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NONFLAMMABLE HYDRAULIC POWER SYSTEM FOR TACTICAL AIRCRAFT

VOLUME II: EQUIPMENT AND SYSTEMS TEST AND EVALUATION

McDonnell Aircraft Company
McDonnell Douglas Corporation
P.O. Box 516
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Final Technical Report for Period June 1988 – March 1990

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This technical report has been reviewed and is approved for publication.

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The objective of the Nonflammable Hydraulic Power System for Tactical Aircraft program was to develop and demonstrate an advanced hydraulic system design operating at a maximum pressure of 8000 psi using an Air Force Developed, nonflammable fluid, chlorotrifluoroethylene (CTFE). It followed four previous programs directed at this technology at Boeing and MCAIR. It was further complemented by three other Air Force sponsored programs which embrace either 8000 psi, CTFE or both. These programs were conducted by Parker Bertea Aerospace (Seal Evaluation), by Vickers Incorporated (High Pressure Pump Development) and by Rockwell International (High Pressure Distribution System Evaluation.

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In order to place the technology in a low risk category which can be embraced for future programs, many complementary technologies were addressed to enhance the benefits of the nonflammable fluid at high operating pressure. Power efficient technologies, which have resulted from previous programs such as Low Energy Consumption Hydraulic Techniques (LECHT) were used to improve the efficiency of the system and reduce heat exchanger requirements to a minimum. Advanced construction materials were exploited to provide minimum weight and long fatigue life. Redundancy management has been addressed with proven techniques such as multiple systems, reservoir level sensing shutoff valves and pressure operated shuttle valves. With expanded interest in airframe powered engine nozzle actuators, the program included several actuators designed for high temperature operation and active cooling techniques.

In phase V of the program, 324 hours of a planned 550 hour system level endurance test were accumulated prior to program termination due to lack of funding. This test was conducted on a complete aircraft shipset of central power generation and distribution equipment, about half of a complete fly-by-wire flight control set, a complement of engine nozzle actuators and several other advanced actuation devices.

FOREWORD

This report was prepared by the McDonnell Aircraft Company (MCAIR) for the United States Air Force under contract Number F33615-86-C-2600. This contract was accomplished under project number 30350102. Reported herein is the period of performance from 30 June 1988 through 21 March 1990. This work was administered under the direction of the Aero Propulsion and Power Laboratory at the Wright Research Development Center, Air Force Systems Command, Wright-Patterson AFB, Ohio. Mr. W. B. Campbell served as Project Manager until January 1989. He was succeeded by Mr. P. G. Colegrove (WRDC/POOS-1) who served as Project Manager throughout the remainder of the program. Technical assistance with the CTFE hydraulic fluid was provided by Mr. C. E. Snyder and Mrs. L. Gschwender of the Materials Laboratory (WRDC/MLBT).

Program functions at MCAIR were administered by Mr. J. B. Greene as Program Manager with Mr. J. A. Wieldt as Principal Investigator. Mr. N. J. Pierce served as Program Advisor until his retirement in August 1987. MCAIR hydraulic design staff contributors included Mssrs. A. O. Harmon, P. R. Lewis, J. D. Linerode, M. A. Orf, J. M. Roach, J. P. Rodgers and J. J. Sheahan. Laboratory activities were supervised by Mssrs. L. E. Clements and E. A. Koertge. Instrumentation and control development was coordinated by Mr. R. Lai with the assistance of C.G. Bunting and D.V.Nguyen. Mr. D. W. Bradrick, T. F. Dowty and M. A. Stratemeyer coordinated the design of the test fixtures and construction of the facility. Mssrs. S. C. Crusius, P. J. Ellerbrock, R. P. Ritzel and Ms. B. L. Spalding operated the facility under the direction of Mr. R. Lai.

This report is the second of two volumes which document the technical efforts for the program. Volume I describes the level of effort expended in Phases I, II, III and the equipment being developed in Phase IV. This Volume reports the results of the individual component tests performed in Phase IV and system level tests performed on the Laboratory Technology Demonstrator (LTD) in Phase V.

Phase I established a baseline aircraft hydraulic system based on the F-15 STOL Maneuvering Technology Demonstrator (S/MTD) Aircraft. This hydraulic power and flight control system was selected as representative of future tactical aircraft power needs and for duplication using nonflammable CTFE hydraulic fluid at 8000 psi operating pressure. This Phase also included setting of system and equipment reliability goals. It was concluded by an industry wide oral briefing at WPAFB on June 25, 1987.

Phase II consisted of a computer analysis effort of the systems to size hydraulic lines, predict hydraulic pressure transients and predict pump performance. During this phase, trade studies were performed to evaluate design approaches intended to enhance system performance with reduced energy consumption.

Phase III included the design of the LTD in the laboratory environment and finalization of subcontracted equipment requirements. Several documents such as a Preliminary Hazards Analysis (PHA), an Operational and Support Hazard Analysis (OASHA) and a Laboratory Test Plan were also developed.

Phase IV activities included placement of purchase orders with selected suppliers and all of the activities associated with the design, development and test, and delivery of equipment to be demonstrated on the LTD. Because of the maturity of the equipment design requirements, this phase was allowed to begin concurrently with Phase I at the onset of the program. This was necessary to meet the overall program schedule. Volume I describes all the equipment needed for this demonstration program. This Volume describes the results of the supplier level testing.

Phase V included the fabrication and installation of the laboratory technology demonstrator (LTD) facility and subsequent shakedown, performance and endurance testing of the flight type equipment on a system level. This Phase culminated in an industry wide oral briefing at MCAIR on March 15, 1990 which concluded the program.

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LIST OF ABBREVIATIONS AND ACRONYMS

ABDR	Aircraft Battle Damage Repair
ADP	Advanced Development Program
AMAD	Airframe Mounted Accessories Drive
BSN	Barium Dinonylnapthalene Sulfonate
CBW	Chemical Biological Warfare
cipr	cubic inches per revolution
cis	cubic inches per second
CRES	Corrosion Resistant Steel
CTFE	Chlorotrifluoroethylene
CWSR	Cold Worked and Stress Relieved
gpm	gallons per minute
GSE	Ground Support Equipment
HIM	Hydraulic Integrity Monitor
hp	horsepower
HSFR	Hydraulic System Frequency Response (Computer simulation program)
HYTRAN	Hydraulic Transient Analysis (Computer simulation program)
HX	Heat Exchanger
IRAD	Independent Research and Development
JFS	Jet Fuel Starter
L/H	Left Hand
LCC	Life Cycle Cost
LECHT	Low Energy Consumption Hydraulic Techniques (Air Force CRAD Program)
LEF	Leading Edge Flap
LTD	Laboratory Technology Demonstrator
LVDT	Linear Variable Differential Transformer (Displacement Transducer)

LIST OF ABBREVIATIONS AND ACRONYMS - Continued

MCAIR	McDonnell Aircraft Company
MTBF	Mean-Time-Between-Failures
MFHBF	Mean-Flight-Hours-Between-Failure
MMHFH	Maintenance-Man-Hours-per-Flight-Hours
NHPSTA	Nonflammable Hydraulic Power System For Tactical Aircraft
OASHA	Operational and Support Hazard Analysis
PC	Primary Control
PDU	Power Drive Unit
PHA	Preliminary Hazard Analysis
PI	Pressure Intensifier
psi	pounds per square inch (lbs/in^2)
psid	pounds per square inch (lbs/in^2) differential
QD	Quick Disconnect
R/H	Right Hand
RLS	Reservoir Level Sensing
R&M	Reliability and Maintainability
rpm	revolutions per minute
RVDT	Rotary Variable Differential Transformer (Displacement Transducer)
SSFAN	Steady State Flow Analysis (Computer simulation program)
S/MTD	STOL Maneuvering Technology Demonstrator
STOL	Short Take-Off and Landing
TAAF	Test Analyze And Fix
VDHM	Variable Displacement Hydraulic Motor
WPAFB	Wright-Patterson Air Force Base
WRDC	Wright Research and Development Center

SECTION I

INTRODUCTION AND SUMMARY

The Nonflammable Hydraulic Power System for Tactical Aircraft (NHPSTA), Contract No. F33615-86-C-2600, an Air Force Advanced Development Program (ADP), was awarded to McDonnell Aircraft Company (MCAIR) on 30 March 1987 and spanned a 36-month period. The purpose of the program was to develop and demonstrate an advanced hydraulic system designed to operate using an Air Force developed, nonflammable fluid, chlorotrifluoroethylene (CTFE), at a maximum operating pressure of 8000 psi.

A total quantity of 600 gallons CTFE base stock was manufactured for this program by Halocarbon Products and blended with lubricity and anti-corrosion additives by the Air Force Materials Laboratory (WRDC/MLBT).

A major portion of an advanced aircraft flight control system was duplicated using flight-weight hydraulic components developed by 24 equipment suppliers contracted to support the program. In addition to the high pressure and new fluid, the program integrated several advanced concepts which reduce power consumption and system heat rejection. The most significant of these is variable system pressure which allows the system to remain at a lower pressure setting (3000 psi) until a power demand occurs.

Energy savings remain a key issue with this new technology as future tactical aircraft are projected to require three times as much hydraulic power at peak demands as conventional aircraft. The increased operating pressure serves to reduce system weight and volume, offsetting the increased weight of CTFE fluid.

After the demonstration facility was completed, the equipment performance established and the endurance testing started, the successful points in the demonstration could be identified as well as the more salient problems. The overwhelming success was that the operating pressure level of 8000 psi presented no special effort over that which would be required for any other system pressure level. There were also no problems in the laboratory with the fluid; rather problems related to pumping the fluid. Pumps (40 gpm, CTFE) proved to be the major shortfall in the program. If there were but one ongoing contracted activity in support of nonflammable fluid technology, it should be the continued development of high power pumps. Any technology improvements could likely be applied to conventional fluid pumps, resulting in significant improvements in reliability and service life.

Even though there were few difficulties with the fluid in the laboratory, several suppliers experienced abnormal degradation of the fluid; more specifically the corrosion inhibitor Barium Dinonylnaphthalene Sulfonate (BSN). This additive has been superseded by a zinc based inhibitor which has been tested by the Materials Lab (WRDC/MLBT) but not in time to be used in this program. This Air Force test included a 930 hour pump (3000 psi) test at 275 ^{o}F operating temperature, the upper operating temperature of the pump.

This design experience with CTFE permits one obvious conclusion, design activity cannot make fluid trades considering nonflammability alone. This 8000 psi CTFE system has been shown to be weight competitive with a 3000 psi system with conventional fluid but this is irrelevant for all practical purposes. When total system weight is the principal trade-off, an 8000 psi system with CTFE cannot compete with an 8000 psi system with conventional fluid. Some weight penalty will always be paid for nonflammability and must be justified by improved survivability and reduced life cycle costs. This weight penalty for nonflammability is reduced as system operating pressures are increased.

Demonstration of variable pressure operation on a multi-system level was a significant accomplishment of the program. Variable pressure operation was expected to present several operating anomalies but actually presented none of any consequence. Of the many power efficient technologies which have been demonstrated, variable pressure is the most effective approach reducing hydraulic system power consumption by as much as half.

The hydraulic equipment suppliers had little difficulty with the design of the equipment; stainless steel and titanium were used almost exclusively for pressure vessels. Seals did not present difficulties except in three instances; all of which were special cases. Otherwise, conventional seal glands and running clearances were used in every item without incidence. The direct drive valves used in servoactuators included linear single stage, linear two stage, rotary-linear single stage and rotary single stage. The only preference to be stated is for rotary-linear; it appears to have more flexibility for manifold packaging.

Fabrication of the distribution system using a wide variety of high pressure fittings as well as odd size tubing for pressure supply proved to be the most routine of all the activities. Fittings used included Permaswage, Cryofit, Rynglok, Dynatube and Welded Lipseals. Line breaks which did occur were no more dramatic than at lower pressure. The high pressure atomizes the fluid stream; posing no safety problem. None of the line breaks were attributed to high pressure; rather improper fitting installation or excessive pressure transient cycling induced by unstable servovalve control. The facility was found to be the "driest" of any assembled at MCAIR.

In summary, there is little to no risk at present in using 8000 psi operating pressure in advanced tactical aircraft. Caution is offered, however, that the only incentive for high pressure is reduced system volume and weight. Servoactuators which are stiffness critical must rely on control electronics for dynamic stiffness enhancement to avoid oversizing the entire hydraulic power and distribution system. This issue is critical to achieving significant weight savings with 8000 psi technology. Pumps must be carefully sized based on a well defined system duty cycle, particularly in aircraft with three and four systems where one pump size must serve for commonality. The designer cannot rely on current design approaches for design factors and distribution system sizing and expect to save weight. Guidelines are offered herein to maximize the weight savings.

1.1 REPORT ORGANIZATION

This report has been organized chronologically by the program tasks as far as practical. Technical details are integrated with the applicable task and by particular subject matter in order to describe the many technical issues. To avoid repetition where technical information is needed more than once, the principal task indicates where additional information is provided.

Because this was a demonstration program and dealt with many broad technical issues, no attempt has been made to include all of the technical background and detail which has evolved from previous Air Force programs and MCAIR Independent Research and Development (IRAD). Where appropriate, references to the applicable documentation have been included; additional pertinent documents not referenced are called out in the Bibliography which appears after the Appendices.

This report is comprised of two volumes which document the technical efforts for the program. This volume describes the results of the individual component tests and supplier experiences from Phase IV and the system level test experience with a Laboratory Technology Demonstrator (LTD) in Phase V. The first volume, Reference 1, describes the level of effort in Phases I, II and III as well as description of the equipment being developed in Phase IV. In the event of conflict of information between the two volumes, Volume II shall take precedence for technical accuracy.

1.2 PROGRAM SCHEDULE

The program master schedule, shown in Figure 1, displays that the program was organized into the five phases.

Phase I was dedicated to establishing the baseline system which was to be simulated in the Phase V demonstration test.

Phase II included all of the system computer analysis and several technical trade studies.

Phase III covered the design of the Laboratory Technology Demonstrator (LTD), development of equipment requirements and Volume I of the final report. Because of advanced work, equipment requirements had been established in preparation for the program technical proposal and therefore preempted certain Phase III tasks.

Phase IV design, development and test of the flight-weight subcontracted equipment began concurrently with Phase I. This approach was absolutely essential for conducting this program in the time span required by the Air Force.

Phase V included the fabrication of the LTD and the system level testing of the subcontracted equipment.

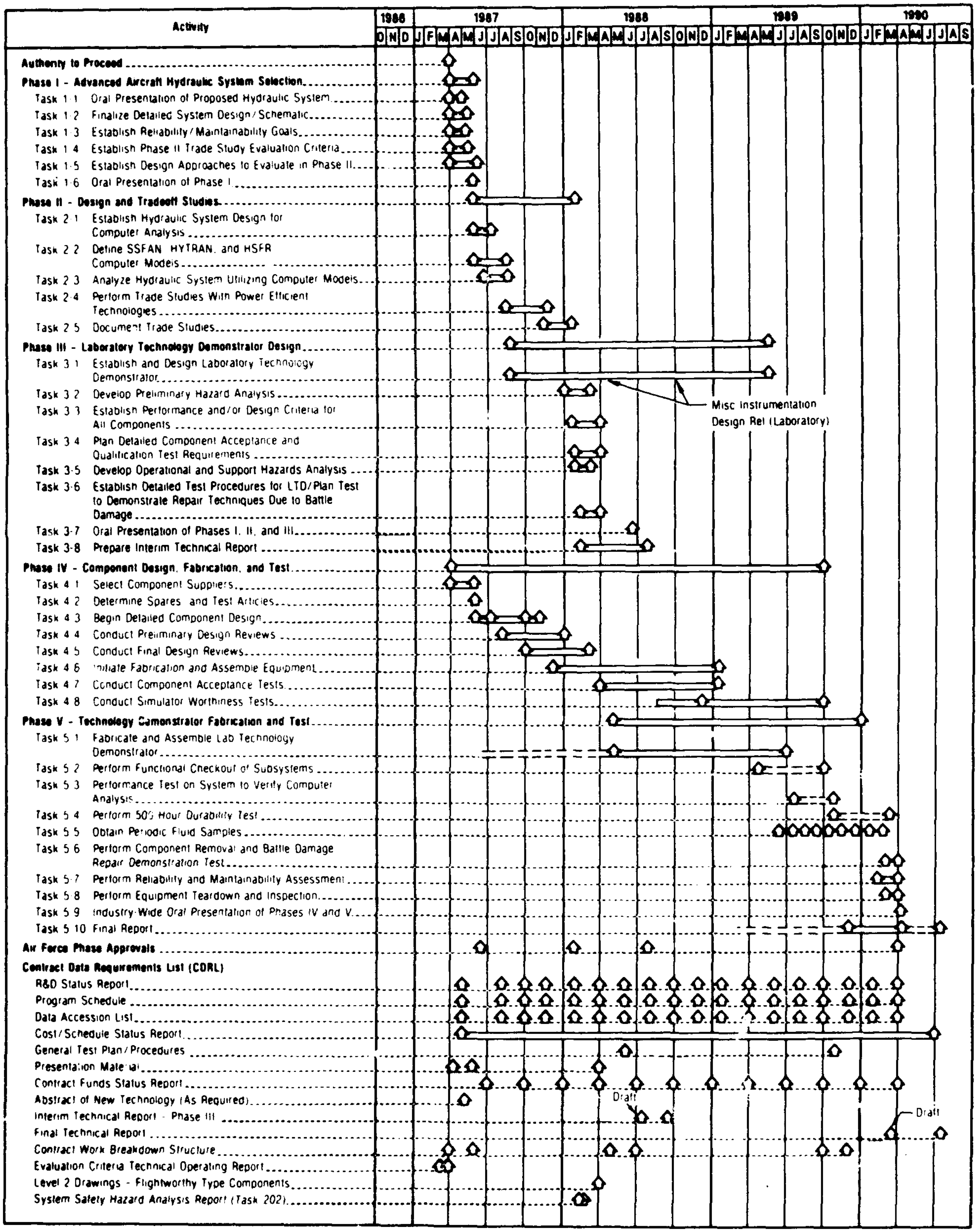


Figure 1. Program Master Schedule

SECTION II

PROGRAM DEVELOPMENT

Over the total program span, several events occurred which required redirection of certain program elements. These will be discussed in turn since explanation is required to remain in concert with program technical description provided in Volume I.

2.1 MCAIR FACILITY DEVELOPMENT

MCAIR proposed that the Laboratory Technology Demonstrator (LTD) be constructed adjacent to existing flight control iron birds in the MCAIR Flight Dynamics Laboratory. MCAIR provided, at no cost to the program, four, variable speed, 350 hp, electric drive motors for hydraulic pump power complete with an acoustically attenuated pump room with all attendant features. MCAIR also provided several actuation fixtures as well as a control room, a complement of instrumentation and controls, and other facility amenities. This facilities investment allowed contract funds to be applied almost totally to technical efforts to demonstrate nonflammable hydraulics technology while providing a facility which would be suitable for future IRAD needs.

2.2 NAVPRO SUBCONTRACT PRICE PROTECTION CLAUSE

MCAIR proposed that equipment subcontractor efforts should occur from the onset of program go-ahead (30 March 1987) as a result of a mature specification requirements base and the need for advanced go-ahead in order to meet total program schedule. Several purchase orders were placed, however in August 1987, NAVPRO ceased approval of standard purchase orders and put into effect a price protection clause. The clause was resisted by the suppliers and negotiations were required at all levels. Five months of the program were expended in resolving the issue and purchase order placement resumed in January 1988. Because many suppliers were continuing to work in the design phase anticipating an eventual resolution, it could not be predicted what effect this delay would eventually have on the total program. Indeed, most of the major equipments experienced significant delays in delivery to MCAIR which precluded timely performance testing.

2.3 PROGRAM DOWNSCOPING (FY88)

In February 1988, immediately after the NAVPRO price protection clause resolution, MCAIR was notified that there would be less funding for the fiscal year than planned and that program redirection would be required.

2.3.1 FY88 Funding Restrictions - In response to the funding shortfall, MCAIR proposed certain equipment procurement terminations and a 4-month program extension in order to achieve a balance with available funding. In addition some tasks were deferred until Fiscal 1989 in order to continue with reduced funding.

2.3.1.1 Metal Bellows Reservoirs - It was originally proposed that there would be two sources of reservoirs, Parker Aerospace and Metal Bellows. The complement of reservoirs would be used in the demonstrator and in the test programs at the pump suppliers. The Metal Bellows Corp. was subsequently acquired by Parker Hannifin, and due to the funds shortage, it was decided that the metal bellows reservoir be terminated for two reasons: (1) it was the smaller of the two units and (2) it was designed to use many of the detail parts (reservoir level sensing valve subassembly) designed for the larger unit being built by Parker Aerospace. Also the quantity (four) of the larger units was adequate for the program needs.

2.3.1.2 Canard Actuator (Parker Bertea/HR-Textron) - In the original proposal it was planned that Parker Bertea would be contracted to design and fabricate an actuator which suited the needs of the F-15 S/MTD Canard application. Due to a heavy commitment to advanced aircraft programs, Bertea was later unable to accept the subcontract, and negotiations were opened with HR-Textron. The FY88 funding shortage subsequently forced termination of the efforts to place a subcontract with HR-Textron.

2.3.1.3 Aileron Actuator (HR-Textron) - One of the conditions which was necessary for HR-Textron to accept the Canard actuator subcontract was termination of an aileron actuator subcontract which was to be performed at no cost. This procurement was terminated prior to negotiations for the Canard actuator and was not resumed due to loss of time.

2.3.1.4 LECHT Program Actuator - Because of the shortage of actuators resulting from the activity described above, a decision was made to refurbish the actuator originally supplied by Parker Bertea for the Low Energy Consumption Hydraulic Techniques program. This unit would subsequently assume the role of the Canard Actuator.

2.3.2 Deletion Of 350^{o}F CTFE Fluid - Concurrently, MCAIR was notified that a CTFE fluid capable of 350^{o}F continuous operation would not be forthcoming and that the contract would be modified to recognize this change. Several features of the program were keyed to having 350^{o}F fluid. A large complement of engine nozzle actuators were being fabricated in order to demonstrate high temperature operation as well as integral active cooling concepts. Decision and plans to construct a thermal chamber for the nozzle actuators was delayed until January 1989. Ultimately it was decided that the risk associated with possible dissociation of CTFE, from contact with heating elements, was too high and the effort was downscoped to working with one actuator with local heating.

2.4 SUBCONTRACTED EQUIPMENT ADDITIONS

Several changes occurred in response to the funding issue and other factors.

2.4.1 Garrett 40 GPM Hydraulic Pump - Early in the program it became apparent that high power pumps capable of acceptable long life using CTFE fluid were rapidly becoming high risk items. A small amount of funding had become available which would cover the procurement cost of one pump. The Garrett pump had certain design features which it was felt would offer enhanced performance with a low lubricity fluid such as CTFE. This procurement was initiated in September 1988, 18 months into the program.

2.4.2 MC 4 Way, 3 Position Solenoid Valve - Due to difficulties experienced by Parker Aerospace in obtaining titanium castings for their 4-way, 3-position solenoid valves, MC Aerospace Corporation provided a modified valve from the F-4 program so the LTD test could be started on schedule. This procurement was initiated in August 1989, 29 months into the program, and hardware was delivered in 8 weeks.

2.5 CTFE TOXICITY ISSUE AND CONSIDERATIONS

In September 1988, the Air Force Toxic Hazards Division of the Armstrong Aerospace Medical Research Laboratory held a briefing to disclose the preliminary results of toxicology experiments conducted the previous year on CTFE Hydraulic Fluid. The results were far from encouraging, with strong suggestions based on rodent studies that CTFE 3.1 fluid could be toxic to humans, possibly causing severe liver damage from chronic low level exposure to its vapor. After disclosure to the industry, a widespread reluctance to continue testing with the fluid occurred, and several of our subcontractors were unable to continue testing until the issue was resolved; some disassembling their test capability altogether.

Additional toxicology studies were planned with June 1989 being the target date for presentation of the risk assessment. Based on further testing, no link was established between metabolic response in laboratory rats and humans for the observed liver damage. To put the relative risk associated with the use of CTFE-based fluids in perspective, repeated dosing studies were performed with three conventional hydraulic fluids. All of these fluids produced significant toxicity in subchronic dosing situations, but the nature of the toxicity was different than for 3.1 fluid. The hydrocarbon-based fluids caused kidney damage of a kind associated with kidney cancer in male rats. Once again, this toxicity, which has been observed for many hydrocarbon based fluids including gasoline, is not believed to be a reliable predictor of human response.

In summary, all of the hydraulic fluids examined show some degree of toxicity in rats and would be likely to cause tumors in the liver or kidney of exposed rats if a lifetime cancer study were to be performed. Although the target tissue in the rodent is different for CTFE-based fluids than for the hydrocarbon-based fluids, neither of the two responses are considered likely to be predictive of human risk. The use of CTFE-based hydraulic fluids is therefore not expected to cause a significantly increased hazard compared to other in-use and proposed hydraulic fluids. However, because the rodent data do at least suggest the potential to be toxic, both CTFE-based and hydrocarbon-based hydraulic fluids should be handled prudently, with appropriate industrial hygiene precautions taken to minimize inhalation exposure as well as skin contact.

2.6 HYDRAULIC PUMP DEVELOPMENT

The single most recurring concern has been for the development of high power hydraulic pumps which would have an acceptably long life when operating on CTFE hydraulic fluid. Because CTFE lacks lubricity and has poor thermal transport properties, certain aspects of pump design proved to be a significant challenge. Late in 1988, a work around plan was formulated in anticipation of a significant delay in delivery of 40 gpm pumps.

2.6.1 Pump Work Around Plan - One particular pump design had previously been successful with CTFE, having accumulated a total of 3000 hours of operation at several facilities. This pump was built by Abex Corp and was capable of 8000 psi operation with a capacity of 15 gpm. A major technical element in the program was servo controlled variable pressure operation and a number of pumps of this type had been previously produced. Four constant pressure pumps which had been used on previous Air Force programs were allocated and returned to Abex for refurbishment and conversion to variable pressure units. These pumps would be used for performance and endurance testing of the LTD until such time that the larger capacity units became available. Their 15 gpm capacity was adequate for all of the actuator duty cycles in the primary flight control circuits, but required a reduction of the engine nozzle actuator stroke to reduce flow requirements in the utility system.

2.6.2 Pump Drive Motor Tachometers - Four 350 hp AC motors were used to drive the hydraulic pumps during the testing. The drive systems were supplied by Magnetek Louis Allis Drives and Systems. These drive systems had problems while powering hydraulic pumps; 11 failures occurred from April 1989 to February 1990. Three of these failures were attributed to excessive vibration in the tachometers. The other failures were attributed to poor workmanship and/or bad components on the part of the supplier. The vibration was generated by the overhanging hydraulic pumps. The encoder was coupled directly to the motor shaft and provided feedback for drive system control. This arrangement resulted in a 21.4 g acceleration versus the specification limit of 10 g's and motor vibrations of 0.5 in/sec peak versus the limit of 0.1 in/sec peak at the pump pulsation frequency. A belt coupled tachometer mounted on the motor base concrete mounting pad was used in place of the original encoder. Motor base vibration levels were recorded at 1.98 g's and 0.159 in/sec peak at the pump pulsation frequency.

2.7 PROGRAM TERMINATION IN FY 90

A stop work order was received on 21 March 1990 due to reductions in FY90 funding needed to complete the program. At this point, 324 hours of the intended 500 hours of endurance testing had been completed. Remaining funding was used to complete the final report and close out outstanding supplier commitments.

SECTION III

SYSTEMS DESCRIPTION

3.1 LABORATORY TECHNOLOGY DEMONSTRATOR (LTD) FACILITY

The LTD test facility resides in the MCAIR Hydraulic Flight Controls Laboratory along with the F-15 and AV-8B aircraft "Iron Birds." A pictorial overview of the LTD Facility is shown in Figures 2 through 22.

Because the LTD was developed solely with digital electronic control (control-by-wire) technology, it was not necessary to support equipment for relative location in the aircraft structure. Each actuator is supported in an individual fixture fitted in the most convenient location which can still simulate the hydraulic line length in the baseline aircraft.

The LTD simulates nearly all of the aircraft hydraulic flight control system functions. The flight control actuators are powered by the Primary Control (PC) pumps designated as PC-1 and PC-2. The engine nozzle and utility function actuator are powered by two Utility (UT) System pumps designated as UT-1 and UT-2. The utility system also served as backup system for the flight control actuators. The final system layout is illustrated in Appendix A.

3.1.1 Hydraulic Pump Room - Figure 7 shows the interior of the acoustically insulated pump room which houses four 350 horsepower drive motors for powering the three central hydraulic systems. Each drive is fitted with a Lebow Torque Sensor which measured pump input torque and speed. A remote control video camera is installed in the pump room for the convenience of the test operator.

3.1.2 Central Hydraulic Systems - Primary control central system equipment is mounted on a large distribution panel shown in Figure 8 and similarly in Figure 9 for the utility system. Even though position is not the same as placement in the aircraft, line lengths and elevation closely matched requirements. The power distribution lines are mounted on an overhead rail for convenience. All of the electronic controls and instrumentation equipment are located in a closed control room.

3.1.3 Flight Control Actuation Systems - The primary flight control actuators in the left-hand (PC-1) system represent a stabilator, a flaperon, a rudder, and a canard. The primary flight control actuators in the right-hand (PC-2) system represent a stabilator, a rudder and a flaperon (flow simulator valve).

The utility system's heaviest loads are a left-hand and right-hand engine nozzle actuation system. The left-hand engine nozzle system consists of two upper divergent flap actuators, two lower divergent flap actuators, two convergent flap and two reverser vane actuators. The right-hand nozzle system consists of two reverser vane actuators, two arc valve actuators divergent flap and convergent flap control valves with flow restrictors to simulate the actual load. This equipment was supplied by MOOG and Parker Bertea Aerospace. Additional utility functions were provided by leading edge flap actuation system powered by a variable displacement hydraulic motor provided by Sundstrand (an IRAD program), an engine inlet diffuser ramp actuator supplied by Cadillac Gage as well as several other components provided by the many equipment suppliers. An equipment description is provided in Volume I.

