



AEROSPACE INFORMATION REPORT

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Superseding AIR4543B

Aerospace Hydraulics and Actuation Lessons Learned

RATIONALE

This document has been determined to contain basic and stable technology which is not dynamic in nature.

STABILIZED NOTICE

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1. SCOPE

This SAE Aerospace Information Report (AIR) contains Lessons Learned from aerospace actuation, control and fluid power systems technologies. The lessons were prepared by engineers from the aerospace industry and government services as part of SAE Committee A-6, Aerospace Fluid Power, Actuation, and Control Technologies, and were presented to the A-6 during meetings held from 1989 through 1999. The document is organized into five sections covering systems, actuation, hydromechanical components, electrical components and miscellaneous, each further divided into subsections. The lessons are presented in a concise format of Problem, Issue, Solution and Lesson Learned, often with accompanying descriptive diagrams and illustrations for clarity and understanding.

Because of the potential growth in the size of the document as new lessons are published, those presented to the A-6 Committee in 2000 and later years are planned to be released in separate slash number documents, AIR4543/1, AIR4543/2 and so on.

1.1 Further Information About this Revision

The attempt has been made to transfer all of the technical information unchanged from the Revision A to this Revision B document. Several spelling and other typos have been corrected and a duplicate of one lesson was deleted. Two other lessons, which have been revised and repeat presented to A-6 on dates close to the publication for this revision, have also been deleted and will reappear in the first slash number document.

- NOTE: 1. The Lessons Learned contained in this document were first published a minimum of 11 years before the publication date. The reader is advised that some may have been overtaken by technology and developing industry practice.
2. The allocation of the lessons to the various categories is typically obvious, because of their focused content, but occasionally arbitrary because of mixed content. Text searches are suggested to ensure that all lessons of interest are found.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The material in this document is informational and historical. Many of the Lessons Learned were originally published many years before the published date of this revision and the incident dates and relevant issues of the referenced publications are not known. Some of them have been superseded by other standards and this information is provided by parenthetical statements in the body of the document. Both the superseded publications and those current at the time of publication are listed below.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001. Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

AIR1243	Anti Blow-By Design Practice for Cap Seals
AIR1569	Handling and Installation Practice for Aerospace Hose Assemblies
AMS-P-83461	Packing, Preformed, Petroleum Hydraulic Fluid Resistant, Improved Performance at 275 °F (135 °C)
AMS-R-83485	Rubber, Fluorocarbon Elastomer, Improved Performance at Low Temperatures
ARP4150	Procedure for Inspection of Inservice Airborne Accumulators for Corrosion and Damage
ARP4378	Aerospace - Accumulator, Hydraulic, Welded Bellows, Factory Precharged
ARP4379	Aerospace - Accumulator, Hydraulic, Cylindrical, Piston Separated
ARP4553	Aerospace - Accumulator, Hydraulic, Self-Displacing

AS604	Hose Assembly, Polytetrafluoroethylene, Metallic Reinforced, 3000 psi, 400 °F, Heavyweight, Hydraulic
AS620	Hose Assemblies, Convolute Polytetrafluoroethylene Metallic Reinforced, High Temperature, Medium Pressure, Aircraft
AS1241	Fire Resistant Phosphate Ester Hydraulic Fluid for Aircraft
AS1339	Hose Assembly, Polytetrafluoroethylene, Metallic Reinforced, 3000 psi, 400 °F, Lightweight, Hydraulic and Pneumatic
AS4059	Aerospace Fluid Power - Cleanliness Classification for Hydraulic Fluids
AS4623	Hose Assembly, Polytetrafluoroethylene, Para-Aramid Reinforced, 3000 psi, 275 °F, Heavy Duty, Aircraft Hydraulic Systems
AS4716	Gland Design, O-Ring and Other Elastomeric Seals
AS5440	Hydraulic Systems, Aircraft, Design and Installation Requirements For
AS8775	Hydraulic System Components, Aircraft and Missiles, General Specification For
AS28775	Packing, Preformed, - MS28775 O-Ring
AS83461/1	Packing, Preformed, MS83461 O-Ring
AS83461/2	Packing, Preformed, MS83461 Straight Thread Tube Fitting Boss

2.1.2 AIA Publications

Available from Aerospace Industries Association, 1000 Wilson Boulevard, Suite 1700, Arlington, VA 22209-3928, Tel: 703-358-1000, www.aia-aerospace.org.

NAS1638 Cleanliness Requirements of Parts Used in Hydraulic Systems (Inactive for new design)

2.1.3 ASTM Documents

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM F1940 Standard Test Method for Process Control Verification to Prevent Hydrogen Embrittlement in Plated or Coated Fasteners

2.1.4 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591. Tel: 866-835-5322, www.faa.gov.

14CFR Part 25 Code of Federal Regulations, Part 25 Airworthiness Standards: Transport Category Airplanes

2.1.5 Joint Aviation Authorities Committee Publications

Available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado, 80112-5776. Tel: 1-800-854-7179 (inside USA and Canada) or 1-303-397-7956 (outside USA), <http://global.ihs.com>

JAR 25 Joint Airworthiness Requirements, Large Aeroplanes

2.1.6 US Government Publications

Available from the Document Automation and Production Service (DAPS), Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, <http://assist.daps.dla.mil/quicksearch/>.

MIL-DTL-5498	Accumulators, Hydraulic, Cylindrical 3000 psi, Aircraft
MIL-F-8815	Filter and Filter Elements, Fluid Pressure, Hydraulic Line, 15 micron absolute and 5 micron absolute, Type II Systems, General Specification for
MIL-F-8815/2	Filter, Fluid, Pressure, Hydraulic Line, 3000 psi, Absolute 15 Micron, Style B, Non Bypass, -65 Degrees to +275 Degrees F (Inactive for new design.)
MIL-F-24402	Filters (Hydraulic), Filter Elements (High Efficiency), and Filter Differential Pressure Indicators, General Specification for
MIL-G-5514	Gland Design; Packings, Hydraulic, General Requirements for (Inactive for new design)
MIL-P-25732	Packing, Preformed, Petroleum Hydraulic Fluid Resistant, Limited Service at 275 Deg. F (135 Deg. C) (Inactive for new design)
MIL-PRF-680	Degreasing Solvent
MIL-PRF-5606	Hydraulic Fluid, Petroleum Base; Aircraft, Missile and Ordnance (Inactive for new design)
MIL-PRF-6083	Hydraulic Fluid, Petroleum Base, for Preservation and Operation
MIL-PRF-17331	Performance Specification, Lubricating Oil, Steam Turbine and Gear, Moderate Service
MIL-PRF-46170	Hydraulic Fluid, Rust Inhibited, Fire Resistant, Synthetic Hydrocarbon Base, NATO Code No. H-544
MIL-PRF-81836	Cleanliness Requirements of Parts Used in Hydraulic Systems
MIL-PRF-83282	Hydraulic Fluid, Fire Resistant Synthetic Hydrocarbon Base; Aircraft,
MIL-PRF-87257	Hydraulic Fluid, Fire Resistant Synthetic Hydrocarbon Base; Aircraft
MIL-R-25988	Rubber, Fluorosilicone Elastomer, Oil- and Fuel Resistant, O-Rings
MS27595	Retainer, Packing Backup, Continuous Ring, Polytetrafluoroethylene (Inactive for new design)
MS28774	Retainer, Packing Backup, Single Turn, Polytetrafluoroethylene (Inactive for new design)

2.1.7 Referenced Publications Now Canceled

The following documents are referenced in the legacy Lessons Learned contained in this document. In each case they were valid when the Lesson was first published but should now be disregarded since they have been canceled and usually superceded. The superceding documents are provided in the body of the Lesson through parenthetical notes and listed in the preceding subsections.

NOTE: The original references have been retained so that the reader can access the author's intent if any of the lessons are found to conflict with the superceding document.

Canceled SAE Publications

AIR4150	Inspection of Inservice Airborne Accumulators for Corrosion and Damage
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Canceled Government Specifications and Standards

MIL-H-5440	Hydraulic Systems, Aircraft, Design and Installation Requirements for
MIL-H-8775	Hydraulic System Components, Aircraft and Missiles, General Specification For
MIL-P-83461	Packing, Preformed, Petroleum Hydraulic Fluid Resistant, Improved Performance at 275 deg F (135 deg C)
MIL-P-87175	Packing, Preformed, Petroleum Hydraulic Fluid Resistant, Phosphonitrilic Fluoroelastomer
MIL-R-83485	Rubber, Fluorocarbon Elastomer, Improved Performance at Low Temperatures
MS28775	Packing, Preformed, Hydraulic, +275 deg F ("O" Ring)
P-D-680	Dry Cleaning and Degreasing Solvent

2.2 Definitions

Refer to ARP4386.

3. TECHNICAL INFORMATION

3.1 Systems Lessons Learned

3.1.1 All Systems

This subsection addresses lessons generally applicable to systems of all types.

3.1.1.1 Biased Trade Studies

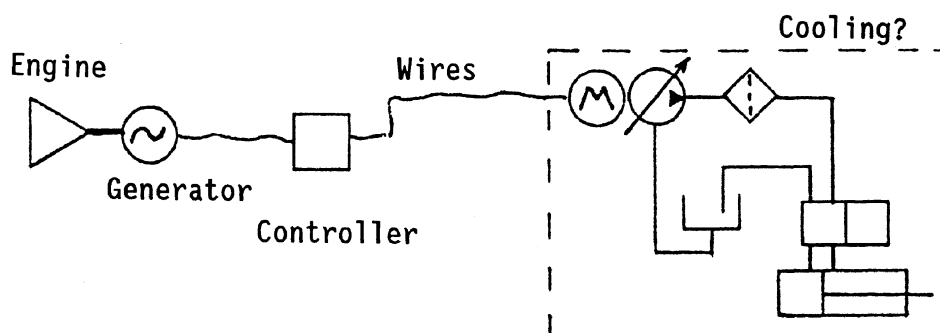
PROBLEM: Trade Studies Biased by Omissions

ISSUE: Trade studies often fail to assess all influences on the air vehicle. Frequently in such trade studies the following issues are not compared:

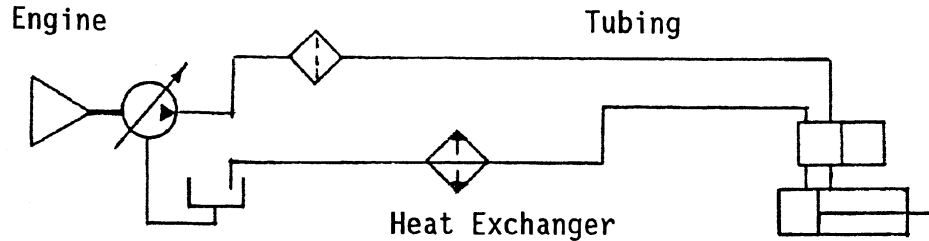
- Cooling
- Power transmission
- Power conversion

ILLUSTRATION:

Distributed hydraulic packages:



Centralized hydraulic system



SOLUTION: Conduct the trade study from the point of original power generation (usually the engine) to the point of final utilization.

3.1.2 Flight Control Systems

3.1.2.1 Effect of JAR/FAR 25.671 Requirement

PROBLEM: Spoiler surface operation not compliant with JAR/FAR 25.671 requirement.

