STUDY OF HYDRAULIC ACTUATION SYSTEM

FOR

SPACE SHUTTLE MAIN ENGINE
PROPELLANT VALVES

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HYDRAULIC ACTUATION SYSTEM FOR
SPACE SHUTTLE MAIN ENGINE
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1.0 INTRODUCTION

This report was prepared to document the analysis and tests conducted in response to Attachment J-1 of Contract NAS8-39711 issued by Marshall Space Flight Center, NASA. The report was a requirement of Attachment J-2 of the contract.

2.0 BACKGROUND

The Space Shuttle Main Engine Propellant Valve Actuator assemblies have been the source of recurring problems since their inception. The troublesome areas have been studied and design and process improvements have been made to eliminate the problems. However there have been recent performance concerns with the operation of a bypass valve which is located within the actuator assembly. These concerns led to a request for an independent assessment and study of the Propellant Valve Actuator assemblies.

Moog Inc. responded to this request with a proposal and received a contract to study the system.

3.0 OBJECTIVE

The main objectives of the study were to recommend changes to improve the system reliability and decrease maintenance costs while preserving the present interfacing with other Shuttle hardware and software. The system performance requirements were to remain as presently specified.

4.0 ANALYSIS SUMMARY

The Propellant Valve Actuation System was studied and the requirements were reviewed to obtain a good understanding of the functions and operation of the system.
The system employs technologies that were current in the late 1960's and early 1970's when the design was first conceived. The design is basically sound but could be changed to take advantage of modern improvements that are presently available for hydraulic systems.

**Contamination**

The servovalve pilot stage orifices are extremely small and therefore subject to plugging from small contaminants. The small orifices are required to comply with the low allowable leakage requirements. Two stage valves are also used as switches in the failure detection and correction part of the actuation system, probably for commonality with the two servovalves. Solenoid valves with essentially zero leakage could be used for this function. This would allow a redistribution of the tare leakage loses and permit larger servovalve orifices to be used. Single inlet servovalves such as deflector jet or jet pipe types would offer the advantages of minimizing hard-over failures and reduced contamination sensitivity.

The actuator housing contains several blind or dead ended passageways which are very difficult to clean. A design without stagnant fluid in blind passages would be preferred. The sleeves or bushings that house the spools for the servovalves, bypass valve and switching valve use elastomeric seals to separate fluid from adjoining areas. Laminar metallic sealing lands could be used to isolate fluids of different pressures and eliminate many elastomeric seals. This technique would eliminate temperature sensitive materials and reduce another source of contamination. Contaminants are often introduced when hydraulic lines and fittings are installed or changed. The present system has a filter located upstream of the interfaces between the hydraulic lines and actuators with no provision for filtering particles that might be generated as the lines are installed. This situation could be alleviated by installing filters within the actuators and adding a flushing/bypass valve to each actuator. The lines could then be flushed after installation without the danger of adding contaminants to the sensitive actuator components.

**Bypass Valve**

A majority of the study effort was focused on the bypass valve section of the actuator assemblies. Detailed finite element models of the sleeve and spool had
been created by engineers from Marshall Space Flight Center and by the actuator supplier. The conclusions reached from the modeling and analysis indicated the possibility of interference between the sleeve and spool. Moog engineers verified that the clearance between certain sections of the sleeve/spool assembly could indeed decrease significantly during switching transients. We believe that this decrease in the inside diameter of the sleeve could be one of the contributors to a tendency for the spool and sleeve to bind as the spool moves with respect to the sleeve or bushing.

Since the bypass valve is inactive during normal operation, a collection of very fine contaminants will be deposited on the spool lands where low levels of leakage flow exists. This action is commonly referred to as silting. Silting occurs even in very clean systems with low micron filtering. When spool motion is commanded, these fine particles can wedge between the two parts that have motion relative to one another. The very small or non-existent clearance between the parts, coupled with the wedging action of the contaminants which drives the parts eccentric to one another, can cause severe galling. This results in an inoperative valve. Because the spool and sleeve are manufactured from the same material, which they should be to allow for thermal considerations, the parts are very susceptible to galling problems. Also any minute manufacturing defects can amplify the tendency of the parts to gall, upset surface metal and quickly seize.

Larger drive areas which increase the force available to drive the spool, are effective for chip shearing capability, but have little value once the metal is upset by the rubbing action between the two parts.

