PRELIMINARY ENGINEERING REPORT
FOR DESIGN OF A SUBSCALE
EJECTOR/DIFFUSER SYSTEM FOR
HIGH EXPANSION RATIO
SPACE ENGINE TESTING

April 1984

FINAL REPORT, CONTRACT NAS8-35051

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MARSHALL SPACE FLIGHT CENTER, AL 35812

by
C. J. Wojciechowski
S. C. Kurzius
M. F. Doktor

Lockheed
Research & Development Division
Huntsville Research & Engineering Center
4800 Bradford Drive, Huntsville, AL 35807

APPROVED
C. D. Andrews, Manager
Systems Analysis & Simulation Section
S. V. Bourgeois
Director
FOREWORD

This preliminary engineering report is for the design of a subscale jet engine driven ejector/diffuser system for installation at MSFC's Cold Flow Calibration Facility, Building 4554. The work was performed by personnel of the Lockheed-Huntsville Research & Engineering Center under the direction of C.J. Wojciechowski, Project Engineer. The effort was conducted for NASA-Marshall Space Flight Center under Contract NAS8-35051. Included herein are analytical results and preliminary design drawings and plans. This document is the final report required under this contract. The NASA-MSFC Contracting Officer's Representative for this study was Mr. K.E. Riggs, EP23.

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NOMENCLATURE

A  area
A*  sonic or throat area
GN2  gaseous nitrogen
L  length
M  Mach number
m, w  flow rate
NBP  normal boiling point
P,p  pressure
R  radius
RH  relative humidity
r  ejector mass flow to pumped mass flow ratio
T  temperature
U  velocity
W_{BL}  J-57 air bleed flow rate

Greek

\( \tau \)  time

Subscripts

c  cell or chamber
d  detonation conditions
e_x,ex  ejector mixing tube exit
j  pertains to ejector
m  mixing tube
s  static conditions
T  total conditions
1, 2  downstream of a normal shock
1. INTRODUCTION

The National Aeronautics and Space Administration long range plans indicate the need for a high expansion ratio, high performance upper stage engine. An altitude simulation test facility will be needed, first to develop the technology for such an engine, and second to provide the development testing for the engine. State-of-the-art steam driven ejector systems are projected to be extremely costly, and as a result NASA has been exploring other less costly means of providing altitude simulation capability. One of the more promising concepts uses the exhaust of conventional jet engines to provide the working fluid for driving the ejectors. In a recent study conducted by Lockheed (Contract NAS8-33981) such a system was found to be analytically feasible. MSFC intends to experimentally demonstrate the concept through the design, fabrication and test of a subscale pilot model.

This document is the final report under this contract. During the course of the design study, several oral presentations were presented to NASA-MSFC at the COR's request. Documentation from these presentations are considered as part of the overall study documentation. Presentations that were given are listed below.

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2. OBJECTIVES AND REQUIREMENTS

This subscale design effort was initiated on 2 April 1983. In the process of developing the subscale design, significant safety questions arose regarding the performance of a full scale system during an actual hot firing of a space engine, especially hydrogen detonation hazards and how they may be controlled. An added scope of work to this contract was issued by MSFC on 11 January 1984 to study the full scale safety issues. The original and added scope of work objectives are listed below:

• Original Objectives

1. Design a subscale working model for future full scale testing of OTV engines in a simulated space environment.

2. Verify that the analyses, design, and performance prediction techniques previously developed are valid and applicable to this concept.

3. Identify for further consideration areas where the analyses and design techniques may not be complete and fully developed and must be supplemented with test data to be obtained in this facility.

4. Provide final design drawings for a prototype system.

• Amended Scope of Work Objectives.

5. Perform a full scale system safety analysis and determine the mechanisms to suppress detonation by design or operational procedure.

6. Develop full scale configuration detail to support the above objective and determine the design drivers for adjustable ejectors.

7. Provide the design data necessary to make modifications to the subscale system for adequate simulation of the full scale safety issues and performance.
8. Determine the sensitivity of the design to engine physical and performance characteristics.

Secondary Objectives

These objectives are considerations only, and the prototype design will not be compromised because of them:

1. Use as a test facility for OTV thruster engines with 0.5 to 1.0 lbm/sec flow rate.
2. Provide compatibility with Hot Gas II Facility.

Requirements

The subscale, pilot model gas driven ejector will be designed to the following requirements:

A. Test cell pressure: 0.02 psia
B. Thruster flow rate: 0.50 lbm/sec of gaseous hydrogen
C. Thruster area ratio: 650:1
D. Initial inerting with gaseous nitrogen
E. Capable of being installed at and operating from MSFC's Cold Flow Calibration Facility using a J-57 turbojet engine bleed air and exhaust as the ejector driving medium
F. Provision for adequate simulation of the full scale facility hazard control mechanism.

Requirement E above was changed after contract award to use the J-57 turbojet engine exhaust instead of the MSFC Hot Gas Facility hot air exhaust to drive the ejector system. Detailed design of the J-57 engine controls, fuel tanks and exhaust ducting was beyond the scope of this contract. Sufficient design of the J-57 exhaust ducting to the ejector system was performed however, to enable a systems compatibility analysis to be performed. The last requirement (F) was added because of the amended Scope of Work.
3. ENGINEERING ANALYSIS AND DESIGN

In the course of performing this task special attention was given to defining such issues and concerns as ejector performance, safety issues such as hydrogen detonation hazards, ejector stability and controllability, ejector cooling requirements, and transient operation. The main analytical computer programs which were used in this study are listed in Refs. 1 through 3. The semi-empirical one-dimensional diffuser/ejector design program developed in the Ref. 1 study, was modified in this study to accommodate temperature dependent ratios of specific heats (gamma).

The final subscale ejector/diffuser design as presented herein was driven by the safety analysis results and ejector performance requirements. The mass flows to each ejector stage were dictated by the safety analysis results when the facility is pumping hydrogen (H₂) gas. The main safety criterion arrived at, at the 30 percent design review (Ref. 4), was to design the facility to suppress H₂ detonation hazard potentials. The proposed engineering approach was to:

1. Force the mixture ratio to be out-of-hazard range.

   - First Stage: Operate rich.
   - Second Stage: Operate lean.
   - Third Stage: Dilute second stage effluent to flammability limit.

2. Suppress ignition in first and second stage mixing ducts by operating at low static temperatures and pressures in the presence of condensation fine particulate matter (snow from ambient moisture).

   - First Stage: \( (T_s < 200 \text{ K}, T_T < 700 \text{ K}, P_{T,2} < 1.1 \text{ psia}) \)
   - Second Stage: \( (T_s < 300 \text{ K}, T_T < 700 \text{ K}, P_{T,2} < 6.6 \text{ psia}) \)
- Third Stage: Rarely flammable after mixing, non-detontable but flammable prior to mixing ($T_a < 660 \text{ K}$, $T_T < 750 \text{ K}$, $P_{r,2} < 22.6 \text{ pta}$)

One of the objectives was to obtain subscale ejector performance data to enable design of a full scale system. Ejector systems are normally point designs, i.e., the blank-off capability and the pumping capability are defined. However, since this was to be a test bed to obtain data for future design, the ejectors had to be designed for variable area ratio to cover the range of anticipated full scale applications. The main reasons for developing and testing variable area ratio ejectors in the subscale design are:

1. Proof-of-concept data can be obtained from a working model.

2. A complete data base can be obtained applicable to full scale design.

3. The full scale ejector/diffuser must accommodate a family of space engines and modes of operation. Each engine will require the ejector system to operate at different ejector driving pressures and flow rates depending on safety considerations and ejector performance.

4. Turbojet engine operation is sensitive to exhaust exit area. Consultation with Pratt & Whitney indicated that this should not be a problem for the jet engine application in this case if the exhaust area can be adjusted to the particular jet engine. Experience has shown that jet engines, although manufactured to the same specifications, have individual characteristics — especially after several years usage — and therefore must be treated separately. Since the jet engines to be used in the prototype, and eventually in the full scale facility, are Air Force surplus engines, they will not be identical in performance. Designing the second and third stage ejector throat areas to be variable will enable fine tuning of the jet engine being used. In addition, the prototype diffuser/ ejector system will not be dependent on a single jet engine. Engine interchangeability is a design feature since the jet engines are surplus Air Force engines.

5. Since the actual ejector throat area (vena contracta) is not known "a priori" due to the compound curvature of the upper

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and lower ejector throat surfaces, designing all three ejector throat areas to be variable will facilitate fabrication and assembly of the ejectors to the proper area as compared with the very close tolerance required for a fixed area ratio ejector.

6. The added complication of differential thermal growth between the upper and lower ejector throat surfaces during long duration tests can be adjusted dynamically during the test using real time monitoring of the ejector flow rates. Third stage ejector throat area changes during the tests can be detected by deviation in the low pressure compressor rotor speed falling off the jet engine calibration curve.

3.1 SUBSCALE DIFFUSER DESIGN

The subscale jet engine driven diffuser ejector system at the 90 percent point is shown in Fig. 1. The design of the subscale jet engine driven ejector/diffuser system as presented herein meets all of the requirements presented previously. The features of the subscale design are:

- Three-stage ejector system required to obtain test cell pressure of 0.02 psia
- High pressure compressor bleed air to be utilized to drive the first stage ejector
  - Normal rated power bleed parameters: \( P_T = 150 \text{ psia}; T_T = 1137 \text{ R; } \dot{W}_{BL} = 8.64 \text{ lbm/sec} \)
  - Military rated power bleed parameters (30 minutes): \( P_T = 162 \text{ psia; } T_T = 1182 \text{ R; } \dot{W}_{BL} = 1.65 \text{ lbm/sec} \)
- Turbine exhaust utilized to drive the second and third stage ejectors
  - Normal rated power exhaust parameters: \( P_T = 33 \text{ psia; } T_T = 1405 \text{ R; } \dot{W} = 157 \text{ lbm/sec} \)
  - Military rated power exhaust parameters (30 minutes): \( P_T = 36 \text{ psia, } T_T = 1500 \text{ R; } \dot{W} = 165 \text{ lbm/sec} \)
- Ejector design to be scale-up of previously tested design.
FMD = Flow measuring device
PFCV = Pressure and flow control valve
CV = Check valve
EMCV = Electromechanical control valve
FLOP = Flow limiting orifice plate

Fig. 1 90 Percent Review - Jet Engine Driven Ejector/Diffuser System
The J-57 turbojet normal rated power level will be used. The design features an altitude test chamber and a 650:1 area ratio H₂ nozzle. To eliminate unnecessary complexities in the subscale model, the H₂ will not be ignited. The H₂ chamber pressure will be 1200 psia. The H₂ nozzle lip pressure will be 0.02 psia. The total pressure of the H₂ + N₂ bleed stream entering the first stage ejector will be 3.0 psia, based on the diffuser normal shock recovery pressure.

The design incorporates the rapid turbojet exhaust/GN₂ switchover design which was developed for the subscale as a result of the full scale safety analysis for a full scale abort condition. The rapid switchover design has been incorporated into the second stage ejector for checkout and verification. The design includes a quick acting (100 msec) Electro-Mechanical Control Valve (EMCV) in the jet exhaust vent line, a Digicell Pressure and Flow Control Valve (PFCV) in the GN₂ line and a full ported swing check valve (CV) in the ejector line downstream of the vent line EMCV. The CV will close rapidly (less than 50 msec) on a negative pressure differential of 0.5 psi. The GN₂ operates at 40 psia and the exhaust operates at 33 psia so that the negative differential will be much greater than 0.5 psi. The same electrical signal would operate both the PFCV and the EMCV. The altitude cell and the first and third stage ejectors are fitted with small GN₂ inerting purge lines to completely purge out all cavities where H₂ could accumulate prior to and after the H₂ tests.

The first stage ejector design summary is presented in Fig. 2. The ejector throat area is designed to be variable and can be completely closed off. The ejector area ratio Λ₂/Λ₃ can be varied from 22 to infinity. The design blank off suction pressure and pumping capacity is shown in Fig. 2 along with the characteristic dimensions. The variation of the minimum cell pressure to exit pressure ratio as a function of ejector area ratio is shown in Fig. 3. Shown in Fig. 3 are Lockheed's analytical results for no second throat and for a second throat compared to experimental data. The first stage ejector is a scale up of the ejector 2 design from Ref. 5. The
Design Conditions with Condensation Effects

\[
\frac{A_j}{A_j^*} = 29.52 \quad A_j^* = 25.58 \text{ in}^2 \\
\frac{P_{T_j}}{P_{T_j}^*} = 6.34 \text{ psia} \quad T_{T_j} = 1138 \text{ R} \\
\dot{m}_j = 2.79 \text{ lbm/sec} \\
r = \frac{\dot{m}_j}{\dot{m}_1} = 5.47
\]

Blank Off Suction Pressure = 0.02 psia
Pumping Capability = 0.51 lbm/sec at 2.8 psia
\[
\frac{A_j}{A_j^*} = \text{Variable from 22 to infinity}
\]

Fig. 2 First Stage Ejector Design Summary
Fig. 3 Variation of Minimum Pressure to Which Ejector will Pump (As a function of ratio of mixing-tube cross-sectional area to ejector-throat area. No flow being pumped (from NASA TN D-23))
Ejector 2 design of Ref. 5 was not a second throat ejector design. The first stage ejector performance as a function of ejector total pressure is shown in Fig. 4. The ejector is designed for nominal total pressure of 6.94 psia, at which point the cell pressure will be 0.012 psia without condensation effects. Additional first stage performance data as a function of area ratio is presented in Fig. 5, again without condensation effects. The effects of condensation due to ambient temperature and relative humidity are:

- The primary effect is to add moisture to the ejector driver streams. This moisture condenses in a shock-free condensation front (Wegener and Pouring, Physics of Fluids, Vol. 7, pp. 352-361, 1967), increasing pressure and temperature by release of latent heat to the gas phase in the first and second stages.

- The equilibrium condensed phase is solid (snow), with particle sizes on the order of several hundred Angstroms - a good size for efficient flame suppression.

- Total stream moisture consists of driver engine combustion product and ambient contributions. At low temperatures and humidity, combustion moisture dominates. Under hot, humid ambient conditions air moisture dominates, but does not overwhelm combustion moisture (ratio is approximately 2.5:1 at 100 F, 100% RH corresponding to effluent moisture mole fractions of 0.0976 and 0.0253 (dry air); at design condition (70 F, 50% RH) ratio is approximately 0.5:1, corresponding to an effluent moisture mole fraction of 0.0373.)

- The ejector design can accommodate wide swings in ambient temperature (0 to 100 F) and relative humidity (0 to 100%).

The ejector design ambient conditions are 70 F and 50 percent relative humidity. The calculated onset of water vapor condensation as a function of axial distance from the ejector exit is shown in Fig. 6 for both the first and second stage ejectors. No condensation is predicted for the third ejector stage. The condensation effects on the first stage ejector performance are shown in Fig. 7. The blank off pressure will increase by 28 percent to 0.015 psia which is still comfortably below the 0.02 psia requirement.
Fig. 4 First Stage Ejector Performance as a Function of Ejector Total Pressure

\[ \frac{A_m}{A_j^*} = 29.5 \]
\[ \frac{P_e}{P_{e_x}} = 0.00204 \]
\[ \frac{T_f}{T_{j_e}} = 1138 \text{ R} \]
\[ A_j^* = 23.58 \text{ in}^2 \]

Mass Flow, m (lbm/sec)
\( \dot{m} = 2.79 \text{ lbm/sec} \)

**Fig. 5** First Stage Ejector Performance as a Function of Area Ratio
First Stage Ejector Saturation Line

Unsaturated Flow

Ejector Driver Stream Moisture Line

2nd Stage

Supersaturation Region

Second Stage Ejector Saturation Line

Critical
Super-
Saturation
Ratio (=12)

T = 220 K

Snow in Flow

Snow in Flow

Fig. 6 Water Vapor Condensation (70 F, 50% RH Ambient Air)
Fig. 7 Effects of Ambient Temperature and Relative Humidity on First Stage Ejector Due to Condensation
It is of interest to note that the J-37 turbojet engine is already set up with water injection ports at the compressor inlet station. Future full scale space engine hot firing tests could make use of this water injection mechanism to cool the space engine exhaust products. This would relieve some of the diffuser cooling problems and enable the ejectors to operate more efficiently. At the takeoff power setting, the system is capable of 20 gpm water injection rate. The use of water injection at other than the take-off power setting would have to be explored.

The second stage ejector design summary is presented in Fig. 8. The ejector throat area is designed to be variable and can be completely closed off. The ejector area ratio can be varied from 2.38 to infinity. The design blank off suction pressure and pumping capabilities are shown in Fig. 8.

The third stage ejector design summary is presented in Fig. 9. The third stage ejector is designed to operate in all modes of operation. The ejector area ratio can be varied from 2.59 to 10. The third stage ejector is designed to operate by itself using all of the turbojet exhaust products.

