POWER EFFICIENT HYDRAULIC SYSTEMS
Volume II
HARDWARE DEMONSTRATION PHASE

Rockwell International
North American Aircraft
4300 East Fifth Avenue
P.O. Box 1259
Columbus, Ohio 43216

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Energy saving concepts for aircraft hydraulic systems were studied in a two-phase program. Task I was an investigation of methods and techniques to reduce overall hydraulic system power requirements by lowering system demands and increasing component efficiencies. Task II involved hardware demonstration tests on selected concepts.

Task I: Study Phase. A baseline hydraulic system for an advanced aircraft design was established. Twenty energy saving techniques were studied as candidates for application to the baseline vehicle. A global systems analysis approach was employed. The candidates were compared on the basis of total fuel consumption and six qualitative factors. Nine of the most promising techniques were applied to a "Target System". The target system had a 28% reduction in energy consumption and an 860 lb weight reduction over the baseline aircraft. The study made one conclusion clear: Don't add weight to save energy.

Task II: Hardware Demonstration Phase. Two techniques demonstrated for energy savings.
were control valves with overlap and dual pressure level systems. Tests were conducted on control valves, a servo actuator, dual pressure pumps, and a lightweight hydraulic system simulator. Valves with 0.002 in. overlap reduced system energy consumption 18% compared to using valves with zero lap. Operation at 4000 psi reduced system energy consumption 53% compared to operation at 8000 psi. Pressure level switching was accomplished with excellent results.
FOREWORD

This report presents the results of the second phase of a two phase program to study and demonstrate methods and techniques to improve the operating efficiency of hydraulic systems in advanced Navy aircraft. The results of Task I (study phase) are presented in Volume I of this report. The results of Task II (demonstration phase) are presented herein.

The study phase consisted of the following:

- Determination of study methodology
- Definition of baseline vehicle
- Establishment of baseline hydraulic system
- Evaluation of candidate energy saving techniques
- Application of the most promising techniques to a target system
- Determination of weight and energy savings of the target system over the baseline.

The hardware demonstration phase consisted of the following:

- Design test parts
  - Actuator modification
  - Test fixture modification
- Procure demonstration hardware
  - Direct drive control valves and electronics
  - Dual pressure pumps
- Analyze test results
- Summarize results
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1.0 HARDWARE DEMONSTRATION PHASE (TASK II)

1.1 APPROACH

1.1.1 Introduction

The study phase, reported in Volume I, determined that certain energy conservation techniques can significantly reduce aircraft fuel consumption. Techniques considered to be effective in reducing losses and selected for laboratory demonstration testing were:

- Control valves with overlap and shaped orifices
- Dual pressure level systems

Specially designed hardware were fabricated to validate the potential of these energy saving techniques. Tests were then conducted to determine the energy consumption of the different techniques. In addition, dual pressure level switching transients were investigated, and actuator performance changes resulting from the use of the special control valves were examined. Section 1.1 describes the demonstration hardware, tests performed, and instrumentation used. Test procedures and results are presented in Section 1.2. A summary is given in Section 1.3.

1.1.2 Demonstration Hardware

1.1.2.1 Control Valves. Quiescent leakage in control valves causes appreciable power loss. Most of this internal leakage occurs at the spool null position and is a function of valve size, spool/sleeve clearance, and orifice geometry. Total internal leakage is the sum of the dynamic leakage that occurs when the valve is operating plus null leakage when the spool is stationary. Two approaches were investigated to determine potential energy savings: overlap and shaped orifices (see Section 2.4.5 in Volume I).
Valve design and performance requirements were established by a specification prepared to procure the valves. This specification is presented in Appendix A. Considerable latitude was permitted for deviating from the specification requirements providing the basic goals of the test program could be met with the proposed design. Cost was an important consideration in supplier selection.

Two companies were chosen to provide the test valves: Bendix Electrodynamics and E-Systems. Bendix provided both the valves and electronics on a consignment loan basis. E-Systems provided the valve electronics on a consignment basis. Descriptions of the test valves are given in the following paragraphs.

**Bendix Electrodynamics.** The test valve is a modified version of a 5,000 psi unit built for a prior Bendix project. The valve has separate motor and spool/sleeve assemblies that combine in one housing to form the valve assembly. The motor and spool both have rotary motion. Three interchangeable spool/sleeve assemblies provide three different configurations:

- Zero overlap with linear slot orifices
- High overlap with linear slot orifices
- Small overlap with T-slot orifices

Spool travel is $+10^\circ$ ($+0.0327$ in.). Rated flow is 5 gpm. Multi-metering orifices are employed to minimize the maximum chip size the spool must shear. The maximum available shear-out force is 80 lb. Flow forces are exceptionally low due to special design features.

The motor is a brushless DC type with samarium-cobalt magnets to provide a high torque-to-power ratio, and is an "inside-out" design with magnets on the rotor and windings on the stator. The motor drives the spool directly; a torsional centering spring is attached to the opposite end of the spool. No seals are required on the spool. An RVDT provides the spool position feedback signal. The valve/motor assembly is shown on Figure 1.
Figure 1. Bendix direct drive servo valve

Figure 2. E-Systems direct drive servo valve
The Bendix electronics package drives the torque motor with an analog signal, and provides feedback loop closure around the valve spool and actuator piston. Loop gain adjustments are available.

NOTE: Flow gain, pressure gain, internal leakage, and frequency response tests were completed on the zero overlap and T-slot configurations (the high overlap valve had not yet been received). The T-slot valve failed during the servo actuator tests (see Section 1.2.2.2). No further tests were conducted on the Bendix valves due to program scheduling constraints.

E-Systems. The test valve was originally designed to control two independent systems on a dual system actuator, and has a single, linear-motion spool. The valve design was modified so that one side has zero overlap and the other side has 0.002 in. overlap. Rated flow is 3.5 gpm on each side. The valve mounting block is made so that only one system can be operated at a time. A linear motion LVDT is used to close the loop around the spool and provide a spool position signal. Available chip shear-out force is 45 pounds. The valve is shown on Figure 2.

The valve electronics package drives the force motor with a pulse-width-modulated signal, provides feedback loop closure around the valve spool, and has a manual bias control. A second electronics package provides loop closure around the servo actuator piston and has feedforward and feedback compensation adjustments.

1.1.2.2 Servo Actuator. The actuator was built by Vought for the LHS Advanced Development Program, reference 1, and was designed to operate the unit horizontal tail (UHT) on an A-7E test bed aircraft. The servo actuator has dual tandem cylinders and a dual tandem mechanical input control valve, Figure 3. Feedback is accomplished with mechanical linkages.
Figure 3. Original unit horizontal tail actuator

Figure 4. Modified UHT actuator with Bendix valve

Figure 5. Modified UHT actuator with E-Systems valve
The UHT actuator was modified to mount it in a mass load test fixture and to accommodate the Bendix and E-Systems control valves. Changes made were:

- The FC-2 piston with unbalanced areas was replaced with a balanced area piston. The FC-1 side of the actuator was de-activated.
- A new piston rod seal cartridge was made to fit the new size piston rod.
- An LVDT was installed inside the piston rod to provide electrical feedback.
- A new rod end was fabricated to mate with the mass load fixture.
- The mechanical control valve housing was replaced with a manifold designed to interface with the Bendix and E-Systems test valves.

The modified UHT actuator with the test valve installations is shown on Figures 4 and 5. Major design parameters are:

- Operating pressure: 8000 psi
- Piston diameter: 2.368 in.
- Rod diameter: 1.185 in.
- Piston stroke: 6.58 in.
- Extend/retract piston area: 3.301 in.$^2$
- Stall output force: 26,400 lb

1.1.2.3 Dual Pressure Pump. A 4000/8000 psi pressure level system offers substantial energy savings, reference Section 2.4.6 in Volume I. The dual pressure level concept employs a logic system to determine the pressure mode used. Important advantages obtained, in addition to energy savings, are reduced heat rejection and an increase in MTBF for hydraulic system components.
The test pumps were originally procured for the LHS Advanced Development Program, reference 1, and are a pressure compensated, variable delivery axial piston design. The units, built by Vickers Aerospace Division, were designed for use on the LHS simulator, and were identified as M/N PV3-047-2, S/N 346580 and S/N 346581. Rated flow is 10 gpm at 5900 rpm. One pump (S/N 346581) has accumulated 1150 hours of endurance cycling during LHS programs; the other unit (S/N 346580) has accumulated 227 hours.

The pumps were modified to operate at two pressure levels by Vickers. The Statement of Work and Performance Requirements Specification Sheet are presented in Appendix A. The modification permits switching from a high pressure (8000 psi) to a low pressure (4000 psi) mode of operation and from the low pressure to the high pressure mode. Control pressure is ported to the pump compensator mechanism using a 3-way solenoid valve. Loss of electrical power to the valve will revert the pump to the high pressure mode. The modified pump, M/N PV3-047-4, is shown on Figure 6.

1.1.2.4 LHS Simulator. The original purpose for the simulator was to demonstrate the concept of using an 8000 psi operating pressure to achieve smaller and lighter weight hydraulic components than those used in aircraft with conventional 3000 psi systems, reference 1. The LHS simulator is a steel structure with hydraulic component installations designed to represent a full scale A-7E 8000 psi flight control system, Figure 7. A modular design approach was employed. Two types of modules are used:

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Figure 6. Vickers dual pressure pump with switching valve
Each power module contains a pump, reservoir, filters, and valving to supply hydraulic fluid to the flight control actuators. Each actuator is mounted in a load module that duplicates the kinematics of an A-7E installation. Load/stroke conditions imposed on each actuator are based on specific, individual requirements. Twelve 8000 psi flight control actuators are installed in the simulator:

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The simulator can be operated manually or automatically. Manual control is by "pilot stick" or through manipulating dials and switches on a console panel. Automatic control is by a mechanical programmer.

1.1.3 Tests Conducted

1.1.3.1 Control Valves. The primary objective was to determine the effects of overlap on valve flow gain, pressure gain, internal leakage, and frequency response. Flow gain is a plot of spool position versus no-load flow. Flow gain directly affects loop gain and therefore influences system stability. Pressure gain is a plot of spool position versus the difference in pressure between the valve cylinder ports which are temporarily blocked for this measurement. Pressure gain provides servo actuators with the capability to break away large friction loads with little error. Internal leakage is plotted as a curve of spool position versus return line flow with the cylinder ports blocked. Internal leakage dominates valve performance in the null region and is a continuous power loss. Frequency response involves plotting the output divided by the input (amplitude ratio in db) versus frequency. A valve with good response operates with minimum overshoot and undershoot and minimum phase lag within a required frequency band. Tests conducted were:
1.1.3.2 Servo Actuator. The effects of valve overlap and dual pressure level operation on actuator performance were investigated by determining actuator response to step and sinusoidal inputs, by measuring piston position changes and pressure transients resulting from pressure level switching, and by comparing the energy consumption of the different valve/actuator combinations. The dynamic operation of servo actuators is typically characterized by the accuracy with which they track square wave commands and their ability to follow sinusoidal inputs over a given frequency band. Loop gains and command amplitude directly affect performance and must be carefully selected to provide valid test data. Switching pressure levels from 4000 to 8000 psi and 8000 to 4000 psi may produce undesirable side effects -- pressure transients and actuator position disturbances. The extent of these occurrences were to be determined. The energy consumption using an overlapped valve was compared to the energy consumption using a zero lapped valve. These measurements provided the basis for energy savings achieved.

Tests conducted on the servo actuator were:

<table>
<thead>
<tr>
<th>Test</th>
<th>Actuator Configuration</th>
<th>Pressure Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic Response</td>
<td>E-Systems Valve</td>
<td>4000 &amp; 8000 psi</td>
</tr>
<tr>
<td>Pressure Level Switching</td>
<td>E-Systems Valve</td>
<td>4000 &amp; 8000 psi</td>
</tr>
<tr>
<td>(cycling flow)</td>
<td>zero overlap</td>
<td></td>
</tr>
<tr>
<td>Energy Consumption</td>
<td>0.002 in. overlap</td>
<td></td>
</tr>
</tbody>
</table>
1.1.3.3 **Dual Pressure Pump.** Pump performance was based on four operating characteristics: overall efficiency, pressure ripple, transient response, and heat rejection. Overall efficiency is delivered hydraulic power divided by input horsepower, and is measured at rated operating conditions of speed, flow, and temperature. Pressure ripple is caused by the stroking action of the pump pistons. This ripple causes standing pressure waves in the pump discharge line which can, if the right frequencies are present and amplitudes are sufficient, cause undesirable vibration in system tubing. Transient response is a measure of the ability of the pump to respond to rapid changes in flow demand. Slow response causes large amplitude pressure transients -- both overshoot and undershoot. Overshoot causes high stresses in system components; undershoot results in degraded actuator performance. Heat rejection is the result of internal leakage used to lubricate and cool the pump, and is caused by fluid throttling from high pressure to low pressure which raises fluid temperature. High fluid temperatures are harmful to seals and increases internal leakage rates in other components. Heat exchangers are frequently needed to remove heat added to systems by pumps with high heat rejection.

Tests conducted on the dual pressure pump were as follows:

<table>
<thead>
<tr>
<th>Test</th>
<th>Pressure Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Efficiency</td>
<td>4000 &amp; 8000 psi</td>
</tr>
<tr>
<td>Pressure Ripple</td>
<td></td>
</tr>
<tr>
<td>Transient Response</td>
<td></td>
</tr>
<tr>
<td>Heat Rejection</td>
<td></td>
</tr>
<tr>
<td>Pressure Level Switching</td>
<td>4000 &amp; 8000 psi</td>
</tr>
<tr>
<td>(steady flows)</td>
<td></td>
</tr>
</tbody>
</table>
1.1.3.4 LHS Simulator. The LHS simulator was used to determine the effects of overlapped valves and dual pressure levels on the operation of a full scale hydraulic system. The overall objective was to demonstrate that overlapped valves can be employed to conserve energy without seriously degrading actuator performance, and that switching operating pressure levels does not cause harmful pressure transients. The actuator was mounted in the LH UHT load module (see Figure 7). FC-1 system was used to power the actuator. FC-1 and FC-2 systems were operated for the pressure level switching tests.

Tests conducted on the LHS simulator were as follows:

<table>
<thead>
<tr>
<th>Test</th>
<th>Configuration</th>
<th>Operating Mode</th>
<th>Pressure Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH UHT ACTUATOR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamic Response</td>
<td>E-Systems Valve</td>
<td>step input</td>
<td>4000 &amp; 8000 psi</td>
</tr>
<tr>
<td></td>
<td>zero lap</td>
<td>sinusoidal input</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.002 in. overlap</td>
<td>output loaded</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>FC-1 only</td>
<td></td>
</tr>
<tr>
<td>Pressure Level Switching</td>
<td>E-Systems Valve</td>
<td>output motionless</td>
<td>4000 &amp; 8000 psi</td>
</tr>
<tr>
<td></td>
<td>zero lap</td>
<td>output moving</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.002 in. overlap</td>
<td>output loaded</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>FC-1 only</td>
<td></td>
</tr>
<tr>
<td>Energy Consumption</td>
<td>E-Systems Valve</td>
<td>sinusoidal output</td>
<td>4000 &amp; 8000 psi</td>
</tr>
<tr>
<td></td>
<td>zero lap</td>
<td>output unloaded</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.002 in. overlap</td>
<td>output loaded</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>FC-1 only</td>
<td></td>
</tr>
<tr>
<td>SYSTEM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure Level Switching</td>
<td>FC-1 &amp; FC-2 systems</td>
<td>All actuators cycling</td>
<td>4000 &amp; 8000 psi</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Operating modes:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2%, 10%, and 50% load/stroke</td>
<td></td>
</tr>
<tr>
<td>Test</td>
<td>Configuration</td>
<td>Operating Mode</td>
<td>Pressure Levels</td>
</tr>
<tr>
<td>------------------------------</td>
<td>--------------------------------------</td>
<td>---------------------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>Pressure Ripple</td>
<td>FC-1 &amp; FC-2 systems</td>
<td>All actuators at null</td>
<td>4000 &amp; 8000 psi</td>
</tr>
<tr>
<td>Spectrum Analysis</td>
<td>FC-1 &amp; FC-2 systems</td>
<td>All actuators at null</td>
<td>4000 &amp; 8000 psi</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pump speed sweep</td>
<td></td>
</tr>
<tr>
<td>Energy Consumption</td>
<td>{E-Systems Valve}</td>
<td>LH UHT actuator cycling</td>
<td>4000 &amp; 8000 psi</td>
</tr>
<tr>
<td></td>
<td>Zero lap</td>
<td>All other actuators at null</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.002 in. overlap</td>
<td>LH UHT unloaded</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LH UHT loaded</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>FC-1 only</td>
<td></td>
</tr>
</tbody>
</table>

1.1.4  Instrumentation

1.1.4.1  Hydraulic Test Bench. The performance of the Bendix and E-Systems valves was evaluated using a bench designed for testing 8000 psi hydraulic components, Figure 8. The test stand, built by Dayton T. Brown, is capable of delivering flows up to 18 gpm at pressures up to 8000 psi. Flow is measured by a positive displacement meter with readout in any desired units on a microprocessor based indicator. Fluid temperature can be controlled at levels between +100 and +200°F. The bench contains fluid per specification MIL-H-83282; fluid filtration is 3 microns absolute.

1.1.4.2  Electronic Data Analysis System. A multi-channel computer based data analysis system was used to support all tests, Figure 9. A block diagram of the system and component identification are given on Figure 10. Signal processing is performed on an analyzer with pre-programmed waveform analysis/manipulation functions for both time and frequency domain measurements. Capabilities include transient analysis, spectrum analysis, and mathematical operations from basic to complex such as fast fourier transforms. The analyzer is also a digital oscilloscope with flexible multi-trace display capabilities. Bandwidth is 100 KHz with 14 bit A/D resolution; accuracy is 0.1%. 

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Figure 8. 8000 psi hydraulic test bench

Figure 9. Electronic data analysis system
Figure 10. Block diagram of data analysis system
Operation of the data processor is enhanced through the use of a CPU and customized software. Soft keys located on the computer keyboard are pre-programmed to execute special functions. Menu driven programs were employed to make various types of graphs on an interactive X-Y plotter. Special data presentation capabilities include order tracking and three-dimensional cascade displays.

1.1.4.3 Transducers. Several different types of transducers were employed in the demonstration tests to measure pressure, flow, temperature, torque, and speed; these are listed on Table 1. The transducers produce electrical signals which must be conditioned; signal conditioning and readout equipment are listed in Table 2.

All transducers were calibrated so that calibration factors could be developed for use in the data analysis system. The system has provisions for entering engineering units per volt, such as \( \text{in}^3/\text{sec/volt}, \text{psi/volt}, \text{lb-in/volt}, \text{and rpm/volt} \).