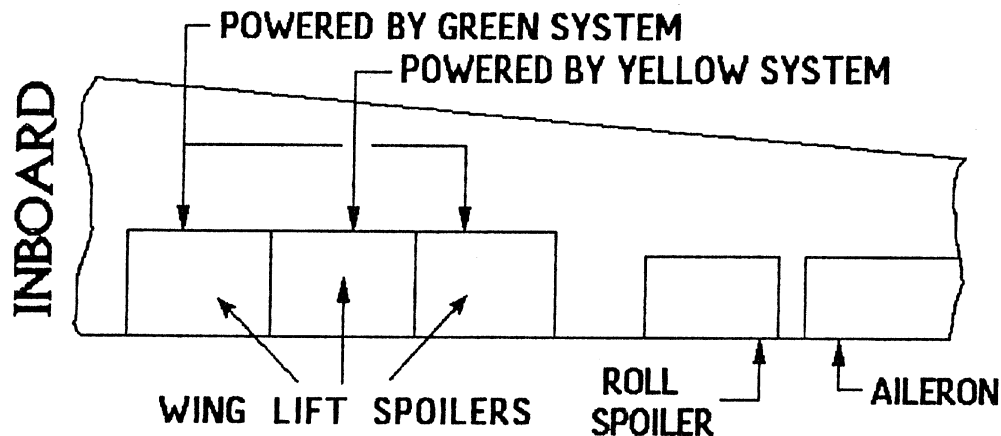
ISSUES:

- a. Noncompliance with JAR/FAR 25.671.

[The reference "JAR/FAR 25.671" is to paragraph 25.671 from 14CFR Part 25 and JAR 25 Ed.]

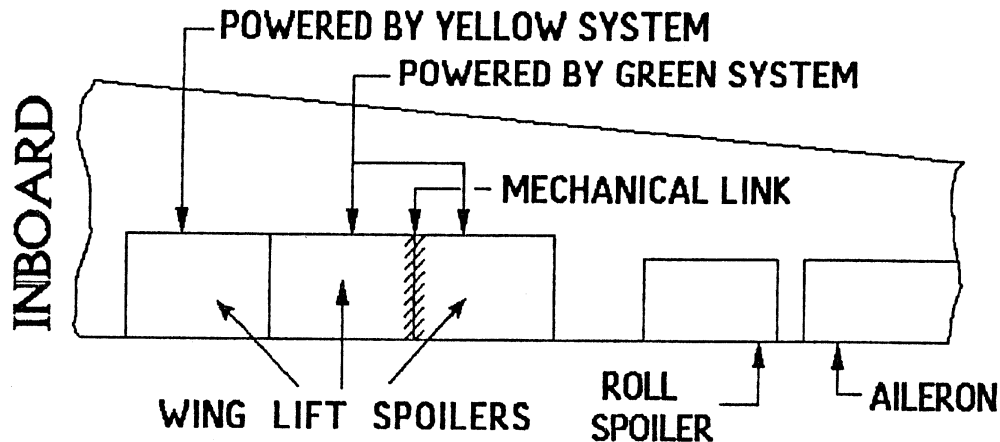
- b. A single failure of a flight control surface attachment point could cause a catastrophic event.
- c. The center or outboard ground lift spoiler panel could deploy, following the failure of the eye end attachment point for example, such that an inadvertent rolling moment could not be controlled.

ILLUSTRATION:



SOLUTION: Reroute hydraulic supplies to the lift spoilers and link the center and outboard panels.

ILLUSTRATION:



3.1.2.2 Failure of all Four Hydraulic Systems

PROBLEM: Failure of all four hydraulic systems due to blowout of the aft bulkhead. (Normal flight control was lost and the airplane crashed into a mountain.)

ISSUES:

- The bulkhead was replaced and mistakenly fastened with a single row of rivets rather than the required double row.
- The released cabin air over pressurized the fin, causing failure of the hydraulic lines.

SOLUTION:

- The access port from the tail section (aft of the bulkhead) was closed.
- A hydraulic fuse was installed in one of the four hydraulic pressure lines leading to the fin.

3.1.2.3 Flight Control Attachment Bolt Failure

PROBLEM: Flight control attachment bolt failure – 3/16 in.

ISSUE: Critical flight control linkage bolt joints using 3/16 in bolts may be over torqued and stay together but fail later in service.

SOLUTION: Use 1/4 in or larger diameter bolt for all critical linkage joints.

3.1.3 Power Distribution Systems

3.1.3.1 Power Conversion Efficiency

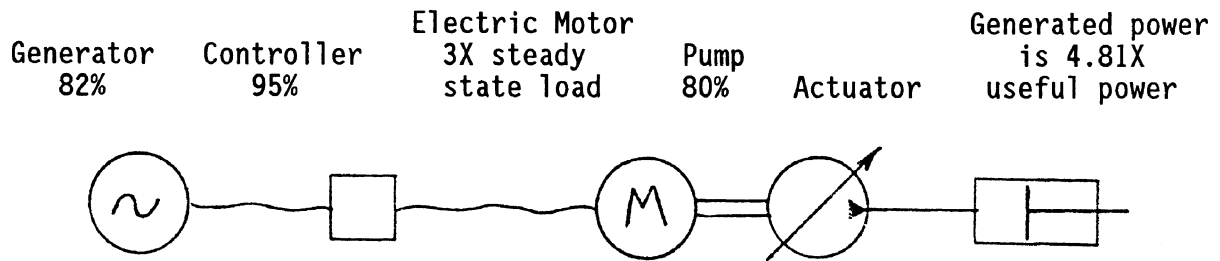
PROBLEM: Multiple power conversions degrade efficiency.

ISSUE: Efficiency is lost for each of the following power conversions:

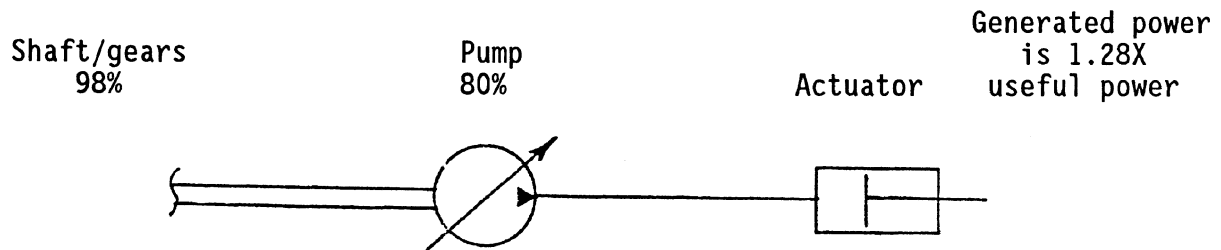
- Mechanical
- Electrical
- Hydraulic
- Pneumatic

ILLUSTRATION:

Hydraulic power from an all-electric engine:



Hydraulic power from the engine shaft:



SOLUTION: Minimize the number of energy conversions between source and use.

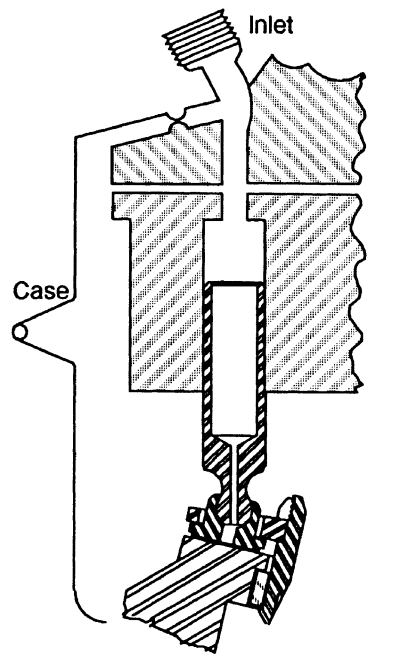
3.1.3.2 Pump Overheat and Rapid Wear

PROBLEM: Pump overheat and rapid wear installed in aircraft system.

ISSUE:

- Pump case drain line too small
- Creates high back pressure (case)
- Creates high discharge pressure (flow)
- Overheat (pump)
- Excessive pump shoe wear

ILLUSTRATION:



SOLUTION:

- a. Increase line size (case drain)
- b. Use bypass type filters
- c. Reroute line to reduce pressure drop
- d. Internally drain (to inlet) if minimum system demand available

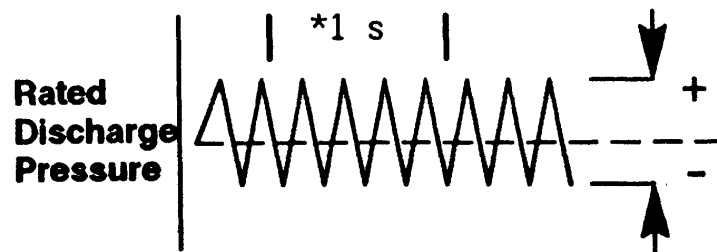
3.1.3.3 Excessive Pump Pressure Ripple

PROBLEM: Hydraulic system life and noise degraded by excessive pump pressure ripple.

ISSUE:

- a. Line fatigue
- b. Excessive wear (moving parts)
- c. Vibration/noise

ILLUSTRATION:



NOTE: Ripple amplitude: Acceptable +/- 10%, Desirable +/- 5 %, Achievable +/- 2%

$$\text{Ripple Frequency} = \left(\frac{\# \text{ Pistons} \times \text{rpm}}{60} \right) \text{cps}$$

SOLUTION:

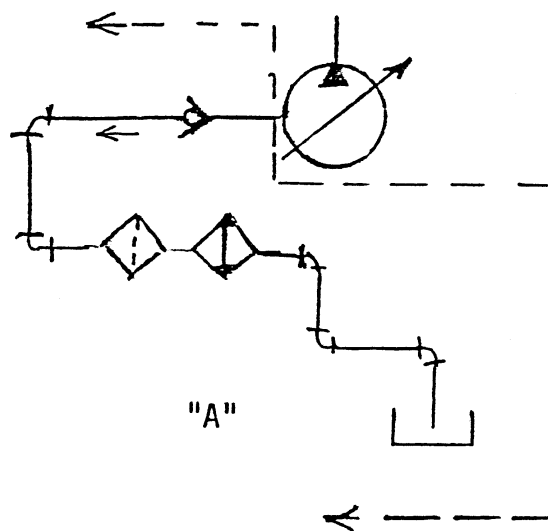
- a. Generate dynamic analysis of total system
- b. "Tune" pump to match system compliance
- c. Provide matched attenuator (pump to system)

3.1.3.4 Pump or Motor Case Drain Line Design

PROBLEM: Pump or motor life reduced by case drain line design.

ISSUE: Restrictions in the hydraulic pump/motor case drain plumbing can cause high pressure and subsequent failure of the pump/motor case. Restrictions can be caused by too small diameter tubing, long tubing lengths, or improper component installations. The restrictions can result in high line pressure drop, resulting in high pressures in the pump or motor case. Pump and motor cases are generally designed to a 500 lbf/in² (3450 kPa) proof pressure or less.

ILLUSTRATION: - Typical "Case Circuit":



SOLUTION:

- a. Analyze the installation and determine the pressure drop of the pump or motor case drain plumbing from the case to the reservoir. The analysis should include evaluations considering delta pressure of all possible case drain flow and fluid temperature combinations, case drain filter variables, transient flows, and component installation.
 1. The pressure drop considerations. A, include:
 2. Line length, line size, bends, fittings, check valve, reservoir, heat exchanger
 3. The total pressure drop A summation must be the same or lower than the pump/motor case allowed design operating pressure.
 4. All case drain temperature/flow combinations must be considered in pressure drop calculation. Some design margin should be included to reduce the effects of pressure spikes in the pump or motor case.
- b. Use maximum size tubing and short line lengths. Plumbing to the hydraulic return lines should be considered if decreased pressure levels are attained.
- c. Conduct the test if possible to verify the analysis prior to design freeze.

3.1.3.5 Pump Cavitation

PROBLEM: Pump cavitation causing hydraulic system failures.