Figure 2. Laboratory Technology Demonstrator - R/H

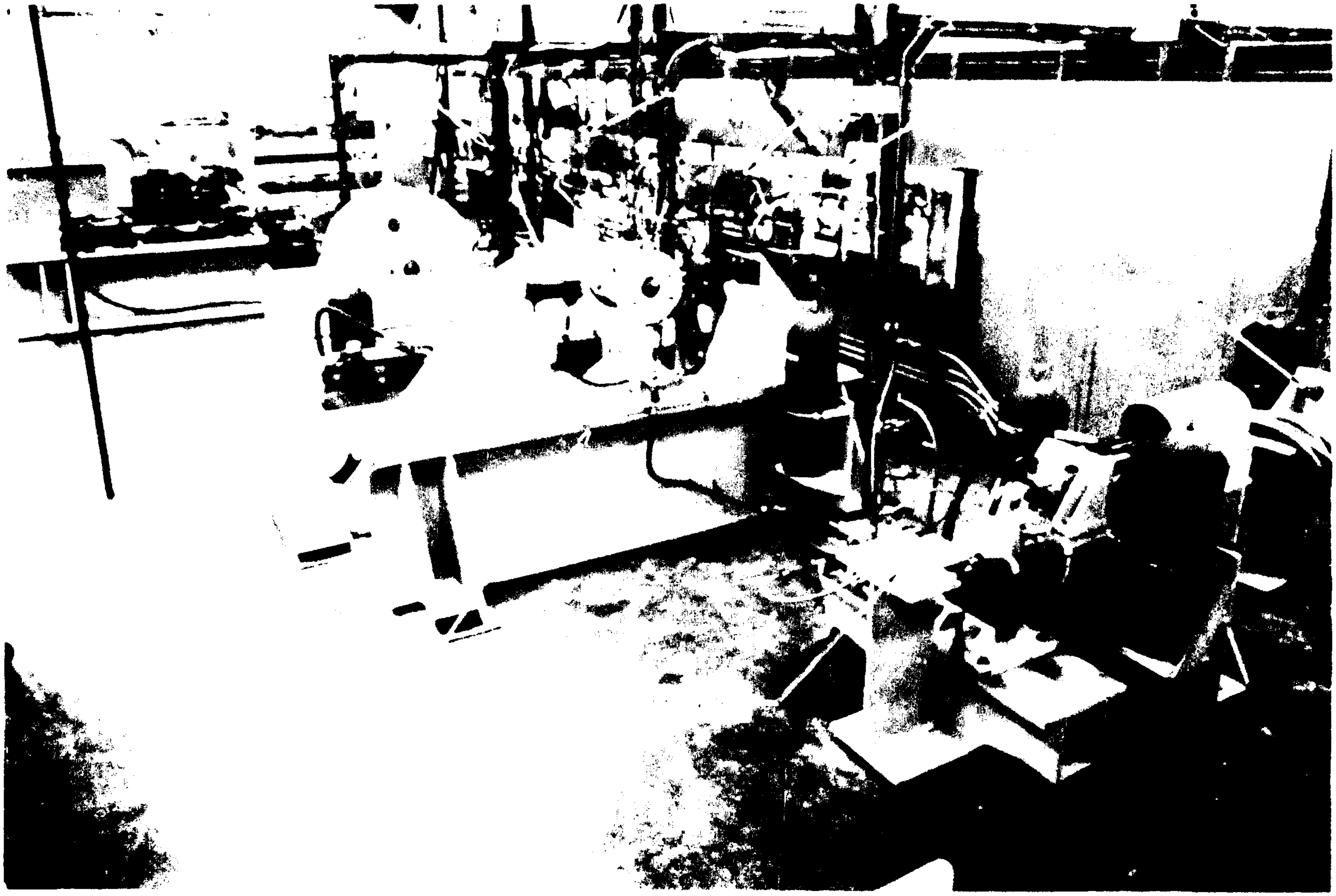


Figure 3. Laboratory Technology Demonstrator - L/H

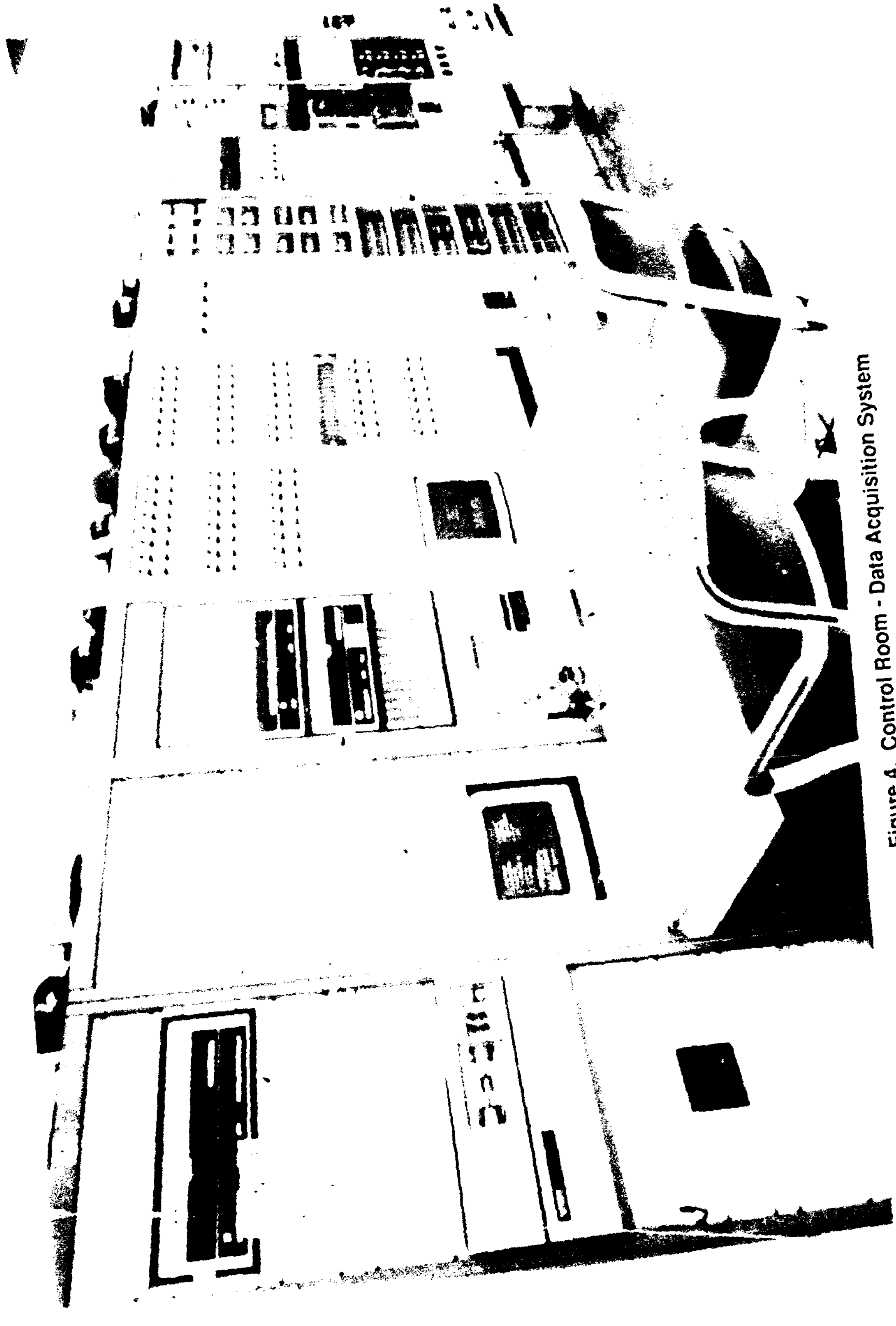


Figure 4. Control Room - Data Acquisition System

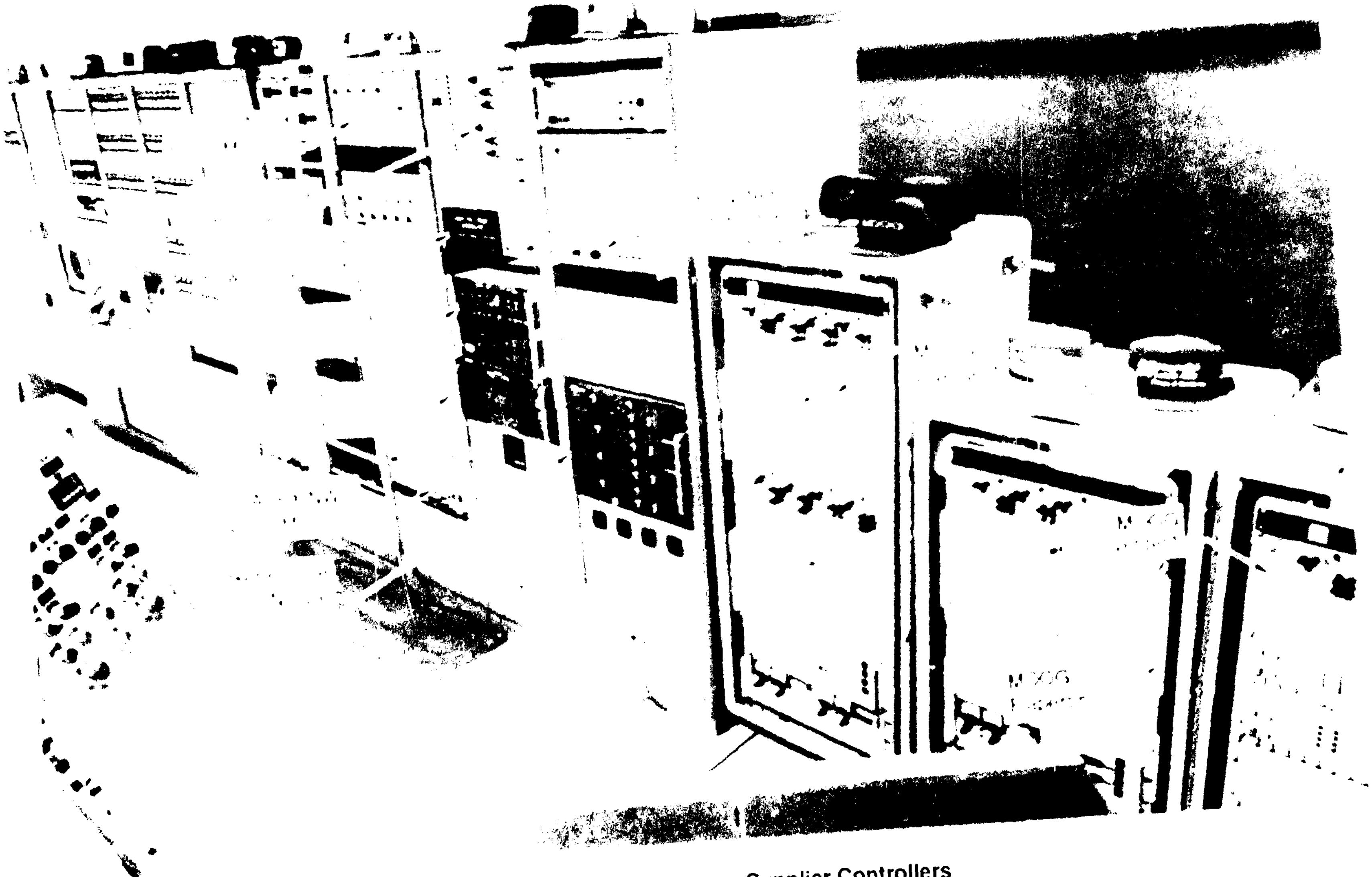


Figure 5. Control Room - Supplier Controllers

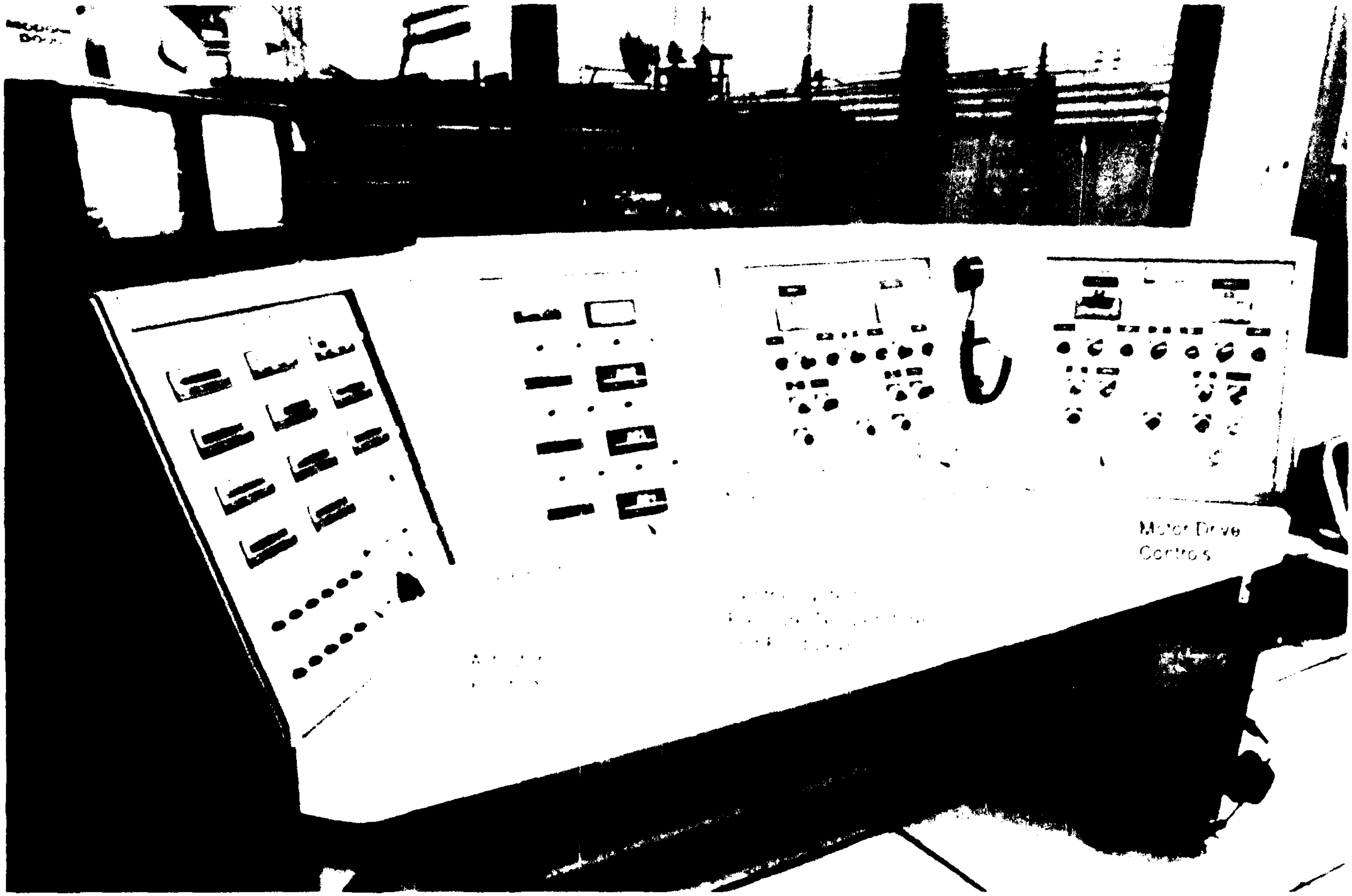


Figure 6. Control Room - Main Control Panel

Figure 7. Acoustic Pump House and Drive Motors

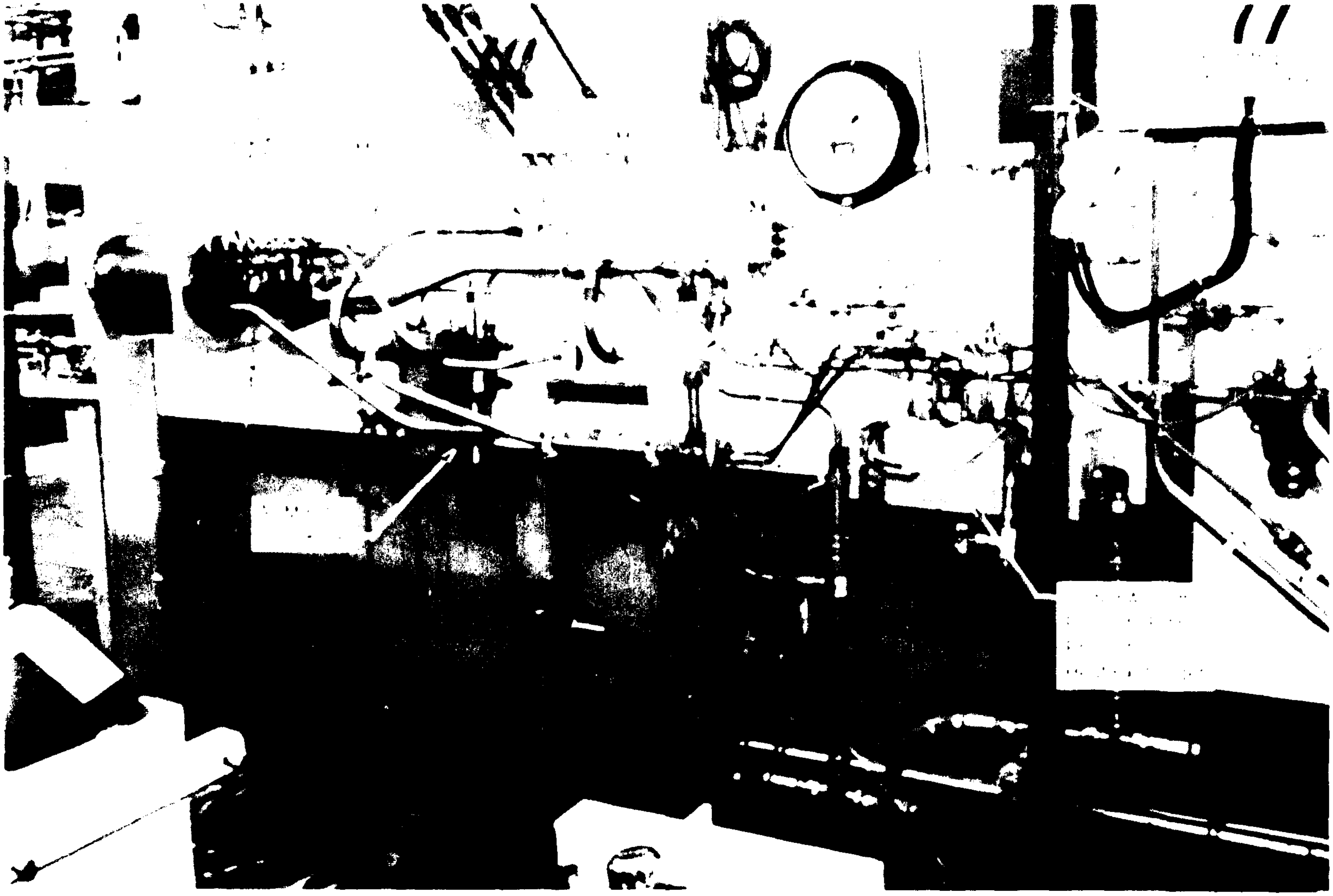


Figure 8. Primary Controls Central System

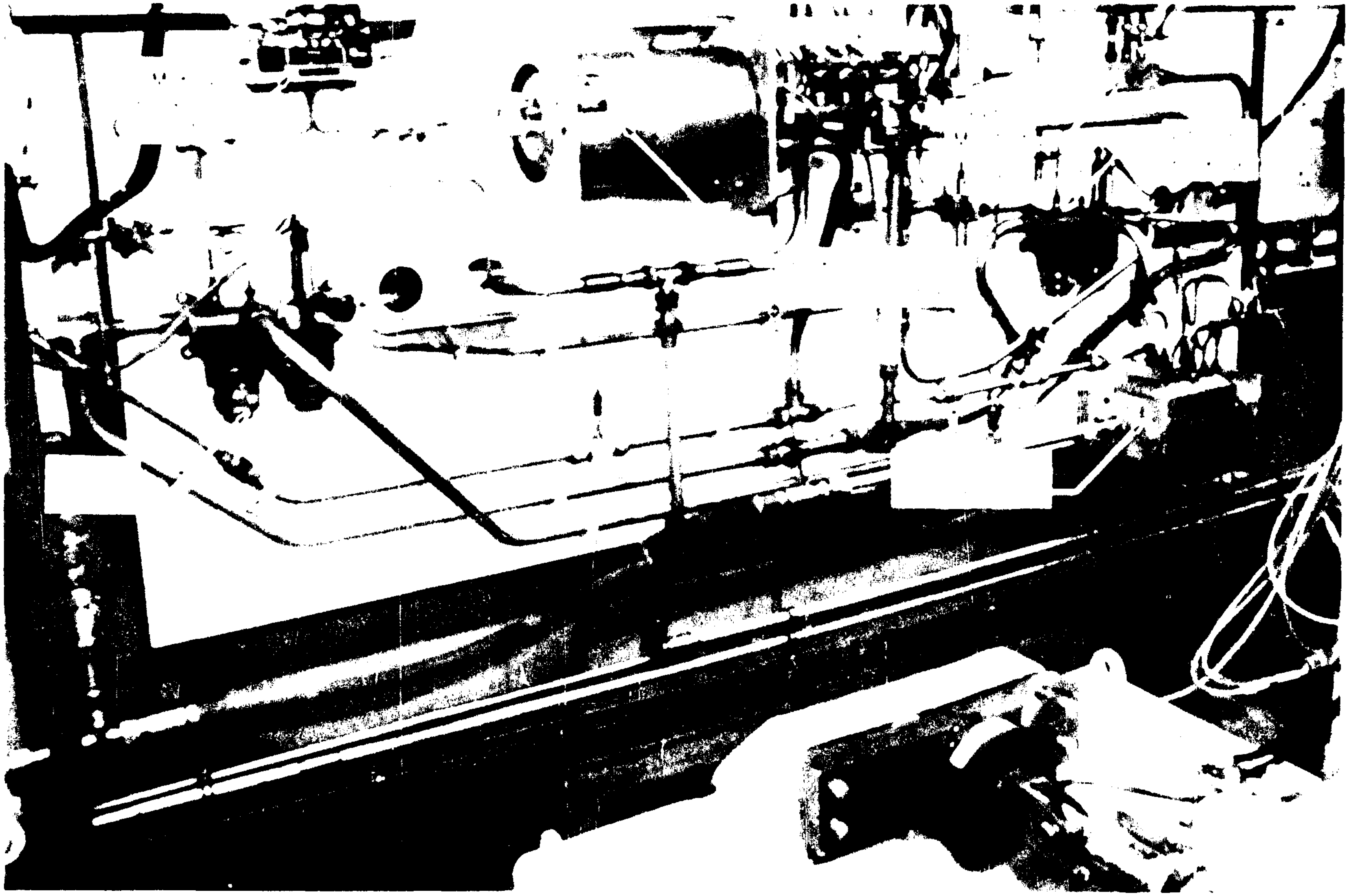


Figure 9. Utility Central System

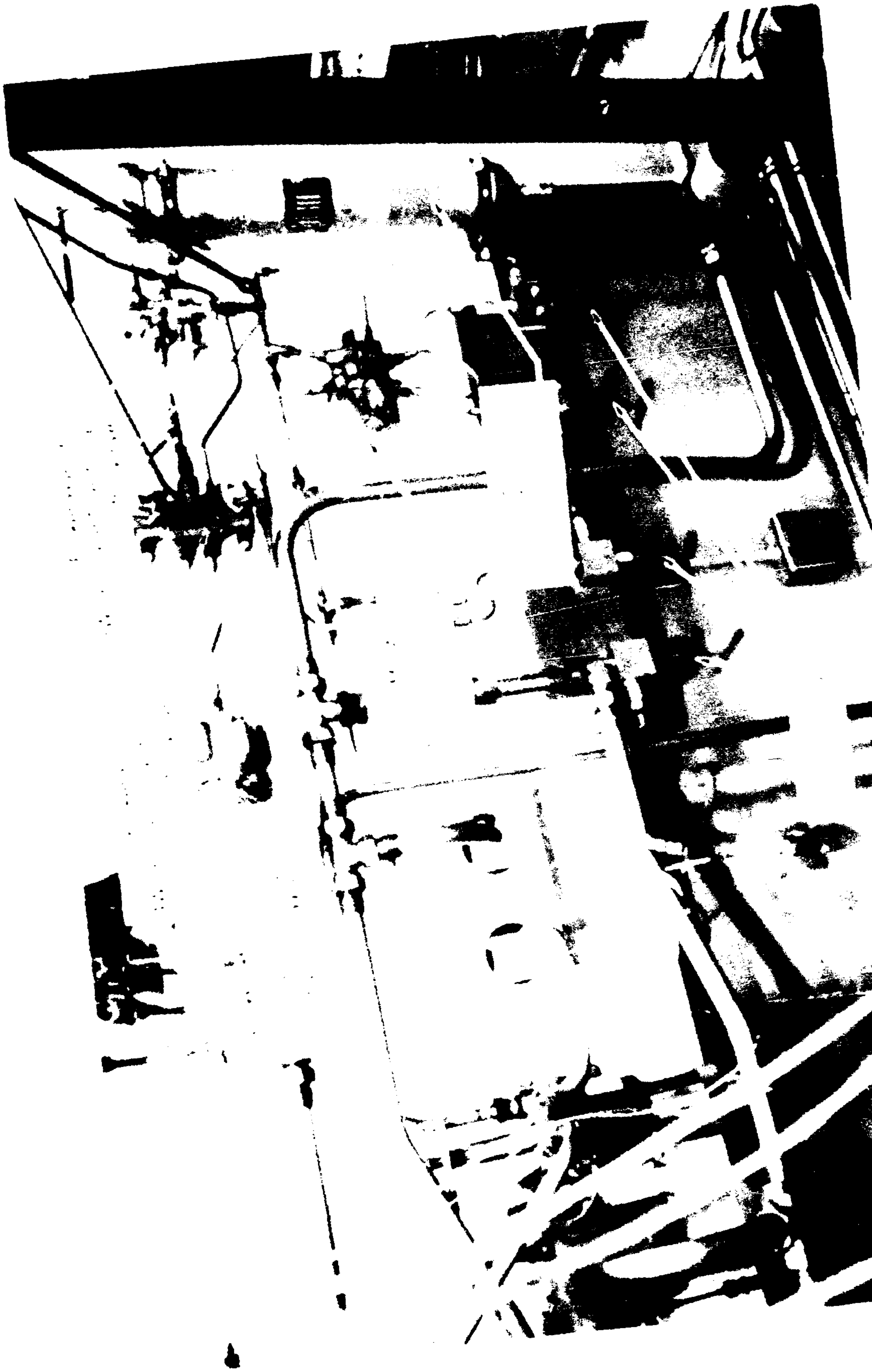


Figure 10. JFS/Gun Drive and Utility Functions

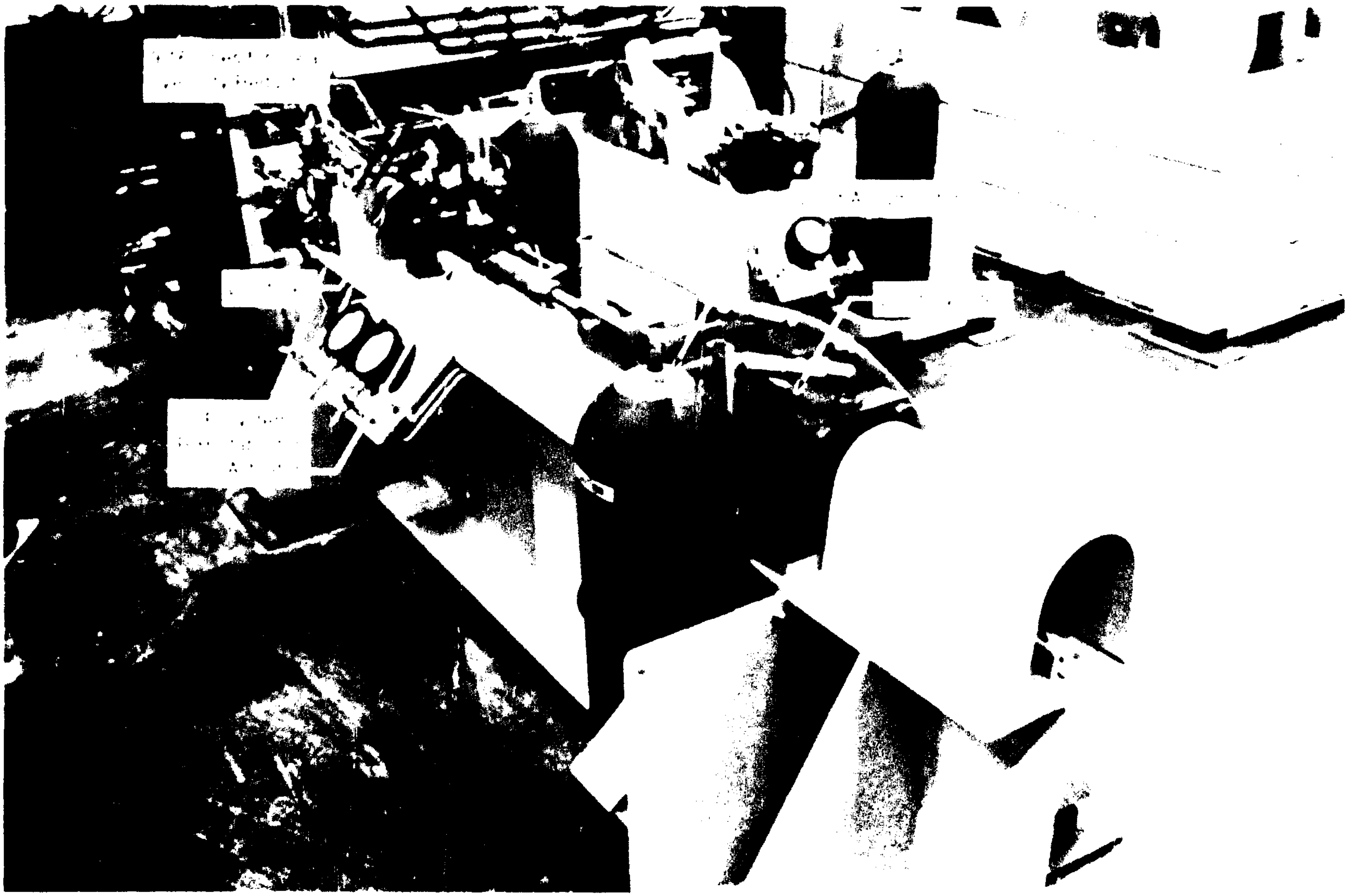


Figure 11. E-Systems – R/H Stabilator Installation

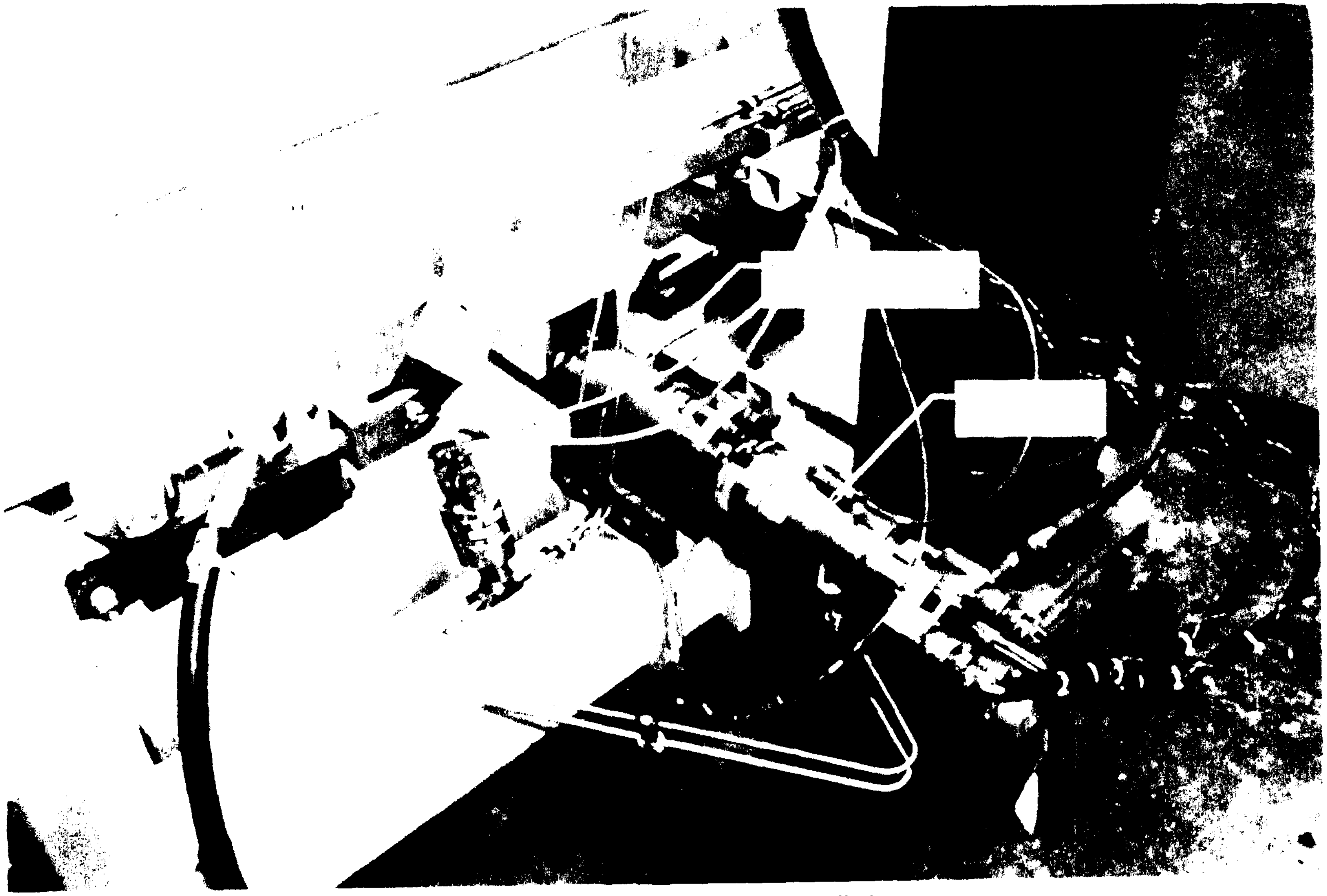


Figure 12. HR Textron - R/H Rudder Installation

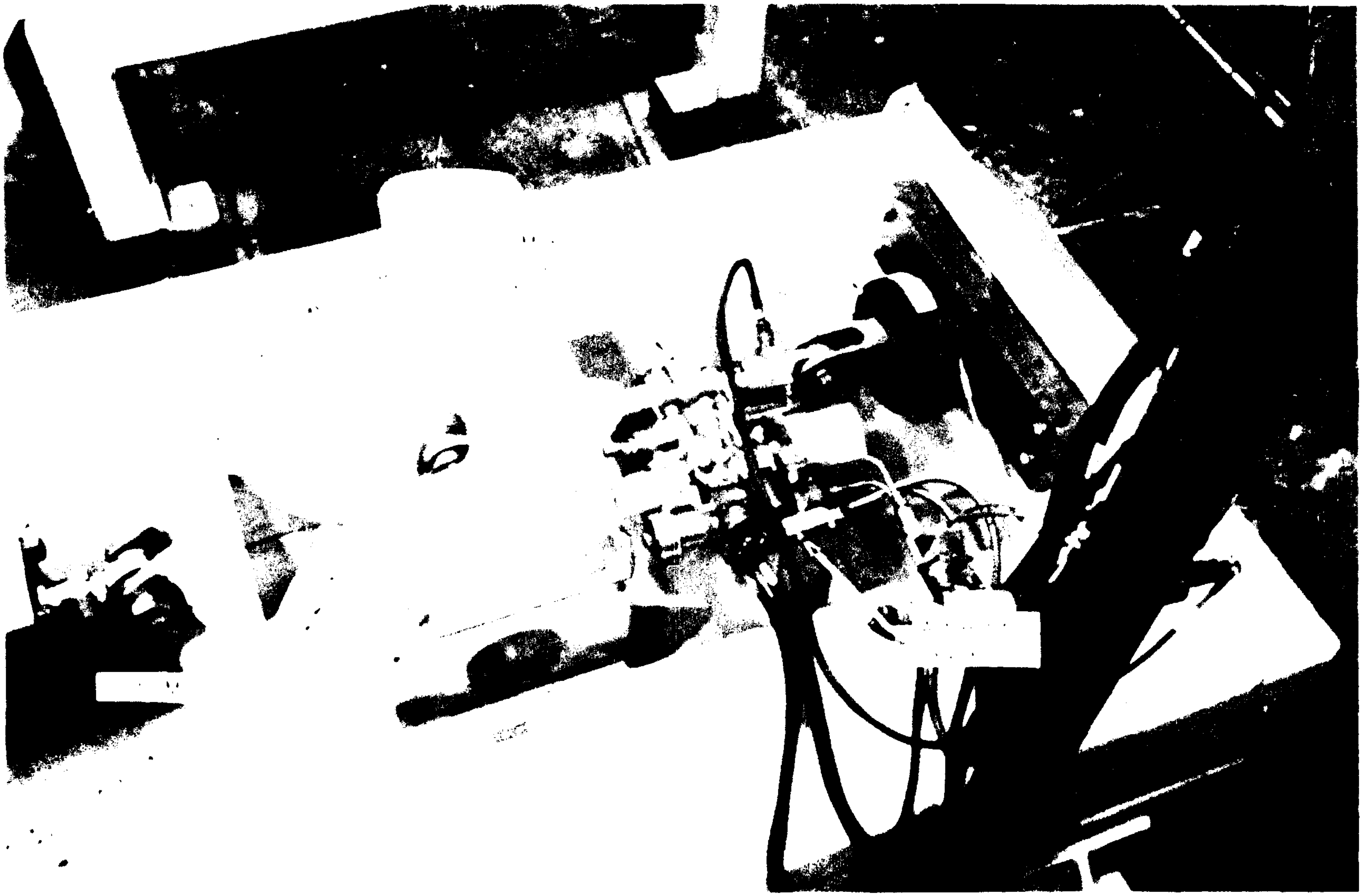


Figure 13. MOOG - Flaperon Installation

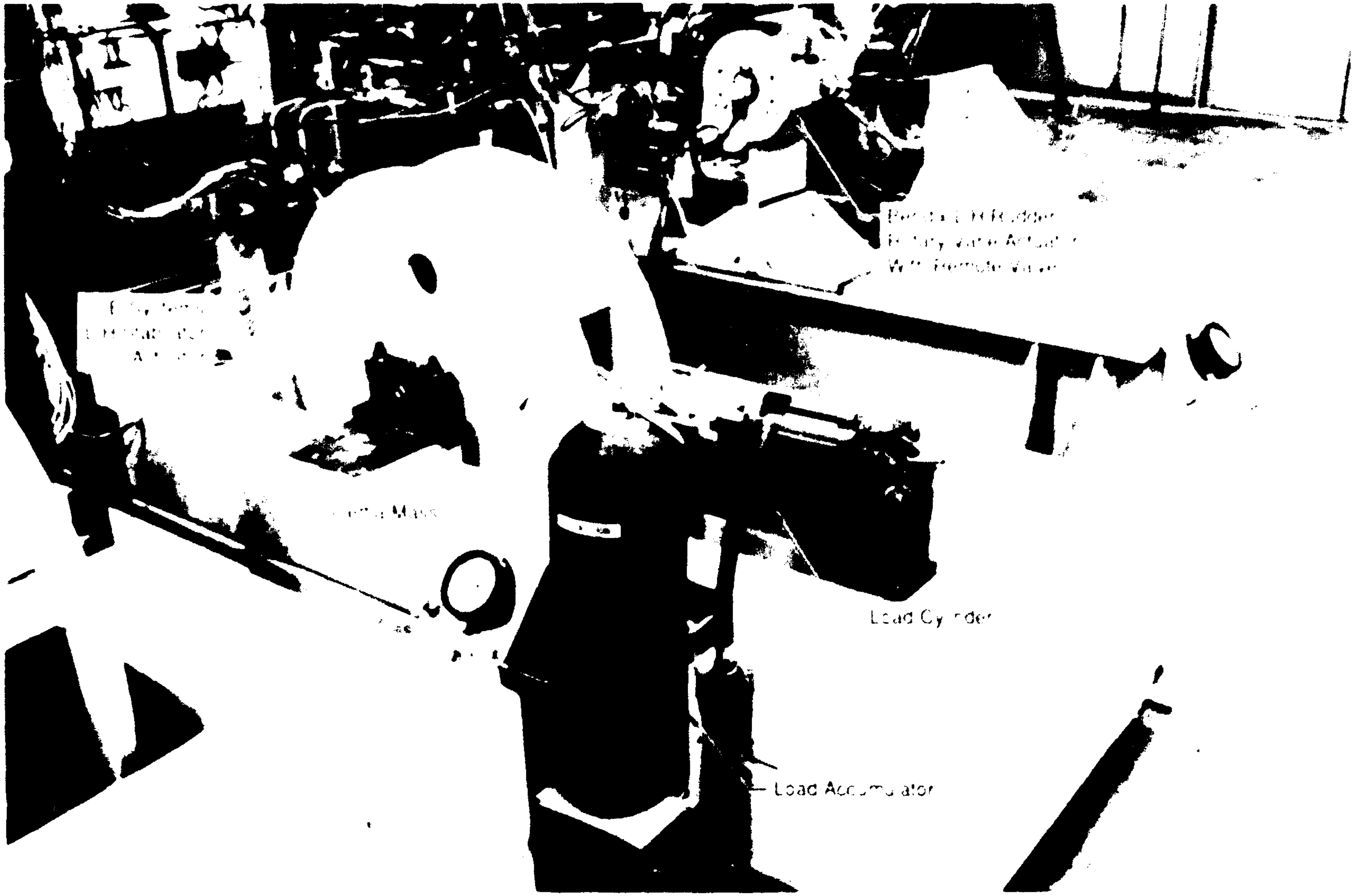


Figure 14. L/H Stabilator and Rudder Installations

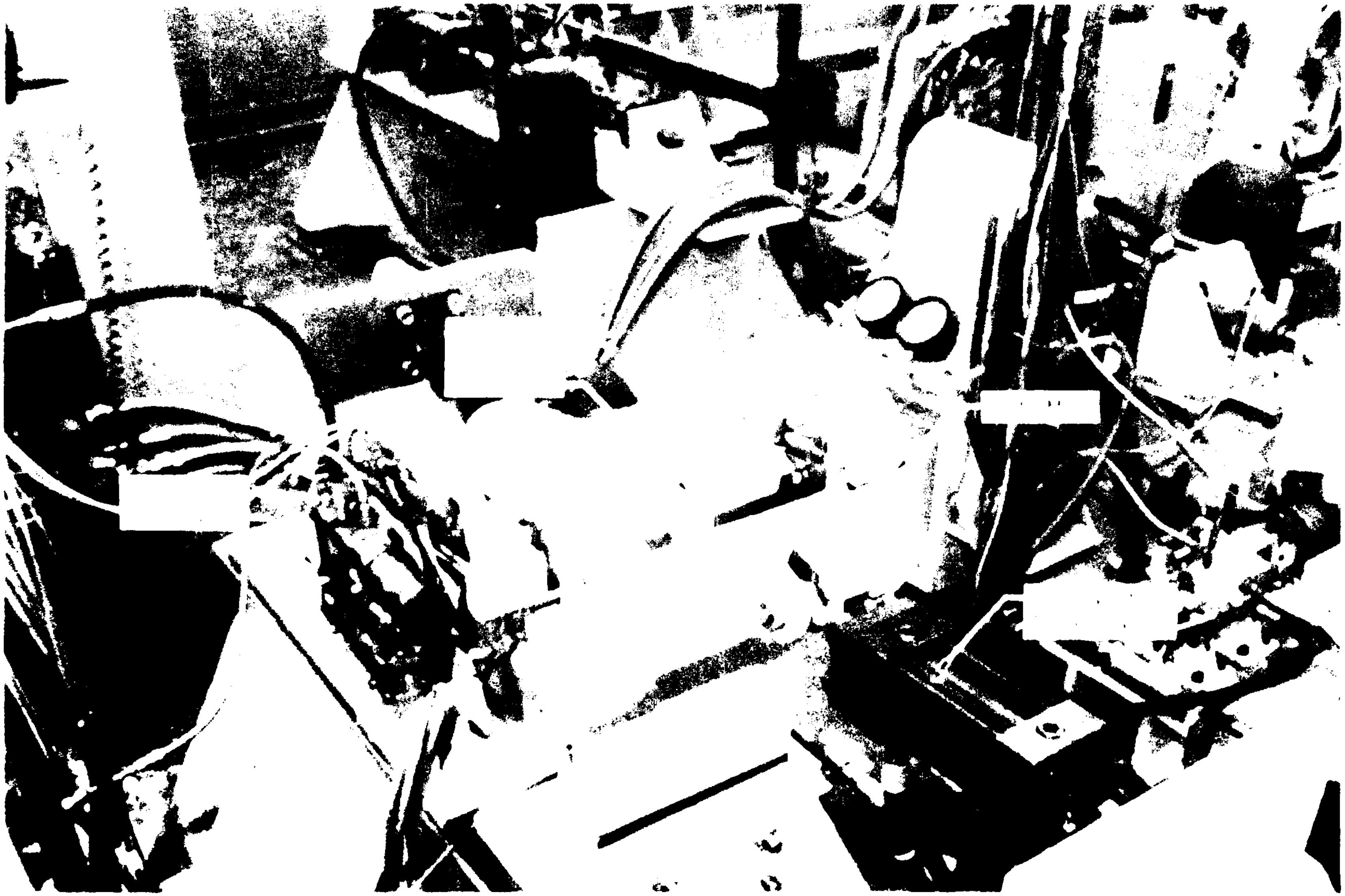


Figure 15. Bendix - L/H Rudder Installation

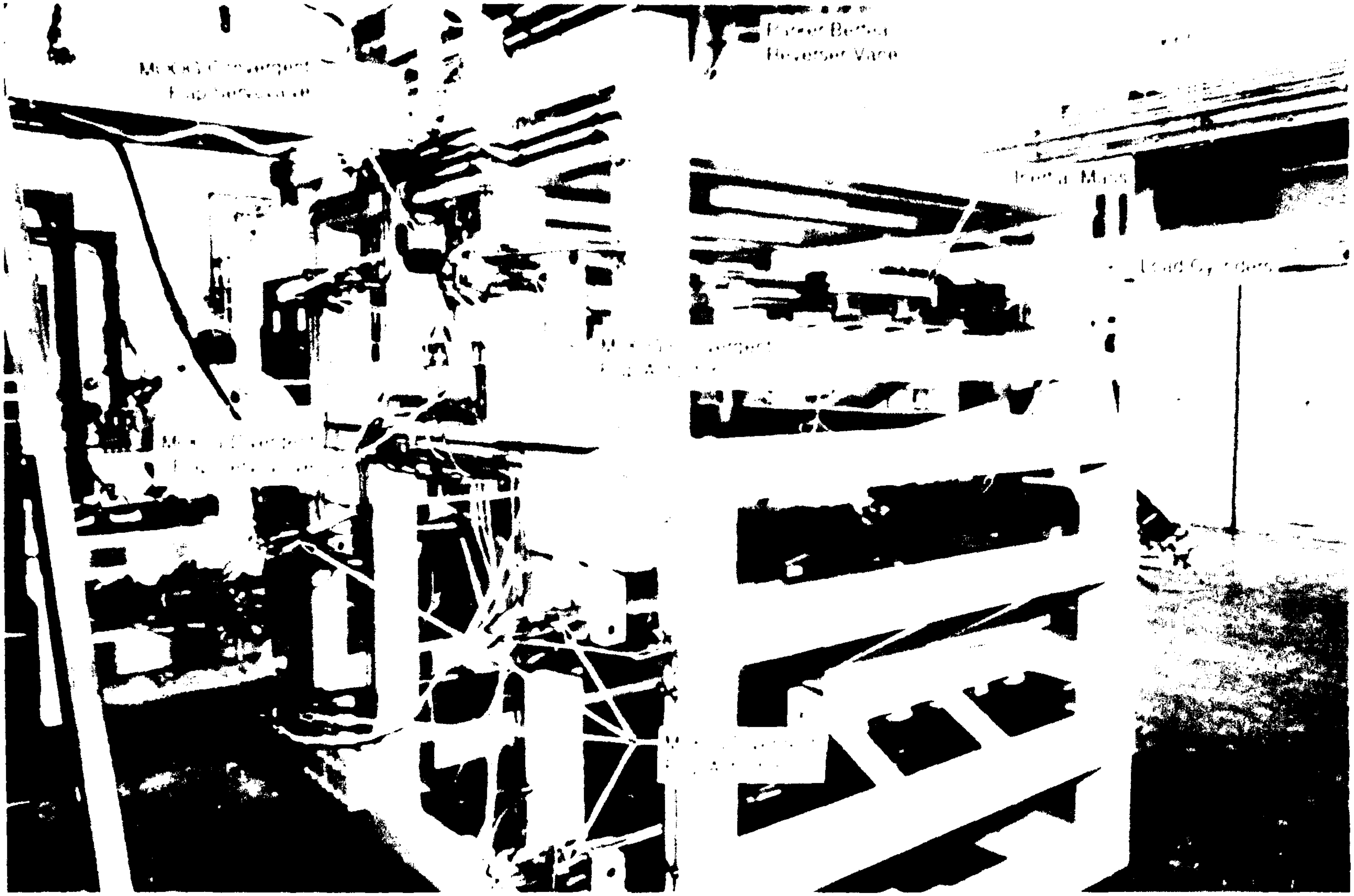


Figure 16. L/H Engine Nozzle System Installation

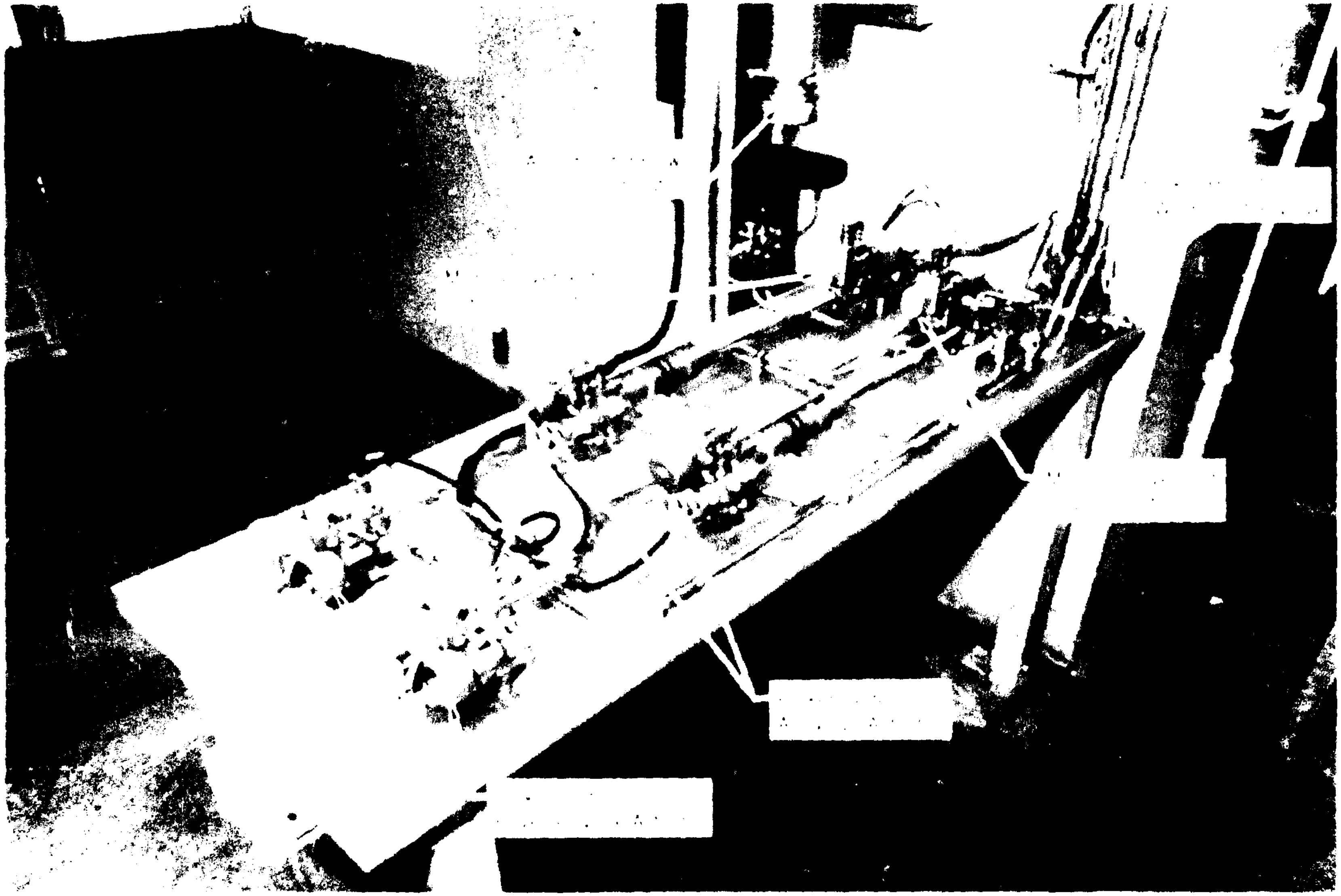


Figure 17. R/H Engine Nozzle Actuation Simulator

Figure 18. Engine Nozzle Actuator Thermal Enclosure

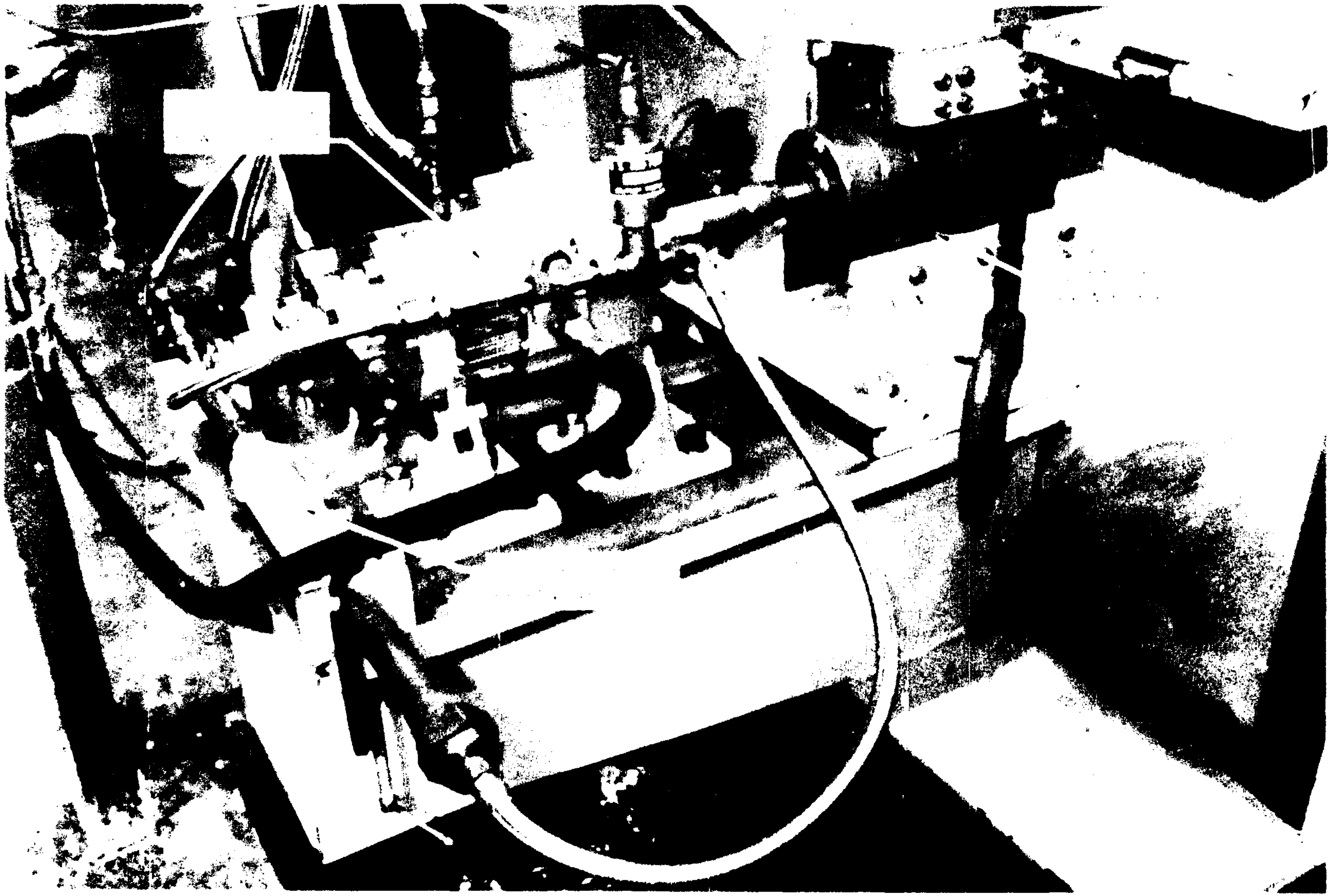


Figure 19. Sundstrand - Leading Edge Flap Installation

Figure 20. Cadillac Gage - Diffuser Ramp Installation

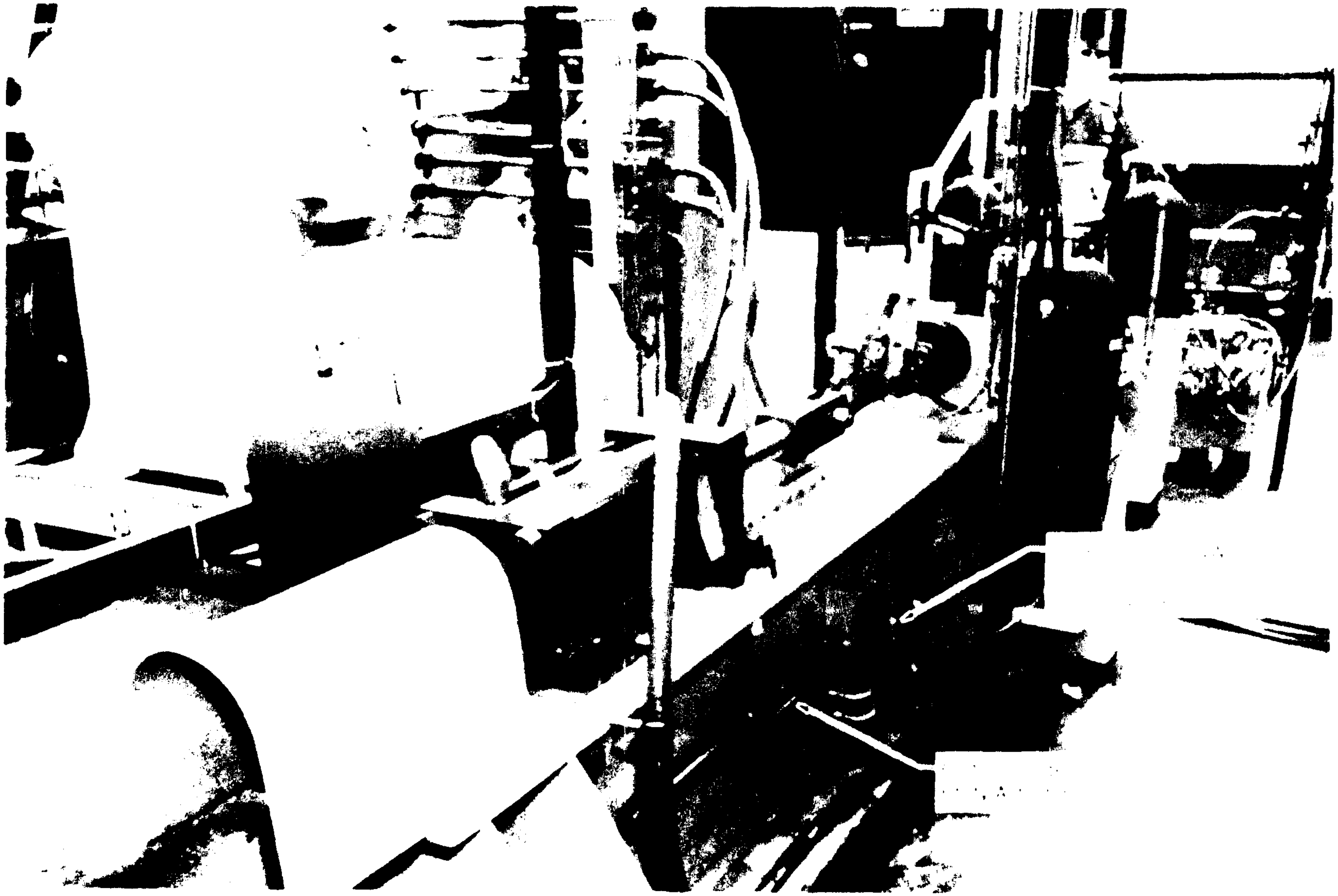


Figure 21. Cadillac Gage - Utility Actuator Installation

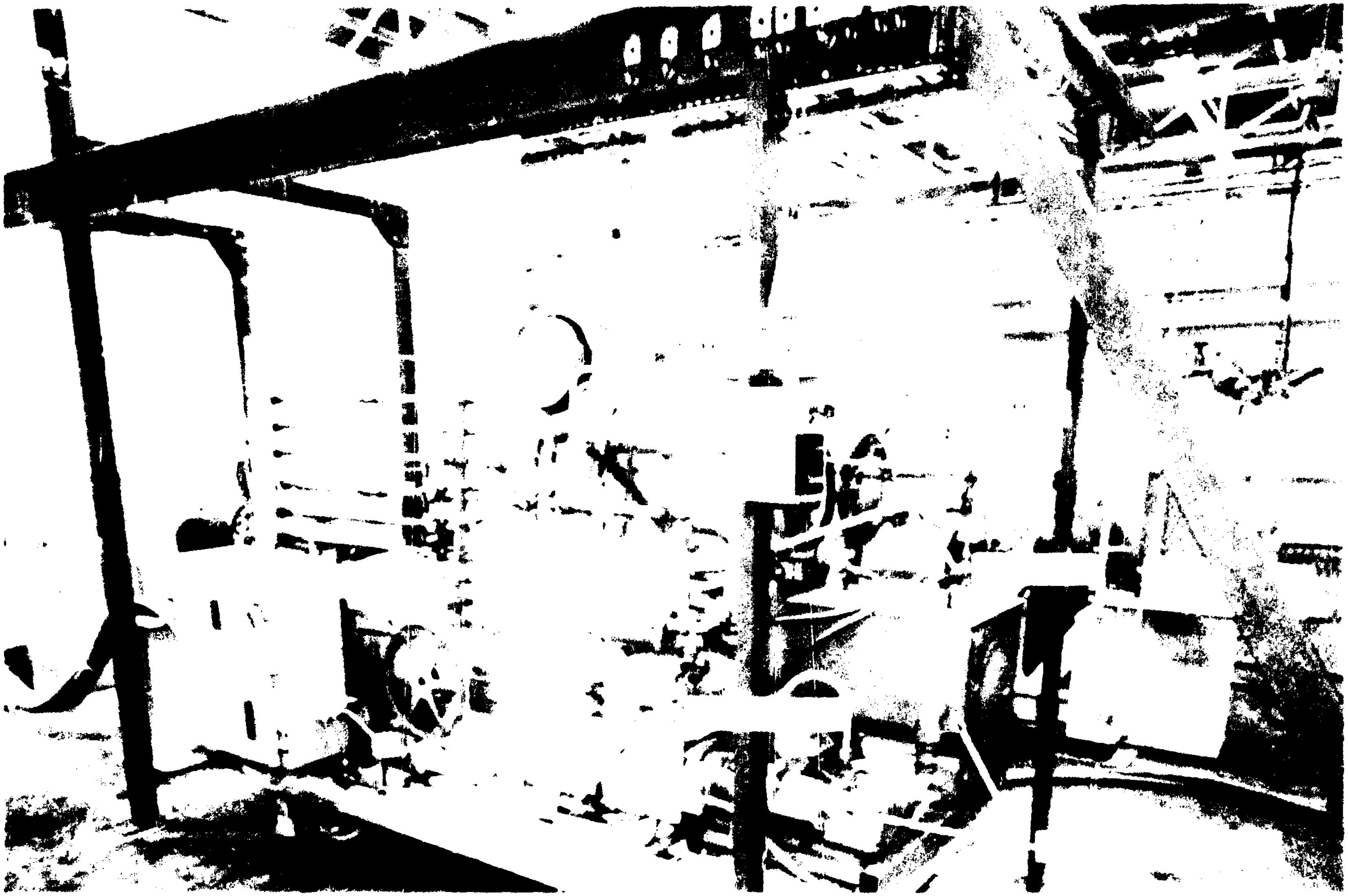


Figure 22. 8000 psi Auxiliary Power Supply

3.2 ACTUATION SYSTEMS TEST FIXTURES

Twelve test fixtures were constructed of structural steel and individually tailored to support the various actuators or actuation systems. Some fixtures were designed to provide a load on the actuator with respect to stroke position while others duplicated the dynamic inertial/spring characteristics of the flight control surface and aircraft backup structure. Figures 23 and 24 show the structural characteristics of the various fixtures. Air load was simulated by two gas over fluid, bladder separated accumulators. Each was connected to one side of a load cylinder to simulate a linear load spring. Much difficulty was experienced with this approach. Since zero piston leakage was needed in the loading cylinders, a high frictional load resulted from the tight piston seals. Relaxation of the seal leakage reduced the friction load but resulted in migration of fluid from one accumulator to the other under certain conditions. This resulted in load unbalance but the overall effect on the endurance cycling was not a problem. The migration was cumulative and the load systems were balanced periodically.

Aircraft Actuator	Load Cylinder Attach Config	Inertia Size	Load @ Stroke Position End Points
R/H Stabilator	Direct linear		-43,000Lb @ 3.91in / 39,000Lb @ -3.9in
R/H Rudder	Rotating inertia		+ -22,000 in -Lb. @ + -30°
L/H Diffuser	Direct linear		-5,000Lb @ 0.0 in / 21,000Lb @ 10.18in
L/H Flaperon	Rotating inertia	1.93 Slug-Ft^2	-23,400Lb @ .71in / 18,500Lb @ -.71in
L/H Leading Edge Flap	Direct linear		+ -120,000 in-Lb @ + -15°
L/H Stabilator	Rotating inertia	36.0 Slug-Ft^2	-43,000Lb @ 3.9in / 38,000Lb @ -3.91n
L/H Rudder	Rotating inertia	0.43 Slug-Ft^2	+ -22,000in-Lb @ +-30°
L/H Nozzle			
Divergent Flap	Direct linear	94.5 Lbm	8,300Lb @ 15.2 in/ 2,900Lb @ 0.0in
Convergent Flap	Direct linear	84.5 Lbm	17,400Lb @ 10.03in / 5,400Lb @ 0.0in
Reverser Vane	____________	25.1 Lbm	--
L/H Canard	Rotating inertia	36.5 Slug-Ft^2	-22,800Lb @ 7.7in / 36,900Lb @ 0.0in

Notes: Negative forces are compression.
Negative positions are ram positions retracted from neutral position.
Neutral positions are not necessarily zero force positions.

Figure 23. Aircraft Inertia and Load Sizes

Aircraft actuator	Back-up Structure	Surfaces
R/H Stabilator	-----------	----------
R/H Rudder	-----------	----------
L/H Diffuser	-----------	----------
L/H Flaperon	3.69×10^6 Lb / in	2.08×10^6 Lb / in
L/H Leading Edge Flap	-----------	----------
L/H Stabilator	1.20×10^6 Lb / in	0.338×10^6 Lb /in
L/H Rudder	4.7×10^6 in - Lb / radian	-----------
L/H Nozzle		
Divergent Flap	0.79×10^6 Lb / in	0.02×10^6 Lb / in
Convergent Flap	0.62×10^6 Lb / in	0.05×10^6 Lb / in
Reverser Vane	0.27×10^6 Lb / in	---------
L/H Canard	1.20×10^6 Lb / in	0.34×10^6 Lb / in

Figure 24. Aircraft Structural Spring Rates

3.3 FLUID POWER DISTRIBUTION ELEMENTS

Three tubing manufacturers supplied the odd sized titanium tubing required in the high pressure lines. The tubing was supplied to the standard being used in the Rockwell, Reference 2, High Pressure Hydraulic Distribution Elements development program. A wide variety of 8000 psi fittings from the entire segment of the industry were used in assembling the LTD. The approach taken was to have each supplier supply one (or more) odd line size connector group as well as the tooling required for installation. The 8000 psi titanium tubing sizes that were used in the program are shown in Figure 25.

Suppliers	Tubing O.D.	Wall Thickness
Haynes International Inc.	0.3125" (5/16)	0.034"
Haynes International Inc.	0.4375" (7/16)	0.049"
Haynes International Inc.	0.6875" (11/16)	0.076"
Nikko Wolverine Inc.	0.5625" (9/16)	0.063"
Superior Tube Co.	0.1875" (3/16)	0.021"

NOTES: All tubing was Ti 3Al-2.5V per AMS4944

Figure 25. 8000 psi Tubing Wall Schedule

3.3.1 Rosan Fluid Port Adapters - In order to integrate ODD-EVEN line sizing for 8000 psi design, the equipment had to have compatible odd sized fluid ports. This was accomplished with the cooperation of the Rosan Company. The total quantity of odd sized fittings required for the complete complement of subcontracted equipment was procured as a single order along with the porting and installation tools which were shared by each of the equipment subcontractors. This approach is recommended for any prototype or limited production program to minimize cost.