1.2 HARDWARE DEMONSTRATIONS

1.2.1 Control Valves

1.2.1.1 Procedure. Schematic diagrams of the setups used for the flow gain, pressure gain, and internal leakage tests are presented in Figure 11. Command signal waveforms and frequencies are also given on Figure 11. The test data are based on spool displacement, therefore different displacement amplitudes were employed for the Bendix and E-Systems valves. These amplitudes, given on Figure 11, were based on the signal amplitude generated by the spool position feedback transducer (LVDT or RVDT). Spool displacements used in the flow gain and internal leakage tests were the same. Spool displacement used to determine pressure gain was approximately 25% of that used in the other tests. All tests were conducted with valve inlet pressures of 4000 and 8000 psi; return pressure was approximately 100 psi. Test bench fluid temperature was controlled at 120 ±5°F. A view of the flow gain test setup with the E-Systems valve is shown on Figure 12.
### TABLE 1. Transducer information

<table>
<thead>
<tr>
<th>TEST</th>
<th>PARAMETER</th>
<th>TYPE</th>
<th>MODEL NO.</th>
<th>MANUFACTURER</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control Valves</td>
<td>Pressure</td>
<td>Strain Gage</td>
<td>122EF76</td>
<td>Viatran</td>
</tr>
<tr>
<td></td>
<td>Servo Actuator</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dual Press. Pump</td>
<td>Pressure</td>
<td>Piezoelectric</td>
<td>108A02</td>
<td>PCB Piezotronics</td>
</tr>
<tr>
<td></td>
<td>LHS Simulator</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dual Press. Pump</td>
<td>Flow</td>
<td>Turbine</td>
<td>10C1510A</td>
<td>Fischer &amp; Porter</td>
</tr>
<tr>
<td></td>
<td>LHS Simulator</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Control Valves</td>
<td>Flow</td>
<td>Metering Cylinder</td>
<td>514C-1</td>
<td>Industrial Measurements</td>
</tr>
<tr>
<td></td>
<td>Servo Actuator</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dual Press. Pump</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LHS Simulator</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>Temperature</td>
<td>Thermocouple</td>
<td>None</td>
<td>Rockwell International</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Servo Actuator</td>
<td>Torque</td>
<td>Stain Gage</td>
<td>1615K123</td>
<td>Lebow Products</td>
<td></td>
</tr>
<tr>
<td>Dual Press. Pump</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHS Simulator</td>
<td>Speed</td>
<td>Magnetic Pickup</td>
<td>3010-AN</td>
<td>Electro Corp.</td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE 2. Signal conditioning and readout equipment

<table>
<thead>
<tr>
<th>SIGNAL CONDITIONING</th>
<th>TYPE</th>
<th>M/N</th>
<th>MANUFACTURER</th>
<th>READING</th>
<th>M/N</th>
<th>MANUFACTURER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (strain gage)</td>
<td>Bridge balance &amp; DC amplifier</td>
<td>9608</td>
<td>Tegam</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure (piezoelectric)</td>
<td>Power supply</td>
<td>484B</td>
<td>PCB Piezotronics</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbine meter</td>
<td>Oscillator/pre-amplifier</td>
<td>55GE223B</td>
<td>Fischer &amp; Porter</td>
<td>Microprocessor w/digital readout</td>
<td></td>
<td>ITK 7650 NES, Inc.</td>
</tr>
<tr>
<td></td>
<td>Frequency to DC converter</td>
<td>50103</td>
<td>Spectral Dynamics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actuator LVDT</td>
<td>Demodulator/DC amplifier</td>
<td>ATA-101</td>
<td>Schaevitz</td>
<td>Digital Multimeter 3466A **</td>
<td></td>
<td>Hewlett-Packard</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5503</td>
<td>Bay Laboratories</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow cylinder</td>
<td>DC amplifier</td>
<td>5503</td>
<td>Bay Laboratories</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torque (rotary transformer)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>Frequency to DC Converter</td>
<td>7540</td>
<td>Lebow</td>
<td>Digital indicator 7540</td>
<td></td>
<td>Lebow</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Data processing system (see Section 1.1.4.2)
Figure 11. Schematic diagrams of valve test setups

Flow Gain Setup

Command signal wave form: Sine (single cycle)
Wave period: 10 sec
Feedback signal amplitude:
  Bendix valve: ±3.5 V (F.S.)
  E-Systems valve: ±10.5 V (F.S.)

NOTE: Flow rate limited to 3 gpm due to capacity of flow metering cylinder.

Pressure Gain Setup

Command signal wave form: Ramp (single cycle, p-p)
Wave period: 100 sec
Feedback signal amplitude:
  Bendix valve: ±0.9 V (F.S.)
  E-Systems valve: ±2.0 V (F.S.)

NOTE: Fluid volume at C1 and C2 was as small as practical.

Internal Leakage Setup

Command signal wave form: Cosine (single cycle)
Wave period: 100 sec
Feedback signal amplitude:
  Bendix valve: ±3.5 V (F.S.)
  E-Systems valve: ±10.5 V (F.S.)

NOTE: Fluid volume at C1 and C2 was equal and approximately 0.6 in at each port.
Figure 12. View of flow gain test setup
1.2.1.2 **Results.** Flow gain, pressure gain, and internal leakage plots made by the data analysis system are presented in Appendix B. Examples of this data are shown on Figures 13, 14, and 15. Results of the Bendix and E-Systems valve tests are discussed in the following paragraphs.

**Bendix.** Performance values obtained from the plots in Appendix B are listed in Table 3. Qualitative evaluations of valve operation are given in Table 4. The flow and pressure gain curves have a null offset caused by the Bendix electronic package. Symmetrical signals applied to the input of the package were unsymmetrical at its output. Bias adjustments are available inside the package; none are available outside. No attempt was made to bias the command input signal in order to balance the output.

Performance of the zero lap configuration was affected by internal friction. Bendix acknowledged that alignment between the spool axis and torque motor output axis were not as good as desired because of adverse tolerance build-ups. It should be noted that the T-slot configuration was installed in valve assembly P/N 3335661-2; the zero lap spool was installed in valve assembly P/N 3336730.

**E-Systems.** Performance values obtained from the plots in Appendix B are listed in Table 5. Qualitative evaluations of valve operation are given in Table 6. The flow and pressure gain plots contain small irregularities. This was due to the pulse-width-modulation (PWM) signal of the E-Systems electronic package. The PWM in effect imposed a small dither motion on the spool, and was most evident on the pressure gain plots. The horizontal irregularities are due to small spool displacements sensed by the LVDT; the vertical irregularities are due to pressure fluctuations caused by the small spool displacements. Although the plots do not have a neat appearance, the "noise" was not considered detrimental to valve performance.

PWM caused problems during the entire test program because of the "electrical noise" it generates. Considerable effort was required to shield other test instrumentation from conducted and radiated PWM noise so that noise-free data could be obtained. PWM caused the E-Systems valve to work hard, and on some occasions the motion of the servo actuator piston was observed to contain high frequency, low amplitude irregularities.
Figure 13. Flow gain data, Bendix zero lap valve
Figure 14. Pressure gain data, E-Systems overlapped valve
INTERNAL LEAKAGE

Bendix P/N 3335661-2
Configuration: T-Slot

1. Supply Pressure: 8000 psi
2. Ports: C1 & C2 blocked
3. Fluid: MIL-H-83282
4. Fluid Temp: +120 Deg F

Figure 15. Internal leakage data, Bendix T-slot valve
### TABLE 3. Quantitative performance, Bendix valves

<table>
<thead>
<tr>
<th></th>
<th>3rd QUADRANT</th>
<th>NULL</th>
<th>1st QUADRANT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FLOW GAIN, in³/sec/deg</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zero Lap Valve</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000 psi</td>
<td>0.71</td>
<td>0.64</td>
<td></td>
</tr>
<tr>
<td>8000 psi</td>
<td>1.06</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>T-Slot Valve</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000 psi</td>
<td>1.63</td>
<td>1.27</td>
<td></td>
</tr>
<tr>
<td>8000 psi</td>
<td>2.57</td>
<td>1.88</td>
<td></td>
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<tr>
<td><strong>PRESSURE GAIN, psi/deg</strong></td>
<td>8511</td>
<td>1828</td>
<td>13,072</td>
</tr>
<tr>
<td>Zero Lap Valve</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000 psi</td>
<td>8511</td>
<td>13,072</td>
<td>1828</td>
</tr>
<tr>
<td>8000 psi</td>
<td>13,072</td>
<td>4846</td>
<td></td>
</tr>
<tr>
<td>T-Slot Valve</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000 psi</td>
<td>4250</td>
<td>4250</td>
<td></td>
</tr>
<tr>
<td>8000 psi</td>
<td>8016</td>
<td>8016</td>
<td></td>
</tr>
<tr>
<td><strong>INTERNAL LEAKAGE, in³/sec/deg</strong></td>
<td>.057</td>
<td>.105</td>
<td></td>
</tr>
<tr>
<td>Zero Lap Valve</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>4000 psi</td>
<td>.057</td>
<td>.105</td>
<td></td>
</tr>
<tr>
<td>8000 psi</td>
<td>.275</td>
<td>.512</td>
<td></td>
</tr>
<tr>
<td>T-Slot Valve</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000 psi</td>
<td>.275</td>
<td>.512</td>
<td></td>
</tr>
<tr>
<td>8000 psi</td>
<td>.275</td>
<td>.512</td>
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</table>

### TABLE 4. Qualitative performance, Bendix valves

<table>
<thead>
<tr>
<th></th>
<th>GAIN BALANCE</th>
<th>GAIN LINEARITY</th>
<th>HYSTERESIS</th>
<th>NULL AREA GAIN CHANGE</th>
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<tbody>
<tr>
<td><strong>FLOW GAIN</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zero Lap</td>
<td>good</td>
<td>fair</td>
<td>good</td>
<td>high</td>
</tr>
<tr>
<td>T-Slot</td>
<td>fair</td>
<td>excellent</td>
<td>good</td>
<td>high</td>
</tr>
<tr>
<td><strong>PRESSURE GAIN</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zero Lap</td>
<td>poor</td>
<td>poor</td>
<td>good</td>
<td>high</td>
</tr>
<tr>
<td>T-Slot</td>
<td>excellent</td>
<td>excellent</td>
<td></td>
<td>none</td>
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</tbody>
</table>

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TABLE 5. Quantitative performance, E-Systems valves

<table>
<thead>
<tr>
<th></th>
<th>3rd QUADRANT</th>
<th>NULL</th>
<th>1st QUADRANT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FLOW GAIN, in³/sec/in</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zero Lap Valve</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000 psi</td>
<td>895</td>
<td>895</td>
<td></td>
</tr>
<tr>
<td>8000 psi</td>
<td>1351</td>
<td>1351</td>
<td></td>
</tr>
<tr>
<td>.002 Overlap Valve</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000 psi</td>
<td>918</td>
<td>896</td>
<td></td>
</tr>
<tr>
<td>8000 psi</td>
<td>1339</td>
<td>1336</td>
<td></td>
</tr>
<tr>
<td><strong>PRESSURE GAIN, psi/in</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zero Lap Valve</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000 psi</td>
<td>13.4 x 10⁶</td>
<td>13.4 x 10⁶</td>
<td></td>
</tr>
<tr>
<td>8000 psi</td>
<td>21 x 10⁶</td>
<td>21 x 10⁶</td>
<td></td>
</tr>
<tr>
<td>.002 Overlap Valve</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000 psi</td>
<td>2.94 x 10⁶</td>
<td>1.82 x 10⁶</td>
<td>2.78 x 10⁶</td>
</tr>
<tr>
<td>8000 psi</td>
<td>5.46 x 10⁵</td>
<td>3.09 x 10⁶</td>
<td>5.80 x 10⁶</td>
</tr>
<tr>
<td><strong>INTERNAL LEAKAGE, in³/sec/in</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zero Lap Valve</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000 psi</td>
<td>0.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8000 psi</td>
<td>0.39</td>
<td></td>
<td></td>
</tr>
<tr>
<td>.002 Overlap Valve</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000 psi</td>
<td>0.023</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8000 psi</td>
<td>0.067</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE 6. Qualitative performance, E-Systems valves

<table>
<thead>
<tr>
<th></th>
<th>GAIN BALANCE</th>
<th>GAIN LINEARITY</th>
<th>HYSTERESIS</th>
<th>NULL AREA GAIN CHANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FLOW GAIN</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zero Lap</td>
<td>excellent</td>
<td>excellent</td>
<td>good</td>
<td>none</td>
</tr>
<tr>
<td>.002 Overlap</td>
<td>excellent</td>
<td>excellent</td>
<td>excellent</td>
<td>high</td>
</tr>
<tr>
<td><strong>PRESSURE GAIN</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zero Lap</td>
<td>excellent</td>
<td>excellent</td>
<td>excellent</td>
<td>none</td>
</tr>
<tr>
<td>.002 Overlap</td>
<td>excellent</td>
<td>excellent</td>
<td>excellent</td>
<td>high</td>
</tr>
</tbody>
</table>
Frequency Response. Frequency response tests were conducted by Bendix and E-Systems; the plots are presented in Appendix B. Bendix ran their tests at 3000 psi using MIL-H-83282 fluid, E-Systems conducted a single test at 8000 psi using CTFE fluid. A summary of results is given below:

<table>
<thead>
<tr>
<th>Spool Displacement</th>
<th>-3 db Point</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency, Hz</td>
</tr>
<tr>
<td><strong>Bendix Valves</strong></td>
<td></td>
</tr>
<tr>
<td>Zero Lap</td>
<td>+10%</td>
</tr>
<tr>
<td></td>
<td>+25%</td>
</tr>
<tr>
<td>T-Slot</td>
<td>+10%</td>
</tr>
<tr>
<td></td>
<td>+25%</td>
</tr>
<tr>
<td><strong>E-Systems</strong></td>
<td>.002 in. Overlap</td>
</tr>
</tbody>
</table>

1.2.2 Servo Actuator

1.2.2.1 Procedure. Three different types of tests were conducted: dynamic response, pressure level switching, and energy consumption. Each test employed different instrumentation and methods of acquiring the data. A general setup was used, however, for all three tests. A schematic diagram of the hydraulic system is presented on Figure 16.

The servo actuator was mounted in a fixture designed to simulate the mass load of a horizontal stabilizer on the RA-5C airplane, Figure 17. The fixture was originally built to test an actuator developed for the LHS program, reference 2. Installation of the UHT actuator in the fixture required new mounting provisions; these are indicated in Figure 17. The fixture was made very rigid to minimize structural dynamics. The effective mass load on the actuator was 6.94 lb·sec²/in. Prior tests conducted on the fixture have established that a mass load/actuator natural frequency occurs in the range of 19 to 23 Hz.
Figure 16. Schematic diagram of hydraulic system
Figure 17. Servo actuator/mass load fixture installation
(depending upon the actuator and fluid being used). Operation in this frequency region could cause physical damage to test parts. An upper limit of 18 Hz was therefore used for frequency response tests conducted with the mass load.

**Dynamic Response Tests.** A schematic diagram of the instrumentation is shown on Figure 18. The function generator signal was used as the valve input signal in the frequency response tests because: 1) the E-Systems electronic drive unit employed PWM; and 2) the response characteristics of the EDU would have a negligible effect on test results. The feedback and loop gains were optimized by observing actuator performance with step inputs and using settings that produced slight ringing with operation at 8000 psi. These selected gain values were maintained during all tests. A block diagram showing gain values is shown on Figure 19.

The step input tests were conducted using an actuator output of 0.100 in. p-p at 1 Hz. The frequency response test was performed using an input that produced an output of 0.100 in. p-p at 0.4 Hz and maintaining this input constant over the frequency sweep range. The step input and frequency response tests were conducted with and without the mass load on the actuator.

**Pressure Level Switching.** The effect of switching operating pressure level on actuator piston position was determined with the piston both motionless and moving during the pressure level switchover. A block diagram of the instrumentation is shown on Figure 20. All tests were conducted with the actuator piston attached to the load mass. Piston motion was sinusoidal with 0.250 in. peak-to-peak travel at 1 Hz. Data were acquired with the pressure level switchover made at 0° and at 90° during the sinusoidal motion tests. Loop gain values were the same as those used for the dynamic response tests (see Figure 19).
Figure 18. Schematic diagram of dynamic response test instrumentation
Figure 20. Pressure level switching test instrumentation
Energy Consumption Tests. A schematic diagram and photograph of the instrumentation are shown on Figures 21 and 22, respectively. The heat rejection of the pump, servo actuator, and system were determined while the actuator was operated sinusoidally over a frequency range of 1 to 4 Hz. The data were taken at the point of maximum power consumption, i.e., at the 45° point on the output waveform. This was done by using the "clock" input on the analyzer, and applying a sinusoidal signal to this input that was 45° out-of-phase with the actuator output. The clocking signal triggered the analyzer to take data at each zero crossing having a positive slope (clocking signal). The time duration of the sweep from 1 Hz to 4 Hz was limited by the piston travel in the flow cylinder and was approximately 25 seconds. The input amplitude was held constant over the frequency sweep range, and was a value that produced an actuator output of 0.100 in. p-p at 0.4 Hz. Testing was conducted with and without the mass load on the actuator. The pump, actuator, and system heat rejections were calculated by the data analyzer using the parameters and equations given in Table 7. Pump speed was 5400 rpm. It should be noted that pump S/N 422717 was used for these tests. (Pumps S/N 346580 and S/N 346581 had not yet been received, see Section 1.1.2.3.)

