability analysis of the Phoebus-2 injector-chamber configuration was performed. The system studied was similar to the NERVA nozzle test-configuration, except that the maximum chamber-diameter was increased to 59 in. from the NERVA diameter of 36 in. The NERVA analysis and test results were used to provide a baseline for the Phoebus stability predictions. Modified NERVA injector patterns in 22- and 30-in. diameter injectors were considered in the analysis. Also investigated was the possibility of using injection distribution-control (with a coaxial-element injector) as a means of achieving stability.

II. CONCLUSIONS

The use of a small injector with a large-diameter chamber enhances the possibility of radial modes of high-frequency combustion instability. In the proposed Phoebus configuration, the injector/chamber diameter ratio is only 0.37. This particular value of the ratio also increases the possibilities of certain radial-tangential combined modes, which have frequencies likely to be amplified by the combustion process. The modes of primary interest in the Phoebus chamber are the first and second radial, the first tangential-first radial, and the second tangential-first radial. No direct data concerning possible detrimental effects of radial modes are available. However, the radial modes are similar to longitudinal modes, which can increase the wall heat-flux by a factor of two. With tangential components (as in combined modes) the heat flux increase is usually much larger.

The NERVA chamber analysis predicted that the first radial mode would be spontaneously unstable. No test records were examined. However, the tests were apparently deemed satisfactory by NERVA project personnel, although two of the tests were terminated by the combustion stability monitor (CSM). Assuming that the NERVA chamber was basically stable, it was concluded that

the additional stabilization not predicted analytically was attributable to the tapered injector-chamber adapter. A correction factor was then applied in the Phoebus analysis to account for the assumed adapter stabilization.

The Phoebus stability analysis indicated that the first and second radial modes would be unstable, and that the first tangential-first radial combined mode would be only marginally stable (for an unbaffled injector). Injection distribution control appears promising with a baffled 30-in. injector but does not offer as much improvement if a 22-in. injector is used.

III. DISCUSSION

The stability analysis of the Phoebus combustion chamber was based on the sensitive time-lag theory. Briefly, the dynamics of the combustion process are represented by two parameters: (1) the sensitive time lag, τ ; and (2) the interaction index, n . Consideration of a large number of thrust chambers has shown that the interaction index lies always between 0.6 and 0.9 and is insensitive to element design characteristics. The time lag has been found to be a function of chamber pressure, injector orifice-diameter, and, in liquid oxygen/liquid hydrogen systems, of fuel-to-oxidizer injection velocity ratio (at least for coaxial elements).

For a cylindrical combustion chamber, it is possible to calculate ranges of the parameters n and τ for which operation of the combustor will be unstable. The procedure followed in making a stability analysis is: (1) determine the regions of instability on the n, τ plane; and (2) estimate, from past experience, the n and τ values associated with the candidate injector pattern, and determine whether the n, τ point for the given injector falls within or near any of the unstable regions. It must be kept in mind that the theory as developed to date is able to treat cylindrical chambers only, and that non-linear effects can be included only semi-quantitatively.

The unstable n , τ regions for the NERVA chamber are shown in Figure B-1 as the regions above the solid curves, which have been drawn for the first and second tangential (1T, 2T) and first and second radial (1R, 2R) modes. The cylindrical chamber assumed in the analysis is shown in Figure B-2. Based on testing in 22-in. diameter chambers, the injector n , τ point was located within the shaded rectangle, and it was predicted that the NERVA chamber would be unstable in the first radial mode, unless additional stabilization was provided by the tapered adapter.

Although two tests were terminated by the combustion stability monitor (1.2-03-NNJ-002 and 1.2-07-NNJ-004), the operation of the chamber was apparently found to be satisfactory. No records were examined. At this writing, it has not been possible to review these tests. For the Phoebus chamber analysis, it has been assumed that the NERVA chamber operation was stable and that the CSM shutdowns were due to malfunctions of the monitor. As shown in Figure B-1, stability of the first radial mode requires that the n -values of the radial mode instability region boundaries be increased by a factor of two. For the present, this factor is assumed to represent the stabilizing effect of the adapter and has therefore been applied to the Phoebus chamber as well.

The chamber configuration assumed for the Phoebus analysis is shown in Figure B-3. As for the NERVA chamber, the analysis was based on a cylindrical chamber and corrected for the conical adapter. Computer program 8050 was used to establish the curves that bound the instability regions. This program includes the effects of the exhaust nozzle and of the actual injection distribution (referred to the maximum chamber diameter). Figure B-4 shows the unstable regions for the 22-in. injector. Even with the correction for the tapered adapter, the analysis predicts radial mode instability for the modified NERVA pattern, which has essentially a flat injection-distribution. The use of a 30-in. injector would improve the stability (as shown in Figure B-5) but the chamber remains only marginally stable.