3.3.2 8000 psi Fittings - In order to make odd sized fittings affordable for the program, it was necessary to limit the configurations to a minimum and have each supplier concentrate their efforts on one of the odd sizes. Because of the variety of separable fitting attachment techniques used, the demonstration included internally swaged (i.e. Resistoflex, Aeroquip) and externally swaged (i.e. Deustch, Aeroquip Linair) fittings and tooling. A list of the suppliers and the fittings they supplied are shown in Figures 26 and 27. Permanent line joints used Raychem Cryofit, Deutsch Permaswage and Aeroquip Linair Rynglok.

3.4 LABORATORY CONTROL SYSTEMS

The control system for the LTD is integrated in the control room shown in Figures 4 and 5. The control system is two independent systems: pump drive motors and actuation systems. The actuator duty cycle and pump control is directed by a microprocessor and various electronic controllers supplied by each of the actuator subcontractors. The four pump drive motors are operated from the main control panel, totally independent of the other controllers.

3.4.1 Actuation Duty Cycle and Pressure Control - The core element of the control system is a 14-channel microprocessor which was developed to generate the actuator duty cycle and control the pressure output of the four variable pressure hydraulic pumps. Command signals are provided for each of the electronic controllers used to drive the various actuation systems. In turn, the actuator valve position was monitored by the microprocessor and summed through a pump pressure control algorithm. The resulting pressure command was then directed to the pump electronic controller.

The actuation duty cycle was derived from predicted flight control surface activity for reduced stability and unstable aircraft. These data had been requested from the Air Force for this program and consisted of percent load and stroke, frequency of occurrence and duration for several surfaces. These duty cycles were compared with flight control surface activity taken from the F-15 S/MTD flight simulator. The F-15 data base included takeoff and climb, some cruise and descent to a landing. The approach taken was to merge the two data bases to produce the most severe combined spectrum, generally using the S/MTD for takeoff, climb, descent and landing and the predicted (unstable aircraft) duty cycle for cruise and combat. The actuator cycling rate was then increased so that 500 hours of laboratory test time would represent 2000 hours of flight time.

Suppliers	Description	Size
Aeroquip	connector, tube coupling, male reducer	beam (-06) / tube (-04)
"	connector, tube coupling, male reducer	beam (-10) / tube (-06)
"	connector, tube coupling, female	(-04)
"	connector, tube coupling, female	(-06)
"	connector, tube coupling, female	(-08)
"	connector, tube coupling, female	(-10)
"	connector, tube coupling, female	(-16)
"	connector, tube coupling, female reducer	beam (-06) / tube (-04)
Aeroquip	connector, tube coupling, female reducer	beam (-08) / tube (-06)
(Linair)	connector, tube coupling, male reducer	beam (-11) / tube (-07) *
"	connector, tube coupling, female	(-05)
"	connector, tube coupling, female	(-11) *
"	reducer tee, dynamic beam, permanent	beam (-05) (-03) / tube (-09)
"	tee, dynamic beam, permanent on run	(-05)
(Linair)	tee, dynamic beam, permanent on run	(-11) *
Airdrome	tee, dynamic beam, permanent on run	(-03)
"	tee, dynamic beam	(-08)
"	tee, dynamic beam	(-10)
"	tee, dynamic beam	(-16)
"	connector, tube coupling, female	(-11)
Airdrome	reducer, swivel nut to male	(-11) / (-07)
Deutsch	tee, dynamic beam, permanent on run	(-03)
"	tee, dynamic beam, permanent on run	(-07)
"	connector, tube coupling, female	(-07)
"	reducer, swivel nut to male	(-05) / (-03)
Deutsch	reducer, swivel nut to male	(-070 / (-05)
Krueger	connector, tube coupling, female	(-11)
Krueger	connector, tube coupling, female	(-07)
Resistoflex	connector, tube coupling, female	(-03)
Sierracin	reducer, swivel nut to male	(-07) / (-03)
Sierracin	connector, tube coupling, female	(-09)

* (-11) mates with Linair male/female beam only

A: Airdrome separable fitting - dual seal (welded)
B: Aeroquip / Resistoflex separable fitting - dynatube (internal swage)
C: Aeroquip (Linair) separable fitting - arc seal (Rynglok)
D: Deutsch separable fitting - lip seal / permaswage (external swage)
E: Krueger separable fitting - 'K' seal (welded)

Figure 26. System Fittings and Suppliers

Suppliers	Description	Size
Aeroquip	adapter, dynamic beam (male) to pipe	beam (-03) / (-02)
"	adapter, dynamic beam (male) to pipe	beam (-05) / (-04)
Aeroquip	adapter, dynamic beam (male) to pipe	beam (-04) / (-04)
Aerofit	reducer, dynamic beam (male) to AN	beam (-05) / AN (-04)
"	reducer, dynamic beam (male) to AN	beam (-07) / AN (-04)
"	reducer, dynamic beam (male) to AN	beam (-09) / AN (-04)
"	reducer, dynamic beam (male) to AN	beam (-11) / AN (-04)
"	reducer, dynamic beam (male) to AN	beam (-11) / AN (-08)
"	reducer, dynamic beam (male) to AN	beam (-16) / AN (-12)
"	adapter, dynamic beam (male) to flareless	beam (-03) / (-04)
"	adapter, dynamic beam (male) to flareless	beam (-05) / (-06)
"	adapter, dynamic beam (male) to flareless	beam (-07) / (-08)
"	adapter, dynamic beam (male) to flareless	beam (-09) / (-10)
"	adapter, dynamic beam (male) to flareless	beam (-11) / (-10)
"	tee, dynamic beam boss (-04) on side	(-03)
"	tee, dynamic beam boss (-04) on side	(-04)
"	tee, dynamic beam boss (-04) on side	(-05)
"	tee, dynamic beam boss (-04) on side	(-07)
"	union, dynamic beam	(-05)
"	union, dynamic beam	(-07)
"	union, dynamic beam	(-09)
Aerofit	union, dynamic beam	(-11)
Linair	tee, Rynglok (-04) boss on side	(-11) / (-11)
"	tee, Rynglok (-04) boss on side	(-11) / (-10)
"	tee, Rynglok (-04) boss on side	(-11) / (-10)
"	connector, dynamic beam (8000 psi)	(-04)
"	connector, dynamic beam (8000 psi)	(-06)
Linair	connector, dynamic beam (8000 psi)	(-10)

NOTES: Odd sizes are 8000 psi rated fittings
Even sizes are 4000 psi qualified fittings

Figure 27. Special Fittings and Suppliers

The control system block diagram is shown in Figure 28. The operational duty cycles, based on Appendix B, for the PC and Utility systems are a programmable input file in the microprocessor. Figures 29 and 30 show a portion of the duty cycle which was used in the test efforts. The flight actuator servovalve position was utilized as the input signal to the microprocessor for computation of the variable pressure pump command.

