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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

\( \text{GN}_2 \)
gaseous nitrogen

\( L \)
length

\( M \)
Mach number

\( \dot{m}, \dot{w} \)
flow rate

\( \text{NBP} \)
normal boiling point

\( P, p \)
pressure

\( R \)
radius

\( \text{RH} \)
relative humidity

\( r \)
ejector mass flow to pumped mass flow ratio

\( T \)
temperature

\( U \)
velocity

\( \dot{\dot{W}}_{BL} \)
J-57 air bleed flow rate

Greek

\( \tau \)
time

Subscripts

\( c \)
cell or chamber

\( d \)
detonation conditions

\( e_x, \text{ex} \)
ejector mixing tube exit

\( j \)
pertains to ejector

\( m \)
mixing tube

\( q \)
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.

○ Ammended 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-detonatable but flammable prior to mixing ($T_e < 660 \text{ K}$, $T_P < 750 \text{ K}$, $P_{in} < 22.6 \text{ psia}$)

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
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 dura-
tion 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 per-
cent 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 pres-
sure of 0.02 psia

- High pressure compressor bleed air to be utilized to drive the
  first stage ejector
  - Normal rated power bleed parameters: \( P_T = 150 \text{ psia}; \)
    \( T_T = 1137 \text{ R}; \ W_{BL} = 8.64 \text{ lbm/sec} \)
  - Military rated power bleed parameters (30 minutes): \( P_T =
    162 \text{ psia}; T_T = 1182 \text{ R}; W_{BL} = 1.65 \text{ lbm/sec} \)

- 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.
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 \( \Lambda_2/\Lambda_3 \) 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

\[ \frac{A_3}{A_j^*} = 29.52 \quad A_j^* = 25.58 \text{ in}^2 \]

\[ P_{T_j} = 6.34 \text{ psia} \quad T_{T_j} = 1138 \text{ R} \]

\[ \dot{m}_j = 2.79 \text{ lbm/sec} \]

\[ r = \frac{\dot{m}_j}{\dot{m}_1} = 5.47 \]

Blank Off Suction Pressure = 0.02 psia

Pumping Capability = 0.51 lbm/sec at 2.8 psia

\[ \frac{A_3}{A_j^*} = \text{Variable from 22 to infinity} \]

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 0.0876 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 blankoff 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

\[ \frac{A_m}{A_j^*} = 29.5 \]

\[ \frac{P_e}{P_{e_x}} = 0.00204 \]

\[ \frac{P_{e_x}}{P_{e_x}} = 9.06 \]

\[ A_j^* = 1338 R \]

\[ \eta_j = 25.58 \text{ in}^2 \]

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

Fig. 5 First Stage Ejector Performance as a Function of Area Ratio
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-57 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 blankoff 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
Fig. 9 Third Stage Ejector Design Summary

Design Conditions

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

\[ \frac{P_{T_j}}{T_{T_j}} = 33 \text{ psia} \quad T_{T_j} = 1400 \text{ R} \]

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

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

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

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
Table 1 WORST CASE HAZARD ASSESSMENT

Kinetics Ignition Delay Behind Normal Shock in Duct

\[ \tau_{\text{ignition}} = \frac{8 \times 10^{-9} \exp(9600/T_s)}{P_s, \text{atm}} \text{sec} \] (NASA TP 1457, Aug 79, Huber et al.)

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

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

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

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

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

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

- The Available Ignition Source (i.e., the Jet Engine Exhaust) Operates at Temperatures Too Low to Ignite the H\textsubscript{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
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 2 J-57 TURBOJET ENGINE CHARACTERISTICS

| Cruise-Rated Air Flow Rate: | 157 lb-sec^{-1} (70 F, 50% RH) |
| Cruise-Rated Fuel Flow Rate: | 7,050 lb-hr^{-1} |
| Engine Exhaust - | |
| Total Flow Rate: | 158.96 lbm-sec^{-1} |
| Total Temperature: | 1400 R |
| Total Pressure: | 33 psia |
| Composition - | |
| N₂ | 77.03 vol.% |
| O₂ | 16.70 vol.% |
| CO₂ | 2.51 vol.% |
| H₂O | 3.74 vol.% |
| NO₅ | 87 ppm |
| CO | 60 ppm |
| CH₄ | 84 ppm |

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
\( P_D = \text{Detonation Pressure}; P_{T, i} = \text{Initial Total Pressure} \)
Driver: J-57 Jet Engine Exhaust

<table>
<thead>
<tr>
<th>Space Engine Condition</th>
<th>( \frac{P_D}{P_{T, i}} ) max</th>
<th>Worst Case Detonation Pressure (psia)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \text{Thrust} )</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>8.5</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>6.7</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>2.3</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>1.5</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 N\(_2\) 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>Flammability Limits (vol.%)</th>
<th>Hydrogen-Air</th>
<th>H(_2)-J57 Jet Engine Effluent*</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0 &lt; F &lt; 75</td>
<td>4.0 &lt; F &lt; 75</td>
<td>4.2 &lt; F &lt; 66</td>
</tr>
<tr>
<td>18.3 &lt; D &lt; 60</td>
<td>19 &lt; D &lt; 55</td>
<td></td>
</tr>
</tbody>
</table>

*Estimated, based on effects of dilution of air with N\(_2\), CO\(_2\), and H\(_2\)O as reported in Ref. 6.
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
RL10-IIB 100% Thrust
Main Stage Operation

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

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

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

**Fig. 15** Full Scale RL10-IIB 100 Percent Thrust Diffuser/Ejector Pressure Distribution
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 FR-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.
Fuel: H_2-Rich Space Engine Effluent
AECE-R Engine: 3.7 lb/sec, Low Thrust
11.2 lb/sec, Full Thrust
RL10-IIB Engine: 3.2 lb/sec, Low Thrust
32.6 lb/sec, Full Thrust
Oxidizer: J57 Jet Engine Exhaust: O_2:
16.7 vol.%; T_e=6: 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

**Fig. 17 H_2-LOX Engine Exhaust Autoignition Characteristics**
Table 5 FIVE CANDIDATE SPACE ENGINES FOR THE OTV (REF. 1)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>AECE-A</th>
<th>AECE-P</th>
<th>AECE-R</th>
<th>ASK</th>
<th>RL10-1IB</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></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Thrust</td>
<td>sec</td>
<td>2500</td>
<td>2500</td>
<td>2500</td>
<td>2500</td>
<td>2500</td>
</tr>
<tr>
<td>Gimbal Capability</td>
<td></td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Propellants</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>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>462</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></td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>27.1</td>
<td>10</td>
</tr>
<tr>
<td>LH₂</td>
<td></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>

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presented in Ref. 13. Startup transient, main stage operation, and shut off transient behavior of the O/F ratio for the ARCB-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 as 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 3.3.3) results in the transient hazard assessment synopsized 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

<table>
<thead>
<tr>
<th>ENGINE</th>
<th>SUMMARY</th>
</tr>
</thead>
<tbody>
<tr>
<td>AECE-R Engine (Based on ASE Engine Data)</td>
<td></td>
</tr>
<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>
<tr>
<td>RL10-IIB Engine (Based on RL10A-3-3A Engine Data)</td>
<td></td>
</tr>
<tr>
<td><strong>Startup</strong></td>
<td>Potential Hazard; O/F &lt; 2.0 from 0.2 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 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 \( \text{GN}_2 \) driving mediums. In all cases, with the stages being driven by the jet engine's exhaust, excess \( \text{H}_2 \) is progressively burned at high temperature and the flow ultimately leaves the facility with negligible residual hydrogen. With \( \text{GN}_2 \) driving the stages: (1) at low thrust, \( \text{H}_2 \) 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 \( \text{H}_2 \) 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, \( \text{H}_2 \) 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 \( \text{H}_2 \) content in the facility effluent. Thus for the vast majority of test operation virtually no \( \text{H}_2 \) is discharged from the facility, and there is no requirement for an external torch to burn residual \( \text{H}_2 \).

As discussed previously, start/stop transients are to be controlled by \( \text{GN}_2 \) flow to the first two stages such that the peak \( \text{H}_2 \) concentration in the flow entering the third stage is maintained below the lower detonation limit. At low thrust, with 50 lb/sec \( \text{GN}_2 \) driving the first two stages, the full main stage cold flow of \( \text{H}_2 \) can be controlled, as also is shown in Table 7. At high thrust, with 150 lb/sec \( \text{GN}_2 \) driving the first two stages, about 60 percent of the full main stage cold flow of \( \text{H}_2 \) 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 \( \text{H}_2 \) flow is required. Alternatively the full thrust transient \( \text{GN}_2 \) driver flow can be uprated to 250 lb/sec, if a full rated \( \text{H}_2 \) cold flow requirement is needed for engine acceleration or other tests.

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<table>
<thead>
<tr>
<th>Engine Status</th>
<th>Driver (Stages 1 &amp; 2)</th>
<th>Stage</th>
<th>RL10-IIB Engine Exhaust</th>
<th>AECE-R Engine Exhaust</th>
<th>Minimum P_{static} (psia)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>T_{T}, K</td>
<td>Vol.% H\textsubscript{2}</td>
<td>T_{T}, K</td>
</tr>
<tr>
<td>Main Stage Burn</td>
<td>J-57\textsubscript{s}</td>
<td>Engine 1</td>
<td>2958</td>
<td>29.5</td>
<td>2756</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Engine 2</td>
<td>2628</td>
<td>16.9</td>
<td>2565</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Engine 3</td>
<td>1968</td>
<td>0.1</td>
<td>2310</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Engine 4</td>
<td>871</td>
<td>N\textsubscript{11}</td>
<td>926</td>
</tr>
<tr>
<td>• H\textsubscript{2} is burned virtually to completion in first and second stages.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main Stage Burn</td>
<td>GN\textsubscript{2}</td>
<td>(50 lb/sec)</td>
<td>Engine 1</td>
<td>2958</td>
<td>29.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Engine 2</td>
<td>2461</td>
<td>15.4</td>
<td>2304</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Engine 3</td>
<td>958</td>
<td>2.8</td>
<td>955</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Engine 4</td>
<td>799-</td>
<td>0.3-</td>
<td>799-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Engine 5</td>
<td>825</td>
<td>N\textsubscript{11}</td>
<td>878</td>
</tr>
<tr>
<td>• Flow enters third stage with H\textsubscript{2} well below detonation limit.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start/Stop Transients</td>
<td>GN\textsubscript{2}</td>
<td>(50 lb/sec)</td>
<td>Engine 1</td>
<td>300</td>
<td>99.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Engine 2</td>
<td>300</td>
<td>56.5</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Engine 3</td>
<td>300</td>
<td>11.5</td>
<td>300</td>
</tr>
<tr>
<td>• H\textsubscript{2} flow is diluted with GN\textsubscript{2} to below the detonation limit in stages 1 and 2. The full maximum rated cold H\textsubscript{2} flow at low thrust can be controlled.</td>
<td></td>
<td></td>
<td></td>
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</table>
### 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_T, K)</th>
<th>Vol.% (H_2)</th>
<th>(T_T, K)</th>
<th>Vol.% (H_2)</th>
<th>Minimum (P_{static}) (psia)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Stage</td>
<td>J-57s</td>
<td>Engine 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>Engine 2</td>
<td>2958</td>
<td>29.5</td>
<td>2958</td>
<td>29.5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Engine 3</td>
<td>2872</td>
<td>16.3</td>
<td>2869</td>
<td>15.8</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>Not Driven</td>
<td>Engine 1</td>
<td>1545</td>
<td>NIL</td>
<td>1519</td>
<td>NIL</td>
<td>14.0</td>
</tr>
</tbody>
</table>