1 Flow and pressure in the actuator were sinusoidal in form and 90° out-of-phase. Power consumed by the actuator is: Power = (∆P · sin θ · Q · cos θ) + 1714, where ∆P = P1 – P2 in psid and Q = flow in gpm. Maximum power occurs when θ = 45° and is: Power = 0.5 · ∆P · Q + 1714. Maximum actuator efficiency also occurs when θ = 45°.
Figure 21. Schematic diagram of energy consumption test instrumentation
## TABLE 7. Actuator test parameters and equations

<table>
<thead>
<tr>
<th>CHANNEL NO.</th>
<th>SYMBOL</th>
<th>DESCRIPTION</th>
<th>FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T</td>
<td>Pump input torque</td>
<td>-400 lb-in/v</td>
</tr>
<tr>
<td>2</td>
<td>N</td>
<td>Pump speed</td>
<td>5000 rpm/v</td>
</tr>
<tr>
<td>3</td>
<td>F</td>
<td>Actuator frequency</td>
<td>13.93 Hz/v</td>
</tr>
<tr>
<td>4</td>
<td>P</td>
<td>Pump discharge pressure</td>
<td>1784 psi/v</td>
</tr>
<tr>
<td>5</td>
<td>PC1</td>
<td>Actuator cylinder pressure</td>
<td>1474 psi/v</td>
</tr>
<tr>
<td>6</td>
<td>PC2</td>
<td>Actuator cylinder pressure</td>
<td>1456 psi/v</td>
</tr>
<tr>
<td>7</td>
<td>Q</td>
<td>Return flow</td>
<td>2.366 gpm/v</td>
</tr>
</tbody>
</table>

### TEST EQUATIONS

\[
HR_1 = (HP_1 - HP_2) \cdot K_4 \\
HR_2 = (HP_2 - HP_3) \cdot K_4 \\
HR_3 = (HP_1 - HP_3) \cdot K_4
\]

where,

- \( HR_1 \) = Pump heat rejection, BTU/min
- \( HR_2 \) = Actuator heat rejection, BTU/min
- \( HR_3 \) = Overall heat rejection, BTU/min
- \( HP_1 \) = Input power to pump, hp
- \( HP_2 \) = Power delivered by pump, hp
- \( HP_3 \) = Power delivered by actuator, hp
- \( K_4 = 42.4 \) BTU/min/hp

\[
HP_1 = K_1 \cdot T \cdot N \\
HP_2 = K_2 \cdot (P-90) \cdot Q \\
HP_3 = K_3 \cdot |PC1-PC2| \cdot Q
\]

where,

- \( K_1 = 1/63030 \)
- \( K_2 = 0.96/1714 \)
- \( K_3 = 0.98/1714 \)
1.2.2.2 Results

Dynamic Response Tests. Performance plots made during the step input and frequency response tests are presented in Appendix C. Examples of the data are shown on Figures 23 and 24. A summary of this data is given in Table 8. Actuator performance was degraded by valve overlap. Using zero lap data as a baseline, 0.002 in. of valve overlap resulted in the following performance decreases:

<table>
<thead>
<tr>
<th>Actuator Load</th>
<th>Pressure Level, psi</th>
<th>Step Response</th>
<th>Frequency Response (at -3 db point)</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>4000</td>
<td>-4%</td>
<td>-24%</td>
</tr>
<tr>
<td>none</td>
<td>8000</td>
<td>-34%</td>
<td>-21%</td>
</tr>
<tr>
<td>mass</td>
<td>4000</td>
<td>-12%</td>
<td>-26%</td>
</tr>
<tr>
<td>mass</td>
<td>8000</td>
<td>-22%</td>
<td>-42%</td>
</tr>
</tbody>
</table>

A valve failure occurred during the operational checkout tests. The Bendix T-slot valve was selected for testing first and was being operated with 4000 psi applied. A preliminary frequency sweep from 0.4 Hz was in progress when the motor end cover came off as the 15 Hz level was approached. The end cover is exposed to return pressure and at the time of failure was being subjected to a fluctuating pressure near 400 psi. Examination disclosed no failed parts. The motor housing has a groove in which a circular cross-section ring (2-3/8 in. dia.) is used to retain the motor end cover. This groove was observed to have a sloped outer edge. The retainer ring apparently slid up this slope due to approximately 1000 pounds of force imposed on the end cover by the return pressure. The supplier was notified of the failure. The Bendix valves and electronics were then returned for investigation of the problem. Because of program scheduling constraints, a decision was made to proceed with the planned tests using the E-Systems valves.
Figure 23. Actuator step response data, E-Systems zero lap valve
Figure 24. Actuator frequency response data, E-Systems overlapped valve
### TABLE 8. Servo actuator dynamic performance, mass load

<table>
<thead>
<tr>
<th>VALVE</th>
<th>OVERLAP</th>
<th>ACT' R LOAD</th>
<th>PRESSURE</th>
<th>TRANSIT TIME, SEC</th>
<th>STEP RESPONSE</th>
<th>FREQUENCY RESPONSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-3 db POINT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FREQUENCY, Hz</td>
<td>PHASE ANGLE, DEG</td>
<td></td>
</tr>
<tr>
<td>E-Systems</td>
<td>Zero</td>
<td>None</td>
<td>4000</td>
<td>.086</td>
<td>9.0</td>
<td>-80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8000</td>
<td>.062</td>
<td>11.3</td>
<td>-93</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass</td>
<td>4000</td>
<td>.076</td>
<td>10.4</td>
<td>-86</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8000</td>
<td>.059</td>
<td>17.0</td>
<td>-112</td>
</tr>
<tr>
<td>.002</td>
<td>None</td>
<td></td>
<td>4000</td>
<td>.089</td>
<td>6.8</td>
<td>-75</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8000</td>
<td>.083</td>
<td>8.9</td>
<td>-82</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass</td>
<td>4000</td>
<td>.085</td>
<td>7.7</td>
<td>-82</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8000</td>
<td>.072</td>
<td>9.8</td>
<td>-88</td>
</tr>
</tbody>
</table>
Pressure Level Switching Tests. Plots of the pressure level switching tests are presented in Appendix C; a plot example is given on Figure 25. A listing of the data is given in Table 9. The results are summarized below:

Pressure Level Switching Tests:

<table>
<thead>
<tr>
<th>Pressure Level Switch</th>
<th>4000 to 8000 psi</th>
<th>8000 to 4000 psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valve operating time, sec</td>
<td>0.092</td>
<td>0.052</td>
</tr>
<tr>
<td>(average) (on to off)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure level switching</td>
<td>0.070</td>
<td>0.148</td>
</tr>
<tr>
<td>time, sec (average)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3400 rpm pump speed</td>
<td>0.139</td>
<td>0.205</td>
</tr>
<tr>
<td>5900 rpm pump speed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure over/under shoot, psi</td>
<td>410 (over)</td>
<td>290 (under)</td>
</tr>
<tr>
<td>(average)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3400 rpm pump speed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5900 rpm pump speed</td>
<td>680 (over)</td>
<td>280 (under)</td>
</tr>
</tbody>
</table>

Significant findings were:

- Actuator position disturbance was not detectable when the piston was moving and was 0.001 to 0.002 in. when the piston was stationary.
- Pressure transients that occurred during pressure level switching were well under the acceptable limit of 1600 psi (maximum).
- The time required for pressure level switchover depended upon pump speed. The average total times were: (valve + pump operating times)

<table>
<thead>
<tr>
<th>Pump Speed, rpm</th>
<th>4000 to 8000 psi time, sec</th>
<th>8000 to 4000 psi time, sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>3400</td>
<td>0.232</td>
<td>0.259</td>
</tr>
<tr>
<td>5900</td>
<td>0.160</td>
<td>0.199</td>
</tr>
<tr>
<td>43</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
PRESSURE LEVEL SWITCHING

Vickers Pump S/N MX-346581
E-Sys. Valve: zero lap

System Pressure, psi

1. Pump Speed: 5900 rpm
2. Actuator Motion: 9.250 in. p-p @ 1 Hz
3. Switching Pt.: 90 Deg
4. Fluid Temp.: +200 deg F
5. Fluid: MIL-H-83282

Time, sec

Switching Valve 'ON'  Actuator Displacement

Switching Valve 'OFF'

Figure 25. Actuator pressure level switching data, E-Systems zero lap valve
TABLE 9. Pressure level switching data, mass load

<table>
<thead>
<tr>
<th>E-Systems Valve</th>
<th>Actuator Motion</th>
<th>Pump Speed, rpm</th>
<th>Switch-Over Pt.</th>
<th>4000 psi to 8000 psi</th>
<th>8000 psi to 4000 psi</th>
<th>Pressure Level Switching</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Switching Time, sec</td>
<td>Pressure Overshoot, psi</td>
<td>Switching Time, sec</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zero lap</td>
<td>none</td>
<td>3400</td>
<td>-</td>
<td>.103</td>
<td>.130</td>
<td>440</td>
</tr>
<tr>
<td></td>
<td>5900</td>
<td>-</td>
<td>.093</td>
<td>.068</td>
<td>730</td>
<td>.048</td>
</tr>
<tr>
<td>Zero lap</td>
<td>sinusoidal</td>
<td>3400</td>
<td>0°</td>
<td>.096</td>
<td>.129</td>
<td>460</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>.089</td>
<td>.154</td>
<td>350</td>
<td>.061</td>
<td>.177</td>
</tr>
<tr>
<td></td>
<td>5900</td>
<td>0°</td>
<td>.084</td>
<td>.068</td>
<td>740</td>
<td>.051</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>.095</td>
<td>.069</td>
<td>720</td>
<td>.052</td>
<td>.141</td>
</tr>
<tr>
<td>Overlap</td>
<td>sinusoidal</td>
<td>3400</td>
<td>0°</td>
<td>.086</td>
<td>.136</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>.093</td>
<td>.146</td>
<td>350</td>
<td>.054</td>
<td>.189</td>
</tr>
<tr>
<td></td>
<td>5900</td>
<td>0°</td>
<td>.096</td>
<td>.068</td>
<td>600</td>
<td>.050</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>.060</td>
<td>.075</td>
<td>620</td>
<td>.033</td>
<td>.144</td>
</tr>
</tbody>
</table>
Valve lap was not a significant factor in pressure level switchover time.

The zero lap valve produced an excellent sine wave motion of the actuator piston; the overlapped valve produced a slightly distorted wave form.

**Energy Consumption Tests.** Heat rejection plots of the pump, actuator, and system are presented in Appendix C. An actuator plot is shown on Figure 26. A summary of this data is given in Table 10. Significant findings were:

- Actuator load had a negligible effect on system (total) heat rejection.
- Energy losses at 4000 psi were approximately 53% of the losses that occurred at 8000 psi.
- Pump heat rejection accounted for 85 to 90% of the total losses.
- Valve overlap reduced actuator losses from 15% (zero overlap) of total system losses to 10% (.002 in. overlap).
- System energy losses were approximately constant over the actuator frequency range of 1 to 3 Hz. Energy consumption began to increase above 3 Hz.
Figure 26. Actuator energy consumption data, E-Systems overlapped valve
TABLE 10. Energy consumption data, mass load

<table>
<thead>
<tr>
<th>E-SYSTEMS VALVE</th>
<th>ACTUATOR LOAD</th>
<th>PRESSURE LEVEL, psi</th>
<th>*HEAT REJECTION, BTU/min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>PUMP</td>
<td>ACTUATOR</td>
</tr>
<tr>
<td>Zero lap none</td>
<td>4000</td>
<td>160</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>8000</td>
<td>298</td>
<td>50</td>
</tr>
<tr>
<td>Zero lap mass</td>
<td>4000</td>
<td>162</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>8000</td>
<td>287</td>
<td>56</td>
</tr>
<tr>
<td>Overlapped none</td>
<td>4000</td>
<td>162</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>8000</td>
<td>286</td>
<td>32</td>
</tr>
<tr>
<td>Overlapped mass</td>
<td>4000</td>
<td>158</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>8000</td>
<td>280</td>
<td>38</td>
</tr>
</tbody>
</table>

*Heat rejection data are average values over the frequency range of 1 to 3 Hz. See Appendix C.
1.2.3 Dual Pressure Pump

1.2.3.1 Procedure. Four different types of tests were conducted: pressure ripple, transient response, pump performance, and pressure level switching. A block diagram of the pump test instrumentation is shown on Figure 27. The pump was mounted on a torque meter attached to a 50 hp vari-drive. Controls and monitors for pump speed, discharge pressure, return flow, and input torque were located on a console.

Pressure ripple was measured using a piezoelectric transducer teed into the pressure line at the pump discharge port. The clocking and trigger inputs of the data analyzer were employed to enable measuring pressure fluctuations that occurred during one revolution of the input shaft. The pulsations could thus be correlated to shaft position and individual pump pistons.

Transient response was determined using a strain gage transducer teed into the -8 size discharge line 10 feet from the pump and immediately upstream of a 3-way solenoid valve. System fluid volume at high pressure was approximately 125 cubic inches. Discharge flow was controlled by two pre-set needle valves; one valve was set for 0.5 gpm with the solenoid valve "off", the other was set for 9 gpm with the solenoid valve "on". These flow values were selected based on the requirement to switch from 5% to 90% to 5% of rated flow, reference 3.

Pump operating characteristics in the flow cut-off range of 7700 to 8200 psi were determined in the pump performance tests. Overall efficiency, heat rejection, and discharge pressure were plotted versus discharge flow using the capabilities of the data analyzer. The equations employed are given in Table 11. Data were acquired and results calculated based on pre-selected discharge pressures inserted into the computational program.
Figure 27. Schematic diagram of pump test instrumentation
### TABLE 11. Pump test parameters and equations

<table>
<thead>
<tr>
<th>CHANNEL NO.</th>
<th>SYMBOL</th>
<th>DESCRIPTION</th>
<th>CALIBRATION FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P</td>
<td>Pump discharge pressure</td>
<td>1784 psi/v</td>
</tr>
<tr>
<td>2</td>
<td>Q</td>
<td>Return flow</td>
<td>4.368 gpm/v</td>
</tr>
<tr>
<td>3</td>
<td>T</td>
<td>Pump input torque</td>
<td>-400 lb-in/v</td>
</tr>
<tr>
<td>4</td>
<td>N</td>
<td>Pump speed</td>
<td>5000 rpm/v</td>
</tr>
</tbody>
</table>

**TEST EQUATIONS**

\[
\text{EFF} = \frac{\text{HP}_2}{\text{HP}_1} \times 100
\]

\[
\text{HR} = (\text{HP}_1 - \text{HP}_2) \cdot K_3
\]

where,
- \( \text{EFF} \) = Pump overall efficiency, \( \% \)
- \( \text{HR} \) = Pump heat rejection, BTU/min
- \( \text{HP}_1 \) = Input power to pump, hp
- \( \text{HP}_2 \) = Power delivered by pump, hp
- \( K_3 = 42.4 \text{ BTU/min/hp} \)

now,
- \( \text{HP}_1 = K_1 \cdot T \cdot N \)
- \( \text{HP}_2 = K_2 \cdot (P - 90) \cdot Q \)

where,
- \( K_1 = 1/63030 \)
- \( K_2 = 0.96/1714 \)
The dual pressure level pumps were designed to operate with 90 psig suction pressure. The minimum operating pressure is 45 psig at the pump suction port. Reservoir-to-pump suction line losses and the suction line quick disconnect loss must be factored in; the reservoir should therefore be pressurized to at least 60 psig. The LHS simulator employs bootstrap type reservoirs which provide 90 psig suction pressure when system pressure is 8000 psi. The reservoir provides 45 psig suction pressure when 4000 psi is applied to the bootstrap port. Since this is less than the minimum 60 psig pressure, pump performance at 4000 psi was conducted using a small auxiliary hydraulic power unit to supply 8000 psi to the reservoir bootstrap port.

The effects of switching operating pressure level were determined at pump idle and rated speeds with 0.5 and 5.0 gpm discharge flows. Items of interest were the duration of the switch and pressure transients that occurred. Two parameters were plotted versus time: discharge pressure and voltage applied to the pressure level switching valve. Instrumentation was similar to that used in the actuator pressure level switching tests, Figure 20.

1.2.3.2 Results.

**Pump Pressure Ripple.** Plots of pump pressure ripple are shown on Figure 28. A summary of results is given below:

<table>
<thead>
<tr>
<th>Pressure Level, psi</th>
<th>Pressure Ripple, psi p-p</th>
</tr>
</thead>
<tbody>
<tr>
<td>4000</td>
<td>140</td>
</tr>
<tr>
<td>8000</td>
<td>320</td>
</tr>
</tbody>
</table>

The ripple occurred at a frequency of 885 Hz and the pumping action of each of the nine pistons was clearly discernable. Ripple magnitude was less than the design allowables, reference Appendix A.
Figure 28. Pump pressure ripple data
Pump Transient Response. Plots of pump transient response are shown on Figure 29. A summary of results is given below:

<table>
<thead>
<tr>
<th>Operating Pressure Level</th>
<th>4000 psi</th>
<th>8000 psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>5% flow pressure, psi</td>
<td>4125</td>
<td>8130</td>
</tr>
<tr>
<td>90% flow pressure, psi</td>
<td>4040</td>
<td>8040</td>
</tr>
<tr>
<td>Pressure overshoot at 5% flow, psi</td>
<td>520</td>
<td>510</td>
</tr>
<tr>
<td>Pressure undershoot at 90% flow, psi</td>
<td>520</td>
<td>970</td>
</tr>
<tr>
<td>Transient response time at 5% flow, sec</td>
<td>.023</td>
<td>.017</td>
</tr>
</tbody>
</table>

The pressure compensator settings for 4000 psi and 8000 psi were slightly out-of-tolerance; this was considered to be a minor discrepancy. Pressure over/under shoot and transient response times were all well within design requirements, reference Appendix A.

Pump Performance. Plots of pump performance are shown on Figure 30. A summary of results is given below:

<table>
<thead>
<tr>
<th>Operating Pressure Level</th>
<th>4000 psi</th>
<th>8000 psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall efficiency at rated flow, %</td>
<td>83</td>
<td>87</td>
</tr>
<tr>
<td>Heat rejection at full cut-off, BTU/min</td>
<td>187</td>
<td>385</td>
</tr>
<tr>
<td>Pressure droop, psi/gpm</td>
<td>2</td>
<td>5</td>
</tr>
</tbody>
</table>

Pump performance was considered to be satisfactory except for heat rejection at 8000 psi which was higher than the design goal of 330 BTU/min.

Pressure Level Switching. Plots of pressure level switching are presented in Appendix D. A summary of results is given in Table 12. Pressure level switching time was dependent upon pump speed and flow demand. The design goal of 0.100 sec maximum was met at rated speed for the switch from 4000 to 8000 psi which is the most important operating situation. Pressure transients were well within design allowables. It should be noted that the observed transients do not reflect the effect of change in pump suction pressure which would occur if a non-isolated bootstrap reservoir were used (see Section 1.2.3.1).
PUMP TRANSIENT RESPONSE

VICKERS M/N PV3-047-4
S/N MX-346581

Discharge Pressure, psi

Time, sec

1. Pressure Setting: 6000 psi
2. Pump Speed: 3900 rpm
3. Flow: 8.5 to 8 to 0.3 gpm
4. Inlet Fluid Temp: 4200 deg F
5. Fluid: MIL-H-83262

Discharge Pressure, psi

Time, sec

1. Pressure Setting: 4000 psi
2. Pump Speed: 3900 rpm
3. Flow: 8.5 to 8 to 0.3 gpm
4. Inlet Fluid Temp: 4200 deg F
5. Fluid: MIL-H-83262

Figure 29. Pump transient response data
Figure 30. Pump performance data
TABLE 12. Pressure level switching data (pump test)

<table>
<thead>
<tr>
<th>*Discharge Flow, gpm</th>
<th>Pump Speed, rpm</th>
<th>Pressure Level Switching 4000 psi to 8000 psi</th>
<th>8000 psi to 4000 psi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Switching Time, Sec</td>
<td>Pressure Overshoot, psi</td>
</tr>
<tr>
<td>0.5</td>
<td>3400</td>
<td>0.094</td>
<td>0.121</td>
</tr>
<tr>
<td>0.5</td>
<td>5900</td>
<td>0.075</td>
<td>0.069</td>
</tr>
<tr>
<td>5.0</td>
<td>3400</td>
<td>0.094</td>
<td>0.281</td>
</tr>
<tr>
<td>5.0</td>
<td>5900</td>
<td>0.086</td>
<td>0.081</td>
</tr>
</tbody>
</table>

* Flows are at 8000 psi
1.2.4 **LHS Simulator**

1.2.4.1 **Procedure.** Five different types of tests were conducted: dynamic response, pressure level switching (actuator tests and system tests), pressure ripple, spectrum analysis, and energy consumption. Each test employed different instrumentation and methods of acquiring the data. A schematic diagram of the LHS simulator hydraulic systems is presented as Figure 31.