ISSUE:

- a. High levels of pressure oscillation have resulted from:
 1. Poor maintenance (excessive air in system)
 2. Pump cavitation due to system malfunction
- b. Bracket and hydraulic line failures between the engine driven pumps and the filter module have occurred.

SOLUTION:

- a. Install an attenuator in the pump outlet line to reduce oscillations during cavitation.
- b. Tune the attenuator to the system configuration.
- c. Remove all free air from system.

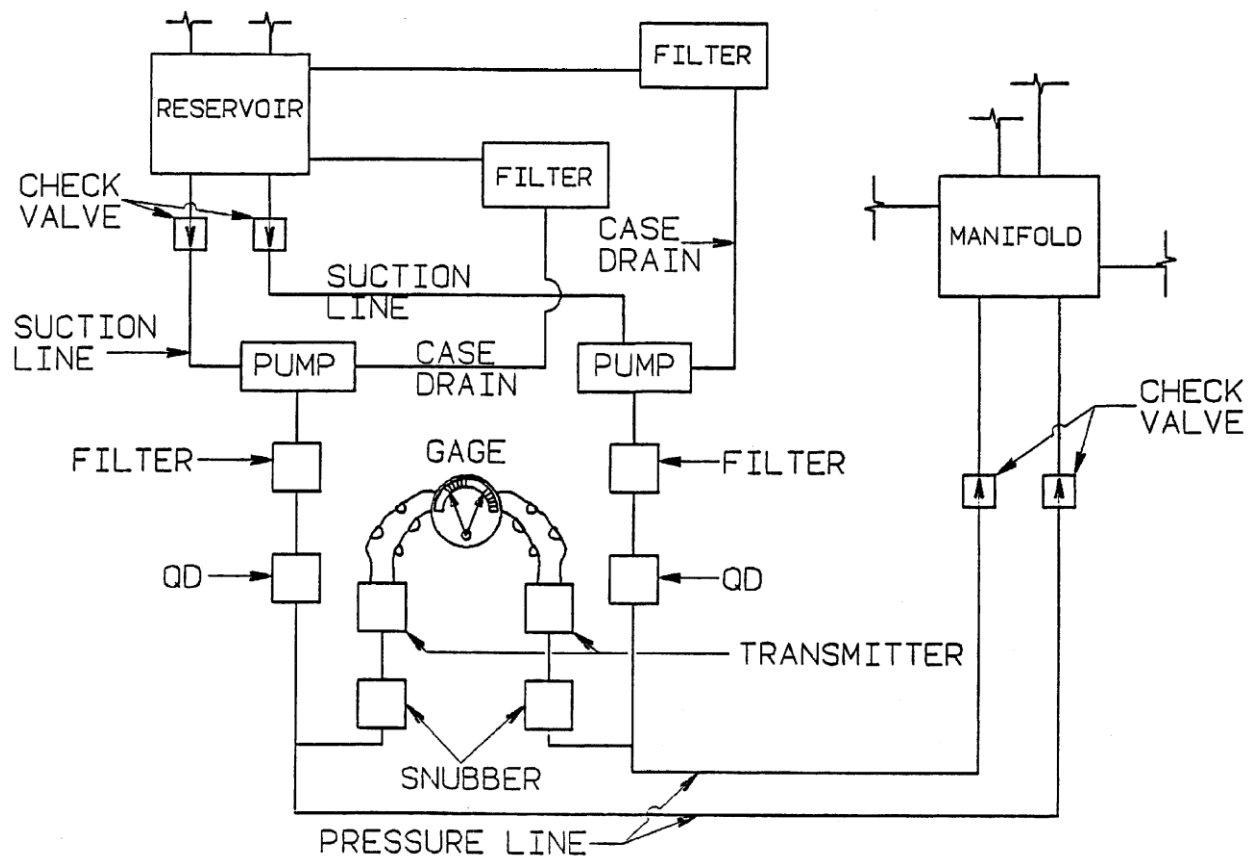
3.1.3.6 Pump Suction Line Bursting

PROBLEM: Pump suction line bursting.

ISSUE:

- a. On the initial engine run of a twin engine aircraft the R/H pump suction line burst.
- b. The line was replaced and the R/H engine started - no problem.
- c. The L/H engine was started and the R/H suction line burst.
- d. The line was replaced and the L/H engine started - no problem.
- e. The R/H engine was then started and the R/H suction line burst.

ILLUSTRATION:



SOLUTION:

- a. The R/H pump compensator was found to have a slightly lower pressure setting than required.
- b. A failed pump outlet check valve created a reverse pumping situation on the R/H side.
- c. Pump and check valve were replaced.

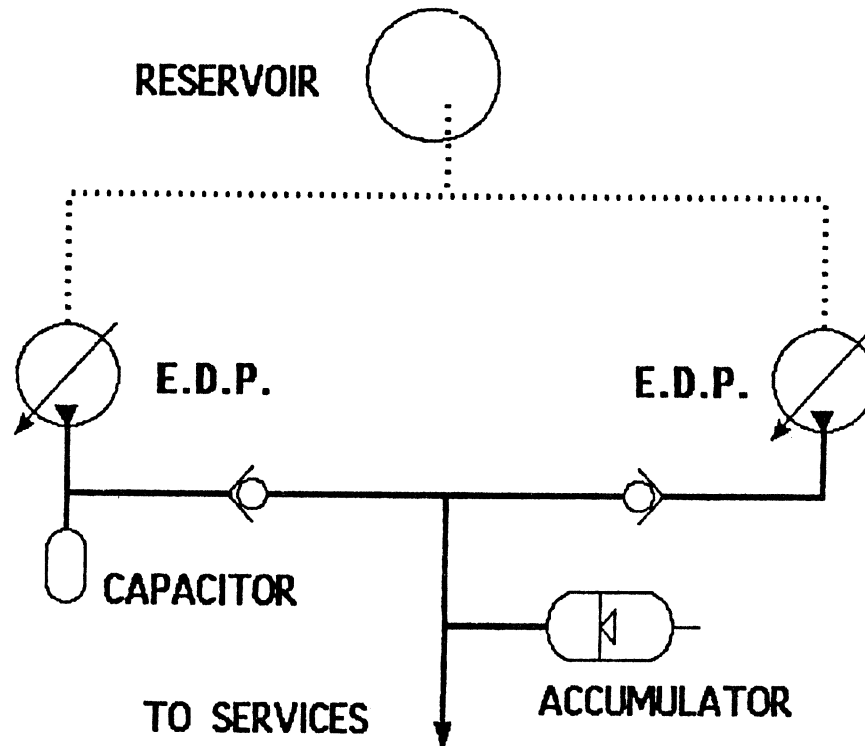
3.1.3.7 Hydraulic System Noise

PROBLEM: Hydraulic system noise.

ISSUES:

- a. With a twin engine driven pump (E.D.P.) hydraulic system, there were complaints of noise, although not encountered with:
 1. Earlier production aircraft;
 2. When system is pressurized by ground rigs.
- b. Resonance condition occurred in the shortest line downstream of E.D.P. due to the reduced volume of the high pressure part of the hydraulic system.

ILLUSTRATION: - Simplified System Diagram



SOLUTIONS:

- Initially increase the accumulator size to that previously fitted.
- Finally, revert to a smaller accumulator and add a “capacitor” (a small pressure vessel (22 in³) (360 cm³) to the system).

3.1.3.8 Low Pressure Cavitation During Valve Endurance Test

PROBLEM: Low pressure cavitation during valve endurance test.

ISSUE: As the demand valve cycled, the return line in the test circuit would pull a vacuum when flow was abruptly shut off from 25 gal/min (1.6 L/s). The valve cap eroded through in about 35 000 cycles. The area of the valve which eroded was exposed only to 60 lbf/in² (410 kPa) maximum and a negative 10 lbf/in² (70 kPa).

SOLUTION:

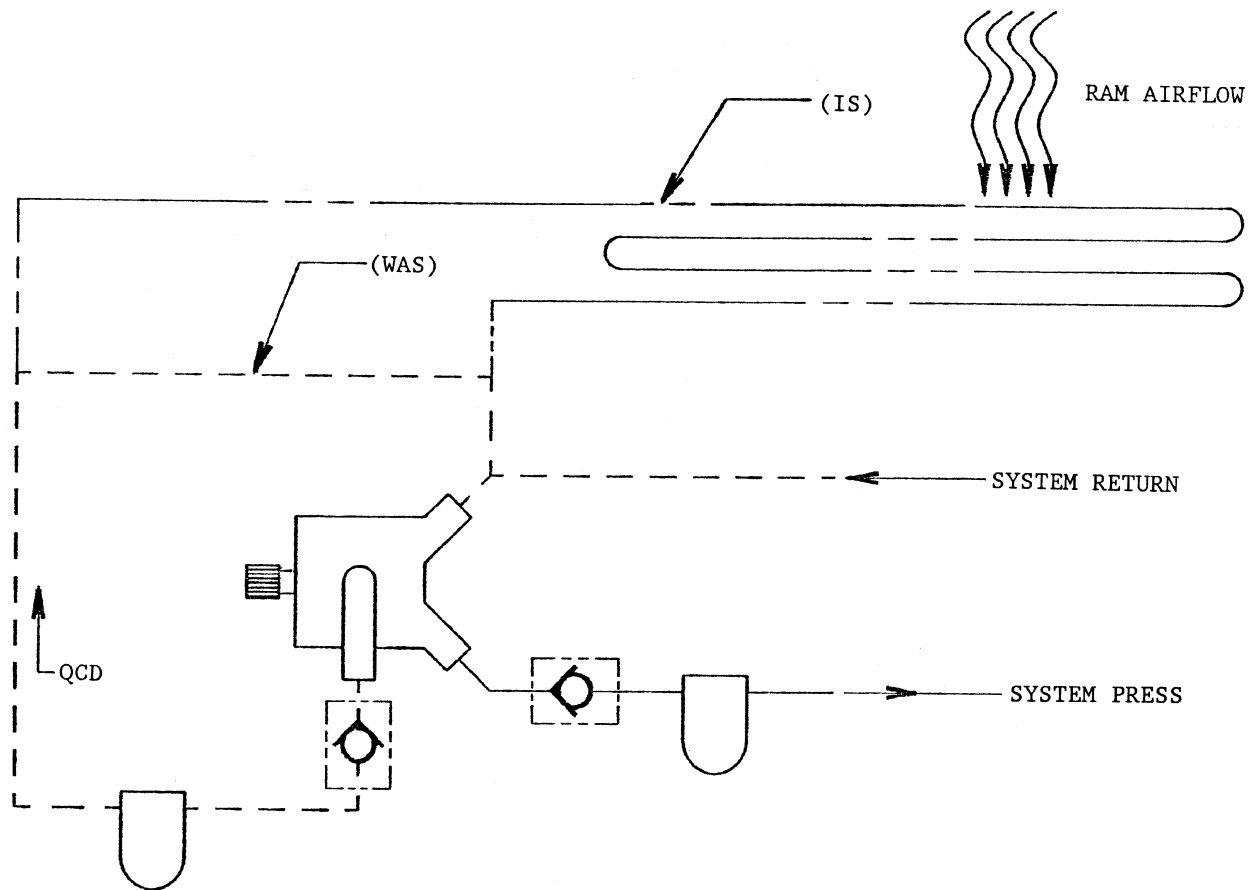
- A relief valve set at 150 lbf/in² (1030 kPa) was put into the return line of the circuit to maintain a positive pressure in the area. This solved the problem.
- A later metallurgical analysis confirmed the low pressure cavitation.

3.1.3.9 System Overheat

PROBLEM: System overheat caused by inefficient pump and lack of heat exchanger.