3.2 SUBSCALE JET ENGINE DRIVEN EJECTOR/DIFFUSER SAFETY ANALYSIS

The results of this analysis were presented at the 60 percent design review meeting. The key results are presented here. The worst case hazard assessment is presented in Table 1. The main point to be made from Table 1 is that ignition is improbable within the ejector/diffuser tubes. The first stage ejector mixing and explosion hazard analysis results are presented in Fig. 10. The worst case detonation pressures are approximately 8 psia. The second stage ejector mixing and explosion hazard results are presented in Fig. 11. The worst case detonation pressure is 37 psia. It should be pointed out that operating temperatures are too low within the facility to cause a detonation. The facility will be grounded to eliminate a lightning bolt source of energy. However, it is not anticipated that a test would be conducted on threatening weather days.
Design Conditions with Condensation Effects

\[ \frac{A_4}{A_j} = 11.8 \quad A_j = 80.86 \text{ in}^2 \]

\[ P_T = 33 \text{ psia} \quad T_T = 1400 \text{ R} \]

\[ \dot{m}_j = 37.3 \text{ lbm/sec} \]

\[ r = \frac{\dot{m}_j}{\dot{m}_1} = 11.3 \]

Blank Off Section Pressure = 0.20 psia

Pumping Capability = 3.3 lbm/sec at 0.82 psia and 802 R

\[ \frac{A_4}{A_j} \text{ Variable from 2.38 to Infinity} \]

Fig. 8 Second Stage Ejector Design Summary
Design Conditions

\[ R_1 = 16.73'' \]
\[ R_2 = 14.33'' \]
\[ R_3 = 18.30'' \]
\[ R_4 = 14.28'' \]

\[ \frac{A_3}{A_j^*} = 4.09 \]
\[ A_j^* = 257.31 \text{ in}^2 \]

\[ P_T^* = 33 \text{ psia} \]
\[ T_T^* = 1400 \text{ R} \]

\[ \dot{m}_j = 118.77 \text{ lbm/sec} \]

\[ A_3/A_j^* \text{ Variable from 2.59 to 10} \]

\[ r = \frac{\dot{m}_j}{\dot{m}_2} = 2.93 \]

Blank Off Suction Pressure = 0.98 psia

Pumping Capability

40.6 lbm/sec at 5.5 psia and 1235 R

30.5 lbm/sec at 5.5 psia and 2200 R

Fig. 9 Third Stage Ejector Design Summary
Table 1 WORST CASE HAZARD ASSESSMENT

Kinetics Ignition Delay Behind Normal Shock in Duct

\[ \tau_{\text{ignition}} = \frac{3 \times 10^{-5}}{P_{\text{atm}}} \exp \left( \frac{9000}{T_{\text{H2}}} \right) \text{ sec (NASA TP 1457, Aug 79, Huber et al.)} \]

**First Stage:** \( T_{S,2} = 429 \text{ K; } M_2 = 0.454; U_2 = 1073 \text{ ft/sec; } P_{S,2} = 0.821 \text{ psia} \)

\[ \tau_{\text{ignition,NS}} = 760 \text{ sec} \]
\[ L_{\text{ignition,NS}} = 8.2 \times 10^5 \text{ ft} \]

*No problem, by a wide margin of safety.*

**Second Stage:** \( T_{S,2} = 663 \text{ K; } M_2 = 0.444, U_2 = 801 \text{ ft/sec; } P_{S,2} = 5.52 \text{ psia} \)

\[ \tau_{\text{ignition,NS}} = 4.2 \times 10^{-2} \text{ sec} \]
\[ L_{\text{ignition,NS}} = 33.5 \text{ ft} \]

*Safe, with no ignition in duct.*

**Third Stage:** \( T_{S,2} = 701 \text{ K; } M_2 = 0.644; U_2 = 1128 \text{ ft/sec } P_{S,2} = 16.7 \text{ psia} \)

\[ \tau_{\text{ignition,NS}} = 6.2 \times 10^{-3} \text{ sec} \]
\[ L_{\text{ignition,NS}} = 7.0 \text{ ft} \]

*Safe, with potential gentle ignition in open duct downstream of shock.*

- The Available Ignition Source (i.e., the Jet Engine Exhaust) Operates at Temperatures Too Low to Ignite the \( \text{H}_2 \) Fuel Within the Flow Facility.
Fig. 10 First Stage Mixing and Worst Case Explosion Hazard Analysis
**Fig. 11  Second Stage Mixing and Worst Case Explosion Hazard Analysis**

- **Suppression by:**
  1. Low Temperature ($T_I < 700$ K; $T_S < 300$ K)
  2. Low Pressure ($P_T < 6.6$ psia)
  3. Condensation Fine Particulate Matter (Snow-1.8 wt. %)

- **No Hazard**

- **Potential Hazard (Confined to Mixing Region)**

- **Fuel-Lean**

- **Flow Composition**

- **Atmospheric Pressure**

- **P_{D_{\text{max}}}, based on Worst Case Chapman-Jouguet Detonation Behind a Normal Shock for Design Flow Conditions**

- **No Hazard**
3.3 FULL SCALE HAZARD CONTROL ANALYSIS

The hazard to be controlled is a potential detonation of unburned space engine hydrogen fuel within the diffuser/ejector duct work. In the past, this hazard has been eliminated by using an inert driver—steam. With the proposed use of jet engine effluent as the driving medium a potential for explosion of mixtures exists, as the jet engines are operated fuel-lean and consequently have an appreciable oxygen content (see Table 2).

<table>
<thead>
<tr>
<th>Table 2 J-57 TURBOJET ENGINE CHARACTERISTICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruise-Rated Air Flow Rate: 157 lb/sec⁻¹ (70 F, 50% RH)</td>
</tr>
<tr>
<td>Cruise-Rated Fuel Flow Rate: 7,050 lb/hr⁻¹</td>
</tr>
<tr>
<td>Engine Exhaust -</td>
</tr>
<tr>
<td>Total Flow Rate: 158.96 lbm/sec⁻¹</td>
</tr>
<tr>
<td>Total Temperature: 1400 R</td>
</tr>
<tr>
<td>Total Pressure: 33 psia</td>
</tr>
<tr>
<td>Composition -</td>
</tr>
<tr>
<td>N₂: 77.03 vol.%</td>
</tr>
<tr>
<td>O₂: 16.70 vol.%</td>
</tr>
<tr>
<td>CO₂: 2.51 vol.%</td>
</tr>
<tr>
<td>H₂O: 3.74 vol.%</td>
</tr>
<tr>
<td>NOₓ: 87 ppm</td>
</tr>
<tr>
<td>CO: 60 ppm</td>
</tr>
<tr>
<td>CH₄: 84 ppm</td>
</tr>
</tbody>
</table>

3.3.1 Worst Case Hazard Analysis

To place the potential hazard in perspective consider Fig. 12 in which computed Chapman-Jouguet detonation pressure ratios are plotted as a function of mixture H₂ concentration for mixtures of space engine effluent.
Fig. 12 Hazard Analysis: Worst Case Chapman-Jouguet Detonation Pressure Ratio Characteristics at Prevailing Stream Total Temperatures
and J-57 turbojet driver effluent at 0.5 atm initial pressure*. As is evident from the figure the worst case overpressures occur when 100 percent H2 is exhausted from the test engine and are higher for cryogenic H2 than for regeneratively heated H2 at room temperature. For main stage space engine operation at engine O/F ratios of 4 or 6 a considerable decrease in the worst case detonation pressure ratio results. This is a direct consequence of the higher initial mixture temperature due to combustion in the space engine. Table 3 summarizes the maximum, i.e., worst case, potential detonation pressure ratios for the various space engine effluents considered, using J-57 turbojet exhaust as the diffuser/ejector driver. The corresponding worst case detonation pressures possible in each stage at 10 percent and 100 percent thrust engine operation are also shown in Table 3. These data are based on the calculated pressure distributions for the full scale facility shown in Figs. 13, 14, and 15.

3.3.2 Hazard Control Analysis

• Transient Operations

As is evident from Fig. 12 and Table 3, the maximum potential hazard exists during cold flow operations, which normally are tests of short duration. The highest potential overpressure would occur in the third ejector stage and could approach an upper limit of 272 psia, with cryogenic H2. (Room temperature H2 represents somewhat less of a potential hazard, but would however be more readily ignited.) A nearly 100 percent H2 engine flow can also be encountered during engine startup and shutoff transients, as discussed in more detail in Section 3.3.3.

*These computations were performed using the NASA-Lewis CEC code (Ref. 2). The detonation pressure ratios were found to be largely insensitive to initial pressure over the range of interest (i.e., subatmospheric) to this study.
Table 3 Maximum Chapman-Jouguet Detonation Pressures

\(P_D = \text{Detonation Pressure}; \ P_{T,2} = \text{Initial Total Pressure}\)

Driver: J-57 Jet Engine Exhaust

<table>
<thead>
<tr>
<th>Space Engine Condition</th>
<th>(\left(\frac{P_D}{P_{T,2}}\right)_{\text{max}})</th>
<th>Worst Case Detonation Pressure (psia)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\text{Thr} \ %)</td>
<td>1st Stage</td>
</tr>
<tr>
<td>Cold Flow of Cryogenic (H_2)</td>
<td>8.5</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Cold Flow of Room Temperature (H_2)</td>
<td>6.7</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Main Stage, Engine O/F = 4</td>
<td>2.3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Main Stage, Engine O/F = 6</td>
<td>1.5</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

To control the startup/shutoff transient hazard, and also to allow short duration cold flow engine acceleration tests without oxidizer, Lockheed proposes the use of tank farm nitrogen as driver for the first and second diffuser/ejector stages during start/stop transients, and also during short duration cold flow tests without oxidizer flow. Sufficient GN2 is to be used to dilute the peak \(H_2\) flow in the overall mixture leaving the 2nd stage to below the lean detonation limit (see Table 4), i.e., to about 19 vol.% or less.

Table 4 Flammability and Detonation Limits (Ref. 6)

<table>
<thead>
<tr>
<th></th>
<th>Hydrogen-Air</th>
<th>(H_2)-J57 Jet Engine Effluent*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flammability Limits (vol.%)</td>
<td>4.0 &lt; F &lt; 75</td>
<td>4.2 &lt; F &lt; 66</td>
</tr>
<tr>
<td>Detonation Limits (vol.%)</td>
<td>18.3 &lt; D &lt; 60</td>
<td>19 &lt; D &lt; 55</td>
</tr>
</tbody>
</table>

*Estimated, based on effects of dilution of air with \(N_2\), \(CO_2\), and \(H_2O\) as reported in Ref. 6.
AECE-R 10% Thrust
Main Stage Operation
\[ \frac{O}{F} = 4.0 \]
\[ P = 198 \text{ psia} \]
\[ m_c = 3.7 \text{ lbm/sec} \]

Fig. 13 Full Scale AECE-R 10 Percent Thrust Diffuser/Ejector Pressure Distribution
Fig. 14 Full Scale RL10-IIB 10 Percent Thrust Diffuser/Ejector Pressure Distribution
Fig. 15 Full Scale RL10-IIB 100 Percent Thrust Diffuser/Ejector Pressure Distribution

RL10-IIB 100% Thrust Main Stage Operation

\[ \frac{O}{F} = 6.0 \]
\[ P_c = 400 \text{ psia} \]
\[ m = 32.6 \text{ lbm/sec} \]

**Note:** This curve also applies to the AECE-R engine for 100% Thrust

\[ \frac{O}{F} = 6.0 \]
\[ P_c = 1539 \text{ psia} \]
\[ m = 31.2 \text{ lbm/sec} \]
Main Stage Operation

Long duration tests - 30 minutes or more - are required for the engines in main stage operation, at both low and high thrust levels. Tests of such length preclude use of CH₂ as driver, even in the first and second stages of the diffuser/ejector. Therefore at main stage the J-57 jet engines' exhausts will be used as driver in all of the stages, and the hazard control will be to ensure that the space engine excess fuel is combusted continuously in each of the stages as rapidly as it mixes with the driving medium. Three conditions that must be met simultaneously to achieve this are:

1. Mixture compositions must lie within the flammability limits summarized in Table 4. This is a restriction which is only operative on the fuel-rich side of engine operation in the present analysis. If mixtures are already too lean to burn, they are also too lean to detonate and are no longer a potential hazard. On the rich side of the flammability limits, mixtures exhausting from the space engines with greater than 66 to 75 percent H₂ (Table 4) - corresponding to engine O/F ratios of 2.5 to 2.0 or less - might require further dilution by the driving medium prior to the recommencing of combustion. If other conditions are correct it would seem probable that burning would resume in such mixtures prior to their being diluted sufficiently to enter into the detonable range - 55 to 60 percent H₂. To be prudent, however, engine mixtures entering the diffuser with an O/F ratio less than 2.0 should be regarded as potentially hazardous (see also below).

2. Static pressure must everywhere be higher than the lower ignition limit pressure to assure the continuity of the combustion process. Spark igniter ignition limits for H₂-GOX mixtures at room temperature obtained by Pratt & Whitney (Ref. 7) in a relatively small chamber (4 in. diameter, 15 in. long) are shown in Fig. 16, which indicates a lower limit pressure of 0.2 psia for these conditions. Also shown is the lowest static pressure (from Figs. 13, 14, and 15) in the proposed full scale diffuser facility, i.e., 0.7 psia. The latter pressure is the lowest encountered, in the first stage, at low space engine thrust levels. It is, however, sufficiently high that combustion of hot main stage exhaust proceeds as the gases mix even at the lowest pressure encountered.
Fig. 16  H₂-GOX Static Ignition Limits (Spark Igniter 4 in. Diameter x 15 in. Long Chamber, PWA PR-303, Nov 61, Ref. 7)
It is useful in this regard to note that the lower pressure limit obeys an inverse response to increases in temperature (exponential response), vessel size and ignition source strength (see, e.g., Refs. 8 and 9). At main stage engine operation all of these factors are operative in a direction to assure continuous combustion.

3. Static temperature must be sufficiently high everywhere that kinetics are rapid with respect to mixing. In Fig. 17, hydrogen-air autoignition delay times from Ref. 10 are shown as a function of static temperature. These delay times - inversely proportional to pressure - are a measure of the rapidity of hydrogen combustion.

As indicated, at static temperatures above 1300 K the product of pressure and ignition delay is approximately $10^{-5}$ atm-sec or less. Thus even at the 0.7 psia lowest static pressure (first stage, 10 percent thrust) delay times will be shorter than $2 \times 10^{-4}$ sec for $T > 1300$ K - corresponding to engine O/F ratios greater than 2.0 accelerated to Mach numbers which are restricted by design to 2.0 or less within the diffuser/ejector facility. Noting that gas residence times in the first, second, and third stages are approximately 5, 10, and 30 msec, respectively, this ensures that the gases burn as rapidly as they mix, under all conditions, for engine O/F ratios of 2.0 or greater.

3.3.3 AECE-R and RL10-IIB Space Engine Transient Characteristics

Operating parameters of five candidate space engines for the orbital transfer vehicle are shown in Table 5 from Ref. 1. Of these advanced engines, two - the AECE-R and the RL10-IIB - were selected for analysis of potential transient operational test hazards in the proposed diffuser facility.

AECE-R engine startup transient and main stage characteristics were derived from ASE data presented in Ref. 11; shutoff data came from Ref. 12. Similar data for the RL10-IIB engine were derived from RL10A-3-3A data.
### H₂-LOX Combustor Temperatures

<table>
<thead>
<tr>
<th>Engine O/F</th>
<th>T₀ K (M=0)</th>
<th>T₁ K (M=1)</th>
<th>T₂ K (M=2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0</td>
<td>2958</td>
<td>2847</td>
<td>2563</td>
</tr>
<tr>
<td>4.0</td>
<td>2756</td>
<td>2610</td>
<td>2186</td>
</tr>
<tr>
<td>2.0</td>
<td>2019</td>
<td>1781</td>
<td>1301</td>
</tr>
<tr>
<td>1.0</td>
<td>1257</td>
<td>1072</td>
<td>731</td>
</tr>
<tr>
<td>0.75</td>
<td>1034</td>
<td>874</td>
<td>590</td>
</tr>
<tr>
<td>0.5</td>
<td>798</td>
<td>670</td>
<td>450</td>
</tr>
<tr>
<td>0.25</td>
<td>552</td>
<td>462</td>
<td>308</td>
</tr>
</tbody>
</table>

**Fuel:** H₂-Rich Space Engine Effluent

**AECE-R Engine:** 3.7 lb/sec, Low Thrust

**RL10-IIB Engine:** 3.2 lb/sec, Low Thrust

**Oxidizer:** J57 Jet Engine Exhaust: O₂

<table>
<thead>
<tr>
<th>Stage</th>
<th>Flow Rate</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Stage</td>
<td>2.8 lb/sec</td>
<td>Low Thrust Only</td>
</tr>
<tr>
<td>2nd Stage</td>
<td>23.2 lb/sec</td>
<td>Low Thrust</td>
</tr>
<tr>
<td>3rd Stage</td>
<td>451 lb/sec</td>
<td>Low and Full Thrust</td>
</tr>
</tbody>
</table>