- \(H_2\) is burned as rapidly as it mixes in second and third stages.

| Main Stage Burn | GN\(_2\) (50 lb/sec) | Engine 1 | 2958 | 29.5 | 2958 | 29.5 | - |
|                |                       | Engine 2 | 2958 | 29.5 | 2958 | 29.5 | - |
|                |                       | Engine 3 | 1855 | 7.4  | 1806 | 7.1  | 6.5 |
|                | Not Driven            | Engine 1 | 1324 | NIL | 1300 | NIL | 14.0 |

- \(H_2\) flow is diluted with GN\(_2\) 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(_2) (150 lb/sec)</th>
</tr>
</thead>
</table>

- \(H_2\) flow is diluted and cooled with GN\(_2\) to below the detonation limit in second stage. Up to 60 percent of the full maximum rated cold \(H_2\) 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 lbf 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. GN2 supply line to the present site from the northeast side of Building 454A and shutoff valve with downstream bolt flange connection to flow 73 lb/sec
4. Gaseous 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) GN2 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 subscale 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
  - 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. Riggs, EP23, 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 GN2 pressure is satisfactory.
4. Verify that the GH2 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. ( ) GN2 as needed
   b. ( ) GH2 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 GN2 system per procedure.
6. Set the following pressure regulators to the proper pressures.
   a. GN2
   b. GH2
   c. GH2 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.
11. Verify that cutoff checks are satisfactory.
12. Verify that sequence test has been conducted per procedure.
13. Verify that TV monitors are functioning properly.
14. Verify that video recordings for TV are ready.
15. Activate the J-57 starter air system.
16. Activate the Firex system.
17. Verify that GH2 leak detectors are active.
18. Verify that data system and controls are ready for X-30 minutes.
20. Activate the GH2 system per procedure.
21. Set up road blocks at test stand.
22. Make X-15 minutes announcement. (Close HGF area to all personnel.)
23. Verify duration timer set at [TBD] second and power switch ON.
24. Intercom tape ON.
25. Open the GH2 main shutoff.
26. Prepare the GN2 system for test.
27. Prepare the J-57 control system for test per procedure.
28. Make the X-10 minutes warning announcement.
30. Prepare the \( \text{CH}_2 \) system for test.
31. Turn data system ON - SLOW
32. Turn video recording ON
33. Adjust the ejector \( \text{GN}_2 \) flow controller
34. Adjust the \( \text{CH}_2 \) flow controller.
35. Make X-5 minute warning announcement.
36. Verify that the following systems are ready:
   a. Control
   b. Data system
   c. Camerman
   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. \( \text{GN}_2 \) purges - ON
   b. Cameras - OFF
48. Deactivate the \( \text{CH}_2 \) system.
49. Deactivate the \( \text{GN}_2 \) 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 GASDYNAMIC
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>
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</tr>
<tr>
<td>D</td>
<td>Subscale Design Recommendation</td>
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<tr>
<td>E</td>
<td>Diffuser Sensitivity Analysis</td>
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</tr>
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<td></td>
<td>Intermediate Reviews</td>
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</tr>
<tr>
<td></td>
<td>90% Design Review</td>
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</tr>
<tr>
<td></td>
<td>Final Report</td>
<td>▼</td>
</tr>
</tbody>
</table>
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, H\textsubscript{2} is normally dumped overboard on shutdown, with a maximum total of 1/4 lb H\textsubscript{2} flowed through the nozzle on shutdown.

---

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

Use a Purge GN\textsubscript{2} Flow as the Inert Gas Driver in 1st and 2nd Stages During Transients, as Required
REVIEW

Primary Concern - Potential Hazard on Startup and Shutdown with Hot, \( \text{H}_2 \)-Rich Engine Effluent Driven by Air-Rich Jet Engine Ejector Streams.

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

\[ \{ \text{10\% and 100\% Thrust} \]
HAZARD ANALYSIS: WORST CASE
CHAPMAN-JOUQUET DETONATION PRESSURE RATIO
CHARACTERISTICS AT PREVAILING STREAM
TOTAL TEMPERATURES
FULL SCALE AECE-R 10% THRUST DIFFUSER/EJECTOR PRESSURE DISTRIBUTION

AECE-R 10% Thrust
Main Stage Operation

\[ \frac{O}{F} = 4.0 \]
\[ P_c = 196 \text{ psia} \]
\[ \dot{m} = 3.7 \text{ lbm/sec} \]

AECE-R/Ejector
Mixture Total Pressure

Static Pressure

Duct Pressure (psia)

First Stage Ejector | Second Stage Ejector | Third Stage Ejector
FULL SCALE 10% THRUST
DIFFUSER/EJECTOR PRESSURE DISTRIBUTION

RL10-IIB 10% Thrust
Main Stage Operation

\[ \frac{O/F}{S} = 6.0 \]
\[ P_c = 40 \text{ psia} \]
\[ \cdot c = 3.26 \text{ lbm/sec} \]

RL10-IIB/Ejector
Mixture Total
Pressure

Duct Pressure (psia)

0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34

First Stage Ejector  Second Stage Ejector  Third Stage Ejector

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

RL10-IIB 100% Thrust
Main Stage Operation

- O/F = 6.0
- $P_{c} = 400$ psia
- $m = 32.6$ lbm/sec

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

- O/F = 6.0
- $P_{c} = 1539$ psia
- $m = 31.2$ lbm/sec

Duct Pressure (psia)

0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30

Static Pressure

1st Stage Ejector (Shut Off) 2nd Stage Ejector 3rd Stage Ejector

RL10-IIB/Ejector Mixture Total Pressure
H$_2$-GOX STATIC IGNITION LIMITS

(Spark igniter, 4 in. diameter x 15 in. long chamber, PWA FR-303, Nov 61)

![Graph showing H$_2$-GOX static ignition limits](image-url)
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.%; Tₚ₀ = 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

<table>
<thead>
<tr>
<th>Engine O/F</th>
<th>Tₛ, K (M=0)</th>
<th>Tₛ, K (M=1)</th>
<th>Tₛ, 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:
AECE-R ENGINE TRANSIENT CHARACTERISTICS

(Estimated from ASE Engine Data)
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-3A ENGINE START TRANSIENT CHARACTERISTICS
AECE-R ENGINE 2nd STAGE DIFFUSER TRANSIENT OPERATION

(100% Thrust; Driver: GN$_2$, 150 lb/sec)

- Lower Detonation Limit
- Main Stage
- Total Temperature of Flow to 3rd Stage
- H$_2$ Concentration in Flow to 3rd Stage
- Diluted Below Limit in 3rd Stage Prior to Approaching Ignition Temperature

Graph showing time (sec) vs. volume % H$_2$ in 2nd stage exhaust and time (msec) vs. 2nd stage exhaust temperature (K).
## 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, K )</td>
<td>Vol. % ( H_2 )</td>
</tr>
<tr>
<td>Main Stage</td>
<td>J57s</td>
<td>Engine</td>
<td>2958</td>
<td>29.5</td>
</tr>
<tr>
<td>Burn</td>
<td></td>
<td>1</td>
<td>2628</td>
<td>16.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1968</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>871</td>
<td>Nil</td>
</tr>
</tbody>
</table>

- \( H_2 \) is burned virtually to completion in 1st and 2nd stages.

| Main Stage    | GN2                   | Engine | 2958 | 29.5 | 2756 | 46.6 |
| Burn          |                       | 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.

### Start/Stop Transients

<table>
<thead>
<tr>
<th>GN2</th>
<th>Worst Cases:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RL10-IIB Engine: Full Fuel Flow, 0.466 lb ( H_2 )/sec</td>
</tr>
<tr>
<td></td>
<td>AECE-R Engine: Full Fuel Flow, 0.74 lb ( H_2 )/sec</td>
</tr>
<tr>
<td>Engine</td>
<td>adhesive</td>
</tr>
<tr>
<td>1</td>
<td>300</td>
</tr>
<tr>
<td>2</td>
<td>300</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</th>
<th>Driver (Stages 1 &amp; 2)</th>
<th>Stage</th>
<th>RL 10-I1B Engine Exhaust</th>
<th>AECE-R Engine Exhaust</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$T_T$, K</td>
<td>Vol. % $H_2$</td>
</tr>
<tr>
<td>Main Stage Burn</td>
<td>J57s Engine</td>
<td>Engine</td>
<td>2958</td>
<td>29.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2958</td>
<td>29.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2872</td>
<td>16.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1545</td>
<td>Nil</td>
</tr>
</tbody>
</table>

- $H_2$ is burned as rapidly as it mixes in 2nd and 3rd stages.

| Main Stage Burn     | GN2 Engine             | Engine | 2958      | 29.5         | 2958      | 29.5         |
|                     |                        | 1      | 2958      | 29.5         | 2958      | 29.5         |
|                     |                        | 2      | 1855      | 7.4          | 1806      | 7.1          |
|                     |                        | 3      | 1324      | Nil          | 1300      | Nil          |

- $H_2$ flow is diluted with GN2 to well below detonation limit in 2nd stage and burns as rapidly as it mixes in 3rd stage.