ISSUE: System can exceed 275 °F (135 °C)

ILLUSTRATION:



SOLUTION:

- Revise the specifications to buy the pump with guaranteed efficiency and case drain flow over the life of the pump.
- Increase the case drain line diameter and the filter housing size.
- Reroute the case drain line to increase surface area and also expose to area with ram air.

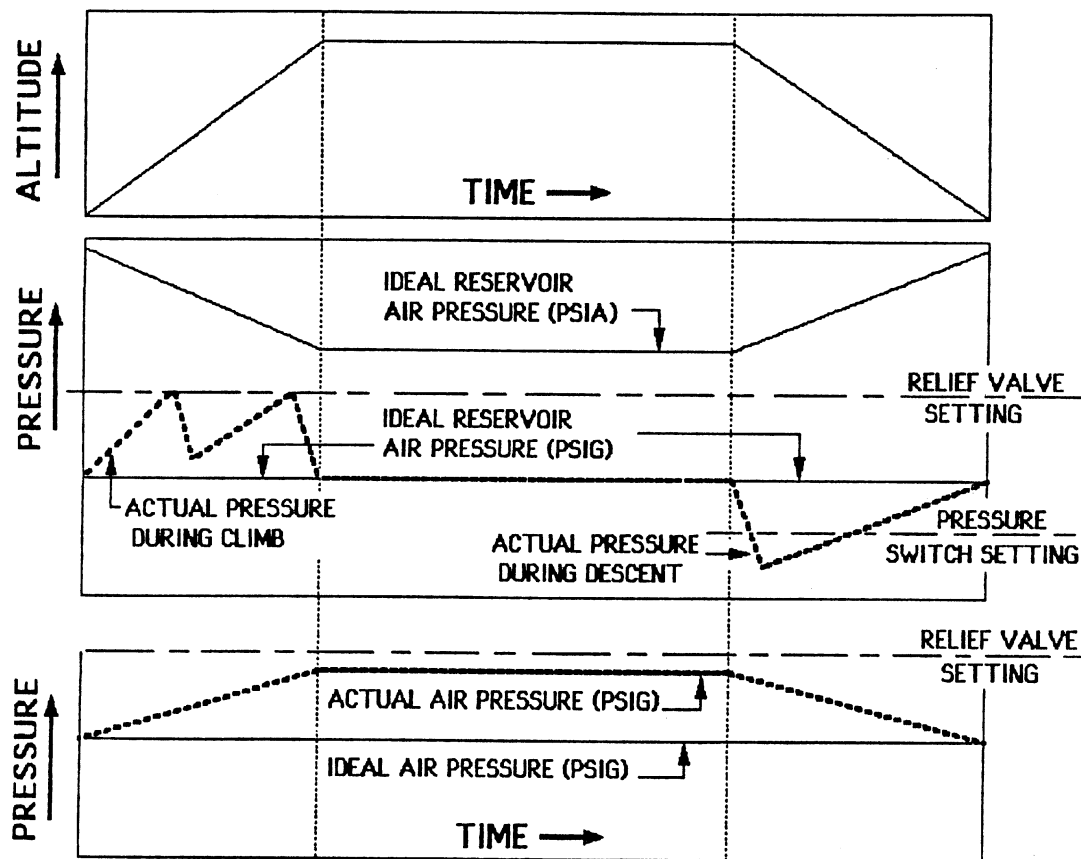
3.1.3.10 Spurious Hydraulic Reservoir Warning

PROBLEM: Spurious hydraulic reservoir low air pressure warning.

ISSUE:

- During aircraft descent, hydraulic reservoir low air pressure warnings occurred although the reservoir pneumatic pressurization system was fully serviceable.
- The engine bleed air pressure with engines at flight idle was less than the pressure switch setting.

ILLUSTRATION:



SOLUTION: Either reset the pressure switch to be less than the minimum bleed pressure or set the relief valve so that it does not operate during aircraft climb.

3.1.3.11 Tire Burst in the Wheel Well

PROBLEM: Hydraulic system failures due to tire burst in the wheel well.

ISSUE: FAR 729 (f) Requirement: Protection of equipment in wheel wells. Equipment that is essential to safe operation of the airplane and that is located in wheel wells must be protected from damaging effects of (1) a bursting tire, unless it is shown that a tire cannot burst from overheating; and (2) a loose tire tread, unless it is shown that a loose tire tread cannot cause damage. Tire overheating due to hard braking or dragging brake prior to takeoff causes the tire to blow out at a weak spot in the tread. The direct jet impingement and the wheel well overpressure can fail hydraulic tubing and blow off the wheel well doors.

[The reference "FAR 729" is to paragraph 25.729 from 14CFR Part 25 Ed.]

SOLUTION: Since this event cannot be prevented, critical hydraulic components and tubing must be located and routed to provide the best possible protection. In aircraft with multiple hydraulic systems, system separation is essential in order to meet requirements. One has to remember that the energy levels due to a tire or wheel blow out are potentially so high that shielding may not be effective and may even cause more damage than the tire blow out. System separation around wheels and tires is a must for all operating aircraft systems such as pneumatics, fuel, controls, electrical, avionics.

3.1.3.12 Failure of Both Hydraulic Systems due to Landing Gear Failure

PROBLEM: Failure of both hydraulic systems due to failure of a landing gear link.

ISSUE: When the link failed with the gear retracted in flight, it swung into tubing in both hydraulic systems causing their failure, and loss of the aircraft.

SOLUTION: Provide adequate system separation so that no such equipment failure can damage all hydraulic systems.

3.1.3.13 Inadvertent Actuation of Switches and Valves in High Response Servoactuators

PROBLEM: Inadvertent actuation of ΔP switches or ΔP operated valves in servoactuators for high response rate flight controls.

ISSUE: A pressure spike occurs in the return system at the servo, due to the initiation of a high return flow rate from the servoactuator.

SOLUTION:

- a. Return system tubing should be sized with consideration for ΔP required to accelerate the fluid.
- b. ΔP switches and ΔP operated valves should be designed with damping to prevent problems from pressure transients.

3.1.3.14 Hydraulic Component Accessibility

PROBLEM: Servicing difficult because of poor hydraulic component accessibility.

ISSUE: Excessive time is required to service frequent maintenance components such as reservoirs, accumulators and system filters in the wheel well or engine compartment.

SOLUTION: In arriving at a location for installation of reservoirs, accumulators and system filters one must keep in mind the need for servicing these components. Provide good accessibility to permit the servicing in the shortest time possible. Keep in mind never to require removal of components in order to service another component.

3.1.4 Utility Control Systems

This subsection applies to systems that provide control of non-critical functions for aircraft and other vehicles.

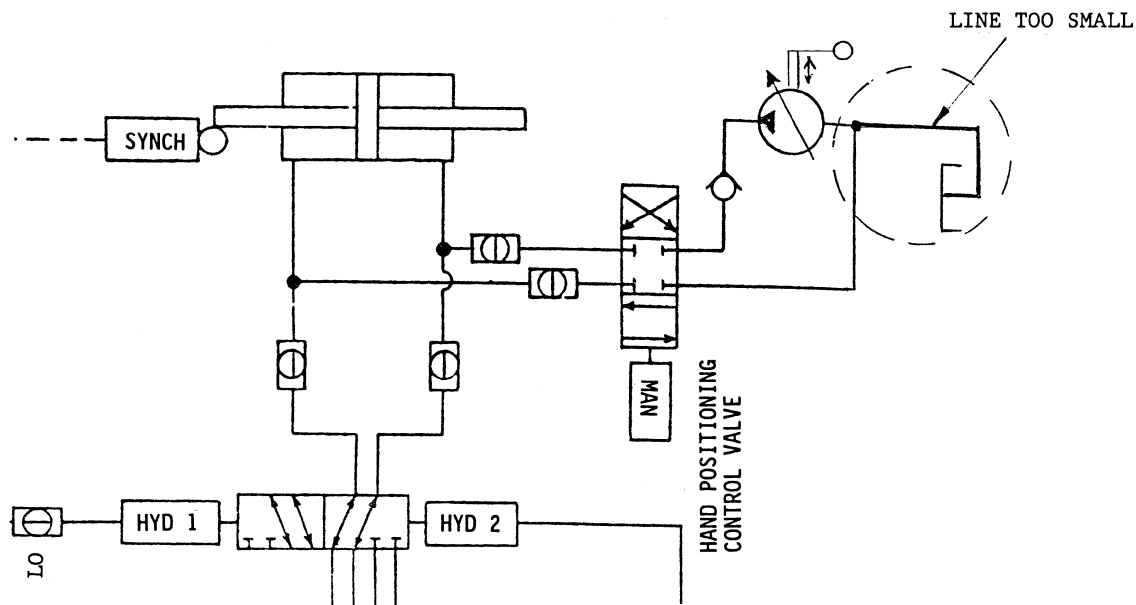
3.1.4.1 Hand Pump Suction Line

PROBLEM: Inadequately sized hand pump suction line causes unacceptable performance.

ISSUES:

- a. The hand pump doesn't operate the submarine steering cylinder at the required rate.
- b. The pump operates satisfactorily in the shop but not when installed in the ship.

ILLUSTRATION:



SOLUTION: The variable displacement hand pump discharges fluid as the pump handle is stroked in each direction. However, analysis indicated that the pump takes suction only when the pump is stroked in one direction. As a result, considerable flow is required from the unpressurized reservoir during the suction stroke even though the cylinder is balanced (equal volume for each direction of travel). The diameter of the make-up line from the reservoir to the pump suction had been sized for minimal flow and had to be increased to obtain rated pump capacity.

3.1.4.2 Sequencing of System Functions

PROBLEM: Unwanted simultaneous or out-of-order sequencing of system functions.

ISSUE: Failures in the electrical control logic (limit switches, coils, relays) and wiring.

SOLUTION: Mechanical sequencing of hydraulic valves

- a. Push-pull rods
- b. Bell cranks
- c. Cables

[Note that this belief in mechanically controlled processes was widely held in the 70s but in later years, as technology advanced, gave way to the almost universal use of electronic control Ed.]

3.2 Actuation Lessons Learned

3.2.1 Electric Servoactuators and Actuators

This subsection will contain Lessons Learned in the design and development of electrically powered servoactuators and actuators.

3.2.2 Hydraulic Servoactuators and Actuators

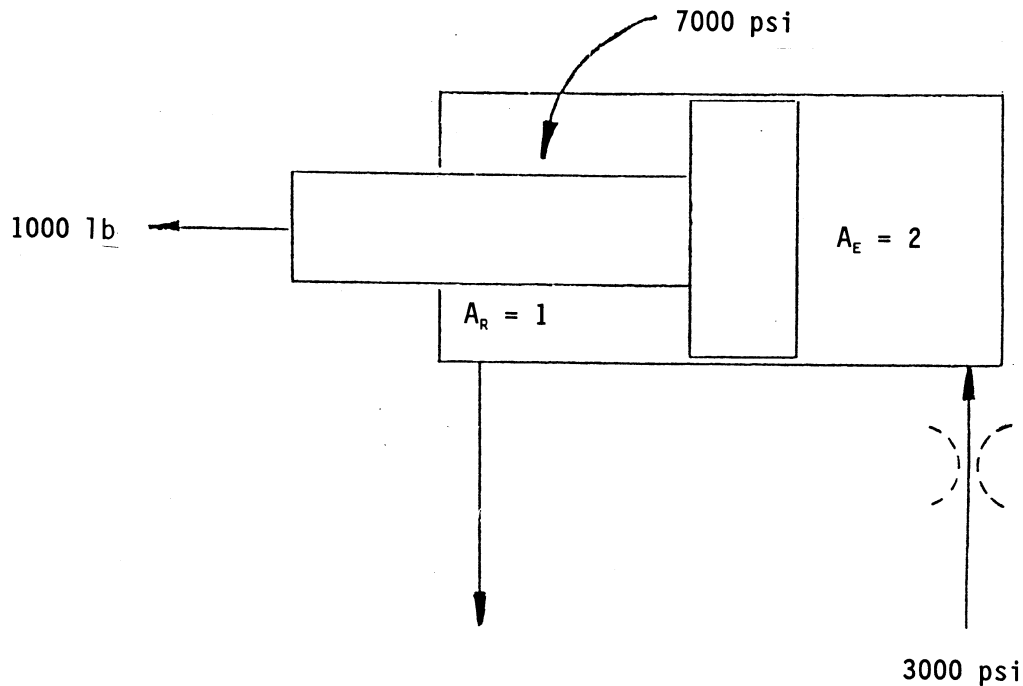
This section contains Lessons Learned relating to hydraulically powered servoactuators and actuators.