The test servo actuator was mounted in a fixture designed to simulate the kinematics and load of the unit horizontal tail (UHT) installation in the A-7E aircraft, Figure 32 (see reference 1). The UHT actuator load/stroke curve is shown on Figure 33. The actuator was plumbed into FC-1 hydraulic system. FC-1 system was used for all tests; FC-2 system was operated only during the pressure level switching, pressure ripple, and spectrum analysis tests. The dual pressure pump installation is shown on Figure 34.

**Dynamic Response Tests.** The instrumentation and procedure were similar to those used for the tests conducted on the mass load fixture and described in Section 1.2.2.1. Loop gains were also the same as those used previously and are shown on Figure 19. The step input tests were conducted with a 5000 and 10,000 lb tension load on the servo actuator for 4000 and 8000 psi operation, respectively. The frequency response tests were performed with a 5000 lb tension load on the actuator for both 4000 and 8000 psi operation.

**Pressure Level Switching (Actuator Tests).** The instrumentation and procedure were similar to those used for the tests conducted on the mass load fixture and described in Section 1.2.2.1. A 5000 lb tension load was imposed on the actuator during the pressure level switching. This load is approximately 20% of the maximum actuator output (at 8000 psi) and occurs when the piston is retracted 0.62 in. from neutral, see Figure 33. Data were collected with the actuator motionless and with the piston moving sinusoidally. Pressure level switching was performed at two locations on the output sine wave -- 0° and 90°.
Figure 32. Test actuator in LH UHT load module

Figure 33. UHT actuator load/stroke curve
Figure 34. FC-1 and FC-2 system dual pressure pumps
Pressure Level Switching (System Tests). FC-1 and FC-2 hydraulic systems were
run concurrently during the pressure level switching tests. The primary
flight control actuators on the simulator were operated in a manner similar to
that employed during mission/profile endurance cycling (see reference 1).
Actuator load/stroke cycling modes used were 2%, 10%, and 50%. Although the
same cycling mode was used for the pitch, roll, and yaw axes during a given
test, cycling was independent and not in phase. Operation of the LH UHT
actuator was different from the other actuators during the 50% mode tests; the
unit was intentionally operated near flow saturation. Actuator cycling was
sinusoidal in form and at 3, 1, and 0.5 Hz for the 2%, 10%, and 50% operating
modes, respectively. The LH UHT actuator (alone) was cycled at 1 Hz during
the 50% mode. Pressure level switching was performed at the 90° point on
the output sine wave of the LH UHT actuator (actuator load was approximately
5000 lb tension at this point in time).

Four parameters were recorded during the pressure level switching tests:

1. Voltage to the pressure level switching valves mounted on
   the pumps.
2. LH UHT actuator piston position.
3. & 4. System pressure immediately downstream of the pressure
   line filters in FC-1 and FC-2 systems (see Figure 31).

Data were collected for the following conditions:

<table>
<thead>
<tr>
<th>Test</th>
<th>System</th>
<th>Cycling Mode</th>
<th>Pressure Level Switching</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2,3</td>
<td>FC-1 &amp; FC-2</td>
<td>2%, 10%, 50%</td>
<td>8000 to 4000 to 8000 psi</td>
</tr>
<tr>
<td>4,5,6</td>
<td>{FC-1}</td>
<td>2%, 10%, 50%</td>
<td>8000 to 4000 to 8000 psi</td>
</tr>
<tr>
<td></td>
<td>{FC-2}</td>
<td></td>
<td>not switched, 8000 psi</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>maintained</td>
</tr>
</tbody>
</table>

Pump speed was 5900 rpm and pump inlet fluid temperature was +200°F.
Pressure Ripple. Pump pressure ripple was measured in FC-1 and FC-2 systems using a piezoelectric transducer teed into the pressure line at the pump discharge port. The clocking and trigger inputs of the data analyzer were employed to enable measuring pressure fluctuations that occurred during one revolution of the pump input shaft (see Figure 27). All flight control actuators in the simulator were motionless and at their null position during the pressure ripple measurements. Pump speed was 5900 rpm and pump inlet fluid temperature was +200°F. Pump suction pressure was maintained at 90 psig for operation at 8000 psi and 4000 psi. A small auxiliary hydraulic power supply was used to apply 8000 psi to the bootstrap port on the FC-1 reservoir when the 4000 psi pressure level tests were conducted. The emergency reservoir pressurization circuit provided in FC-2 system (see Figure 31) maintained 8000 psi on the FC-2 reservoir bootstrap port when system operating pressure was 4000 psi.

Spectrum Analysis. The frequency and amplitude components of the pressure fluctuations in the pump discharge lines were determined using the FFT (Fast Fourier Transform) capability of the data analysis system. A piezoelectric transducer teed into the pressure line 1.25 inches from the pump discharge port was used to provide the pressure signal. This location was selected as likely to provide high amplitude components. Standing waves downstream could possibly produce higher amplitude components, but time did not permit searching for anti-nodes (their location and amplitude vary with pump speed). The data provided by the analyzer are RMS values or 0.707 of the peak value. The test was conducted by collecting FFT data while performing pump speed scans. Ten scans were made between 3400 and 4400 rpm, and between 4900 and 5900 rpm. This data was presented in map form (3-dimensional cascade display). The scan judged to have the highest amplitude components on the map was then selected for detail analysis which was presented on a 2-dimensional frequency domain plot. All flight control actuators in the simulator were motionless and at their null position during the scans. Data were obtained for FC-1 and FC-2 systems operating at 4000 and 8000 psi.
Energy Consumption Tests. The instrumentation and procedure were similar to those used for the tests conducted with the mass load and described in Section 1.2.2.1. Two flows were planned to be used in the data analysis calculations: LH UHT actuator return flow (measured by a positive displacement flow cylinder) and FC-1 system return flow (measured by a turbine meter). The flow cylinder has a velocity transducer that produces a DC voltage proportional to flow. A frequency-to-DC converter was used with the turbine meter to provide a DC voltage proportional to flow. Unfortunately, the slight phase lag that is inherent in all frequency-to-DC converters was sufficient that the data collected from the turbine flowmeter was not valid. The procedure for acquiring the data and performing the energy consumption calculations was therefore modified.

The energy consumption tests were conducted with the LH UHT actuator operating over a frequency range of 1 to 4 Hz while all other actuators in FC-1 system were stationary at null. The total leakage through the control valves on the simulator actuators plus the combined leakage of other system components such as solenoid valves, check valves, and relief valve were essentially constant during a test run. This tare leakage was measured with system pressures of 4000 psi and 8000 psi and a pump inlet fluid temperature of +200°F. These power losses were then inserted as constants into the energy consumption calculations. Since this total leakage was less than 0.3 gpm at 8000 psi, it had negligible effect on pump heat rejection, no affect on actuator heat rejection, and permitted the test to be conducted without using a system return flow meter. All tests were conducted with a pump speed of 5400 rpm. (This speed was used in the energy consumption tests performed with the mass load, see Section 1.2.2).

1.2.4.2 Results.

Dynamic Response Tests. Performance plots made in the step input and frequency response tests are presented in Appendix E. A summary of this data is given in Table 13. Actuator performance was degraded by valve overlap. Using zero lap data as a baseline, 0.002 in. of valve overlap resulted in the following decreases:
TABLE 13. Servo actuator dynamic performance, force load

<table>
<thead>
<tr>
<th>VALVE</th>
<th>OVERLAP</th>
<th>ACT'R LOAD, LB</th>
<th>PRESSURE, PSIG</th>
<th>STEP RESPONSE</th>
<th>FREQUENCY RESPONSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TRANSIT TIME, SEC</td>
<td>-3 dB POINT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FREQUENCY, Hz</td>
<td>PHASE ANGLE, DEG</td>
</tr>
<tr>
<td>E-Systems</td>
<td>Zero</td>
<td>5000</td>
<td>4000</td>
<td>.078</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>10000</td>
<td>8000</td>
<td>.055</td>
<td>7.6</td>
<td>-77</td>
</tr>
<tr>
<td>.002</td>
<td>5000</td>
<td>4000</td>
<td>.079</td>
<td>3.3</td>
<td>-63</td>
</tr>
<tr>
<td></td>
<td>10000</td>
<td>8000</td>
<td>.064</td>
<td>4.4</td>
<td>-68</td>
</tr>
</tbody>
</table>
Pressure Level Switching (Actuator Tests). Plots of the pressure level switching tests are presented in Appendix E and sample data is shown on Figure 35. A listing of pertinent data is given in Table 14. The results are summarized below:

<table>
<thead>
<tr>
<th>Load (psi)</th>
<th>Pressure Level, psi</th>
<th>Pressure Level Switching (Actuator piston moving)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>4000</td>
<td>4000 to 8000 psi</td>
</tr>
<tr>
<td>10,000</td>
<td>8000</td>
<td>8000 psi</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Valve operating time, sec (average)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.107 .053</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pressure level switching time, sec. (average)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3400 rpm pump speed .118 .464</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5900 rpm pump speed .075 .471</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pressure over/under shoot, psi (average)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3400 rpm pump speed 440 (over) 102 (under)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5900 rpm pump speed 752 (over) 88 (under)</td>
</tr>
</tbody>
</table>
Figure 35. Pressure level switching data (actuator test), E-Systems overlapped valve
<table>
<thead>
<tr>
<th>E-Systems Valve</th>
<th>Actuator Motion</th>
<th>Pump Speed, rpm</th>
<th>Switch-Over Pt.</th>
<th>4000 psi to 8000 psi</th>
<th>8000 psi to 4000 psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero lap</td>
<td>none</td>
<td>3400</td>
<td>-</td>
<td>.099 .121 470 .044 .697 40</td>
<td>.059 .677 40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5900</td>
<td>-</td>
<td>.126 .074 770</td>
<td></td>
</tr>
<tr>
<td>Overlap</td>
<td>none</td>
<td>3400</td>
<td>-</td>
<td>.108 .105 450 .050 .1019 40</td>
<td>.055 .1323 40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5900</td>
<td>-</td>
<td>.124 .068 840</td>
<td></td>
</tr>
<tr>
<td>Zero lap</td>
<td>sinusoidal</td>
<td>3400</td>
<td>0° 90°</td>
<td>.105 .116 500 .046 .467 80</td>
<td>.055 .435 90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5900</td>
<td>0° 90°</td>
<td>.104 .120 380</td>
<td>.057 .467 100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.108 .075 830</td>
<td>.059 .423 50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.104 .075 660</td>
<td></td>
</tr>
<tr>
<td>Overlap</td>
<td>sinusoidal</td>
<td>3400</td>
<td>0° 90°</td>
<td>.114 .105 510 .055 .495 150</td>
<td>.054 .460 90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5900</td>
<td>0° 90°</td>
<td>.106 .133 370</td>
<td>.054 .460 90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.110 .076 830</td>
<td>.057 .493 90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.110 .076 690</td>
<td>.042 .503 110</td>
</tr>
</tbody>
</table>

*Actuator load: 5000 lb tension*
Significant findings were:

- With a 5000 lb tension load applied (20% of maximum output at 8000 psi), actuator position disturbance was not detectable when the piston was moving and was less than 0.005 in. when the piston was stationary.

- Pressure transients that occurred during pressure level switching were well under the acceptable limit of 1600 psi (maximum).

- The 8000 to 4000 psi switch-over time was significantly higher when: 1) the actuator piston was stationary; and 2) valve overlap was used.

- The average total times were: (valve + pump operating times, actuator piston moving)

<table>
<thead>
<tr>
<th>Speed, rpm</th>
<th>Pump 4000 to 8000 psi time, sec</th>
<th>Pump 8000 to 4000 psi time, sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>3400</td>
<td>0.226</td>
<td>0.517</td>
</tr>
<tr>
<td>5900</td>
<td>0.182</td>
<td>0.525</td>
</tr>
</tbody>
</table>

- The zero lap valve produced an excellent sine wave motion of the actuator piston; the overlapped valve produced a slightly distorted wave form.

Pressure Level Switching (System Tests). Plots of the pressure level switching tests are presented in Appendix E and sample data is shown on Figure 36. A listing of pertinent data is given in Table 15. The total time to switch from 4000 psi to 8000 psi was fairly constant and averaged 0.173 sec.
Figure 36. Pressure level switching data (system test), E-Systems zero lap valve
### TABLE 15. Pressure level switching data (system test)

<table>
<thead>
<tr>
<th>System Switched</th>
<th>Operating Mode</th>
<th>Pressure Level Switching</th>
<th>8000 psi to 4000 psi</th>
<th>4000 psi to 8000 psi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FC-1</td>
<td>FC-2</td>
<td>FC-1</td>
</tr>
<tr>
<td>FC-1 &amp; FC-2</td>
<td>2%</td>
<td>.326</td>
<td>1.102</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>10%</td>
<td>.197</td>
<td>.650</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>.124</td>
<td>.410</td>
<td>255</td>
</tr>
<tr>
<td>FC-1</td>
<td>2%</td>
<td>.324</td>
<td>-</td>
<td>113</td>
</tr>
<tr>
<td></td>
<td>10%</td>
<td>.202</td>
<td>-</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>.109</td>
<td>-</td>
<td>250</td>
</tr>
</tbody>
</table>

*Switching valve operating time plus pressure level switching time*
The total time to switch from 8000 psi to 4000 psi depended upon flow demand and system internal leakage; elapsed time ranged from 0.109 sec to 1.102 sec. FC-1 system had higher leakage than FC-2 due to the yaw AFCS actuator in FC-1. A check valve installed in the pressure line at the RH UHT actuator also contributed to the pressure bleed down time because 8000 psi pressure was trapped in the actuator and could drop to 4000 psi only by throttling or leaking through the actuator control valve. (The check valve was removed from the LH UHT actuator pressure line to facilitate conducting the energy consumption tests.)

Pressure transients resulting from switching FC-1 and FC-2 from 8000 psi to 4000 psi to 8000 psi were minor and well within acceptable limits. No problems occurred when FC-1 pressure level was switched to 4000 psi while FC-2 was held at 8000 psi. Overall, the results of the system pressure level switching tests were excellent.

The effects of overloading the E-Systems valve were examined during the pressure level switching tests and can be seen on the plots for the 50% mode presented in Appendix E. Operation at 8000 psi was near flow saturation as evidenced by slight distortion in the actuator piston output wave form. At 4000 psi, the actuator output wave form was severely distorted and decreased in amplitude. This was considered to be typical performance degradation for the given operating conditions.

**Pressure Ripple.** Time history plots of FC-1 and FC-2 pressure ripple near the pumps are shown in Appendix E and an example is presented on Figure 37. A summary of results is given below:

<table>
<thead>
<tr>
<th>System</th>
<th>Pressure Level, psi</th>
<th>Pressure Ripple, psi p-p</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC-1</td>
<td>4000</td>
<td>124</td>
</tr>
<tr>
<td></td>
<td>8000</td>
<td>155</td>
</tr>
<tr>
<td>FC-2</td>
<td>4000</td>
<td>191</td>
</tr>
<tr>
<td></td>
<td>8000</td>
<td>249</td>
</tr>
</tbody>
</table>

Ripple magnitude was well under the design allowables at both 4000 psi and 8000 psi operating levels.
Figure 37. Pump pressure ripple data, FC-1 system
Spectrum Analysis. Two types of spectrum analysis plots are presented in Appendix E: 1) 3-dimensional pump speed scan map; and 2) 2-dimensional detail examination of the map scan containing the highest magnitude components. An example of this data is shown on Figure 38. The test results are summarized in Table 16. The pressure component at the fundamental frequency (Hz = \( \frac{rpm \times 9}{60} \)) was generally the largest, and all were under 65 psi (RMS peak) or 184 psi p-p. No spurious frequencies were found, and no harmonics occurred over 5000 Hz. The pressure dynamics resulting from pump ripple appeared to be well behaved at both the 4000 psi and 8000 psi operating levels.

Energy Consumption Tests. Heat rejection plots of FC-1 pump, LH UHT actuator, and FC-1 system are presented in Appendix E. Sample data is shown on Figure 39. A summary of this data is given in Table 17. Significant findings were:

- Actuator load had a negligible effect on system (total) heat rejection.
- Energy losses at 4000 psi averaged 47% of the losses that occurred at 8000 psi.
- Pump heat rejection accounted for about 80% of the total losses.
- Valve overlap reduced actuator losses approximately 20%.
- System energy losses gradually increased as frequency increased and reached a maximum between 3 and 4 Hz.
SPECTRUM ANALYSIS, FC-2 SYSTEM

Vickers Pump M/N PV3-047-4
S/N MX-346580

1. System Pressure: 8000 psi
2. Pressure Transducer Location:
   1.25 in. from pump
3. Inlet Fluid Temp: +200 deg F
4. Fluid: MIL-H-83282

Figure 38. Spectrum analysis data, FC-2 system
**TABLE 16. Spectrum analysis data**

<table>
<thead>
<tr>
<th>System</th>
<th>Pressure Level, psi</th>
<th>Speed, rpm</th>
<th>Pressure Ripple Components, psi (RMS peak)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fundamental</td>
</tr>
<tr>
<td>FC-1</td>
<td>4000</td>
<td>3600</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5800</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>8000</td>
<td>3900</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5200</td>
<td>55</td>
</tr>
<tr>
<td>FC-2</td>
<td>4000</td>
<td>3900</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5800</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>8000</td>
<td>3900</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5800</td>
<td>38</td>
</tr>
</tbody>
</table>

*Speed selection based on speed scan map data.
Selected speed produced the highest magnitude pressure pulsation components*
Figure 39. System energy consumption, E-Systems zero lap valve
TABLE 17. Energy consumption data, LHS simulator

<table>
<thead>
<tr>
<th>E-SYSTEMS VALVE</th>
<th>ACTUATOR LOAD</th>
<th>PRESSURE LEVEL, psi</th>
<th>*HEAT REJECTION, BTU/min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>PUMP</td>
</tr>
<tr>
<td>Zero lap</td>
<td>none</td>
<td>4000</td>
<td>192</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8000</td>
<td>414</td>
</tr>
<tr>
<td>Zero lap</td>
<td>5000 lb</td>
<td>4000</td>
<td>194</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8000</td>
<td>425</td>
</tr>
<tr>
<td>Overlapped</td>
<td>none</td>
<td>4000</td>
<td>204</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8000</td>
<td>410</td>
</tr>
<tr>
<td>Overlapped</td>
<td>5000 lb</td>
<td>4000</td>
<td>198</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8000</td>
<td>429</td>
</tr>
</tbody>
</table>

*Heat rejection at 2 Hz. See Appendix E.
1.3 DEMONSTRATION PHASE SUMMARY

1.3.1 Control Valves

Evaluation of the Bendix valves was stopped when a failure occurred during dynamic testing. The failure was the result of design and was not caused by a technological problem or related to the DDV concept. Performance of the E-Systems valves was excellent during all the hardware demonstration tests. The zero lap and 0.002 in. overlap valves provided test data that clearly showed the effects of overlap on valve performance.