![Fig. 17 H₂-LOX Engine Exhaust Autoignition Characteristics](image-url)
Table 5  FIVE CANDIDATE SPACE ENGINES FOR THE OTV (REF. 1)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>ARCE-A</th>
<th>ARCE-P</th>
<th>ARCE-R</th>
<th>ASE</th>
<th>RL10-11B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust, Full</td>
<td>lb</td>
<td>15000</td>
<td>15000</td>
<td>15000</td>
<td>20000</td>
<td>15000</td>
</tr>
<tr>
<td>Thrust, Low</td>
<td>lb</td>
<td>2000</td>
<td>1500</td>
<td>1800</td>
<td>1850</td>
<td>1500</td>
</tr>
<tr>
<td>Maximum Test Duration @ MR = 6.0</td>
<td>sec</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>Full Thrust</td>
<td>sec</td>
<td>2500</td>
<td>2500</td>
<td>2500</td>
<td>2500</td>
<td>2500</td>
</tr>
<tr>
<td>Low Thrust</td>
<td></td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Gimbal Capability</td>
<td></td>
<td>LOX/LH₂</td>
<td>LOX/LH₂</td>
<td>LOX/LH₂</td>
<td>LOX/LH₂</td>
<td>LOX/LH₂</td>
</tr>
<tr>
<td>Propellants</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixture Ratio, Full Thrust</td>
<td></td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Low Thrust</td>
<td></td>
<td>6.0</td>
<td>6.0</td>
<td>4.0</td>
<td>2.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Nozzle Area Ratio</td>
<td></td>
<td>473</td>
<td>642</td>
<td>625</td>
<td>400</td>
<td>205</td>
</tr>
<tr>
<td>Engine Envelope:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outside Diameter @ Noz. Exit</td>
<td>in.</td>
<td>62.7</td>
<td>66.1</td>
<td>63.25</td>
<td>58.08</td>
<td>73.0</td>
</tr>
<tr>
<td>Inside Diameter @ Noz. Exit</td>
<td>in.</td>
<td>60.7</td>
<td>64.1</td>
<td>61.25</td>
<td>56.08</td>
<td>71.0</td>
</tr>
<tr>
<td>Length, Gimbal Pad to Noz. Exit</td>
<td>in.</td>
<td>120</td>
<td>114</td>
<td>117</td>
<td>100</td>
<td>110</td>
</tr>
<tr>
<td>Length, Gimbal Pad to Inlet Flange</td>
<td>in.</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>27.1</td>
<td>10</td>
</tr>
<tr>
<td>LOX</td>
<td>in.</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>27.1</td>
<td>10</td>
</tr>
<tr>
<td>LH₂</td>
<td>in.</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>36.87</td>
<td>10</td>
</tr>
<tr>
<td>Engine Weight</td>
<td>lb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chamber Pressure, Full Thrust</td>
<td>psia</td>
<td>1200</td>
<td>1505</td>
<td>1539</td>
<td>2028</td>
<td>400</td>
</tr>
<tr>
<td>Chamber Pressure, Low Thrust</td>
<td>psia</td>
<td>160</td>
<td>150</td>
<td>198</td>
<td>187</td>
<td>40</td>
</tr>
<tr>
<td>Noz. Exit Wall Press., Full Thrust</td>
<td>psia</td>
<td>0.196</td>
<td>0.163</td>
<td>0.172</td>
<td>0.406</td>
<td>0.19</td>
</tr>
<tr>
<td>Noz. Exit Wall Press., Low Thrust</td>
<td>psia</td>
<td>0.026</td>
<td>0.016</td>
<td>0.022</td>
<td>0.037</td>
<td>0.019</td>
</tr>
<tr>
<td>Total Flow Rate, Full Thrust</td>
<td>lb/sec</td>
<td>31.4</td>
<td>31.2</td>
<td>31.2</td>
<td>43.01</td>
<td>32.6</td>
</tr>
<tr>
<td>Total Flow Rate, Low Thrust</td>
<td>lb/sec</td>
<td>4.2</td>
<td>3.2</td>
<td>3.7</td>
<td>4.06</td>
<td>3.26</td>
</tr>
<tr>
<td>H₂ Flow Rate, Low Thrust</td>
<td>lb/sec</td>
<td>0.600</td>
<td>0.457</td>
<td>0.74</td>
<td>1.35</td>
<td>0.466</td>
</tr>
<tr>
<td>H₂ Flow Rate, Full Thrust</td>
<td>lb/sec</td>
<td>4.49</td>
<td>4.46</td>
<td>4.46</td>
<td>6.00</td>
<td>4.66</td>
</tr>
</tbody>
</table>
presented in Ref. 13. Startup transient, main stage operation, and shutoff transient behavior of the O/F ratio for the ARCE-N engine at 10 percent and full thrust are shown in Fig. 18, along with the temporal response of the fuel flow rate at full thrust. Transient, startup and main stage operational data for the RL10-A-3-3A are shown in Fig. 19; detailed shutdown transient data were unavailable for the RL10 engine, other than the manufacturer’s specification that on shutdown fuel is vented overboard, with a maximum of 0.25 lb total throughput of H₂ flowing through the engine nozzle.

The cross-hatched areas on Figs. 18 and 19 correspond to times during which the engine O/F ratio drops below 2.0, i.e., times during which a potential hazard exists with J-57 turbojet engine exhaust as the diffuser/ejector facility driving medium (as discussed previously in Section 3.3.2). Figure 20 emphasizes the potential startup and shutdown transient hazards which could occur if the J-57 turbojet engine exhaust were used as the driver during the transients: H₂ concentrations in the flow leaving the second stage would be well above the lower detonation limit, with or without reaction in the diffuser; additionally, static temperatures at Mach 2 would be too low during portions of the startup and shutdown to ensure reaction at the gases mix – resulting in potential detonable mixtures which could be set off by complex shock structures, hot spots or accidental means such as an electrical discharge. For this, and the previously reviewed reasons, operation during startup and shutdown transients will use inert, gaseous nitrogen as the driving medium.

3.3.4 Space Engine Transient Hazard Assessment and Control

Combining the hazard control analysis (Section 3.3) with the transient characteristics of the space engines considered (Section 2.3.3) results in the transient hazard assessment synopized in Table 6. For both engines a potential hazard is identified during startup and shutdown transients. The proposed control to eliminate these hazards is to use a purge GN₂ flow as
Fig. 18 AECE-R Engine Transient Characteristics (Estimated from ASE Engine Data, Refs. 11 and 12)
Fig. 19 RL10A-3-3A Engine Start Transient Characteristics (Ref. 13)
(Note: J-57 Turbojet exhaust will not be used as driver during transients.)

Fig. 20 AECE-R Engine Second Stage Diffuser Transient Characteristics with J-57 Jet Engine Exhaust as Driver (26 lb/sec)
the inert gas driver in the first and second stages during transients, as required. No hazard exists during main stage engine operation.

Table 6 SYNOPSIS OF ENGINE TRANSIENT HAZARD ASSESSMENT

(DIFFUSER DRIVER: J57 JET ENGINE EXHAUST)

<table>
<thead>
<tr>
<th>AECE-R Engine (Based on ASE Engine Data)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Startup</strong></td>
<td>Potential Hazard, O/F &lt; 2.0 from 0 to 2.4 sec after Start Signal</td>
</tr>
<tr>
<td><strong>Main Stage</strong></td>
<td>No Hazard, O/F = 6.0, High Thrust; O/F = 4.0, Low Thrust</td>
</tr>
<tr>
<td><strong>Shutdown</strong></td>
<td>Potential Hazard; O/F &lt; 2.0 at Shutoff Signal + 150 msec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RL10-IIB Engine (Based on RL10A-3-3A Engine Data)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Startup</strong></td>
<td>Potential Hazard; O/F &lt; 2.0 from 0.20 to 1.58 sec after Start Signal</td>
</tr>
<tr>
<td><strong>Main Stage</strong></td>
<td>No Hazard; O/F = 6.0 for Low and High Thrust Operation</td>
</tr>
<tr>
<td><strong>Shutdown</strong></td>
<td>Potential Hazard; Quantitative Transient Data Inputs are Required.</td>
</tr>
</tbody>
</table>

**Pratt & Whitney Inputs on RL10 Shutdown:**

1. If a graphite nozzle is used, oxidizer-rich shutdown must be avoided to protect hot engine and red hot nozzle.
2. Somewhat in conflict with 1, H₂ is normally dumped overboard on shutdown, with a maximum total of 1/4 lb H₂ flowed through the nozzle on shutdown.

**Proposed Control to Eliminate Potential Start/Stop Hazards:**

Use a Purge N₂ Flow as the Inert Gas Driver in 1st and 2nd Stages During Transients, as Required.

Temporal response of the diluted, inerted flow leaving the second stage diffuser during 100 percent thrust AECE-R engine run transients with 150 lb/sec of N₂ as the driving medium is shown in Fig. 21. As is evident, the hydrogen content of the exit stream is diluted well below the lower detonation limit for all times at which the mixture static temperature is significantly above room temperature. (A slightly higher flow of N₂-170 lb/sec—would ensure an overall H₂ concentration entering the third stage below the detonation limit even during the engine shutoff interval after 190 msec, after which time the oxidizer flow rate is negligible.)
Fig. 21 AECE-R Engine Second Stage Diffuser Transient Operation
Main stage operation of both engines at low and full thrust is summarized for each stage in Tables 7 and 8, respectively, for both J-57 jet engine exhaust and GN2 driving mediums. In all cases, with the stages being driven by the jet engine's exhaust, excess H2 is progressively burned at high temperature and the flow ultimately leaves the facility with negligible residual hydrogen. With GN2 driving the stages: (1) at low thrust, H2 is diluted in the first two stages to a safe 2.8 or 8.5 percent in the two engines, with a second stage exhaust total temperature of only 955 or 958 K; in the third stage the mixture is further diluted, resulting in a near zero exhaust H2 concentration of only 0.3 or 0.9 percent from the facility, assuming no further combustion, or to zero if combustion is completed in the third stage; (2) at full thrust, H2 is diluted in the second stage to a safe 7.4 or 7.1 percent, but at a high total temperature of 1855 or 1806 K; in the third stage combustion continues at high temperature with a resultant negligible H2 content in the facility effluent. Thus for the vast majority of test operation virtually no H2 is discharged from the facility, and there is no requirement for an external torch to burn residual H2.

As discussed previously, start/stop transients are to be controlled by GN2 flow to the first two stages such that the peak H2 concentration in the flow entering the third stage is maintained below the lower detonation limit. At low thrust, with 50 lb/sec GN2 driving the first two stages, the full main stage cold flow of H2 can be controlled, as also is shown in Table 7. At high thrust, with 150 lb/sec GN2 driving the first two stages, about 60 percent of the full main stage cold flow of H2 can be controlled. Thus in the event of a stuck oxidizer valve on startup, provision of an automatic engine shutdown prior to reaching 60 percent of the full rated H2 flow is required. Alternatively the full thrust transient GN2 driver flow can be uprated to 250 lb/sec, if a full rated H2 cold flow requirement is needed for engine acceleration or other tests.
Table 7 LOW THRUST OPERATION

<table>
<thead>
<tr>
<th>Engine Status (Stages 1 &amp; 2)</th>
<th>Driver</th>
<th>Stage</th>
<th>RL10-IIB Engine Exhaust</th>
<th>AECE-R Engine Exhaust</th>
<th>Minimum Pressure  (psia)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Stage Burn</td>
<td>J-57a</td>
<td>Engine</td>
<td>2958, 29.5, 2756, 48.6</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>2628</td>
<td>16.9</td>
<td>2565, 33.2</td>
<td>0.7</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>1968</td>
<td>0.1</td>
<td>2310, 1.3</td>
<td>4.2</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>871</td>
<td>N11</td>
<td>926, N11</td>
<td>17.6</td>
</tr>
</tbody>
</table>

- H₂ is burned virtually to completion in first and second stages.

<table>
<thead>
<tr>
<th>Engine Status (50 lb/sec)</th>
<th>Driver</th>
<th>Stage</th>
<th>RL10-IIB Engine Exhaust</th>
<th>AECE-R Engine Exhaust</th>
<th>Minimum Pressure  (psia)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Stage Burn</td>
<td>GN₂</td>
<td>Engine</td>
<td>2958, 29.5, 2756, 48.6</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>2461</td>
<td>15.4</td>
<td>2304, 33.1</td>
<td>0.7</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>958</td>
<td>2.8</td>
<td>955, 8.5</td>
<td>4.2</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>799</td>
<td>0.3</td>
<td>799, 0.9</td>
<td>17.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>825</td>
<td>N11</td>
<td>878, N11</td>
<td></td>
</tr>
</tbody>
</table>

- Flow enters third stage with H₂ well below detonation limit.

<table>
<thead>
<tr>
<th>Star/Stop Transients (50 lb/sec)</th>
<th>Driver</th>
<th>RL10-IIB Engine: Full Fuel Flow, 0.466 lb H₂/sec</th>
<th>AECE-R Engine: Full Fuel Flow, 0.74 lb H₂/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>300</td>
<td>99.8</td>
<td>300, 99.8</td>
</tr>
<tr>
<td>1</td>
<td>300</td>
<td>56.5</td>
<td>300, 67.3</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
<td>11.5</td>
<td>300, 17.1</td>
</tr>
</tbody>
</table>

- H₂ flow is diluted with GN₂ to below the detonation limit in stages 1 and 2. The full maximum rated cold H₂ flow at low thrust can be controlled.
Table 8 100 PERCENT THRUST OPERATION

<table>
<thead>
<tr>
<th>Engine Status</th>
<th>Driver (Stages 1 &amp; 2)</th>
<th>Stage</th>
<th>T&lt;sub&gt;T&lt;/sub&gt;, K</th>
<th>Vol.% H&lt;sub&gt;2&lt;/sub&gt;</th>
<th>RL10-IIB Engine Exhaust</th>
<th>AECE-R Engine Exhaust</th>
<th>Minimum P&lt;sub&gt;static&lt;/sub&gt; (psia)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Stage</td>
<td>J-57s</td>
<td>Engine</td>
<td>2958</td>
<td>29.5</td>
<td>2958</td>
<td>29.5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Not Driven</td>
<td>1</td>
<td>2958</td>
<td>29.5</td>
<td>2958</td>
<td>29.5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2872</td>
<td>16.3</td>
<td>2869</td>
<td>15.8</td>
<td>6.5</td>
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<td></td>
<td></td>
<td>3</td>
<td>1545</td>
<td>N11</td>
<td>1519</td>
<td>N11</td>
<td>14.0</td>
</tr>
</tbody>
</table>

- H<sub>2</sub> is burned as rapidly as it mixes in second and third stages.

<table>
<thead>
<tr>
<th>Main Stage Burn</th>
<th>GN&lt;sub&gt;2&lt;/sub&gt; (50 lb/sec)</th>
<th>Engine</th>
<th>2958</th>
<th>29.5</th>
<th>2958</th>
<th>29.5</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not Driven</td>
<td>1</td>
<td>2958</td>
<td>29.5</td>
<td>2958</td>
<td>29.5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1855</td>
<td>7.4</td>
<td>1806</td>
<td>7.1</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1324</td>
<td>N11</td>
<td>1300</td>
<td>N11</td>
<td>14.0</td>
</tr>
</tbody>
</table>

- H<sub>2</sub> flow is diluted with GN<sub>2</sub> to well below detonation limit in second stage and burns as rapidly as it mixes in third stage.

<table>
<thead>
<tr>
<th>Stop/Start Transients</th>
<th>GN&lt;sub&gt;2&lt;/sub&gt; (150 lb/sec)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
</table>

- H<sub>2</sub> flow is diluted and cooled with GN<sub>2</sub> to below the detonation limit in second stage. Up to 60 percent of the full maximum rated cold H<sub>2</sub> flow can be controlled.
4. SUBSCALE DIFFUSER MECHANICAL/STRUCTURAL DESIGN

The subscale ejector/diffuser system described in Section 3 of this report has been designed. The design details are discussed in this section.

4.1 GENERAL DESCRIPTION

The facility shown in LMSC Drawing R82734 is designed to flow non-combusted H₂ gas through a 650:1 area nozzle into a three stage ejector/diffuser system. The facility will consist of a H₂ chamber, throat, 650:1 area ratio nozzle, altitude cell, H₂ diffuser tube, and the three stage ejector/diffuser system. The altitude cell is designed to be pumped by the H₂ nozzle flow to maintain the required cell pressure during the H₂ flow tests. The ejector expansion area ratio is designed to be adjustable by varying the ejector throat area while maintaining a constant exit area. This is accomplished by translating the outer ejector throat and nozzle surface relative to the fixed inner ejector surface. The outer movable ejector surface is allowed to translate fore and aft being held in position radially by either a three or four pipe support system. By necessity, the third stage ejector has a four pipe support system while the first and second stage ejectors have a three pipe support system. The details of the three pipe support system are shown on LMSC Drawings R82737 and R82738. The ejector outer surface is translated using four equally spaced electrical actuators.

The actuators are capable of handling 5000 lb each and have a 3 in. stroke for the first and second stage ejectors and a 6 in. stroke for the third stage ejector. The actuator details are not available at this time, although several suppliers are available. The first and second stage ejector throat areas are designed to be completely closed off and inerted.
with GN₂. The diffusers for the first and second stage ejectors are the efficient "second throat type" diffuser design. The third stage ejector is designed to be "started" and run by itself utilizing all of the turbojet exhaust. This ejector is designed to keep the pumped flow subsonic for better pressure recovery. Start-up should not be a problem since the ejector flow will be exhausting into a duct at an initial pressure of approximately 14.7 psia, thereby effectively limiting the ejector area expansion ratio. A few milliseconds later, after the ejector has evacuated the upstream duct system, the cell pressure will drop to 1.0 psia, and the ejector will operate at an area expansion ratio of 3.1:1.0.

The facility will be mounted on the existing rail and support system located at MSFC's Cold Flow Calibration Facility adjacent to the Hot Gas Facility, Building 4554. The site plan is shown in LMSC Drawing R82733. The plan and elevation view is shown in LMSC Drawing R82732. The ejector inlet piping from the J-57 turbojet engine is shown in planform view in LMSC Drawing R82736. The J-57 piping details other than those shown in R82736 were beyond the scope of this contract as mentioned previously in Section 2. The facility will not require cooling water.

The facility also consists of: (1) a J-57 turbojet engine and its fuel tank and controls; (2) the gaseous hydrogen system (piping and components) and high pressure GN₂ supply lines; (3) overhead hoist system for materials handling; (4) hydrogen leak detectors; (5) remote control Firex system; (6) TV camera surveillance system and communication system; (7) remote control systems from Building 4554; and (8) an instrumentation system with remote readout in Building 4588.

4.2 GOVERNMENT-FURNISHED EQUIPMENT LIST

It was beyond the scope of this contract to develop a detailed GFE list. The following list of GFE equipment required to support this facility is preliminary:
1. One working J-57 turbojet engine complete with fuel tank, starter system, instrumentation, and controls
2. One J-57 turbojet engine support structure
3. Approximately 100 ft of 5 in. S/N supply line to the present site from the northeast side of Building 454A, shutoff valve with downstream bolt flange connection to flow 73 lb/sec
4. Gasous hydrogen trailer and control system with 1 in. pipe type AN flared fitting for attachment to the facility to flow 0.5 lb/sec
5. A low pressure (150 psig) S/N purge line system to flow 2 lb/sec
6. Facility instrumentation system with remote readout in Building 4588
7. Overhead hoist or ground support equipment for materials handling
8. Hydrogen leak detector system
9. Remote controlled Firex system
10. TV camera surveillance system and communication system, and
11. Computer system for remote control and data reduction and plotting.