3.2.2.1 Pressure Intensification

PROBLEM: Pressure intensification in extending cylinder.

ISSUE: There have been many cases where designers failed to recognize the high pressure that can occur on the retract side of a cylinder due to pressure intensification and/or an aiding load.

ILLUSTRATION:



NOTE: The illustration values of 7000 lbf/in^2 , 3000 lbf/in^2 and 1000 lbf are equivalent to $48\,300 \text{ kPa}$, $20\,700 \text{ kPa}$ and 4450 N , respectively.

SOLUTION: Include restrictor in the extend line so that the extend pressure is reduced to an acceptable level.

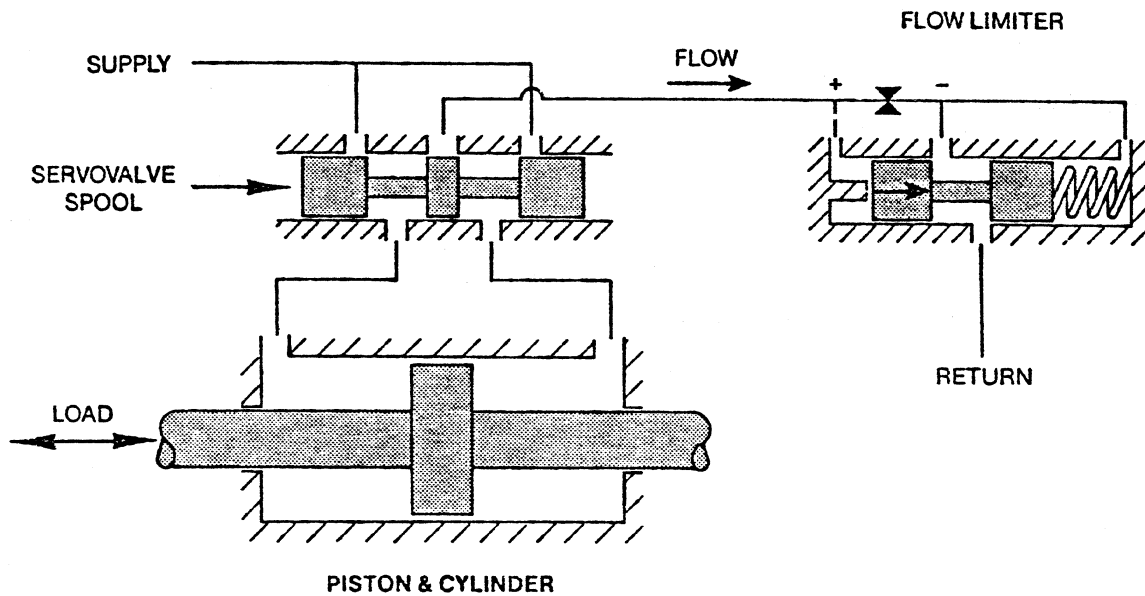
3.2.2.2 Servovalve Separation from the Manifold

PROBLEM: Servovalve separation from the manifold due to servoactuator velocity limiting.

ISSUE:

- During the countdown for the initial launch of the Gemini two-man space vehicle, the primary servovalve of the dual redundant thrust vector control actuator blew off the manifold.
- The actuator flow limiter used to restrict excessive thrust vector control rate caused high back pressure during engine start transient.
- The high impulse loads can create transient back pressure on the servovalve. Alternate configurations for limiting actuator velocity should be considered if impulse loads cannot be suppressed.

ILLUSTRATION:



SOLUTION:

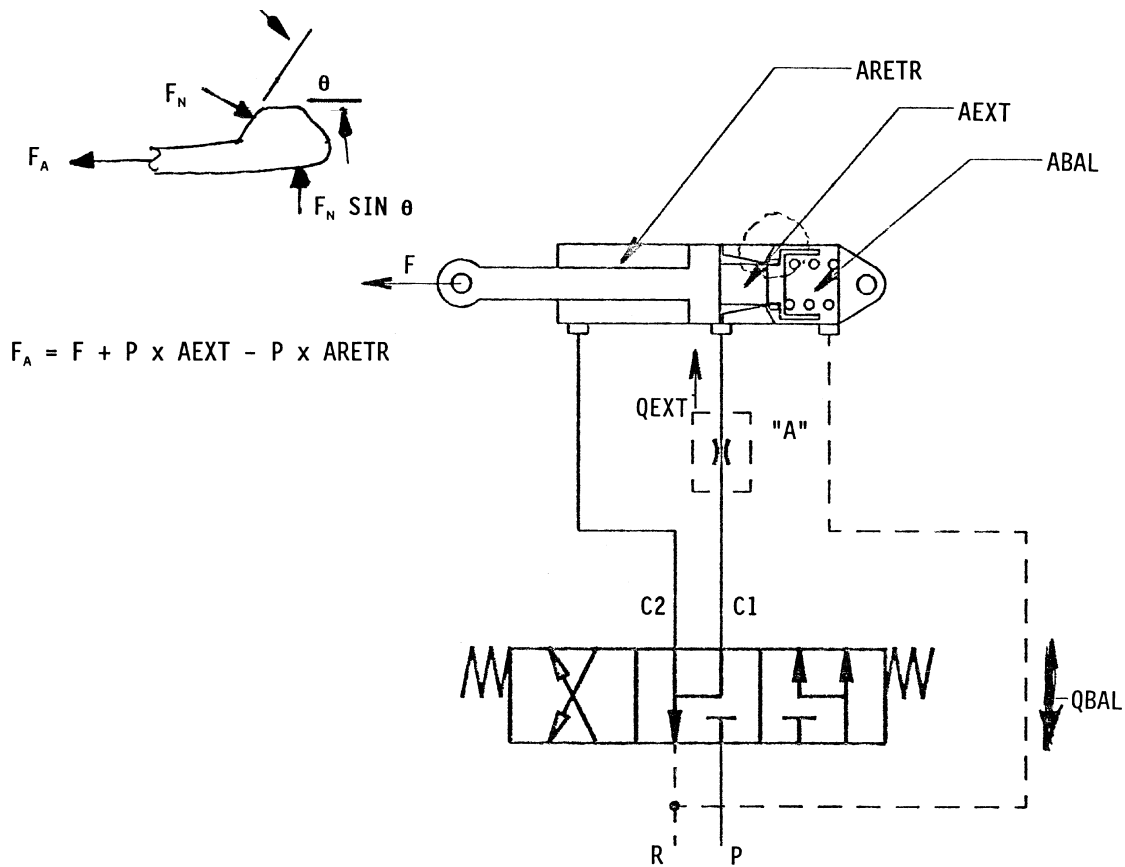
- A quick fix was to beef-up the servovalve body and mounting.
- A long-term solution has been to add cylinder bypass (pressure relief) valves to dissipate energy of hard engine/rocket motor starts.

3.2.2.3 Galling of the Cylinder Lock Mechanism

PROBLEM: Galling of the cylinder lock mechanism when unlocked under high loads.

ISSUE: The contact area approaches zero at the point of lock release.

ILLUSTRATION:



SOLUTION:

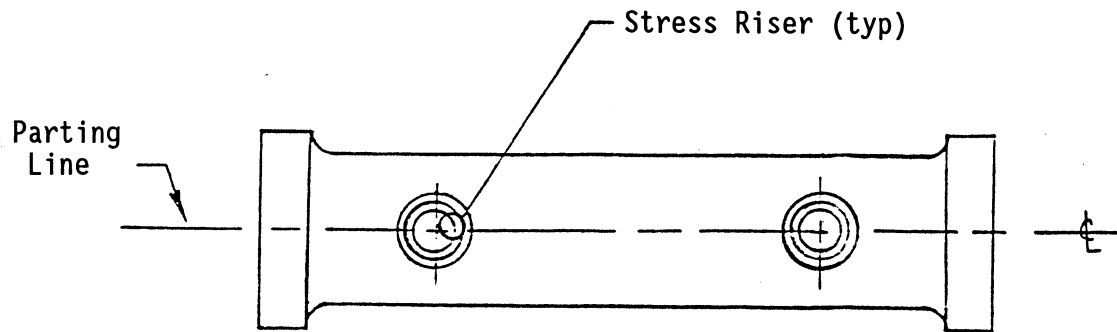
- Size port and line to ABAL for high transient flow.
- Relieve external F on fingers by application of retract pressure before application of extend pressure.
- Choke the inlet flow $QEXT$ at "A" to reduce the rate of pressure rise to AEXT.
- Use one selector valve per actuator.
- Guide and lock piston hardness to be much higher than lock fingers.

3.2.2.4 Parting Plane Fatigue Failures in Cylinders

PROBLEM: Fatigue failures in cylinders with parting plane through ports.

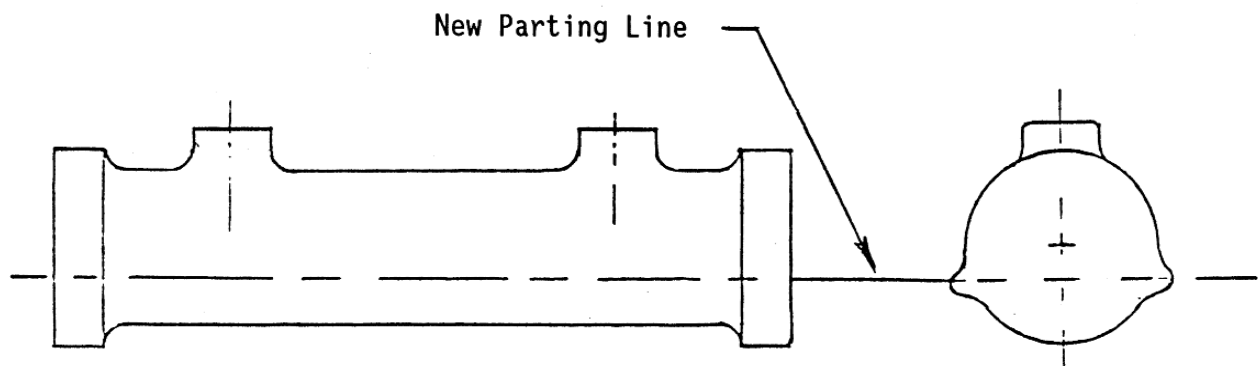
ISSUE: The parting line placement on the cylinder centerline for "shallow draw" forging creates stress risers at the ports and at the thinnest section of the cylinder. This can result in fatigue failures or shortened life (see Illustration 1).

ILLUSTRATION: - 1



SOLUTION: Relocate the parting line off the cylinder centerline and completely off the ports (see Illustration 2).