<table>
<thead>
<tr>
<th>Stop/Start Transients</th>
<th>GN2</th>
</tr>
</thead>
</table>

- $H_2$ in flow is diluted and cooled with GN2 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

$\text{GN}_2$ Inerting
Purge 5 lb/sec
\(P = 41\) psia
\(T = 295\) K

Vent

$\text{GN}_2$ Inerting
Purge 45 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
\(P_T = 33\) psia

Comp Burner Turbine

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

FULL SCALE 10% THRUST JET ENGINE DRIVEN EJECTOR/DIFFUSER SYSTEM
RL10-IIB OR AECE-R ENGINE
STARTUP AND SHUTDOWN OPERATION
FULL SCALE 100% THRUST JET ENGINE DRIVEN EJECTOR/DIFFUSER SYSTEM

Engine Test Cell

1st Stage Ejector

2nd Stage Ejector

3rd Stage Ejector

Engine Diffuser

Vent

Closed Off

GN₂ Inerting Purge 150 lb/sec
P = 75 psia
T = 295 K

Closed Off

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

m = 451 lb/sec
Engine Effluent
T = 778 K
P_T = 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

3 J57 Turbojet Engines
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.
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<table>
<thead>
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<th>Section</th>
<th>Page</th>
</tr>
</thead>
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<td>FOREWORD</td>
<td>B-11</td>
</tr>
<tr>
<td>SUBSCALE FACILITY MARGIN SUMMARY</td>
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<tr>
<td>MATERIAL PROPERTIES</td>
<td>B-3</td>
</tr>
<tr>
<td>SUBSCALE FACILITY OPERATING CONDITIONS</td>
<td>B-4</td>
</tr>
<tr>
<td>STRUCTURAL ANALYSIS</td>
<td>B-8</td>
</tr>
<tr>
<td>SUBSCALE FACILITY SUPPORT STRUCTURE</td>
<td>B-48</td>
</tr>
<tr>
<td>Part No.</td>
<td>DESCRIPTION</td>
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<tr>
<td>K82704</td>
<td>ALTITUDE SIMULATION CELL</td>
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<tr>
<td>K82767</td>
<td>ALTITUDE CELL &amp; PLATE</td>
</tr>
<tr>
<td>L92781</td>
<td>INLET PLATE</td>
</tr>
<tr>
<td>P92702</td>
<td>H2 CHAMBER -</td>
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<tr>
<td>K82768</td>
<td>ALTITUDE CELL &amp; PLATE</td>
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<tr>
<td>K92704</td>
<td>NOZZLE DISCERNISE TUBE</td>
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<tr>
<td>L92774</td>
<td>EXPANSION SECTION - NOZ. SMD.</td>
</tr>
<tr>
<td>L92774</td>
<td>EXTRACT TUBE - FIRST STAGE</td>
</tr>
<tr>
<td>L92776</td>
<td>EXPANSION SECTION - 1ST STAGE</td>
</tr>
<tr>
<td>L92776</td>
<td>ADJUSTABLE HEAD ASSY</td>
</tr>
<tr>
<td>T92777</td>
<td>FIRST STAGE CONTRACTION SCLT.</td>
</tr>
<tr>
<td>T92778</td>
<td>1ST TO 2ND STRAIGHT SECTION</td>
</tr>
<tr>
<td>R92723A</td>
<td>EXTRACTOR KINGS - 2ND STAGE</td>
</tr>
<tr>
<td>R92723</td>
<td>EXPANSION SECTION - 2ND STAGE</td>
</tr>
<tr>
<td>T92724</td>
<td>ADJUSTABLE HEAD ASSY</td>
</tr>
<tr>
<td>T92725</td>
<td>2ND TO 3RD STAGE STRAIGHT</td>
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<tr>
<td>T92726</td>
<td>3RD STAGE EXTRACTOR KINGS</td>
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<td>Item</td>
<td>Description</td>
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<td>----------</td>
<td>------------------------</td>
</tr>
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<td>K82727</td>
<td>3rd Stage Section</td>
</tr>
<tr>
<td>K827271</td>
<td>Forehead Section - Third Stage</td>
</tr>
<tr>
<td>K82731</td>
<td>Straight Section - Third Stage</td>
</tr>
<tr>
<td>K82730</td>
<td>Exit Taper Section</td>
</tr>
<tr>
<td>K82700</td>
<td>Nozzle Body</td>
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<tr>
<td>K837031</td>
<td>Structural Support</td>
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<tr>
<td></td>
<td>Sliding Mending Pipe</td>
</tr>
<tr>
<td></td>
<td>Diagonal Tube Stop</td>
</tr>
<tr>
<td></td>
<td>Top of Frame, Kennel</td>
</tr>
<tr>
<td></td>
<td>Side of Frame, Kennel</td>
</tr>
<tr>
<td></td>
<td>Fastenings to Trail</td>
</tr>
</tbody>
</table>

*Original piece of good quality*
MATERIAL PROPERTIES 304 L STAINLESS STEEL

<table>
<thead>
<tr>
<th>304 L ST. ST.</th>
<th>E</th>
<th>FTU</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 EJECTORS/DIFFUSERS.

TYPICALLY ARE ACCOUNTED FOR THROUGH THE CALCULATIONS OF
HYDROSTATIC PRESSURES. ALLOWABLE PRESSURES, THEREFORE,
WILL BE A MAXIMUM PRESSURE (MINUS A MINUS)
A TYPICAL SECTION FOR IDENTIFIED axe loads ARE ASSUMED
AS TYPICAL PRESSURES. FOR EXAMPLE:

\[
\text{HYDROSTATIC PRESSURE} \quad \text{LATERAL PRESSURE}
\]

SINCE AXIAL STRESS DUE TO HYDROSTATIC PRESSURE IS HALF
THAT OF MEEP 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 REJECTED AXIALLY
THROUGH THE HYDROSTATIC PRESSURE TO THE REACTION STATIONS. THIS
AXIAL LOAD WOULD NOT BE ACCOUNTED FOR UNDER THE
HYDROSTATIC ASSUMPTION ABOVE.

ALL EJECTOR EQUATIONS ARE FROM
NASA STRUCTURES MANUAL, SECTION C-3.0.

B-8
Since the 1200 psi load overmatches the 14.7 psi load, all considerations will be made to the larger load.

For the high pressure diameter of 2½ in., the 900 lb flange standard gives a blind flange thickness of:

\[ Q = \frac{2}{\sqrt{2}} \text{ in.} \]  
(See page 110-111) or ASME B16.5

Material \( \rightarrow \) ASTM A105 Grade II

Material ASTM A105 Grade II \( F_y = 36 \)ksi (See page 115)

\[ F_y \text{ ratio} = \frac{\text{ASTM A105 Grade II}}{304 L} = \frac{36}{25} = 1.44 \]

The 900 lb standard has a working pressure of 2100 psi at 1½ in. (See page 151)

2½ in. 304 L has a working pressure of \( \frac{3600}{144} = 1500 \) psi

The 3 in. thickness should have a working pressure of at least \( \left( \frac{3}{2.6} \right) 1500 = 1800 \).

\[ M.S. = \frac{1800}{1200} - 1 = 1.5 \text{ YBD} \]

With a factor of safety of 2.
ADJUST MARGIN CALCULATIONS TO REFLECT 4 X 1.6
OLD ULT./YLD %

\[ M.S. = \frac{2(1800)}{1.6(1200)} - 1 = 4.875 \text{ YLD} \]

RATIO LYS 704 L ULT./YLD STRENGTHS:

\[ M.S. = \frac{(7/8) 2(1800)}{4(1200)} - 1 = 1.1 \text{ ULT} \]

ORIGINAL LATEST
OF POOR QUALITY
PIPE, FITTING AND FLANGE MATERIALS—Continued

Stainless Steels

For sizes ½" through 2½" use 1500 lb. flanges.

<table>
<thead>
<tr>
<th>Size</th>
<th>0.5</th>
<th>1½</th>
<th>2</th>
<th>2½</th>
<th>3½</th>
<th>1½</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.57</td>
</tr>
<tr>
<td>1½</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.57</td>
</tr>
<tr>
<td>1¼</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.66</td>
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</table>

<table>
<thead>
<tr>
<th>Size</th>
<th>2¾</th>
<th>3¼</th>
<th>4</th>
<th>4½</th>
<th>5¼</th>
<th>2¼</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>6.72</td>
<td>8.73</td>
<td>8.63</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>6.72</td>
<td>8.73</td>
<td>8.63</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10.58</td>
<td>12.58</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

B-11
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>Tensile strength (min)</th>
<th>10,000 lb per sq in.</th>
<th>15,000 lb per sq in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield point (min)</td>
<td>10,000 lb per sq in.</td>
<td>15,000 lb per sq in.</td>
</tr>
<tr>
<td>Elongation in 2 in. (min)</td>
<td>25 per cent</td>
<td>35 per cent</td>
</tr>
<tr>
<td>Reduction of area (min)</td>
<td>25 per cent</td>
<td>35 per cent</td>
</tr>
<tr>
<td>Phosphorus (max)</td>
<td>0.03 per cent</td>
<td>0.02 per cent</td>
</tr>
<tr>
<td>Sulphur (max)</td>
<td>0.04 per cent</td>
<td>0.03 per cent</td>
</tr>
<tr>
<td>Carbon (max)</td>
<td>0.45 per cent</td>
<td>0.45 per cent</td>
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</tbody>
</table>

Physical and Chemical Requirements, STEEL FORGINGS for FLANGES,
at Primary Service Pressure Ratings of 150- to 2500-Lb per Sq In.

PRESSURE TEMPERATURE RATINGS of American Standard Carbon* Steel Pipe Flange

<table>
<thead>
<tr>
<th>Pressure (lb per sq in.)</th>
<th>425</th>
<th>1100</th>
<th>1450</th>
<th>2175</th>
<th>3250</th>
<th>4400</th>
<th>9000</th>
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<tbody>
<tr>
<td>Service Temperature</td>
<td>275</td>
<td>720</td>
<td>980</td>
<td>1440</td>
<td>2160</td>
<td>3800</td>
<td>8000</td>
</tr>
<tr>
<td></td>
<td>255</td>
<td>710</td>
<td>940</td>
<td>1400</td>
<td>2120</td>
<td>3600</td>
<td>7915</td>
</tr>
<tr>
<td></td>
<td>240</td>
<td>700</td>
<td>930</td>
<td>1400</td>
<td>2100</td>
<td>3500</td>
<td>7650</td>
</tr>
<tr>
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<td>235</td>
<td>690</td>
<td>920</td>
<td>1350</td>
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<td>3450</td>
<td>7500</td>
</tr>
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<td>910</td>
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<td>7400</td>
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<td>670</td>
<td>890</td>
<td>1250</td>
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<td>3350</td>
<td>7300</td>
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<td>220</td>
<td>660</td>
<td>880</td>
<td>1200</td>
<td>2010</td>
<td>3300</td>
<td>7200</td>
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<td>215</td>
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<td>870</td>
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<td>1990</td>
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<td>190</td>
<td>600</td>
<td>820</td>
<td>900</td>
<td>1890</td>
<td>3000</td>
<td>6600</td>
</tr>
<tr>
<td></td>
<td>185</td>
<td>590</td>
<td>810</td>
<td>850</td>
<td>1870</td>
<td>2960</td>
<td>6500</td>
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<tr>
<td></td>
<td>180</td>
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<td>170</td>
<td>560</td>
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<td>700</td>
<td>1810</td>
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<td>740</td>
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<td>1730</td>
<td>2680</td>
<td>5800</td>
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<td>730</td>
<td>450</td>
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<td>140</td>
<td>500</td>
<td>720</td>
<td>400</td>
<td>1690</td>
<td>2600</td>
<td>5600</td>
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<td>300</td>
<td>1650</td>
<td>2520</td>
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NOOP STRESS

\[ \sigma = \frac{7D}{2I} = \frac{(1200 \times 0.875)}{2 \times 0.875} = 4714 \text{ psi} \]

\[ \text{M.S.} = \frac{70k}{4 \times (4.714)} - 1 = +2.71 \text{ ULT} \]

\[ \text{M.S.} = \frac{25k}{1.6 \times (4.714)} - 1 = +2.31 \text{ YLD} \]