Increasing the clearance between the spool and sleeve is not recommended for two reasons. Primarily, in this type of application, increased diametrical clearance can allow larger particles to wedge between the parts resulting in an even greater susceptibility for seizure. The other disadvantage to larger clearance is the creation of a greater leakage path between sections of the spool that are now isolated by the laminar clearance and limit the fluid flow. The increased leakage could affect the functionality of the assembly and certainly would create an additional fluid power drain.
Based on the information given above, the main thrust of the study was concentrated toward solving the suspected design problem. The objectives were twofold. First, to eliminate the clamp down action of the sleeve that occurs during switching between operational modes. The second objective was to maintain interchangeability between any modified parts and those being replaced. The proposed solution is shown in Figure 1. The design of the sleeve and spool assembly could be simplified if the interchangeability criterion was not used.

The proposed design permits the use of all of the ancillary piece parts that are contained in the present assembly including springs, seats, spacers, pivots, seals and end caps. The new approach does, however, eliminate the differential pressure across the sleeve that is believed to be a major source of the present problem.

An additional change was incorporated to alleviate the concern over the complexity of the filtered timing orifice. This orifice is used to control the actuator rate when the bypass valve moves to the actuator bypass position and to control the valve closing sequence and timing. The low allowable rate precipitated the use of a small orifice between one actuator cylinder cavity and the return fluid port. This small orifice is subject to plugging and is therefore protected by a filter which is built into the bypass valve assembly.

The suggested solution takes advantage of a reduced diameter on a section of the spool. Flow through the curtain area formed by this reduced section of the spool and a hole that exits to the return port, creates the necessary pressure drop to control the actuator rate in the bypass mode. This design creates a self cleansing action that eliminates the need for the orifice filter. This feature is shown in Figure 4.

5.0 TEST RESULTS

The early analyses and suggestions are presented to Marshall Space Flight Center personnel at a program status review meeting. This meeting was held approximately one month after the study was initiated. It was agreed at the meeting that a sleeve and spool assembly which represented the proposed solution should be designed, fabricated and tested as part of the study program. Three sets of proof of concept hardware were built and tested at Moog and shipped to the
servoactuator production vendor. The ancillary centerline parts used to demonstrate functionality were supplied by the production vendor from production stock.

All testing was conducted at fluid temperature between 70 and 100 deg. F. using MIL-H-83282 as the test fluid.

The assemblies were tested in the test block shown in Drawing BT00353. Initially, cross port leakage and basic functionality were checked. Plots were generated from flow versus switching pressure to demonstrate switching pressure levels and spool threshold or friction. Bypass flow and required pressure to move the spool to the bypass position were recorded to demonstrate the effectiveness of the revised orifice configuration. The assemblies were operated with control pressures from 500 psi to 3000 psi to demonstrate consistency over sleeve pressure extremes. The units were cycled after sitting pressurized for extended periods of time in an attempt to introduce problems caused by silting at the spool lands. Test results are included with this report as Appendix A.

The assemblies operated as expected throughout the test sequence. No anomalous behavior was observed. The tests were conducted to demonstrate functionality which was the main goal. We recommend further testing at the servoactuator level. Tests at temperature extremes and under vibration loads are recommended as additional proof of concept.

S/N 001 TEST SUMMARY

Operate to Lockup
Lockup to Operate
Friction
Lockup to Bypass
Bypass flow thru orifice
Leakage in locked mode at 3000 psid
  C1P to C1V
  C1P to Return
  C1P to C2P
  C2P to C2V
  C2P to Return
  C2P to C1P

  approximately 1050 psid
  approximately 1050 psid
  less than 4 pounds
  250 to 300 psid
  0.5 cis at 500 psid
  2.7 cc/min
  2 drops/min
  11 drops/min
  7 drops/min
  4 cc/min
  12 drops/min
6.0 RECOMMENDATIONS

It is probably not sensible to embark on a complete redesign of the servoactuators. The design is mature and well understood and the manufacturing processes are well past development. Any start up problems have been eliminated and early performance difficulties have been addressed. There are no problems known to exist with the exception of the bypass spool jamming. However, if the scope of the Space Shuttle Program were to drastically increase, some of the basic design features could be improved. Three areas that are candidates for change are:

1. The filtration scheme that was discussed in the analysis section.
2. The use of more contamination tolerant servovalve designs.
3. Use of solenoid type valves for failure correction switches.

All of these changes would require modifications to the actuator interfaces and requirements which is probably not practical at this time.