4.3 MATERIALS AND COMPONENTS SELECTION

The sub-scale ejector/diffuser facility will be constructed of 304L stainless steel except as noted. The turbojet exhaust ducting will be constructed of 321 stainless steel of 0.060 in. thickness except for the flanged connections which will be thicker. All flange gaskets will be Sepco Grafoil crinkle gasket tape style SG6360. The 1/4 in. by 1/4 in. ejector sliding seals will be fabricated from Sepco Grafoil sheet style SG36 of 0.015 in. thickness. A local supplier of the Sepco products is TENN-VAL, Inc., of Decatur, Alabama. The full ported check valve is AGCO model CV-2 supplied by the Blythe Company, Indian Trail, N.C. The Digicell valves are supplied by Horton Instrument Company, Birmingham, Alabama. The EMCV valve, the electromechanical actuator, and thermal expansion joints will be custom made for this facility.

The thermal expansion joints shown in LMSC Drawing R82736 can be supplied by U.S. Bellows, Santee, California. The electromechanical control valve (EMCV) and the electromechanical actuator specifications and possible suppliers are listed below.
Electromechanical Control Valve (EMCV) Specifications

Opening Time: 100 msec
Actuator:
- Solenoid with pressurized GN2 over hydraulic
- GN2 pressure available: 4000 psig
- Hydraulic pressure available: 2500 psig
- Hydraulic flow available: 35 gpm
Valve Type: Butterfly
Operating Environment:
- Temperature: 940 F
- Pressure: 18 psig
Supplier: The Blythe Company, Indian Trail, N.C.

Electromechanical Actuator Specifications

Maximum Operating Force: 5000 lbf
Operating Voltage: 28 Vdc
Stroke Speed: 3 in./min.
Stroke:
- First and Second Stage Ejector: 3 in.
- Third Stage Ejector: 6 in.
Dimensions:
- Closed Length: 10 in.
- Outside Diameter: 6 in.
Environment:
- Ambient plus capability of being inerted using GN2 purge to eliminate all explosion hazards
Potential Suppliers:
- Inland Motor, Radford, Va.
- Plessey Dynamics, Hillside, N.J.
- Clifton Precision, Clifton Heights, Pa.

4.4 DRAWINGS

A detailed list of all the drawings which were developed for this facility under this contract is listed in Appendix C. Copies of the drawing set will be released at the discretion of Mr. K.E. Rigsby, FP23, MSFC Contracting Officer's Representative.

4.5 STRESS ANALYSIS

The detailed stress analysis of each facility drawing is contained in Appendix B. The factors of safety which were used are 1.6 on yield strength and 4.0 on ultimate strength. A safety margin summary is contained in Appendix B and shows that each part has an adequate margin of safety.
5. PLANS

Under this contract, a Preliminary Test Plan, an Instrumentation Plan, and a System Operating Procedure Plan were developed. The preliminary test plan was published under separate cover as Ref. 14. The Instrumentation and Operational Procedures Plans are described in this section.

5.1 INSTRUMENTATION PLAN

The subscale ejector/diffuser facility is shown in Fig. 1. The first stage ejector will operate at the highest duct-to-ejector-throat-area ratios, the second stage ejector will operate at medium ejector area ratios and the third stage ejector will operate at the lowest ejector area ratio. The range of ejector area ratios will be between 3 and 300 considering the full scale design. The purpose of the subscale test is to obtain an experimental data base in a subscale facility which when combined with the analytical models, will yield an empirical data base to define completely the operational data base for high volume, low pressure ejector systems such that a full scale design can be accomplished. The subscale data will define the ejector blank-off capability and pumping capability as a function of ejector-to-secondary mass-flow ratio, ejector driving pressure, and ejector area ratio. Data will be obtained from all three ejector stages and will span the ejector area ratio range from 4 to 300, ejector driving pressure range from 4 to 40 psia, and ejector mass flow ratios from 3 to infinity. The variables which will be measured will be cell pressure, ejector exit and duct pressures, exit static and total pressure, the ejector driving total pressure, the driven mass flow rate (secondary), the ejector mass flow rate, and the ejector throat area. The ejector throat area will be calibrated as a function of ejector axial position. The preliminary test matrix configurations and the test matrix were developed in the test plan (Ref. 14).
The following is a preliminary list of the instrumentation required to conduct the test.

1. J-57 turbojet engine instrumentation as called out in Ref. 15.

2. Flow measuring devices
   a. J-57 air flow data taken by means of a smooth approach inlet mounted on the engine fitted with static and total pressure takers as defined in ASHAE Fan Test code.
   b. J-57 fuel flowmeter
   c. One 0.5 in. diameter sharp edge orifice to measure the altitude cell GN₂ purge
   d. One 1 in. diameter venturi meter to measure the GN₂ flow
   e. One 3 in. diameter Digicell flow and pressure control valve to measure the first stage ejector mass flow
   f. One 24 in. diameter venturi meter to measure the second stage ejector J-57 mass flow
   g. One 5 in. diameter Digicell flow and pressure control valve to measure the second stage ejector GN₂ flow rate

3. 150 pressure transducers to record pressures throughout the facility

4. Fifty temperature measurement locations throughout the facility

5. Digicell control computer.

Locations of all instrumentation/measurements will be specified during the next phase of the facility development. Drawing No. R82716-1, "Nozzle Piece, First Stage," shows typical instrumentation port (pressure) and thermocouple attachment details.

5.2 OPERATIONAL PLAN

The operational procedure plan will be developed more completely as the facility construction progresses. The preliminary operational plan follows assuming a diffuser/ejector test using gaseous H₂.
5.2.1 Present

1. Photograph the facility.
2. Verify that the J-57 fuel tank level is adequate.
3. Verify that the GN$_2$ pressure is satisfactory.
4. Verify that the GH$_2$ trailer pressure is satisfactory.
5. Connect instrumentation.
6. Verify that the test instrumentation has been installed per instructions of Test Request Sheet and the Run Time and Test Conditions annotated on the TCP.

7. Schedule the ejector/diffuser test.
   a. ( ) GN$_2$ as needed
   b. ( ) GH$_2$ as needed
   c. ( ) Photography
   d. ( ) Closed Circuit TV
   e. ( ) Instrumentation
   f. ( ) Control.

5.2.2 Test Day

1. Verify that the instrumentation and controls are ready for the X-1 hour announcement.
2. Make the X-1 hour announcement.
3. Verify that all ground support equipment is parked and that power is OFF.
4. Check out test stand for proper electrical power.
5. Activate GN$_2$ system per procedure.
6. Set the following pressure regulators to the proper pressures.
   a. GN$_2$
   b. GH$_2$
   c. GH$_2$ line purge.
7. Set the ejector throat areas in accordance with test request sheet.

8. Activate hydraulic system per procedure.

9. Cycle all valves to verify satisfactory operation.

10. Check that all J-57 engine controls are operating satisfactorily.

12. Verify that cutoff checks are satisfactory.

13. Verify that sequence test has been conducted per procedure.

14. Verify that TV monitors are functioning properly.

15. Verify that video recordings for TV are ready.

16. Activate the J-57 starter air system.

17. Activate the Firex system.

18. Verify that GH$_2$ leak detectors are active.

19. Verify that data system and controls are ready for X-30 minutes.

20. Give X-30 minute warning announcement.

21. Activate the GH$_2$ system per procedure.

22. Set up road blocks at test stand.

23. Make X-15 minutes announcement. (Close HGF area to all personnel.)

24. Verify duration timer set at (TBD) second and power switch ON.

25. Intercom tape ON.

26. Open the GH$_2$ main shutoff.

27. Prepare the GN$_2$ system for test.

28. Prepare the J-57 control system for test per procedure.

29. Make the X-10 minutes warning announcement.
30. Prepare the GH₂ system for test.
31. Turn data system ON - SLOW
32. Turn video recording ON
33. Adjust the ejector GH₂ flow controller
34. Adjust the GH₂ flow controller.
35. Make X-5 minute warning announcement.
36. Verify that the following systems are ready:
   a. Control
   b. Data system
   c. Cameraman
   d. Analog recorder, and
   e. Test stand.
37. Cutoffs ready - ON
38. Sound X-20 second siren.
39. Set J-57 data systems on FAST
40. Give firing command.
41. Start J-57 engine per procedure.
42. Verify J-57 operation at IDLE power setting.
43. Allow J-57 warmup time.
44. Advance J-57 throttle position to TEST SET position; check J-57 operation per procedure.
45. Verify ejector system operation according to test request.
46. Conduct test per test request.
47. Cutoff
   a. GH₂ purges - ON
   b. Cameras - OFF
48. Deactivate the GH₂ system.
49. Deactivate the GH₂ system.
50. Clear the test stand for designated crew.

51. Turn Intercom - OFF.

52. Turn data system - OFF.

53. Turn video recording - OFF.

5.2.3 On Stand Post-Test

1. Perform appropriate post-test check outs of instrumentation and J-57 engine.

2. Deactivate Firex system.

3. Deactivate hydraulics.

4. Reset pressure regulators to 0 psig.

5. Remove road blocks.


7. Shut off electrical power to test stand.

5.3 SAFETY PLAN

5.3.1 Grounding Requirements


5.3.2 Purge Requirements

Since this facility uses hydrogen, the purging requirements for electrical equipment and wiring will be as specified in KSC STD-E-002, Revision A, "Hazard Proofing of Electrical Equipment."
6. REFERENCES


Appendix A

FULL SCALE GASDYNAMIC SAFETY ANALYSIS
DESIGN OF A SUBSCALE DIFFUSER
FOR HIGH EXPANSION RATIO
ENGINE TESTING

FULL SCALE GASEODYNAMIC
SAFETY ANALYSIS

by
C. J. Wojciechowski
S. C. Kurzius

13 April 1984

Lockheed
Missiles & Space Company, Inc.
Huntsville Research & Engineering Center
AGENDA

1. Objective

2. Milestones and Schedule

3. Concept of Preliminary Full Scale Design

4. Technical Issues and Concerns

5. Key Progress to Date
   - Analysis Shows Safe Operation
   - Design Meets All Requirements

6. Future Work
# AMENDED SCOPE OF WORK SCHEDULE AND MILESTONES

<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
<th>Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Full-Scale Design Analysis</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Full-Scale Gas Dynamic Hazard Analysis</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Full-Scale Ejector Analysis</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Subscale Design Recommendation</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Diffuser Sensitivity Analysis</td>
<td></td>
</tr>
</tbody>
</table>

**Intermediate Reviews**

**90% Design Review**

**Final Report**
TECHNICAL ISSUES AND CONCERNS

- Ejector Stability and Controllability
- Transient Operation
- Overall Ejector Performance
  - Scale Effects (Langley, MSFC Prototype - Full Scale)
- Safety
  - Suppression of Hydrogen Detonation to be Evaluated by Analysis and Test Data
  - Facility to be Designed to Detonation Loads
SYNOPSIS OF ENGINE TRANSIENT HAZARD ASSESSMENT
(DIFFUSER DRIVER: J57 JET ENGINE EXHAUST)

**AECE-R Engine** (Based on ASE Engine Data)

**Startup**  -  Potential Hazard, O/F < 2.0 from 0 to 2.4 sec after Start Signal

**Main Stage**  -  No Hazard, O/F = 6.0, High Thrust; O/F = 4.0, Low Thrust

**Shutdown**  -  Potential Hazard, O/F < 2.0 at Shutoff Signal + 150 msec

**RL10-IIB Engine** (Based on RL10A-3-3A Engine Data)

**Startup**  -  Potential Hazard; O/F < 2.0 from 0.20 to 1.58 sec after Start Signal

**Main Stage**  -  No Hazard; O/F = 6.0 for Low and High Thrust Operation

**Shutdown**  -  Potential Hazard; Quantitative Transient Data Inputs are Required.

**Pratt & Whitney Inputs on RL10 Shutdown:**

1. If a graphite nozzle is used, oxidizer-rich shutdown must be avoided to protect hot engine and red hot nozzle.

2. Somewhat in conflict with 1, H₂ is normally dumped overboard on shutdown, with a maximum total of 1/4 lb H₂ flowed through the nozzle on shutdown.

**Proposed Control to Eliminate Potential Start/Stop Hazards:**

Use a Purge GN₂ Flow as the Inert Gas Driver in 1st and 2nd Stages During Transients, as Required.
REVIEW


Analysis Path

- Review Engine Performance Data
- Initialize Diffuser Design for Engine Tests
- Evaluate Hazard
- Modify Design and Operation to Eliminate Hazard as Required

Space Engines Analyzed

- RL-10-IIB
- AECE-R

10% and 100% Thrust
HAZARD ANALYSIS: WORST CASE

CHAPMAN-JOUQUET DETONATION PRESSURE RATIO

CHARACTERISTICS AT PREVAILING STREAM
TOTAL TEMPERATURES

![Graph showing Chapman-Jouquet Detonation Pressure Ratio](image)

- Maximum, NBP H₂
- Cryogenic H₂
- Maximum 300 K H₂
- Room Temperature H₂
- Potentially Hazardous Mixtures
- No Hazard
- Main Stage Engine Effluent
- Air Lean Limit
- Air Rich Limit

Chapman-Jouquet Detonation Pressure Ratio, $P_d/P_1$

Mixture H₂ Concentration, Vol % (No Combustion)

A-6
FULL SCALE 10% THRUST
DIFFUSER/EJECTOR PRESSURE DISTRIBUTION

RL10-IIIB 10% Thrust
Main Stage Operation

\[
\begin{align*}
O/F &= 6.0 \\
C &= 40 \text{ psia} \\
m &= 3.26 \text{ lbm/sec}
\end{align*}
\]

RL10-IIIB/Ejector
Mixture Total
Pressure

Duct Pressure (psia)

First Stage Ejector  Second Stage Ejector  Third Stage Ejector

FULL SCALE RL10-IIB 100% THRUST DIFFUSER/EJECTOR PRESSURE DISTRIBUTION

RL10-IIB 100% Thrust
Main Stage Operation

\[ \frac{O}{F} = 6.0 \]
\[ P_c = 400 \text{ psia} \]
\[ m = 32.6 \text{ lbm/sec} \]

Note: This curve also applies to the AECE-R engine for 100% Thrust

\[ \frac{O}{F} = 6.0 \]
\[ P_c = 1539 \text{ psia} \]
\[ m = 31.2 \text{ lbm/sec} \]
H$_2$-GOX STATIC IGNITION LIMITS

(Spark igniter, 4 in. diameter x 15 in. long chamber, PWA FR-303, Nov 61)
H₂-LOX ENGINE
EXHAUST AUTOIGNITION
CHARACTERISTICS

Fuel: H₂-Rich Space Engine Effluent

AECE-R Engine: 3.7 lb/sec, Low Thrust
31.2 lb/sec, Full Thrust

RL10-IIB Engine: 3.2 lb/sec, Low Thrust
32.6 lb/sec, Full Thrust

Oxidizer: J57 Jet Engine Exhaust: O₂
16.7 vol.%: Tₘ₀ = 778 K

1st Stage: 2.8 lb/sec (Low Thrust Only)

2nd Stage: 23.2 lb/sec: Low Thrust
26.0 lb/sec, Full Thrust

3rd Stage: 451 lb/sec, Low and Full
Thrust

\[ \text{H}_2\text{-LOX Combustor Temperatures} \]

<table>
<thead>
<tr>
<th>Engine O/F</th>
<th>( T_P, \text{K} ) (M=0)</th>
<th>( T_s, \text{K} ) (M=1)</th>
<th>( T_s, \text{K} ) (M=2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0</td>
<td>2958</td>
<td>2847</td>
<td>2563</td>
</tr>
<tr>
<td>4.0</td>
<td>2756</td>
<td>2610</td>
<td>2188</td>
</tr>
<tr>
<td>2.0</td>
<td>2019</td>
<td>1781</td>
<td>1301</td>
</tr>
<tr>
<td>1.0</td>
<td>1257</td>
<td>1072</td>
<td>731</td>
</tr>
<tr>
<td>0.75</td>
<td>1034</td>
<td>874</td>
<td>590</td>
</tr>
<tr>
<td>0.5</td>
<td>798</td>
<td>670</td>
<td>450</td>
</tr>
<tr>
<td>0.25</td>
<td>552</td>
<td>462</td>
<td>308</td>
</tr>
</tbody>
</table>

No Hazard

Gases Burn as Rapidly as They Mix

Potential Hazard

No Hazard
AECE-R ENGINE TRANSIENT CHARACTERISTICS

(Estimated from ASE Engine Data)

![Graph showing performance characteristics of AECE-R engine.](image-url)
AECE-R ENGINE SECOND STAGE DIFFUSER TRANSIENT CHARACTERISTICS WITH J57 JET ENGINE EXHAUST AS DRIVER (26 lb/sec)

(Note: J57 WILL NOT BE USED AS DRIVER DURING TRANSIENTS)
RL10A-3-3A ENGINE START TRANSIENT CHARACTERISTICS

[Diagram showing mixture ratio, O/F, fuel flow rate, and time from start signal (sec).]

- Fuel Flow Rate 100% Thrust
- O/F
- Potential Hazard at Engine Start
- Main Stage
- RL10-IIB
AECE-R ENGINE 2nd STAGE DIFFUSER TRANSIENT OPERATION

(100% Thrust; Driver: \( \text{GN}_2 \), 150 lb/sec)

- Lower Detonation Limit
- Total Temperature of Flow to 3rd Stage
- \( \text{H}_2 \) Concentration in Flow to 3rd Stage
- Diluted Below Limit in 3rd Stage Prior to Approaching Ignition Temperature

Graph showing:
- Vol. % \( \text{H}_2 \) in 2nd Stage Exhaust vs. Time (sec)
- 2nd Stage Exhaust, \( T_e \) (K) vs. Time (msec)

Time (sec) vs. Time (msec)
# LOW THRUST OPERATION

<table>
<thead>
<tr>
<th>Engine Status</th>
<th>Driver (Stages 1 &amp; 2)</th>
<th>Stage</th>
<th>KL 10-IIB Engine</th>
<th>AECE-R Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$T_T$, K</td>
<td>$T_T$, K</td>
</tr>
<tr>
<td>Main Stage Burn</td>
<td>J57s</td>
<td></td>
<td>2958</td>
<td>2756</td>
</tr>
<tr>
<td></td>
<td>Engine</td>
<td></td>
<td>29.5</td>
<td>48.6</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td></td>
<td>2628</td>
<td>2565</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>16.9</td>
<td>33.2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>2958</td>
<td>2310</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>16.9</td>
<td>33.2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>2958</td>
<td>2310</td>
</tr>
<tr>
<td></td>
<td>Engine</td>
<td></td>
<td>29.5</td>
<td>48.6</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td></td>
<td>2628</td>
<td>2565</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>16.9</td>
<td>33.2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>2958</td>
<td>2310</td>
</tr>
</tbody>
</table>

- $H_2$ is burned virtually to completion in 1st and 2nd stages.

| Main Stage Burn     | GN2                    | Engine | 2958 | 29.5 | 2756 | 48.6 |
|                     |                        | 1      | 2461 | 15.4 | 2304 | 33.1 |
|                     |                        | 2      | 958  | 2.8  | 955  | 8.5  |
|                     |                        | 3      | 799-825 | 0.3-Nil | 799-878 | 0.9-Nil |

- Flow enters 3rd stage with $H_2$ well below detonation limit.