FLANGE THICKNESSES OF 2.5 IN ARE USED WITH THE SAME THICKNESS AS INLET PLATE THICKNESS (T82701).

\[ \text{M.S.} = \frac{1500}{700} - 1 = +.25 \]

WITH A YIELD FACTOR OF 2 IN THE NUMERATE.

\[ \text{M.S.} = \frac{7(1500)}{1.6(1200)} - 1 = +1.66 \text{ YLD} \]

WITH A YIELD FACTOR OF 1.6 AND TAKING 75% THE ULT:

\[ \text{M.S.} = \frac{70k}{25 \sqrt{2}(1500) / 4 \times (1200)} - 1 = +.75 \text{ ULT} \]
**DIMENSIONS of Seamless and Welded STEEL PIPE**

ASA-B36.10 and B36.19

<table>
<thead>
<tr>
<th>NOMINAL</th>
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**ORIGINAL PRINT OF POOR QUALITY**
**LOAD: VACUUM AT RT**

**ORIGINAL DRAWING OF POOR QUALITY**

**D = \frac{E L^3}{12 (1-\nu^2)} = 28 \times 10^6 \left(188^3\right)/12 \times (9216) = 16823**

**Z = \frac{L^2 (1-\nu^2)^{1/2}}{RT} = 12.8^2 \sqrt{9216}/8.92 (188) = 94.85**

**HYDROSTATIC PRESSURE WHERE: \delta = .56 \& \delta Z = 53.1**

**M.S. = 919/4 (14.7) - 1 =**

**HOOP STRESS**

**\sigma = \frac{PD}{2\pi} = 14.7 (17633) / 2 (188) = 689.755**

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

**M.S. = 25/1.6 (.69) - 1 =**
The nozzle body support can be considered a 'blind flange' and using the thickness on page 1 (for the end plate - 782701) the 2.5 in. thickness has a working pressure of 1500 psi.

This working pressure has a yield factor of safety of at least 2. Therefore:

\[
\text{M.S.} = \frac{2(1500)}{1.6(1200)} - 1. = +56 \text{ YLD}
\]

Ratio and for the ultimate strength:

\[
\text{M.S.} = \frac{700}{25} \cdot 2(1500)/4(1200) - 1. = +75 \text{ ULT}
\]

Coresets are conservatively ignored.

\[\Rightarrow 2.5 \Leftarrow\]
THREAT OF NOZZLE -

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

\[ \frac{P}{2T} = \frac{1200(2.65)}{2(0.38)} = 4134 \text{ PSI} \]

\[ M.S. = \frac{70}{4(4.134)} - 1.0 = +38.18 \]

\[ M.S. = \frac{25}{1.6(4.134)} - 1.0 = +2.73 \]

CONSERVATIVE LOAD - Since 1200 PSI decreases from ODI to NOZZLE'S END.

ORIGINAL DRAWING OF POOR QUALITY
GUIDED EDGES

LOAD = 14.7 PSI MAXIMUM PRESSURE AT T-Y:
PLUS CENTER LOAD = 14.7 + 10.7 = 25.4 PSI

TOARR 5TH ED P 336 CASE 1.F

\[ W = 1951 / 2 \pi \times 6.5 = 47.77 \text{ lb/in} \]

\[ M_{cb} = waL_{c}/c_s = 47.8(6.1^2) / 27 = 51.74 \text{ in-lb} \]

\[ L_0 = \frac{13}{4(17.63)} \left[ (\frac{13}{17.63})^2 - 1 + 2 \ln \left( \frac{17.63}{13} \right) \right] = 0.028 \]

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

\[ \sigma_T = 6M/L^2 = 6(51.74)/25 = 130.45 \text{ PSI} \]

CASE 2.F

\[ M = 4 \delta^2 L_{14}/c_s = 14.7(7.81^2) \times 0.025 / 25 = 13.02 \text{ in-lb} \]

\[ L_{14} = \frac{1}{16} \left[ 1 - \left( \frac{13}{17.63} \right)^4 - 4 \left( \frac{13}{17.63} \right)^2 \ln \left( \frac{17.63}{13} \right) \right] = 0.0216 \]

\[ \sigma_T = 6M/L^2 = 6(13.02)/25 = 312.6 \text{ PSI} \]

\[ \sigma_T = 130.4 + 312.6 = 1452.6 \text{ PSI} \]

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

\[ M.S. = 25 / 1.6 (1.69) - 1 = +3.24 \text{ YLD} \]
**Title**: Cylindrical Diffuser/Nozzle Discharge Tube

**Prepared by**: LMT
**Date**: 4/24
**Checked by**: 
**Date**: 
**Approved by**: 
**Date**: 

**Page Temp. From**: 
**Model**: 
**Report No.**: D-82709

---

**72"**

**LOAD = VACUUM AT 1K{T**}

**TECHNIQUE**: NASA Structure Manual, Sect C3, P.13

\[ D = \frac{E t^3}{12(1 - \nu^2)} = \frac{2\times 10^6 (0.322^3)}{12 (2.125)} = 84537 \]

\[ E = \frac{L^2 (1 - \nu^2) Y^2}{R T} = 72^2 \times 2.125 / 4.3 (3.22) = 35414 \]

\[ P_{in} = K_p \times T^2 D / R L^2 = 4.5 \times \pi^2 \times 84537 / 4.3 \times 72^2 = 168.4 \text{ psi} \]

**HYDROSTATIC PRESSURE WHERE**

\[ \kappa = 0.5 \]

\[ \bar{E} = 201616 \]

\[ K_p = 4.5 \]

\[ M.S. = 168.4 / 4 (14.7) = 1.186 \text{ psi} \]

**HOOP STRESS**

\[ \sigma = \frac{P D}{2 t} = 14.7 (798) / 2 (0.322) = 180.751 \]

\[ M.S. = -10. / 4 (1.8) - 1 = -96.2 \text{ psi} \]

\[ M.S. = 25 / 1.6 (1.8) - 1 = -85.8 \text{ psi} \]

---

B-19
LOAD VACUUM AT RT

HYDROSTATIC PRESSURE -- CONSERVATIVE.

REF. NASA STRUCTURES MANUAL, SECT. C3.0, P 67.

\[ \Delta_{\text{crit}} = 0.12 \frac{F}{(\frac{L}{2})^{3/2}} \]

where \( F = \frac{(9.74 + 4.2)}{2 \cos 30^\circ} = 7.95 \)

\[ \Delta_{\text{crit}} = 0.92 \times 10^{-6} \times \frac{7.95}{(10.05)(7.95)}^{3/2} = 16.81 \text{ PSI} \]

\[ \text{M.S.} = \frac{4681}{4(14.7)} - 1 = +78.6 \text{ BUCKLING} \]


tension:

\[ T = \frac{PD}{2h} = 14.2 \times (19.6)/2(0.3125) = 461. \text{ PSI} \]

\[ \text{M.S.} = \frac{70}{4(461)} - 1 = +36.96 \text{ ULT} \]

\[ \text{M.S.} = \frac{28}{1.6(461)} - 1 = +32.9 \text{ YLD} \]
Axial load on the 10.35 in. cylinder due to ejector flow:

Axial load due to ejector pressure of 6.34 psia:

\[ F = 6.34 \pi \left( 20.72^2 - 19.58^2 \right) / 4 = 46.44 \text{ psi} \]

Axial stress:

\[ \sigma = \frac{F}{A} = \frac{46.44 \text{ psi}}{0.375 \pi (19.58^2)} = 2.01 \text{ psi} \]

Original material of poor quality.

NEGLECTIBLE
LOAD - VACUUM AT 100K
(Conservative)

\[ E = 26 \times 10^6 \text{ psi} - 400 \text{ F} \]

\[ F_{cy} = 18. \text{ KSI} - 240 \text{ F} \]

**INNER CYLINDER - BUCKLING**

Ref NASA Structures Manual, Sec. 3.1.3

\[ D = \frac{E t^3}{12(1-\nu^2)} = 26 \times 10^6 \times 0.375^3/12(0.925) = 123991 \]

\[ Z = L^2 (1-\nu^2) \sqrt{12t} = 14.25^2 \times \sqrt{12(0.375)} = 53.04 \]

\[ P_{cr} = \frac{K_p \pi^2 D}{T} = 6 \times \pi^{2} \times 3689/9.8(14.25^2) = 3689, \text{ KSI} \]

\[ \sigma = 56 + 56(55) = 29.7 \quad K_p = 6 \]

\[ MS = 3689/4(14.7) - 1 = +61.7 \]

**HOOP STRESS**

\[ \sigma = PD/2T = (14.7)19.584/2(0.375) = 383.7 \text{ KSI} \]

\[ n_s = 55/4 (.384) - 1 = +34.8 \text{ ULS} \]

\[ n_s = 16/1.6 (.384) - 1 = +28.3 \text{ YLD} \]
**Outer Cylinder**

**Tuckling:**

\[
D = 2.4 \left(10^6\right) \times \frac{375^2}{12 \times 1.9215} = 123991
\]

\[
E = 10.4^2 \times 19215 \div 15.3 \times 375 = 18.09
\]

\[
T_{cr} = 4 \times \frac{11 \times 123991}{15.3 \times 10.4^2} = 2957.9 \text{ ksi}
\]

\[
T = 15/18.1 \times 10.85 = 10.85 \quad K = 4
\]

\[
M.S. = \frac{2758}{4 \times 14.7} - 1.0 = +49.5 \text{ sec/ft}
\]

**Ring Stress**

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

\[
M.S. = 65 \times \frac{1}{4 \times 2} - 1.0 = +21.9 \text{ ult}
\]

\[
M.S. = 18 \times \frac{1}{1.6 \times 300} - 1.0 = +17.7 \text{ yield}
\]
TRING -- OUTER CYLINDER END
- ASSUME ALL ACTUATOR LOADS REACTED BY INNER GUSSET.
- VERY APPROXIMATELY IGNORE INNER GUSSETS FOR THE FOLLOWING PRESSURE LOADS.