A schematic of the pump pressure control algorithm is presented in Figures 31 and 32, for the PC and Utility systems respectively. The pressure transition points and flow gains, for the PC system, for example, were selected based on the following criteria: 20% stabilator valve position, 70% flaperon valve position or 30% canard valve position would result in a command to 8000 psi. In addition, an array of combinations of lesser valve commands would also result in higher pressures.

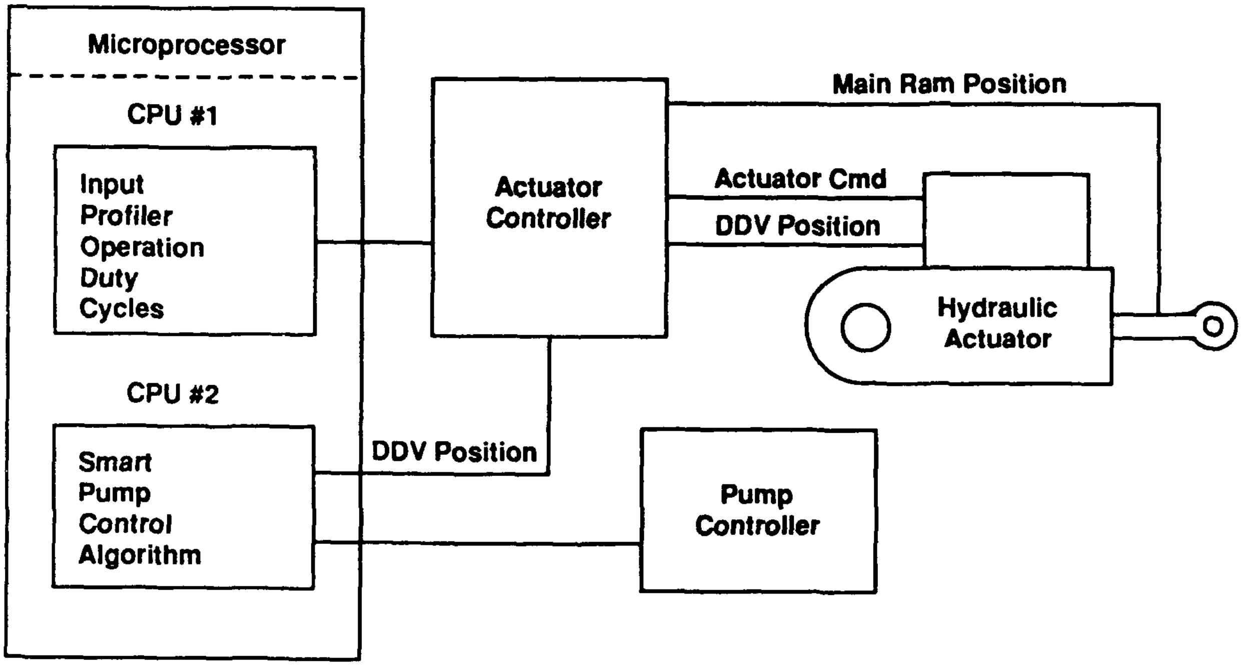


Figure 28. Control System Block Diagram

Stabilator	Canard	Flaperon	Rudder
Stol (17 sec)			
.235 Hz	**.235 Hz**	**.705 Hz**	**.235 Hz**
2/7V	2/8V	2/10V	2/8V
2/8V	2/7V	10/8V	2/7V
Climb (399 sec)			
1.153 Hz	**1.654 Hz**	**.631 Hz**	**1.153 Hz**
125/.2V	15/5V	2/9V	15/5V
15/5V	15/3V	20/5V	15/3V
75/.2V	100/.2V	50/7V	75/.2V
15/3V	15/5V	25/3V	15/5V
15/5V	125/.2V	50/7V	125/.2V
200/.2V	15/3V	40/3V	15/3V
15/3V	375/.2V	30/5V	200/.2V
–	–	35/3V	–
Cruise (1336 sec)			
1.871 Hz	**1.572 Hz**	**1.684 Hz**	**1.871 Hz**
500/.2V	150/1V	350/.2V	150/1V
150/1V	500/.2V	100/1V	500/.2V
500/.2V	175/1V	400/.2V	100/1V
100/1V	400/.2V	200/1V	500/.2V
500/.2V	200/1V	500/.2V	175/1V
175/1V	500/.2V	100/1V	500/.2V
500/.2V	175/1V	500/.2V	75/1V
75/1V	200/.2V	100/1V	500/.2V
Combat (612 sec)			
.31 Hz	**.313 Hz**	**2.209 Hz**	**.31 Hz**
6/9V	35/5V	300/1V	40/5V
40/5V	8/9V	75/7V	6/9V
30/7V	30/7V	150/3V	30/7V
40/5V	6/9V	400/1V	3/10V
3/10V	15/8V	75/7V	40/5V
38/7V	45/5V	2/10V	38/7V
3/10V	15/8V	300/1V	3/10V
30/8V	38/7V	50/8V	30/8V

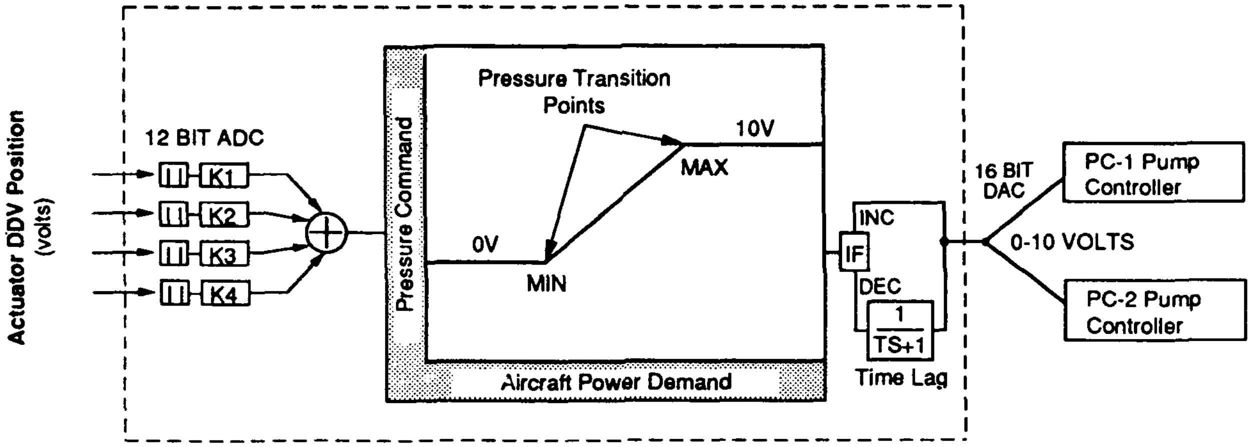
Of Cycles / Command (1V = 10% stroke) i.e. 5/1V = 5 cycles @ 10% stroke

Figure 29. PC Systems Duty Cycle Input File

Divergent Flap	Convergent Flap	Reverser Vane	Arc Valve	Diffuser Ramp	Leading Edge Flap PDU
Stol (17 sec)					
.705 Hz	.705 Hz	1.0 Hz	.705 Hz	.058 Hz	.471 Hz
5/1V	2/5V	10/.2V	5/1V	1/3V	2/8V
2/5V	10/1V	1/10V	2/5V	–	2/10V
5/1V	–	1/5V	5/1V	–	2/8V
–	–	5/.2V	–	–	2/0V
Climb (399 sec)					
.481 Hz	.441 Hz	–	.481 Hz	.04 Hz	.514 Hz
30/3V	10/1V	Not commanded to operate during this time.	30/3V	5/1V	25/5V
2/8V	25/.2V		2/8V	3/5V	50/3V
25/.2V	2/8V		1/8V	5/1V	2/9V
40/3V	40/3V		40/3V	3/3V	25/5V
20/1V	9/.2V		20/1V	–	25/7V
30/3V	40/3V		30/3V	–	50/3V
25/.2V	10/1V		25/.2V	–	3/9V
20/3V	40/3V		20/3V	–	25/7V
Cruise (1336 sec)					
1.104 Hz	1.104 Hz	–	1.104 Hz	.194 Hz	1.346 Hz
100/.2V	50/1V	Not commanded to operate during this time.	100/.2V	260/1V	300/.2V
400/0V	125/.2V		400/0V	–	100/1V
150/.2V	50/1V		150/.2V	–	500/.2V
50/1V	400/0V		50/1V	–	100/1V
150/.2V	250/.2V		150/.2V	–	200/.2V
100/1V	50/1V		100/1V	–	100/1V
125/.2V	400/0V		125/.2V	–	400/.2V
400/0V	150/.2V		400/0V	–	100/1V
Combat (612 sec)					
.403 Hz	.398 Hz	.263 Hz	.403 Hz	.022 Hz	1.575 Hz
50/.2V	40/7V	2/9V	50/.2V	4/8V	200/1V
8/8V	10/1V	4/5V	8/8V	3/7V	10/7V
10/1V	50/.2V	50/.2V	10/1V	3/9V	60/3V
3/9V	8/8V	15/3V	3/9V	4/8V	4/7V
50/.2V	75/.2V	6/7V	50/.2V	–	300/1V
40/7V	11/5V	50/.2V	40/7V	–	30/7V
75/.2V	3/9V	4/5V	75/.2V	–	300/1V
11/5V	47/.2V	30/.2V	11/5V	–	60/3V

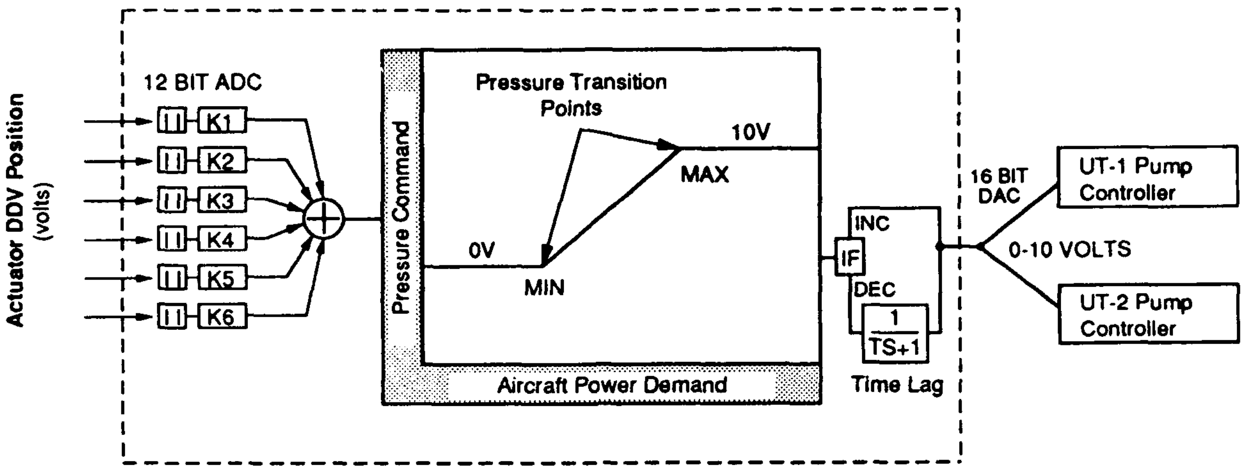
Of Cycles / Command (1V = 10% stroke) i.e. 5/1V = 5 cycles @ 10% stroke

Figure 30. Utility Systems Duty Cycle Input File



Actuator	Flow Gains	Pressure Transition Points
		Power Demand — Pressure Command
R/H & L/H Stab	K1 = .86	Min = 2.0 Volts ==> 0 Volts = 3000 psi
L/H Canard	K2 = 1.15	Max = 5.0 Volts ==> 10 Volts = 8000 psi
L/H Flaperon	K3 = .25	
R/H & L/H Rudder	K4 = .10	Time Constant (Lag) T = 2.0 sec

Figure 31. PC Pump Pressure Control Schematic and Parameters



Actuator	Flow Gains	Pressure Transition Points			
		<u>Power Demand</u>		<u>Pressure Command</u>	
L/H Divergent Flap	K1 = .375	Min = 2.4 Volts	==>	0 Volts	= 3000 psi
L/H Convergent Flap	K2 = .25	Max = 6.0 Volts	==>	10 Volts	= 8000 psi
R&L/H Reverser Vane	K3 = .25				
L/H Diffuser Ram	K4 = .25				
L/H L.E.F.	K5 = .25	Time Constant (Lag)			
R/H Arc Valve	K6 = .56	T = 2.0 sec			

Figure 32. *Utility Pump Pressure Control Schematic and Parameters*

3.4.2 <u>Pump Drive Motors</u> - Each of the four hydraulic pumps were driven by 350 hp variable speed electric motors supplied by the Louis Allis Company. Each motor had its own electronic control panel to allow the motors to be operated independently with variable speed and with controlled acceleration. Acceleration control is essential for evaluating pump characteristics through the engine starting cycle. Each of the pumps was interfaced to the drive motors with a Lebow torque sensor. These units are used to determine pump input power since their output is shaft torque and speed. The pump control panel is shown in Figure 6.

3.5 INSTRUMENTATION

Strain gage pressure transducers, turbine flowmeters, force/load transducers and thermocouples were used on the Laboratory Technology Demonstrator (Iron Bird) to measure system pressures, flows, forces or loads and temperatures. Laboratory instrumentation parameters were channeled by signal conditioning equipment to the data recording system. The actuator instrumentation parameters were channeled through buffer cards to the recording system. Temperatures were obtained with a thermocouple reference junction box and a look-up table stored in the data recording system. The instrumentation parameters are listed in Volume I of this report.

3.5.1 Data Acquisition System - Performance data were processsed by a Neff Series 620 data acquisition system consisting of a Series 500 measurement and control I/O system, one Series 410 high speed, high level differential multiplexer, and one Series 100 low level differential multiplexer. The Series 500 I/O system provided communication between the controlling computer (DEC PDP-11/73), the Series 410 and Series 100 Multiplexers, and other analog or digital I/O function cards. A block diagram of the data recording system is shown in Figure 33.

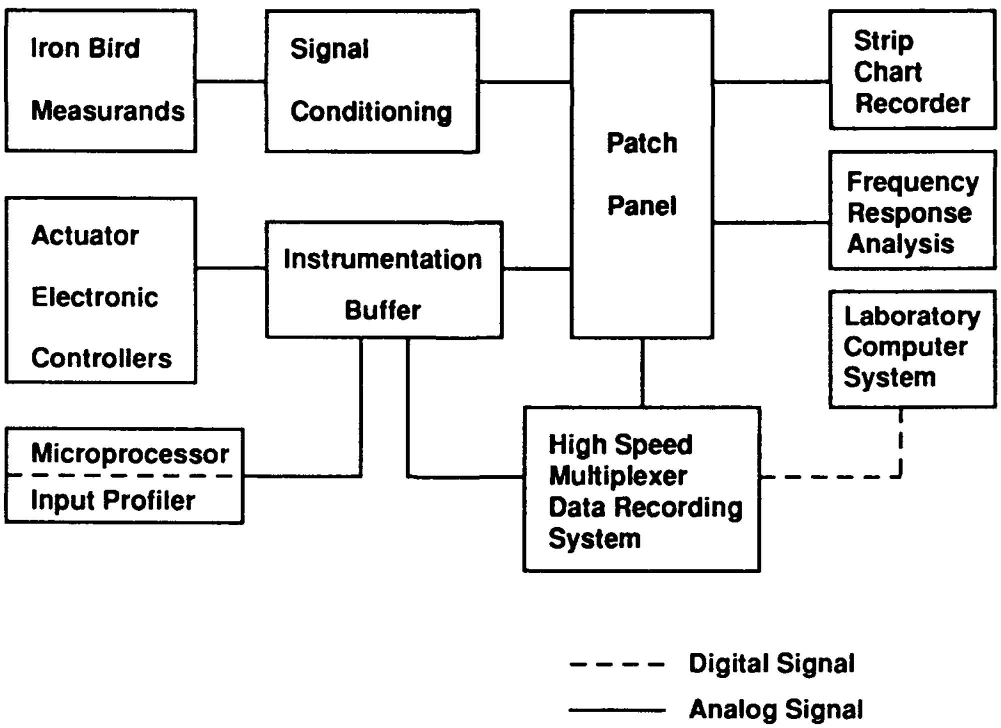


Figure 33. Data Recording System Block Diagram

The Series 410 Multiplexer is a high speed, solid-state analog multiplexer that accommodates 256 differential input channels and has a programmable gain differential amplifier, and a 16-bit analog-to-digital converter. System accuracy is +/- 0.05% full scale.

The Series 100 multiplexer is designed to accept 52 analog inputs ranging from +/- 5 mV to +/- 10 volt full scale. Both the Series 410 and Series 100 system feature throughput rates up to 50 kHz.

As test data are collected, it is transferred from the Series 500 Measurement and Control I/O System to the PDP-11/73 computer in 4K word blocks and stored on the RD52A disk drive or transferred the data to the PDP-11/750 computer for data formatting, plotting and permanent storage after the test is completed.

A four-channel Soltron Frequency Response Analyzer, Model 1254, was used for recording frequency response data. The analyzer has a built-in generator and can stimulate a test system with sinusoidal, triangular, or square waves in the frequency range of 0.01 Hz to 65.5 kHz and amplitudes from 0.01 to 10.23 volts peak. The analyzer can analyze both AC or DC signals. Bode plots of amplitude ratio and phase lag vs. frequency is the most common output format used.

SECTION IV

PHASE IV - EQUIPMENT DEVELOPMENT AND TESTING

4.1 PROGRAM TASK FLOW (Contract Statement Of Work)

4.1.1 Task 4-1 Select Component Suppliers - Nearly all of the major suppliers of equipment to be used in the demonstration had expressed a commitment to participate in the program prior to contract award. This was necessary to determine how much equipment could be developed in the period of performance and to assemble pricing data for the program proposal. In order to meet the rigorous schedule, Phase IV began concurrently with Phase I. Figure 34 shows the equipment suppliers and the hardware which were contracted for demonstration.

4.1.2 Task 4-2 Determine Spares and Test Articles - Depending on the type of equipment being provided, spares and test articles were selected so as to provision an adequate stock of detail parts which, based on mutual experience, would be required to repair the equipment. Figure 35 shows the equipment list and the type of spares and test hardware provisioning which was selected. Test hardware to be used in the supplier testing consisted of complete units which would be endurance tested and pressure vessels which would be pressure impulse tested to demonstrate fatigue life.

4.1.3 Task 4-3 Begin Detailed Component Design - Detailed component design was closely coordinated with each supplier in order to share an accumulation of data at MCAIR on high pressure technology and requirements for use with nonflammable CTFE fluid. A design newsletter was circulated periodically to distribute program information, design guides and interface design requirements which were generic to most equipment.

4.1.4 Task 4-4 Conduct Preliminary Design Reviews - Formal design reviews were conducted for each major equipment with MCAIR cognizant personnel and the Air Force program manager in attendance. Long lead items were identified and approved for advanced fabrication. Where redirection was necessary, supplementary design reviews were scheduled.

4.1.5 Task 4-5 Conduct Final Design Reviews - Final design reviews were held when the equipment had been completely designed. The supplier was then allowed to incur cost to develop the equipment. Complete stress analysis had been completed at this point and was formally presented at the design reviews as well as schedules and test plans.

4.1.6 Task 4-6 Initiate Fabrication and Assemble Equipment - The program statement of work required that the equipment be flight weight, flight worthy design. The pressure vessels were fabricated from conventional or advanced materials by recognized production techniques such as contour profiling or strip profiling of hand forgings or castings. "Hogouts" or "slab block" piece parts were only allowed where the preferred approach presented schedule risk. In these instances, the suppliers were asked to provide detailed weight estimates for a flight weight profile.

Specification No.	Subcontractor	Component Description
71-136901	Moog	Flaperon
71-136904	Cadillac Gage	Diffuser Ramp (Utility)
71-136907	Moog	Engine Nozzles
71-136908	Abex	Variable Disp. and Press. Pump
71-136909	Lucas	Variable Disp. and Press. Pump
71-136910	APM	Filter Manifold (40 GPM)
71-136912	Abex	Fixed Displacement Motor
71-136913	Parker Aerospace	Hyd. Integrity Monitor (HIM)
71-136915	Parker Aerospace	4W - 3P Valve
71-136917	Parker Aerospace	3W - 2P Valve
71-136918	Vickers	Variable Disp. and Press. Pump
IRAD Demo	HR Textron	Rudder (16000 psi)
71-136922	Parker Aerospace	Pressure Intensifier
71-136925	Circle Seal	Relief Valve
71-136928	Parker Aerospace	Shuttle Valve 6W-2P
71-136930	Consolidated Controls	Pressure Switch
71-136930	ITT Neodyne	Pressure Switch
71-136931	Consolidated Controls	Pressure Transmitter
71-136932	Circle Seal-Brunswick	Pneumatic Fill Gage
71-136934	E-Systems Inc.	Stabilator
71-136936	Parker Aerospace	Accumulator
71-136937	Allied Signal Electrodynamics	Rudder
71-136938	Parker Bertea	Reverser/Arc Valve
71-136939	Parker Aerospace	Reservoir (Utility)
IRAD Demo	Sundstrand	Leading Edge Flap (LEF)
71-136941	PTI	Filter Manifold (60 GPM)
840-40102	Pulsco	Pulsation Attenuator
	UAP	Heat Exchanger
	Garrett	Variable Disp. and Press. Pump
	Gar-Kenyon	Auxilary RLS Valve
	M.C. Aerospace	4W-3P Valve
	Gar-Kenyon	Augmented Cooling Valve

Figure 34. Major Equipment Subcontractors

Component	Quantities			
	System Test	Spares	Worthiness Test	Impulse Test b
Pumps	4	3a	6	0
Motor, Hyd.	1	1a	1	0
Rudder	2	1 & 1a	1	1
Fill Gage	2	1	0	0
Diffuser Ramp	1	1a	1	1
UT Actuator	1	0	0	0
Relief Valve				
High Pressure	11	2	0	0
PC System 15psi	1	1	0	0
UT System 100psi	2	1	0	0
Stab/Canard	2	1a	1	1
Flaperon	1	c	0	1
Simulator	1	c	0	0
Pressure Switch				
Filter Manifold	5	8	–	–
Reservoir	9	7	–	–
Pressure Transmitter	4	1	–	–
Leading Edge Flap	1	0	0	0
Attenuator	4	1	–	–
Heat Exchanger	3	1	–	–
Reservoirs	3	1	0	0
H. I. M. Valve	2	1a	1	1
4W - 3P Valve	5	1a	1	1
3W - 2P Valve	3	1	0	0
Shuttle Valve	2	1	0	0
Intensifier	1	1a	1 d	0
Accumulator	1	1	0	0
Reverser Vane	4	0	0	0
Arc Valve	2	0	0	0
Filter Manifolds	4	5	0	2
Filter Elements 1 micron	–	24	–	–
Filter Elements 5 micron	–	24	–	–
Flap Nozzles				
Servo Valves				
Divergent	2	1a	1	1
Convergent	1	c	0	0
Output Rams				
Divergent	4	1a	1	–
Convergent	2	c	0	–
Simulators				
Divergent	2	0	0	–
Convergent	1	0	0	–

a: refurbished worthiness test unit
b: manifold only
c: spare parts available for refurbishing unit
d: tested at H. R. Textron

Figure 35. Subcontracted Equipment List

4.1.7 Task 4-7 Conduct Component Acceptance Tests - The program required that all of the equipment which was to be used in the Laboratory Technology Demonstrator be tested prior to delivery. Further, it was a goal that break-in time be accumulated as well to insure that all infantile failures were eliminated.

4.1.8 Task 4-8 Conduct Simulator Worthiness (Endurance) Tests - Those suppliers of pumps and flight control actuators who had high power CTFE test capabilities were to conduct life testing at their facility on endurance test hardware. This equipment would later be refurbished for use in the Demonstrator endurance test or retained as a spare. It was originally intended that the endurance testing of the pumps would also include a filter manifold and a system reservoir.

4.2 COMPONENT WEIGHT COMPARISONS

Component weight estimates and comparisons between two operating pressure levels requires comparable ground rules in order to have a fair comparison for trade studies. When there are existing designs for comparison, it would seem to simplify the task except that the existing designs often contain added features which are not scaled by pressure or flow rate. Materials can be selected for reasons other than strength to weight ratio or the design requirements may differ from a standard approach. Presented herein are the weight data for the 8000 psi equipment, distribution system and fittings as well as weights for similar equipment designed for lower operating pressures.

4.2.1 Methods For Weight Comparisons - For the most general comparison, component weight estimates could be made with transmitted power being a constant. However, the pressure loss allowable in any given component is related to the pressure loss distribution in the system. The more loss that can be allowed in a distribution element, the smaller the part can be made because of the smaller passages required. Asymmetric line loss tends to require components with lower losses. Because of the obvious need to use standard line sizes, the loss allotted to a given line varies widely and more or less loss may be allowed in the components in those line runs. The overall weight of the system is the only real concern. Therefore any weight comparisons for system pressure trade studies must compare not just component for component but all elements which contribute to pressure loss.

4.2.2 8000 psi Equipment Weights - Actual and Optimized - The equipment which was provided for the program was required to be of flight weight and flight worthy design. Due to time to build constraints and risk some of the equipment, while being flight weight are not minimum weight. In these instances, the supplier has provided estimates of what the final weight would be with total optimization.

(a) Hydraulic Pump Weights - Figure 36 shows wet and dry weight for the several pumps involved in the program. Also shown are weight variances attributed to variable pressure capability. The program 40 gpm pumps were designed with different displacements and rated operating speed. Weight reduction which could be attained with further optimization of material usage is also cited. Pumps should compare well on a horsepower per pound basis regardless of operating pressure since the weight associated with pressure containment is but a small fraction of the overall weight. Traditionally, there has been severe financial and schedule pressures to use an existing pump design or a derivative in order to avoid a lengthy development. Although low weight is always cited as a premium attribute, goals for reliability and long life can take precedence.

	ADP Pump Suppliers				**F-15 / F-18**
	Abex	**Garrett**	**Lucas**	**Vickers**	**Abex**
Rated Speed (rpm)	4400	5700	5200	3625	3780 / 4600
Displacement (cipr)	2.2	1.8	1.97	3.05 (1)	2.8
Wet Weight (lbs)	47.2	58.5	82.5	133.8	29.5 (2)
Dry Weight (lbs)	44.6	52.9	72.5	121.7	26.5
Optimum Weight (lbs)					
Variable Pressure	43	45	66	100	—
Constant Pressure	33.2	39.6	60	69.6	
Fluid Volume (cu. in.)	40	85.4	152	185	97
Max Hp @ Rated Speed	195	207	207	223	82 / 98

(1) Tested using MIL-H-83282 to 55 gpm.

(2) Weight includes pump manifold and MIL-H-83282 fluid.

Figure 36. Program Pump Comparisons

(b) <u>Servoactuator Weights</u> - Flight control actuators have less volume at higher operating pressure but can be heavier based on pressure containment alone. Some of the flight control actuators which have been built are lighter in weight than other units but the savings has been attributed to attendant technology such as using titanium direct drive valves and some simplification and/or elimination of mechanization with the use of direct drive valves. All of the actuators have been sized for stall load and no load rate; none have been oversized for any other design parameter such as stiffness, column bending/vibration, commonality to other actuators etc. Figure 37 shows the comparison of 3000 psi S/MTD actuators and the 8000 psi ADP actuators. The F-15 S/MTD servoactuators also use direct drive valves but the manifolds are not optimum weight.

Component	ADP		F-15 S/MTD
	Weight (lbm)		Weight (lbm)
	Actual	Optimized	Actual
Stabilator	63.8	58.9	70.11
Canard (LECHT)	47.0	47.0	70.11
L/H Rudder Actuator	13.5	12.0	28.21 (1)
Valve	19.4	13.45	
R/H Rudder	55.8 (2)	46.0	28.21
Flaperon	29.26	29.26	34.81
L.E.F. PDU	19.2	17.0	N/A
Diffuser Ramp	21.0	21.0	19.22 (3)
<u>ENGINE NOZZLES</u>			
Reverser Vane	9.1	9.1	11.5
Arc Valve	13.4	13.4	N/A
Convergent Ram	19.9	19.9	13.9
Valve	9.4	7.99	5.91
Divergent Ram	20.5	20.5	12.4
Valve	8.08	6.48	4.71

(1) Weight for Actuator and Valve Assembly
(2) Weight includes the 33.1 lb ballscrew actuator
(3) Production F-15 Diffuser Ramp

Figure 37. Actuator Weight Comparisons

(c) Reservoir Weights - The central system reservoirs were individually sized for the PC and the Utility systems; however, program funding limitations forced cancellation of the smaller unit and the larger units were used in all three systems instead. Figure 38 shows capacities, the actual weight of the larger unit, and an estimated weight of the required smaller unit. The volume required in the reservoirs relates to system volume, actuator unbalanced volume, thermal expansion and a leakage allowance. Reservoir level sensing also duplicates volume requirements by circuit.

System leakage allowance in the reservoirs has traditionally been 5 percent of system volume. The F-15 aircraft reservoirs have a leakage allowance of 2.5 percent because of the use of permanent joints and lipseal separable fittings which were shown to have less leakage potential than the older fitting systems. Since the total number of potential leak points remains approximately the same, the LTD reservoirs have a leakage volume allowance of 5 percent in order to have essentially the same fluid reserve.

Company	System	Capacity (cu. in.)		Dry Weight (lbs.)
		Normal	Maximum	
Parker Hannifin Bootstrap w/3 RLS circuits	UT	380	547	18.55
Parker Metal Bellows precharged unit w/3 RLS circuits	PC-1 & PC-2	233	395	26.5 est
Production F-15 and F-18 (3000 PSI System)				
Crane / Hydroaire Div. Bootstrap w/ 2 RLS circuits	F - 15 PC 1&2	237	355	15.2
	F - 15 UT	590	950	24.95
Parker Hannifin Bootstrap w/ 2 RLS circuits	F - 18 SYS 1	547	766	26.10 max.
	F - 18 SYS 2	364	450	23.25

Figure 38. Reservoir Weight Comparisons

(d) Filter Manifold Weights - Weight data for the two hydraulic filter manifolds is presented in Figure 39. The PTI manifold is a one piece, profiled titanium manifold with the ports compactly arranged for an optimization of the F-15 utility filter manifold requirements. This filter manifold also has much less dirt holding capacity with its smaller elements which reduces weight.

The APM unit is a two piece manifold using aluminum for the return half and titanium on the high pressure half. It follows the F-15 filter manifold envelope very closely. Figure 39 also shows a weight comparison of other manifolds that are comparable but have different pressure and flow ratings. The filter manifolds did not present weight savings compared to the 3000 psi manifolds because they do not transmit equivalent power.

Manufacturer	Fluid	Flow Rate (gpm)	Pressure (psi)	Dry Weight (lbm)	Volume (cu in)
APM	CTFE	40	8000	23	82.2
PTI	CTFE	40	8000	13.9	45
PTI (F-15)	MIL-H-83282	47	3000	20	60.5
APM (F-18)	MIL-H-83282	56	3000	23.5 (1)	64.4

(1) Includes weight of fluid sampling valve; case drain is filtered separately.

Figure 39. Filter Manifold Weight Comparisons

(e) Directional Control Valves - Figures 40 thru 42 show weight and design comparisons of the three types of directional control valves used in the Demonstrator. Also shown are the flow/pressure drop ratings and materials. Titanium was used for two of the three types and resulted in lightest possible configuration. Physical data provided by Parker Aerospace are shown for several valves used in lower pressure systems. The 6-way, 2-position valve used in the Demonstrator presents a difficult example for comparison since no flight weight valve of this type has ever been designed at an equivelent power level at lower pressure.

System Pressure (psi)	Rated Flow (gpm)	Pressure Loss at Rated Flow (psid)	Housing Material	Remarks / Configuration		Weight 'Dry' (lbs)
3000	8	40	Al casting	1 solenoid	(1)	1.5
3000	2	20	Al	mechanically actuated	(1)	0.7
3000	6	60	Al casting	manual operation	(1)	1
3000	28	100	Al	press oper priority	(2)	1.93
3000	2.5	50	Al	sol oper linear control	(2)	1.05
3000	1	38	Al	sol oper linear control	(2)	2.2
3000	2	50	Al	manually oper popit	(2)	2.3
4000	13	40	Al casting	1 solenoid	(3)	2.03
4000	7	40		1 solenoid	(3)	1.17
4000	25	900		2 solenoid	(3)	3.2
4000	30	200		1 solenoid	(3)	2
4000	10	150		shear seal (no detent)	(3)	3.3
8000	10	400	Steel	1 solenoid	(4)	2.2
8000	13 /30	400 / 200		Al/Ti slide	(3)	2.0 / 3.0
8000	30	200		Al/Ti slide	(3)	3
8000	10	65		shear seal w/detent	(3)	10
8000	3	900		interflow - mag latch	(3)	3
8000	0.5	900		pilot/latch/manual	(3)	2.25
8000	0.5	900		latch pilot	(3)	1

(1) F-15 Production hardware
(2) F-18 Production hardware
(3) Parker supplied data
(4) ADP Program hardware

Figure 40. 3W-2P Valve Weight Comparisons

System Pressure (psi)	Rated Flow (gpm)	Pressure Loss at Rated Flow (psid/leg)	Housing Material	Remarks / Configuration	Weight 'Dry' (lbs)
3000	3	75	Al	manually operated (1)	0.86
3000	4	30	Al casting	dual coil, opposing ports (1)	2.05
3000	4.5	40	Al casting	dual coil, opposing ports (1)	2.1
3000	17	150	Al casting	dual coil, opposing ports (1)	2.9
3000	4	300	Al	manually operated (2)	2.8
8000	10	250	Ti casting	dual coil,opposing ports (3)	3.65
8000	10.2	100	Steel	dual coil,opposing ports (3)	6.0
8000	10	100		dual coil (4)	8.5
8000	10	125		dual coil (4)	8.2
8000	3	1800		poppet & sleeve (4)	3.25
8000	3	1800		slide/shrink fit (4)	3.7
8000	0.5	1800		pilots (4)	2.5

(1) F-15 Production hardware
(2) F-18 Production hardware
(3) ADP Program hardware
(4) Parker supplied data

Figure 41. 4W-3P Valve Weight Comparisons

System Pressure (psi)	Rated Flow (gpm)	Pressure Loss at Rated Flow (psid)	Housing Material	Remark / Configuration	Weight 'Dry' (lbs)
3000	14.5	200	Al	Switching Valve (1)	5.7
3000	14.5	410	Al	Switching Valve (2)	5.8
3000	10	210	Al	Switching Valve (2)	4.7
8000	24	190 psid/leg	Ti casting	Shuttle Valve (3)	3.83

(1) F-15 Production hardware
(2) F-18 Production hardware
(3) ADP Program hardware

Figure 42. 6W-2P Valve Weight Comparisons

4.2.3 System Weight Comparisons - Past studies have predicted overall weight savings of 20 to 25 percent in a transition from a 3000 psi MIL-H-83282 fluid system to an 8000 psi CTFE system. Figure 43 shows a P-1 system weight comparison for the Demonstrator. The system weight differences when expressed as percentages show that the 8000 psi system with CTFE was 14 percent lighter than a 3000 psi system with MIL-H-83282. Also, the comparison shows that the 8000 psi system with CTFE carried a 9 percent weight penalty over 8000 psi with MIL-H-83282. Finally, the 8000 psi system with MIL-H-83282 is more than 21 percent lighter than the 3000 psi with MIL-H-83282. Several differences can be noted in this system level comparison from the components weights shown previously.