<table>
<thead>
<tr>
<th>Start/Stop Transients</th>
<th>GN2</th>
<th>Worst Cases: KL 10-IIB Engine: Full Fuel Flow, 0.466 lb $H_2$/sec</th>
<th>AECE-R Engine: Full Fuel Flow, 0.74 lb $H_2$/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Engine</td>
<td>Engine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>300 99.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>300 67.3</td>
</tr>
</tbody>
</table>

- $H_2$ flow is diluted with GN2 to below detonation limit in stages 1 and 2 even with the full maximum rated flow of unburned $H_2$ at low thrust.
### 100% THRUST OPERATION

<table>
<thead>
<tr>
<th>Engine Status (Stages 1 &amp; 2)</th>
<th>Driver</th>
<th>Stage</th>
<th>RL 10-IIB Engine Exhaust</th>
<th>AECE-R Engine Exhaust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Stage Burn</td>
<td>J57s</td>
<td></td>
<td>T&lt;sub&gt;T&lt;/sub&gt;, K</td>
<td>Vol. % H&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td>Not Driven</td>
<td>Engine</td>
<td>1</td>
<td>2958</td>
<td>29.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2958</td>
<td>29.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1545</td>
<td>Nil</td>
</tr>
</tbody>
</table>

- H<sub>2</sub> is burned as rapidly as it mixes in 2nd and 3rd stages.

<table>
<thead>
<tr>
<th>Main Stage Burn</th>
<th>GN&lt;sub&gt;2&lt;/sub&gt;</th>
<th>Engine</th>
<th>T&lt;sub&gt;T&lt;/sub&gt;, K</th>
<th>Vol. % H&lt;sub&gt;2&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Driven</td>
<td></td>
<td>1</td>
<td>2958</td>
<td>29.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1855</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1324</td>
<td>Nil</td>
</tr>
</tbody>
</table>

- H<sub>2</sub> flow is diluted with GN<sub>2</sub> to well below detonation limit in 2nd stage and burns as rapidly as it mixes in 3rd stage.

### Stop/Start Transients

- H<sub>2</sub> in flow is diluted and cooled with GN<sub>2</sub> to below detonation limit in 2nd stage.
RL10-IIB AND AECE-R STARTUP AND SHUTDOWN OPERATION

FULL SCALE 10% THRUST JET ENGINE DRIVEN EJECTOR/DIFFUSER SYSTEM

Engine Test Cell

1st Stage Ejector
Engine Diffuser

2nd Stage Ejector

3rd Stage Ejector

Vent

GN2 Inerting Purge 5 lb/sec
P = 41 psia
T = 295 K

2.8 lb/sec Effluent
P = 33 psia
T = 778 K

23.2 lb/sec Effluent
P = 33 psia
T = 778 K

m = 451 lb/sec
Engine Effluent
T = 778 K
P = 33 psia

Comp Burner Turbine

3 J57 Turbojet Engines
RL10-IIB OR AECE-R ENGINE STEADY STATE OPERATION

FULL SCALE 100% THRUST JET ENGINE DRIVEN EJECTOR/DIFFUSER SYSTEM

Engine Test Cell

1st Stage Ejector

Engine Diffuser

Vent

Closed Off

GN₂ Inerting
Purge 0 lb/sec
P = 75 psia
T = 295 K

Vent

Closed Off

26 lb/sec Effluent
P = 33 psia
T = 778 K

2nd Stage Ejector

26 lb/sec Effluent
P = 33 psia
T = 778 K

Comp Burner Turbine

3 J57 Turbojet Engines

3rd Stage Ejector

Engine Effluent
P = 451 lb/sec
T = 778 K
Pₜ = 33 psia
Appendix B

ORIGINAL STRESS NOTES
SUBSCALE FACILITY PRELIMINARY DESIGN

by

D.N. Tilley

Structures & Materials Group
FOREWORD

This strength analysis was performed as a preliminary check on the safety and feasibility of the overall design approach as of April 1984. The overall dimensions of the basic structures were used with conservative load assumptions. No attention was given at this time to detailed parts. This limited analysis does not constitute an endorsement of the design for fabrication.
CONTENTS

FOREWORD
SUBSCALE FACILITY MARGIN SUMMARY
MATERIAL PROPERTIES
SUBSCALE FACILITY OPERATING CONDITIONS
STRUCTURAL ANALYSIS
SUBSCALE FACILITY SUPPORT STRUCTURE

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8-3
8-4
8-8
8-48

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LOCKHEED-HUNTSVILLE RESEARCH & ENGINEERING CENTER
<table>
<thead>
<tr>
<th>ITEM</th>
<th>DESCRIPTION</th>
<th>BUCKLING</th>
<th>UFL</th>
<th>YIELD</th>
</tr>
</thead>
<tbody>
<tr>
<td>K82764</td>
<td>ATTITUDE SIMULATION CELL</td>
<td>+14.16</td>
<td>+24.3</td>
<td>+21.6</td>
</tr>
<tr>
<td>K82765</td>
<td>ATTITUDE, CELL &amp; PLATE</td>
<td>-</td>
<td>+41.56</td>
<td>+8.24</td>
</tr>
<tr>
<td>K82761</td>
<td>INSERT PLATE</td>
<td>+6.1</td>
<td>-</td>
<td>-7.5</td>
</tr>
<tr>
<td>K82762</td>
<td>Lu Cylindrical -</td>
<td>-</td>
<td>+7.6</td>
<td>+5.6</td>
</tr>
<tr>
<td>K82767</td>
<td>ATTITUDE CELL &amp; PLATE</td>
<td>-</td>
<td>+9.35</td>
<td>+8.24</td>
</tr>
<tr>
<td>K82769</td>
<td>NERBLE DISCRIMINATE SATE</td>
<td>+1.86</td>
<td>-19.2</td>
<td>+8.58</td>
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<tr>
<td>K82766</td>
<td>EXPANSION SECTION - NO. 3</td>
<td>+78.6</td>
<td>+33.96</td>
<td>+3.9</td>
</tr>
<tr>
<td>K82764</td>
<td>EJECTOR TUBE - FIRST STAGE</td>
<td>+49.3</td>
<td>+14.03</td>
<td>+3.12</td>
</tr>
<tr>
<td>K82764</td>
<td>EXPANSION SECTION - 1ST STAGE</td>
<td>+24.3</td>
<td>+6.33</td>
<td>+5.0</td>
</tr>
<tr>
<td>K82766</td>
<td>ADJUSTABLE TUBE ASSY</td>
<td>+22.4</td>
<td>+27.7</td>
<td>+27.7</td>
</tr>
<tr>
<td>K82767</td>
<td>FIRST STAGE CONSTRUCTION SATE</td>
<td>-10.4</td>
<td>+27.9</td>
<td>+27.9</td>
</tr>
<tr>
<td>K82768</td>
<td>1ST TO 2ND STAIR SATE</td>
<td>+5.6</td>
<td>+30.0</td>
<td>+27.9</td>
</tr>
<tr>
<td>K82764</td>
<td>EJECTOR TUBE - 2ND STAGE</td>
<td>+21.6</td>
<td>+3.43</td>
<td>+1.17</td>
</tr>
<tr>
<td>K82764</td>
<td>EXPANSION SECTION - 2ND STAGE</td>
<td>+12.0</td>
<td>+10.1</td>
<td>+8.1</td>
</tr>
<tr>
<td>K82764</td>
<td>ADJUSTABLE TUBE ASSY</td>
<td>+11.72</td>
<td>+52.2</td>
<td>+18.0</td>
</tr>
<tr>
<td>K82764</td>
<td>2ND TO 3RD STAGE STRAIGHT</td>
<td>+0.96</td>
<td>+40.1</td>
<td>+7.33</td>
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<tr>
<td>K82764</td>
<td>3RD STAGE EJECTOR TUBE</td>
<td>+7.52</td>
<td>+10.32</td>
<td>+2.27</td>
</tr>
<tr>
<td>Type</td>
<td>Description</td>
<td>Tacking</td>
<td>Cut</td>
<td>YLD</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------------------</td>
<td>---------</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>R827271</td>
<td>3rd stage selector</td>
<td>+11.77</td>
<td>+7.18</td>
<td>+2.89</td>
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<tr>
<td>R827279</td>
<td>Conical section - third stage</td>
<td>+17.98</td>
<td>+9.03</td>
<td>+2.67</td>
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<tr>
<td>R827291</td>
<td>Straight section - third stage</td>
<td>-1.97</td>
<td>-9.3</td>
<td>+2.67</td>
</tr>
<tr>
<td>R827230</td>
<td>Exit tank section</td>
<td>+8.75</td>
<td>+9.29</td>
<td>+2.67</td>
</tr>
<tr>
<td>R827061</td>
<td>Nozzle body</td>
<td>+0.75</td>
<td>+6.6</td>
<td></td>
</tr>
<tr>
<td>R827067</td>
<td>Structural support</td>
<td>+0.74</td>
<td>+8.4</td>
<td></td>
</tr>
<tr>
<td>R827087</td>
<td>Sliding boxing pipe</td>
<td>+1.37</td>
<td>+1.50</td>
<td></td>
</tr>
<tr>
<td>R827087</td>
<td>Diagonal tubing</td>
<td>+1.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R827087</td>
<td>Top of frame kennel</td>
<td>-1.08</td>
<td>+1.78</td>
<td></td>
</tr>
<tr>
<td>R827087</td>
<td>Side of frame kennel</td>
<td>+2.11</td>
<td>+3.17</td>
<td></td>
</tr>
<tr>
<td>R827087</td>
<td>Fasteners to rail</td>
<td>+4.44</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ORIGINAL PRINT IS OF POOR QUALITY
### MATERIAL PROPERTIES 304 L STAINLESS STEEL

<table>
<thead>
<tr>
<th>304 L ST. ST.</th>
<th>E</th>
<th>FTY</th>
<th>FCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>At RT</td>
<td>$28 \times 10^6$</td>
<td>70 ksi</td>
<td>25 ksi</td>
</tr>
<tr>
<td>312 F (772 R)</td>
<td>$27 \times 10^6$</td>
<td>59 ksi</td>
<td>22 ksi</td>
</tr>
<tr>
<td>440 F (900 R)</td>
<td>$25.5 \times 10^6$</td>
<td>55 ksi</td>
<td>18 ksi</td>
</tr>
<tr>
<td>778 F (1238 R)</td>
<td>$23 \times 10^6$</td>
<td>51.5 ksi</td>
<td>13.5 ksi</td>
</tr>
</tbody>
</table>
NOTE:

Axial loads in the subscale ejector/diffuser piping are accounted for through the calculations of hydrostatic, blockage, and compressible pressures. Hydrostatic pressure is used in analyzing a pipe section for identified axial loads and assumed as truth at the ends unless specified.

**Hydrostatic Pressure**

**Lateral Pressure**

Since axial stress due to hydrostatic pressure is half that of hoop stress, axial stresses are not calculated.

An exception to this is for sections between the reaction stations and the ejectors. The high energy entering the system at the ejectors is reacted axially to the piping to the reaction stations. This axial load would not be accepted for under the hydrostatic assumption above.

All 'check' equations are from NASA Structures Manual, Section C-3.0.
Since the 1200 psi load overshadows the 14.7 psi load all considerations will be made to the larger load.

- For the high pressure diameter of \( \phi \) 2.1 in. the 900 lb flange standard gives a blind flange thickness of \( Q = 2y \) in (zebzo page 110-111) or ASA 16G.
  
- Material: ASTM A105 Grade II

- Material: ASTM A105 Grade II \( F_y = 36,000 \text{ psi} \) (zebzo 7-152)

- Stress ratio: \( \frac{F_y}{304} \) = 1.44

- The 900 lb standard has a working pressure of 2100 psi at 1.1 in. (zebzo page 161)

- A 2.5 in. blind flange has a working pressure of \( \frac{2100}{1.44} = 1500 \text{ psi} \).

- The 2 in. thickness should have a working pressure of at least \( (3/2.6) \times 1500 = 1800 \).

- M.S. = \( \frac{1800}{1200} - 1 = \)

- With a factor of safety of 2.

-- Continued
ADJUST MARGIN CALCULATIONS TO REFLECT 4 X 1.6
OLD ULT. & YLD :

\[ M.S. = \frac{2(1800)}{1.6(1200)} - 1. \]

\[ M.S. = \frac{2(1800)}{1.6(1200)} - 1. \]

TRATION YLD.

\[ M.S. = \frac{(70)}{2(1200)} - 4(1200) - 1. \]

\[ M.S. = \frac{(70)}{2(1200)} - 4(1200) - 1. \]

ORIGINAL DATA:
OF POOR QUALITY.
### Stainless Steels

<table>
<thead>
<tr>
<th>Size (in)</th>
<th>3/4</th>
<th>1 1/4</th>
<th>1 1/2</th>
<th>1 1/4</th>
<th>1 1/2</th>
<th>1 1/2</th>
<th>1 1/2</th>
<th>1 1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weights (lbs)</td>
<td>3.57</td>
<td>3.50</td>
<td>3.50</td>
<td>3.50</td>
<td>4.67</td>
<td>4.60</td>
<td>4.60</td>
<td>4.60</td>
</tr>
<tr>
<td>Weights (lbs)</td>
<td>5.68</td>
<td>5.69</td>
<td>5.69</td>
<td>5.69</td>
<td>6.73</td>
<td>6.73</td>
<td>6.73</td>
<td>6.73</td>
</tr>
<tr>
<td>Weights (lbs)</td>
<td>8.73</td>
<td>8.73</td>
<td>8.73</td>
<td>8.73</td>
<td>10.88</td>
<td>10.92</td>
<td>10.92</td>
<td>10.92</td>
</tr>
</tbody>
</table>

For sizes 3/4" through 2 1/4" use 1500 lb flanges.
PHYSICAL and CHEMICAL REQUIREMENTS of Flange, Bolt, and Nut Steels

Physical and Chemical Requirements, STEEL FORGINGS for FLANGES, at Primary Service Pressure Ratings of 150- to 300-Lb per Sq In. (ASTM A181)

<table>
<thead>
<tr>
<th>Temperature (°F)</th>
<th>275</th>
<th>300</th>
<th>350</th>
<th>400</th>
<th>450</th>
<th>500</th>
<th>550</th>
<th>600</th>
<th>650</th>
<th>700</th>
<th>750</th>
<th>800</th>
<th>850</th>
<th>900</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield point (ksi)</td>
<td>250</td>
<td>300</td>
<td>350</td>
<td>400</td>
<td>450</td>
<td>500</td>
<td>550</td>
<td>600</td>
<td>650</td>
<td>700</td>
<td>750</td>
<td>800</td>
<td>850</td>
<td>900</td>
</tr>
<tr>
<td>Tensile strength (min)</td>
<td>50,000</td>
<td>55,000</td>
<td>60,000</td>
<td>65,000</td>
<td>70,000</td>
<td>75,000</td>
<td>80,000</td>
<td>85,000</td>
<td>90,000</td>
<td>95,000</td>
<td>100,000</td>
<td>105,000</td>
<td>110,000</td>
<td>115,000</td>
</tr>
<tr>
<td>Reduction of area (%)</td>
<td>25</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>45</td>
<td>50</td>
<td>55</td>
<td>60</td>
<td>65</td>
<td>70</td>
<td>75</td>
<td>80</td>
<td>85</td>
<td>90</td>
</tr>
<tr>
<td>Phosphorus (max)</td>
<td>0.02%</td>
<td>0.03%</td>
<td>0.04%</td>
<td>0.05%</td>
<td>0.06%</td>
<td>0.07%</td>
<td>0.08%</td>
<td>0.09%</td>
<td>0.10%</td>
<td>0.11%</td>
<td>0.12%</td>
<td>0.13%</td>
<td>0.14%</td>
<td>0.15%</td>
</tr>
<tr>
<td>Sulphur (max)</td>
<td>0.035%</td>
<td>0.040%</td>
<td>0.045%</td>
<td>0.050%</td>
<td>0.055%</td>
<td>0.060%</td>
<td>0.065%</td>
<td>0.070%</td>
<td>0.075%</td>
<td>0.080%</td>
<td>0.085%</td>
<td>0.090%</td>
<td>0.095%</td>
<td>0.100%</td>
</tr>
</tbody>
</table>