THK = 0.375
LOAD = UNLOAD AT 440°F
E = 29 x 10^6 KSI
Ftu = 55 KSI
Fty = 18 KSI

REF - ROARK 5TH ED., P 340, CASE 2F.
Mxz = \( q \beta^2 \bar{L} \bar{W} / C_0 \) = \( 14.7 (15.3)^2 \times 0.0518 / 0.279 = 63.96 \)
C0 = \( 0.5 \left[ 1 - \left( \frac{10.17}{15.3} \right)^2 \right] \) = 0.279
Lw = \( \frac{1}{12} \left[ 1 - \left( \frac{10.17}{15.3} \right)^4 - 4 \left( \frac{10.17}{15.3} \right)^2 \ln \left( \frac{15.3}{10.17} \right) \right] \) = 0.00518

C = \( 6M / \bar{W}^2 = 6 (644) / 0.375^2 = 2729.751 \)
M.S. = \( 55 / 4 (2.73) - 1, = \frac{+ 4.03}{\text{ULT}} \frac{0.03}{\text{very conservative}} \)
M.S. = \( 18 / 1.6 (2.73) - 1, = \frac{+ 3.12}{\text{YLD}} \frac{0.03}{\text{very conservative}} \)

B-24
CYLINDER - LOAD = 14.7 - 2.7 = 12 PSIG  - SAY 14.7 PSIG AT 440°F
R.E.F. NASA STRUCTURES MANUAL, C3, 7.13

\[ D = \frac{26 \times 10^6 \times 0.375^3}{12 (9216)} = 123991 \]

\[ E = 7.1^2 \sqrt{9216} / 15.6 (1375) = 8.27 \]

\[ \sigma_t = \frac{3}{7.1^2} \frac{123991}{15.6 (7.1)^2} = 4668 \text{ PSI} \]

\[ \sigma = 0.56 + 4.63 = 4.63 \quad K = 3. \]

\[ \sigma_S = 4668 / 14.7 (4) - 1 = -178.4 \]

\[ \text{HOOP STRESS} \quad \sigma_t = \frac{-78}{2} = 14.7 (1.2) / 2 (375) = 6.16 \text{ psi} \]

\[ \sigma_{S} = 1.65 / 4 (1.61) - 1 = 17.0 \]

\[ \sigma_{S} = 18 / 1.6 (1.61) - 1 = 17.4 \text{ YLD} \]
CONF. LOAD = -14,776 lb & RT

22F NASA STRUCTURES MANUAL, C3.0, P67

\[
P_c = \frac{9.2 \times \frac{E}{t}}{\left(\frac{t}{E}\right)^{\frac{3}{2}}} = \frac{9.2 \left(28 \times 10^6 \right) 76}{\left(24.16 \right) \left(13.22 \right)^{\frac{3}{2}}} = 1432.6 \text{ psi}
\]

\[
\bar{E} = \frac{(15.5 + 10.365)}{2} \cos 12 = 13.22
\]

M.S. = 1432 / 14.7 (4.) - 1. = + 24.3

HOOP STRESS

\[
t = \frac{P_d}{2t} = 14.7 \left(31.\right) / 2 \left(375\right) = 607.6 \text{ psi}
\]

M.S. = 10.1 / 10.1 / 1. = + 1.7

M.S. = 25.1 / 1.6 (607.6) - 1. = + 24.7

B-25b
Load = -14.7 psi (conservative) & axially loaded

Load at edge of 296/π 20.73 = 14.46 1b/in² = \( \omega \)

PEF 1 CACK - 3th 2D, P 350, CASE 1F

\( \gamma = 7.76 \) in

14.7 psi

45.46 lb/in²

- inner edge guided
- outer edge fixed
- very conservatively ignore gussets

\[ \begin{align*}
M &= \omega a L_0 \left/ \sigma_s \right. = 45.46 (15.6) \times 0.043 \times \frac{1}{0.719} = 109.11 \\
L_0 &= \frac{10.36}{4 (15.6)} \left[ \left( \frac{10.36}{15.6} \right)^2 - 1 + 2 \ln \frac{15.6}{10.36} \right] = 0.043 \\
\sigma_s &= 0.6 \left[ 1 - \left( \frac{10.36}{15.6} \right)^2 \right] = 0.279 \\
\end{align*} \]

CASE 2F

\[ \begin{align*}
M &= 14.7 \times 2.14 \left/ \sigma_s \right. = 14.7 (15.6) \times 0.0032 \times \frac{1}{0.279} = 66.675 \\
L_{14} &= \frac{1}{16} \left[ 1 - \left( \frac{10.36}{15.6} \right)^4 - 4 \left( \frac{10.36}{15.6} \right)^2 \ln \frac{15.6}{10.36} \right] = 0.0052 \\
\end{align*} \]

\[ \begin{align*}
\sigma &= \frac{6(109.1 + 66.7)}{1.75^2} = 1975, \text{ PSI} \\
M_S. &= 18,000 / 1.0 (1975) - 1 = 6.40 \\
M_S. &= 5,000 / 4.0 (1875) - 1 = 6.33 \text{ ULT} \\
\end{align*} \]
LOAD = -14.7 P.S.I. AT T.T. 
CONSERVATIVE:

\[ T = 31.051 \text{ in} \]

\[ k = 20.46 \]

\[ \text{REF. - NASA STRUCTURES MANUAL, p. 13} \]

\[ D = E \left( \frac{1}{12} \right) \frac{1 - \nu^2}{1 - \nu^2} = 28 K(0.375)^3 / 12 (9215) = 133528. \]

\[ E = L^2 (1 - \nu^2) / 12L = 20.46(19215) / 15.62(0.375) = 68.97 \]

\[ P_T = k_P \pi^2 D / 12 L^2 = 6.5 \pi^2 133528 / 15.62(20.46)^2 = 1319.7 \text{ psi} \]

\[ \text{WHERE} \quad t = 0.56 \quad \& \quad \delta = 0.38 \mu \quad \& \quad k_P = 6.5 \]

\[ M.S. = 1320 / 4 (14.7) - 1. = 22.4 \]

\[ \text{HOOP STRESS} \]

\[ \sigma T = P D / 2L = 14.7 \left( \frac{31.05}{2} \right) / 2 (0.375) = 608.58 \text{ psi} \]

\[ M.S. = 28000 / 1.6 (609) - 1. = 27.7 \text{ YLD} \]

\[ M.S. = 70000 / 4 (609) - 1. = 27.7 \text{ ULT} \]

B-27
LOAD \rightarrow -14.77 \pi \sigma
TET (CONSERVATIVE)

\bar{R} = \frac{30.87 + 22.034}{4 \cos 49.2^\circ} = 13.27

REF. - NASA STRUCTURES MANUAL, 3.0, P.67.

\tau_{cr} = \frac{92 \pi t}{(4)(0.375)} = \frac{92 (8.4 \times 10^6)(0.75)}{13.27(0.375)} = 671.75 \text{ PSI}

\text{H.S.} = \frac{671}{4.(14.7)} - 1. = +10.4

\text{HOOP STRESS}

\tau = \frac{PD}{2t} = 14.7 \left(\frac{30.87}{2 \times 0.375}\right) = 605 \text{ PSI}

\text{H.S.} = \frac{28000}{1.6 (605)} - 1. = +27.9 \text{ YIELD}

\text{H.S.} = \frac{70000}{4 \times (605)} - 1. = +27.9 \text{ ULT}

B-29
LOAD: -14.7 psig at 312°F
(Conservative)

2) 33 psia = 18.3 psig
at 440°F

Original photo is of poor quality.

The buckling R2F NASA Structures Manual, C3.0, P. 13

D = \frac{27 \times 10^6 \times (0.375)}{12 \times (0.9215)} = 128746,

E = \frac{12^2 \times 7.9215}{12 \times (0.375)} = 30.41

P_{cr} = \frac{5 \times 12 \times 128746 \times \sqrt{12^2 (0.375)}}{12.12^{1.5}} = 4010.9

\varepsilon = 0.56 (30.41) = 17... K_p = 5.

M.S. = 4011 / 4 (14.7) - 1. =

\text{ hoop stress -- same as previous section:}

\text{ B-30}
AXIAL LOAD IN 12.0 IN CYLINDRICAL SECTION DUE TO EJECTOR FLUID:

\[ P = \left(33 - 14.7\right) \pi \left(32^2 - 24.2^2\right) / 4 = 6,300 \text{ lb} \]

\[ \sigma = P/A = 6,300 / \pi 12.1^2 = 13.7 \text{ ksi} \]

This would correspond to a hydrostatic pressure of:

\[ \sigma = \frac{PD}{4t^2} = 13.7 = P \frac{24.2}{4 (1.373)} \]

\[ \therefore P = 0.85 \text{ ksi} \]

Since the hydrostatic buckling of this cylinder is 4010.9 ksi \( \ast \), GOOD BY INSPECTION

\( \ast \) FICIOUS PAGE.
OCTBIC CYLINDER BUCKLING - REF NASA STRUCTURES MANUAL

\[ D = \frac{27 + 10^6 (1.373)}{12 (0.9215)} = 128746 \]

\[ E = \frac{12.5^2 \sqrt{0.9215}}{21.145 (0.875)} = 19.91 \]

\[ \frac{E_t}{E} = \frac{4 - \pi^2}{128746/21.145 (12.5^2)} = 1538.4 \text{ PSI} \]

\[ \sigma_T = 0.54 (19.91) = 10.6 \quad K_p = 4 \]

\[ M_s = 1538.4/4 (14.7) - 1 = \frac{25.16}{4} \]

Hoop Stresses (Using Max Pos. Pressure, 33 - 14.7 = 18.3 PSI)

\[ \sigma = \frac{PD}{2T} = \frac{18.3 (42.29)}{2 (3.375)} = 1031.87 \text{ PSI} \]

\[ M_s = 135.155/4 (1032) - 1 = \frac{12.3}{4} \]

\[ M_s = 135.155/1.6 (1032) - 1 = \frac{9.9}{4} \]

Original Report of Poor Quality
LOAD - MAX AT IS 19.3 KGF
AT 440°F
Ftu = 55 KSF
Fty = 18 KSF

- THE LOADS FROM THE ACTUATORS ARE ASSUMED TO BE TRANSFERRED THROUGH THE INNER GSUSETS.
- VERY CONSERVATIVELY IGNORE THE FOUR INNER GSUSETS WHEN CONSIDERING THE PRESSURE ON THE RING.