	F - 15 S/MTD System			ADP 8000 psi System			
	Dry Wt (lbm)	Volume (cu. in.)	Wet Wt 83282 (lbm)	Dry Wt (lbm)	Volume (cu. in.)	Wet Wt 83282 (lbm)	Wet Wt CTFE (lbm)
Central Sys							
Pump	26.5	96.7	29.4	22.4	30.0	23.3	24.4
Fltr manifold	20.0	60.5	21.9	13.9	45.0	15.3	16.9
Reservoir	15.2	237.0	22.5	17.0	233.0	24.2	32.3
Tubing	5.4	136.8	9.6	4.8	105.2	8.0	11.7
Subtotal	67.1	531.0	83.3	58.1	413.2	70.8	85.3
Distr Sys							
Canard	70.1	110.5	73.5	51.6	42.7	52.9	54.4
Stabilator	70.1	110.5	73.5	51.6	42.7	52.9	54.4
Rudder	28.2	8.2	28.5	25.5	16.3	26.0	26.5
Flaperon	34.8	13.0	35.2	29.3	5.0	29.4	29.6
Tubing	11.6	299.7	20.8	11.0	146.3	15.5	20.6
Subtotal	214.8	541.9	231.4	169.0	253.0	176.7	185.5
Total	281.9	1072.9	**314.8**	227.1	666.2	**247.5**	**270.8**

Figure 43. PC-1 System Weight Comparisons

The pump weight shown is based on data provided by Abex since neither the 40 gpm pumps nor the 15 gpm pumps used were equivalent in power level to the size (25 gpm) originally predicted for the system at 8000 psi.

The reservoir weight has been estimated from the actual weight of the reservoirs used because they were sized for the utility system. The PC systems require 233 cubic inches of fluid at normal full compared to 347 cubic inches for the utility system.

The weight quoted for the filter manifolds is for the PTI units. This was based on the fact that when downsizing the central system to 25 gpm for the weight comparison, it was recognized that filter manifold weights for this power level were not available. Since the PTI units had much less dirt holding capacity than the APM units, it was felt that the PTI unit weight would be more representative for the reduced power level for the purpose of a weight comparison.

The stabilator and canard actuator weight has been adjusted to remove the weight associated with flow augmentation as has the distribution system. Flow augmentation is not unique to 8000 psi, and its weight difference has been removed from the comparison since it is not in the 3000 psi sizing.

Because the flow augmented actuators are heavier, an explanation of how this design approach saves system weight is appropriate. Flow augmentation adds weight to actuators, and in this instance the distribution system, while saving weight from downsizing of the central system, particularly pumps and filter manifolds.

Flow augmentation in flight control actuators requires low supply line loss because of the large pressure loss attributed to the jet pump primary nozzle. The flow augmented actuator also uses a low loss servovalve which is estimated to be 4.0 lbs. heavier than a servovalve with conventional loss characteristics. Further, E-Systems has estimated that the additional flow augmentation provisions increase the weight increment to 7.3 lbs. A smaller (or restricted) return line is used to provide added back pressure to enhance recirculation flow. The smaller return line does not offset the added weight of the larger high pressure line, however.

Four flow augmented stabilator and canard actuators on the PC systems could allow each pump capacity to be reduced by approximately 9.0 gpm. The estimated (Abex) pump weight savings for this reduction in flow capacity is 7.4 lbs. Since the pumps are sized for the PC's and are used in the Utility system for commonality, this could result in a total pump weight savings of 29.6 lbs. compared with 29.2 lbs. of added weight in four stabilator/canard actuators. Additional weight savings exist which would offset approximately 7.0 lbs. of pressure supply line penalty. These savings would be accrued by downsizing four filter manifolds and system heat exchangers for less flow capacity.

Distribution weight predicted analytically can be difficult to match in actual practice if standard sizes fail to provide the best power loss characteristic. Figure 44 shows how pressure loss and weight compare as line sizes are reduced. A small weight savings occurs between 1/4- and 3/16-inch line size while the pressure loss becomes unacceptable. An alternate size near 0.200 inside diameter which provides Murphy proofing could avoid this penalty.

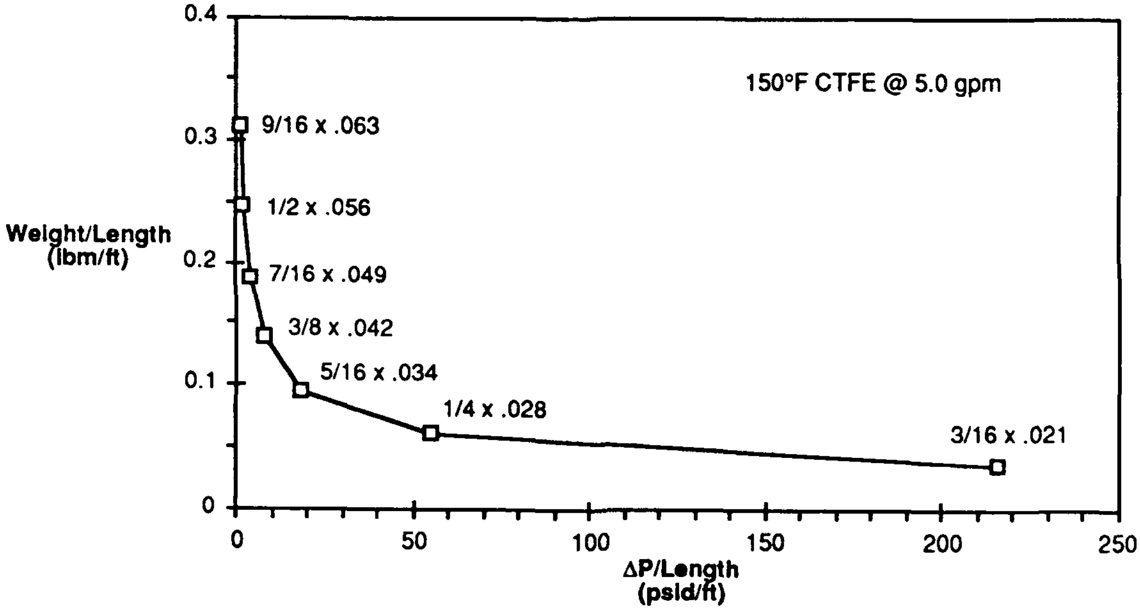


Figure 44. Tubing Weight vs Pressure Loss

4.2.4 Distribution Element Weights - The following weight data are presented for reference. The user is cautioned to make allowance for tube length associated with fitting insertion depth and straight length to first bend. The appropriate supplier should be contacted for complete fitting data for trade studies since shape fittings such as elbows and tees have a large influence on total distribution system weight.

a. Hydraulic Tubing - The high pressure tubing used in the program follows the tubing/wall schedule that was used in Reference 2 program conducted by Rockwell. Figure 45 shows the pertinent weight and tube data for all of the tube stock used in the program.

O.D. (in.)	Wall (in.)	I.D. (in.)	Flow Area (sq. in.)	Fluid (lb/ft)	Tube Wt. (lb/ft)	Wet Wt. (lb/ft)
3,000 psi System Pressure (Return)						
1/4	0.016	0.218	0.037	0.029	0.023	0.052
3/8	0.019	0.337	0.089	0.070	0.041	0.111
1/2	0.026	0.448	0.158	0.124	0.075	0.199
5/8	0.032	0.561	0.247	0.194	0.116	0.310
1.000	0.051	0.898	0.633	0.498	0.296	0.794
8,000 psi System Pressure (Supply)						
3/16	0.021	0.146	0.017	0.013	0.021	0.035
5/16	0.034	0.245	0.047	0.037	0.058	0.095
7/16	0.049	0.340	0.091	0.071	0.116	0.188
9/16	0.063	0.437	0.150	0.118	0.192	0.310
11/16	0.076	0.536	0.225	0.177	0.284	0.461

CTFE Hydraulic Fluid - Density @ 70°F & 0 psi (.0656 lb/cu.in.)
Titanium Tubing - Density (.162 lb/cu.in.)

Figure 45. Tubing Sizes and Weights

b. Permanent Line Joints (Cryofit, Rynglok, Permaswage) - Figure 46 shows the weight comparisons of the titanium tube-to-tube fittings which were available for the program. Odd sized fittings are all 8000 psi rated with even sized Cryofit fittings being 4000 psi rated, Permaswage fittings 3000 psi rated and the Rynglok fittings are rated for 8000 psi. The weight trends of these fittings illustrates large weight variances in the smaller sizes; however, weight is not nearly as varied with sizes larger than half inch.

Tube-to-Tube Fitting Weights (Weight in lbm)			
Size	**Cryofit**	**Permaswage**	**Rynglok**
Odd Size	8000 psi	8000 psi	8000 psi
-3	0.0044	0.0066	0.016
-5	0.017	–	0.034
-7	0.043	–	0.057
-9	0.084	–	0.093
-11	0.147	–	0.153
Even Size	4000 psi	3000 psi	8000 psi
-4	0.010	0.007	0.024
-6	0.021	0.015	0.045
-8	0.037	0.042	0.071
-10	0.063	0.054	0.120
-16	0.260	0.115	0.271

Figure 46. Line Joint Fitting Weights

c. Separable Fittings - The high pressure fittings were designed to the same structural standard as those fittings being evaluated in the Rockwell program, Reference 2. All of the return system utilized current production 3000 psi tubing and fitting standards. Weight data for the distribution elements and fittings used have been included in Figure 47.

Size	Company	Type	Weight (lbm) (1)
Odd Sizes (8000 psi)			
-03	Resistoflex	Dynatube	0.011
	Aeroquip Linair	Rynglok	0.018
-05	Aeroquip Linair	Rynglok	0.034
-07	Krueger	Aerofit Welded	0.030
	Deutsch	Permaswage	0.064
-09	Sierracin/Harrison	Internal Swage Lipseal	0.049
-11	Airdrome	Dualseal Welded	0.055
	Krueger	Aerofit Welded	0.068
	Aeroquip Linair	Rynglok	0.151
Even Sizes (3000 psi)			
-04	Resistoflex	Dynatube	0.015
	Aeroquip Linair	Rynglok	0.026 (2)
-06	Resistoflex	Dynatube	0.023
-08	Resistoflex	Dynatube	0.037
-10	Resistoflex	Dynatube	0.053
	Aeroquip Linair	Rynglok	0.112 (2)
-16	Resistoflex	Dynatube	0.164

(1) Weights may not be directly comparable due to tube tare length.
(2) 8000 psi rated

Figure 47. Separable Fitting Weights

Welded fittings were the lowest weight types used in the system. The principle reason for the weight savings is that no fitting material is required for attachment by swaging. Weight is also less since the tube is not inserted into the fitting. The Airdrome fittings were welded by AstroArc using an internal/external simultaneous weld and the Krueger fittings were manufactured and welded by Aerofit Products. Three styles of swaged fittings were used for the LTD fabrication, externally swaged (Rynglok), internally swaged (Resistoflex and Sierracin-Harrison) and externally crimped (Deutsch). Since only a few of the 8000 psi fittings were manufactured by more than one supplier, there are no weight comparisons to be reported.

4.3 SUPPLIER TEST PROGRAMS

Supplier test and evaluation was focused on performance, structural integrity and endurance. Discussed herein are the test efforts which were conducted by several equipment suppliers for this program. In terms of technical challenge, the development of 8000 psi, 40 gpm units designed for operation with CTFE hydraulic fluid dominated the subcontracted effort.

4.3.1 Abex Pump Development - The Abex pump was a derivative of the F-14 aircraft pump with the necessary changes to accommodate 8000 psi and variable pressure operation. Performance testing with conventional hydraulic fluid has shown that the design is adequate for 8000 psi.

Subsequent testing with CTFE produced wear and damage at the (1) port plate and barrel face, (2) the thrust washer, (3) the shoe retainer plate and (4) piston shoes. Corrosion and lack of lubricity were considered principle factors. Port plate wear was eliminated by using a Molybdenum base coating along with a redesign of the balance grooves. The thrust washer was also redesigned to allow for better lubrication. The shoe retainer plate/shoe clearance was increased after hanger deflection was identified as the cause. Shoe separation was a two-fold problem; piston jamming was corrected by using ion implantation to prevent corrosion while the shoe attachment was redesigned along with a change of material and swaging tools. Ion implantation was also added for the servovalve spool after it was found to eliminate the corrosion on a similar part in the Abex 15 GPM pumps.

4.3.2 Vickers Pump Development - Vickers experience with CTFE was similar to the port plate problem experienced by Abex; the bronze plating was eroding on the port plate high pressure sealing lands. Attempts were made to run a steel cylinder block with ion implantation against a port plate machined from M50 tool steel. This proved unsuccessful and the erosion problem was not resolved during the program.

4.3.3 Garrett Pump Development - The Garrett pump had several areas which required further development to operate with CTFE. Servovalve stability was the first design optimization addressed. Stability was improved by adjusting the spool to an underlap on the supply. In the process, an erroneous underlap on the return was discovered and the spool was remanufactured. With the new spool installed stability was greatly improved. Some stiction was still present at times but not to the point of impairing pump operation. The nose seal balance was adjusted to increase the seal life and reduce the shaft seal leakage to less than 1 drop per minute.

Pressure pulsations have been the major concern. Pulsation tests were performed varying port timing as well as hanger materials. Figures 48 and 49 show the respective port plate timing and the test results.

	Valve -1	Valve -2
Pressure Slot Start Angle	17.5°	25.7°
Pressure Slot End Angle	17.5°	14.9°
Suction Slot Start Angle	17.4°	20.6°
Suction Slot End Angle	17.4°	14.9°

Figure 48. Garrett Pump Valve Plate Timing

		MIL-H-83282 S'ST Hanger (-1 Port Plate)		CTFE S'ST Hanger (-1 Port Plate)		CTFE Ti Hanger (-1 Port Plate)		CTFE Ti Hanger (-2 Port Plate)	
Outlet Pressure (psig)	Outlet Flow (gpm)	Over. Eff. (%)	Press. Puls. (± %)	Over. Eff. (%)	Press. Puls. (± %)	Over. Eff. (%)	Press. Puls. (± %)	Over. Eff. (%)	Press. Puls. (± %)
3000	Full	80.6	22.2	75.4	23.4	76.7	21.2	76.0	15.8
3000	20	72.6	20.4	64.0	19.0	65.3	16.3		
3000	2	22.8	18.4	15.8	16.1	15.1	14.4		
5000	Full	82.2	16.5	76.3	14.8	81.1	14.8	80.9	12.7
5000	20	75.0	14.0	69.8	15.9	72.1	16.0		
5000	2	28.3	13.7	22.0	16.1	16.7	15.1		
8000	Full	82.1	15.4	78.2	18.2	78.7	17.6	81.1	18.6
8000	20	72.3	14.0	69.2	18.7	72.2	18.7		
8000	2	19.3	14.0	20.9	16.8	20.4	16.7		

Fluid @ 160°F Inlet

Figure 49. Garrett Pump Pulsation Levels and Efficiency

Step response was the last issue addressed. Figure 50 shows test results with CTFE fluid using both a steel and titanium hanger. The response time is within specification requirements when changing flow at a constant pressure, but lags when changing pressure at constant flow. The servo valve/control piston subsystem response coupled with the circuit response for compressing or expanding fluid is believed to slow response time for changing the pressure at a fixed flow rate. The titanium hanger improved the response time in all of the test situations, but improvement is still indicated for response time when changing pressure at a constant flow.

Cycle 1		Cycle 2		S'ST Hanger		TI Hanger	
Outlet Pressure (psig)	Outlet Flow (gpm)	Outlet Pressure (psig)	Outlet Flow (gpm)	Response Time (msec)	Pressure Transient (psid)	Response Time (msec)	Pressure Transient (psid)
3000	4	3000	36	24.5	-1764.7	25.5	-1908.4
5000	4	5000	36	39.0	-2503.4	36.0	-2503.4
8000	4	8000	36	66.6	-3960.4	46.5	-4104.0
3000	36	3000	4	43.5	2893.3	42.5	2647.1
5000	36	5000	4	47.5	2524.0	38.0	2236.7
8000	36	8000	4	49.0	2831.8	31.0	2872.8
3000	3	8000	3	125.5	1908.4	113.0	2052.0
8000	3	3000	3	–	–	166.5	-266.8

Figure 50. Garrett Pump Step Response

4.3.4 Lucas Pump Development - The Lucas checkvalve pump underwent several test sequences, using MIL-H-83282, aimed chiefly at determining its pressure pulsation characteristics. The pump was run with a fixed swashplate, first at 50% and then at 75% of full displacement (4° and 6° angles). Pressure pulsations were recorded from a pressure sensor mounted directly in the discharge port of the pump. The results presented in Figure 51 show the pressure pulsation levels well within the ± 5% required.

During development testing, the Lucas pump experienced several structural failures typical when testing a new design. One major drawback of the Lucas design was uncovered during testing where the pump rotating assembly needed to be rebalanced when displacement angle was changed. This problem was not resolved prior to conclusion of the program.

Outlet Pressure (psig)	Swashplate Angle (deg)	Outlet Flow (gpm)	Overall Efficiency (%)	Pressure Pulsations (± %)
3000	4	19.8	49	2.4
3000	6	30.5	58	3.4
5000	4	17.3	56	1.3
5000	6	28	67	2.6
8000	4	13.3	56	1.7
8000	6	24	68	1.5

Notes: Speed: 5200 rpm
Fluid: MIL-H-83282
Fixed Swashplate (4° and 6° angles)

Figure 51. Lucas Pump Pulsation Levels and Efficiency

4.3.5 <u>Hydraulic Filtration</u> - Degree of filtration or filtration efficiency for testing filter elements is defined by MIL-F-8815 for 5- and 15-micron elements. Since two suppliers provided 1- and 5-micron filter elements with different dirt holding capacities, the combined data are presented for comparison.

Figure 52 shows the basic acceptance data for the two filter packages and pertinent subassemblies.

Test Parameter	Total Flow (gpm)	Pressure Drop (1) (psid) PC Manifold	UT Manifold
Pressure Inlet / Pressure Outlet	40 / 60	174 / –	199 / 434
External Pressure / Pressure Outlet	15	28	82 (2)
Return Inlet / Return Outlet	40 / 60	28 / –	91 / 165
Reservoir Fill / Return Outlet	15	173	23
Case Drain / Return Inlet to Return Outlet	44	26	102
Bypass Valve Cracking Pressure	–	93	235
Bypass Valve Reseat Pressure	–	90	150
Differential Pressure Indication		156 - 190	185

(1) Tested with MIL-H-5606 @ 110°F
(2) With Screens in Crissair Check Valve

Figure 52. Filter Manifold Acceptance Test Data

(a) Hydraulic Filter Requirements - The Primary Control and Utility System filters had requirements similar to the F-15 manifolds with some exceptions in the element design criteria.

- o The rated flow for the utility system filter elements was 60 GPM as compared to 40 GPM for the primary control manifold. Additional total pressure loss for the unit was permitted at the higher flow.

- o Dirt holding capacity, of the 5-micron elements for the PC filters had a requirement of 5 grams with 100 psid at 40 GPM while the utility filter had a requirement of 5 grams with 190 psid at 60 GPM.

Filter element sizing is directly related to these requirements. Both the 1 and 5-micron elements were to be the same physical size with the baseline being the 5-micron element. Each supplier tested all four configurations. These tests included bubble point, gravimetric efficiency, dirt holding capacity and a multipass test. MIL-H-5606 at 100°F was used instead of CTFE for these tests. MIL-H-5606 at 100°F and 0 psig has the equivalent absolute viscosity of CTFE at 120°F and 8000 psig. It should be noted that cold start, which was not included in these tests, will reduce dirt holding capacity. The test results are presented in Figures 53 and 54.

	Tested By		Tested By		Tested By		Tested By	
	APM	PTI	APM	PTI	APM	PTI	APM	PTI
Element	Bubble Point Test (in. of water)		Gravimetric Efficiency (%)		Clean Element ΔP @ 40 gpm (psid)		Dirt Capacity 40 gpm @ 100 psid (grams)	
APM 1μm	22.7	18.7	–	–	61.2	69.5	3.29	2.95
PTI 1μm	17.8	15.7	–	–	76.1	71	0.7	1.1
APM 5μm	19.0	14.4	95.5	95.4	10.5	13.5	10.7	11.6
PTI 5μm	14.0	10.9	94.9	94.8	32.3	40	2.06	2.4
5μm Spec	3.0	3.0	94.0	94.0	25.0	25.0	5.0	5.0

Figure 53. Filter Element Test Results

	PTI Tests (Average)				APM Tests (Inverse Time Average)			
Micron	APM 1μm	PTI 1μm	APM 5μm	PTI 5μm	APM 1μm	PTI 1μm	APM 5μm	PTI 5μm
0.5	–	–	–	–	711	2.0	–	–
0.7	–	–	–	–	960	1.9	–	–
1	2169	253	10.3	12.4	1951	3.2	2.4	1.9
2	2287	415	16.7	18.7	3665	105	31	12
3	2207	647	33.2	32.1	4020	432	950	122
4	2094	818	–	–	–	–	–	–
5	1982	867	142	83.8	2566	580	1860	250
7	1839	987	607	168	–	–	5360	677
10	–	–	266	280	–	–	∞	∞

Figure 54. Filter Element Multipass Results

4.3.6 Actuation Systems - Several design approaches for direct drive servovalves were incorporated in the servoactuators for this program. Other advanced technology used in the stabilator and canard actuators included: flow augmentation, overlapped valves, load recovery and anti-cavitation check valves, and multiple redundancy. Rudder actuators were both rotary type actuators; one utilizing a remote rotary/rotary direct drive servovalve and a rotary vane actuator and the other being a linear to rotary direct drive valve with a linear actuator coupled to a reciprocating ballscrew. The engine nozzle actuators were paralleled with a single valve: one system being a regenerative design using a 3W-2P valve and the other using a 4W-3P control valve. The diffuser ramp actuator used a mechanical retract lock in a cylinder with a titanium barrel and a valve manifold fabricated from aluminum metal matrix.

The flight worthiness testing of the actuators included impulse testing of the manifolds and endurance testing of the complete unit. The testing completed is discussed herein. Figure 55 shows the basic acceptance test data from the suppliers, this includes no-load rates, hysteresis and leakage. Section 5 includes data from system endurance testing for comparison.

4.3.7 Utility Equipment - The utility equipment include such items as 4W-3P, 3W-2P, 6W-2P control valves, gun drive accumulator, hydraulic motor, an auxiliary RLS valve, a pressure intensifier and augmented cooling valve.

Figure 56 show the typical valve ATP data of the control valves, including leakage and pressure drop data, using MIL-H-83282 and calculated data using CTFE. During testing of the 4W-3P and 6W-2P valves, internal leakage was found to have a nonlinear increase between 1000 and 8000 psi as shown in Figure 57. The supplier attributed this to a slight mislocation of the seals. The 6W-2P valve had intersystem leakage caused by misalignment of the two spool halves. This problem was corrected by increasing the tolerance of the mating slot and reducing one area of the center lands to create a pressure imbalance.

4.3.8 Subsystem Tests - HR-Textron performed compatibility tests using the Parker Aerospace pressure intensifier and the HR rudder actuator. The pressure intensifier was a 2:1 unit with a bypass circuit for no-load operation. Figure 58 shows the load flow and pressure curves for the intensifier. This illustrates that with a 0.25 gpm leakage, the maximum obtainable output would be 15,100 psi, and the pump piston would be operating at approximately 9 Hz. With the actuator flow demand of 0.77 gpm, the maximum initial output would be 13,100 psi resulting in a maximum output force of 18,000 in-lbs instead of the specified 22,000 in-lbs and 24.5 degrees as opposed to the specified 30 degrees with full load. Figure 59 shows the actual test data for torque output and intensified pressure output with a constant supply pressure. With the actuator stalled, the intensifier would then continue to operate at 6-8 Hz until the maximum pressure was obtained at a corresponding leakage rate. Figure 60 shows the internal leakage characteristics of the direct drive valve.

Company	Component	No - Load Rate (in. / sec.)	Hysteresis (% of full stroke)	Threshold (% of full stroke)	Freq Resp (-3Db -90°)	Mid-Stroke Internal Leakage (cc/min)
E-Systems	L/H Stab S/N 002	8.0 E 7.1 R	(0.20%)	(0.0125%)	2% stroke 13.5 Hz 28.5 Hz	900. FWD 640. AFT
Bendix	L/H Rudder	105 deg/sec	(0.40%)	(0.04%)	5% stroke 31 Hz 20 Hz	256
HR Textron	R/H Rudder	106 deg/sec	(1.20%)	(0.60%)	10% stroke 8.6 Hz 10.5 Hz 1% stroke 27 Hz 20 Hz	211
Sundstrand	L.E.F.	116 deg/sec	(0.70%)	(0.70%)	10% stroke 18 Hz 13 Hz	2270
Parker Bertea	L/H Canard (1)	16. E 19. R (w/o flow augmentation)	(0.90%)	47 mA	5% stroke 8.0 Hz 20.0 Hz 1% stroke 1.1 Hz 3.5 Hz	570. R1 980. R2
	Rev Vane (1)	7.3 E 6.9 R	(0.02%)	2.7 mA	5% stroke >20 Hz >20 Hz	960 (2)
	Arc Valve (1)	11.6 E 10.3 R	(0.16%)	3.4 mA	5% stroke 3.5 Hz 9.0 Hz	1400 (2)
Moog	Conv. Ram S/N 001	12.3 E 12.2 R	125 mA	2.7 mV (0.01%)	N/A	1600
	Div. Ram	19.5 E 20.6 R	140 mA	3.9 mV (0.02%)	N/A	960
Cadillac Gage	Diff. Ramp (3)	0.89 E 0.57 R	95 mA	50 mA	N/A	50

(1) Tested with MIL-H-83282

(2) Includes 550 cc/min cooling flow

(3) Tested with MIL-H-46170

N/A Not Available

Figure 55. Actuator Acceptance Test Data

Internal leakage				
Component	Supply Pressure (psi)	Check Port	Leakage (cc/min)	
			MIL-H-83282	CTFE
3W-2P NC	8000 @ P1	P2 &R	<1 drop/5 min.	
4W-3P	8000 @ P1	R	23.2	50 (1)
6W-2P (Shuttle Valve)	8000 @ P1 & P3	R1 R3	8.8 40	11 (2) 17 (2)

Flow Capacity and Pressure Drop				
Component	Flow Rate (gpm)	Leg/Looped	Pressure Drop (psid)	
			MIL-H-83282	CTFE
3W-2P NC	10	P1-P2	165	
4W-3P	10	looped	270	590 (1)
6W-2P (Shuttle Valve)	24	looped: primary secondary	300 380	665 (1) 830 (1)

(1) Calculated values
(2) Measured at McAir

Figure 56. Directional Control Valves Acceptance Test Data

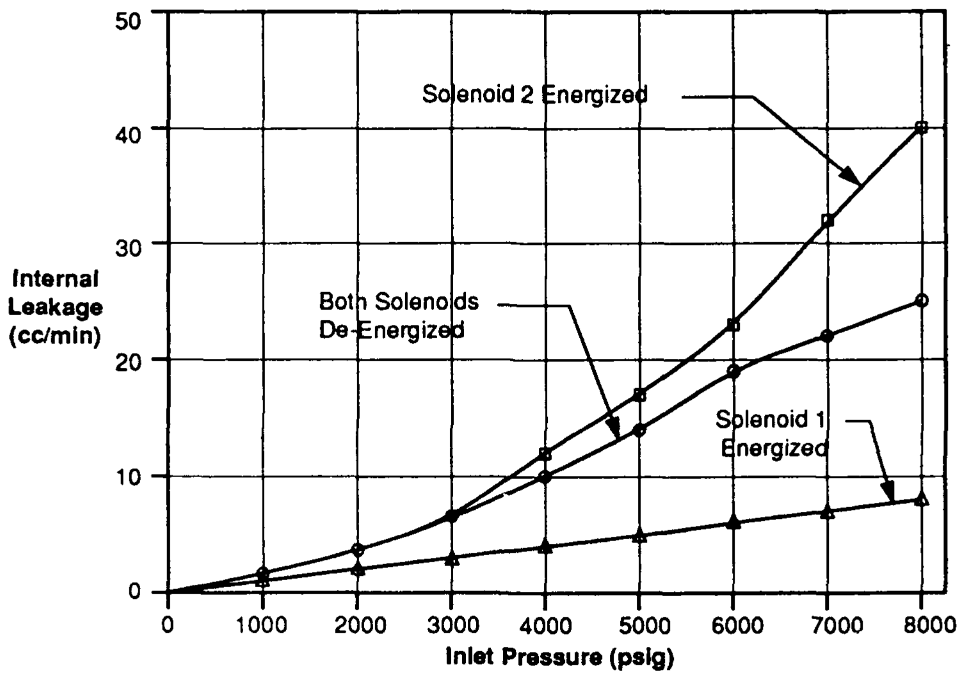


Figure 57. Parker 4W - 3P Valve Internal Leakage vs Pressure

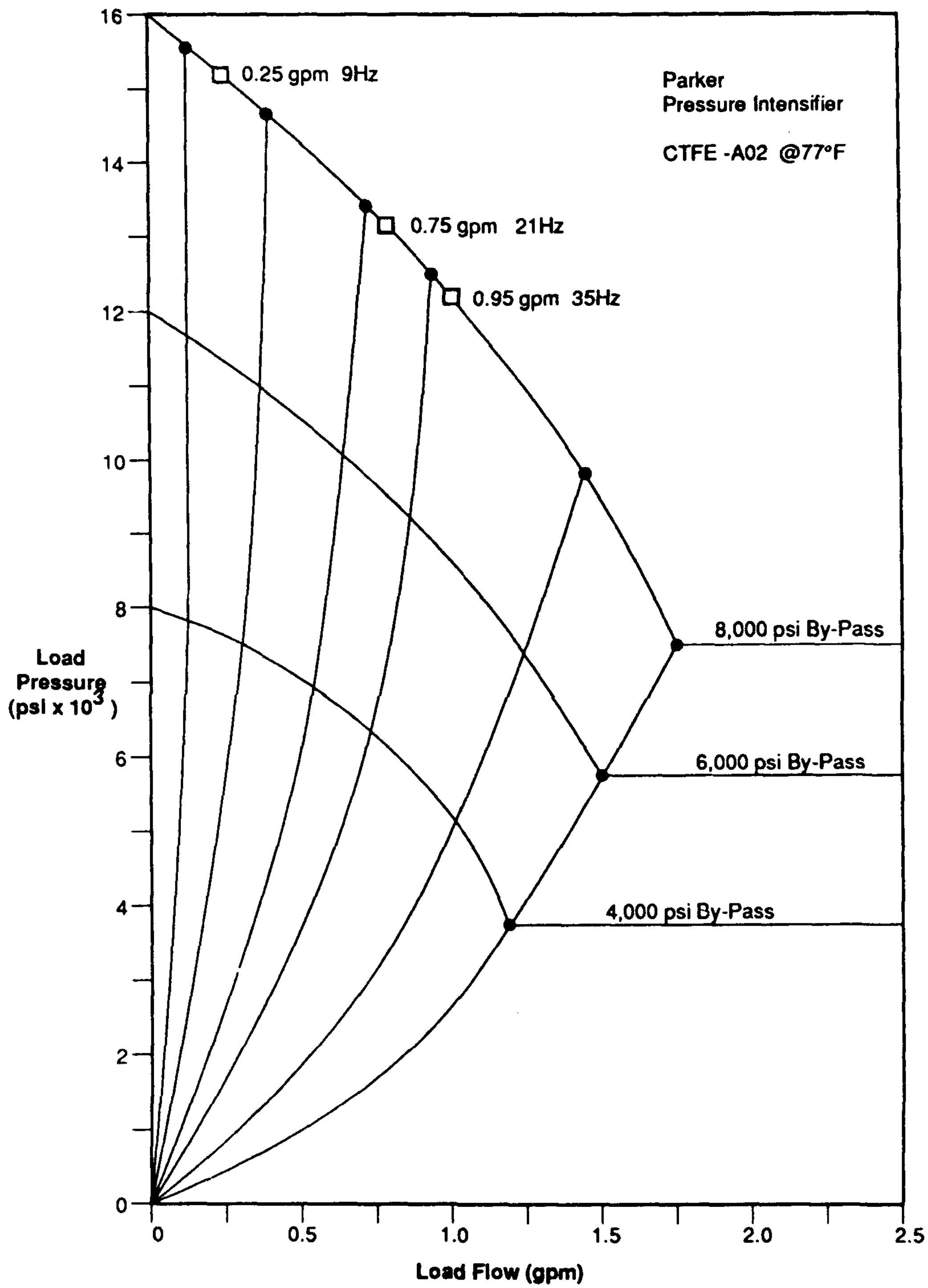


Figure 58. Pressure Intensifier Load Flow Curves

Intensifier Pressure - psi			Torque in. - lb	
Input	Output		Output	
	Extend	Retract	Extend	Retract
8100	14,100	13,800	19,400	19,100