Operating pressure level had the following general effects on valve performance: (8000 psi data used as the basis for comparison)

<table>
<thead>
<tr>
<th></th>
<th>Performance at 4000 psi</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flow Gain</strong></td>
<td></td>
</tr>
<tr>
<td>Zero lap valve</td>
<td>0.66</td>
</tr>
<tr>
<td>Overlapped valve</td>
<td>0.68</td>
</tr>
<tr>
<td><strong>Pressure Gain</strong></td>
<td></td>
</tr>
<tr>
<td>Zero lap valve</td>
<td>0.64</td>
</tr>
<tr>
<td>Overlapped valve</td>
<td>0.51</td>
</tr>
<tr>
<td><strong>Internal Leakage</strong></td>
<td></td>
</tr>
<tr>
<td>Zero lap valve</td>
<td>0.74</td>
</tr>
<tr>
<td>Overlapped valve</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Valve overlap had the following general effects on performance: (zero lap data used as the basis of comparison)
Performance with 0.002 in. overlap

<table>
<thead>
<tr>
<th>Flow Gain</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4000 psi</td>
<td>1.00</td>
</tr>
<tr>
<td>8000 psi</td>
<td>0.99</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pressure Gain</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4000 psi</td>
<td>0.22</td>
</tr>
<tr>
<td>8000 psi</td>
<td>0.27</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Internal Leakage</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4000 psi</td>
<td>0.08</td>
</tr>
<tr>
<td>8000 psi</td>
<td>0.17</td>
</tr>
</tbody>
</table>

As expected, pressure gain and internal leakage were affected by overlap. The reduction in internal leakage due to overlap agreed well with estimates made in Section 2.4.5 of Volume I.

1.3.2 Servo Actuator

Valve overlap had little effect on actuator response to step inputs. Actuator frequency response was affected by operating pressure level and overlap. The break frequency (-3 db point) that occurred with operation at 8000 psi was about 25% lower at 4000 psi. Fortunately, the response requirements for operation at 4000 psi are lower than the requirements for 8000 psi. Valve overlap (0.002 in.) decreased the break frequency an average of 28%. Methods to compensate for this reduction are discussed in Section 2.4.5 of Volume I.

The break frequency that occurred when the actuator was force loaded was less than one-half of the break frequency when the actuator was mass loaded. Mass loading was relatively small during the force load test. (This would tend to increase the break frequency.) The principal cause for the difference was believed to be due to the high spring rate of the mass load fixture structure compared to the relatively low spring rate of the load fixture structure in the LHS simulator.
The pressure level switching tests produced excellent results:

- Actuator piston position disturbances were negligible
- Pressure transients were minor.
- The time required for the 4000 psi to 8000 psi switch-over was somewhat higher than desired but considered acceptable. (The 8000 psi to 4000 psi switch-over time is not critical.)

The energy consumption tests conducted on the pump/servo actuator system disclosed that pump heat rejection accounted for 85 to 90% of the total losses. Valve overlap reduced actuator losses from 15% (with zero lap) of total system losses to 10% (with 0.002 in. overlap).

The test system had one control valve. A realistic assessment of the distribution of energy losses should involve the number of servo valves employed in a typical flight control system. The test pump, rated for 10 gpm at 7800 psi, was designed for use in an A-7E aircraft, reference 1. Rated flow of the E-Systems test valve is 3.5 gpm; this could be considered as an average size valve on the A-7E. The A-7E has 8 primary flight control dual system servo actuators. Using this information as the basis for a hypothetical system, the distribution of energy losses would be:

<table>
<thead>
<tr>
<th>Valve Configuration</th>
<th>System Pressure</th>
<th>Percent of Total Losses</th>
<th>Pump</th>
<th>8 Control Valves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero lap</td>
<td>4000</td>
<td>48%</td>
<td>52%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8000</td>
<td>41%</td>
<td>59%</td>
<td></td>
</tr>
<tr>
<td>Overlapped</td>
<td>4000</td>
<td>57%</td>
<td>43%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8000</td>
<td>50%</td>
<td>50%</td>
<td></td>
</tr>
</tbody>
</table>
Pump losses now account for roughly one-half of the total losses. The use of 0.002 in. of overlap reduces valve losses about 18%; this agrees well with estimates made in Section 2.4.5 of Volume I.

1.3.3 Dual Pressure Pump

The modification to convert the test pump from a single to a dual pressure level pump was successful. Pump operation at 8000 psi was approximately the same as that observed during tests in prior programs, reference 1: pressure ripple, transient response, and performance were within design requirements except for heat rejection. Operation at 4000 psi was found to be completely satisfactory. Pressure level switching produced only minor pressure transients and the time required to switch from 4000 psi to 8000 psi was under the design goal of 0.100 sec at rated speed (switching valve operating time not included).

Dual pressure level operation in a system that has a bootstrap reservoir requires a new design consideration: pump suction pressure will vary with system operating pressure level. Three options are available to handle this situation.

1. Design the pump to operate with the suction pressure provided by the reservoir when system pressure is 4000 psi.

2. Design the reservoir to provide minimum pump suction pressure when system pressure is 4000 psi.

3. Install a check valve and an accumulator in the line to the reservoir bootstrap port to trap 8000 psi pressure and provide adequate pump suction pressure when system pressure is 4000 psi. A 2-way solenoid would be required to release the trapped 8000 psi pressure for maintenance purposes.

Options 1 and 2 would add about one pound to component weight; option 3 would add about 4 pounds to the system.
1.3.4 LHS Simulator

Valve overlap had a minor effect on actuator response to step inputs. Actuator frequency response was affected by operating pressure level and overlap. The break frequency that occurred with operation at 8000 psi was about 27% lower at 4000 psi. Valve overlap (0.002 in.) reduced the break frequency an average of 32%. Methods to compensate for this decrease are discussed in Section 2.4.5 of Volume I.

Pressure level switching tests conducted on the servo actuator and system produced excellent results. Pressure transients were minor. Switching time (valve operating time + pressure level switching time) averaged 0.180 sec for the 4000 psi to 8000 psi switch. This was considered acceptable.

System pressure dynamics were excellent. Operation of the dual pressure pump did not introduce spurious frequencies or undesirable pressure pulsations.

Energy consumption tests conducted on the LHS simulator showed that losses at 4000 psi averaged 47% of those that occurred when operating at 8000 psi. This clearly demonstrated the advantage of switching to 4000 psi to conserve energy.
Successful completion of the laboratory demonstration tests verified that:

- Energy savings achieved through the use of dual pressure level systems and overlapped servo valves are substantial.
- Hardware can be readily designed and fabricated for use in 4000 psi/8000 psi hydraulic systems.

Although the performance of the test pump was excellent, heat rejection was higher than desired. Pump heat rejection is an area where basic changes in pump design could have a significant impact in reducing system energy consumption. The hybrid pump discussed in Volume I is one approach toward remedying this condition.

As expected, overlapped valves offer important energy savings but at the price of impaired actuator performance. This situation can be helped by the use of an "intelligent" valve amplifier as discussed in Volume I. However, this is an area that needs additional study and verification testing.

Results of the 8000 psi/4000 psi pressure level switching tests conducted on the full scale dual system LHS simulator were excellent. No adverse operating conditions were found. The possibility of using a pressure level lower than 4000 psi, such as 3000 psi, should be considered for achieving additional energy savings.
3.0 RECOMMENDATIONS

The study conducted in Volume I established that the top four candidates for saving energy in aircraft hydraulic systems were:

- Advanced materials
- Dual-pressure systems
- Pumps
- Non-linear valves

Advanced materials provide the most benefits. Two areas in aircraft hydraulic systems that could provide the largest savings are transmission lines and actuators. The application of new titanium alloys and composites to these areas should be explored further, parts fabricated, and evaluation tests conducted.

The dual pressure level system was demonstrated to be a simple and effective method for reducing energy consumption. This concept should be examined to determine an optimum pressure for the lower operating pressure level, such as 3000 psi or 2000 psi.

Pumps are the major consumer of energy in aircraft hydraulic systems. Decreasing pump heat rejection can therefore have a significant impact on energy savings. Basic changes in the conventional aircraft pump design are needed. Innovative concepts such as the hybrid check valve pump should be pursued further.

Overlap in control valves was demonstrated to provide substantial energy savings -- but at a cost in actuator performance. Methods to alleviate this impairment have been proposed, but their potential remains to be proven. Additional study and hardware demonstrations are recommended.
Tests on flow augmentors were planned to be conducted in this program if an NAAO-Columbus IR&D study progressed sufficiently. Although good progress was made, the study was halted because of funding limitations. The application of flow augmentation to flight control actuators has good potential for conserving energy and further work in this area is warranted.
REFERENCES

Reference No.


3 LHS-8810A, Pumps, Hydraulic, Variable Delivery, 8000 psi, General Specification For, dated 15 August 1985
**LIST OF ABBREVIATIONS AND SYMBOLS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/D</td>
<td>analog-to-digital</td>
</tr>
<tr>
<td>AFCS</td>
<td>automatic flight control system</td>
</tr>
<tr>
<td>BTU/min.</td>
<td>British thermal units per minute</td>
</tr>
<tr>
<td>C1, C2</td>
<td>cylinder port No. 1, cylinder port No. 2</td>
</tr>
<tr>
<td>CPU</td>
<td>central processing unit</td>
</tr>
<tr>
<td>CTFE</td>
<td>chlorotrifluorethylene</td>
</tr>
<tr>
<td>db</td>
<td>decibel</td>
</tr>
<tr>
<td>DC</td>
<td>direct current</td>
</tr>
<tr>
<td>DDV</td>
<td>direct drive valve</td>
</tr>
<tr>
<td>deg</td>
<td>degree (angle or temperature)</td>
</tr>
<tr>
<td>dia.</td>
<td>diameter</td>
</tr>
<tr>
<td>EDU</td>
<td>electronic drive unit</td>
</tr>
<tr>
<td>F</td>
<td>frequency</td>
</tr>
<tr>
<td>°F</td>
<td>degrees Fahrenheit</td>
</tr>
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<td>FC-1</td>
<td>flight control system No. 1</td>
</tr>
<tr>
<td>FC-2</td>
<td>flight control system No. 2</td>
</tr>
<tr>
<td>F.S.</td>
<td>full scale</td>
</tr>
<tr>
<td>gpm</td>
<td>gallons per minute</td>
</tr>
<tr>
<td>hp</td>
<td>horsepower</td>
</tr>
<tr>
<td>hr.</td>
<td>hour</td>
</tr>
<tr>
<td>HR</td>
<td>heat rejection</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz (cycles per second)</td>
</tr>
<tr>
<td>in.</td>
<td>inch</td>
</tr>
<tr>
<td>in³</td>
<td>cubic inches</td>
</tr>
<tr>
<td>K</td>
<td>kilo (1000)</td>
</tr>
<tr>
<td>lb</td>
<td>pound</td>
</tr>
<tr>
<td>lb-in</td>
<td>pound-inches (torque)</td>
</tr>
<tr>
<td>LVDT</td>
<td>linear variable differential transformer</td>
</tr>
<tr>
<td>M/N</td>
<td>model number</td>
</tr>
<tr>
<td>min.</td>
<td>minute (time)</td>
</tr>
</tbody>
</table>
### LIST OF ABBREVIATIONS AND SYMBOLS (Continued)

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTBF</td>
<td>mean-time-between-failures</td>
</tr>
<tr>
<td>N</td>
<td>pump speed</td>
</tr>
<tr>
<td>NAAO</td>
<td>North American Aircraft Operations</td>
</tr>
<tr>
<td>No.</td>
<td>number</td>
</tr>
<tr>
<td>O.D.</td>
<td>outside diameter</td>
</tr>
<tr>
<td>P</td>
<td>pressure</td>
</tr>
<tr>
<td>ΔP</td>
<td>differential pressure</td>
</tr>
<tr>
<td>PC1</td>
<td>pressure in cylinder port No. 1</td>
</tr>
<tr>
<td>PC2</td>
<td>pressure in cylinder port No. 2</td>
</tr>
<tr>
<td>p-p</td>
<td>peak-to-peak</td>
</tr>
<tr>
<td>P/N</td>
<td>part number</td>
</tr>
<tr>
<td>psi</td>
<td>pounds per square inch</td>
</tr>
<tr>
<td>psig</td>
<td>pounds per square inch gage pressure</td>
</tr>
<tr>
<td>Pt.</td>
<td>point</td>
</tr>
<tr>
<td>PWM</td>
<td>pulse width modulation</td>
</tr>
<tr>
<td>Q</td>
<td>flow</td>
</tr>
<tr>
<td>R</td>
<td>return</td>
</tr>
<tr>
<td>RH</td>
<td>right hand</td>
</tr>
<tr>
<td>RMS</td>
<td>root-mean-square</td>
</tr>
<tr>
<td>rpm</td>
<td>revolutions per minute</td>
</tr>
<tr>
<td>RVDT</td>
<td>rotary variable differential transformer</td>
</tr>
<tr>
<td>sec</td>
<td>second (time)</td>
</tr>
<tr>
<td>S/N</td>
<td>serial number</td>
</tr>
<tr>
<td>sys.</td>
<td>system</td>
</tr>
<tr>
<td>T</td>
<td>torque</td>
</tr>
<tr>
<td>V</td>
<td>volt</td>
</tr>
<tr>
<td>UHT</td>
<td>unit horizontal tail</td>
</tr>
</tbody>
</table>
APPENDIX A

HARDWARE PROCUREMENT DOCUMENTS

<table>
<thead>
<tr>
<th>Contents</th>
<th>Page</th>
</tr>
</thead>
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<td>92</td>
</tr>
<tr>
<td>Dual pressure pump statement of work</td>
<td>106</td>
</tr>
</tbody>
</table>
SPECIFICATION

VALVE, DIRECT DRIVE, ELECTROHYDRAULIC,
SERVO CONTROL, 8000 PSI, ENERGY EFFICIENT

BASIC SPECIFICATION
1.0 PURPOSE

This document defines hardware for use in a laboratory evaluation and demonstration of energy saving techniques applied to aircraft flow control valves. This hardware will be utilized in support of the Power Efficient Hydraulic Systems contract between Rockwell International-NAAO and the Naval Air Development Center in Warminster, Pennsylvania.

2.0 SCOPE

The objective of the Power Efficient Hydraulic System Program is to reduce overall hydraulic power requirements in Navy aircraft by lowering system demands and increasing component efficiencies. Internal leakage in actuator control valves produce significant power loss and is an area where energy saving techniques can be applied effectively to reduce overall energy consumption. One approach used in the subject program to improve the operating efficiency of flight control servo valves is the use of valve overlap and orifice shaping. The test concept is depicted in Figure 1.

One (1) energy efficient direct drive valve assembly with three (3) interchangeable spool/sleeves (or spool/sleeve/housing) and one (1) valve drive electronics package (optional) will be procured by this specification (See Note 2, Page 5). The valve assembly will be mated with an actuator via a manifold furnished by Rockwell.

Since the servo valve will be used for laboratory testing only, considerable latitude will be permitted in deviating from the requirements of this specification, providing the basic goals of the test program can be met with the proposed design. Cost should be an important consideration in concept and design selection.
3.0 REQUIREMENTS

The following general requirements are for a direct drive single stage electrohydraulic flow control servo valve. Requirements specified as TBD (to be determined) shall be established by the seller and stated in the proposal.

**Mechanical**

- Envelope: TBD
- Mechanical Interface: ARP490 type modified for pressure
- External Null Adjustment: Required
- Spool Diameter: TBD
- Spool Travel: .020 in. (minimum)
- Chip Shear Out Force: See Note 1
- Interchangeable Spool/Sleeves: 3 Required (See Note 2)
- Sleeve Rigidity:
  - Sleeve rigidity shall be sufficient to prevent distortion (due to pressure) from affecting valve performance.

**Electrical**

- Valve Drive Motor Coil(s):
  - Quantity: 2, 3, or 4 coils
  - Current: .5 to 1.5 Amp/Coil
  - Resistance: TBD
  - Inductance: TBD
- Electrical Connector: TBD
- Spool Position Transducer:
  - Redundancy: TBD (compatible with No. of coils)
  - Excitation Voltage: TBD
  - Excitation Frequency: TBD
Hydraulic

- Number of Hydraulic Systems: 1
- Operating Pressure: 8000 psi
- Proof Pressure: See Note 3
- Burst Pressure: See Note 4
- Fluid: MIL-H-83282
- Internal Leakage: Figure 2
- Orifice Shape: Figure 2
- Lap: Figure 2
- Temperature Range (Design): -40° to +275°F
- System Fluid Cleanliness: 5 Micron Filtration

Performance

- Rated Conditions
  - Valve Pressure Drop: 7000 psi
  - Inlet Fluid Temperature: +150°F
- Static Performance
  - Rated Flow: 3.6 to 5 gpm
  - Linearity: TBD
  - Symmetry: TBD
  - Hysteresis: TBD
  - Threshold: Figure 3
  - Flow Gain: Figure 3
- Null
  - Lap: Figure 2
  - Null bias: 5% (of rated current)
  - Null shift: 2% (of rated current)
  - Null Pressure Gain: Figure 4
- Frequency Response: Figure 5
Electronic Unit (Optional)

- Valve Drive Electronics (See Note 5)
  An electronic unit to provide actuation loop closure and to operate
  the valve drive motor shall be provided. The unit should be capable
  of providing closed loop performance for each of the three
  spool/sleeve valve designs. A single-channel unit is acceptable.