REF: ROARK 5th EDITION P340, CASE 2F, \( \gamma_0 = 6 \)

\[
M_{\text{bs}} = \frac{4}{3} a^2 L_{14} / C_s = 19.3 (2114^2) \cdot 0.00932 / 325 = 274.63
\]

\[
C_s = 0.5 \left[ 1 - \left( \frac{12.6}{2114} \right)^2 \right] = 0.725
\]

\[
L_{14} = \frac{1}{16} \left[ 1 - \left( \frac{12.6}{2114} \right)^4 - 4 \left( \frac{12.6}{2114} \right)^2 / \ln \frac{2114}{12.6} \right] = 0.00932
\]

\[
\sigma = 6M / I^2 = 6 (274.6) / 375^2 = 9584.4 \text{ KSF}
\]

\[
M_S = 65 / 4 (9.584) - 1 = \frac{+ \text{ 4.3 ULT}}{\text{CONSERVATIVE}}
\]

\[
M_S = 18 / 1.6 (9.584) - 1 = \frac{+ \text{ 17 YIELD}}{\text{CONSERVATIVE}}
\]
Buckling of large dia cyl-in vacum at 440°F - GAGEMANUEL.

\[ D = \frac{23.5\times10^6}{375} \div 12 \times 0.9215 = 1227.146 \]

\[ Z = \frac{7.2^2 - 0.1125}{21.81 \times 375} = 6.02 \]

\[ T_{k} = 2.6 \times 123746 \div 21.81 \times 7.213^2 = 2911.155 \]

\[ \varepsilon = 0.42 (6.02) = 3.4 \quad (P = 2.6) \]

\[ M_S = 2911.14 \div 4 \times (14.7) - 1 = +49.5 \text{ Buckling} \]

Hoop Stress - USE 33-14.7 = 18.3756 at 440°F

\[ T = \frac{PD}{2t} = 18.3 (45.63) \times 2 (375) = 1064.751 \]

\[ M.S. = 55.4 \div (1064) - 1 = +9.72 \text{ U.T.} \]

\[ M.S. = 18.1 \div 16 (1064) - 1 = +19.67 \text{ V.I.D.} \]

B-34
L = 22.37 in, R = 16 in, Thickness = .375 in
Load = Vacuum at 2.1 psi

\[ D = 28 \times 10^6 \left( \frac{.375^3}{12 \times .9216} \right) = 133,528 \]
\[ E = \frac{22.37^2 \times 19,125}{16 \times (.375)} = 79,67 \]
\[ E_t = \frac{7.5 \times \pi^2 \times 133,528}{16 \times (22.37^2)} = 1234 \]
\[ Z_5 = .66 \times 79.67 = 44.6, K_T = 7.5 \]
\[ M.S. = 1234 \times 4 (14.7) - 1 = +19.98 \]

**Stress**

\[ \sigma = \frac{PD}{2T} = 14.7 (32) / 2 \times .375 = .627 \text{ psi} \]
\[ M.S. = 70/4 \times .627 \times -1 = +26.9 \text{ U.T.} \]
\[ M.S. = 28/1.6 \times .627 \times -1 = +26.9 \text{ Y.L.D.} \]
CYLINDER PIN NO = ASSUME 8 BRACKETS ACT ACTUATOR LOAD
- VERY CONSERVATIVELY (6) BRACKETS IN PIN NO.
- PRESSURE ANALYSIS BELOW

\[
\text{THC} = 0.66
\]

\[
\text{LOAD} = 18.3 \text{ psi} \text{ at } 440 \text{°F}
\]

\[
\frac{\pi b^2 L_{14}}{8} = 18.3 \left(21.8^2\right) \frac{0.0023}{0.217} = 8.776
\]

\[
C_5 = 0.8 \left[1 - \left(\frac{16.4}{21.8}\right)^2\right] = 0.217
\]

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

\[
G = \frac{GM}{L_{14}^2} = 60(8.776)/0.66^2 = 1236 \text{ psi}
\]

\[
M.S. = 55/4 \times 1.236 - 1. = +10.12 \text{ ULT}
\]

\[
M.S. = 18/1.6 \times 1.236 - 1. = +8.1 \text{ YLD}
\]

CONSERVATIVE

GENERAL COMMENT:
OF POOR QUALITY

B-36
LOAD CO UNEEK AT T'T

(2) H318A UNEEK
(43-14.7 = 28.3 PSIG)
AT T'T

34.84

\[ \tau = \frac{375}{11} \]

--- 30.5 --- [CONSERVATIVELY LOWER SHORT CAME ENDS.

**BECKLING -- TELE NASA STRUCTURES MANUAL**, 3.0, P.13

\[ D = \frac{E t^3}{12 (1-\nu^2)} = \frac{284,10^6 (3/2)^3}{12 (0.215)} = 135528.8 \]

\[ \tau = \frac{E t^2}{2 L T} = \frac{284,10^6 (0.215)^{3/2}}{17.42 (0.215)} = 136.7 \]

\[ P_{cr} = \frac{S^2 D}{R L^2} = \frac{9.2 \pi^2 13628}{17.42 (30.5^2)} = 748.19 \text{ psi} \]

\[ t = \frac{50}{S} \]

\[ \tau = \frac{50}{S} \left( 30.5 \right) = 760.53 \]

\[ M.S. = \frac{748.2}{4} (14.7) - 1 = \]

\[ +11.72 \]

**BECKLING HYDROSTATIC**

--- HOOP STRESS -- FOR ABOVE LOAD CASE

\[ \tau = \frac{P D}{2T} = \frac{14.7 (34.84)}{2 (3.75)} = 682.8 \text{ psi} \]

\[ M.S. = \frac{28}{1.6} (682) - 1 = \]

\[ +24.62 \text{ yield} \]

--- HOOP STRESS -- FOR BURST PRESSURE OF 26.3 PSIG

\[ \tau = \frac{P D}{2T} = \frac{28.3 (34.84)}{2 (3.75)} = 1314.6 \text{ psi} \]

\[ M.S. = \frac{70}{(1.314)} - 1 = \]

\[ +52.7 \text{ ult.} \]

\[ M.S. = \frac{25}{(1.314)} - 1 = \]

\[ +18.0 \text{ yield} \]
The image contains a page from a technical document with handwritten calculations and notes. The content seems to be part of a structural engineering analysis, possibly related to stress analysis in mechanical engineering. Here is the text transcribed into a plain text format:

```
\[ \text{Load} = 2.5 \text{ thousands of} \text{psi} \text{ at} 778^\circ \text{F} \]

\[ D = 2.3 \times 10^6 \cdot (375^2) / 12 \cdot (925) = 109684 \]

\[ E = 116 \cdot \sqrt{925} / 16.75 \cdot (375) = 2058.9 \]

\[ P_{cr} = 35 \cdot \pi^2 \cdot 109684 / 16.75 \cdot (140.3)^2 = 115 \text{ psi} \]

\[ \chi = 0.66 \cdot k = 0.66 \cdot 2058.9 = 1152 \quad \text{ksi} \]

\[ M_{si} = 115 \left( \frac{1}{4} \right) (14.7) - 1 = 11.89 \text{ ksi yield} \]

\[ \text{Hoop Stress - For Above Load Case} \]

\[ \sigma = PD / 2t = 14.7 \cdot (33.46) / 2 \cdot (375) = 655 \text{ psi} \]

\[ M_{si} = 13.6 \left( \frac{1}{1.6} \cdot 655 \right) - 1 = 4.01 \text{ ksi yield} \]

\[ \text{Hoop Stress - For Tensile Pressure} \]

\[ \sigma = PD / 2t = 28.3 \cdot (33.46) / 2 \cdot (375) = 1262 \text{ psi} \]

\[ M_{si} = 61.5 / (1.262) - 1 = 7.53 \text{ ksi yield} \]
```

The handwritten notes and calculations suggest a detailed analysis of stress and load distribution, typical in engineering design and analysis.
INNER CYLINDER – REF. NASA STRUCTURES MANUAL, C.3.O, P. 75

LOAD (LOAD 0)  \( D = \frac{28 \times 10^6 (3.75^2)}{12 (926)} = 133528 \) psi
\( Z = 17.2 \frac{1.9212}{16.73(3.75)} = 44.21, Z_k = 0.56(44.21) = 24.76 \)
\( T_{ck} = 5.2 \pi^2 133528 / 16.73 (17^2) = 1417 \) psi

Hoop Stress = Load (LOAD 2)
\( \sigma = \frac{T D}{Z} = 28.3 (33.16) / 2 (3.75) = 1267.5 \) psi
\( M.S. = 70 / (1267.5) - 1. = \)
\( M.S. = 25 / (1267.5) - 1. = \)

LOAD REL.  \( T = 44.7 (3.16) / 2 (3.75) = 144.8 \) psi
\( M.S. = 22 / 4.6 (4.55) - 1. = \)
Axial load on 17.1 in cylinder due to eccentric fuel:

\[ P = (33.147) \frac{\pi}{14}(37.4^2 - 37.465^2) = 4012.7 \text{ lb} \]

Axial stress

\[ \sigma = \frac{P}{A} = \frac{4012.7}{.375(\pi)} = 10179 \text{ psi} \]

Hydrostatic equivalent pressure:

\[ \frac{P}{A} = \frac{35.46}{4(37.5)} \]

Hydrostatic tsuzuki-kohga limit (H3.0000T) is 1417 psi

Conservatively adding the two pressures

\[ \text{TOTAL} = 324 + 1417 = 1741 \text{ psi} \]

MS = 1417 psi / 4 (0.71) - 1 = 17.52

Original page of poor quality
OUTER CYLINDER, LOAD 3

\[
\sigma = \frac{Td}{2A} = \frac{18.3(49.75)}{2(1.375)} = 1239 \text{ PSI}
\]

\[
M.S. = \frac{55}{4} \left(1.214\right) - 1 = 10.32
\]

\[
M.S. = \frac{18}{1.6} \left(1.214\right) - 1 = 8.27
\]

OUTER CYLINDER, CASE = SEE POSITIVE PRESSURE ONLY

GOOD BY INSPECTION — SEE PAGE 16.

INNER CYLINDER, LOAD 0 — REF NASA STRESS MANUAL

\[
\bar{r} = \left(28.66 + 33.46\right) / 2 = 8.6 = 15.7
\]

\[
P_t = 0.2 \left(23 \times 10^6\right) \left(\frac{15.7}{15.7}\right) \left(\frac{15.7}{3.95}\right) = 1399.3 \text{ PSI}
\]

\[
M.S. = 1399 / 4(14.7) - 1 = +22.8
\]

LOAD STRESS LOAD CASE 2 \rightarrow SAME AS INNER CYLINDER
CASE 1 18.3 psi @ 440°F

CASE 2 -14.7 psi @ RT

CASE 3 19.3 psi @ RT

LOAD 1

LOAD 2

LOAD 3

INFER CYLINDER - BUCKLING - REF. NASA STRESS MANUAL, C2, P13

\( D = 28 \times 10^6 \frac{3}{12} \times 0.9215 = 173528 \)

\( \sigma = \frac{27.4^2 \sqrt{921.5}}{18.7 \times 375} = 102.77 \quad \sigma_2 = 57.5 \quad \text{PSI} \)

\( \sigma_F = 8 \pi^2 \times 173528 \times \frac{18.7 \times 27.4^2}{27.4^2} = 760.96 \quad \text{PSI} \)

\( M.S. = 781 / 4 \times (14.7) - 1 = +11.77 \text{ BUCKLING} \)

Hoop Stress LOAD 2

\( \sigma = \frac{PD}{2} = 14.7 \times 37.4 / 2 \times 375 = 733 \quad \text{PSI} \)

\( M.S. = 28 / 1.1 \times 0.733 = +22.87 \text{ ULT} \)

LOAD 3

\( \sigma = 139.3 \times 37.4 / 2 \times 375 = 6946 \quad \text{PSI} \)

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

\( M.S. = 75 / (6.95) - 1 > 8-42 \) + 2.59 \( \text{ PSF} \)