Figure B-1 - Instability Zones, NERVA Configuration,
22-in. Diameter Injector

Figure B-2 - Analytical NERVA Configuration

Figure B-3 - Analytical Phoebus Configuration

Figure B-4 - Instability Zones, Phoebus Configuration,
22-in. Diameter Injector

Figure B-5 - Instability Zones, Phoebus Configuration,
30-in. Diameter Injector

Two means of improving the stability are available: (1) injection-distribution control; and (2) baffles. The effect of a nonuniform injection density (lb/sec-in.²) can be expressed by the following equation:

$$n(\tau) = \frac{n_{\text{unif}}(\tau)}{A},$$

where $n(\tau)$ is the ordinate of the instability-zone boundary on the n, τ plane, n_{unif} is the value for the case of a uniform injection-distribution, and A is a coefficient that depends on the injection density-distribution and the mode of instability.

If $A > 1$, the instability zone lies below that for uniform injection ($A = 1$): hence increasing A is an unstabilizing tendency. Figure B-6 shows curves of A for injection concentrated at a single diameter. For an actual distribution, the value of A is essentially a weighted average of the values shown. The horizontal dashed line in Figure B-6 represents the largest value of A consistent with stability of the 22-in. injector. It is clear that such stability cannot be achieved by injection control. For the 30-in. injector, the A required is larger, and stabilization of the radial modes can be achieved.

In any case, Figure B-6 indicates that the injection distribution requirements for the radial and radial-tangential modes are generally in conflict. Therefore, it appears that a baffle of some sort will be required. Two effects are produced by baffles: (1) the transverse gas-velocity patterns associated with high-frequency acoustic modes are disrupted in the critical region near the injector face; and (2) the acoustic energy in the transverse-wave motion is scattered and dissipated. To stabilize tangential modes, radial blades are required, sufficient in number to produce pockets that are too small to be compatible with any likely mode. For radial modes, cylindrical hubs should be used, although there is practically no experience with radial modes reported in the literature. For the Phoebus configuration, seven radial blades should be adequate. In addition, a cylindrical hub appears to

Figure B-6 - Distribution Coefficient for Radially Concentrated Injection (All Injection at Diameter, D_i)

be necessary to block the radial modes. This hub should be about 19 in. in diameter. Experience indicates that a baffle length of about 3 in. should be adequate.

A more versatile injector pattern for the liquid oxygen/liquid hydrogen propellant combination comprises coaxial elements in a "rigimesh" transpiration-cooled face. Testing at NASA-LeRC, as well as at Aerojet-General, indicates that the combustion dynamic behavior of such an injector is a function of the size of the element and the fuel-to-oxidizer injection velocity ratio. Increasing either the size of the element or the velocity ratio (no matter by what means) appears to increase the sensitive time lag, which is generally a stabilizing trend. For the Phoebus injector, elements that deliver 1000 lb each are most reasonable. A velocity ratio between 6 and 10 should put the operating point of the coaxial injector in the right half of the shaded rectangle of Figures B-4 and B-5. An optimum injector pattern would also have an injection distribution that reaches a maximum value at a diameter of about 18 in., as shown in Figure B-6.

Finally, it should be noted that the conclusions and recommendations resulting from this analysis are dependent on the assumed correction for the injector-adapter shape. For a definitive stability analysis, this shape effect must be taken into account quantitatively. A theoretical approach, involving a coordinate transformation, appears promising, and should be pursued. In addition, acoustical testing of models of cylindrical and tapered chambers can yield significant information about the stabilizing effects of chamber shape. The techniques are well developed: a study of influence of the adapter taper and injector recess on resonant frequencies and damping rates can be accomplished.

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APPENDIX C

FINAL DESIGN REVIEW PHOEBUS COAXIAL INJECTOR
P/N 1115321

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I. INTRODUCTION

This report of the final design review of coaxial injector assembly, P/N 1115321, is submitted to comply with Phoebus-2 design review system requirements outlined in Report No. RP-TR-0003, Phoebus-2 Nozzle Reliability Program Plan.

II. DISCUSSION

The following presentations were made:

A. DESIGN ENGINEER

The following action items had been assigned at the intermediate design review 1 October 1965:

1. Determine the degree of separation at the dome joint with no thrust transmitted through the injector.
2. Analyze the injector/adaptor joint separation considering no thrust take-out at the injector.
3. Analyze the Rigimesh face/plate joint for thermal stress.
4. Analyze the element swage joint.
5. Determine the capability of the injector to support the cantilevered TCA during start transients.

The above action items were assigned to the Stress Department.

6. Investigate the feasibility of X-ray inspection of the Rigimesh face-plate welds. This action item was assigned to the Reliability and Quality Assurance Department.

The results of these action items at the time of the design review meeting were:

1. Stress calculations indicated a maximum separation of 0.0013-inch at the seal surface when there is no thrust take-off from the injector. The allowable seal tolerance is 0.015 inch. Thus, the injector dome seal joint is adequate.

2. The analysis of the coaxial injector/adapter joint separation was not complete at the time of the meeting.

3. Preliminary analysis of thermal stresses in the Rigimesh face/plate joint indicated a maximum stress of 147,200 psi versus an allowable stress of 86,400 psi. The stress area is being analyzed by more refined techniques. This type of joint has performed well in similar environments in similar designs. This action item was not complete at the time of the meeting.

4. Stress analysis of the element/Rigimesh plate swage joint indicated a maximum stress of 516 pounds force per joint versus a calculated ultimate joint strength of 1100 pounds force. Thus, the joint design is adequate.