ILLUSTRATION: - 2

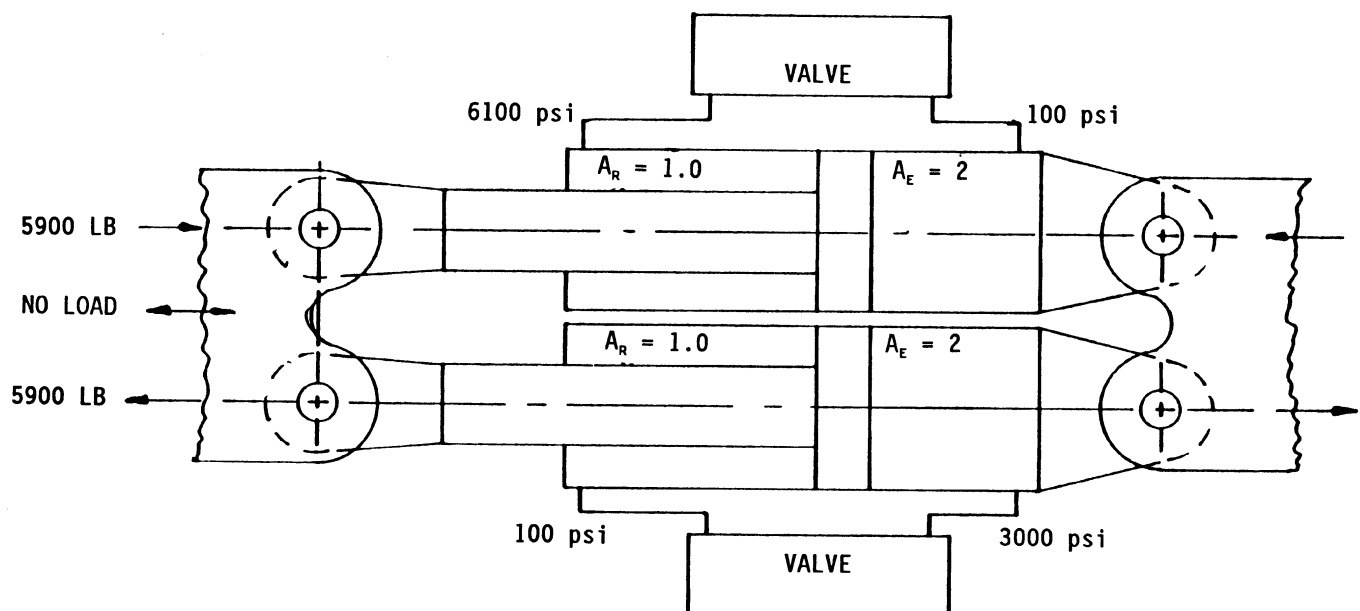


3.2.2.5 Fatigue Damage to Dual Side-by-Side Cylinders

PROBLEM: Fatigue damage to loaded structure and cylinders of side-by-side cylinders.

ISSUE: Force fight in side-by-side cylinders driven by separate valves.

ILLUSTRATION:



NOTE: The pressures and loads, 6100 lbf/in², 3000 lbf/in², 100 lbf/in² (two places) and 5900 lbf (two places), referenced in the illustration are equivalent to 42 100 kPa, 20 700 kPa, 690 kPa (two places) and 26 200 N (two places), respectively.

SOLUTION:

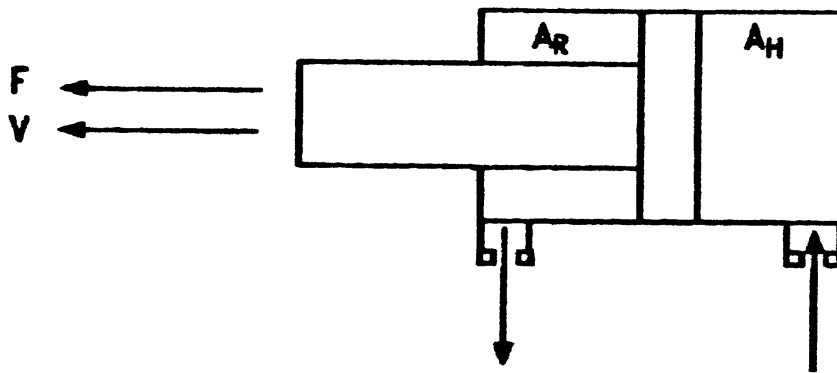
- Use a single tandem valve for control pressure matching.
- Mechanically couple separate valves for control pressure matching.
- Use pressure transducers and electronic equalization to match control pressures.
- Use underlapped separate servovalves to match control pressures at null (may still have a dynamic force fight problem).

3.2.2.6 Velocity Control of Extending Actuator

PROBLEM: Damage caused by poor velocity control of extending actuator.

ISSUE: Velocity control restrictors must be sized to prevent overpressure and cavitation.

ILLUSTRATION:



SOLUTION:

$$F = \left[P_R + \frac{A_R^2 V^2 C_1^2}{C_R^2} \right] A_R - \left[P_S - \frac{A_H^2 V^2 C_1^2}{C_H^2} \right] A_H$$

CHECKS:

Equation not valid if $\frac{A_H^2 V^2 C_1^2}{C_H^2}$ exceeds P_S

F positive is aiding load

F negative is opposing load

$$\text{Rod end pressure} = \left[P_R + \frac{A_R^2 V^2 C_1^2}{C_R^2} \right]$$

$$\text{Head end pressure} = \left[P_S - \frac{A_H^2 V^2 C_1^2}{C_H^2} \right]$$

NOTE: C_R and C_H contain the restrictor sizes and are defined in the TERMS list.

FORCE EQUATION TERMS:

NOTE: Also applicable to the retracting case in 3.2.2.7.

- F = Actuator force, lbf (positive F = aiding load, negative F = opposing load)
 V = Actuator piston velocity, in/s
 A_R = Rod end area, in²
 A_H = Head end area, in²
 C_1 = 0.26
 P_R = Return pressure, lbf/in²
 P_S = System pressure, lbf/in²
 C_R = $29.8 \times C_{DR} d_R^2 / \sqrt{S}$, in⁴/lbf^{0.5}.s²
 C_{DR} = Coefficient of discharge, rod end restrictor
 d_R = Diameter, rod end restrictor, in
 C_H = $29.8 \times C_{DH} d_H^2 / \sqrt{S}$, in⁴/lbf^{0.5}.s²
 C_{DH} = Coefficient of discharge, head end restrictor
 d_H = Diameter, head end restrictor, in
 S = Fluid specific gravity

[The coefficients C_R and C_H have the units of area divided by the square root of mass density, identical to the units of the prefix to the standard orifice turbulent flow equation Ed.]

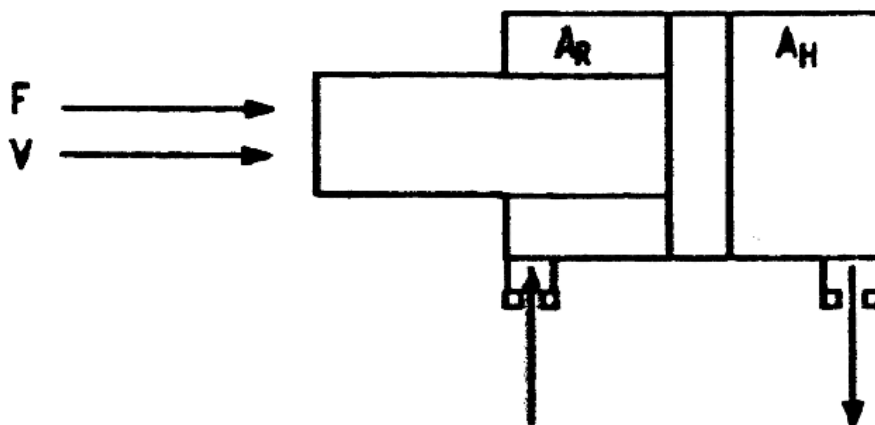
[The quadratic flow equations do not readily allow a single closed-end solution. Given the applied force and required velocity, restrictor diameter sizes can be chosen, in an iterative manner, to meet the performance required while preventing overpressure and cavitation of the rod end and head end cavities Ed.]

3.2.2.7 Velocity Control of Retracting Actuator

PROBLEM: Damage caused by poor velocity control of retracting actuator.

ISSUE: Velocity control restrictors must be sized to prevent overpressure and cavitation.

ILLUSTRATION:



SOLUTION:

$$F = \left[P_R + \frac{A_H^2 V^2 C_1^2}{C_H^2} \right] A_H - \left[P_S - \frac{A_R^2 V^2 C_1^2}{C_R^2} \right] A_R$$

CHECKS:

Equation not valid if $\frac{A_R^2 V^2 C_1^2}{C_R^2}$ exceeds P_S

F positive is aiding load

F negative is opposing load

$$\text{Rod end pressure} = \left[P_S - \frac{A_R^2 V^2 C_1^2}{C_R^2} \right]$$

$$\text{Head end pressure} = \left[P_R + \frac{A_H^2 V^2 C_1^2}{C_H^2} \right]$$

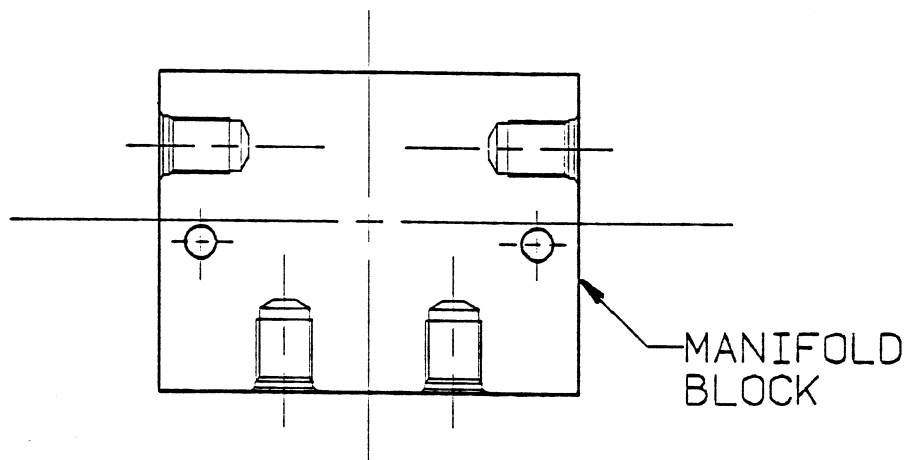
[The quadratic flow equations do not readily allow a single closed-end solution. Given the applied force and required velocity, restrictor diameter sizes can be chosen, in an iterative manner, to meet the performance required while preventing overpressure and cavitation of the rod end and head end cavities Ed.]

3.2.2.8 Aileron Failed to Operate

PROBLEM: Installed aileron actuator failed to operate.

ISSUE: No hydraulic oil was being delivered to the L/H aileron actuator. After extensive troubleshooting, it was found that a manifold block passage had not been drilled.

ILLUSTRATION:



SOLUTION: Although the manifold had passed inspection it was decided to replace it. Afterwards the aileron worked.

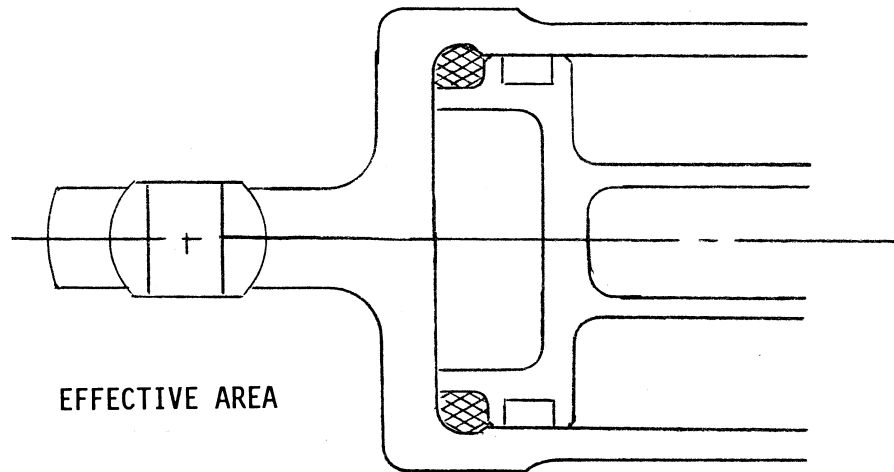
Never take for granted that any part is per the drawing.