We do recommend changing the Bypass Valve to a design that is less subject to interference between the spool and sleeve. We also recommend a change to the method presently used to protect the timing orifice from contaminants. The design used to “prove the concept” operated well during laboratory testing and should be considered as a replacement for the existing design. The interchangeability features should make this effort relatively painless. A substantial amount of testing should be done on the complete servoactuator assembly before the change is incorporated. Environmental testing at extremes of temperature and vibration are recommended as a minimum.
**Uncoupling Pressure:** CV = 500 psi

### Subset 1

<table>
<thead>
<tr>
<th>Subset 1 Press (Psi)</th>
<th>Flow CV → CI P (cfs)</th>
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</thead>
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<td>500</td>
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<tr>
<td>1000</td>
<td>10.25 &lt; 0.068 &lt; 0.068</td>
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<td>1050</td>
<td>12.6</td>
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<td>1100</td>
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</table>

### Subset 2

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<td>500</td>
<td>&lt; 0.068</td>
</tr>
<tr>
<td>1000</td>
<td>&quot;</td>
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<td>1375</td>
<td>15.4</td>
</tr>
<tr>
<td>1400</td>
<td>15.4</td>
</tr>
</tbody>
</table>
SUO SW = 0 (locked up)

C2V = 3000 psi

LEAKAGE \( \bar{C}_2P = < 0.04 \text{ eis} \) NEW ONE FLOW RATE

\( R = < 1 \text{ drop/min} \)

C1V = 3000 psi

LEAKAGE \( \rightarrow C_2P = < 0.04 \text{ eis} \) NOW ONE FLOW RATE

\( R = < 1 \text{ drop/min} \)

To Cycle From Operate To lock To

By-Pass -

1. PRESSURIZE C1V & C2V \( \bar{C} = 500 \text{ psi} \)

2. PRESSURIZE \( \bar{C}_2P \) \( \bar{C} = 500 \text{ psi} \)

3. Port \( \bar{C}_1P \) & Return To Flow Rate

4. CONNECT PNEU To He cylinder

5. Connect SUO SW To Supply \( \bar{C} \)

SUO SW Return From Pneu From \( \bar{C}_2P \rightarrow \bar{C}_1P \)
Space Shuttle HAS
By Pass Valve #1

Operating Pressures

Operate \rightarrow Look Up \rightarrow By Pass \rightarrow Operate

<table>
<thead>
<tr>
<th>Time</th>
<th>SV O SW (Pb1)</th>
<th>Flow (L/min)</th>
<th>Pressure (PSI)</th>
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</thead>
<tbody>
<tr>
<td>5/10</td>
<td>5/10</td>
<td>12.32</td>
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<td>620</td>
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<td>5/10</td>
<td>5/10</td>
<td>3636</td>
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</table>
Space Shuttle Has
By Pass Value #1

By Pass Mode \( C_1 V = C_2 V = 500 \text{ psi} \)
\( C_2 P = 500 \)

<table>
<thead>
<tr>
<th>Pneu Press</th>
<th>( C_2 P \rightarrow C_1 P )</th>
<th>( C_2 P \rightarrow C_1 P + C_2 P + R )</th>
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</thead>
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<td>&lt; .06</td>
<td>&lt; .06</td>
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<tr>
<td>350</td>
<td>0.50</td>
<td>5.10</td>
</tr>
<tr>
<td>400</td>
<td>0.50</td>
<td>5.10</td>
</tr>
</tbody>
</table>

\( C_1 P = 500 \text{ psi} \)

<table>
<thead>
<tr>
<th>Pneu Press</th>
<th>( C_1 P \rightarrow C_2 P )</th>
<th>( C_1 P \rightarrow R + C_1 P \rightarrow C_2 P )</th>
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<td>.32</td>
<td>.34</td>
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<tr>
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<td>.43</td>
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<tr>
<td>400</td>
<td>.47</td>
<td>.47</td>
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</table>
Space Shuttle H.A.S
By Pass Valve #1
By Pass Flow C.P. - C.P.