5. The Reliability and Quality Assurance Department made a radiographic study and found that a radiograph of Rigimesh plate shows a fabric-like image of short lines. This image, superimposed on the majority of the weld image, would mask small weld-defects and reduce the overall sensitivity of the radiographic technique. Gross defects would still be

detectable, but small cracks, elongated porosity (a likely defect in welds of this material), and incomplete fusion would probably be masked. The Rigimesh plate has a structural margin of safety of 7.4 and several holes will be drilled through the weld to permit visual inspection of the internal weld. The conclusion of the study was that visual inspection would be adequate and that X-ray inspection would not significantly aid in evaluating the weld quality.

The function of the injector is to combine the fuel and oxidizer in the proper proportion to produce stable combustion at 750 psia chamber pressure, a total propellant flow of 741 pounds per second, and a mixture ratio of 5.5. The design criteria are presented in Table C-1.

The position of the injector in the test assembly is shown in Figure C-1. Figure C-2 is a cutaway of the injector assembly. Figure C-3 shows the oxidizer and fuel circuits. Figure C-4 indicates details of the injector element. Figure C-5 shows an igniter in place. Figure C-6 shows the angular location of the four igniters and the temperature and pressure instrumentation bosses. Figure C-7 indicates the location of the potential baffle when used.

The design is based on performance, reliability, and producibility. Problems resolved were combustion stability, absence of face-plate burnout, seal integrity, and structural adequacy. These problems, or potential modes-of-failure, have been outlined in the modes-of-failure-analysis as Structural, Face Plate Burnout, and Seal Leakage. The design includes the preventive factors and design features outlined in the modes-of-failure analysis.

The injector consists of 242 propellant elements arranged in seven concentric circles. The elements consist of an oxidizer tube surrounded by a concentric fuel annulus. The injector face-plate is pervious for fuel film-cooling. The oxidizer velocity is 62 fps and the fuel velocity is 898 fps. Oxidizer tubes are recessed 0.200 into the face plate. To stabilize combustion, the fuel/oxidizer velocity ratio is 15. The thrust per element is approximately 1200 pounds force.

TABLE C-1

COAXIAL INJECTOR DESIGN PARAMETERS

$\dot{W}_f = 114 \text{ lb/sec}$	$T_f = 90^\circ\text{R}$
$\dot{W}_o = 627 \text{ lb/sec}$	$T_o = 180^\circ\text{R}$
$MR = 5.5$	$\gamma_f = 2.35 \text{ lb/ft}^3$
$P_c = 750 \text{ psia}$	$\gamma_o = 68.5 \text{ lb/ft}^3$
$\dot{W}/\text{Element} = 3 \text{ lb}$	$\Delta P_f = 300 \text{ psi (elements \& manifolds)}$
$V_f/V_o = 15$	$\Delta P_o = 215 \text{ psi (elements \& manifolds)}$

Figure C-1 - Coaxial Injector Test Assembly

Figure C-2 - Coaxial Injector

Figure C-3 - Coaxial Injector Propellant Circuits

Figure C-4 - Injector Element Assembly

Figure C-5 - Coaxial Injector Igniter Installation

Figure C-6 - Coaxial Injector - Instrumentation

Figure C-7 - Location of Baffle

Combustion studies indicate that if unstable burning did occur, the probable mode would be radial and could be suppressed by a cylindrical baffle. While unstable combustion is not expected, a film-cooled cylindrical baffle will be designed for installation in the second unit (See Figure C-7).

Seal integrity is involved in the oxidizer dome/injector plate interface and in the injector/adaptor interface. The joint stress is now greater since it is planned to take-out the thrust from the adaptor support instead of the injector.

The seals between the elements and the plate are made by flowing braze metals into the threads between the fuel element and the plate, and by welding the oxidizer element to the plate.

B. STRUCTURAL ENGINEER

Stress studies were based on the following parameters:

1. Material Properties at Ambient Temperature

a. CRES 347 Steel Cond A - per QQ-S-766

$$F_{tu} - 75,000 \text{ psi}$$

$$F_{ty} - 30,000 \text{ psi}$$

$$F_{by} - 1.2 F_{ty} - 36,000 \text{ psi}$$

$$F_{sy} - 0.55 F_{ty} - 16,500 \text{ psi}$$

b. Rigimesh

$$F_{ty} - 0.8 \times 30,000 - 24,000 \text{ psi}$$

c. Center Bolt Material

A-286, Cold Hard Rolled Steel, AMS-5753

F_{tu} - 220,000 psi

F_{ty} - 180,000 psi

d. Plate Stud Material

KNS - 624S-18 (Keensert)

CRES 303 (Mil-S-7720 Cond B)

F_{tu} - 125,000

F_{ty} - 100,000

e. Protective Cover Plate Material

Aluminum Alloy 6061 T6 per QQ-A-327

2. Loads

a. Chamber Pressure - 900 psia

b. Engine Thrust - 330,000 pound force

c. Load Factor for Pressure Vessel, Nozzle, Shield and Thrust Structure - 1.25

d. Load Factor for Pressure Loads - 1.15

3. Results

Dynamic stresses were not included in the study. The results of stress analysis of the major structural components were:

<u>Component</u>	<u>Margin of Safety</u>	<u>Comments</u>
Injector Plate		To be re-analyzed
Rigimesh Plate	7.39	
Conical Shell	0.21	
LOX Inlet Manifold		To be completed
Center Bolt	0.58	
Plate Studs (No Thrust Transmitted)		To be calculated
Dome/Plate Interface Seal Separation	Max. Separation - 0.0013 Allowable separation - 0.015	
Injector/Adapter Interface Seal Separation		To be calculated
Rigimesh Face/Plate Joint Under Thermal Stress		Being studied

C. RELIABILITY AND QUALITY ASSURANCE ENGINEER

The modes-of-failure analysis had been previously distributed to members of the board. It was accepted with an action item requesting that the proposed cylindrical baffle be included in the preventive design features for the second-article injector.