3.2.2.9 Fully Retracted Actuator Fails to Extend

PROBLEM: Fully retracted actuator fails to extend against load.

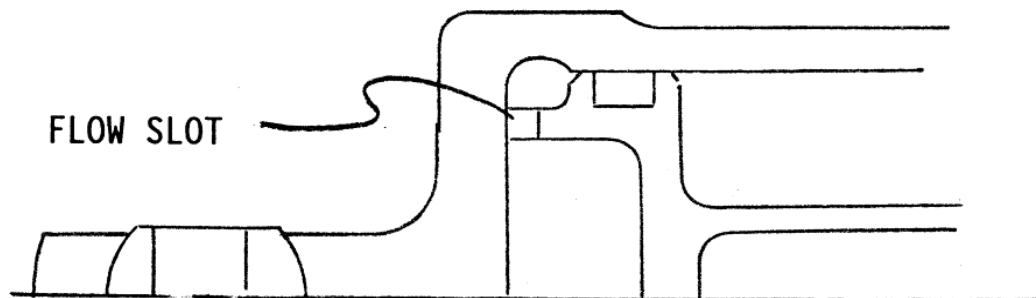
ISSUE: Piston retract stop ring acts as face valve, reducing extend area.

ILLUSTRATION:



SOLUTION: Add flow slot in retract stop ring to assure that full head area is pressurized.

ILLUSTRATION:

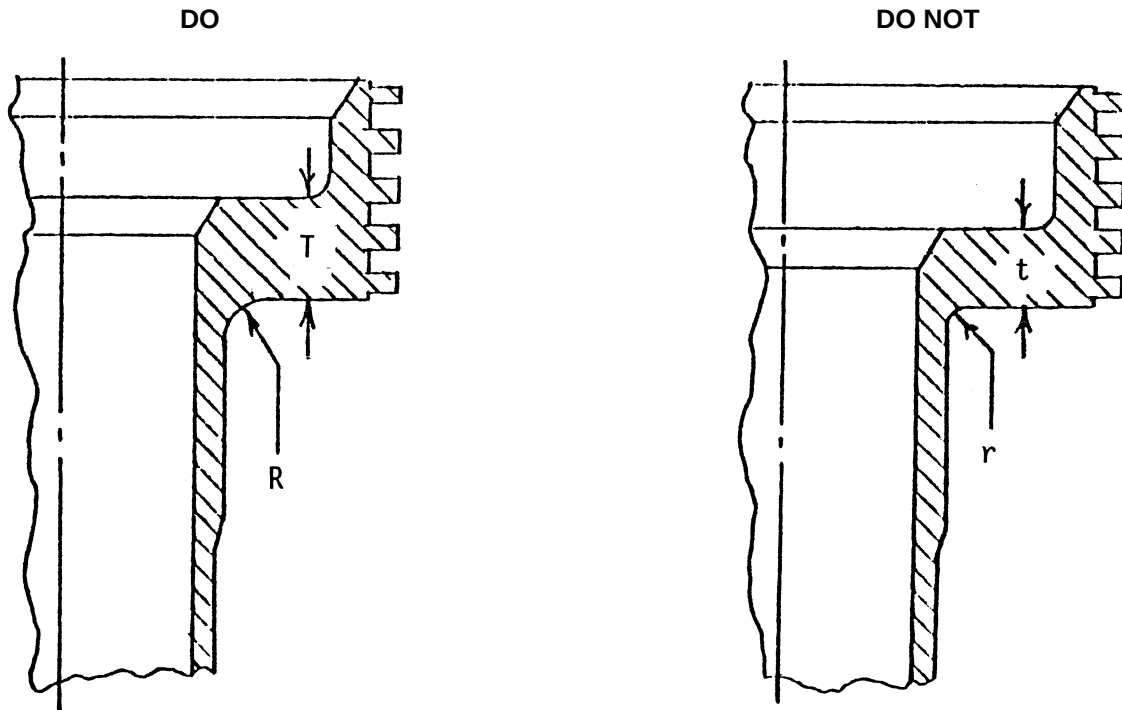


3.2.2.10 Piston Head Separation

PROBLEM: Piston head separation in service.

ISSUE: Hydraulic cylinder piston heads have separated from the piston rods at the fillet between the head and rod.

ILLUSTRATION:



SOLUTION: Design pistons with ample wall thickness (T) and generous fillet radii (R). Consideration must be given to peak transient loading. The type loading, whether pure tensile or combined tensile and bending, must be considered in relation to the stress distribution at the piston head fillet to prevent stress risers.

3.2.2.11 Fatigue Failure of Internal Threads in Aluminum Components

[See AIR4543/1 for revised version. Ed.]

3.2.2.12 Ball Bearing Failures on Servoactuator Input Shaft

PROBLEM: Bearing balls supporting servo input shaft have come out of bearing races and jammed main valve spool causing stab to lock up.

ISSUE: Support bearing may be axially loaded (forced into position) during assembly of the servovalve, causing balls to come out of bearing races. Since the bearing is used in a backup input control, this failure can go undetected and is not visually observable.

SOLUTION:

- Split outer race allowing higher ball retention force.
- Caged bearing design if space permits.

3.2.2.13 Ball Bearing Fatigue Failure on Servoactuator Input Shaft

PROBLEM: Ball bearings, supporting servo input shafts, have had many fatigue failures.

ISSUE: Ball bearings are normally qualified by running them for a given number of rotations under their rated load. Bearings which support a servo input shaft are not used as they were qualified. The bearing oscillates through a few degrees - its entire life spent with the load on 1-3 balls in contact with a small arc on the inner and outer races.

SOLUTION: De-rate the bearing load capacity to account for this unusual usage. Assure that the actuator qualification verifies bearing endurance life.

3.2.2.14 Fly By Wire Actuator Pressure Fatigue Failures

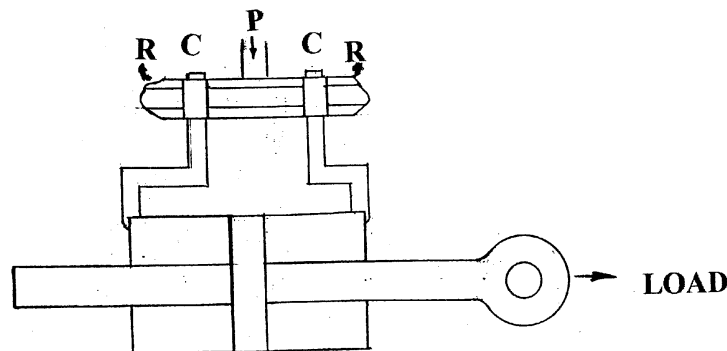
PROBLEM: Early pressure fatigue failures of fly by wire actuators.

ISSUE: Fly by wire servoactuator barrel and end closure pressure fatigue failures occurred in a very short period of use due to a combination of servovalve overlap conditions and continuous small movement command which kept the valve within the overlap region.

To meet low leakage requirements, the supplier provided valves with overlap - long overlap cylinder to return lands and shorter overlap pressure to cylinder lands, tending toward high "no load" null pressures. Combined with an aiding air load, the resisting cylinder pressure may reach a very high pressure value. For example: A constant 1500 lbf/in² (10 300 kPa) extend force pressure load could require the resisting cylinder chamber pressure to approach 4500 lbf/in² (31 000 kPa) in a 3000 lbf/in² (20 700 kPa) system when the valve is in the overlap region and the actuator is extending, depending on the ratio of the overlap lengths.

Combining this condition with small amplitude, low frequency computer generated commands while the aircraft is flying straight and level results in cylinder chamber pressure cycles in the resisting cylinder chamber approaching a 3000 lbf/in² (20 700 kPa) to 4500 lbf/in² (31 000 kPa) range while retracting and extending respectively. If the commands are continuous, even at low frequencies, a substantial number of high pressure cycles may be experienced in a short time even if there is virtually no load change.

ILLUSTRATION:



SOLUTION:

- Minimize overlaps but specify overlap balance conditions if a low leakage is required.
- Insure, via very slow cycle looped cylinder pressure monitoring, that there is a good balance of pressure and return land overlaps if overlaps are substantial, i.e., that the cylinder pressure remains within an approximate $(P + R)/2 \pm 500$ lbf/in² (± 3500 kPa) range in the entire overlap region.
- It is important to know what the FCC is requiring the actuator to do.
- Minimize the frequency of small movement commands (system).

3.2.2.15 Uncommanded T-2C Flight Control System Inputs

PROBLEM: Uncommanded Inputs to the T-2C longitudinal flight control system.

- The training command was experiencing flight incidents, in the form of un-commanded pitch inputs, which led to the grounding of the training fleet due to safety-of-flight concerns.
- A task team consisting of Navy and industry and SAE experts was convened to study the problem.

ISSUE:

- a. Longitudinal flight control actuator utilizes "scarf cut" main piston seals. Teflon cap seal with O-ring energizer in wide groove, 1% squeeze
- b. Longitudinal flight control actuator utilizes force feedback by means of balance pistons. Free floating type.

SUSPECT CAUSES OF PROBLEM:

- a. Main piston seal by-pass results in uncommanded actuator movement through unbalance of feedback pistons
- b. Potential sticking of feedback pistons results in un-commanded inputs

SOLUTION:

- a. Replace scarf cut main piston seal with uncut seal
- b. Increase seal squeeze to prevent by-pass, 10 to 12%
- c. Improve feedback piston design to reduce probability of sticking
- d. More balancing grooves, 13 versus 4
- e. Tighter clearance, 125 μin (3.2 μm)
- f. Reduce jamming potential, reduce travel
- g. Straightness control

VALIDATION OF SOLUTION:

- a. Qualification test of new main piston seal design
- b. Qualification test of improved feedback pistons
- c. Flight test of reworked actuators with design improvements

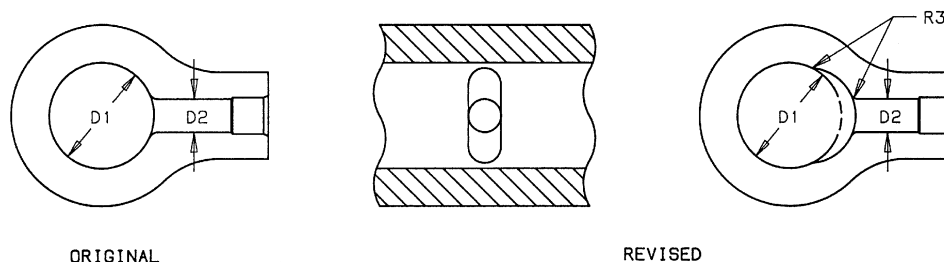
3.2.2.16 Intersecting Passages and Fatigue Life

PROBLEM: Low fatigue life at passage intersections.

ISSUE: Stress concentration decreases as intersecting hole diameter approaches bore diameter.

SOLUTION: Use "fly cut" to create effectively a larger diameter hole.