Flow (lpm)

0 100 200 300 400

By Pass Pressure

1 2 3 4
Source: Source #1

By Pass Valve #1

By Pass Flow C11 - C21

vs 0 - 500 psi

Power

Flow C11 - C21

0 - 400

0 - 300

0 - 200

0 - 100

0
Space Shuttle HAS
By Pass Valve 

Operating Lck Up

1. Pressureize C2V & C2 P @ 3000 psi

2. Pressureize C1V @ x 300 psi -
   Connect C1P to Return From Paper

3. Pressureize SWO SW @ 3000 psi

4. Set Flow C1V C1P @ x 10.3 cie @ 300 psi

5. Lower SWO SW To Zero
   Start To Decrease @ 1100 psi
   Stops Flowing @ 1000 psi < 10

6. Reduce SW To Zero Then
   Increase To Start Flowing @ 1150
   10.3 cie @ 1300 psi

7. Lower Press Flow Starts To Decrease
   @ 1200 psi
   0 Flow @ 1000 psi
Space Shuttle H.A.S.
By Pass Valve #1
C2V & C2 P Pressurized @ 3000 psi
C1V Pressurized @ 300 psi

<table>
<thead>
<tr>
<th>Time</th>
<th>Supply Sw</th>
<th>Flow C1V → C1P</th>
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</thead>
<tbody>
<tr>
<td>08:50</td>
<td>3000</td>
<td>10.3 cis</td>
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<tr>
<td></td>
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</tr>
<tr>
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<tr>
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<td>1300</td>
<td>10.30</td>
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</table>
C1 V / C2 P: Pressure is 3000 psi
C1, V = 300 psi for Indicated or Sear Press

Space Swirls: H.A.S
By Pass Valve #1 4-6-73

Swirling Pressures
Worse Case?
Space Shuttle H/4S By Pass Valve #2

Unloading Pressure - Set C1V = \( \frac{300}{200} \) psi

Monitor Flow C1V to C1P as function of SUO/SW Pressure - Repeat w/C2V = \( \frac{300}{200} \)

<table>
<thead>
<tr>
<th>SUO/SW Pressure</th>
<th>Flow C1V to C1P</th>
<th>Flow C2V to C2P</th>
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<tbody>
<tr>
<td>0</td>
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<td></td>
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<tr>
<td>1600</td>
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</table>

Diagram:
- Value for 3000 psi is indicated as 13.84.
Space Shuttle Has Bypass Valve #2

By-Pass Flow \( S_{0,SW} = 0 \) psi

\[ C_1 U = C_2 U = 500 \text{ psi} \]

\[ C_2 P = -500 \text{ psi} \]

<table>
<thead>
<tr>
<th>Aveui Pressure</th>
<th>Return Flow from later</th>
<th>Return Flow from later</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( C_2 P \rightarrow C_1 P )</td>
<td>( C_2 P \rightarrow C_1 P + C_2 P \rightarrow R )</td>
</tr>
<tr>
<td>0</td>
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<td>250</td>
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<tr>
<td>300</td>
<td>.44</td>
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<td>.52</td>
<td>5.1</td>
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</table>

Repeat w/ \( C_1 P = 500 \) psi

<table>
<thead>
<tr>
<th>Aveui Pressure</th>
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<th>( C_1 P \rightarrow R + C_1 P \rightarrow C_2 P )</th>
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<tbody>
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</tr>
<tr>
<td>400</td>
<td>.53</td>
<td>.53</td>
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</tbody>
</table>
Space Shuttle Has By Pass Valve # 2

Leakage - Locked Mode

\[ SUOW = 0 \text{ psi} \]
\[ PWCL = 0 \text{ psi} \]

\[ C_1 \rightarrow C_1 P = 2000 \text{ psi} \]
\[ \text{Leakage to } C_1 V = 2.7 \text{ drops/minute} \]
\[ \text{To } R = 2 \text{ drops/minute} \]
\[ \text{To } C_2 P = 11 \text{ drops/minute} \]

\[ C_2 P \rightarrow C_2 V = 3000 \text{ psi} \]

\[ \text{Leakage to } C_2 P = 7 \text{ drops/minute} \]
\[ \text{To } R = 4 \text{ cc/minute} = 0.004 \text{ cc/in} \]
\[ \text{To } C_1 \rightarrow C_1 P = 12 \text{ drops/minute} \]

Leakage in Operate Mode:

\[ SUOW \rightarrow 3000 \text{ psi} \]
\[ C_1 \rightarrow 2000 \text{ psi (C1 P Capped) Leakage to } R = 3 \text{ drops/minute} \]
\[ C_2 P \rightarrow 3000 \text{ psi (C2 V Capped) Leakage to } R = 6.4 \text{ cc/min} \]

Both Above Pressurized

Leakage to R = 8 \text{ cc/min}
Space Simulator IAS
By-Pass Valve # 2  5-17-93

By-Pass Flow C.I.P. to C.I.P.

By-Pass Flow (b.i.)

Pneumatic (ps.)