The reliability design review check lists had been circulated and signed by the appropriate engineer prior to the meeting. This document indicated that, in addition to the designers, the technical specialists representing fabrication, materials, stress, and reliability and quality assurance had reviewed and accepted the design.

1. Verification of Interfaces

The following interfaces were verified by review of component drawings:

a. Injector/adaptor flange, as shown in injector drawings, 1115314-NC, 1115084A, and adaptor drawings, 1115173B, 1115468D.

b. Oxidizer inlet flange/oxidizer line as shown in injector drawing 1115315B and oxidizer line drawing 1115499-27A.

2. Final Design Review and Documentation Check List

The Final Design Review and Documentation Check List is a check list of documents required for final acceptance of the design. The purpose is to document the fact that all support groups have completed their work and that documentation is complete.

III. SUMMARY

A. ASSIGNED ACTION ITEMS

1. Determination of lockwire requirements (assigned to the design engineer).

2. Resolve where the flow is to be monitored (assigned to the design engineer).

3. Complete the stress analysis of the liquid oxygen inlet torus with the latest pressure schedule and the torus moment and loads resulting from the thermal contraction of the feed lines (assigned to the Stress Department).

4. Re-analyze the injector plate using the perforated plate theory (assigned to the Stress Department).

5. Add a cylindrical baffle, to be fabricated on the second unit, as an additional preventive design feature in regard to unstable combustion (assigned to the Reliability and Quality Assurance Department).

6. Complete the analysis of the injector/adapter joint separation with no thrust take-off from the injector (assigned to the Stress Department).

7. Complete the thermal stress analysis of the Rigimesh face/plate joint (assigned to the Stress Department).

8. Complete the stress analysis of the dome/plate studs (assigned to the Stress Department).

The board agreed to accept the design unless problems were encountered in completing action items and the Documentation Check List.

IV. WORK PERFORMED SUBSEQUENT TO THE FINAL DESIGN REVIEW

A. STRESS-ANALYSIS ACTION ITEMS COMPLETED

1. Analyze the injector/adapter joint separation considering no thrust take-out at the injector.

The injector/adapter interface seal separation for the coaxial injector was calculated to be 0.0128-inch at a 900 psi chamber pressure. Using the same method of analysis, the separation of the injector flange when coupled to the hydro-tool was 0.033 at the proof pressure of 1175 psi. The coaxial injector was proof tested with this hydro-tool without seal leakage; therefore, it was concluded that the method of analysis was very conservative. The design of the injector/adapter interface was considered adequate.

2. Re-analyze the Rigimesh face/plate weld joint under thermal and pressure stresses.

The revised calculations, based on realistic Rigimesh properties, resulted in a margin of safety of 0.55.

3. Re-analyze the injector plate using the perforated plate theory.

The resulting margin of safety was 0.15; thus completing the action item.

4. Complete the stress analysis of the liquid oxygen inlet torus moment resulting from thermal contraction of the feed lines.

The minimum margin of safety in the liquid oxygen inlet torus was calculated to be 0.56. This completes the action item.

5. Complete the stress analysis of the dome/plate studs.

Completion of the stress analysis of the KNS 624 S-18 studs resulted in a margin of safety of 0.05 at 900 psi chamber pressure. Torque and pull tests were conducted, demonstrating that a 9,000 pound stud load produced a 0.007 elongation. The stud load at 900 psi is 8,370 pounds force. The allowable elongation is 0.015. During the subsequent proof test at 1175 psi, the stud elongated to 0.008 and returned to the original dimension. This proof test is adequate for the hot firing at 750 psi chamber pressure. This injector will be restricted to 750 psi chamber pressure until the higher strength studs, KNS 624-MX-18 (160-180 KSI FTU), are substituted. These studs are being installed on the second injector. The margin of safety using the higher strength studs at 900 psi chamber pressure is 0.31. This completes the action item.

B. OTHER ACTION ITEMS COMPLETED

1. Determination of Lockwire Requirements

The question arose as to whether the igniter would be lock-wired in place upon assembly. The history of the igniters was reviewed and no past use of lockwire was found. There was no reported leakage due to igniters loosening; therefore, it was concluded that lockwire was not needed.

2. Resolve Where the Flow is to be Monitored

Test assembly drawings have been prepared showing instrumentation locations (See Figure C-6).

3. Cylindrical Baffle Addition to the Modes-of-Failure Analysis

Completed.

V. FINAL ACCEPTANCE OF COAXIAL INJECTOR DESIGN

The design review board accepted the design.