- Actuation Performance Figure 6
- Actuation Reference Data Figure 7

- Current limiting shall be provided to protect the valve drive motor.

- Preferred supply power 400 Hz 115 vac or 28 VDC

NOTES:

1. The valve drive motor shall be capable of shearing a hard steel
   particle (130,000 psi shear ultimate) with a cross sectional area equal
to 67 percent of the largest single valve orifice area with all coils
operating.

2. Where interchangeable sleeves or bodies are not practical, separate
   valve assemblies with identical valve drive motors may be provided.

3. Proof pressure values:
   Pressure and cylinder ports: 12,000 psi.
   Return port: 8000 psi.
   In order to utilize available valve drive motor designs and minimize
   costs, lower return port proof pressures will be considered.
   (Approval required)
4. Burst pressure values:
   Pressure and cylinder ports: 16,000 psi
   Return port: 12,000 psi
   In order to utilize available valve drive motor designs and minimize costs, lower return burst pressures will be considered. (Approval Required)

5. Laboratory Breadboard type electronics are acceptable.
4.0 ACCEPTANCE TESTING

Acceptance tests shall be conducted on each of the three (3) valve configurations by the seller prior to delivery of the hardware to Rockwell. Recommended acceptance test procedures to establish baseline performance characteristics shall be prepared by the seller and approved by Rockwell. The tests shall include as a minimum:

- Proof pressure
- Flow gain
- Pressure gain
- Internal leakage
- Frequency response
DEMONSTRATION HARDWARE

FIGURE 1
Rockwell International
North American Aircraft Operations

FSCM NO. 89372
24 November 1986

**INTERNAL LEAKAGE**

<table>
<thead>
<tr>
<th>VALVE</th>
<th>TYPE</th>
<th>LEAKAGE*</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>ZERO LAP</td>
<td>0.1 GPM (MAX)</td>
</tr>
<tr>
<td>B</td>
<td>HIGH OVERLAP</td>
<td>TBD</td>
</tr>
<tr>
<td>C</td>
<td>V SHAPES</td>
<td>TBD</td>
</tr>
</tbody>
</table>

**OVERLAP**

<table>
<thead>
<tr>
<th>VALVE</th>
<th>OVERLAP IN</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>.004 (MIN)</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
</tr>
</tbody>
</table>

*TEMPERATURE EFFECTS TO BE ESTIMATED

---

**ORIFICE SHAPES:**

- **VALVE A**
- **VALVE B**
- **VALVE C**

(TYPICAL VARIATIONS ACCEPTABLE)

**FIGURE 2 VALVE TYPES**

---

9
FIGURE 3  TYPICAL FLOW GAIN CHARACTERISTICS
null pressure gain $(k_p)$, psi/in

<table>
<thead>
<tr>
<th>VALVE</th>
<th>MINIMUM</th>
<th>3000 PSI</th>
<th>8000 PSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2 x 10^6</td>
<td>4 x 10^6</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>TBD</td>
<td>TBD</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>TBD</td>
<td>TBD</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4 Typical Pressure Gain Characteristics
FIGURE S VALVE FREQUENCY RESPONSE
FIGURE 6 ACTUATION FREQUENCY RESPONSE (REFERENCE DATA)
### ACTUATION REFERENCE DATA

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuator Type</td>
<td>Balanced</td>
</tr>
<tr>
<td>Piston Diameter</td>
<td>2.368 in.</td>
</tr>
<tr>
<td>Rod Diameter</td>
<td>1.185 in.</td>
</tr>
<tr>
<td>Piston Area</td>
<td>3.301 in.²</td>
</tr>
<tr>
<td>Stroke</td>
<td>6.58 in.</td>
</tr>
<tr>
<td>Design Pressure</td>
<td>8000 psi</td>
</tr>
<tr>
<td>Load Inertia</td>
<td>1000 in-lb-sec²</td>
</tr>
<tr>
<td>Moment Arm</td>
<td>12 in.</td>
</tr>
<tr>
<td>Load Weight</td>
<td>2000 lbs.</td>
</tr>
</tbody>
</table>
STATEMENT OF WORK

FOR

ENERGY EFFICIENT

DUAL PRESSURE PUMP
1.0 SCOPE

This statement of work defines the tasks required to modify a variable displacement 8000 psi hydraulic pump to demonstrate dual pressure level system operation. The pump to be modified is a Vickers Model PV3-047-2 developed for the Lightweight Hydraulic System Program. The program schedule is included as Attachment 1 hereto.

This work shall be accomplished by an aircraft hydraulic pump supplier, hereinafter referred to as the Seller, for Rockwell International Corporation, hereinafter referred to as the Buyer.

2.0 PROGRAM TASKS

2.1 Design. - The Seller shall design the modification of a Vickers Model Number PV3-047-2 pump to provide the capability for dual pressure operation at 8000 psi or 4000 psi. The modification will permit hydraulic switching from the high pressure (8000 psi) to the low pressure (4000 psi) mode of operation and from the low pressure to the high pressure mode. Control pressure shall be ported to the pump compensator mechanism using an 8000 psi, 3-port, 2-position, normally closed, pilot operated selenoid valve (Sterer P/N 15390-1). Loss of electrical power to the valve will revert the pump output to the high pressure (8000 psi) mode.

Requirements for documenting the modification design are specified on the SDRL, Attachment 2 hereto.

2.2 Performance Requirements. - The original pump design, in general, meets the performance requirements of Specification LHS-8810. The modified pump shall meet the requirements of the Specification Sheet, Attachment 3 hereto.

2.3 Fabrication/Modification. - The Seller shall fabricate the hardware to modify two (2) Vickers Model Number PV3-047-2 pumps and perform the modifications in accordance with the design developed under 2.1.

2.4 Checkout Tests. - The Seller shall conduct inspection and checkout tests on the modified pumps to verify dual mode pressure operation in accordance with the Seller-prepared Buyer-approved test procedures (See SDRL, Attachment 2). The tests shall include as a minimum:

   a. Examination of Product
   b. Pump run-in and dual pressure operation to total two (2) hours.
   c. Determine at high and low mode pressure operation:

      (1) Efficiency
      (2) Heat Rejection
      (3) Ripple
      (4) Switching pressure transients and time.
The Seller shall notify the Buyer at least two (2) weeks prior to the start of testing so that a Buyer representative may witness the testing, if desired.

2.4.1 Redesign and Retest. - In the event a modified pump should malfunction, the Seller shall notify the Buyer for resolution of any problem prior to proceeding with any design change or retest.

2.5 Buyer Provided Hardware. - The Buyer shall deliver to the Seller at contract go-ahead, two (2) Vickers Model Number PV3-047-2 Pumps, Serial Numbers 346581 and 346580, and one (1) Sterer Valve, P/N 15390-1, Serial Number 2, to be utilized in the performance of the effort herein.

2.6 Delivery. - The Seller shall deliver the modified pumps and valve of 2.5, following the checkout tests of paragraph 2.4, to the Buyer's facility not later than seven (7) months after contract go-ahead. The Seller shall preserve and package the items in accordance with good commercial practice in a manner that will provide protection from damage during delivery to the Buyer by common carrier.

2.7 Data and Reviews. - The Seller shall prepare and provide data to the Buyer in accordance with the attached SDRL, Attachment 2 hereto.

The Seller shall host a program review five (5) months after contract go-ahead at which time program status will be discussed.
PERFORMANCE REQUIREMENTS SPECIFICATION SHEET

1. BASIC INFORMATION

Pump Type: Variable delivery, pressure compensated, axial position

Hydraulic Fluid: MIL-H-83282
Fluid Filtration: 5 micron
Rated Speed: 5900 rpm
Operating Speed Range: 3400 to 6000 rpm
Maximum Discharge Pressure: 8000 psi
Rated Discharge Flow: 10 gpm
Rated Operating Temperature: +200°F (Inlet Fluid)
Transient Response Time: 0.050 sec (max)
Suction Pressure: 50 psig

2. MODIFIED PUMP PERFORMANCE GOALS

<table>
<thead>
<tr>
<th></th>
<th>High Pressure</th>
<th>Low Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Cut-off Pressure</td>
<td>8000 ± 100 psi</td>
<td>4000 ± 150 psi</td>
</tr>
<tr>
<td>Maximum Full-flow Pressure</td>
<td>7850 ± 150 psi</td>
<td>3750 ± 200 psi</td>
</tr>
<tr>
<td>Maximum Pump Ripple (peak to peak):</td>
<td>± 200 psi</td>
<td>± 250 psi</td>
</tr>
<tr>
<td>Operating Efficiency (min):</td>
<td>85%</td>
<td>85%</td>
</tr>
<tr>
<td>Heat Rejection (max):</td>
<td>330 BTU/min</td>
<td>200 BTU/min</td>
</tr>
<tr>
<td>(at 0.5 gpm discharge flow)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode Switching Time:</td>
<td>0.100 sec (max)</td>
<td></td>
</tr>
<tr>
<td>Mode Switching Pressure:</td>
<td>9600 psi (max)</td>
<td></td>
</tr>
<tr>
<td>Transient (125in³ system)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. DEVIATIONS

Deviations to these requirements require approval by Rockwell.
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APPENDIX B

CONTROL VALVE TEST DATA

<table>
<thead>
<tr>
<th>Contents</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow gain, Bendix zero lap valve</td>
<td>112</td>
</tr>
<tr>
<td>Flow gain, Bendix T-slot valve</td>
<td>113</td>
</tr>
<tr>
<td>Flow gain, E-Systems zero lap valve</td>
<td>114</td>
</tr>
<tr>
<td>Flow gain, E-Systems overlapped valve</td>
<td>115</td>
</tr>
<tr>
<td>Pressure gain, Bendix zero lap valve</td>
<td>116</td>
</tr>
<tr>
<td>Pressure gain, Bendix T-slot valve</td>
<td>117</td>
</tr>
<tr>
<td>Pressure gain, E-Systems zero lap valve</td>
<td>118</td>
</tr>
<tr>
<td>Pressure gain, E-Systems overlapped valve</td>
<td>119</td>
</tr>
<tr>
<td>Internal leakage, Bendix zero lap valve</td>
<td>120</td>
</tr>
<tr>
<td>Internal leakage, Bendix T-slot valve</td>
<td>121</td>
</tr>
<tr>
<td>Internal leakage, E-Systems zero lap valve</td>
<td>122</td>
</tr>
<tr>
<td>Internal leakage, E-Systems overlapped valve</td>
<td>123</td>
</tr>
<tr>
<td>Frequency response, Bendix zero lap valve</td>
<td>124</td>
</tr>
<tr>
<td>Frequency response, Bendix T-slot valve</td>
<td>125</td>
</tr>
<tr>
<td>Frequency response, E-Systems overlapped valve</td>
<td>126</td>
</tr>
</tbody>
</table>
FLOW GAIN

Bendix P/N 3336730
Configuration: Zero Lap

1. Supply Pressure: 8000 psi
2. Valve Load: none
3. Ports: C1 & C2 interconnected
4. Fluid: MIL-H-83282
5. Fluid Temp: +120 Deg F

Spool Displacement, degrees

Bendix P/N 3336730
Configuration: Zero Lap

1. Supply Pressure: 4000 psi
2. Valve Load: none
3. Ports: C1 & C2 interconnected
4. Fluid: MIL-H-83292
5. Fluid Temp: +120 Deg F

Spool Displacement, degrees
FLOW GAIN

1. Supply Pressure: 8000 psi
2. Valve Load: none
3. Ports: C1 & C2 interconnected
4. Fluid: MIL-H-83282
5. Fluid Temp: +120 Deg F

Spool Displacement, degrees

1. Supply Pressure: 4000 psi
2. Valve Load: none
3. Ports: C1 & C2 interconnected
4. Fluid: MIL-H-83282
5. Fluid Temp: +120 Deg F

Spool Displacement, degrees
FLOW GAIN

E-Systems P/N 183300-100
Valve Overlap: zero

1. Supply Pressure: 6000 psi
2. Valve Load: none
3. Ports: C1 & C2 interconnected
4. Fluid: MIL-H-83282
5. Fluid Temp: +120 Deg F

Flow, in^3/sec

Spool Displacement, 0.001 in.

1. Supply Pressure: 4000 psi
2. Valve Load: none
3. Ports: C1 & C2 interconnected
4. Fluid: MIL-H-83282
5. Fluid Temp: +120 Deg F

Spool Displacement, 0.001 in.

114
FLOW GAIN

1. Supply Pressure: 8000 psi
2. Valve Load: none
3. Ports: C1 & C2 interconnected
4. Fluid: MIL-H-83282
5. Fluid Temp: +120 Deg F

Valve Overlap: 0.002 in.

Spool Displacement, 0.001 in.

1. Supply Pressure: 4000 psi
2. Valve Load: none
3. Ports: C1 & C2 interconnected
4. Fluid: MIL-H-83282
5. Fluid Temp: +120 Deg F

Valve Overlap: 0.002 in.

Spool Displacement, 0.001 in.
PRESSURE GAIN

**Bendix P/N 3336730**

**Configuration:** Zero Lap

1. Supply Pressure: 8000 psi
2. Ports: C1 & C2 blocked
3. Fluid: MIL-H-83282
4. Fluid Temp: +120 Deg F

**Spool Displacement, degrees**

---

**Bendix P/N 3336730**

**Configuration:** Zero Lap

1. Supply Pressure: 4000 psi
2. Ports: C1 & C2 blocked
3. Fluid: MIL-H-83282
4. Fluid Temp: +120 Deg F

**Spool Displacement, degrees**

116
PRESSURE GAIN

Bendix P/N 3335661-2
Configuration: T-Slot

1. Supply Pressure: 8000 psi
2. Ports: C1 & C2 blocked
3. Fluid: MIL-H-83282
4. Fluid Temp: +120 Deg F

Spool Displacement, degrees

---

Bendix P/N 3335661-2
Configuration: T-Slot

1. Supply Pressure: 4000 psi
2. Ports: C1 & C2 blocked
3. Fluid: MIL-H-83282
4. Fluid Temp: +120 Deg F

Spool Displacement, degrees
PRESSURE GAIN

1. Supply Pressure: 8000 psi
2. Ports: C1 & C2 blocked
3. Fluid: MIL-H-83282
4. Fluid Temp: +120 Deg F

E-Systems P/N 183300-100
Valve Overlap: 0.002 in.

Spool Displacement, 0.001 in.

E-Systems P/N 183300-100
Valve Overlap: 0.002 in.

Spool Displacement, 0.001 in.
INTERNAL LEAKAGE

1. Supply Pressure: 8000 psi
2. Ports: C1 & C2 blocked
3. Fluid: MIL-l+-83282
4. Fluid Temp: +120 Deg F

-Leakage, in³/sec-

-Spool Displacement, degrees-

1. Supply Pressure: 4000 psi
2. Ports: C1 & C2 blocked
3. Fluid: MIL-H-83282
4. Fluid Temp: +120 Deg F

-Leakage, in³/sec-

-Spool Displacement, degrees-
INTERNAL LEAKAGE

Bendix P/N 3335661-2
Configuration: T-Slot

1. Supply Pressure: 8000 psi
2. Ports: C1 & C2 blocked
3. Fluid: MIL-H-83282
4. Fluid Temp: +120 Deg F

Leakage, in^3/sec

Spool Displacement, degrees

Bendix P/N 3335661-2
Configuration: T-Slot

1. Supply Pressure: 4000 psi
2. Ports: C1 & C2 blocked
3. Fluid: MIL-H-83282
4. Fluid Temp: +120 Deg F

Leakage, in^3/sec

Spool Displacement, degrees
INTERNAL LEAKAGE

E-Systems P/N 183300-100
Valve Overlap: zero

1. Supply Pressure: 6000 psi
2. Ports: C1 & C2 blocked
3. Fluid: MIL-H-83282
4. Fluid Temp: +120 Deg F

Spool Displacement, 0.001 in.

E-Systems P/N 183300-100
Valve Overlap: zero

1. Supply Pressure: 4000 psi
2. Ports: C1 & C2 blocked
3. Fluid: MIL-H-93282
4. Fluid Temp: +120 Deg F

Spool Displacement, 0.001 in.
INTERNAL LEAKAGE

E-Systems P/N 183300-100
Valve Overlap: 0.002 in.

1. Supply Pressure: 8000 psi
2. Ports: C1 & C2 blocked
3. Fluid: MIL-H-83282
4. Fluid Temp: +120 Deg F

Leakage, in^3/sec

Spool Displacement, 0.001 in.

E-Systems P/N 183300-100
Valve Overlap: 0.002 in.

1. Supply Pressure: 4000 psi
2. Ports: C1 & C2 blocked
3. Fluid: MIL-H-83282
4. Fluid Temp: +120 Deg F

Leakage, in^3/sec

Spool Displacement, 0.001 in.
FREQUENCY RESPONSE

Bendix P/N 3335661-2
Configuration: T-Slot

ROCKWELL DDV 007
FREQUENCY RESPONSE
SLIDE POS. vs. VIN.
DISPL +/- 10 % F.S.