Locked

By-Pass

0 100 200 300 400
Unlocking Pressure

Some Sharpne "HIPS"

By-Pass Unleus # 2

5-17-93

Flow CN to CP

CP 300

CP 360 psi
SPACE SHUTTLE HAS 5-17-93

By-Pass Valve # 2

By Pass Flow C.P. -> C.P.

\( P_{\text{new}} \)

\( C_2 = 300 \text{ psi} \)

By Pass Flow C.P. -> C.P.
Space Shuttle HAS ByPass Valve #3

Unlocking Pressure - Set $C_iV = \frac{300}{C_iV}$ psi

Monitor Flow $C_{iU}$ to $C_{iP}$ as function of $SUOSW$ Pressure - Repeat with $C_{iU} = 300$

<table>
<thead>
<tr>
<th>SUOSW PRESS</th>
<th>Flow $C_{iU}$ to $C_{iP}$</th>
<th>Flow $C_{iV}$ to $C_{iP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.03</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>2.03</td>
<td></td>
</tr>
<tr>
<td>1025</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1050</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1075</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1125</td>
<td>1.26</td>
<td>8.15</td>
</tr>
<tr>
<td>1150</td>
<td>2.39</td>
<td>9.20</td>
</tr>
<tr>
<td>1175</td>
<td>5.0</td>
<td>9.68</td>
</tr>
<tr>
<td>1200</td>
<td>6.02</td>
<td>10.11</td>
</tr>
<tr>
<td>1250</td>
<td>6.62</td>
<td>10.91</td>
</tr>
<tr>
<td>1300</td>
<td>7.62</td>
<td>11.77</td>
</tr>
<tr>
<td>1400</td>
<td>10.31</td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td>10.21</td>
<td></td>
</tr>
<tr>
<td>1600</td>
<td>10.01</td>
<td></td>
</tr>
<tr>
<td>1950</td>
<td>10.01</td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Space Shuttle Has By-Pass Valve ≠ 3

By-Pass Flow \( SUOSW = 0 \) psi

- \( C_1U - C_2U = 500 \) psi
- \( C_2P = -500 \) psi

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Return Flow</th>
<th>(From Later)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( C_2P \rightarrow C_1P )</td>
<td>( C_2P \rightarrow C_1P + C_2P \rightarrow R )</td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>&lt;06</td>
<td>47</td>
</tr>
<tr>
<td>225</td>
<td>.48</td>
<td>5.2</td>
</tr>
<tr>
<td>300</td>
<td>.54</td>
<td>.59</td>
</tr>
<tr>
<td>350</td>
<td>.54</td>
<td>.59</td>
</tr>
<tr>
<td>400</td>
<td>.54</td>
<td>.59</td>
</tr>
<tr>
<td>( \sqrt{2} )</td>
<td>( 29/69 ) = 1.34</td>
<td></td>
</tr>
</tbody>
</table>

Repeat \( w/ C_1P = 500 \) psi

<table>
<thead>
<tr>
<th>Pressure</th>
<th>( C_1P \rightarrow C_2P )</th>
<th>( C_1P \rightarrow R )</th>
<th>( C_1P \rightarrow C_2P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>&lt;06</td>
<td>.22</td>
<td>.29</td>
</tr>
<tr>
<td>150</td>
<td>.06</td>
<td>.24</td>
<td>.31</td>
</tr>
<tr>
<td>200</td>
<td>.06</td>
<td>.24</td>
<td>.31</td>
</tr>
<tr>
<td>250</td>
<td>.06</td>
<td>.24</td>
<td>.31</td>
</tr>
<tr>
<td>280</td>
<td>.06</td>
<td>.24</td>
<td>.31</td>
</tr>
<tr>
<td>300</td>
<td>.06</td>
<td>.24</td>
<td>.31</td>
</tr>
<tr>
<td>350</td>
<td>.06</td>
<td>.24</td>
<td>.31</td>
</tr>
<tr>
<td>400</td>
<td>.06</td>
<td>.24</td>
<td>.31</td>
</tr>
</tbody>
</table>
Space Shuttle HAS ByPass Valve # 3

Leakage - Locked Mode
Swing = 0 psi
Pneu = 0

\( C_1P = 3000 \text{ psi} \)

Leakage
\( \frac{\text{To} \to C_1V}{\text{To} \to C_1P} = \frac{36 \text{ drops/} \text{min}}{20 \text{ drops/} \text{min}} = 1.8^\circ/\text{min} \)