RELIABILITY DESIGN REVIEW CHECK LIST

Part/Assembly Title: Injector Coaxial

Date: November 12, 1965

Reliability Engineer: C. H. Hughes

Verification of adequate consideration of reliability factors is indicated by signature verification of cognizant responsibility. Reasons for noncompliance are to be noted in the space provided.

Item	Description	Signature Verification	Remarks
<u>I. Design Responsibility</u>			
1. Performance Requirements	Performance requirements are defined, complete, and documented. List documents: Test Plan RP-TR-0005	<u>M.H. Smoot</u>	
2. Environmental Requirements	Operational environmental requirements are defined, complete, and documented. List documents:	<u>M.H. Smoot</u>	Not applicable None Required
3. Alternative Designs	Alternative designs have been investigated.	<u>M.H. Smoot</u>	
4. Safety Hazards	Potential safety hazards have been identified and means can be provided to assure adequate personnel safety during manufacture, inspection, test, handling, maintenance, shipping, and use.	<u>M.H. Smoot</u>	Positive margin of safety

Item	Description	Signature Verification	Remarks
5. Interface Requirements	The design is compatible with all system functional and physical interfaces.	<u>C. J. Casady</u>	
6. Test Program	A test program has been devised which investigates necessary parameters.	<u>C. J. Casady</u>	
7. Instrumentation	a. Instrument measurements have been defined. b. Fittings, bosses, etc., have been provided for test instrumentation.	<u>C. J. Casady</u> <u>C. J. Casady</u>	
8. Operational Effects	Operational effects of storage, use, shipping, mission, maintenance, and wear have been considered.	<u>M. H. Smoot</u>	
9. Simplification	The design has been reviewed with respect to the minimum number of parts, standardization of parts, fabrication, assembly/disassembly operations, and functions necessary for effective operation.	<u>M. H. Smoot</u>	
10. Packaging	Mountings, encasements, etc., are utilized for minimum degradation from shock, vibration, friction, moisture, or temperature effects in shipping, storage, or use.	<u>M. H. Smoot</u>	
11. Maintainability	The design has been reviewed to provide for ease of inspection and replaceability for restoration to operational effectiveness with minimum down time.	<u>M. H. Smoot</u>	
12. Classification of Characteristics	Classification of characteristics has been incorporated into design drawing per MIL-W-9411.	<u>M. H. Smoot</u>	

Item	Description	Signature Verification	Remarks
II. <u>Fabrication Responsibility</u>			
1. Manufacturing and Inspection Variability	Allowed fabrication variability in dimensions, composition, and processing is not expected to degrade reliability.	<u>R. Downey</u>	
2. Tolerances	Maximum and minimum tolerance stack-ups are not expected to interfere with fabrication, assembly, and shipping of the article represented by the drawing being reviewed.	<u>R. Downey</u>	
3. Cleanliness and Corrosion	The design is conducive to the maintenance of cleanliness and corrosion resistance.	<u>R. Downey</u>	
III. <u>Materials Responsibility</u>			
1. Material Properties	Material properties are compatible with the application.	<u>X. F. Glasco</u>	
2. Specifications	Material and process specifications are properly specified on the drawing.	<u>X. F. Glasco</u>	
IV. <u>Stress Responsibility</u>			
1. Design Specification Requirements	Evidence or analysis has been completed to show that the design is capable of meeting all requirements of Test Plan RP-TR-0005	<u>Ed Kautt</u>	Pressure Analysis completed. Thermal Stress Analysis not complete.
2. Safety Margins	Safety margins are all positive	<u>Ed Kautt</u>	

Item	Description	Signature Verification	Remarks
V. <u>Reliability Responsibility</u>			
1. Reliability Requirements	Reliability acceptance and non-destructive test requirements have been established for fabrication. List documents: AGC-STD-3010A, Standard, Inspection Penetrant AGC-36163A, Metals, Ultrasonic Inspection
2. Modes of Failure Analysis	A reliability analysis, including review of available failure histories of similar designs, has been performed to determine probable modes of failure, causes, effects, and the results have been taken into design consideration.
3. Modes of Failure Control	Design controls have been established to eliminate or minimize occurrence of modes of failure caused during fabrication and testing.
4. Traceability and Serialization	Items which require traceability, lot control, and serialization have been identified.

COAXIAL INJECTOR P/N 1115321

FINAL DESIGN REVIEW AND DOCUMENTATION CHECK LIST

This form is to be completed by the Design and Development Manager and verified by Reliability and Quality Assurance Engineer. Upon completion, file in Master Design Documentation File.