FACTOR OF SAFETY = 1.0 FOR DESTRONATION PRESSURE.
R 62727

ORIGINAL WORK OF POOR QUALITY

**OUTER CYLINDER - LOAD 1**
**HOOP STRESS**

\[
J = \frac{PD}{2T} = 12.3 \left( \frac{51.1}{2} \left( \frac{3.75}{1247} \right) \right) = 1247 \text{ PSI}
\]

\[
M_s = \frac{5}{4} (1.247) - 1. = +162.0 \text{ UUT}
\]

\[
M_s = 18 \left( \frac{1.247}{1.6} \right) - 1. = + 5.7 \text{ YLD}
\]

**END TRAY - OUTER CYLINDER - VERY CONSERVATIVELY IGNORE COLUMNS.**

**LOAD 0 - REF. TRAY - 5TH CD, PAGE 240, CASL 2F. CO = 6**

\[
\frac{18.3 \text{ PSIG}}{\text{AT 400F}} \quad \frac{M_{eq} = \frac{q \alpha^2 L_1}{L_0} = 18.3 \left( \frac{35.5}{23.5} \right)^2 \cdot 0.032}{1.242}
\]

\[
C_s = \frac{5}{4} \left[ 1 - \left( \frac{18.3}{23.5} \right)^2 \right] = 0.242
\]

\[
L_{111} = \frac{1}{16} \left[ 1 - \left( \frac{18.3}{23.5} \right)^4 - 4 \left( \frac{18.3}{23.5} \right)^2 \ln \left( \frac{23.5}{18.3} \right) \right] = 0.032
\]

\[
J = C_M / L^2 = C_0 \left( \frac{157.57}{7.5^2} \right) = 1680.7 \text{ PSI}
\]

\[
M_s = \frac{56}{4} (1.68) - 1. = + 7.18 \text{ UUT}
\]

\[
M_s = 18 \left( \frac{1.68}{1.6} \right) - 1. = + 5.7 \text{ YLD}
\]

**CONSERVATIVE**

B-43

Load 1

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

\[ Z = \frac{28^2 \sqrt{9216}}{18.3 (375)} = 8.742 \]

\[ P_{cr} = \frac{8 \pi^2 133528}{18.3 (25^2)} = 921.8 \text{ PSI} \]

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

\[ \sigma_s = \frac{28}{1.6 (922)} - 1. = \]

+17.98

Hoop Stress

Load 1

\[ T = \frac{PD}{2A} = \frac{14.7 (366)}{2 (375)} = 717.3 \text{ PSI} \]

\[ \sigma_s = \frac{28}{1.6 (717)} - 1. = \]

+23.4

Load 2

\[ T = \frac{PD}{2A} = \frac{139.3 (366)}{2 (375)} = 6,797.7 \text{ PSI} \]

\[ \sigma_s = \frac{70}{(6.797)} - 1. = \]

+90.03*

\[ \sigma_s = \frac{25}{(6.797)} - 1. = \]

+2.67*

* Factor of safety = 1.0 for detection pressure.
LOAD ①

\[ D = 133528 \]  \quad (\text{REF PREVIOUS PAGE})

\[ \frac{E}{Z} = \frac{120^2 \cdot \sqrt{1215}}{123.3 (0.375)} = 201.4 \]

\[ \frac{E}{Z} = 1127 \]

\[ K_1 = 35 \]

\[ M.S. = \frac{175}{4} (14.7) - 1 = +19.7 \text{ Buckling} \]

\[ \text{HOOP STRESS} = 717.7 \text{ PSI FOR LOAD ① REF PREVIOUS PAGE} \]

\[ M.S. = +25.4 \]

\[ \text{HOOP STRESS} \quad \text{LOAD ②} \]

\[ T = TD/2T = 139.3 \frac{36.6}{2 (0.375)} = 6797 \text{ PSI} \]

\[ M.S. = 25/6797 - 1 = +2.67 \text{ * YLD} \]

\[ M.S. = 70/6797 - 1 = \frac{9.3}{\text{ULT}} \]

\[ \text{F.S. = 1.0 FOR ALL APPLICATIONS PROVIDED} \]
LOAD

1. -14.7 psig / ICT
2. +37.3 psig / ICT
3. 2 psig / 80°F

\[ \bar{F} = (28.56 + 36.6) / 4.68 + 1.635 \]

CODE TOGGLE: - TEE AREA STRUCTURES MANUAL, C. D., P. 67

\[ P_{cr} = \frac{92 \times 10^6 \cdot (375^3)}{(12 \cdot (9215))} = 547.1 \text{ psi} \]

\[ M_{LS} = 547.1 / 4 (14.7) - 1 = 8.3 \text{ Torsion} \]

Cylindrical Torsion: - TEE AS Above, P. 13

\[ D = 28 \times 10^6 (375^3) / 12 (9215) = 128746 \]
\[ Z = 27.2^2 (9215 / 14.28 (375)) = 132.6 \]
\[ P_{cr} = 9 \times 10^6 / 14.28 (27.2)^2 = 1082.75 \text{ psi} \]
\[ T_E = 0.56 (132.6) = 74.3 \]
\[ K_p = 9 \]

\[ M_{LS} = 1082 / 4 (14.7) - 1 = +17.4 \]
Loop Compression - Case
\[ T = 14.7 \left( \frac{36.6}{2} \right) / 2 (0.375) = 717.7 \text{ PSI} \]
M.S. = 28 / 1.6 (7.17) - 1. = 23.4 YLD

Loop Compression - Cylinder
\[ T = 14.7 \left( \frac{28.64}{2} \right) / 2 (0.375) = 560 \text{ PSI} \]
M.S. = 28 / 1.6 (5.64) - 1. = 30.26 YLD

Load 2: Detonation Hoop Stress

Cone
\[ T = 139.3 \left( \frac{36.6}{2} \right) / 2 (0.375) = 679.7 \text{ PSI} \]
M.S. = 70 / 6.797 - 1. = +9.79 YLD
M.S. = 25 / 6.797 - 1. = +2.07 YLD

Cylinder
\[ T = 139.3 \left( \frac{25.64}{2} \right) / 2 (0.375) = 530.4 \text{ PSI} \]
M.S. = 70 / 5.304 - 1. = +12.19 YLD
M.S. = 25 / 5.304 - 1. = +3.71 YLD

Load 3: 2,516 at 802°F

Cylinder
\[ T = 2 \left( \frac{36.6}{2} \right) / 2 (0.375) = 97.6 \text{ PSI} \]
M.S. = High Temp Inspection

* Degradation Factor of Safety = 1.0
DEFLECTION OF 351" SPAN UNLESS TO OWN WEIGHT

\[
\frac{9063}{351} = 25.8 \text{ lb/in}
\]

\[
\Delta = \frac{5 \omega l^4}{384 EI}
\]

\[
\max \Delta = \frac{(5) 25.8 (351^4)}{384 (28 \times 10^6)} \approx 0.0271\text{ in}
\]

\[
\text{W1822 TANGENT SECTION } I = \frac{\pi}{164} \left( 361^4 - 35.85^4 \right) = 661164.
\]
I-BEAM FRAME

\[ \text{Assume: All Facility Weight Reacted Here - Conservative} \]

\[ F = 6 \times 15.3 \quad I = 30.1 \quad S = 10.0 \]

\[ M = \frac{6 \times 15.3}{4} = \frac{5228}{4} = 1006.96 \text{ in-lb} \]

\[ T = \frac{M}{S} = \frac{1006.96}{10} = 100.696 \text{ psi} \]

\[ M.S. = \frac{36k}{3} (10.0) - 1 = +20 \]

\[ M.S. = \frac{57}{5} (10.) - 1 = +14 \text{ (Conserative)} \]

* Possibly During Construction.
CRACK AT STRESS AT

\[ \frac{500 \times 2}{2} = 2946.13 \text{ lb} \]
GUSSET — CONSERVATIVE

\[
F' \rightarrow M \left( \frac{F}{Z} \right) \rightarrow F
\]

\[
\theta = \frac{F \ell^2}{2EI} - \frac{Ml}{EI}
\]

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

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

\[
14.75 M = 2944 \left( \frac{34}{2} \right)^2 - 34 M
\]

\[
M = \frac{34905}{11 - 15} \text{ N-LB}
\]

\[
M_1 = 2944 (34) - 34905 = 65191 \text{ N-LB}
\]

\[
T = \frac{M/s}{65191/10,000} = 6519 \text{ PSI}
\]

\[
M.S. = 36/3 (6.52) - 1 = +84 YLD
\]

\[
M.S. = 57/5 (6.52) - 1 = +74 YLD
\]
SLIDING BEARING PIPE → OD = 4.26 in / ID = 3.15 in

CASE 1 — PLUG WEIGHT IS SUPPORTED BY 2 SLIDING PIPES
WHAT IS THE DEFLECTION?

\[ I = \frac{\pi}{6} \left( 4.26^4 - 3.15^4 \right) = 11.18 \text{ in}^4 \]

\[ \Delta = \frac{P_2 (3 l^2 - 4 a^2)}{24 EI} \]

\[ = \frac{300(35)(216^4 - 490^2)}{24(28)(10)^6 \cdot 11.18} \]

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

CASE 2 — PLUG WEIGHT IS SUPPORTED BY ONE PIPE

\[ M = \omega \frac{l}{4} = 1200(84.)/4 = 25200 \text{ in}^4 \]

\[ Q = \frac{M c}{I} = \frac{25200 (4.26)}{2 (11.18)} = 4789 \text{ PSI} \]

\[ M.S. = \frac{57}{6} (4.79) - 1, \quad 1.37 \]

\[ M.S. = \frac{36}{3} (4.79) - 1, \quad 1.60 \]
### Dimensions of Seamless and Welded Steel Pipe

ASA-936.10 and 936.19

#### Nominal Wall Thickness for Pipe

<table>
<thead>
<tr>
<th>Nominal Diameter (in)</th>
<th>Schedule 10</th>
<th>Schedule 40</th>
<th>Schedule 80</th>
<th>Schedule 160</th>
<th>Schedule X</th>
<th>Schedule XX</th>
<th>Schedule XXX</th>
<th>Schedule 4XX</th>
<th>Schedule 8XX</th>
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#### For Use:

- **B-54**
10763. LB
1529. LB
10474. LB
6733 LB

\[
\frac{10763}{3} = 3587.66 \text{ LB}
\]

DIAG. TURBINE LOAD

\[
\frac{10474}{4} = 2618.5 \text{ LB}
\]

DIAG. TURBINE LOAD

AXIAL REACTIONS
Diagonal Turnbuckles Reacting Axial Thrust Loads — Max Magnitude = \( \frac{10763}{(3) \cos 45^\circ} \) = 6073 lb.

Clevis MS27120 1.0 in. Dia
ULT ALLOWABLE = 33100 lb

Turnbuckle MS27954 1.0 in. Dia
ULT ALLOWABLE = 38000 lb.

\[
M.S. = \frac{33.1}{5(6073)} - 1 = \pm 0.31
\]
MY AXIAL REACTION IS 10424 LB BEFORE THIRD STAGE SEPARATOR.

ACTING ON TOP OF FRAME:

TOTAL L = 62.1 in.