PRESSURE TEMPERATURE RATINGS of American Standard Carbon* Steel Pipe Flange

<table>
<thead>
<tr>
<th>Service Temperature (°F)</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
<th>1100</th>
<th>1200</th>
<th>1300</th>
<th>1400</th>
<th>1500</th>
<th>1600</th>
<th>1700</th>
<th>1800</th>
<th>1900</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength (ksi)</td>
<td>250</td>
<td>300</td>
<td>350</td>
<td>400</td>
<td>450</td>
<td>500</td>
<td>550</td>
<td>600</td>
<td>650</td>
<td>700</td>
<td>750</td>
<td>800</td>
<td>850</td>
<td>900</td>
</tr>
<tr>
<td>Yield point (ksi)</td>
<td>200</td>
<td>250</td>
<td>300</td>
<td>350</td>
<td>400</td>
<td>450</td>
<td>500</td>
<td>550</td>
<td>600</td>
<td>650</td>
<td>700</td>
<td>750</td>
<td>800</td>
<td>850</td>
</tr>
<tr>
<td>Reduction of area (%)</td>
<td>25</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>45</td>
<td>50</td>
<td>55</td>
<td>60</td>
<td>65</td>
<td>70</td>
<td>75</td>
<td>80</td>
<td>85</td>
<td>90</td>
</tr>
<tr>
<td>Phosphorus (max)</td>
<td>0.02%</td>
<td>0.03%</td>
<td>0.04%</td>
<td>0.05%</td>
<td>0.06%</td>
<td>0.07%</td>
<td>0.08%</td>
<td>0.09%</td>
<td>0.10%</td>
<td>0.11%</td>
<td>0.12%</td>
<td>0.13%</td>
<td>0.14%</td>
<td>0.15%</td>
</tr>
<tr>
<td>Sulphur (max)</td>
<td>0.035%</td>
<td>0.040%</td>
<td>0.045%</td>
<td>0.050%</td>
<td>0.055%</td>
<td>0.060%</td>
<td>0.065%</td>
<td>0.070%</td>
<td>0.075%</td>
<td>0.080%</td>
<td>0.085%</td>
<td>0.090%</td>
<td>0.095%</td>
<td>0.100%</td>
</tr>
</tbody>
</table>

* American Standard Carbon Steel Pipe Flange
LOAD - 1200. 151A 127 T

ORIGINAL PAGE IS OF POOR QUALITY

\[
\sigma = \frac{Td}{2} = (1200) \frac{0.875}{2} \times 0.875 = 471.4 \text{ psi}
\]

\[
M.S. = \frac{10.4}{4} \times 471.4 - 1.5 + 2.71 \text{ ULT}
\]

\[
M.S. = \frac{29.6}{1.5} \times 471.4 - 1.5 + 2.31 \text{ YLD}
\]

Flange thicknesses of 2.5 in are used with the small 1.5 in as inlet plate thickness (Ref. 2701).

\[
M.S. = \frac{1500}{1200} - 1 = 0.25
\]

With a yield factor of \( \gamma \) in the numerator,

\[
M.S. = \frac{7(1500)}{1.5(1200)} - 1 = 1.66 \text{ YLD}
\]

With a yield factor of 1.6, a ratio of 7.75 the ult:

\[
M.S. = \frac{70.15(2)1500}{4(1200)} - 1 = 1.75 \text{ ULT}
\]
**DIMENSIONS of Seamless and Welded STEEL PIPE**

ASA-836.10 and B36.10

<table>
<thead>
<tr>
<th>Nominal Size (inch)</th>
<th>Outside (in)</th>
<th>Wall Thickness (in)</th>
<th>Outside Diameter (in)</th>
<th>Outside Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4</td>
<td>0.068</td>
<td>0.068</td>
<td>0.125</td>
<td>3.18</td>
</tr>
<tr>
<td>1/2</td>
<td>0.088</td>
<td>0.088</td>
<td>0.188</td>
<td>4.77</td>
</tr>
<tr>
<td>3/4</td>
<td>0.109</td>
<td>0.109</td>
<td>0.229</td>
<td>5.82</td>
</tr>
<tr>
<td>1</td>
<td>0.125</td>
<td>0.125</td>
<td>0.281</td>
<td>7.14</td>
</tr>
<tr>
<td>1 1/2</td>
<td>0.145</td>
<td>0.145</td>
<td>0.350</td>
<td>8.89</td>
</tr>
<tr>
<td>2</td>
<td>0.165</td>
<td>0.165</td>
<td>0.406</td>
<td>10.30</td>
</tr>
<tr>
<td>2 1/2</td>
<td>0.188</td>
<td>0.188</td>
<td>0.457</td>
<td>11.59</td>
</tr>
<tr>
<td>3</td>
<td>0.200</td>
<td>0.200</td>
<td>0.500</td>
<td>12.70</td>
</tr>
<tr>
<td>4</td>
<td>0.229</td>
<td>0.229</td>
<td>0.625</td>
<td>15.91</td>
</tr>
<tr>
<td>6</td>
<td>0.325</td>
<td>0.325</td>
<td>0.875</td>
<td>22.19</td>
</tr>
<tr>
<td>8</td>
<td>0.406</td>
<td>0.406</td>
<td>1.000</td>
<td>25.40</td>
</tr>
<tr>
<td>10</td>
<td>0.483</td>
<td>0.483</td>
<td>1.250</td>
<td>31.75</td>
</tr>
<tr>
<td>12</td>
<td>0.500</td>
<td>0.500</td>
<td>1.500</td>
<td>38.10</td>
</tr>
</tbody>
</table>

**Note:** The table contains dimensional data for seamless and welded steel pipe, specifying the nominal size, outside diameter, and wall thickness for various pipe sizes. The data is provided in inches and millimeters, with typical applications in the construction and mechanical engineering fields.
**LOAD: VACUUM AT RT**

**ORIGINAL DATA IS OF POOR QUALITY**

**D = E * 3 / 12 (1 - v²) = 28,000,000 (188³) / 12 (9216) = 16823.**

**Z = L² (1 - v²)³ / 2RT = 12.8² * 9216 / 8.92 (188) = 94.82**

**HYPOTENUS EFFECT WHERE:**

\[ \gamma = 0.56 \quad \text{AND} \quad Z = 53.1 \]

**M.S. = 9(9.4 / (4.7)) - 1 = 14.6**

**HOOP STRESS**

\[ \sigma = \frac{PD}{2\tau} = 14.7 (17.633) / 2 (188) = 689.75 \]

**M.S. = 70 / 4 (69) - 1 = 14.6**

**M.S. = 25 / 1.0 (69) - 1 = 14.6**
THE NOZZLE BODY SUPPORT CAN BE CONSIDERED A "THIRD FLANGE" AND USING THE TANGENT ALL ON PAGE 1 (FOR THE END PLATE - RC2701) THE 2.5 IN. THICKNESS HAS A WORKING PRESSURE OF OF 1500 PSI.

THIS WORKING PRESSURE HAS A YIELD FACTOR OF SAFETY OF AT LEAST 2. THEREFORE:

\[ M.S. = \frac{2(1500)}{1.4(1200)} - 1. = +.56 \text{ YLD} \]

RATIO ING FOR THE ULT MAX-125:

\[ M.S. = \frac{75}{25} \frac{2(1500)}{4(1200)} - 1. = +.75 \text{ ULT} \]

CUSHETS ARE CONSERVATIVELY IGNORED

[Diagram of nozzle body support with dimensions and calculations]
THROAT OF NOZZLE —

ASSUME 1200 PSI AT ID = 2.65 & T = .38 & R.T.

\[ F = \frac{PD}{2T} = \frac{1200 (2.65)}{2 (.38)} = 4184 \text{ PSI} \]

M.S. = 70 / 4 (4.184) - 1.0 = +38.18

M.S. = 26 / 1.6 (4.184) - 1.0 = +2.73

CONSERVATIVE LOAD—SINCE 1200 PSI DECREASES FROM CYLINDER TO NOZZLE'S END.
LOADED EDGES

\[
\text{LOAD} = 14.7 \text{ PSI} \quad \text{NORMAL TENSILE FORCE AT TST:}
\]

\[
+\text{PLUS CENTER LOAD} = 14.7 \times 1.23 = 18.0 \text{ KSI}
\]

\[
\text{DISPLACEMENT} = \frac{4}{13} \times \frac{17.63}{17.63} = 0.278
\]

\[
C_S = \frac{1}{2} \left[ 1 - \left(\frac{13}{17.63}\right)^2 \right] = 0.228
\]

\[
S_0 = \frac{6M}{T^2} = \frac{6(13.82)}{0.25} = 1380 \text{ KSI}
\]

\[
\text{CASE 2F:} \quad M = 4 \frac{A^2}{L_4} / C_S = 14.7 \left(\frac{1.69^2}{17.63}\right) 0.25 / 0.25 = 13.02 \text{ KSI}
\]

\[
L_4 = \frac{1}{16} \left[ 1 - \left(\frac{13}{17.63}\right)^2 - 4 \left(\frac{13}{17.63}\right)^2 \ln \left(\frac{17.63}{13}\right) \right] = 0.0026
\]

\[
S_0 = \frac{6M}{T^2} = \frac{6(13.02)}{0.25} = 312.6 \text{ KSI}
\]

\[
T_T = 1380 + 312.6 = 1692 \text{ KSI}
\]

\[
M_{S} = 70 / 4 (1.69) - 1 = +9.35 \text{ ULT}
\]

\[
M_{S} = 25 / 16 (1.69) - 1 = -3.24 \text{ YLD}
\]
TEF: KIGA STRUCTURES MANUAL, SLT C3, P.13

\[ D = \frac{E \pi^2}{12 (1 - \nu^2)} = \frac{28 \times 10^6 (0.322^3)}{12 (0.9215)} = 84537 \text{ in} \]

\[ N = \frac{L^2 (1-\nu^2) R^2}{L T} = \frac{72^2 \sqrt{0.9215/4.3 (0.322)}}{35144} \]

\[ P_{CL} = K_P \pi^2 D / R L^2 = \frac{4.5 \pi^2 84537 / 4.3 (72)^2}{168.4 \pi (14.7)} = 168.4 \pi \]

HYDRAULIC PRESSURE WHERE \( \Delta = 0.6 \), \( \tau = 200 \text{ psi} \)

\[ K_P = 4.5 \]

\[ M.S. = 168.4 / 4 (14.7) = 1186 \text{ psi} \]

Hoop Stress

\[ \sigma = \frac{PD}{2D} = 14.7 (798)/2 (0.322) = 180 \text{ psi} \]

\[ M.S. = -10. \sqrt{4 (0.18)} - 1 = +96.2 \text{ PSI} \]

\[ M.S. = 2 \times \sqrt{1.6 (0.18)} - 1 = +85.8 \text{ YIELD} \]
R82710

LOAD VACUUM AT RT

\[ \text{LOAD} \quad \text{VACUUM AT RT} \]

\[ \text{HYDROSTATIC PRESSURE} \]

\[ \text{CONSERVATIVE} \]

\[ \text{REF. NASA STRUCTURES MANUAL, Sect. C3.0, p 67.} \]

\[ \frac{(1.5)}{(1.0)} \]

\[ \frac{(1.0)}{(1.5)} \]

\[ \frac{(1.5)}{(1.0)} \]

\[ \text{Ultimate} \]

\[ \text{Failure Stress - Conservative} \]

\[ \text{Ultimate} \]

\[ \text{Yield} \]

\[ \text{Ref. NASA STRUCTURES MANUAL, Sect. C3.0, p 67.} \]

\[ \text{Ultimate} \]

\[ \text{Failure Stress - Conservative} \]
**Axial Load on the 10.35 in. Cylinder Due to Ejector Flow:**

Axial load due to ejector pressure of 6.34 psia:

\[ P = 6.34 \pi \left( 20.75^2 - 19.58^2 \right) / 4 = 46.44 \text{ psi} \]

Axial stress:

\[ \sigma = \frac{P}{A} = \frac{46.44 (2)}{0.375 (2) \pi 19.584} = 2.01 \text{ psi} \]

Negligible

Original 10.35 in. Cylinder of P001 Quality
LOAD - VACUUM AT 100 K
\[ E = 26 \times 10^6 \text{ psi} - 640 \text{ F} \]
\[ F_{c-y} = 18 \text{ KSI} - 740 \text{ F} \]

INNER CYLINDER - BUCKLING
\[ D = E \frac{l^2}{12(1-\nu^2)} = 26 \times 10^6 \frac{.375^2}{12(.9215)} = 123991. \]
\[ \pi = L^2 (1-\nu^2) \frac{1}{12} = 14.25^2 \frac{1}{12} = 9.8(.375) = 53.04 \]
\[ P_{cr} = \frac{K_P \pi^2 D}{4.37L^2} = 6 \pi^2 \frac{129.94}{14.25^2} = 3689 \] \text{ PSI}
\[ \sigma = 3689 / 4(14.7) - 0.1 = + 61.7 \]

HOOP STRESS
\[ \sigma = PD/2T : (14.7)(19.934 / 2(.375)) = 383.7 \] \text{ PSI}
\[ M.S. = 55 / 4 (.384) - 1 = + 34.8 \text{ ULT} \]
\[ M.S. = 18 / 1.6 (1.384) - 1 = + 26.3 \text{ YLD} \]
OUTER CYLINDER

TUCKLING:

\[ D = \frac{24 \times (10^6) \times 375^2}{12 \times (975)} = 123991 \]

\[ E = 10.4 \times \sqrt{975} / 15.3 (375) = 18.09 \]

\[ \sqrt{E} = \frac{4 \times 10.4 \times 123991}{15.3 (10.4^2)} = 2957.9 \text{ ksi} \]

\[ E_2 = 1530 (18.1) = 10.83 \quad K = 4 \]

\[ M.S. = 2958 / 4 (14.1) - 1, = +44.3 \text{ ksi} \]

LOOP STRESS

\[ \sigma = P D / 2 T = (14.7) 30.6 / 2 (375) = 600 \text{ ksi} \]

\[ M.S. = 55.1 / 4 (600) - 1, = +21.9 \text{ ult} \]

\[ M.S. = 18.1 / 1.6 (600) - 1, = +17.7 \text{ yield} \]

B-23
TRING - OUTER CYLINDER END
ASSUME ALL ACTUATOR LOADS REACTED BY WAVE GROOVE.

FOLLOWING TENSION LOADING:

\[ \text{THK} = 0.375 \]

\[ \text{LOAD} = \text{VACUUM AT 440^\circ F} \]
\[ F = 26 \times 10^6 \text{ KSI} \]
\[ F_{tu} = 55 \text{ KSI} \]
\[ F_{ty} = 18 \text{ KSI} \]

Ref: Roark 5th Ed., p. 340, Case 2f.

\[ M_{RB} = q \frac{L}{4} \left( \frac{L}{C_5} \right)^2 \]
\[ C_5 = 0.5 \left[ 1 - \left( \frac{10.17}{15.3} \right)^2 \right] = 0.279 \]
\[ L_{tu} = \frac{1}{16} \left[ 1 - \left( \frac{10.17}{15.3} \right)^4 - 4 \left( \frac{10.17}{15.3} \right) \ln \left( \frac{15.3}{10.17} \right) \right] \approx 0.0018 \]

\[ \sigma = \frac{6 M_{max}}{r^2} = \frac{6 (644)}{0.375^2} = 2729 \text{ KSI} \]

\[ \text{M.S.} = \frac{55}{4} (2.73) - 1, = \begin{cases} +4.03 \text{ ULT} \\ \text{VERY CONSERVATIVE} \end{cases} \]

\[ \text{M.S.} = \frac{18}{1.6} (2.73) - 1, = \begin{cases} +2.12 \text{ YLD} \\ \text{VERY CONSERVATIVE} \end{cases} \]
Cylindrical Load = 14.7 - 2.7 = 12 PSIG - Say 14.7 PSIG at 440°F
Ref: NASA Structures Manual, C3, 713

D = 26×10^6 × 315^3 / 12 (9215) = 123991

Z = 7.1^2 × 9215 / 15.6 (1315) = 8.27

Pe = \frac{3}{\pi^2} \frac{71^2 × 123911}{15.6 (7.1)^2} = 4668 TSI (1720 ksi)

\sigma = 560 + 4.63 K = 5

\sigma = 4668 / 14.7 (4) - 1 = 178.4

Hill Stress \quad \sigma = \frac{90}{24} = 14.7 (31.2) / 2 (315) = 0.11 psi

\sigma = 65 / 4 (611) - 1 = 17.0

\sigma = 18 / 1.6 (611) - 1 = 17.4 YLD
CONJ. LOAD = -14.77kN & RT

22 F KUNA STRUCTURES MANUAL, C3.0, P=67

\[ P_c = \frac{92 F X}{(\frac{1}{3})(\frac{8}{3})} = \frac{92(28 \times 10^6)75}{13.22} = 1432.65 \text{ kN} \]

\[ \frac{X}{F} = (15.5 + 10.565)/2 \cos 12 = 13.22 \]

\[ M_S = \frac{1432}{14.7(14)} - 1 = \]

**HOOP STRESS**

\[ \sigma = \frac{P_D}{2F} = \frac{14.7(31)}{2(375)} = 107.6 \text{ ksi} \]

\[ M_S = 10.7(14)1.6 = \]

\[ M_S = 25.16(107.6) - 1 = \]

ORIGINAL PAGE IS OF POOR QUALITY

B-25b
\[ a = 15.6 \quad b = 10.36 \quad \gamma = 0.75 \]

\[ \text{LOAD} = -14.7 \text{ PSIG (CONSERVATIVE)} \quad \text{AXIALLY LOADED} \]

\[ \text{MAXIMUM STRESS OF 296/\pi \cdot 20.73 = 45.46 \text{ lb/in}^2 = 0.4400 \text{ ksi} \]

\[ \text{REF TRUNK - 5TH 2D, \quad } \gamma = 0.75 \quad \text{CASE 1.F} \]

\[ \gamma = 0.75 \text{ IN} \]

\[ \begin{align*}
M &= \pi a L_6 / C_5 = 45.46 (15.6) \cdot 0.043 / 0.279 = 109.11 \\
L_6 &= \frac{10.36}{4 (15.6)} \left[ \left( \frac{10.36}{15.6} \right)^2 - 1 + 2 \ln \frac{15.6}{10.36} \right] = 0.043 \\
C_5 &= 0.5 \left[ 1 - \left( \frac{10.36}{15.6} \right)^2 \right] = 0.279
\end{align*} \]