<u>ITEM</u>	<u>COMPLETED</u> (Enter completed or N/A)	<u>REMARKS</u>
1. Design Criteria	<u>completed</u>	<u></u>
2. Coordinate Design Requirements with:		
a. Heat Transfer Engineering	<u>completed</u>	<u></u>
b. Manufacturing Engineering	<u>completed</u>	<u></u>
c. Materials Engineering	<u>completed</u>	<u></u>
d. Nuclear Analysis	<u>N/A</u>	<u></u>
e. Other	<u>N/A</u>	<u></u>
f. Reliability	<u>completed</u>	<u></u>
g. Structures Engineering	<u>completed</u>	<u></u>
3. Check completion of all action items from design reviews	<u>completed</u>	<u></u>
4. Completion of Required Check Lists	<u>completed</u>	<u></u>
5. Completion of Design File Data - Input of data to Design File:		
a. Layout Prints	<u>completed</u>	<u>1115474</u>
b. Functional & Stress Computation	<u>completed</u>	<u></u>
c. Design Computations	<u>completed</u>	<u></u>
d. Design Review Meeting Reports	<u>completed</u>	<u></u>
6. Drawing Released	<u>completed</u>	<u>Released 11-1-65</u>
Date: <u>3-16-66</u> <u>[Signature]</u> Manager Nozzle Design and Development Dept. Phoebus Division	Date: <u>3/16/66</u> <u>[Signature]</u> Reliability and Quality Assurance Eng. Phoebus Division	

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APPENDIX D

MODES-OF-FAILURE ANALYSIS
PHOEBUS COAXIAL INJECTOR

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PHOEBUS 2 - MODES OF FAILURE ANALYSIS

NAME <u>INJECTOR</u> <u>CO-AXIAL</u>		FUNCTION: METERS PROPELLANT, TRANSMITS THRUST, PROVIDES CLOSURE FOR COMBUSTION CHAMBER		PREPARED BY <u>M. H. Smoot and</u> <u>R. J. Flynn</u>	
DRAWING NO. <u>1115321</u>				PAGE <u>2</u> OF <u>4</u> DATE <u>11-8-65</u>	
MODE OF FAILURE	EFFECTS ON SYSTEM	CAUSE OF FAILURE	PREVENTIVE FACTORS & DESIGN FEATURES	REMARKS	
I.B Braze 1. Element to plate	I.B Loss of element resulting in inter-propellant mixing resulting in possible burning or detonation within injector.	I.B Poor quality braze caused by contamination of joints, design or temperature cycle.	I.B The braze joint design and process are based upon conservative and proven cases developed in the M-1 Program. Samples have been brazed successfully at Pyromet. The threaded joint at the element to plate was designed to provide maximum surface to braze while minimizing the shear load on the brazed joint. The threads extend through the plate so that the braze fillet can be inspected from both sides. Threads joining fuel element and face plate are a redundant feature precluding loss of element in case of braze failure. Final check for joint integrity is made with a leak test using air under water.		
I.C Fasteners 1. Stud assemblies which attach the dome to the plate.	I.C.1 Separation of the dome/injector flange resulting in external oxidizer leakage.	I.C.1 Yielding of the fasteners.	I.C.1 The dome and plate have been designed to minimize flange deflection by including attachment at the center and by making the dome and plate stiff enough to stay within the allowable flange deflection. The fasteners are fabricated of high strength material adequate to withstand hydro-proof testing with a positive margin of safety.		
2. Center bolt	I.C.2 Oxidizer leakage at dome to plate joint if excessive yielding of center bolt occurs.	I.C.2 Yielding of center bolt.	I.C.2 The center bolt has a MS = 0.58		
I.D Face plate/element joint	I.D Deformation or loss of face plate resulting in maldistribution of fuel.	I.D Failure of the swaged joint caused by high ($P_f - P_c$) differential.	I.D The joint was designed for a ΔP of more than 300 psi. The swaging process was developed on the M-1 Program.		

PHOEBUS 2 - MODES OF FAILURE ANALYSIS

NAME <u>INJECTOR</u> <u>CO-AXIAL</u>		FUNCTION : METERS PROPELLANT, TRANSMITS THRUST, PROVIDES CLOSURE FOR COMBUSTION CHAMBER		PREPARED BY <u>M.H.Smoot & R.J.Flynn</u> PAGE <u>1</u> OF <u>4</u> DATE <u>11-8-65</u>	
DRAWING NO. <u>1115321</u>					
MODE OF FAILURE	EFFECTS ON SYSTEM	CAUSE OF FAILURE	PREVENTIVE FACTORS & DESIGN FEATURES	REMARKS	
I. Structural A. Welds 1.Oxidizer torus 2.Oxidizer dome 3.Face Plate 4.Element 5.Bosses	I.A.1 & I.A.2 External oxidizer leakage. Loss of pressure and reduction in oxidizer weight flow rate through injector resulting in drop in Pc and reduction in propellant mixture ratio. I.A.3 Fuel leakage from the fuel plenum to the combustion chamber resulting in mal-distribution of fuel and local low mixture ratio. Refer to Section II. I.A.4 Interpropellant leakage between the dome cavity and the fuel annulus of the element resulting in possible burning or detonation within the element. I.A.5 External propellant leakage and possible erroneous performance measurements.	I.A Poor quality welds such as cold laps, porosity, undercutting, cracks, incomplete penetration and incomplete fusion.	I.A The weld preparations are conservative proven designs based upon recommendations of specialists in stress, welding and fabrication. The weld procedures are reviewed by welding fabrication specialists and Quality Control. Welding is per AGC 46351 by certified welders using automatic equipment whenever possible. The root passes and cover passes of the dome and torus weld are dye penetrant inspected per AGC-STD-3010. The RIGIMESH welds are visually inspected and the completed element and boss welds are penetrant inspected. The injector assembly is subjected to a high pressure proof and a leak test.		