ILLUSTRATION:



ORIGINAL

REVISED

3.2.3 Mechanical Actuation

3.2.3.1 Long-Term Wear of Flight Control Bungee Assemblies

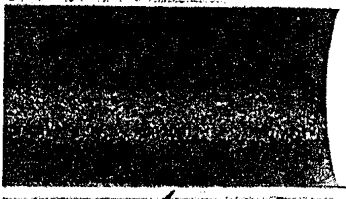
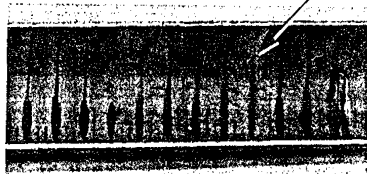
PROBLEM: Springs wearing through bungee tubes.

ISSUE: Flight control bungees sustaining severe wear of bungee tubes caused by vibration of internal springs.

ILLUSTRATION:

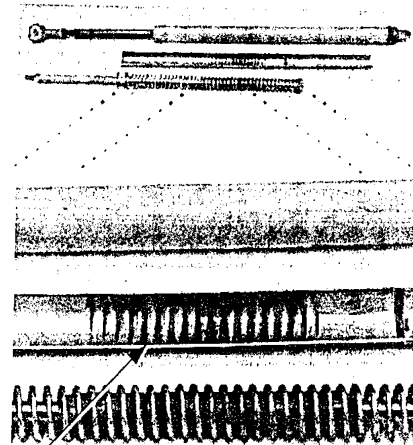
Uncoated and Coated Test Articles

Duplicated Wear Grooves



Bearing Liner

Sectioned Worn Bungee Assembly



Spiral Grooves on I.D. of Tube

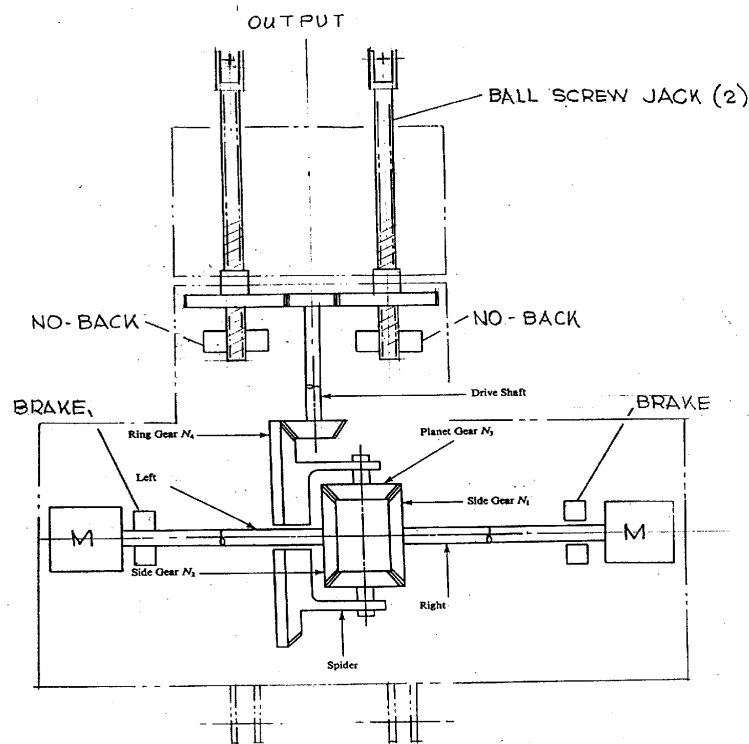
SOLUTION: Apply homogeneous bearing liner to ID of tubes to provide a wear resistant coating.

3.2.3.2 Latent Failures in the Design of Flight Control Components

PROBLEM: Latent failures in the design of flight control components.

ISSUE: Redundancy is frequently employed in the attempt to meet safety and reliability requirements of flight control systems or components. In order to meet the safety requirements, latent failures are sometimes inadvertently incorporated into the design. The subsequent reliability analysis may not properly take into account the actual failure rate of the system or component. In the pitch trim actuator the failure of the mechanical no-backs was undetected because the electro-magnetic brakes at the motors prevented the output from being back driven even after failure of the no-backs. A subsequent failure (open) in the gear train caused the output to be back-driven (the ball screws are reversible) by the air loads at a high rate with no restraint except the inertia of the components.

ILLUSTRATION:



SOLUTION: Carefully examine the component or system for latent failures. If found, the best solution is simply to alter the design and eliminate the latent failure mode. The next best approach is to properly take into account the exposure of the latent failure mode in determining the actual system failure rate. Hopefully the resultant net failure rate is acceptable for the application being considered. If not, a redesign is in order. Alternately, a reduction in the exposure time of the latent mode may be an option.

3.3 Mechanical and Hydromechanical Component Lessons Learned

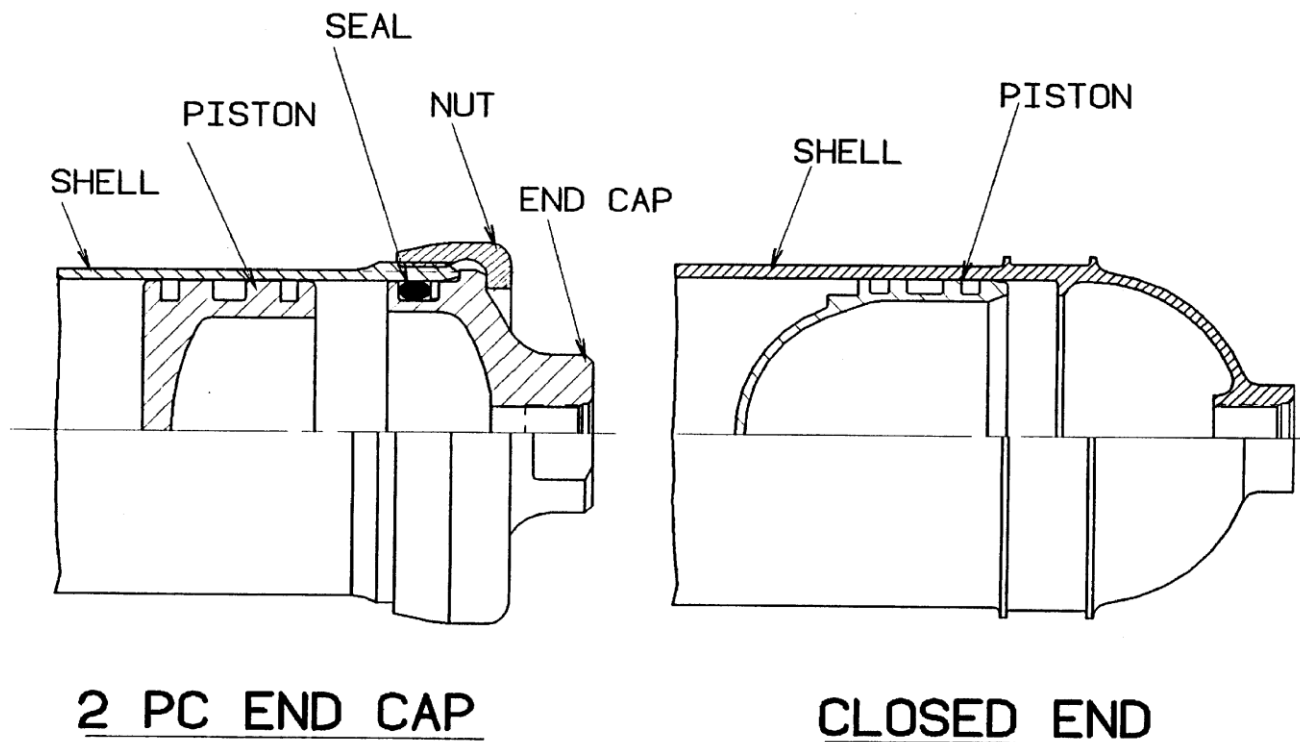
3.3.1 Accumulators

3.3.1.1 Excessive or Premature Leakage Across Accumulator Seals

PROBLEM: Excessive or premature leakage across accumulator seals.

ISSUE: Gas leaking into the system can cause a loss of aircraft or system.

ILLUSTRATION:



SOLUTION:

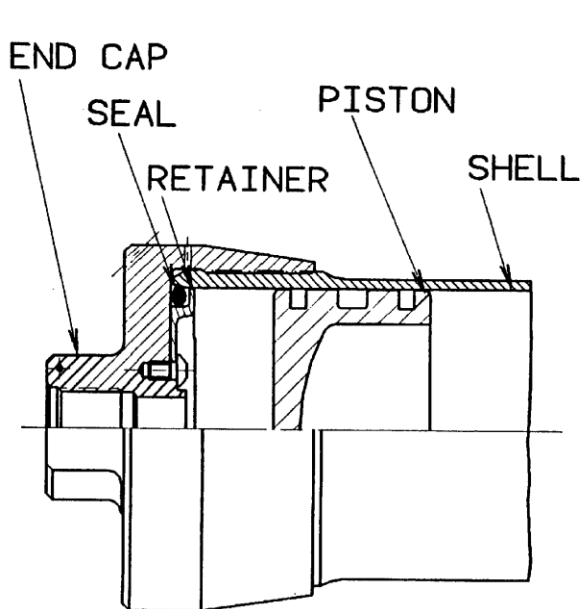
- Ensure that the chrome plate is controlled to minimize cracking (cracks inherent in chrome plating process).
- Ensure that the seal compound meets all temperature, pressure, and pressure discharge requirements. Minimize the compression set and explosive decompression.
- Use the closed end cap on gas side (eliminate static seal).
- Improve the seal concept to improve sealing capability (multiple seals, metal bellows, etc.).

3.3.1.2 Premature Failure of Accumulator End Caps

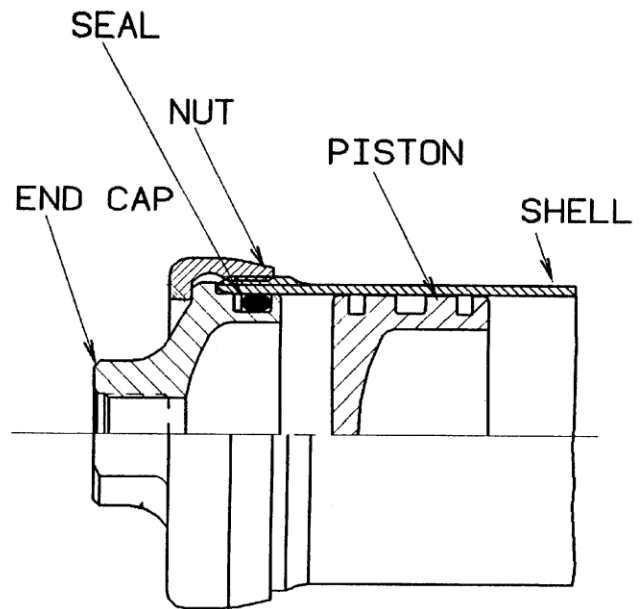
PROBLEM: Premature failure of accumulator end caps.

ISSUE: Failed accumulators are an extreme hazard to aircraft.

ILLUSTRATION:



1 PC END CAP



2 PC END CAP

SOLUTION:

- Replace aluminum with steel or equivalent.
- Ensure that equipment is used at design pressure.
- Use two piece end cap design to distribute stresses (steel nut and aluminum gland).
- Use the closed end cap on gas side.
- Use materials with good fracture toughness - slow crack propagation.
- Provide adequate corrosion protection.

3.3.1.3 False Accumulator Gage Reading

PROBLEM: False accumulator gage reading.

ISSUE:

- The line and filler valve volume on the air side of the accumulator were not correctly included in the air side calculations.
- The fill valve had been relocated after initial sizing. The accumulator piston bottomed before reaching 3000 lbf/in² (20 700 kPa).