CASE 2 F

\[ \begin{align*}
M &= 4 \pi a^2 L_{14} / C_5 = 14.7 (15.6)^2 \cdot 0.0052 / 0.279 = 66.675 \\
L_{14} &= \frac{1}{16} \left[ 1 - \left( \frac{10.36}{15.6} \right)^4 - 4 \left( \frac{10.36}{15.6} \right)^2 / \ln \frac{15.6}{10.36} \right] = 0.0052 \\
\tau &= \sigma (109.1 + 66.7) / 0.75^2 = 1975, \text{ PSI} \\
\text{M.S.} &= 18,000 / 1.6 (1975) - 1 = 4.8 \text{, YLD} \\
\text{M.S.} &= 55,000 / 4 \cdot (1975) - 1 = 16.33 \text{ UTL}
\end{align*} \]
M.S. = 1320 / (4(14.7)) - 1 = 608.58 R
M.S. = 28000 / 4(609) - 1 = 147.3103 / 2(32.5) = 2.12 / 2 = D

D = E1/2 (1-ν2) = 2840 (0.347)1/2(1-0.347) = 2045 (0.347)1/2
E = L2 (1-ν2)/L = 33528 / 1552 (0.347) = 1284.71
P = Kp + D = 6.5 + 384 = 450
Kp = 6.5
V = 1.328
D = 1.477 (A4 T7)
T = 125
D = 1.477 (A4 T7)
L = -1477 (A4 T7)

100% CRITICAL TOLERANCE
**Title:** Cylindrical Sector/Diffuser  
**Model:** 1st to 2nd Single Straight Section

---

**T32718**

**ORIGINAL PAGE IS OF POOR QUALITY**

**LOAD:** $164.7$ kips

$312^\circ F$  
*(Conservative)*

$$E = 27 	imes 10^6 \text{ psi}$$

$$F_{tu} = 59 \text{ ksi}$$

$$F_{ty} = 22 \text{ ksi}$$

---

**REF:** NASA STRUCTURES MANUAL, C3.0, P. 13

**D** = $27 \times 10^6 \left(375^3\right) / 12 \left(9215\right) = 1223,746$

$$Z = 109.16^2 \times \sqrt{9215} / 11 \times 1375 = 2773$$

$$P_{cr} = \frac{40 \times \pi^2 1223,746}{11 \times (109.16)^2} = 387.16 \text{ psi}$$

$$ZK = 0.56 \left(2773\right) = 1552$$

$$K_P = 40$$

**M.S. = 387.8 / 4 \left(14.7\right) - 1. = \left[ + \frac{3.59}{475} \right]$$

---

**HOOP STRESS - BASED ON MAX DIA**

$$T = \frac{PD}{2t} = 14.7 \left(24.24\right) / 2 \left(375\right) = 475 \text{ psi}$$

**M.S. = 22 / 1.6 \left(475\right) - 1. = \left[ + \frac{27.9}{475} \right]$$

**M.S. = 59 / 4 \left(475\right) - 1. = \left[ + \frac{30.05}{475} \right]$$

---

**B-28**
LOAD \rightarrow -14.773 \text{ kips}
TCT (Conservative)

\[ F = \frac{30.87 + 22.034}{4 \cos 4.92^\circ} = 13.27 \text{ kips} \]

REF. - NASA STRUCTURES MANUAL, 6.3.0, P.47

\[ P_{cr} = \frac{.92 E t^3}{(12)(\frac{r}{t})^2} = \frac{.92 \times (23 	imes 10^6) \times 75}{(51.275)^3} = 671 \text{ psi} \]

\[ M.S. = 671 / 4 \times (14.7) - 1. = +10.4 \text{ in.} \]

HOOP STRESS

\[ \sigma = \frac{PD}{2h} = 14.7 \times (30.87) / 2 (3.75) = 605 \text{ psi} \]

\[ M.S. = 28000 / 1.6 \times (605) - 1. = +27.9 \text{ ksi} \]

\[ M.S. = 70000 / 4 \times (605) - 1. = +27.9 \text{ ULT} \]
**Title:** SCAFFOLD EJECTOR / DIFFUSER

**Report No.:** DLX- T82723A

**Page:** 14

**TEMP:** 32°F

**TEMP:** 440°F

**LOAD:**
1. -14.7 psig at 32°F (CONSERVATIVE)
2. 33 psia = 18.3 psig at 440°F

**ORIGINAL PRINT IS OF POOR QUALITY**

**INNER CYLINDER**

**RECOMMEND R2F NASA STRUCTURES MANUAL, C3.0, P. 13**

\[ D = 27 \times 10^4 \left( \frac{.375}{.9215} \right) = 12.746 \]

\[ E = 12^2 \frac{7.9215}{12^2(.375)} = 30.41 \]

\[ P_r = 5 \pi^2 12^2 746.12^2 = 40.10.9 \]

\[ \epsilon_r = \frac{.56 (30.41)}{17} \]

\[ M.S. = \frac{4011}{4(14.7)} - 1 = \]

\[ + 67.2 \]

**HYDROSTATIC**

\[ + 2794 lb \]

\[ + 30.03 \text{ ult} \]

**HOOP STRESS - SAME AS PREVIOUS SECTION:**

**B-30**
AXIAL LOAD IN 12.0 IN CYLINDRICAL SECTION DUE TO EJECTOR FORCE:

\[ P = (33 - 14.7) \pi (32^2 - 24.2^2) / 4 = 6.800 \text{ LBS} \]

\[ \sigma = P / A = 6.300 / \pi 12.1^2 = 13.7 \text{ PSI} \]

This would correspond to a hydrostatic pressure of:

\[ \sigma = \frac{P D}{4 A} = 13.7 = \frac{P 24.2}{4 (13.7)} \]

\[ P = 0.89 \text{ PSI} \]

Since the hydrostatic buckling of this cylinder is 4010.9 PSI \* Good by inspection

\* FICICULS PAGE
OCTIC CYLINDER BUCKLING - REF NASA STRUCTURES MANUAL

\( D = 27 + 10^2 \left( \frac{3.73}{12.9215} \right) = 27 + 10^2 \left( \frac{3.73}{12.9215} \right) = 128.746 \)

\( E = 12.5^2 \sqrt{9215} / 21.145 \left( \frac{3.73}{12.9215} \right) = 19.91 \)

\( P_{cr} = \frac{4}{1} \pi^2 \frac{128.746}{21.145} \left( \frac{12.5^2}{12.9215} \right) = 1538.4 \text{ PSI} \)

\( k_2 = \frac{12.5}{19.91} = 0.6 \quad k_p = 4 \)

\( M = \frac{1538.4}{4} (14.7) - 1 = \frac{1538.4}{4} (14.7) - 1 = +23.16 \)

BUCKLING LIMITS

LOAD

HOOI STRESS (USING MAX POS. PRESSURE, \( 33 - 14.7 = 18.3 \text{ PSIG} \))

\( \sigma = \frac{PD}{2T} = \frac{18.3 (42.29)}{2 \left( \frac{3.73}{12.9215} \right)} = 1031.87 \text{ PSI} \)

\( M.S. = \frac{30 \times 135}{4} (1032.) - 1 = +12.3 \)

\( M.S. = \frac{13 \times 135}{1.6} (1032.) - 1 = +9.9 \text{ YIELD} \)

ORIGINAL SHEET
OF POOR QUALITY.
LOAD - MAX AT IS 11.3 KG
AT 4400 F
FT = 55 KSI
FTY = 18 KSI

---

THE LOADS FROM THE ACTUATORS ARE ASSUMED TO BE TRANSFERRED THRU THE INNER GUSSETS.

---

VERY CONSERVATIVELY IGNORE THE FOUR INNER GUSSETS WHEN CONSIDERING THE PRESSURE ON THE RING.

REF: ROARK 5th EDITION, P. 340, CASE 2F, G0 = 6

\[ M_{RB} = \frac{q \cdot a^2 \cdot L_{14} / C_s}{1 - \left( \frac{12.5}{21.14} \right)^2} = 19.3 \left( \frac{21.14^2}{11.2} \right) \cdot 0.09932 \cdot 1.325 = 224.63 \]

\[ C_s = 0.5 \left[ 1 - \left( \frac{12.5}{21.14} \right)^2 \right] = 0.775 \]

\[ L_{14} = \frac{1}{16} \left[ 1 - \left( \frac{12.5}{21.14} \right)^4 - 4 \left( \frac{12.5}{21.14} \right)^2 + \left( \frac{21.14^2}{12.6} \right) \right] = 0.09932 \]

\[ \sigma = 6 \cdot M_{RB} / r^2 = 6 \cdot (224.6) / 375^2 = 9584.4 \text{ ksi} \]

\[ M_{S.} = 55 / 4 (9584) - 1 = \frac{1143 \text{ ULT}}{1.47 \text{ ULT}} \]

\[ M_{S.} = 18 / 1.6 (9584) - 1 = \frac{117 \text{ YIELD}}{1.17 \text{ YIELD}} \]
ORIGINAL FAILURE OF POOR QUALITY

LOAD (c) 33751A AT 440°F

LOAD (c) 751A AT RT

STRESSES OF LARGE DIA CYL - IN VACUUM AT 440°F - NACA STRUCTURES MANUAL, 63.0, P.15

D = 235.5 x 10^6 (375³) / 12 (9285) = 1267460

Z = 7.2² - 0.1125 / 21.81 (375) = 6.08

\( P_r = 2.6 \frac{\pi^2 126746}{21.81 (7.213^2)} = 2911.715 \)

\( E = \frac{56 (6.08)}{3.4} = 8.5 (K_p = 2.60) \)

\( N_S = Z_k \sqrt{4 (14.7)} - 1. = \)

+419.5 \text{ BUCKLING}

HOOP STRESS - USE 33-14.7 = 18.3 TSIG AT 440°F

\( S = \frac{PD}{2Z} = 18.3 (45.63) / Z (375) = 1064.751 \)

\( M_S = 56 / 4 (1064) - 1. = \)

+119.72 \text{ ULT}

\( M_S = 18. / 1.6 (1064) - 1. = \)

+19.57 \text{ VLD}

B-34
<table>
<thead>
<tr>
<th>Title: SUBSCALE FOCUS / DIFFUSER</th>
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<td>EXPANSION VSOLUTION - SECOND STAGE</td>
<td>Report No.</td>
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</table>

**TWO R52723**

**ORIGINAL PAGE IS OF POOR QUALITY**

**TENSION OF LONG CYLINDER** - REF. NASA STRUCTURES MANUAL

\[ L = 22.37 \text{ in}, R = 16, \text{ in}, \theta \text{ THICKNESS} = .375 \text{ in} \]

**LOAD = VACUUM AT RT:**

\[ D = 28 \times 10^6 (\frac{.375^3}{12 (\frac{.9216})}) = 133528 \]

\[ Z = \frac{22.37^2 \sqrt{1.125}}{16 (\frac{.375})} = 79.67 \]

\[ Pr = \frac{7.5 \pi^2 \times 133528}{16 (22.37^2)} = 1234 \]

\[ ZK = \frac{54 (79.67)} = 44.6 \text{, } KP = 7.5 \]

\[ M.S. = 1234 \times 4 (14.7) - 1, = +19.98 \]

**MEAN STRESS**

\[ T = \frac{PD}{2T} = 14.7 (32) / 2 (375) = .627 \text{ PSI} \]

\[ M.S. = \frac{70}{4 (627)} - 1, = +26.9 \text{ ULT} \]

\[ M.S. = \frac{28}{1.6 (627)} - 1, = +26.9 \text{ YLD} \]
**Cylinder Ring**

- Assume brackets react actuator load
- Very conservatively ignore brackets in ring

**Pressure Analysis Below**

The = .66

Load = 18.3 psi at 440°F

Ref: Toark 5th Ed., Page 340, Case 2.  To = 0.6

\[ V = 2.9 \frac{2}{4} \frac{L_14}{C_5} = 18.3 \left( \frac{21.8^2}{1.8^2} \right) \frac{0.0223}{0.217} = 87.76 \]

\[ C_5 = 1.8 \left[ 1 - \left( \frac{10.4}{21.8} \right)^2 \right] = 2.17 \]

\[ L_{14} = \frac{1}{16} \left[ 1 - \left( \frac{16.375}{21.8} \right)^4 - 4 \left( \frac{16.375}{21.8} \right)^2 \ln \left( \frac{21.8}{16.375} \right) \right] = 0.00273 \]

\[ T = GM^2 \frac{1}{2} = \frac{60(87.76)}{0.00273} = 123.6 \text{ psi} \]

\[ MS_{\text{Ult}} = 55 \cdot \frac{4}{1.236} - 1 = 10.12 \text{ psi} \]

\[ MS_{\text{Val}} = 18 \cdot \frac{1.6}{1.236} - 1 = 8.1 \text{ psi} \]

**Conclusions**

- Analysis of poor quality

---

**B-36**
LOAD 0 UNLOAD AT T=T

(1) 4315 L.WGT

\[(43-14.7 = 28.3 \text{ psi})\]

AT T=T

3484

\[t = 275(1)\]

\[k = 0.8 \rightarrow 30.5\]

\[\text{CONSERVATIVELY MAXIMUM SHORT CENE END}\]

Buckling - Ref NASA Structures Manual, Ch. 30, P. 13

\[D = \frac{E t^3}{12 (1 - \nu^2)} = 28 \times 10^6 \times (37.5)^3 / 12 \times (925) = 135.528.8\]

\[S = \frac{L^2 (1 - \nu^2)}{T^2} = 30.5^2 (925) / 17.42 (37.5) = 136.7\]

\[P_{cr} = K_f \pi^2 D / T L^2 = 9.2 \pi^2 \times 135.528 / 17.42 (30.5^2) = 748.19 \text{ psi}\]

\[k_s = 0.56 \quad \zeta = 0.64 (136.7) = 76.53\]

\[M.S. = 748.2 / 4 (14.7) - 1. = +11.72\]

\[\text{Buckling Hydrostatic}\]

**Hoop Stress - For Above Load Case**

\[S = \frac{P D}{2 T} = 14.7 (34.84) / 2 (375) = 682.8 \text{ psi}\]

\[M.S. = 28 / 1.6 (682) - 1. = +24.02 \text{ YIELD}\]

**Hoop Stress - For Burst Pressure of 28.3 psi**

\[S = \frac{P S}{2 T} = 28.3 (34.84) / 2 (375) = 1314.6 \text{ psi}\]

\[M.S. = 70 / (1.314) - 1. = +322.7 \text{ ULT}\]

\[M.S. = 25 / (1.314) - 1. = +18.0 \text{ YIELD}\]

\[\text{FORM LING 1969}\]

\[\text{FORM LING 1969}\]
DEFORMWORKS NASA STRUCTURAL MANUAL, CT 0, P13

\[ D = 2.3 \times 10^6 \left( \frac{375}{12} \right) = 1076.84 \]

\[ \frac{E}{E_0} = 116.2 \sqrt{9215} / 16.75 \times 375 = 2058.9 \]

\[ P_e = 35 \times \frac{109684}{16.75 \times 1403} = 115 \]

\[ \frac{E}{E_0} = 0.6 \times 0.6 \times 2058.9 = 115 \]

\[ M.S. = \frac{115}{4(14.7) - 1} = +0.95 \text{ HYDROSTATIC STREET} \]

**Hoop Stress - For Above Load Case**

\[ \sigma = \frac{PD}{2T} = 14.7 \left( \frac{33.46}{2(375)} \right) = 655 \text{ PSI} \]

\[ M.S. = 15.5 / 1.6 (655) - 1 = +11.28 \text{ YLD} \]

**Hoop Stress - For Test Pressure**

\[ \sigma = \frac{PD}{2T} = 28.3 \left( \frac{33.46}{2(375)} \right) = 1262 \text{ PSI} \]

\[ M.S. = 61.6 / (1.262) - 1 = +40.1 \text{ ULT} \]

\[ M.S. = 13.5 / (1.262) - 1 = +7.53 \text{ YLD} \]
INNER CYLINDER = REF. NASA STRUCTURES MANUAL, CH. 7, P. 73

TREYING (LOAD 1) D = 28 \times 10^6 (375^2) / (12 (9210)) = 133528.

\[ E = 17.2 \sqrt{\text{mm}} / (16.73 (375)) = 44.21, \text{ and } \varepsilon = 0.56 (44.21) = 24.76 \]

\[ P_t = 5.2 \pi^2 133528 / 16.73 (17^2) = 1417 \text{ psi} \]

M.S. = 1417 / 4 (14.7) - 1. =

HOOP STRESS = LOAD 2

\[ \sigma = PD / 2L = 28.3 (33.466) / 2 (375) = 1267.6 \]

M.S. = 70. / (1267.6) - 1. =

M.S. = 25. / (1267.6) - 1. =

LOAD CHECK (1) T = 147 (33.466) / 2 (375) = 744.8 PSI

M.S. = 74. / 1.6 (4.55) - 1. = 11.39
Axial load on 17.14 cylinder due to ejector fluid:

\[ P = \frac{(33.1 - 14.7)}{14} \left( \frac{37.4^2 - 35.46^2}{2} \right) = 4012.7 \text{ lb} \]

Axial stress:

\[ \sigma = \frac{P}{A} = \frac{4012.7}{.375 \pi (\frac{33.46}{2})} = 101.1 \text{ psi} \]

Hydrostatic equivalent pressure:

\[ \sigma = \frac{PD}{4} = \frac{P}{4} \left( \frac{33.46}{2} \right) \]

Hydrostatic test lining allowance (per 1000 ft SEC) is 1417 psi.

Consequently adding the two pressures:

\[ P_{\text{total}} = 32.4 + 14.7 = 47.1 \text{ psi} \]

\[ M.S. = \frac{1417}{4} (07.1) - 1 = 7.52 \]

Original page 17
of poor quality.
OUTER CYLINDER, LOAD 3

\[ \tau = \frac{P_d \cdot d^2}{2} = 18.3 \left( \frac{49.75}{2} \cdot 3.75 \right) = 1213.9 \text{ PSI} \]

\[ M_S = 55. \div 4 \left( 1.214 \right) - 1.2 = +10.82 \]

\[ M_S = 18. \div 1.6 \left( 1.214 \right) - 1.2 = -8.27 \]

OUTER CYLINDER LOAD SEE POSITIVE PRESSURE ONLY
GOOD BY INSPECTION — SEE PAGE 16.