PHOEBUS 2 - MODES OF FAILURE ANALYSIS

NAME <u>INJECTOR</u> <u>CO-AXIAL</u>		FUNCTION : METERS PROPELLANT, TRANSMITS THRUST, PROVIDES CLOSURE FOR COMBUSTION CHAMBER		PREPARED BY <u>M.H.Smoot & R.J.Flynn</u> PAGE <u>1</u> OF <u>4</u> DATE <u>11-8-65</u>	
DRAWING NO. <u>1115321</u>					
MODE OF FAILURE	EFFECTS ON SYSTEM	CAUSE OF FAILURE	PREVENTIVE FACTORS & DESIGN FEATURES	REMARKS	
I. Structural A. Welds 1.Oxidizer torus 2.Oxidizer dome 3.Face Plate 4.Element 5.Bosses	I.A.1 & I.A.2 External oxidizer leakage. Loss of pressure and reduction in oxidizer weight flow rate through injector resulting in drop in Pc and reduction in propellant mixture ratio. I.A.3 Fuel leakage from the fuel plenum to the combustion chamber resulting in mal-distribution of fuel and local low mixture ratio. Refer to Section II. I.A.4 Interpropellant leakage between the dome cavity and the fuel annulus of the element resulting in possible burning or detonation within the element. I.A.5 External propellant leakage and possible erroneous performance measurements.	I.A Poor quality welds such as cold laps, porosity, undercutting, cracks, incomplete penetration and incomplete fusion.	I.A The weld preparations are conservative proven designs based upon recommendations of specialists in stress, welding and fabrication. The weld procedures are reviewed by welding fabrication specialists and Quality Control. Welding is per AGC 46351 by certified welders using automatic equipment whenever possible. The root passes and cover passes of the dome and torus weld are dye penetrant inspected per AGC-STD-3010. The RIGIMESH welds are visually inspected and the completed element and boss welds are penetrant inspected. The injector assembly is subjected to a high pressure proof and a leak test.		

PHOEBUS 2 - MODES OF FAILURE ANALYSIS

NAME <u>INJECTOR</u> <u>CO-AXIAL</u>		FUNCTION : METERS PROPELLANT, TRANSMITS THRUST, PROVIDES CLOSURE FOR COMBUSTION CHAMBER		PREPARED BY <u>M. H. Smoot And</u> <u>R. J. Flynn</u>	
DRAWING NO. <u>1115321</u>				PAGE <u>2</u> OF <u>4</u> DATE <u>11-8-65</u>	
MODE OF FAILURE	EFFECTS ON SYSTEM	CAUSE OF FAILURE	PREVENTIVE FACTORS & DESIGN FEATURES	REMARKS	
I.B Braze 1. Element to plate	I.B Loss of element resulting in inter-propellant mixing resulting in possible burning or detonation within injector.	I.B Poor quality braze caused by contamination of joints, design or temperature cycle.	I.B The braze joint design and process are based upon conservative and proven cases developed in the M-1 Program. Samples have been brazed successfully at Pyromet. The threaded joint at the element to plate was designed to provide maximum surface to braze while minimizing the shear load on the brazed joint. The threads extend through the plate, so that the braze fillet can be inspected from both sides. Threads joining fuel element and face plate are a redundant feature precluding loss of element in case of braze failure. Final check for joint integrity is made with a leak test using air under water.		
I.C Fasteners 1. Stud assemblies which attach the dome to the plate.	I.C.1 Separation of the dome/injector flange resulting in external oxidizer leakage.	I.C.1 Yielding of the fasteners.	I.C.1 The dome and plate have been designed to minimize flange deflection by including attachment at the center and by making the dome and plate stiff enough to stay within the allowable flange deflection. The fasteners are fabricated of high strength material adequate to withstand hydro-proof testing with a positive margin of safety.		
2. Center bolt	I.C.2 Oxidizer leakage at dome to plate joint if excessive yielding of center bolt occurs.	I.C.2 Yielding of center bolt.	I.C.2 The center bolt has a MS = 0.58		
I.D Face plate/element joint	I.D Deformation or loss of face plate resulting in maldistribution of fuel.	I.D Failure of the swaged joint caused by high ($P_f - P_c$) differential.	I.D The joint was designed for a ΔP of more than 300 psi. The swaging process was developed on the M-1 Program.	I.D Pull tests have been conducted on the M-1 Program with element joints similar to the Phoebus-2 element proving adequacy of the joint.	