\( \frac{\text{To} \to R}{\text{To} \to C_1P} = \frac{2 \text{ drops/} \text{min}}{11 \text{ drops/} \text{min}} \)

\( C_2P = 3000 \text{ psi} \)

Leakage
\( \frac{\text{To} \to C_2V}{\text{To} \to C_1P} = \frac{6.0 \text{ drops/} \text{min}}{11 \text{ drops/} \text{min}} \)

\( \frac{\text{To} \to R}{\text{To} \to C_1P} = \frac{3.1 \text{ cc/} \text{min}}{11 \text{ drops/} \text{min}} \)

Leakage - Operate Mode
Swing = 3000 psi

\( C_1V \geq 3000 \text{ psi} \) \( (C_1P \text{ capped}) \)

Leakage \( \to R = 1 \text{ drop/} \text{min} \)

\( C_2V \geq 3000 \text{ psi} \) \( (C_2P \text{ capped}) \)

Leakage \( \to R = 6.0^\circ/\text{min} \)

Both Above Pressurized

Leakage \( \to R = 7.9^\circ/\text{min} \)
Space Shuttle NXS

By Pass Valve #3 5-18-93

Uncorrected Pressure

From CV to CP
(at 300 psi)

Flow CV to CP

Flow CV to CP

Gage C

Gage C

Press. (psid)
STUDY OF HYDRAULIC ACTUATION SYSTEM

FOR

SSME PROPELLANT VALVES

PRESENTED TO MSFC, NASA

MAY 6, 1993
OBJECTIVES

- Increase Reliability
- Decrease Maintenance Costs
- Preserve Present Interfaces
- Minimize Impact to Interfacing Equipment
IMPROVED RELIABILITY

- Decrease Contamination Sensitivity
- Increase Spool Driving Forces
- Improve Feedback Transducer
- Update Design to 1990's Technology
MAINTAINABILITY

- Use Commonality
- Simplify Design
- Increase Robustness
CONSIDERATIONS FOR CONTAMINATION PROBLEMS

- Increase Orifice Sizes
- Improve Orifice Protection
- Increase Spool to Bushing Clearances
- Simplify Housing Design
- Reduce Quantity of Elastomeric Seals
- Potential Seal Material Change
- Modify Filtration Scheme
SERVOVALVE PILOT STAGE
DEFLECTOR JET VERSUS FLAPPER NOZZLE

- D J Smallest Restriction Typically 4 to 5 Times Larger Than Flapper Nozzle (0.006 vs. 0.0012)
- Flapper Nozzle has Higher Pressure Gain and Higher Maximum Differential Pressure (85% vs. 60%)
- Flapper Nozzle has Higher Flow Recovery
SERVOVALVE POWER STAGE

- Use Conventional Spool/Bushing Configuration

- Slip Fit Busing in Stainless Steel Housing
  - Reduces Number of Elastomeric Seals

- Larger Diameter Spool
  - Increases Driving Force

- Increase Spool/Bushing Clearance
  - Reduces Friction
REASONABLE INTERNAL LEAKAGE

Servovalve Pilot Stage Tare (2) 0.77 cis
Servovalve Spool Leakage (2) 1.6 cis
Solenoid (2) 0.04 cis
Shuttle Valve 0.25 cis
Bypass Valve 0.20 cis
TOTAL 2.86 cis/actuator

2.86 cis Times 5 Actuators = 14.3 cis (3.7 gpm)
FEEDBACK POSITION TRANSDUCER

- Purchase from Established Transducer Manufacturer
- Consider Alternatives to RVDT
  - May Require Different Electrical Power
- RVDT Probably Still Best Choice
FILTRATION

- Present System
  - One Hydraulic Actuator System Filter
  - Individual Servovalve Pilot Stage Filters

- Disadvantages of Present System
  - Hyd. Connections and Lines Downstream of Filter
  - No prefiltration Flushing Capability

- Potential Change
  - Eliminate Present HAS Filter
  - Add Filter to Each Actuator
  - Add Flushing Feature to Each Actuator
  - Keep Individual Pilot Stage Filters
FAIL OPERATE - FAIL SAFE SWITCHING

- Consider Replacing Servovalve Devices with Solenoids
- Solenoid Valves Proven Reliable on Shuttle TVC
- Solenoids Would Reduce Fluid Tare Loss
- Would Require More Power Than Torque Motors
- Solenoids Could Drive Bypass and Switching Valves Directly
BYPASS VALVE ASSEMBLY