Figure 59. Servohinge Torque and Maximum Intensified Pressure

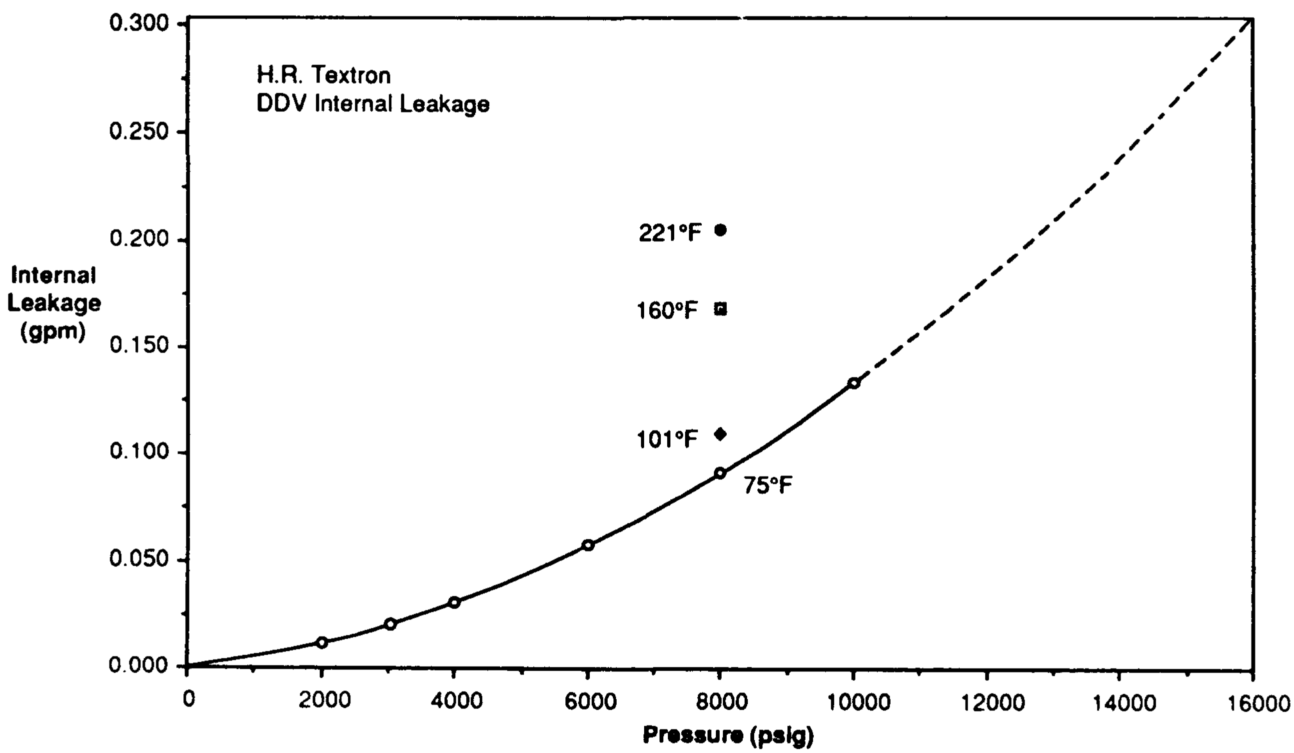


Figure 60. Direct Drive Valve Leakage

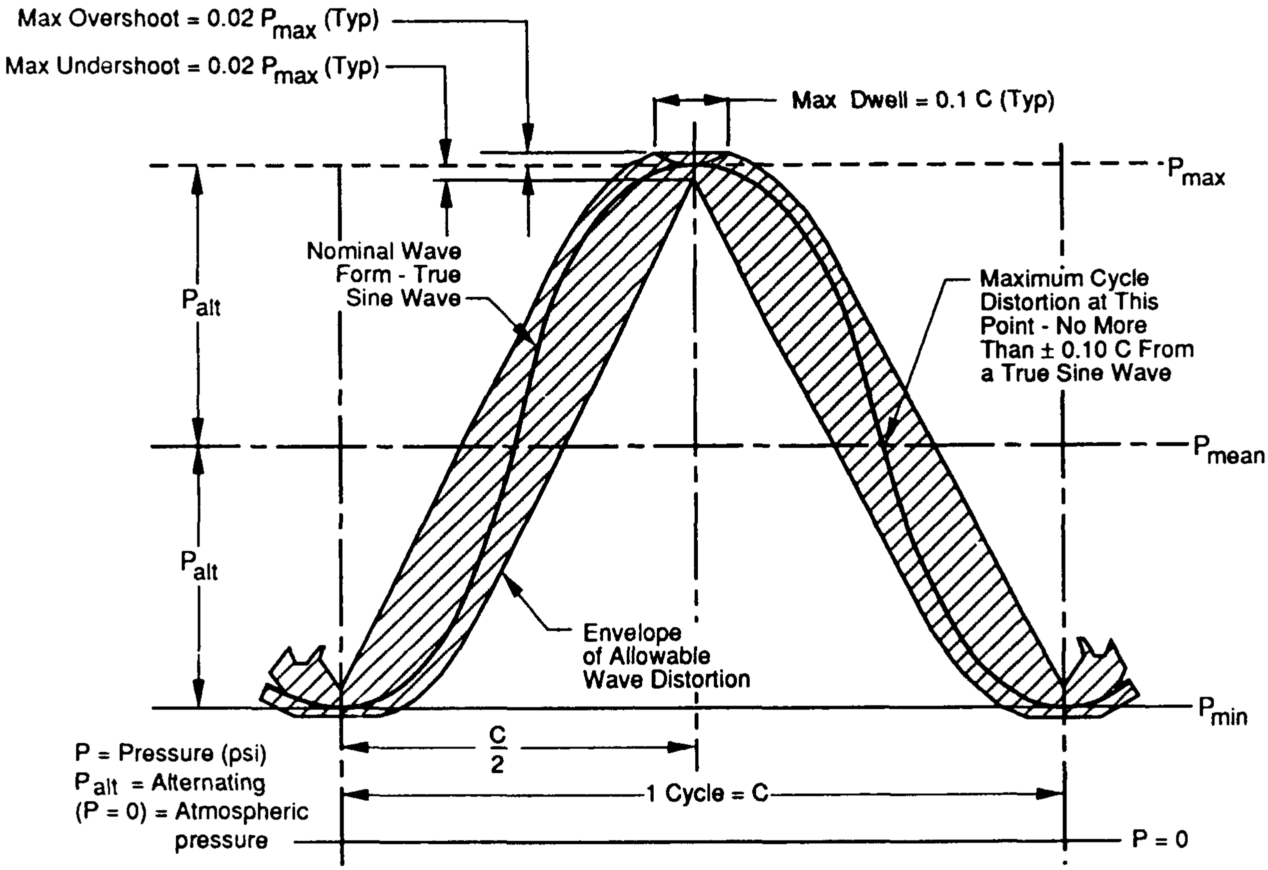
4.3.9 Manifold Impulse Testing - Each supplier was required to subject one hydraulic valve manifold to ten million impulse cycles. Figure 61 shows the spectrum and wave form used for this testing. Results from the tests that were completed prior to program termination are presented herein.

a. PTI Filter Manifold - The impulse test performed on the PTI filter manifold indicated infinite life capability for anticipated pressure environment. PTI analytically showed that the 6Al-4V titanium manifold would have neglible accumulated fatigue damage for variable pressure operation. The manifold was impulse tested from 0 to 8000 psi until failure. Figure 62 shows the failure modes and number of cycles at each failure. The first manifold failure, shown in Figure 63, occurred in the manifold porting with 66,784 cycles, the manifold porting was plugged as indicated in Figure 64 so that testing of the filter bowl/element housing could continue. The last failure occurred at 85,999 cycles. A crack appeared in the pressure bowl thread root (Figure 64). The original design stress analysis had shown that this area had the highest concentration of stresses.

b. APM Filter Manifold - The APM filter manifold is a two piece design which could be tested as two separate assemblies. The 6Al-4V titanium high pressure manifold was to be tested in three segments, ten thousand cycles from 0-8000-0 psi, two million cycles of 4000-8000-4000 psi and 0-8000-0 psi cycling to failure. Only the first phase of this test was completed wherein no failures occurred. The aluminum return manifold was tested for over 6.6 million cycles of the 10 million scheduled when seepage of fluid was detected at the case drain inlet port. Dye penetrant inspection of the unit revealed a crack between the case drain passage and the adjacent outlet passage. The crack had propagated thru the sealing area of the Rosan case drain port fitting port.

c. Cadillac Gage Manifold The aluminum metal matrix material used in this manifold was a reinforced aluminum composite using silicon carbide "whiskers" interspersed throughout the alloy. The impulse test results were not directly related to the metal matrix fatigue properties. The first failure occurred with 87,000 cycles of 0-8000-0 impulse; the pressure operated valve end cap bolts had yielded and lost preload. To continue testing a special clamp was designed to hold the POV end cap. During installation the new clamp was overtorqued which caused separation of the attachment flange on the manifold when 8000 psi was applied. This failure was not related to the fatigue allowable stress of the metal matrix but rather utimate strength.

After the first two failures, the impulse pressure range was changed from 0-8000-0 psi to 2000-8000-2000 psi and cycling was continued. At 124,000 cycles an external crack appeared in the manifold which originated at the intersection of two bores of different diameters. Further inspection revealed a second crack originating from similar geometry. These impulse failures showed that the metal matrix material is feasible for high pressure hydraulic manifolds but has the typical sensitivity to stress concentrations and machining flaws.



Application	Impulse Pressure and Number of Cycles P_{min} to P_{max} 0 to 8000	2000 to 8000	4000 to 8000	0 to 2000
Manifold Pressure	5×10^4	---	9.95×10^6	---
Manifold Return	---	---	---	10^7
Cylinder Ports	5×10^5	2×10^6	7.50×10^6	---

Figure 61. Sine Wave Impulse Test Curve

Number of Impulse Cycles	Remarks
18,316	Replaced "O" ring on check valve fitting
42,500	Replaced "O" ring on check valve fitting
47,674	Replaced "O" ring on filter bowl between bowl and module cavity
63,352	Replaced "O"ring on dummy relief valve
66,784	Unit developed a crack - See Figure 63 for location.
85,999	Housing fractured in area of threads. See Figure 64 for location.

Figure 62. PTI Filter Manifold Impulse Test Results

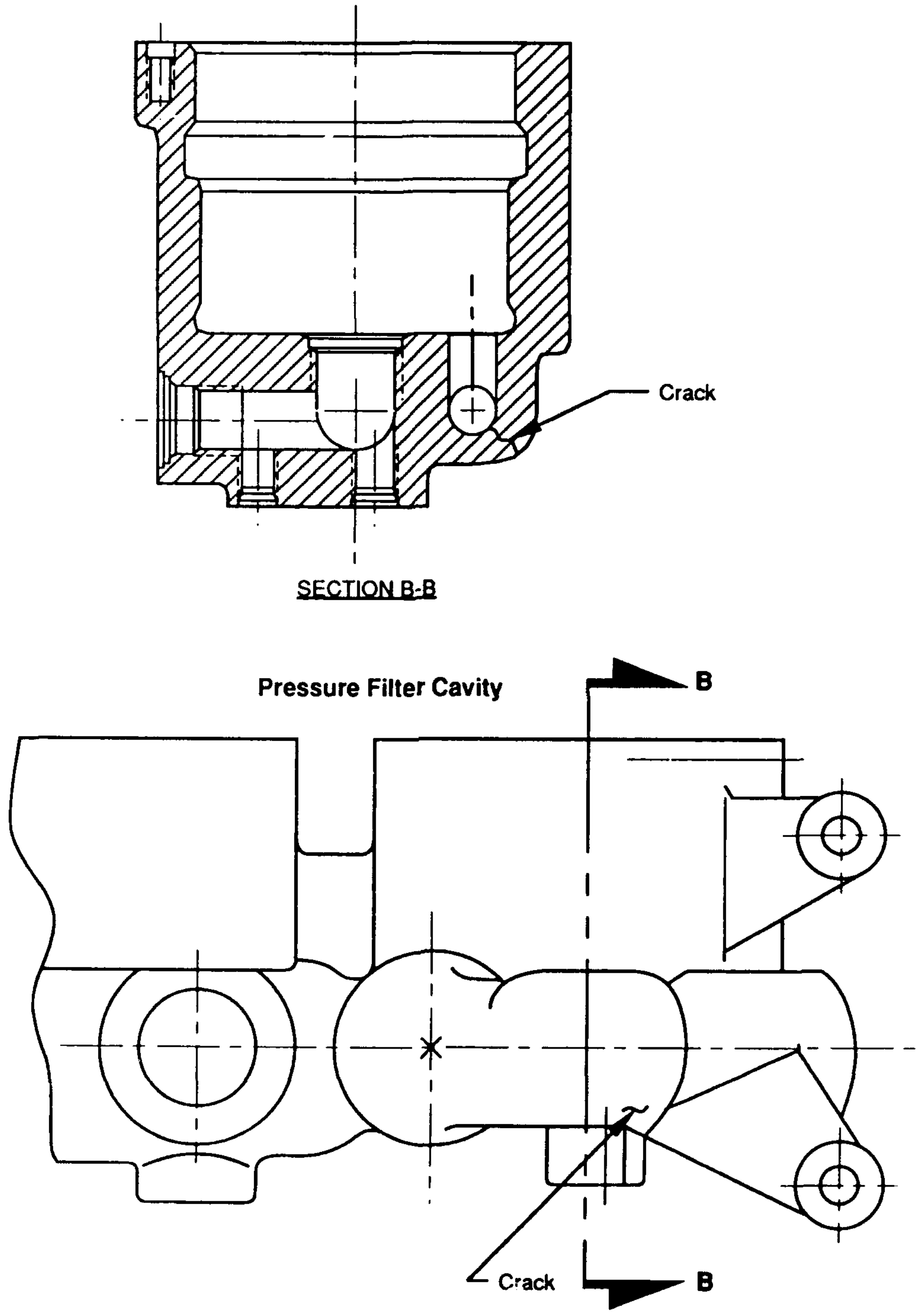


Figure 63. PTI Filter Manifold Failure

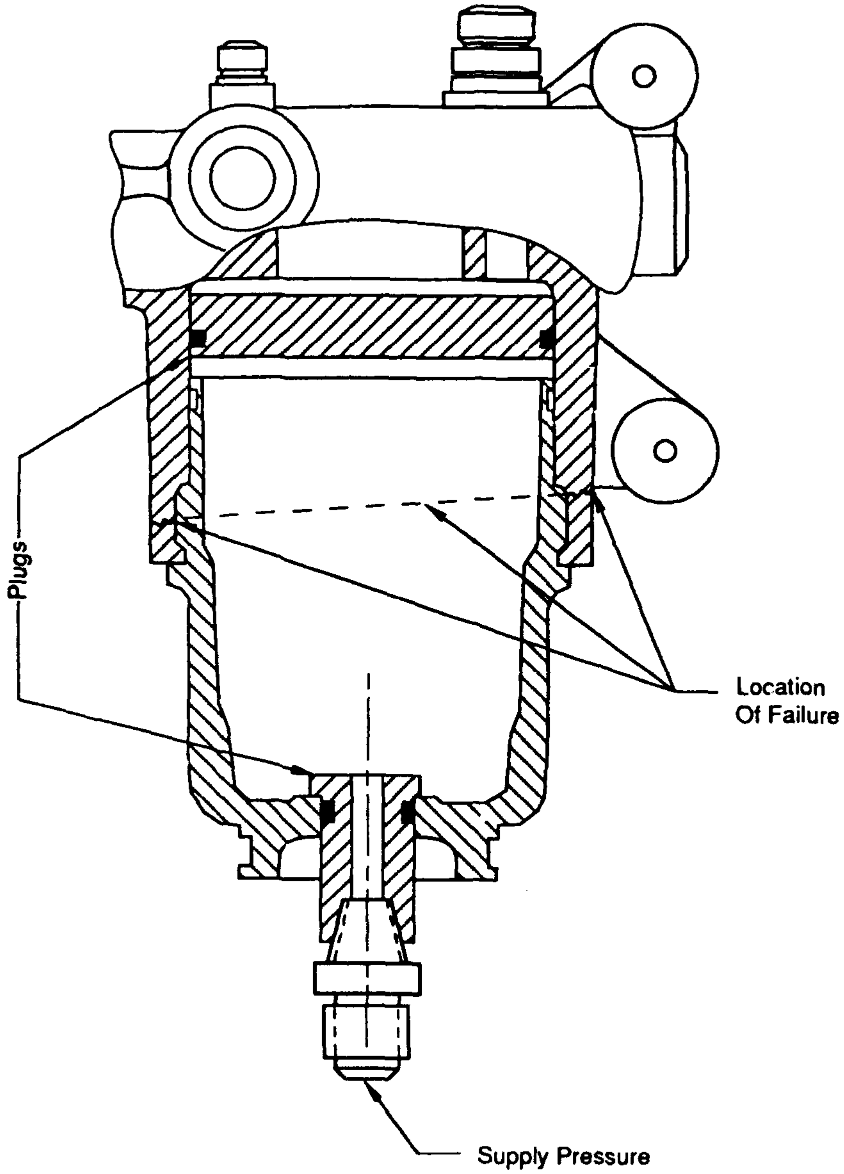


Figure 64. PTI Filter Manifold (Bowl) Failure

d. E-Systems Manifold - This manifold used 6Al-6V-2Sn titanium material. E-Systems analytically showed that the manifold was capable of 5.8 million impulse cycles. After 325,000 impulse cycles of 0-8000-0 psi, an end cap failed. This failure was not considered a relevant failure since it was caused by using a functional mode selector valve rather than a mockup valve which would have been unable to move within the manifold and damage the end cap.

4.3.10 E-Systems Stabilator Actuator Endurance Testing - Endurance testing at the supplier's facility accumulated 1.2 million operating cycles on one unit operating at constant 8000 psi supply pressure. The test was concluded when the actuator was needed for installation on the LTD for continued operation in the 500-hour system endurance test. No failures occurred; however, there was a valuable lesson learned. In order to improve reliability and reduce weight, the main control valve sleeve was installed into the titanium manifold as a shrink fit.

Shrink fit sealing of the sleeve porting lands allows elimination of 8 O-rings and 16 back-up rings which reduces the length of the sleeve by almost half. Since the titanium manifold and the 440C sleeve differ in cooling/heating rate and differ in thermal coefficient of expansion, linear dimensional variances can exist because of linear strain from clamping.

Recognizing from previous experience that this could occur, E-Systems subjected the manifold (after sleeve installation) to several thousand pressure impulse cycles intended to allow the sleeve to seek a relaxed position. After this procedure was accomplished, the slider was then flow ground and matched to the sleeve. After the 1.2 million endurance test cycles and several hours of endurance testing on the LTD, the actuator had developed a null mismatch between the two hydraulic systems. This indicated that the sleeve had undergone a nonuniform axial shift from further relaxation. More production development is indicated for the use of shrink sleeves in dual hydraulic system titanium manifolds. Even though this particular actuator was easily corrected, a technique must be developed to guarantee that null mismatch will not occur after delivery to a production program

SECTION V

PHASE V - LABORATORY TECHNOLOGY DEMONSTRATOR FABRICATION AND TEST

5.1 PROGRAM TASK FLOW (Program Statement Of Work)

5.1.1 Task 5-1 Fabricate and Assemble Laboratory Technology Demonstrator - Fabrication of the facility started with the layout of the facility including the pump house and control room, which were completed in late '88. When equipment installation and top assembly drawings became available, load fixture design and fabrication was initiated along with central system layouts.

5.1.2 Task 5-2 Perform Function Checkout of Subsystems - As each central system or subsystem was completed, that portion was leak checked. Supply circuits were pressurized to 1000 psi to perform an initial leak check and then to 12,000 psi as a proof test. Return systems were tested to 1000 psi and then 8000 psi except for the central system which had a maximum pressure of 3000 psi.

5.1.3 Task 5-3 Performance Test on System to Verify Computer Analysis - Performance tests were conducted on various subsystems to verify the validity of the computer programs including SSFAN and HYTRAN. HSFR was not evaluated due to the lack of 40 GPM pumps.

5.1.4 Task 5-4 Perform 500 Hour Durability Test - Of the specified 500 hours of durability (endurance) test, 324 hours were completed prior to the programs termination. This was accomplished in segments of 2 hour duty cycles simulating a tactical aircraft mission.

5.1.5 Task 5-5 Obtain Periodic Fluid Samples - Fluid samples were taken from each of the three central systems, for MCAIR and WRDC analysis. The samples were taken every 10 hours for the first 200 hours and every 50 hours thereafter. In addition, special on-line particle counting was used for each of the systems with both 1-micron and 5-micron filters.

5.1.6 Task 5-6 Perform Component Removal and Battle Damage Repair Demonstration - Battle damage repair was to be demonstrated by splicing several hydraulic lines with available repair fittings. Removal and installation time and difficulty was to be reported for several types of equipment. An additional 50 hours durability test was to be performed following this task. This task was not completed due to contract termination.

5.1.7 Task 5-7 Perform Reliability and Maintainability Assessment - Reliability and maintainability assessments were conducted by MCAIR personnel using test results and failure data documented during the durability testing.

5.1.8 Task 5-8 Perform Equipment Teardown and Inspection - Equipment disassembly and inspection was not performed for the majority of the equipment due to program termination. Disassembly for failure analysis was completed for several components.

5.1.9 Task 5-9 Industry-Wide Oral Presentation of Phases IV and V. - The final oral presentation was held at MCAIR prior to the completion of the test effort. All prime airframe contractors as well as the participating subcontractors were invited along with government personnel. The briefing included discussion of equipment, test results, recommendations, R&M assessments and a tour of the LTD facility.

5.2 PERFORMANCE TEST RESULTS

Performance testing was conducted on the major components of the system. These tests were conducted as a system level test on each component individually. The test results presented herein should not be compared to those conducted at the suppliers as acceptance tests.

5.2.1 Servoactuators - System level performance tests were conducted on each of the flight control servoactuators with varying conformance of either acceptance test data, which is presented in Section 4.0, or in subsequent repeat tests due to configuration changes.

Frequency response had the greatest variance since it is influenced by system variables. The inertia of the surface or load provides the greatest reduction in frequency response and several test fixtures had this simulation. The test fixtures also had an additional amount of dynamic degradation resulting from the inertia, coulomb friction and damping in the load cylinders. Also, in order to have a reasonable stability margin when operating with these dynamic conditions the control loop gains were reduced from that used in the suppliers' acceptance tests.

There was also a disparity between low and high amplitude frequency response. Optimum frequency response peaked in between measured high and low values, generally around two percent. At lower amplitudes, response was degraded by valve overlap and friction when operating near the threshold of sensitivity. Frequency response improves with increased amplitude until flow saturation occurs. System level frequency response data are presented for each actuator in Figures 65 thru 82; however, the values should not be expected to compare to those values shown in acceptance testing.