INLET 3000 PSIG.
TE151107C.15A/V0 K1=1.3; K2=3.0

FREQUENCY (Hz)

DATA: 27 FEB 1988
TIME: 05:45:40
DATA TAKEN BY T.T.T
APPENDIX C
SERVO ACTUATOR TEST DATA

Contents

Dynamic Response Tests

<table>
<thead>
<tr>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step response, E-Systems zero lap valve, no load</td>
<td>128</td>
</tr>
<tr>
<td>Step response, E-Systems zero lap valve, loaded</td>
<td>129</td>
</tr>
<tr>
<td>Step response, E-Systems overlapped valve, no load</td>
<td>130</td>
</tr>
<tr>
<td>Step response, E-Systems overlapped valve, loaded</td>
<td>131</td>
</tr>
<tr>
<td>Frequency response, E-Systems zero lap valve, no load</td>
<td>132</td>
</tr>
<tr>
<td>Frequency response, E-Systems zero lap valve, loaded</td>
<td>133</td>
</tr>
<tr>
<td>Frequency response, E-Systems overlapped valve, no load</td>
<td>134</td>
</tr>
<tr>
<td>Frequency response, E-Systems overlapped valve, loaded</td>
<td>135</td>
</tr>
</tbody>
</table>

Pressure Level Switching Tests

<table>
<thead>
<tr>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuator Piston Motionless</td>
<td></td>
</tr>
<tr>
<td>E-Systems zero lap valve, 3400 rpm pump speed</td>
<td>136</td>
</tr>
<tr>
<td>E-Systems zero lap valve, 5900 rpm pump speed</td>
<td>136</td>
</tr>
<tr>
<td>Actuator Piston Moving</td>
<td></td>
</tr>
<tr>
<td>E-Systems zero lap valve, 0° switching point</td>
<td>137</td>
</tr>
<tr>
<td>E-Systems zero lap valve, 90° switching point</td>
<td>138</td>
</tr>
<tr>
<td>E-Systems overlapped valve, 0° switching point</td>
<td>139</td>
</tr>
<tr>
<td>E-Systems overlapped valve, 90° switching point</td>
<td>140</td>
</tr>
</tbody>
</table>

Energy Consumption Tests

<table>
<thead>
<tr>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-Systems zero lap valve</td>
<td></td>
</tr>
<tr>
<td>Pump, actuator not loaded</td>
<td>141</td>
</tr>
<tr>
<td>Actuator, actuator not loaded</td>
<td>142</td>
</tr>
<tr>
<td>System, actuator not loaded</td>
<td>143</td>
</tr>
<tr>
<td>Pump, actuator loaded</td>
<td>144</td>
</tr>
<tr>
<td>Actuator, actuator loaded</td>
<td>145</td>
</tr>
<tr>
<td>System, actuator loaded</td>
<td>146</td>
</tr>
<tr>
<td>E-Systems overlapped valve</td>
<td></td>
</tr>
<tr>
<td>Pump, actuator not loaded</td>
<td>147</td>
</tr>
<tr>
<td>Actuator, actuator not loaded</td>
<td>148</td>
</tr>
<tr>
<td>System, actuator not loaded</td>
<td>149</td>
</tr>
<tr>
<td>Pump, actuator loaded</td>
<td>150</td>
</tr>
<tr>
<td>Actuator, actuator loaded</td>
<td>151</td>
</tr>
<tr>
<td>System, actuator loaded</td>
<td>152</td>
</tr>
</tbody>
</table>
STEP RESPONSE

1. Supply Pressure: 8000 psi
2. Mode: closed loop operation
3. Act'r Load: none
4. Fluid: MIL-H-83282
5. Fluid Temp.: 120 Deg F

1. Supply Pressure: 4000 psi
2. Mode: closed loop operation
3. Act'r Load: none
4. Fluid: MIL-H-83282
5. Fluid Temp.: 120 Deg F
STEP RESPONSE

E-Systems P/N 183300-100
Valve Overlap: zero

1. Supply Pressure: 8000 psi
2. Mode: closed loop operation
3. Act'r Load: 6.94 lb-sec/2 in
4. Fluid: MIL-H-83282
5. Fluid Temp.: +120 Deg F

Time, sec
Piston Displacement, in.

E-Systems P/N 183300-100
Valve Overlap: zero

1. Supply Pressure: 4000 psi
2. Mode: closed loop operation
3. Act'r Load: 6.94 lb-sec/2 in
4. Fluid: MIL-H-83282
5. Fluid Temp.: +120 Deg F

Time, sec
Piston Displacement, in.
STEP RESPONSE

E-Systems P/N 183300-100
Valve Overlap: 0.002 in.

1. Supply Pressure: 6000 psi
2. Mode: closed loop operation
3. Actr. Load: none
5. Fluid Temp.: +120 Deg F

130
STEP RESPONSE

E-Systems P/N 183300-100
Valve Overlap: 0.002 in.

1. Supply Pressure: 8000 psi
2. Mode: closed loop operation
3. Act'r Load: 6.94 lb-sec/2/in
4. Fluid: MIL-H-83282
5. Fluid Temp.: +120 Deg F

Time, sec

Piston Displacement, in.

E-Systems P/N 183300-100
Valve Overlap: 0.002 in.

1. Supply Pressure: 4900 psi
2. Mode: closed loop operation
3. Act'r Load: 6.94 lb-sec/2/in
4. Fluid: MIL-H-83282
5. Fluid Temp.: +120 Deg F

Time, sec

Piston Displacement, in.
FREQUENCY RESPONSE

1. Supply Pressure: 8000 psi
2. Mode: closed loop operation
3. Act‘r Load: none
4. Output: 0.100 in. p-p @ 0.4 Hz
5. Fluid: MIL-H-83282
6. Fluid Temp.: +120 Deg F

Frequency, Hz

Amplitude Ratio, db

Phase Angle, deg

1. Supply Pressure: 4000 psi
2. Mode: closed loop operation
3. Act‘r Load: none
4. Output: 0.100 in. p-p @ 0.4 Hz
5. Fluid: MIL-H-83282
6. Fluid Temp.: +120 Deg F

Frequency, Hz

Amplitude Ratio, db

Phase Angle, deg
NADC-88066-60

FREQUENCY RESPONSE

E-Systems P/N 183300-100
Valve Overlap: zero

Amplitude Ratio, db

Phase Angle, deg

Frequency, Hz

1. Supply Pressure: 8000 psi
2. Mode: closed loop operation
3. Actuator Load: 6.94 lb-sec^2/in
4. Output: 0.100 in. p-p @ 0.4 Hz
5. Fluid: MIL-H-83282
6. Fluid Temp.: +120 Deg F

E-Systems P/N 183300-100
Valve Overlap: zero

Amplitude Ratio, db

Phase Angle, deg

Frequency, Hz

1. Supply Pressure: 4000 psi
2. Mode: closed loop operation
3. Actuator Load: 6.94 lb-sec^2/in
4. Output: 0.100 in. p-p @ 0.4 Hz
5. Fluid: MIL-H-83282
6. Fluid Temp.: +120 Deg F

133
E-Systems P/N 183300-100
Valve Overlap: 0.002 in.

1. Supply Pressure: 8000 psi
2. Mode: closed loop operation
3. Act'r Load: none
4. Output: 0.100 in. p-p @ 0.4 Hz
5. Fluid: MIL-H-93292
6. Fluid Temp.: +120 Deg F

Frequency, Hz

Amplitude Ratio, db

Phase Angle, deg

Frequency, Hz

Amplitude Ratio, db

Phase Angle, deg
NADC-88066-60

FREQUENCY RESPONSE

E-Systems P/N 183300-100
Valve Overlap: 0.002 in.

1. Supply Pressure: 6000 psi
2. Mode: closed loop operation
3. Act'r Load: 5.94 lb/sec-2/in
4. Output: 0.100 in. p-p @ .4 Hz
5. Fluid: MIL-H-83282
6. Fluid Temp.: +120 Deg F

Amplitude Ratio, db

Phase Angle, deg

Frequency, Hz
PRESSURE LEVEL SWITCHING

Vickers Pump S/N MX-346581
E-Sys. Valve: zero lap

System Pressure, psi

1. Pump Speed: 5500 rpm
2. Actuator Motion: none
3. Fluid Temp: +200 deg F
4. Fluid: MIL-H-83282

Actuator Displacement

Switching Valve 'ON'

Switching Valve 'OFF'

Time, sec

Vickers Pump S/N MX-346581
E-Sys. Valve: zero lap

System Pressure, psi

1. Pump Speed: 3400 rpm
2. Actuator Motion: none
3. Fluid Temp: +200 deg F
4. Fluid: MIL-H-83282

Actuator Displacement

Switching Valve 'ON'

Switching Valve 'OFF'

Time, sec
PRESSURE LEVEL SWITCHING

Vickers Pump S/N MX-346581
E-Sys. Valve: zero lap

1. Pump Speed: 5900 rpm
2. Actuator Motion: 0.250 in. B.P @ 1 Hz
3. Switching Pt.: zero Deg
4. Fluid Temp: +200 deg F
5. Fluid: MIL-H-83282

System Pressure, psi

Switching Valve 'ON'
Actuator Displacement

Switching Valve 'OFF'

Time, sec
PRESSURE LEVEL SWITCHING

Vickers Pump S/N MX-346581
E-Sys. Valve: zero lap

1. Pump Speed: 5900 rpm
2. Actuator Motion: 0.250 in. p-p @ 0.1 Hz
3. Switching Pt.: 90 Deg
4. Fluid Temp: +200 deg F
5. Fluid: MIL-H-83282

Switching Valve 'ON'
Actuator Displacement

Switching Valve 'OFF'

Time, sec

Vickers Pump S/N MX-346581
E-Sys. Valve: zero lap

1. Pump Speed: 3400 rpm
2. Actuator Motion: 0.250 in. p-p @ 0.1 Hz
3. Switching Pt.: 90 Deg
4. Fluid Temp: +200 deg F
5. Fluid: MIL-H-83282

Switching Valve 'ON'
Actuator Displacement

Switching Valve 'OFF'

Time, sec

138
PRESSURE LEVEL SWITCHING

Vickers Pump S/N MX-346581
E-Sys. Valve: 0.002 in. overlap

1. Pump Speed: 5900 rpm
2. Actuator Motion: 0.250 in. P-P @ 1 Hz
3. Switching Pt.: zero Deg
4. Fluid Temp: +20 deg F
5. Fluid: MIL-H-83282

System Pressure, psi

Switching Valve 'ON'
Actuator Displacement

Switching Valve 'OFF'

Time, sec

---

Vickers Pump S/N MX-346581
E-Sys. Valve: 0.002 in. overlap

1. Pump Speed: 3400 rpm
2. Actuator Motion: 0.250 in. P-P @ 1 Hz
3. Switching Pt.: zero Deg
4. Fluid Temp: +20 deg F
5. Fluid: MIL-H-83282

System Pressure, psi

Switching Valve 'ON'
Actuator Displacement

Switching Valve 'OFF'

Time, sec
PRESSURE LEVEL SWITCHING

Vickers Pump S/N MX-346581
E-Sys. Valve: 0.002 in. overlap

1. Pump Speed: 6000 rpm
2. Actuator Motion: 0.250 in. p-p @ 1 Hz
3. Switching Pt.: 90 Deg.
4. Fluid Temp.: +200 deg F
5. Fluid: MIL-H-68282

Switching Valve 'ON'
Actuator Displacement

Switching Valve 'OFF'

Time, sec
PUMP ENERGY CONSUMPTION

Vickers Pump: S/N MX-422717
E-Systems Valve: zero lap

1. Supply Pressure: 8000 psi
2. Act'r Load: none
3. Piston Motion: 0.100 in. @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Vickers Pump: S/N MX-422717
E-Systems Valve: zero lap

1. Supply Pressure: 4000 psi
2. Act'r Load: none
3. Piston Motion: 0.100 in. @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Heat Rejection, BTU/min
Frequency, Hz
ACTUATOR ENERGY CONSUMPTION

Vickers Pump: S/N MX-422717
E-Systems Valve: zero lap

1. Supply Pressure: 8000 psi
2. Act' r Load: none
3. Piston Motion: 0.100 in. o-p @ 0.4 Hz
4. Fluid: MIL-H-82802
5. Fluid Temp.: +200 Deg F

Vickers Pump: S/N MX-422717
E-Systems Valve: zero lap

1. Supply Pressure: 4000 psi
2. Act' r Load: none
3. Piston Motion: 0.100 in. o-p @ 0.4 Hz
4. Fluid: MIL-H-82802
5. Fluid Temp.: +200 Deg F
SYSTEM ENERGY CONSUMPTION

Vickers Pump: S/N MX-422717
E-Systems Valve: zero lap

1. Supply Pressure: 8000 psi
2. Act'r Load: none
3. Piston Motion: 0.120 in. c-c @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Heat Rejection, BTU/min vs Frequency, Hz

Vickers Pump: S/N MX-422717
E-Systems Valve: zero lap

1. Supply Pressure: 4000 psi
2. Act'r Load: none
3. Piston Motion: 0.120 in. c-c @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Heat Rejection, BTU/min vs Frequency, Hz
PUMP ENERGY CONSUMPTION

Vickers Pump: S/N MX-422717
E-Systems Valve: zero lap

1. Supply Pressure: 8000 psi
3. Piston Motion: 0.100 in. b-e @ 0.4 Hz
5. Fluid Temp.: +200 Deg F

Heat Rejection, BTU/min
Frequency, Hz
ACTUATOR ENERGY CONSUMPTION

Vickers Pump: S/N MX-422717
E-Systems Valve: zero lap

1. Supply Pressure: 6000 psi
2. Actr. Load: 6.94 lb-sec^2/in
3. Piston Motion: 0.100 in. @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Heat Rejection, BTU/min vs. Frequency, Hz

Vickers Pump: S/N MX-422717
E-Systems Valve: zero lap

1. Supply Pressure: 4000 psi
2. Actr. Load: 6.94 lb-sec^2/in
3. Piston Motion: 0.100 in. @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Heat Rejection, BTU/min vs. Frequency, Hz
SYSTEM ENERGY CONSUMPTION

Vickers Pump: S/N MX-422717
E-Systems Valve: zero lap

1. Supply Pressure: 8800 psli
2. Act'r Load: 6.94 lb-sec²/in
3. Piston Motion: 0.100 in. e-e @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Heat Rejection, BTU/min

Frequency, Hz

Vickers Pump: S/N MX-422717
E-Systems Valve: zero lap

1. Supply Pressure: 4000 psli
2. Act'r Load: 6.94 lb-sec²/in
3. Piston Motion: 0.100 in. e-e @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Heat Rejection, BTU/min

Frequency, Hz
PUMP ENERGY CONSUMPTION

Vickers Pump: S/N MX-422717
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 0000 psi
2. Act'r Load: none
3. Piston Motion: 0.100 in. - 0.4 Hz
4. Fluid: MIL-H-6082
5. Fluid Temp.: +200 Deg F

Frequency, Hz

Heat Rejection, BTU/min

Vickers Pump: S/N MX-422717
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 4000 psi
2. Act'r Load: none
3. Piston Motion: 0.100 in. - 0.4 Hz
4. Fluid: MIL-H-6082
5. Fluid Temp.: +200 Deg F

Frequency, Hz

Heat Rejection, BTU/min
ACTUATOR ENERGY CONSUMPTION

Vickers Pump: S/N MX-422717
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 8000 psi
2. Act'r Load: none
3. Piston Motion: 0.100 in. p-e @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Heat Rejection, BTU/min

Frequency, Hz

Vickers Pump: S/N MX-422717
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 4000 psi
2. Act'r Load: none
3. Piston Motion: 0.100 in. p-e @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Heat Rejection, BTU/min

Frequency, Hz

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SYSTEM ENERGY CONSUMPTION

Vickers Pump: S/N MX-422717
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 8000 psi
2. Actr. Load: none
3. Piston Motion: 0.100 in. @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Heat Rejection, BTU/min
Frequency, Hz

Vickers Pump: S/N MX-422717
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 4000 psi
2. Actr. Load: none
3. Piston Motion: 0.100 in. @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Heat Rejection, BTU/min
Frequency, Hz
PUMP ENERGY CONSUMPTION

Vickers Pump: S/N MX-422717
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 8000 psi
2. Act'r Load: 6.94 lb-sec-2/in
3. Piston Motion: 0.180 in. p-p @ 0.4 Hz
5. Fluid Temp.: +200 Deg F

Frequency, Hz
ACTUATOR ENERGY CONSUMPTION

Vickers Pump: S/N MX-422717
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 8000 psi
2. Actr. Load: 6.84 lb/sec^2/in
3. Piston Motion: 0.100 in. @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Heat Rejection, BTU/min
Frequency, Hz
SYSTEM ENERGY CONSUMPTION

Vickers Pump: S/N MX-422717
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 8000 psi
2. Act'k Load: 6.94 lb/sec^2/in
3. Piston Motion: 0.100 in./c-c @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Heat Rejection, BTU/min

Frequency, Hz

Vickers Pump: S/N MX-422717
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 4000 psi
2. Act'k Load: 6.94 lb/sec^2/in
3. Piston Motion: 0.100 in./c-c @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Heat Rejection, BTU/min

Frequency, Hz
# APPENDIX D

**DUAL PRESSURE PUMP TEST DATA**

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PUMP PRESSURE RIPPLE

Vickers M/N PV3-047-4
S/N MX-346581

1. System Pressure: 8000 psi
2. Pump Speed: 5980 rpm
3. Discharge Flow: 6.5 gpm
4. Inlet Pressure: 90 psig
5. Inlet Fluid Temp: +200 deg F
6. Fluid: MIL-H-83282

Input Shaft Rotations

Vickers M/N PV3-047-4
S/N MX-346581

1. System Pressure: 4000 psi
2. Pump Speed: 5980 rpm
3. Discharge Flow: 6.5 gpm
4. Inlet Pressure: 90 psig
5. Inlet Fluid Temp: +200 deg F
6. Fluid: MIL-H-83282

Input Shaft Rotations
PUMP TRANSIENT RESPONSE

VICKERS M/N PV3-047-4
S/N MX-346581

1. Pressure Setting: 8000 psi
2. Pump Speed: 5900 rpm
3. Flow: 0.5 to 3 to 0.5 gpm
4. Inlet Fluid Temp.: +200 deg F
5. Fluid: MIL-H-83282

Time, sec

VICKERS M/N PV3-047-4
S/N MX-346581

1. Pressure Setting: 4000 psi
2. Pump Speed: 5900 rpm
3. Flow: 0.5 to 3 to 0.5 gpm
4. Inlet Fluid Temp.: +200 deg F
5. Fluid: MIL-H-83282

Time, sec
PRESSURE LEVEL SWITCHING

Vickers M/N PV3-047-4
S/N MX-346581

1. Pump Speed: 5900 rpm
2. Discharge Flow: 6.5 gpm @ 6000 psig
3. Fluid Temp: 250 deg F
4. Fluid: MIL-H-83282

System Pressure, psi

Switching Valve 'ON'

Switching Valve 'OFF'

Time, sec

Vickers M/N PV3-047-4
S/N MX-346581

1. Pump Speed: 3420 rpm
2. Discharge Flow: 6.3 gpm @ 6000 psig
3. Fluid Temp: 250 deg F
4. Fluid: MIL-H-83282

System Pressure, psi

Switching Valve 'ON'

Switching Valve 'OFF'

Time, sec
PRESSURE LEVEL SWITCHING

Vickers M/N PV3-047-4
S/N MX-346581

System Pressure, psi

Switching Valve 'ON'

Switching Valve 'OFF'

Time, sec

1. Pump Speed: 5900 rpm
2. Discharge Flow: 5.0 gpm @ 8000 psi
3. Fluid Temp: +200 deg F
4. Fluid: MIL-H-83282

Vickers M/N PV3-047-4
S/N MX-346581

System Pressure, psi

Switching Valve 'ON'

Switching Valve 'OFF'

Time, sec

1. Pump Speed: 3400 rpm
2. Discharge Flow: 5.0 gpm @ 8000 psi
3. Fluid Temp: +200 deg F
4. Fluid: MIL-H-83282
## APPENDIX E