- Has History of Problems
  - Spool Nonfunctional
  - Galling Between Sleeve and Spool

- Analysis Shows Possibility of Interference
  - Localized External Loading of Sleeve

- Possible Clamping Action on Spool

- Clamping Would Occur During Switching Transient

- Spool Normally Stationary
  - Moves in Response to Problem Detection

- Subject to Silting at Spool Circumference
  - Very Fine Particle Build Up
Radial Displacement for a Continuous Open Cylindrical Membrane

\[ \mu = \frac{V}{E \left( b^2 - a^2 \right)} \left[ (1-V) (P_{in}^2 - P_{out}^2) + \frac{(1+V)}{r^2} \left( P_{in}^2 - P_{out}^2 \right) \right] \]

- \( r = \text{Radius of calculated Displacement} \)
- \( E = \text{Modulus of Elasticity} \)
- \( V = \text{Poisson's Ratio} \)
- \( P_{in} = \text{Inside Pressure} \)
- \( P_{out} = \text{Outside Pressure} \)
- \( a = \text{Inside Radius} \)
- \( b = \text{Outside Radius} \)

For \( r = a \) \( \Rightarrow P_{in} = 0 \)

\[ \mu = \frac{a}{E \left( b^2 - a^2 \right)} \left[ \frac{1}{2} \left( 1-V \right) \left( \frac{a^2 - b^2}{2} \right) \right] \]

\[ \mu = \frac{a}{E \left( b^2 - a^2 \right)} \left[ -P_{out}^2 \left( 1 - 2V + 1 + V \right) \right] \]

\[ \mu = \frac{-2a^2 b^2 P_{out}}{E \left( b^2 - a^2 \right)} \]

For \( a = \frac{422}{2} \) \( + b = \frac{792}{2} \) \( (\text{full sem annular}) \)

\[ 3500 \text{ psi} \]

\[ \Delta \]

\[ \mu = \frac{V \left( \frac{422}{2} \right)^2 \left( \frac{792}{2} \right)^2 \left( 3500 \right)}{\left( 30 \times 10^6 \text{ psi} \right) \left[ \left( \frac{1792}{2} \right)^2 - \left( \frac{422}{2} \right)^2 \right]} = 0.0000663 \]

\( \text{Radian} \) or \( 0.000137 \) \( \text{Diametral Reduction} \)

For \( b = 0.0 \)

\[ \mu = \frac{V \left( \frac{422}{2} \right)^2 \left( 1000 \right)^2 \left( 3500 \right)}{\left( 30 \times 10^6 \text{ psi} \right) \left[ \left( \frac{1000}{2} \right)^2 - \left( \frac{422}{2} \right)^2 \right]} = 0.000060 \]

\( \text{Radian} \) or \( 0.00010 \) \( \text{Diametral Reduction} \)

For \( b = 0.1 \)

\[ \mu = \frac{V \left( \frac{422}{2} \right)^2 \left( 1800 \right)^2 \left( 3500 \right)}{\left( 30 \times 10^6 \text{ psi} \right) \left[ \left( \frac{1800}{2} \right)^2 - \left( \frac{422}{2} \right)^2 \right]} = 0.0000550 \]

\( \text{Radian} \) or \( 0.000098 \) \( \text{Diametral Reduction} \)
BYPASS VALVE MODIFICATIONS

- Revised Bushing/Spool Assembly to Preclude Pressure Clampdown During Switching
- Maintains Existing Housings and Allows Retrofit
- Maintains Existing Travel and Operating Force Levels Thereby Utilizing Existing Associated Parts Without Modifications
- Introduces Self-Cleansing "Curtain" Orifice Which Reduces Sensitivity to Contamination
- Minimizes Re- Qualification Requirements Due to Minimum Redesign
- Minimal Cost to Program
TIMING ORIFICE

- Controls Actuator/Load Rate When Bypassed
- Rate Controlled by Orifice Size and Differential Pressure
- Orifice is Small
- Subject to Plugging from Small Contaminants
- Filter Used for Orifice Protection
BYPASS RATE MODIFICATION

- Orifice Replaced by Reduced Spool Diameter Section
- New "Orifice" Created by Curtain Area of Spool and Feed Hole
- Larger Clearances
- Self Cleansing Action
- Eliminates Need for Filter
ORIFICE SIZING