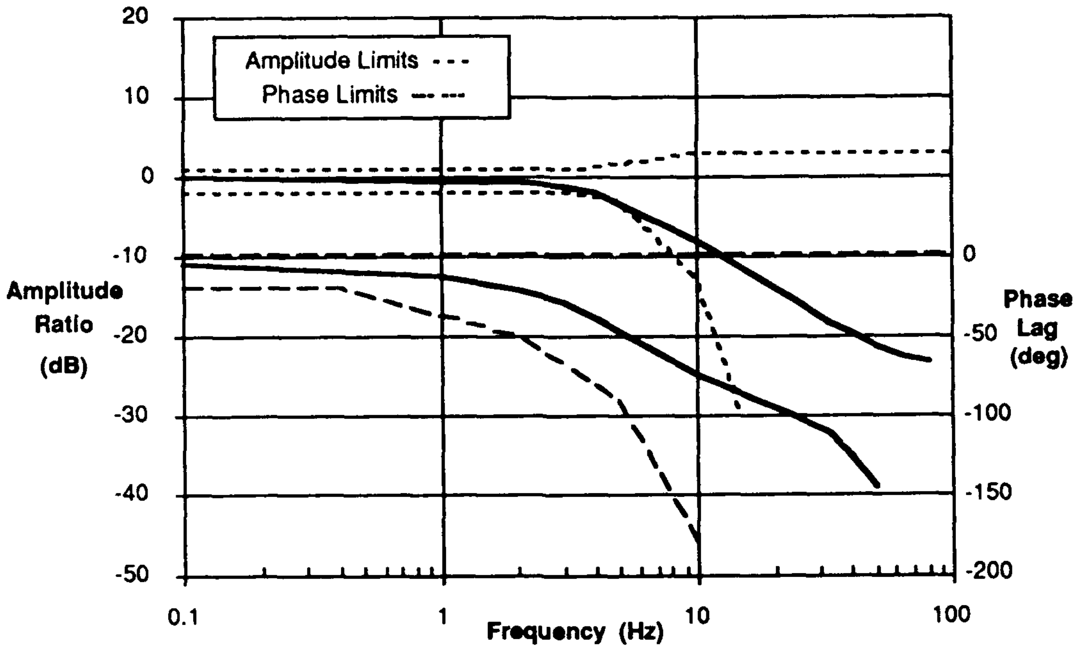


Figure 65. Stabilator Frequency Response
2% Amplitude

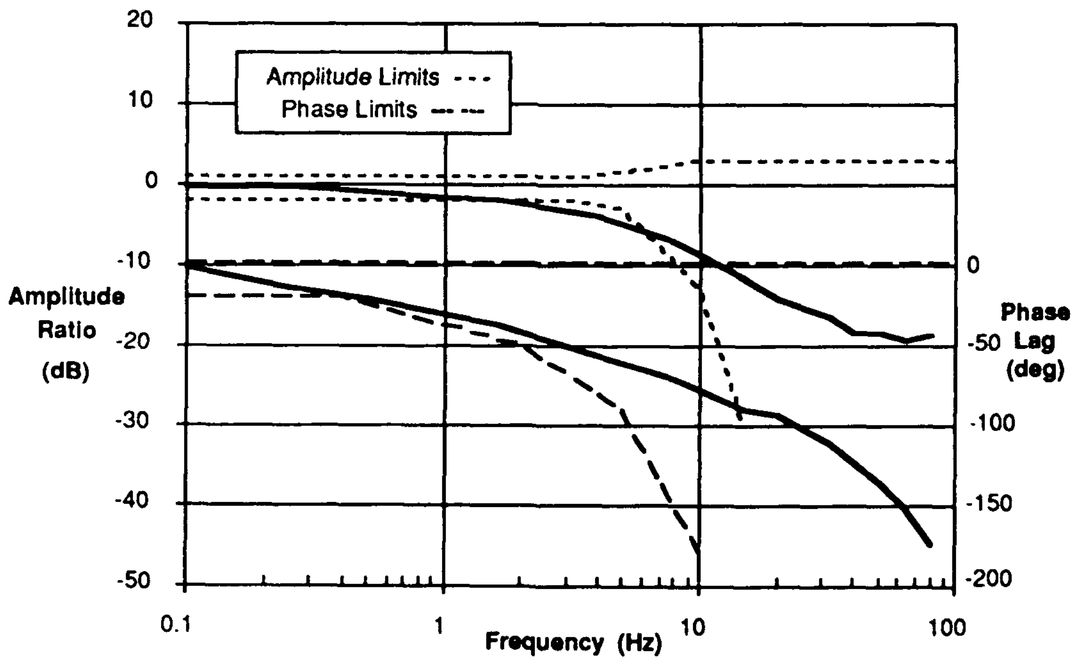


Figure 66. Stabilator Frequency Response
10% Amplitude

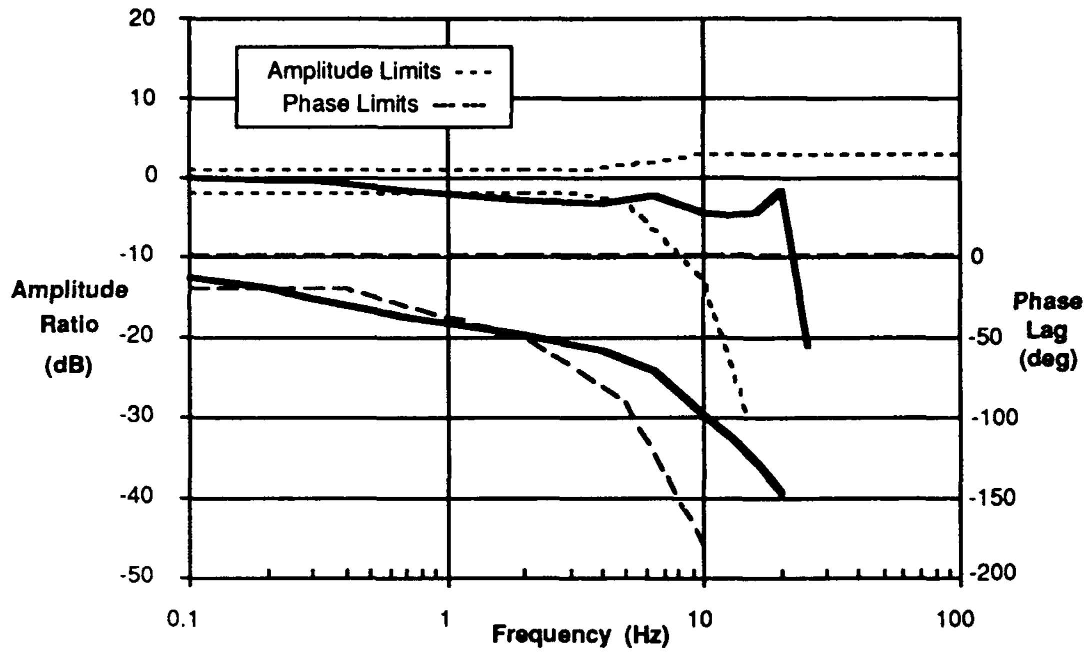


Figure 67. Canard Frequency Response
2% Amplitude

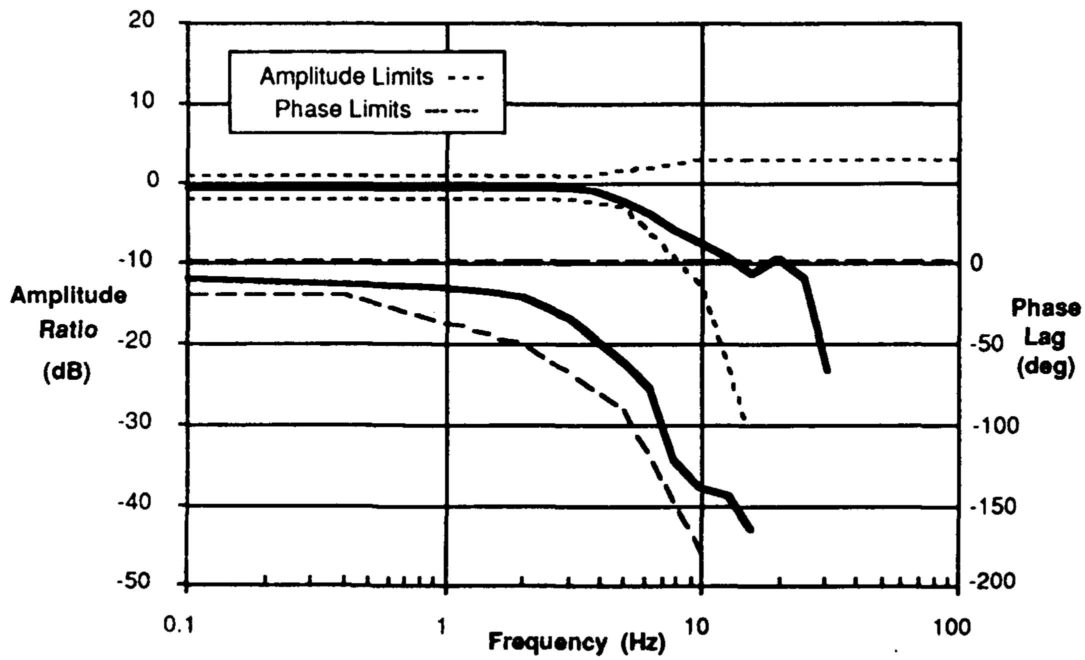


Figure 68. Canard Frequency Response
10% Amplitude

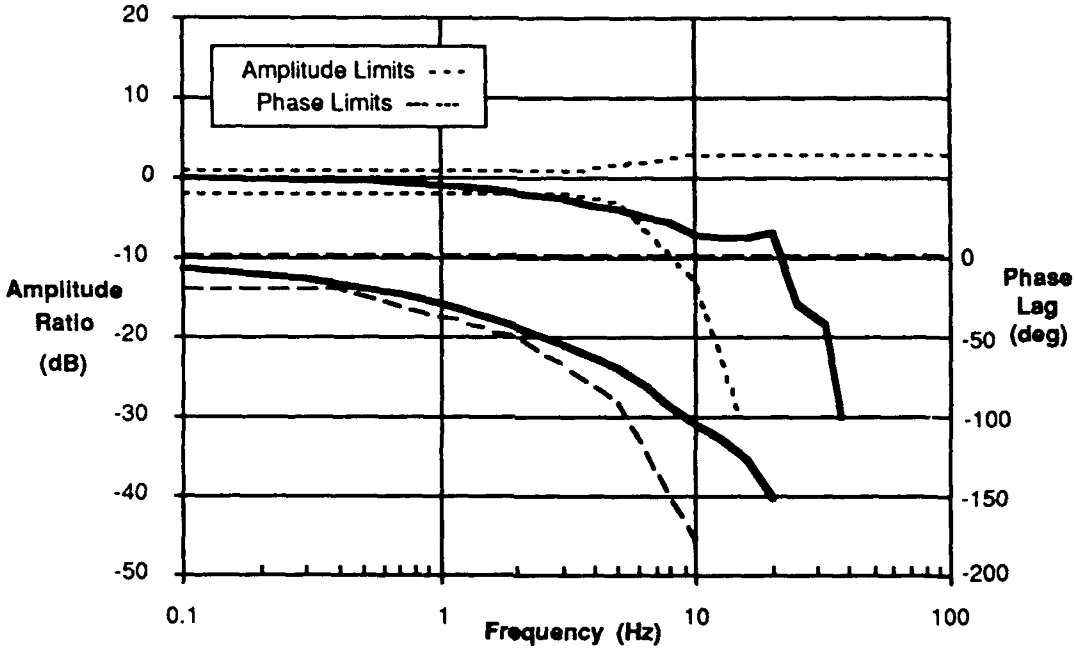


Figure 69. Flaperon Frequency Response
2% Amplitude

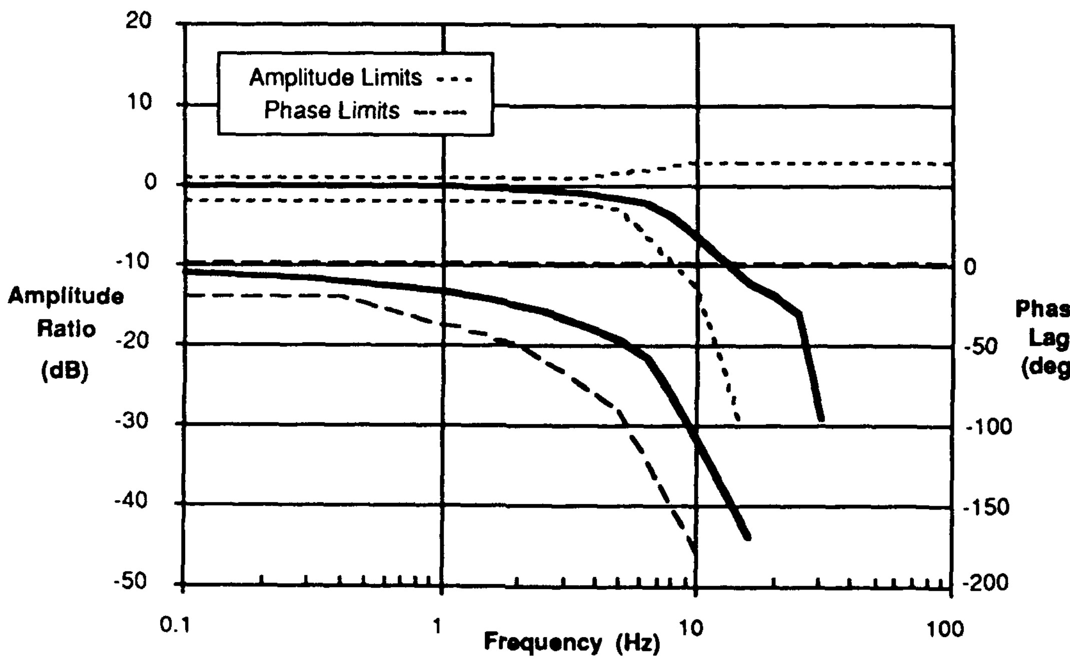


Figure 70. Flaperon Frequency Response
10% Amplitude

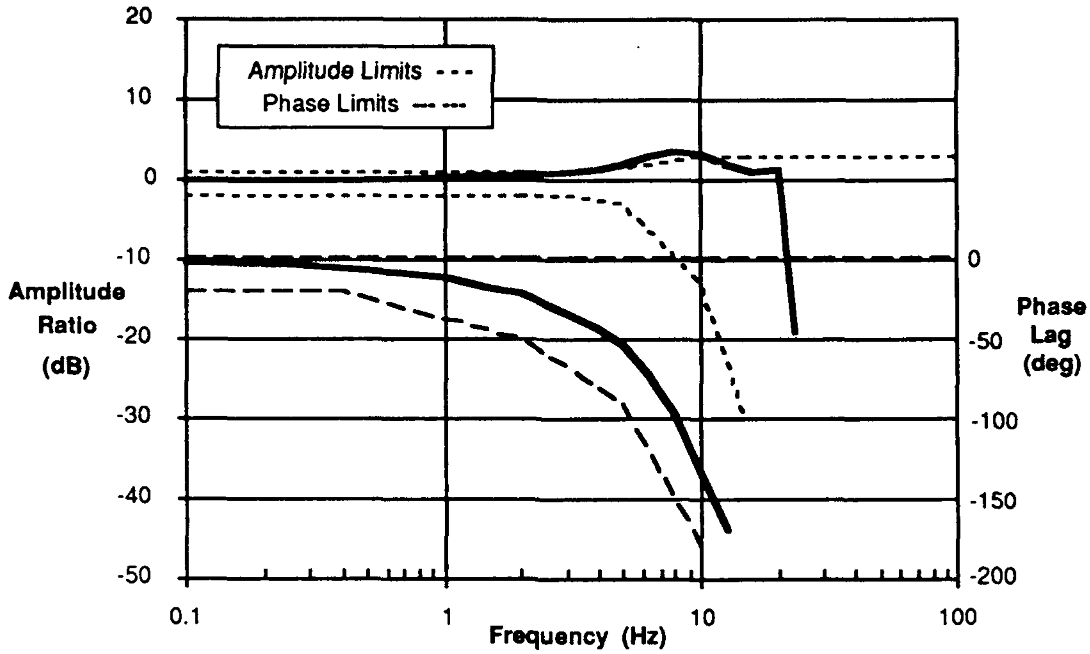


Figure 71. Rotary Vane Frequency Response
2% Amplitude

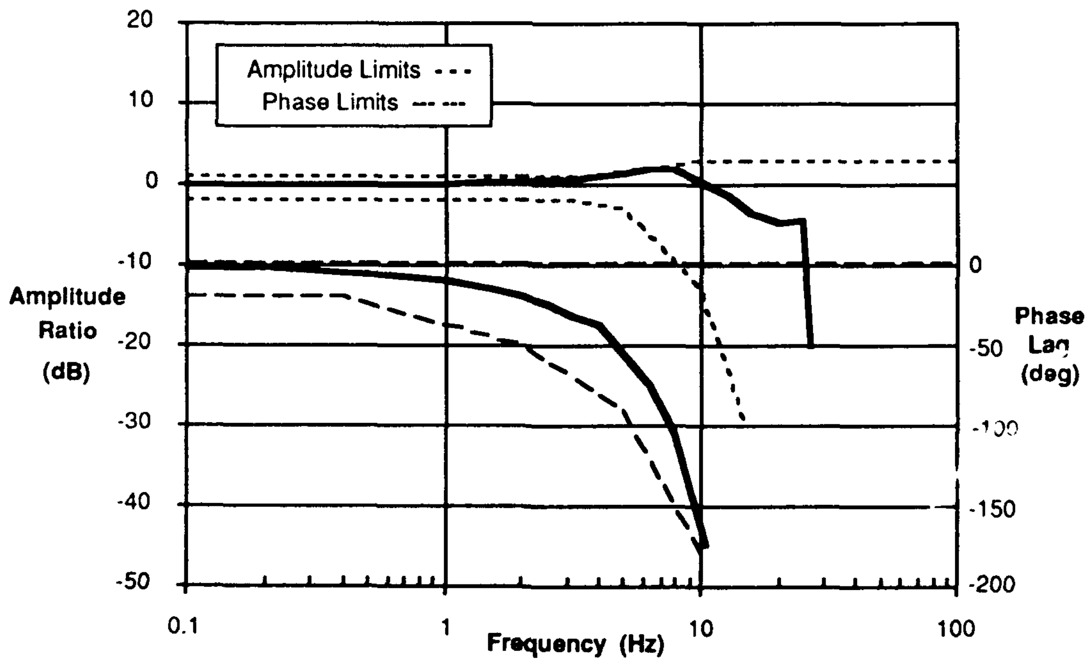


Figure 72. Rotary Vane Frequency Response
10% Amplitude

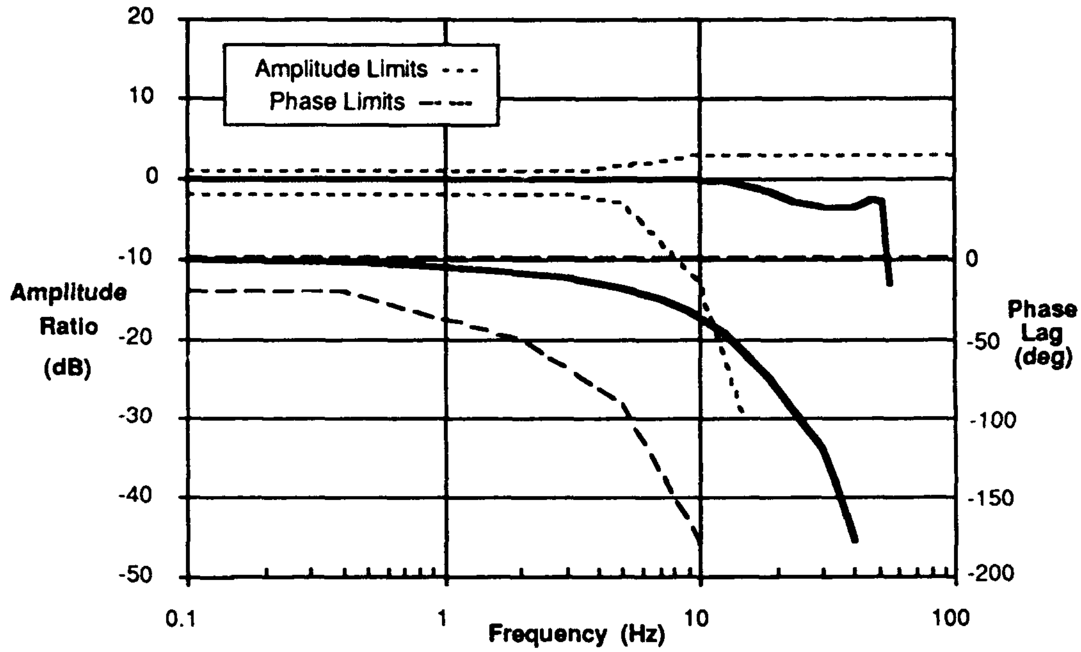


Figure 73 . Linear-Rotary Actuator Frequency Response
2% Amplitude

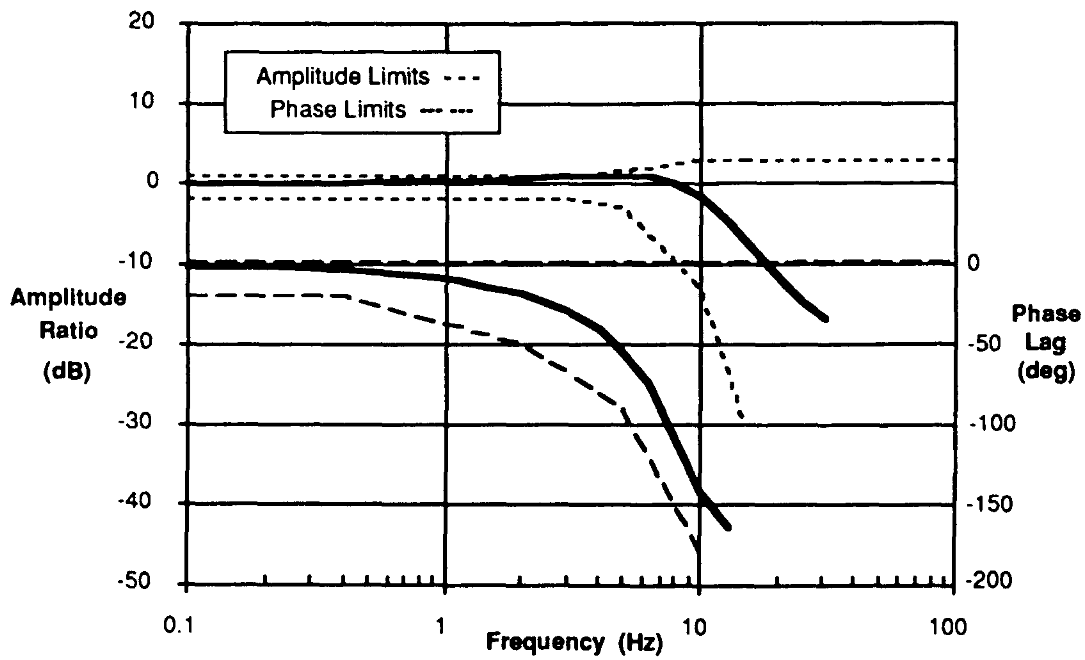


Figure 74. Linear-Rotary Actuator Frequency Response
10% Amplitude

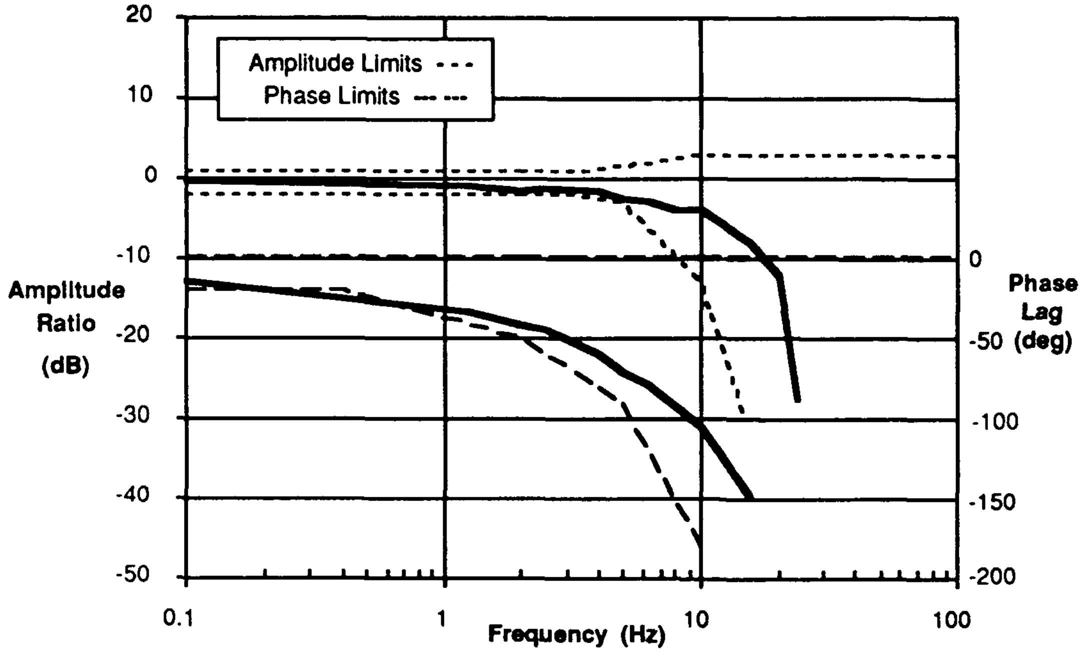


Figure 75. Divergent Flap Frequency Response
2% Amplitude

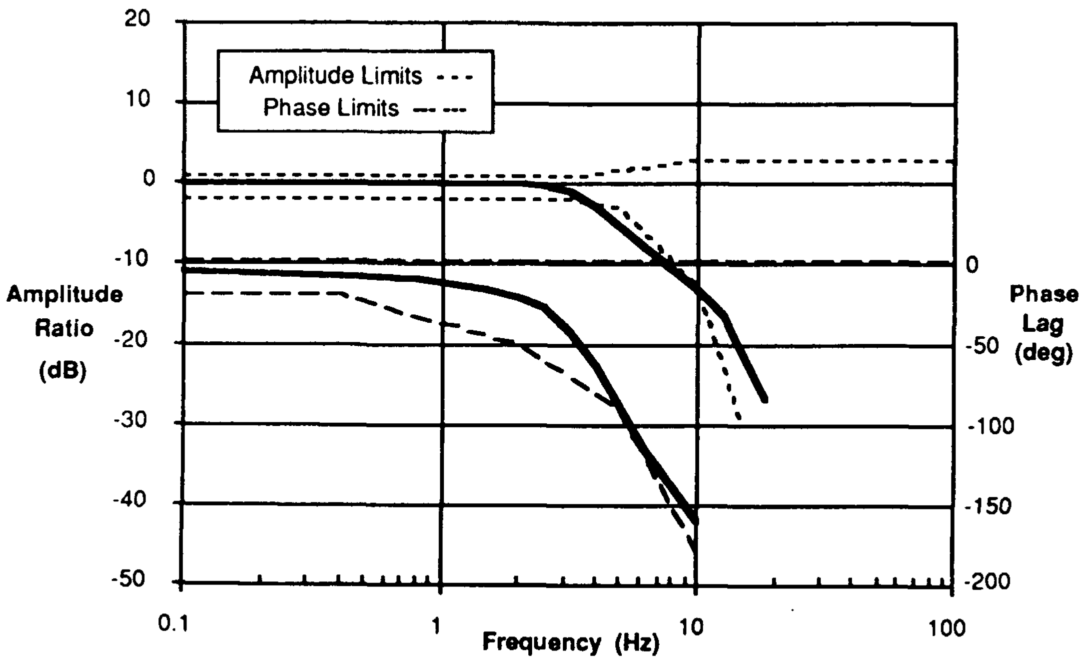


Figure 76. Divergent Flap Frequency Response
10% Amplitude

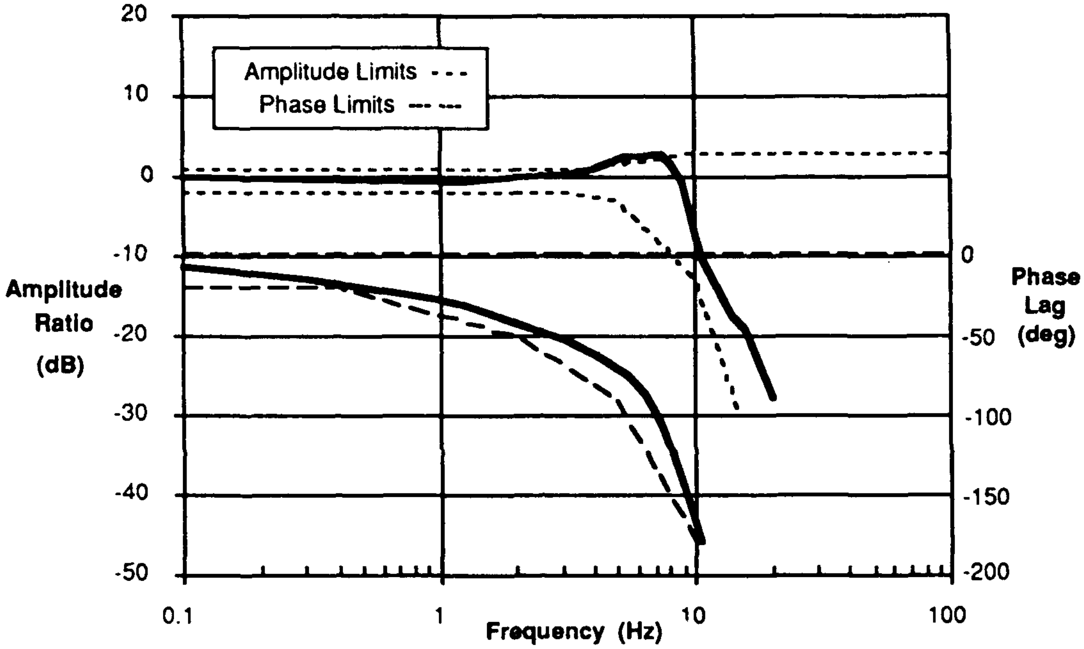


Figure 77. Convergent Flap Frequency Response
2% Ampitude

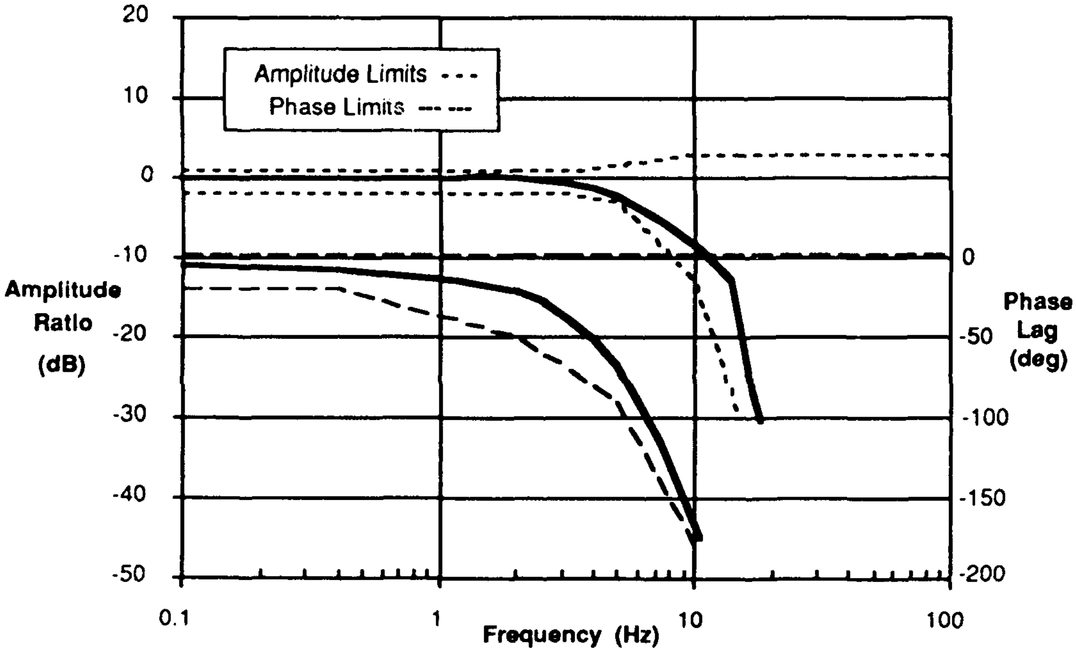


Figure 78. Convergent Flap Frequency Response
10% Amplitude

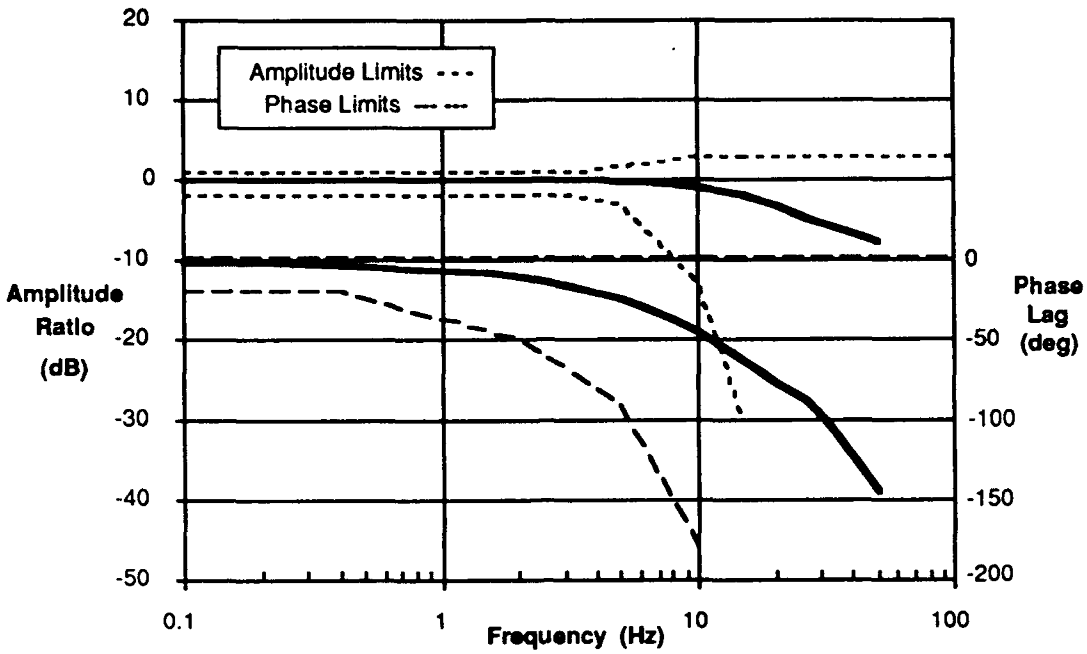


Figure 79. Reverser Vane Frequency Response
2% Amplitude

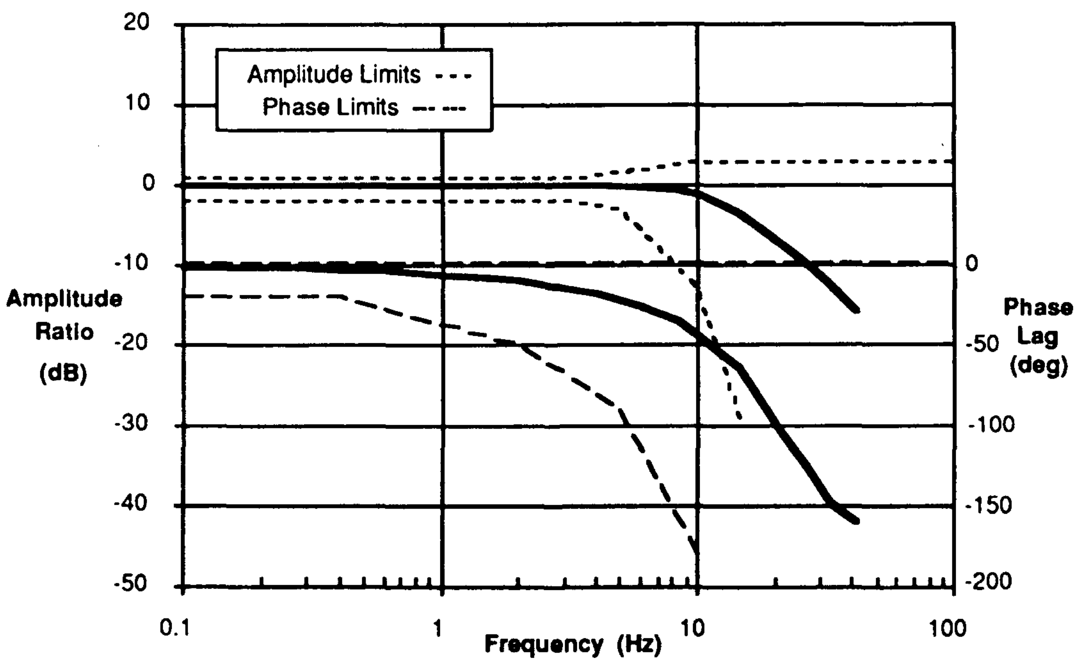


Figure 80. Reverser Vane Frequency Response
10% Amplitude

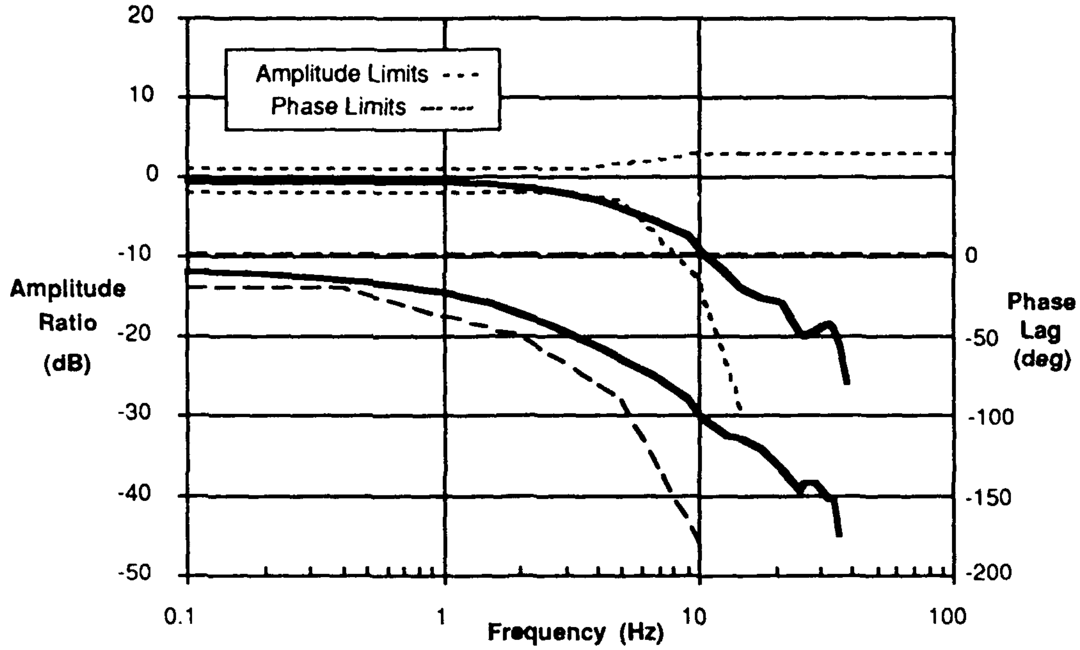


Figure 81. Arc Valve Frequency Response
2% Amplitude

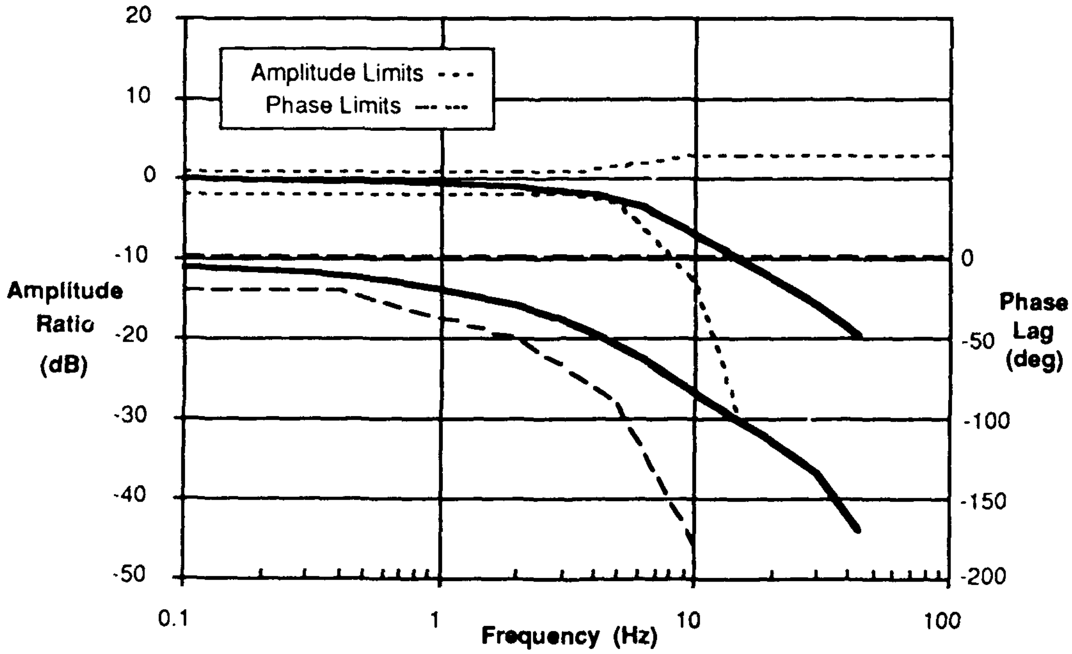


Figure 82. Arc Valve Frequency Response
10% Amplitude

No-load actuator rates are shown in Figure 83, along with the specification values. The rates shown for the canard and stabilators are with flow augmentation equipment. Rates without flow augmentation are effectively doubled due to the low loss main control valve and the elimination of the flow restriction created by the jet pumps.

Actuator	Direction	No-Load Rate (in/sec)	
		Actual	Spec
L/H Stabilator	E R	6.5 7.4	8.2
R/H Stabilator	E R	7.2 7.6	8.2
L/H Canard	E R	7.7 9.0	8.2
L/H Rudder		140 deg / sec	105 deg / sec
R/H Rudder		112 deg / sec 300 deg / sec (1)	105 deg / sec
L/H Flaperon	E R	2.20 2.25	3.3
Divergent Flap	E R	10.9 10.9	11.8 (2)
Convergent Flap	E R	11.4 9.7	7.2 (2)
Reverser Vane	E R	5.6 5.0	4.0 (2)
Arc Valve	E R	13.2 9.6	7.34
Diffuser Ramp	E R	0.45 0.38	0.75 0.50

Notes: (1) Not flow restricted
(2) Rate limited up to at least 2/3 stall load
E denotes extend direction
R denotes retract direction

Figure 83. Actuator No-Load Rates

System level hysteresis data were plotted for each actuator at approximately 150 hours through the endurance test. The primary flight control actuators had over 500,000 cycles when the data were recorded. Comparison with data taken earlier in the test effort revealed no change; see results in Figure 84.

Actuator	Endurance Hours	Hysteresis (% of Full Stroke)
L/H Stabilator	150	1.1
R/H Stabilator	150	0.6
L/H Rudder	120	0.1
R/H Rudder	100	0.1
L/H Flaperon	150	0.4
L/H Reverser Vane	150	0.1
Convergent Flap	150	0.1
Divergent Flap	150	0.8
Arc Valve	138	0.3
Diffuser Ramp	150	2.0 (1)

Notes: Data taken 14 Feb '90 during a .01 Hz, 10 volt peak sinusoidal command under no-load conditions.
(1) High hysteresis caused by non-linearity in prototype ram position transducer.

Figure 84. Actuator Hysteresis

5.2.2 Pumps - A limited amount of testing was conducted on several of the Abex 15 gpm pumps, in order to evaluate the system level performance of variable pressure pumps. Heat rejection and efficiency considerations make low case drain flow more critical with high pressure pumps. Figures 85 and 86 present case drain flow versus pressure at no and full outlet flow rates and case drain versus outlet flow at 8000 psi, respectively. Case drain versus pressure was also recorded for other pumps with very similar results. A nearly linear relationship between case drain flow and pressure is shown.

Pump pressure frequency response data were plotted for the 15 gpm variable pressure pumps. Figure 87 shows a typical response for a 1% amplitude cycle (+/- 50 psi) at 3050 psi in the PC-2 system while Figure 88 shows the same type response for a 2% amplitude cycle (+/- 100 psi) at 7700 psi in the PC-1 system. The pressurized volume in these two systems is approximately 175 cubic inches.

A step response test was performed in the PC-2 system with a pressure command from 0 to 10 volts; this corresponds to a 3000 to 8000 psi outlet pressure. Figure 89 presents these results and shows that the pump response lags the initial pressure command by 25 - 30 milliseconds, when the shaft torque and outlet begin to increase. The pump produces full flow about 65 milliseconds, and the pump outlet pressure reaches 8000 psi 150 milliseconds, after the initial command.

5.2.3 Central System Components - The reservoirs used in each system utilized a trapped bootstrap to provide constant base pressure during variable pressure operation. A metal bellows 8000 psi accumulator was used to supply the bootstrap pressure when pump outlet pressure was less than 8000 psi. Each reservoir had three reservoir level sensing (RLS) circuits. The pressure switch on RLS circuit "A", the first circuit to shut off when a leak occurs, was used as a failsafe indication which triggered a pump drive shutdown before excess fluid loss would induce pump damage. An auxiliary RLS valve, manufactured by Gar-Kenyon was added to minimize the pressure drop of the supply to the engine nozzles. The flow requirement for each nozzle circuit is 30.0 gpm. Without 40 gpm pumps, the performance of the RLS and this circuit could not be fully evaluated.