INNER CYLINDER LOAD 12 — REF NASA STEEL MANUAL

\[ \bar{P} = (28.66 + 33.16) \div 62 \cdot 8.6 = 18.7 \]

\[ P_1 = \frac{0.72 \left( 23.710^6 \right) \cdot 75}{ \left( \frac{15.7}{15.7} \right) \left( \frac{15.7}{31.5} \right) } = 1399.3 \text{ PSI} \]

\[ M_S = 1399 \div 4 \left( 14.7 \right) - 1.2 = +22.8 \]

LOAD CASE 2 → SAME AS INNER CYLINDER
**Load -**

CASE 1: 18.3 PSIG / 440°F

CASE 2: -14.7 PSIG / RT

CASE 3: 157.3 PSIG / RT

**Detonation**

**Lower Cylinder - Buckling - Ref. NASA STRESS MANUAL, C3, p.13**

**Load (2):**

\[ D = 28 \times 10^6 \left( \frac{3}{12} \right) / 12 (9215) = 133328 \]

\[ E = 27.4^2 \sqrt{9215} / 18.7 (375) = 102.77 \]

\[ F = 8 \pi^2 13328 / 18.7 (27.4^2) = 760.96 \text{ PSI} \]

\[ M.S. = 781 / 4 (14.7) - 1 = +11.77 \text{ Buckling} \]

**Hoop Stress - Load (2):**

\[ T = PD / 2T = 14.7 (37.4) / 2 (375) = 733 \text{ PSI} \]

\[ M.S. = 28 / 7.6 (1733) = +22.87 \text{ VLD} \]

**Load (3):**

\[ T = 139.3 (37.4) / 2 (375) = 6946 \text{ PSI} \]

\[ M.S. = 70 / (6.95) - 1 = +9.07 \text{ ULT} \]

\[ M.S. = 75 / (6.95) - 1 > 8.42 \]  

**Factor of Safety = 1.0 for Detonation Pressure**
OUTER CYLINDER - LOAD (1) HOOP STRESSES

\[ T = \frac{Pd}{2t} = \frac{12,3 (31.3)}{\pi (0.375)} = 1247, \text{ PSI} \]

\[ M_S = 36.14 (1.68) - 1 = +718 \text{ ULT} \]

\[ M_S = 18.14 (1.68) - 1 = +57 \text{ YLD} \]

END TRAY - OUTER CYLINDER - VERY CONSERVATIVELY IGNORE COLUMNS.

LOAD (1) - REF. TRACK - 5TH LD, PAGE 240. CASE 2F. Go = 6
LOCKHEED MISSILES & SPACE COMPANY, INC.

SUBSCALE EXACTION/DIFFUSOR (GEOMETRIC SECTION) - TRIAXIAL STAGE

304 L S. S.

**Buckling - TEF NASA Structures Manual, C3.0, P13**

**LOAD 1**

\[ D = 28 \times 10^6 \left( \frac{375^3}{12 \times 0.9216} \right) = 133528 \]

\[ E = 28 \times \frac{\sqrt{0.9216}}{18.3 \times 0.375} = 8.742 \]

\[ P_{cr} = 8 \times \frac{\pi^2}{18.3 \times (28)^2} = 921.8 \text{ psi} \]

\[ K = 48.95 \quad K_p = 8 \]

\[ M.S. = 28 \times (1.6 \times 0.9216) - 1 \quad = \frac{1}{+17.98} \]

**HOOP STRESS**

**LOAD 1**

\[ \sigma = \frac{PD}{2t} = 14.7 \left( \frac{36.6}{2 \times 0.375} \right) = 177.3 \text{ psi} \]

\[ M.S. = \frac{28}{1.6 \times 0.717} - 1 \quad = \frac{1}{+23.4} \]

**LOAD 2**

\[ \sigma = \frac{PD}{2t} = 139.3 \left( \frac{36.6}{2 \times 0.375} \right) = 6797.7 \text{ psi} \]

\[ M.S. = 70 \times (6.797) - 1 \quad = \frac{1}{+9.03*} \]

\[ M.S. = 25 \times (6.797) - 1 \quad = \frac{1}{+2.67*} \]

* Factor of Safety = 1.0 for Detonation Pressure.
T82731

ORIGINAL VIEWS
OF POOR QUALITY

LOAD

1. \(-147.12\text{ kIb/ft}\)
2. \(139.3 \text{ PSI/ft}\)

TREKING
- REF NASA STRUCTURES MANUAL, CB.0, P13.

LOAD 1

\[ D = 133528 \quad \text{(REF PREVIOUS PAGE)} \]
\[ Z = 120^2 \cdot 192.15 / 18.3 \cdot (375) = 2014. \]
\[ P_a = 35 \pi^2 \cdot 133528 / 18.3 \cdot (120^2) = 175 \text{ PSI} \]
\[ E = 1127. \quad K_f = 35. \]
\[ M.S. = 175 / 4 (14.7) - 1 = +1.97 \text{ TREKING} \]

HOOP STRESS = 717.3 PSI FOR LOAD 1 REF PREVIOUS PAGE.

M.S. = +25.4

HOOP STRESS LOAD 2

\[ T = TVD / 2T = 139.3 \cdot 36.60 / 2 (375) = 6797 \text{ PSI} \]
\[ M.S. = 25 / 6797 - 1 = +2.67 \text{ * YLD} \]
\[ M.S. = 70 / 6797 - 1 = 9.3 \text{ * ULT} \]

* FACTOR OF SAFETY = 1.0 FOR TENSION TESTS, PROVENCE.
LOAD

1. -14.7 psi / 10°C
2. +137.3 psi / 10°C
3. +2 psi / 802°F

\( P_e = \frac{9}{4} \pi^2 (12374.6) / 14.28 (27.2)^2 = 1082 \text{ psi} \)
\( T_e = 0.56 (132.6) = 74.3 \)
\( K_p = 9 \)
\( M_S = 1082 / 4 (14.7) - 1. = +7.4 \)}
<table>
<thead>
<tr>
<th>Load</th>
<th>Description</th>
<th>Calculation</th>
<th>Result</th>
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<tbody>
<tr>
<td>1</td>
<td>Loop Compression - Case</td>
<td>$T = 14.7 \left(\frac{36.6}{2}(3.75)\right) = 717.7$ PSI</td>
<td>$23.4$ YLD</td>
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<tr>
<td>2</td>
<td>Loop Compression - Cylinder</td>
<td>$T = 14.7 \left(\frac{28.5}{2}(3.75)\right) = 560$ PSI</td>
<td>$30.28$ YLD</td>
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<tr>
<td>3</td>
<td>Load at $902^\circ F$</td>
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<tr>
<td></td>
<td>Cylinder</td>
<td>$T = 2 \left(\frac{36.6}{2}(3.75)\right) = 97.6$ PSI</td>
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</table>

* Designation Factor of Safety = 1.0
DESIGN LOADS - APPROXIMATE

ASSUMED MATERIAL IS A-36 STEEL

A.36 WELD

FTU = 57 KSI, FTY/Fy = 36 KSI

51 KSI 41 KSI

FACTOR OF SAFETY:

5 ULT

3 YIELD

PRELIMINARY ESTIMATE
DEFLECTION OF 261" SPAN UNLESS ITS OWN WEIGHT

\[ \Delta = \frac{1}{3} \omega l^4 / 384 EI \]

\[ = \frac{1}{3} (5.258) (351^4) / 384 (28 \times 10^6) 66164. \]

\[ = 0.0027\text{ in}. \]

W1822 UHLMAN SECTION \[ I = \frac{1}{6} (36.6^4 - 35.85^4) = 66164. \]
Assuming all facility weight reacted here - conservative

I = \( \frac{60 	imes 15.5}{12} = 10.0 \) in.

\[ M = \frac{60 \times 15.5}{4} = 588.75 \text{ in.-lb} = 1000.96 \text{ lb-in.} \]

\[ T = \frac{M}{s} = \frac{1000.96}{10} = 100.096 \text{ psi} \]

\[ M.S. = \frac{36K}{3} (10.0) - 1 = +0.20 \text{ UL} \]

\[ M.S. = \frac{57}{5} (10.) - 1 = +1.14 \text{ UL (conservative)} \]

* Possibly during construction.

B-50
P 82137

1 Tapp Frame - Closer Look

Calculate stress at corner:

\[ \frac{5822}{2} = 2911 \text{ lb} \]
\[ \Theta = \frac{F L^2}{2EI} - \frac{M L}{EI} \]

\[ \Delta = \frac{F' L^3}{3EI} = \frac{M L^2}{2EI} \quad F' = \frac{3M}{2L'} \]

\[ \Theta = \frac{M L'}{EI} - \frac{F' L^2}{2EI} \]

\[ \frac{M L'}{4EI} = \frac{F L^2}{2EI} - \frac{M L}{EI} \]

\[ 14.75M = 2944 \left( \frac{34}{2} \right)^2 - 54M \quad M = 349.6 \text{ in.-lb} \]

\[ M_1 = 2944 \left( \frac{34}{2} \right) - 34905 = 6519 \text{ in.-lb} \]

\[ T = \frac{M}{S} = \frac{6519}{10} = 651.9 \text{ psi} \]

\[ M.S. = 36/3(6.52) - 1 = +5.84 \text{ yld} \]

\[ M.S. = 57/5(6.52) - 1 = +7.4 \text{ yld} \]

\[ \text{CONSERVATIVE} \]

\[ \text{CONSERVATIVE} \]
SLIDING BEARING PIPE → OD = 4.76 in / ID = 3.15 in

CASE 1 — PLUG WEIGHT IS SUPPORTED BY 2 SLIDING PIPES

WHAT IS THE DEFLECTION?

\[ I = \frac{\pi}{64} \left( 4.76^4 - 3.15^4 \right) = 11.18 \text{ in}^4 \]

\[ \Delta \text{MAX} = \frac{P_2 \left( 3L^2 - 4a^2 \right)}{24EI} = \frac{300(35)(21169 - 4900)}{24(280)10^6 \times 11.18} \]

\[ = 0.0215 \text{ in.} \]

CASE 2 — PLUG WEIGHT IS SUPPORTED BY ONE PIPE

\[ M = \frac{W L}{4} = \frac{1200 (84)}{4} = 25200 \text{ in}^4 \]

\[ \sigma = \frac{Mc}{I} = \frac{25200 (4.26)}{2 \times 11.18} = 4789 \text{ PSI} \]

\[ M_S. = \frac{57}{5} (4.79) - 1 \]

\[ M_S. = \frac{36}{3} (4.79) - 1 \]

B-53
**DIMENSIONS of Seamless and Welded STEEL PIPE**

ASA-256.10 and 836.19

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</table>
\[ \frac{1076.53}{3} = 507.5 \text{ LB} \]

**Axial Reactions**

1. **Diag. Turnbuckle Load**: 
   \[ \frac{10474}{4} = 2618.5 \text{ LB} \]

2. **Diag. Turnbuckle Load**

**Note on the Drawings:**

- The structure is marked with various loads and reactions.
DIAGONAL TURNBUCKLES REACTING AXIAL THRUST LOADS –

MAX MAGNITUDE = \frac{10763}{(3) \cos 45°} = 6073, LB.

CLEVIS MS27120 1.0 IN. DIA
ULT ALLOWABLE = 33100 LB

TURNBUCKLE MS27954 1.0 IN. DIA
ULT ALLOWABLE = 38000 LB.

M.S. = \frac{33.1}{5(6073)} - 1. = +.31
My axial reaction is 10424 lb before third stage section.

Acting on top of frame:

Facility weight $\frac{5858}{3} = 1942$ lb.

$10424 = 3474$ lb axial thrust

Facility weight $\frac{5858}{3} = 1942$ lb.

TOTAL $L = 68.1\text{ in.}$

$I_x = 30.1$  $S_y = 10.0$

$I_y = 9.67$  $S_x = 3.23$

$\Sigma M_c = \Sigma \frac{M}{S} = \frac{33354}{10} + \frac{69658}{3.23} = 21419.6781$

$MS = \frac{57}{5}(21.62) - 1. = -0.47$

$MS = \frac{36}{3}(21.62) - 1. = -0.44$

Will be redesigned — see next page.
### axial reaction and axial weight

**40W1.5 plus 1/2 in. plate both sides**

\[
\begin{align*}
I_x &= \frac{201 + 1.6^3}{12} = 48.1 \text{ in}^4 \\
I_y &= 9.67 + 6.0\left(\frac{7^3 - 5.9^3}{12}\right) = 73.17 \text{ in}^4 \\
\text{AREA} &= 4.56 + 6.0 = 10.56
\end{align*}
\]

**Facility weight**: \(5888/3 = 1962 \text{ lb} \)

\[
\text{Axial - Theory} \quad \text{Axial - Test} \\
\frac{16424}{3} = 5474 \\
5474 \\
\frac{5474}{3} = 1824 \text{ lb}
\]

**Upper plate**

\[
\begin{align*}
M_x &= 1962 \cdot (6.0) / 4 = 23,354 \\
M_y &= 5474 \cdot (6.0) / 4 = 81,068
\end{align*}
\]

\[
T = 2 \cdot 5474 \left(3.354 \left(\frac{3}{2}\right) + \frac{59058 (3.5)}{73.17}\right) = 61705 \text{ psi}
\]

### axial wind alleviates:

\[
\begin{align*}
\text{M.S.} &= \frac{51.15 (4.9)}{-1} = +1.0\% \\
\text{M.S.} &= \frac{41.15 (4.9)}{-1} = +1.78\%
\end{align*}
\]
THIRD STAGE FRAME WHERE AXIAL REACTION IS TAKEN AT FOUR PLACES
TOP OF FRAME IS GOOD PER PREVIOUS CALCULATIONS
SIDE SPANS 8

\[ R_1 = \frac{2606 \text{ lb}}{4} \]
\[ R_2 = \frac{1503 \text{ lb}}{8} \]

\[ R_1 + R_2 = 2606 + 1303 = 3909 \text{ lb} \]
\[ 2M_{x_1} = 2606(42.75) + 1303(68.33) = R_2 86.75 \]
\[ R_2 = 2310.8 \text{ lb} \quad R_1 = 1598.1 \text{ lb} \]

MAX NORMAL = 1598(42.75) = 68314. LB

\[ \sigma = \frac{68314 \times 3.6}{7317} = 3267 \text{ PSI} \]

(1) WELD  \[ MS = \frac{51}{5} (3.27) - 1. = +2.11 \]
\[ MS = \frac{41}{3} (3.27) - 1. = +3.17 \]
DINeERAL TRAEC. AT FRAME

TOTAL AN.1 LOAD = 1678 (1O00 x ACD) + 1303 (2nd REACTIOM) = 2901.170

\[
\frac{2901}{\sin 45°} = 4103.13
\]

\[
T = \frac{P}{A} = \frac{4103}{4.56} = 899.145
\]

- TEAAL SHOULD BE IN TENSION -
- BY EVERING SLOPE
FIRST STAGE SUPPORT WHERE REACTION LOADS ARE TAKEN TO BE EQUAL AT 3 PLACES.

\[ \text{LOAD} = \frac{10763}{3} = 3587 \text{ LB} \]

\[ R_1 + R_2 = 3587 \]

\[ 2M_1 = 6.275 \times 3587 = 80 \text{ in-LB} \]

\[ T_{RZ} = 2813 \text{ LBS} \quad R_1 = 773 \text{ LBS} \]

At weld:

\[ \sigma = \frac{F}{A} = \frac{51759 (3.5)}{73.17} = 2475 \text{ PSI} \]

\[ M.S. = \frac{51}{3} (2.48) - 1 = \frac{+22.11}{1.14} \]

\[ M.S. = \frac{41}{3} (2.48) - 1 = \frac{-14.51}{1.14} \]
FASTENERS TO TAIL

PATTERN OF 8 ½” 301 ST ST $F_{su} = 50$ KSI

$T_{su} = \frac{50 \text{ ksi} \pi \cdot \frac{1}{4}}{4} = 9.817$ KSI

MAX FASTENER PATTERN SHEAR LOAD IS 2901 LB
FROM DIAGONAL BRACE TO FRAME WITH FOUR AXIAL-
THUST LOAD PICKUPS —

$2901/8 = 362 \text{ LB/FAST SHEAR}$

$M_S = 9.8/5 (0.34) - 1. = 4.44$
Appendix C

LIST OF DRAWINGS AND BILL OF MATERIALS
## Subscale Ejector/Diffuser Drawing List

<table>
<thead>
<tr>
<th>Drawing</th>
<th>Number</th>
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<tbody>
<tr>
<td>Site Plan</td>
<td>R82733</td>
</tr>
<tr>
<td>Plan &amp; Evaluation</td>
<td>R82732</td>
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<tr>
<td>Subscale Ejector/Diffuser Assembly</td>
<td>R82734</td>
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<tr>
<td>Ejector Inlet Piping Platform</td>
<td>R82736</td>
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<tr>
<td>Inlet Plate - Nozzle Simulator</td>
<td>R82701</td>
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<tr>
<td>H₂ Diffuser - Nozzle Simulator</td>
<td>R82700</td>
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<tr>
<td>H₂ Cylinder - Nozzle Simulator</td>
<td>R82702</td>
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<td>Nozzle Body - Detail</td>
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<tr>
<td>Altitude Simulation Cell - Nozzle Simulator</td>
<td>R82704</td>
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<tr>
<td>Altitude Cell End Plate - Nozzle Simulator</td>
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<td>Nozzle Discharge Tube - Nozzle Simulator</td>
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<tr>
<td>Expansion Section - Nozzle Simulator</td>
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<td>1st Stage to 2nd Stage Mixing Tube</td>
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### BILL OF MATERIALS
(See Assembly R82734)

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Parker Fluid Power Atlanta, Ga.
Parkertron LDT 2" Bore 6 " Stroke

Parker Fluid Power Atlanta, Ga.

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**Note:** Pertaining to fasteners:
Bolts will be MS16208; washers will be MS15795; nuts will be MS16203;
screw, cap, socket head - hexagon MS16996.