• Present Orifice
  - Area = 0.017 \times 0.015 = 0.000255 \text{ Square Inches}

• New Orifice
  - Area = \pi D X \\
    \text{When } D \text{ is hole diameter} = 0.026 + 0.0025 - 0.0000 \\
    X \text{ is spacing} \\
    X \text{ ranges from 0.001805 to 0.003095}

\begin{align*}
A_{\text{min}} &= 0.0001474 \\
A_{\text{max}} &= 0.0002577
\end{align*}
NOTE

1. LAP BORE OF FIND NO. 1 5 V FINISH
TO ACHIEVE .000110 TO .000140 DIAMETRAL
CLEARANCE WITH FIND NO. 2.
MARKED ENDS OF FIND NOS 1 AND 2 ARE MATCHED.
DEMONSTRATION HARDWARE

• Designed and Manufactured Proof of Concept Hardware
  - Sleeve and Spool Assembly
• Designed and Manufactured Test Fixture
• Received Auxiliary Parts from Rocketdyne
• Tested One Assembly
• Shipped Tested Parts in Test Fixture
• Manufactured Contingency Sleeve and Spool
• Will Fit Contingency Parts, Test and Ship to MSFC
TEST OBJECTIVES

• Demonstrate Normal Functions
• Verify Flow Paths and Leakage
• Show Repeatable Switching
• Check Effects of Silting at Spool Lands
• Demonstrate Compliance with Present Requirements
TEST RESULTS

- All Testing Done Under Normal Ambient Conditions
  - Fluid Per MIL-H-83282
  - Fluid Temperature 70 to 100 Deg. F.

- Assembly Functioned Properly

- No Anomalous Behavior

- Cross Port Leakage Very Low
  - Less Than 1 Drop per Minute

- No Apparent Effect from Silting
TEST RESULTS (CONT'D)

- Operate to Lockup 1050 psi

- Lockup to Operate 1050 psi
  - Less Than 4 Pounds Friction (25 psi)

- Operate to Lockup to Operate
  - Transition Range Less Than 300 psi

- Lockup to Bypass
  - 250 to 300 psi Nitrogen
  - C2P to Return at 250 psi
  - C2P to C1P at 300 psi

- Bypass Flow Thru Orifice
  - 0.5 cis at 500 psid

MOOG
$C_2V + C_2P$ Pressure: $2600$ psi
$C, U, C$ $300$ psi for indication of scale issue

Space Shuttle HA5
By pass valve #1 4-6-93

Switching Pressure
Worst Case?
Space Shuttle PVS

By-Pass Valve #1

By Pass Flow C1P → C2P

\[ P_{\text{pneu}} \]
Space Shuttle HRS

By Pass Valve #1

By Pass Flow C2P → C.P.
RECOMMENDATIONS (BYPASS VALVE)

- Expand Test Program

- Test at Environmental Extremes
  - Temperature
  - Vibration

- Life Cycle
  - Pause Between Cycles
  - Simulate Potential Use

- Test Larger Sample Lot
  - Manufacture and Test by HAS Supplier
  - Detailed Inspection of Parts and Fits
  - Recommend at Least 6 Test Samples
GENERAL RECOMMENDATIONS

- Change Bypass Valve Design
  - Maintain Present HAS Design
  - Create Interchangeable Sleeve and Spool Assembly

- Keep Rest of Existing Design
  - Past Problems Have Been Addressed
  - No Major Problems Except Jammed Spools
  - Production Processes Established

- Probably Not Economically Practical to Start New Design Effort Unless Space Shuttle Scope is Drastically Increased
CONCLUSIONS

- Present Design Driven by Requirements
  - Hydraulic Fluid Consumption (Leakage)
  - Electrical Power Limitation
  - Size and Weight

- Design Technology from 1960's

- Switching Valves Offer No Redundancy
  - Single Point Failure Devices
  - Limited Driving Force Available

- Solenoid Valve as Switches Would Improve Reliability
  - Higher power Required
  - Lower or Redistributed Leakage
  - Would Allow Larger Servo valve Pilot Stage Orifices

- Trade Study Covering New Actuation Techniques Needed for Future Propellant Valve Control
Recent performance concerns involving the Space Shuttle Main Engine Propellant Valve Actuator assemblies prompted the NASA Marshall Space Flight Center to request an independent design assessment. Moog Inc. responded to this request and received a study contract with objectives of increasing valve reliability, decreasing maintenance costs while preserving the existing design interfaces. The results of the Propellant Valve Actuation System review focus on contamination control and the Bypass Valve design. Three proof of concept Bypass Valves employing design changes were built and successfully tested. Test results are presented.