### LHS SIMULATOR TEST DATA

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NADC-88066-60

STEP RESPONSE

E-Systems P/N 183300-100
Valve Overlap: zero

1. Supply Pressure: 8000 psi
2. Mode: closed loop operation
3. Act'r Load: 10000 lb
   (tension force)
4. Fluid: MIL-H-83282
5. Fluid Temp: +120 Deg F

E-Systems P/N 183300-100
Valve Overlap: zero

1. Supply Pressure: 4000 psi
2. Mode: closed loop operation
3. Act'r Load: 5000 lb
   (tension force)
4. Fluid: MIL-H-83282
5. Fluid Temp: +120 Deg F

161
STEP RESPONSE

1. Supply Pressure: 8000 psi
2. Mode: closed loop operation
3. Act'r Load: 10000 lb (tension force)
4. Fluid: MIL-H-83282
5. Fluid Temp: +120 Deg F

1. Supply Pressure: 4000 psi
2. Mode: closed loop operation
3. Act'r Load: 5000 lb (tension force)
4. Fluid: MIL-H-83282
5. Fluid Temp: +120 Deg F
FREQUENCY RESPONSE

1. Supply Pressure: 8000 psi
2. Mode: closed loop operation
3. Actuator Load: 5000 lb tension
4. Output: 0.100 in. p-p @ 6.4 Hz
5. Fluid Temp: +120 Deg F

E-Systems P/N 183300-100
Valve Overlap: zero

Amplitude Ratio, db

Phase Angle, deg

Frequency, Hz

10
10^1
10^2

-10
-200

-50
-100
-150

-100
-50
0

10
10^1
10^2

-10
-200

-50
-100
-150

-100
-50
0

Frequency, Hz

163
E-Systems P/N 183300-100
Valve Overlap: 0.002 in.

1. Supply Pressure: 8000 psi
2. Mode: closed loop operation
3. Act' r Load: 5000 lb tension
4. Output: 0.100 in. p-p @ 6.4 Hz
5. Fluid: MIL-H-83282
6. Fluid Temp: +120 Deg F

Frequency, Hz

Amplitude Ratio, db

Phase Angle, deg
PRESSURE LEVEL SWITCHING

Vickers Pump S/N MX-346581
E-Sys. Valve: zero lap

1. Pump Speed: 5900 rpm
2. Actuator Motion: none
3. Fluid Temp: +250 Deg F
4. Fluid: MIL-H-83282

Actuator Displacement

Switching Valve 'ON'

Switching Valve 'OFF'

Time, sec

Vickers Pump S/N MX-346581
E-Sys. Valve: zero lap

1. Pump Speed: 3400 rpm
2. Actuator Motion: none
3. Fluid Temp: +250 Deg F
4. Fluid: MIL-H-83282

Actuator Displacement

Switching Valve 'ON'

Switching Valve 'OFF'

Time, sec

165
PRESSURE LEVEL SWITCHING

Vickers Pump S/N MX-346581
E-Sys. Valve: 0.002 in. overlap

1. Pump Speed: 5900 rpm
2. Actuator Motion: none
3. Fluid Temp: +200 Deg F
4. Fluid: MIL-H-83282

Actuator Displacement

Switching Valve 'ON'

Switching Valve 'OFF'

Time, sec

Vickers Pump S/N MX-346581
E-Sys. Valve: 0.002 in. overlap

1. Pump Speed: 3400 rpm
2. Actuator Motion: none
3. Fluid Temp: +200 Deg F
4. Fluid: MIL-H-83282

Actuator Displacement

Switching Valve 'ON'

Switching Valve 'OFF'

Time, sec

166
PRESSURE LEVEL SWITCHING

Vickers Pump S/N MX-346581
E-Sys. Valve: zero lap

1. Pump Speed: 5900 rpm
2. Actuator Motion: 0.250 in. p-p @ 1 Hz
3. Switching Pt.: zero Deg
4. Fluid Temp: +200 deg F
5. Fluid: MIL-H-83282

Switching Valve 'ON'
Switching Valve 'OFF'

Actuator Displacement

Time, sec

Vickers Pump S/N MX-346581
E-Sys. Valve: zero lap

1. Pump Speed: 3400 rpm
2. Actuator Motion: 0.250 in. p-p @ 1 Hz
3. Switching Pt.: zero Deg
4. Fluid Temp: +200 deg F
5. Fluid: MIL-H-83282

Switching Valve 'ON'
Switching Valve 'OFF'

Actuator Displacement

Time, sec
PRESSURE LEVEL SWITCHING

Vickers Pump S/N MX-346581
E-Sys. Valve: zero lap

1. Pump Speed: 5900 rpm
2. Actuator Motion: 0.250 in. x-p-p 6.1 Hz
3. Switching Pt.: 80 Deg
4. Fluid Temp: +200 deg F
5. Fluid: MIL-H-83282

Switching Valve 'ON'
Actuator Displacement
Switching Valve 'OFF'

Time, sec

Vickers Pump S/N MX-346581
E-Sys. Valve: zero lap

1. Pump Speed: 3400 rpm
2. Actuator Motion: 0.250 in. x-p-p 6.1 Hz
3. Switching Pt.: 90 Deg
4. Fluid Temp: +200 deg F
5. Fluid: MIL-H-83282

Switching Valve 'ON'
Actuator Displacement
Switching Valve 'OFF'

Time, sec

168
PRESSURE LEVEL SWITCHING

Vickers Pump S/N MX-346581
E-Sys. Valve: 0.002 in. overlap

1. Pump Speed: 5900 rpm
2. Actuator Motion: 0.250 in. p-p @ 1 Hz
3. Switching Pt.: zero Deg
4. Fluid Temp: +200 deg F
5. Fluid: MIL-H-83262

Switching Valve 'ON'
Actuator Displacement

Switching Valve 'OFF'

Time, sec

Vickers Pump S/N MX-346581
E-Sys. Valve: 0.002 in. overlap

1. Pump Speed: 3400 rpm
2. Actuator Motion: 0.250 in. p-p @ 1 Hz
3. Switching Pt.: zero Deg
4. Fluid Temp: +200 deg F
5. Fluid: MIL-H-83262

Switching Valve 'ON'
Actuator Displacement

Switching Valve 'OFF'

Time, sec
PRESSURE LEVEL SWITCHING

Vickers Pump S/N MX-346581
E-Sys. Valve: 0.002 in. overlap

1. Pump Speed: 5900 rpm
2. Actuator Motion: 0.250 in. at 1 Hz
3. Switching Pt.: 90 Deg
4. Fluid Temp: +200 deg F
5. Fluid: MIL-H-83282

Time, sec

Switching Valve 'ON'
Actuator Displacement

Switching Valve 'OFF'

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Vickers Pump S/N MX-346581
E-Sys. Valve: 0.002 in. overlap

1. Pump Speed: 3400 rpm
2. Actuator Motion: 0.250 in. at 1 Hz
3. Switching Pt.: 90 Deg
4. Fluid Temp: +200 deg F
5. Fluid: MIL-H-83282

Time, sec

Switching Valve 'ON'
Actuator Displacement

Switching Valve 'OFF'
PRESSURE LEVEL SWITCHING

FC-1 Pump: S/N MX-346581
FC-2 Pump: S/N MX-346580

1. Pump Sp.: 5900 rpm
2. Act'r Operation:
3. Fluid Temp.: +200 F
4. Fluid: MIL-H-83282

Switching Valve 'OFF'
Switching Valve 'ON'

Time, sec
PRESSURE LEVEL SWITCHING

FC-1 Pump: S/N MX-346581
FC-2 Pump: S/N MX-346580

System Pressure, psi

1. Pump Sp.: 5900 rpm
2. Act' r Operation:
   - 10% Load & Stroke
3. Fluid Temp: +200 F
4. Fluid: MIL-H-83282

Actuator Displacement

Switching Valve 'OFF'

Switching Valve 'ON'

Time, sec

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PRESSURE LEVEL SWITCHING

1. Pump Sp.: 5900 rpm
2. Act'r Operation: 50% Load & Stroke
3. Fluid Temp: +200 F
4. Fluid: MIL-H-83282

Switching Valve 'OFF'

Switching Valve 'ON'

Time, sec
PUMP PRESSURE RIPPLE, FC-1 SYS.

Vickers M/N PV3-047-4
S/N MX-346581

1. System Pressure: 8000 psi
2. Pump Speed: 5500 rpm
3. Operating Mode: Act'rs @ null
4. Inlet Pressure: 98 psi
5. Inlet Fluid Temp: +200 deg F
6. Fluid: MIL-H-83262

Input Shaft Rotations
PUMP PRESSURE RIPPLE, FC-2 SYS.

Vickers M/N PV3-047-4
S/N MX-346580

Input Shaft Rotations

Vickers M/N PV3-047-4
S/N MX-346580

Input Shaft Rotations

1. System Pressure: 8000 psi
2. Pump Speed: 5900 rpm
3. Operating Mode: Actors @ null
4. Inlet Pressure: 90 psig
5. Inlet Fluid Temp: 200 deg F
6. Fluid: MIL-H-83282

Input Shaft Rotations

1. System Pressure: 4000 psi
2. Pump Speed: 5900 rpm
3. Operating Mode: Actors @ null
4. Inlet Pressure: 90 psig
5. Inlet Fluid Temp: 200 deg F
6. Fluid: MIL-H-83282

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SPECTRUM ANALYSIS, FC-1 SYSTEM

Vickers Pump M/N PV3-047-4
S/N MX-346581

1. System Pressure: 4000 psi
2. Pressure Transducer Location: 1.25 in. from pump
3. Inlet Fluid Temp: +200 deg F
4. Fluid: MIL-H-83282

Vickers Pump M/N PV3-047-4
S/N MX-346581

1. System Pressure: 4000 psi
2. Pump Speed: 3600 rpm
3. Pressure Transducer Location: 1.25 in. from pump
4. Inlet Fluid Temp: +200 deg F
5. Fluid: MIL-H-83282
SPECTRUM ANALYSIS, FC-1 SYSTEM

Vickers Pump M/N PV3-047-4
S/N MX-346581

1. System Pressure: 4000 psi
2. Pressure Transducer Location: 1.25 in. from pump
3. Inlet Fluid Temp: +200 deg F
4. Fluid: MIL-H-83282

Vickers Pump M/N PV3-047-4
S/N MX-346581

1. System Pressure: 4000 psi
2. Pump Speed: 5800 rpm
3. Pressure Transducer Location: 1.25 in. from pump
4. Inlet Fluid Temp: +200 deg F
5. Fluid: MIL-H-83282
SPECTRUM ANALYSIS, FC-1 SYSTEM

Vickers Pump M/N PV3-047-4
S/N MX-346581

1. System Pressure: 8000 psi
2. Pressure Transducer Location: 1.25 in. from pump
3. Inlet Fluid Temp: +200 deg F
4. Fluid: MIL-H-83282

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Vickers Pump M/N PV3-047-4
S/N MX-346581

1. System Pressure: 8000 psi
2. Pump Speed: 3900 rpm
3. Pressure Transducer Location: 1.25 in. from pump
4. Inlet Fluid Temp: +200 deg F
5. Fluid: MIL-H-83282

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SPECTRUM ANALYSIS, FC-1 SYSTEM

Vickers Pump M/N PV3-047-4
S/N MX-346581

1. System Pressure: 8000 psi
2. Pressure Transducer Location: 1.25 in. from pump
3. Inlet Fluid Temp: +20 deg F
4. Fluid: MIL-H-83282

Vickers Pump M/N PV3-047-4
S/N MX-346581

1. System Pressure: 8000 psi
2. Pump Speed: 5200 rpm
3. Pressure Transducer Location: 1.25 in. from pump
4. Inlet Fluid Temp: +200 deg F
5. Fluid: MIL-H-83282
SPECTRUM ANALYSIS, FC-2 SYSTEM

Vickers Pump M/N PV3-047-4
S/N MX-346580

1. System Pressure: 4000 psi
2. Pressure Transducer Location: 1.25 in. from pump
3. Inlet Fluid Temp: +200 deg F
4. Fluid: MIL-H-83282

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Vickers Pump M/N PV3-047-4
S/N MX-346580

1. System Pressure: 4000 psi
2. Pump Speed: 3800 rpm
3. Pressure Transducer Location: 1.25 in. from pump
4. Inlet Fluid Temp: +200 deg F
5. Fluid: MIL-H-83282

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Frequency, Hz

Pressure, psi (RMS peak)
SPECTRUM ANALYSIS, FC-2 SYSTEM

Vickers Pump M/N PV3-047-4
S/N MX-346580

1. System Pressure: 4000 psi
2. Pressure Transducer Location:
   1.25 in. from pump
3. Inlet Fluid Temp: +200 deg F
4. Fluid: MIL-H-83282

Vickers Pump M/N PV3-047-4
S/N MX-346580

1. System Pressure: 4000 psi
2. Pump Speed: 5000 rpm
3. Pressure Transducer Location:
   1.25 in. from pump
4. Inlet Fluid Temp: +200 deg F
5. Fluid: MIL-H-83282
SPECTRUM ANALYSIS, FC-2 SYSTEM

Vickers Pump M/N PV3-047-4
S/N MX-346580

1. System Pressure: 8000 psi
2. Pressure Transducer Location: 1.25 in. from pump
3. Inlet Fluid Temp: +200 deg F
4. Fluid: MIL-H-83282
SPECTRUM ANALYSIS, FC-2 SYSTEM

Vickers Pump M/N PV3-047-4
S/N MX-346580

1. System Pressure: 8000 psi
2. Pressure Transducer Location: 1.25 in. from pump
3. Inlet Fluid Temp: +200 deg F
4. Fluid: MIL-H-83282

1. System Pressure: 8000 psi
2. Pump Speed: 5800 rpm
3. Pressure Transducer Location: 1.25 in. from pump
4. Inlet Fluid Temp: +200 deg F
5. Fluid: MIL-H-83282

Frequency, Hz

Pressure, psi (RMS peak)
PUMP ENERGY CONSUMPTION

Vickers Pump: S/N MX-346581
E-Systems Valve: zero lap

1. Supply Pressure: 8000 psi
2. Act'r Load: none
3. Piston Motion: 0.100 in. p-p @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Frequency, Hz
ACTUATOR ENERGY CONSUMPTION

Vickers Pump: S/N MX-346581
E-Systems Valve: zero lap

1. Supply Pressure: 8000 psi
2. Act’r Load: none
3. Piston Motion: 0.100 in, @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Frequency, Hz

Heat Rejection, BTU/min

Vickers Pump: S/N MX-346581
E-Systems Valve: zero lap

1. Supply Pressure: 4000 psi
2. Act’r Load: none
3. Piston Motion: 0.100 in, @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Frequency, Hz

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SYSTEM ENERGY CONSUMPTION

Vickers Pump: S/N MX-346581
E-Systems Valve: zero lap

1. Supply Pressure: 8000 psi
2. Act’t’r Load: none
3. Piston Motion: 0.100 in. p-p 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: -200 Deg F

Frequency, Hz
PUMP ENERGY CONSUMPTION

Vickers Pump: S/N 346581
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 8000 psi
2. Actr' Load: none
3. Piston Motion: 0.100 in. p-p @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +288 Deg F

Frequency, Hz

Heat Rejection, BTU/min

Vickers Pump: S/N 346581
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 4000 psi
2. Actr' Load: none
3. Piston Motion: 0.100 in. p-p @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Frequency, Hz

Heat Rejection, BTU/min
ACTUATOR ENERGY CONSUMPTION

Vickers Pump: S/N 346581
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 8000 psi
2. Act'r Load: none
3. Piston Motion: 0.100 in. p-p @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Frequency, Hz

Vickers Pump: S/N MX-346581
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 4000 psi
2. Act'r Load: none
3. Piston Motion: 0.100 in. p-p @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Frequency, Hz
SYSTEM ENERGY CONSUMPTION

Vickers Pump: S/N 346581
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 800 psi
2. Actr' Load: none
3. Piston Motion: 0.180 in. p.
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Frequency, Hz

Vickers Pump: S/N MX-346581
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 4000 psi
2. Actr' Load: none
3. Piston Motion: 0.180 in. p.
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Frequency, Hz
PUMP ENERGY CONSUMPTION

Vickers Pump: S/N MX-346581
E-Systems Valve: zero lap

Heat Rejection, BTU/min

Frequency, Hz

1. Supply Pressure: 8000 psi
2. Act' r Load: 5000 lb tension
3. Piston Motion: 0.100 in. per 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Vickers Pump: S/N MX-346581
E-Systems Valve: zero lap

Heat Rejection, BTU/min

Frequency, Hz

1. Supply Pressure: 4000 psi
2. Act' r Load: 5000 lb tension
3. Piston Motion: 0.100 in. per 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F
ACTUATOR ENERGY CONSUMPTION

Vickers Pump: S/N MX-346581
E-Systems Valve: zero lap

1. Supply Pressure: 8000 psi
2. Act'r Load: 5000 lb tension
3. Piston Motion: 0.100 in. p-p @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

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Vickers Pump: S/N MX-346581
E-Systems Valve: zero lap

1. Supply Pressure: 4000 psi
2. Act'r Load: 5000 lb tension
3. Piston Motion: 0.100 in. p-p @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

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Frequency, Hz
SYSTEM ENERGY CONSUMPTION

Vickers Pump: S/N MX-346581
E-Systems Valve: zero lap

1. Supply Pressure: 8000 psi
2. Act'r Load: 5000 lb tension
3. Piston Motion: 0.100 in. B-P @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Frequency, Hz

Heat Rejection, BTU/min
PUMP ENERGY CONSUMPTION

Vickers Pump: S/N MX-346581
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 8000 psi
2. Act't Load: 5000 lb tension
3. Piston Motion: 0.100 in. P-P @ 0.4 Hz
4. Fluid: MIL-H-63282
5. Fluid Temp.: +200 Deg F

Frequency, Hz

Vickers Pump: S/N 346581
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 4000 psi
2. Act't Load: 5000 lb tension
3. Piston Motion: 0.100 in. P-P @ 0.4 Hz
4. Fluid: MIL-H-63282
5. Fluid Temp.: +200 Deg F

Frequency, Hz
ACTUATOR ENERGY CONSUMPTION

Vickers Pump: S/N MX-34581
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 8000 psi
2. Actr' Load: 5000 lb tension
3. Piston Motion: 0.100 in. @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F
NADC-88066-60

SYSTEM ENERGY CONSUMPTION

Vickers Pump: S/N MX-346581
E-Sys. Valve: 0.002 in. overlap

1. Supply Pressure: 8000 psi
2. Act'r Load: 5000 lb tension
3. Piston Motion:
   0.100 in. p-p @ 0.4 Hz
4. Fluid: MIL-H-83282
5. Fluid Temp.: +200 Deg F

Frequency, Hz

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