PHOEBUS 2 - MODES OF FAILURE ANALYSIS

NAME <u>INJECTOR</u> <u>CO-AXIAL</u>		FUNCTION : METERS PROPELLANT, TRANSMITS THRUST, PROVIDES CLOSURE FOR COMBUSTION CHAMBER		PREPARED BY <u>M.H.Smoot and R.J.Flynn</u>	
DRAWING NO. <u>1115321</u>				PAGE <u>3</u> OF <u>4</u> DATE <u>11-8-65</u>	
MODE OF FAILURE	EFFECTS ON SYSTEM	CAUSE OF FAILURE	PREVENTIVE FACTORS & DESIGN FEATURES	REMARKS	
I. Structural (con't) I.E Injector Assembly 1.Ring Forging 2.Dome forging 3.Plate,pipe or sheet a.torus b.rigimesh c.injector plate II. Face Plate Burnout	I.E.1., I.E.2 and I.E.3.a same as I.A.1 above I.E.3.b. same as I.A.3 above I.E.3.c. Interpropellant leakage resulting in possible burning or detonation within injector. II. Maldistribution of propellant resulting in more severe face plate burnout.	I.E Heat pressure, vibration, thermal gradient loads or defective material. II.A Contamination of RIGIMESH face plate causing reduction in fuel cooling flow. II.B Plugging of fuel orifices by metal chips or other foreign material.	I.E.1 All materials except the RIGIMESH are procured per AGC, material standard or federal government specification. I.E.2. A fluid pressure and thrust stress analysis based on $P \pm 900$ psi, $P_p = 1200$ psi $P_o = 1350$ psi, Max $^c P$ across injector plate = 300 psi and Max P across rigimesh = 300 psi gives positive margins of safety for the components of the injector. I.E.3 Machined forgings of the dome and ring are ultrasonic inspected per AGC 36163, Class I and penetrant inspected per AGC-STD-3010. I.E.4 Assembly is hydrotested at 1375 psi. II. The face plate material is RIGIMESH which has a controlled hydrogen coolant permability and is therefore resistant to burnout. II.A Fabrication process is controlled by drawing notes which specify that the RIGIMESH must be machined without the use of cutting oils, dye penetrant, and other contaminants. The hydro specification specifies that all fluids used in hydro-testing, flushing and flowing the injector must be filtered to 125 micron or better. II.B The injector is flushed and back-flushed to remove chips and foreign matter. A pattern check will be performed to visually check the flow pattern of the orifices.	I.E. Heat transfer and stress analysis are in process and will be completed in December 1965, no problems are anticipated in these areas.	

PHOEBUS 2 - MODES OF FAILURE ANALYSIS

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DRAWING NO. <u>1115321</u>				PAGE <u>4</u> OF <u>4</u> DATE <u>11-8-65</u>	
MODE OF FAILURE	EFFECTS ON SYSTEM	CAUSE OF FAILURE	PREVENTIVE FACTORS & DESIGN FEATURES	REMARKS	
II. Face Plate Burnout (con't)		II.C Gross recirculation of hot gas 1. Too low element propellant exit velocity. 2. Non-homogeneous mixture ratio across injector face. 3. Poor mixing of fuel and oxidizer.	II.C.1 The elements are designed to give a high velocity at the face thus a high axial gas momentum which will resist recirculation. II.C.2 The injector pattern is designed to have an equal distribution of propellant weight flow across the face, therefore the probability of radial recirculation is minimized. II.C.3 Industry experience has shown that good propellant mixing occurs with no face plate burnout at V_f/V_o of 5. $V_f/V_o = 15$ for this design. III. Joints are leak tested.		
III. Seal Leakage A. Dome to plate B. Center bolt	III. A & B External Oxidizer leakage	III.A. Damaged or contaminated seal or sealing surface. III.B. Improper torque III.C. Lateral movement of joint.	III.A Sealing surfaces are protected during fabrication and seals remain packaged until installation. III.B Torque limits are specified on drawing and were determined based on expected separation loads. III.C. 60 studs and center bolt minimize the probability of lateral movement of dome to plate or center bolt joint.		

APPENDIX E

BASIC PARTS LIST
COAXIAL INJECTOR ASSEMBLY

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BASIC PARTS LIST							DRAWING NO. 1115321-19					
							SHEET 1	OF 2				
LET.	DATE	REVISION	BY	CK.D	TITLE CO-AXIAL INJECTOR ASSEMBLY WITH BAFFLE RING
					AEROJET-GENERAL CORPORATION 2700 J. FAD 3/3/66				DRAWN L. Inboden	DATE 3-2-66		
									CHECKED			
									APPROVED			
SIZE	DWG. NO.	REV.	1	2	3	4	5	6	PART NAME	NO. REQ'D		
E	1115321-19	B	X						Injector Assembly, Co-Axial	1		
D	1013603-5	B	X						Plug	4		
E	1115314-19	B	X						Injector Pl - Machined	1		
E	1115314-3	B		X					Make from 1115314-9	1		
E	1115319-1	A		X					Ring	1		
				X					Weld Rod - CRES-349	AR		
E	1115315-9	B	X						Injector Support - Machined	1		
E	1115085-9	A		X					Injector Support - Weldment	1		
E	1115081-3	NC			X				Support - Forging	1		
D	1115083-1	NC			X				Torus	2		
E	1115087-1	NC			X				Dome - Forging	1		
					X				Weld Rod - CRES 349	AR		
E	1115315-3	B		X					Lug	1		
E	1115089-3	A		X					Flange	1		
E	1115089-1	A			X				Forging - CRES 347	1		
E	1115201-9	NC		X					Adapter	1		
D	1115379-1	NC		X					Adapter Instrumentation	3		
					X				Weld Rod - CRES 349	AR		
D	1115316-1	NC	X						Igniter Adapter	4		
	NAS1291-C6			X					Nut	60		
	AN960C616L			X					Washer, Plain	60		
	1115317-3	NC	X						Washer, Crush	4		
	1115317-1	NC	X						Washer, Crush	4		