$\frac{5858}{3} = 1952$ LB.

$\frac{10424}{3} = 3474$ LB AXIAL THRUST

$T_{max} = 6015.5$

$I_x = 30.1 \quad S_y = 10.0$

$I_y = 9.67 \quad S_x = 3.23$

$M_x = 1962 \cdot (68) / 4 = 33354$ in-lb

$M_y = 3474 \cdot (68) / 4 = 61048$ in-lb

$\Delta = \frac{\Delta M_x \cdot \Delta M_y}{I} = \frac{33354 \cdot 61048}{10} = 21,619.6701$

$M_S = 57 / 5 (21.62) - 1. \quad - \quad -0.47$

$M_S = 36 / 3 (21.62) - 1. \quad - \quad -0.44$

WILL BE REDESIGNED — SEE NEXT PAGE.
MAY AXIAL REACTION & MAX LOAD WIGHT
ACTING ON TOP OF FRAME

\[
G = 16.5 \text{ IN. PLATE BOTH SIDES}
\]

\[
I_x = \frac{20.1 + 1.6^3}{12} = 48.1 \text{ in}^4
\]

\[
I_y = \frac{9.67 + 16(7^3 - 5.9^3)}{12} = 73.17 \text{ in}^4
\]

AREA = 4.56 + 0.8 = 5.36

FAUCIN WEIGHT \( \frac{3888}{3} = 1962 \text{ lb} \)

AXIAL LOAD
\( \frac{1824}{3} = 3474 \)

\[
N_x = 1962 \cdot 308 \times 4 = 33354
\]

\[
N_y = 3470 \times 308 \times 4 = 59708
\]

\[
T = 2 \frac{N_x}{I} = \frac{33354}{2} \left( \frac{4}{12} \right) + \frac{59708(3.5)}{73.17} = 61905 \text{ PSF}
\]

AFFECTED FOLD ALLOWANCES:

\[
M.S. = \frac{51}{5} (4.9) - 1_1 = +1.08
\]

\[
M.S. = \Delta \left( \frac{1}{5} (4.9) - 1_1 = +1.78
\]

B-58
THIRD STAGE FRAME WHERE AXIAL REACTION IS TAKEN AT FOUR PLACES.
TOP OF FRAME IS GOOD PER PREVIOUS CALCULATIONS.
SIDE SPANS:

\[ R_1 = \frac{2606 \text{ LB}}{4} \]

\[ 2606 \text{ LB} = 1303 \text{ LB} \]

\[ R_2 = \frac{12024}{8} \]

\[ R_1 + R_2 = 2606 + 1303 = 3909 \text{ LB} \]

\[ 2M_{r_1} = 2606(42.75) + 1303(63.35) = R_2 86.75 \]

\[ R_2 = 2310.8 \text{ LB} \quad R_1 = 1598.1 \text{ LB} \]

MAX MOMENT = 1598 (42.75) = 68314.4 LB

\[ S = \frac{68314.4 (3.5)}{78.17} = 3267 \text{ PSI} \]

\[ \text{MIN weld} \quad MS = 51 / 5 (3.27) - 1. = \]

\[ MS = 41 / 3 (3.27) - 1. = \]

\[ +2.11 \]

\[ +3.17 \]
Horizontal Brace at Frame 2

Total axial load = 1978 (11000 x 0.147) + 1303 (1st reaction) = 2901.18 lb

\[ \frac{2901}{\sin 45°} = 4103.18 \]

In diagonal

\[ T = \frac{P}{A} = \frac{4103}{4.56} = 891 \text{ PSI} \]

Failure should be in tension - try increasing slope
FIRST STAGE EXITORI CRENEE REACTION LOADS ARE TAKEN TO ENSURE AT 3 PLACES.

\[ \text{LOAD} = 10763 \cdot \frac{1}{3} = 3587 \text{ LB} \]

\[ R_1 + R_2 = 3587 \]

\[ 2/1 = 0.275 (3587) = 80 \text{ R} \cdot \]

\[ T_z = 2813 \text{ LB} \quad R_1 = 773 \text{ LB} \]

\[ T-z = 2813 \text{ LB} \quad R_z = 773 \text{ LB} \]

At weld

\[ \delta = \frac{10.5}{2} = \frac{51759 (3.5)}{73.17} = 2475. \]

\[ M.S. = 51 / 5 (2.48) - 1 = 47.1 \]

\[ M.S. = 411 / 3 (2.48) - 1 = -41.51 \]

\[ \star \text{ CHECKED BY} \quad \star \text{ 11/15} \]

B-61
FASTENERS TO TAIL

PATTERN OF 8 $\frac{1}{2}''$ 301 ST ST $F_{su} = 50$ ksi

$$F_{\mu} = \frac{50 \text{ ksi} \pi (1.5^2/4)}{1} = 97.817 \text{ ksi}$$

MAX FASTENER PATTERN SHEAR LOAD IS 2901 Lb FROM DIAGONAL TRACE TO FRAME WITH FOUR AXIAL THRUST LOAD PICKUPS:

$$2901/8 = 362.5 \text{ lb/fas shear}$$

$$N_5 = 9.8/5 (0.36) - 1 = +4.44$$
Appendix C

LIST OF DRAWINGS AND BILL OF MATERIALS
## SUBSCALE EJECTOR/DIFFUSER DRAWING LIST

<table>
<thead>
<tr>
<th>Drawing</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Plan</td>
<td>R82733</td>
</tr>
<tr>
<td>Plan &amp; Evaluation</td>
<td>R82732</td>
</tr>
<tr>
<td>Subscale Ejector/Diffuser Assembly</td>
<td>R82734</td>
</tr>
<tr>
<td>Ejector Inlet Piping Planform</td>
<td>R82736</td>
</tr>
<tr>
<td>Inlet Plate - Nozzle Simulator</td>
<td>R82701</td>
</tr>
<tr>
<td>H₂ Diffuser - Nozzle Simulator</td>
<td>R82700</td>
</tr>
<tr>
<td>H₂ Cylinder - Nozzle Simulator</td>
<td>R82702</td>
</tr>
<tr>
<td>Nozzle Body- Detail</td>
<td>R82706</td>
</tr>
<tr>
<td>Altitude Simulation Cell - Nozzle Simulator</td>
<td>R82704</td>
</tr>
<tr>
<td>Altitude Cell End Plate - Nozzle Simulator</td>
<td>R82708</td>
</tr>
<tr>
<td>Nozzle Discharge Tube - Nozzle Simulator</td>
<td>R82709</td>
</tr>
<tr>
<td>Expansion Section - Nozzle Simulator</td>
<td>R82710</td>
</tr>
<tr>
<td>Ejector Ring 1st Stage</td>
<td>R82714</td>
</tr>
<tr>
<td>Nozzle Piece 1st Stage Ejector</td>
<td>R82716</td>
</tr>
<tr>
<td>Adjustable Plug Assy 1st Stage</td>
<td>R82715</td>
</tr>
<tr>
<td>Compression Section 1st Stage</td>
<td>R82717</td>
</tr>
<tr>
<td>1st Stage to 2nd Stage Mixing Tube</td>
<td>R82718</td>
</tr>
<tr>
<td>Ejector Ring 2nd Stage Ejector</td>
<td>R82723A</td>
</tr>
<tr>
<td>Nozzle Piece 2nd Stage Ejector</td>
<td>R82723B</td>
</tr>
<tr>
<td>Adjustable Plug Assy 2nd Stage</td>
<td>R82724</td>
</tr>
<tr>
<td>2nd Stage Mixing Tube</td>
<td>R82726</td>
</tr>
<tr>
<td>Ejector Ring 3rd Stage Ejector</td>
<td>R82728</td>
</tr>
<tr>
<td>Nozzle Piece 3rd Stage Ejector</td>
<td>R82727</td>
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<tr>
<td>Adjustable Plug Assy 3rd Stage Ejector</td>
<td>R82729</td>
</tr>
<tr>
<td>Mixing Section 3rd Stage Ejector</td>
<td>R82731</td>
</tr>
<tr>
<td>Exit Taper Section 3rd Stage Ejector</td>
<td>R82730</td>
</tr>
<tr>
<td>Support Carriage</td>
<td>R82735</td>
</tr>
<tr>
<td>Typical Support Buckle</td>
<td>R82738</td>
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<tr>
<td>Structural Support 2nd Stage</td>
<td>R82737</td>
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</tbody>
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## BILL OF MATERIALS
(See Assembly R82734)

<table>
<thead>
<tr>
<th>Qty Rq'd.</th>
<th>Part or Identifying No.</th>
<th>Nomenclature or Description</th>
<th>Material Specification</th>
<th>Zone No.</th>
<th>Item No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R82701-1</td>
<td>Inlet Plate</td>
<td>304L</td>
<td>4</td>
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<tr>
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<td>R82700-1</td>
<td>H2 Diffuser</td>
<td>304L</td>
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<td>R82702-1</td>
<td>H2 Cylinder</td>
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<td>3</td>
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<td>R82706-1</td>
<td>Nozzle Body</td>
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<td>R82704-1</td>
<td>Alt Simulator Cell</td>
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<td>5</td>
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<tr>
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<td>R82708-1</td>
<td>Alt Cell End Plate</td>
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<td>R82709-1</td>
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<td>R82710-1</td>
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<td>R82718-1</td>
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<td>R82724-1</td>
<td>Adj. Plug 2nd St.</td>
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<td>R82726-1</td>
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<td>Parkertron LDT</td>
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<td>2 + 3</td>
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</tbody>
</table>

**Parker Fluid Power Atlanta, Ga.**

<table>
<thead>
<tr>
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<th>Zone No.</th>
<th>Item No.</th>
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<tbody>
<tr>
<td>4</td>
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<td>Parkertron LDT</td>
<td>2&quot; Bore 6&quot; Stroke</td>
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</table>

**Parker Fluid Power Atlanta, Ga.**

<table>
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<th>Zone No.</th>
<th>Item No.</th>
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<tbody>
<tr>
<td>40</td>
<td>SWH-14</td>
<td>Rod End</td>
<td>Super St.</td>
<td>1,2,3</td>
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</tbody>
</table>

Southwest Products Co., Monrovia, Calif.

<table>
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<th>Qty Rq'd.</th>
<th>Part or Identifying No.</th>
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<th>Zone No.</th>
<th>Item No.</th>
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<tbody>
<tr>
<td>69</td>
<td>NS27120-11</td>
<td>Clevis, Rod End Turnbuckle</td>
<td>St. Type</td>
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<td>69</td>
<td>NS27954-6</td>
<td>Turnbuckle</td>
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<td>10</td>
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<td>Turnbuckle</td>
<td>St. Type (Forged)</td>
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</tbody>
</table>

**NOTE:** Pertaining to fasteners:
Bolts will be NS16208; washers will be NS15795; nuts will be NS16203; screw, cap, socket head - hexagon NS16996.

C-2

LOCKHEED-HUNTSVILLE RESEARCH & ENGINEERING CENTER