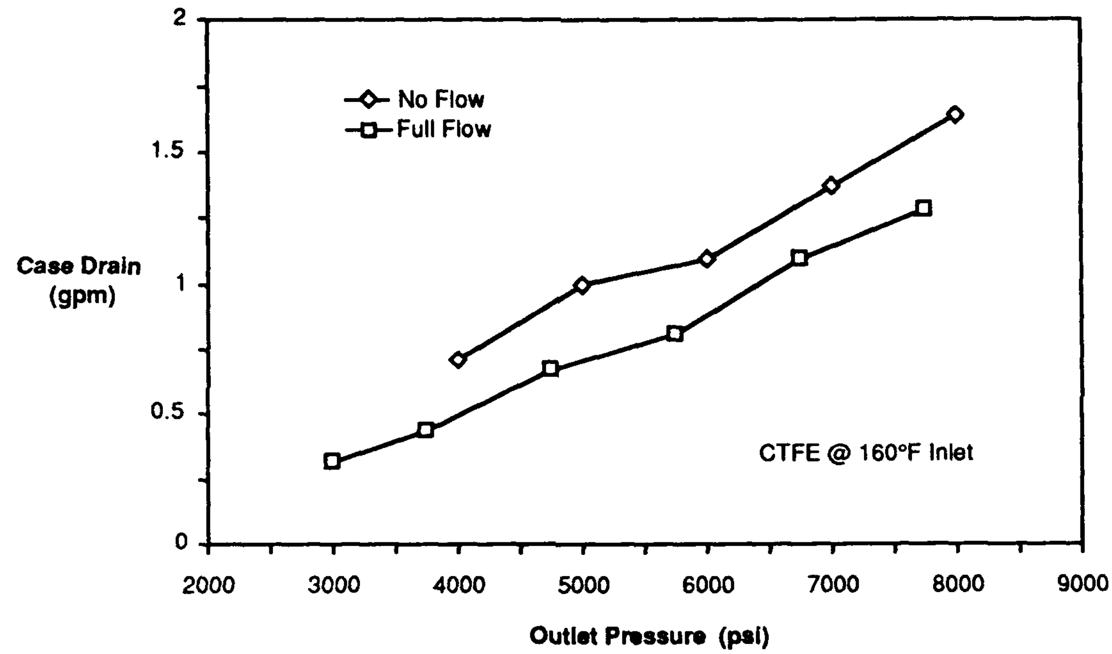


Figure 85. Pump Case Drain vs Discharge Pressure

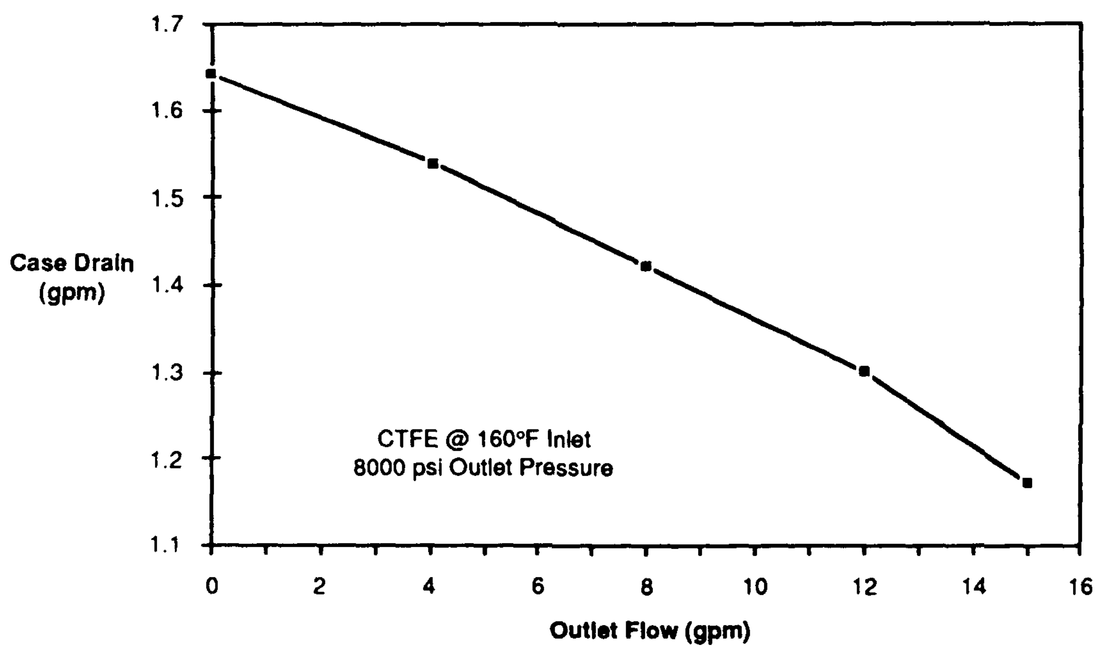


Figure 86. Pump Case Drain vs Discharge Flow

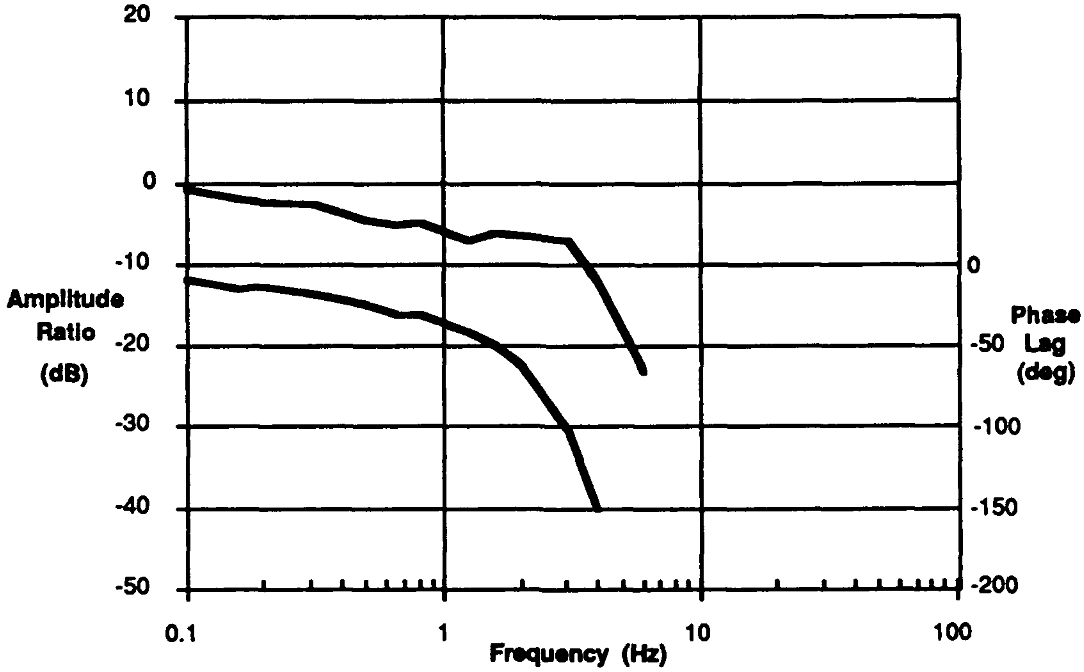


Figure 87. Pump Frequency Response
1% Amplitude

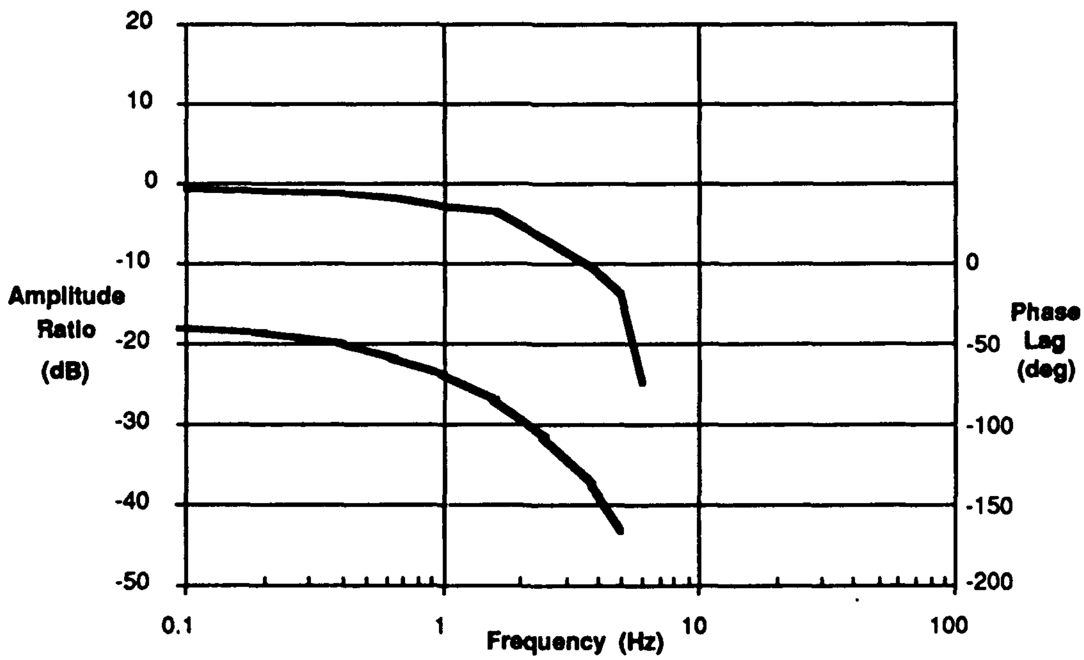


Figure 88. Pump Frequency Response
2% Amplitude

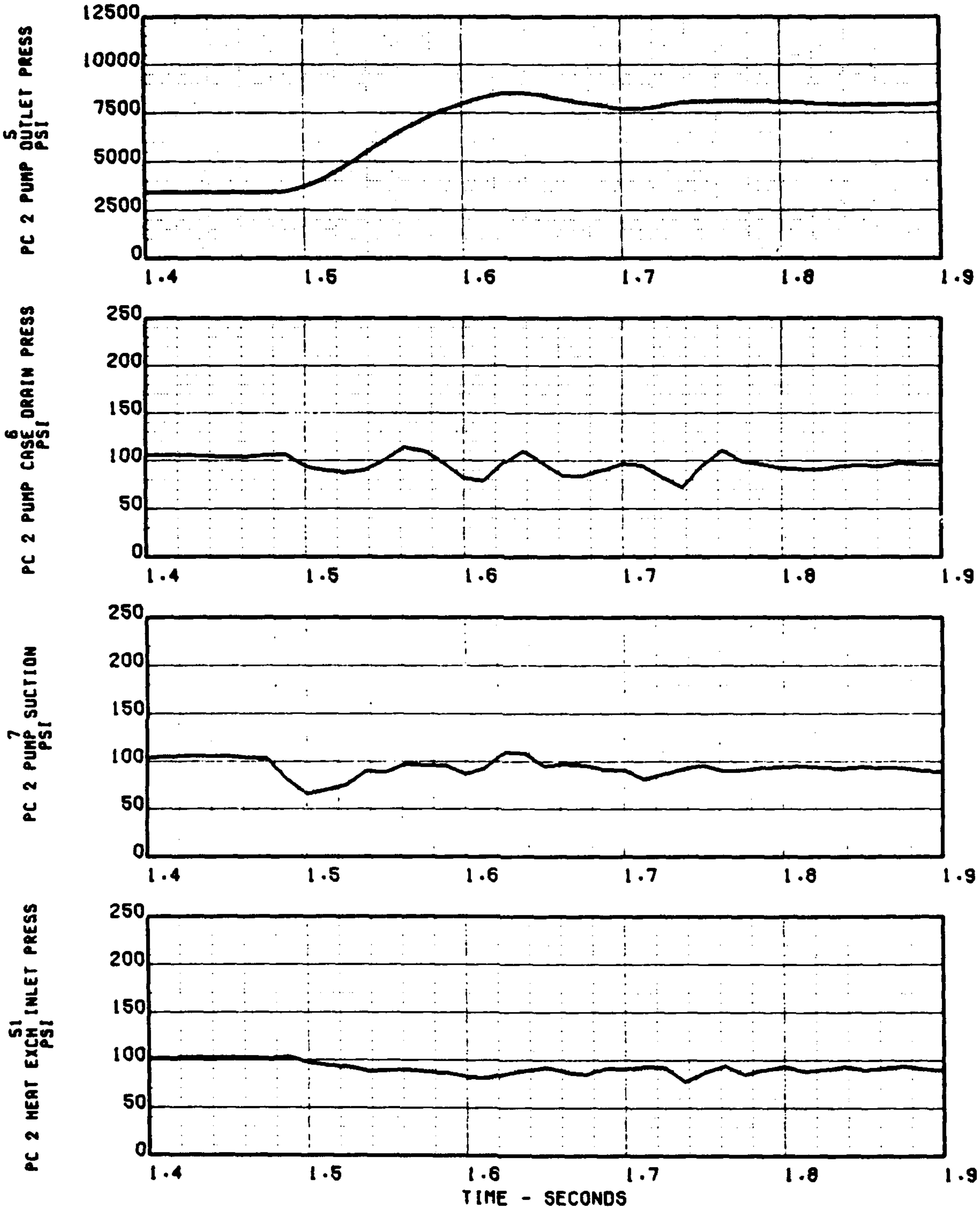


Figure 89. Abex 15 gpm Pump Step Response

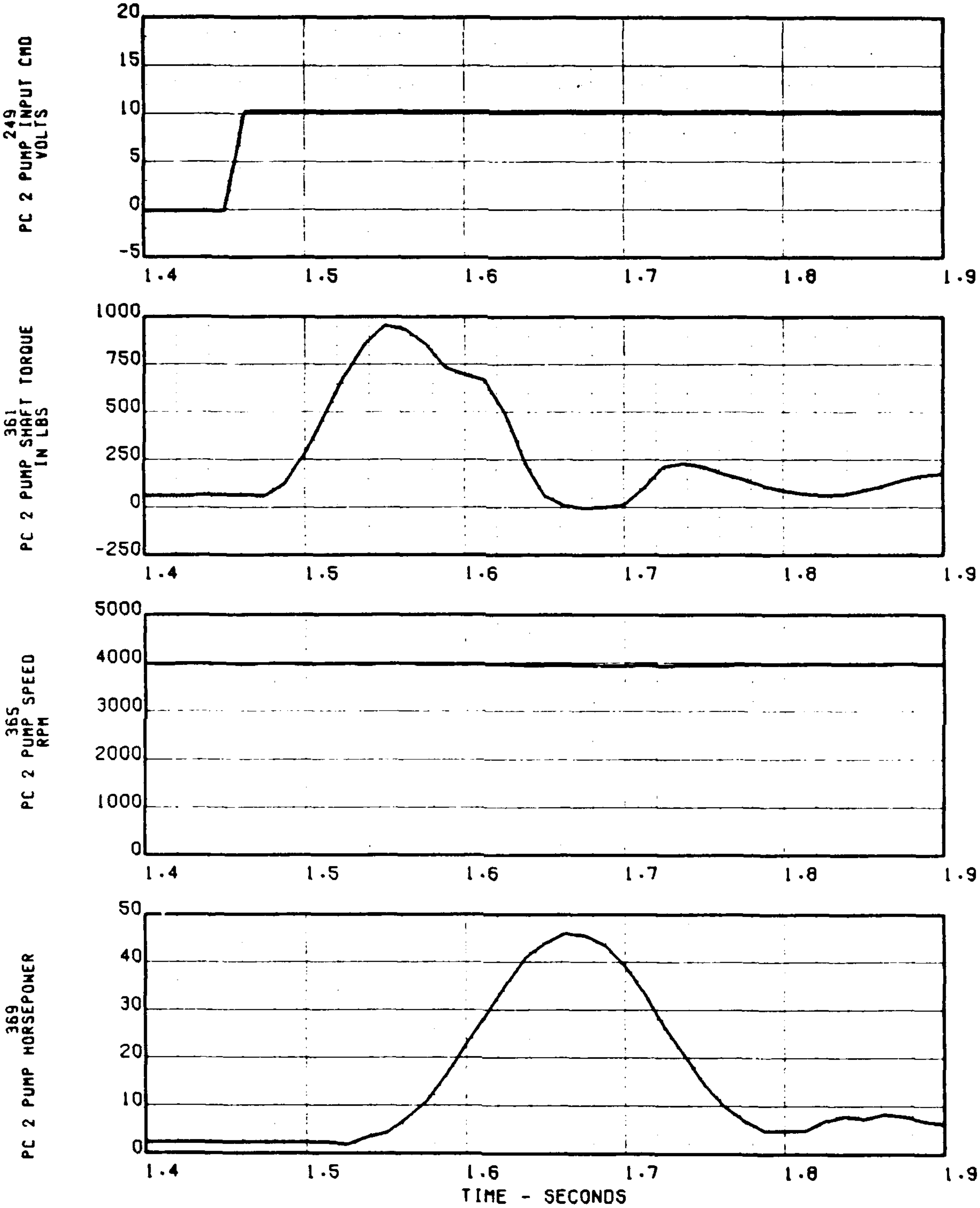


Figure 89. (Concluded) Abex 15 gpm Pump Step Response

Two F-15E fuel/oil heat exchangers were used to cool the hydraulic systems, water being the heat sink. Each heat exchanger cooled two hydraulic systems. PC-1 and UT-1 were plumbed to one heat exchanger, and PC-2 and UT-2 the other. Each heat exchanger had four separate cores. The largest core cooled the utility systems, and the three smaller cores were dedicated to the PC systems. All the heat exchanger cores were utilized throughout most of the program in order to keep fluid temperatures below 225 degrees F. Relief valves were installed in parallel to the heat exchanger/reservoir return circuit. Flow from the heat exchanger was directed through the appendage reservoir to reduce return pressure spikes at the heat exchanger. The relief valve setting in combination with the heat exchanger line sizing were increased to flow 10 gpm per system through the cooling circuit while minimizing pressure spikes transmitted to the heat exchanger core. During stabilator valve reversals, return line pressure spikes may reach 3800 psi at the actuator. This pressure must be attenuated before it reaches any central system components. Heat exchanger inlet pressures reached a maximum of 250 psi during 8000 psi operation and less than 200 psi during most of the variable pressure operation.

Two manufacturers, PTI and APM, provided filter manifolds with 1- and 5-micron elements for the demonstrator. The PTI manifolds were installed in the utility systems and the APM manifolds were installed in PC-1 and PC-2. The utility system was filtered with 1- and 5-micron elements, but the 1-micron elements were used most of the time. Since UT-1 and UT-2 pumps share a common reservoir as a single system, the return filters in that system were either 1- or 5-micron elements, not a combination. Since the PC systems are completely separated, a system to system comparison between 1- and 5-micron filter elements was attempted. One micron elements were installed in the PC-1 system while the PC-2 system used 5-micron elements for the entire test period. One micron elements have had limited use in aircraft hydraulic systems including the Lockheed HTTB transport and the Sikorski CH53 helicopter development programs.

It was not foreseen that taking fluid samples could introduce enough contaminants into the sample to totally mask the actual sample. Special precautions had been tried previously to get a good sample from a one micron system but without success. This included using ultraclean bottles with a puncture cover, long spigots and extended flushing time. Comparison of 1- and 5-micron filtration was accomplished by on-line particle counting under dynamic conditions. This measurement system was installed and operated by the PALL Corporation. Particle counting on fluid samples from upstream and downstream of the return line filter was performed over the entire 2 hour duty cycle. The results of these tests are summarized in Figure 90 and include the average and median particle counts of the four different elements. Both the PC-1 and the utility system 1 micron filters reduced the median number of particles, in the 1- to 3-micron range, when compared to their respective 5-micron counterparts. Above 3 microns, the distinction becomes less apparent. Filter rating has a significant effect on element service life as shown in Figure 91.

System	Filter Elements		Size (µm)					
			>1	>2	>3	>5	>10	>15
	Rating	Age (Hrs)	Particles > Size / 100 ml					
Median Upstream								
PC1	1 µm	82	78,071	5,682	971	273	104	72
Utility	1 µm	11	204,873	15,876	1,789	90	7	3
PC2	5 µm	4	326,269	3,628	474	52	7	5
PC2	5 µm	334	368,872	7,237	766	103	17	12
Utility	5 µm	64	251,989	12,774	2,010	929	704	632
Median Downstream								
PC1	1 µm	82	637	38	7	2	0	0
Utility	1 µm	11	38,109	258	3	0	0	0
PC2	5 µm	4	237,200	318	4	0	0	0
PC2	5 µm	334	234,786	1,609	26	1	0	0
Utility	5 µm	64	147,830	2,418	70	2	0	0

Figure 90. Pall On-Line Dynamic Particle Counting

System	Element Rating (µm)	Loaded	Elapsed Time (hr)	Comments
PC - 1 Return	1	Y	167.1	ΔP Indication, Reset once
UT - 1 Return	1	Y	234.6	ΔP Indication, Reset once
UT - 2 Return	1	Y	232.3	ΔP Indication, Reset once
PC - 1 Return	1	Y	96.2	ΔP Indication, Reset once
PC - 1 Return	1	Y	95.1	ΔP Indication, Reset once
PC - 1 Pressure	1	N	> 366.6	Remains in system
PC - 2 Pressure	5	N	> 356.1	Removed for "on line" filter test (not loaded)
PC - 2 Return	5	N	> 356.1	Removed for "on line" filter test (not loaded)
UT - 1 Pressure	1	N	> 246.0	Remains in system
UT - 2 Pressure	1	N	> 308.6	Remains in system

Figure 91. Filter Element Test Hours

The two primary flight control systems were the first to be checked out and operational. In order to get the endurance test underway, the utility system functional checkout was delayed until the PC systems started endurance cycling. The engine nozzle fixtures that are normally powered by the Utility System were being powered by the PC systems in a backup mode via the Parker 6W-2P shuttle valves. During the first 50 hours of endurance testing, two of the shuttle valves failed in the backup mode of operation. This problem occurred on both the right and left-hand nozzle shuttle valves. Parker Aerospace found that the spool failed as a result of overload in a highly stressed area at the interface of the two spool halves.

5.2.4 System Performance - Several techniques were used in these systems to reduce power consumption; the most significant being variable pressure operation. System level response was initiated with step commands to each of the actuators in the system. The input command was 5% and 75% of full stroke, both with and without variable pressure enabled. A system-wide step response was also recorded for the PC-1 and PC-2 systems. Figure 92 presents data recorded during a 75% step input command to all the actuators in the PC systems, with variable pressure enabled. Figure 93 shows data recorded at constant 8000 psi pump discharge pressure.

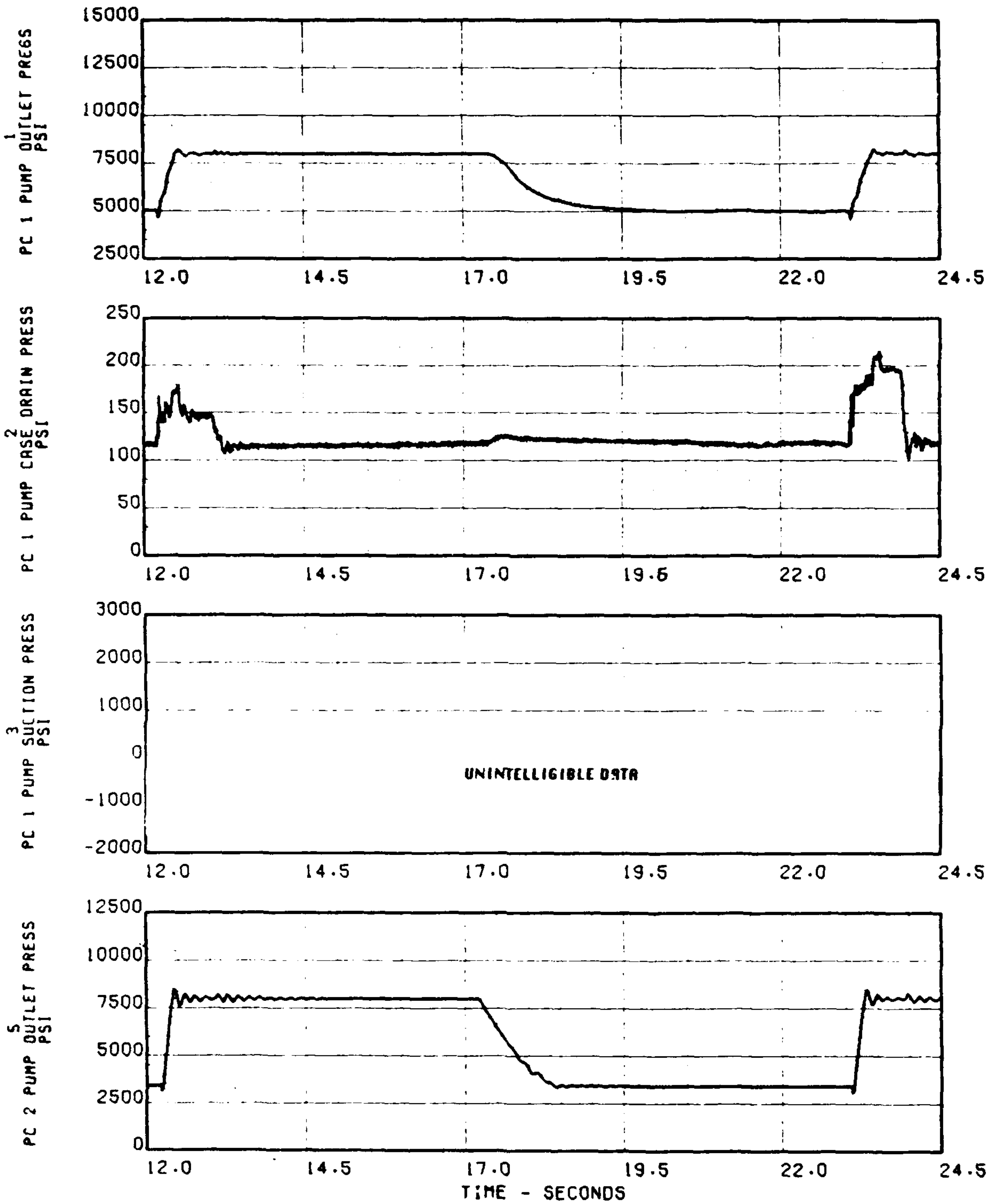


Figure 92. Flight Controls Step Response
Variable Pressure

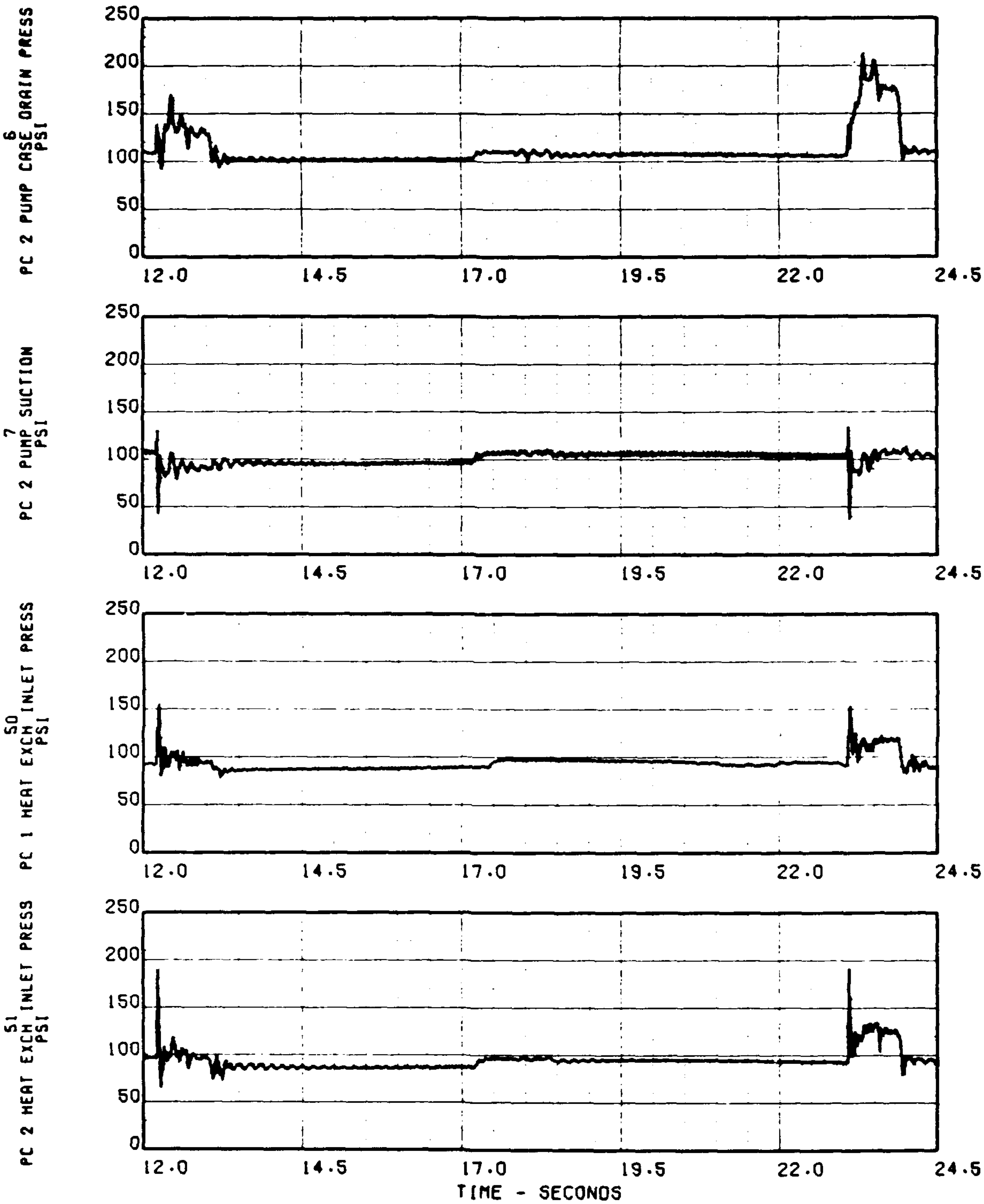


Figure 92. (Continued) Flight Controls Step Response
Variable Pressure

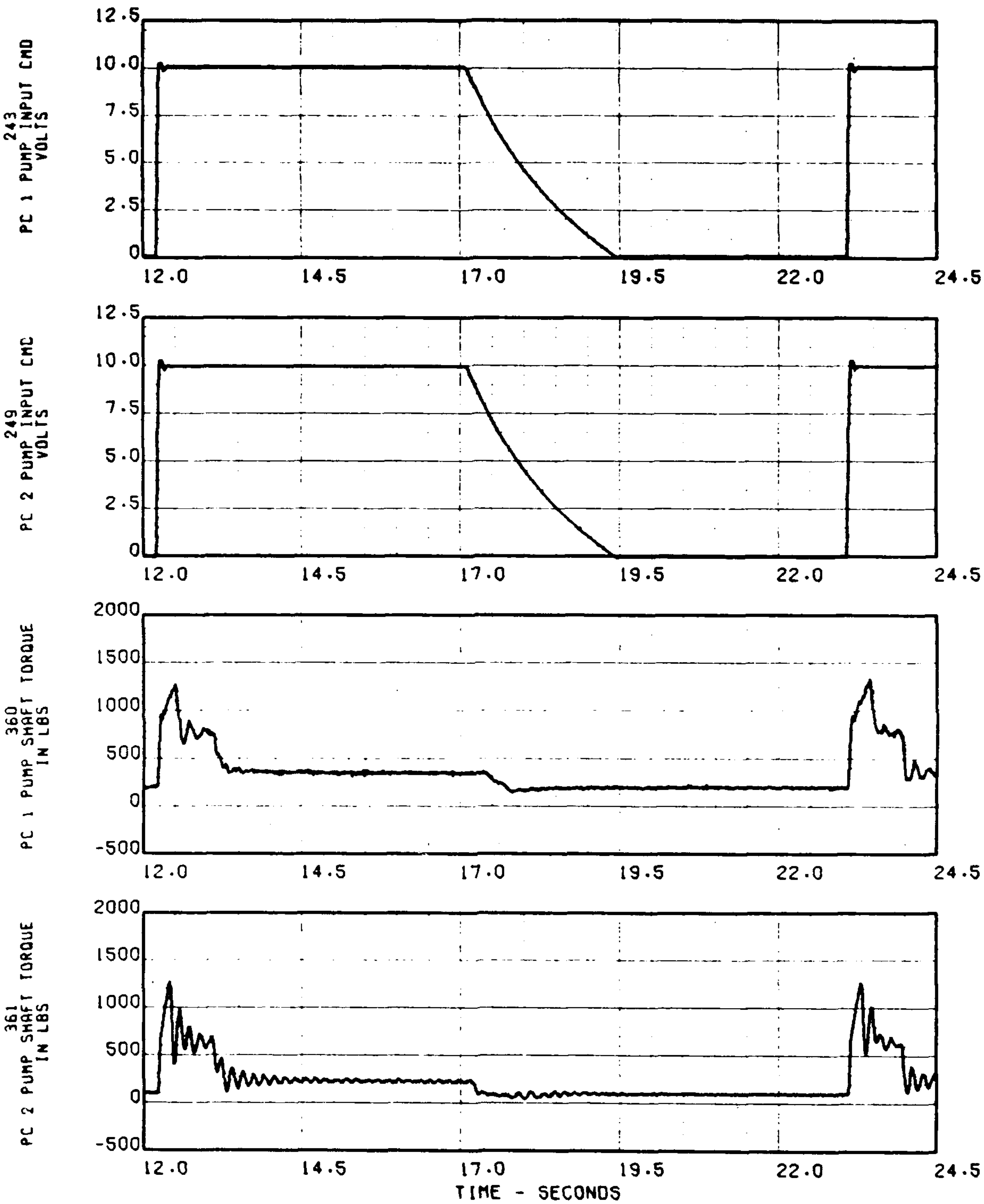


Figure 92. (Continued) Flight Controls Step Response
Variable Pressure

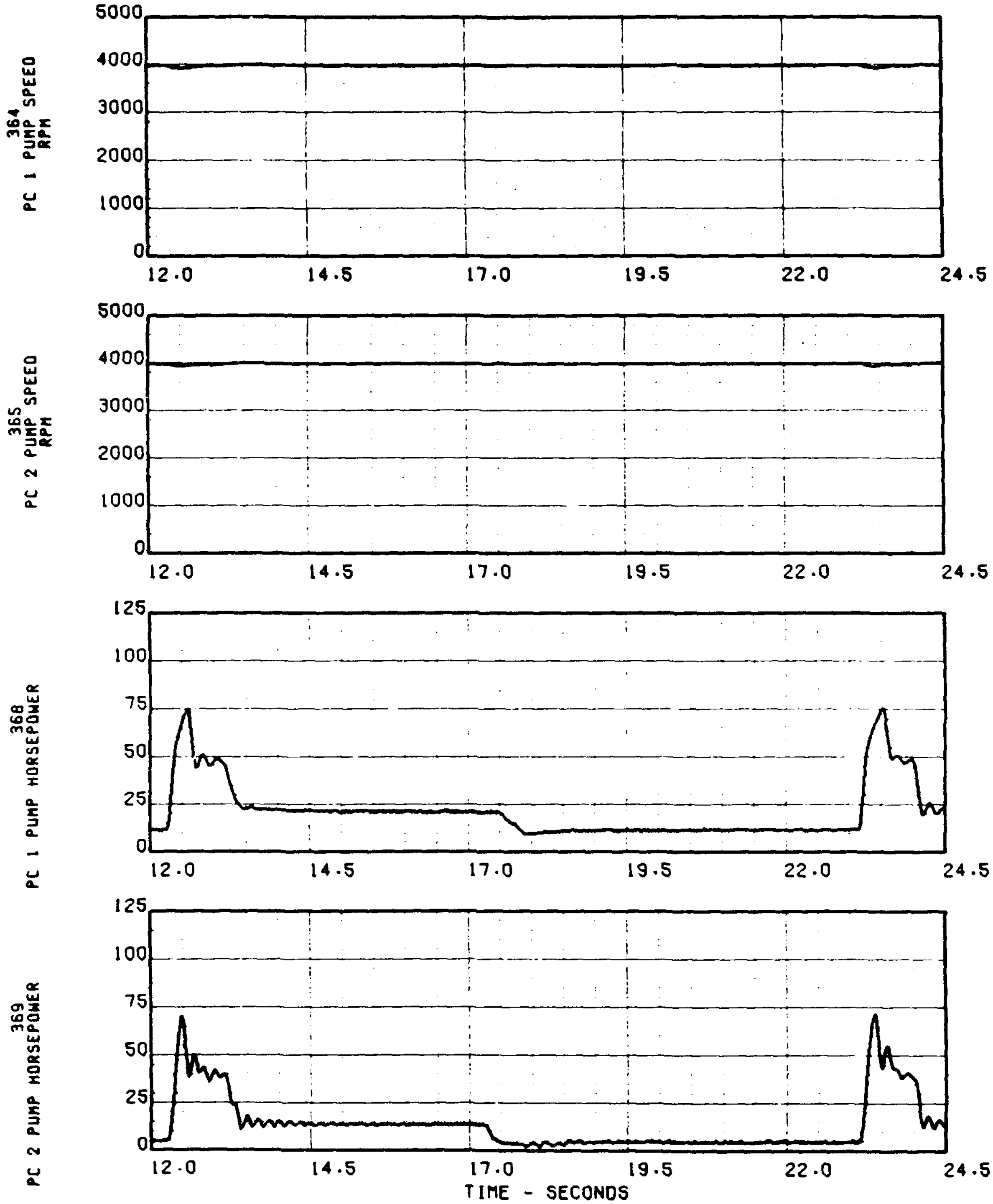


Figure 92. (Continued) Flight Controls Step Response
Variable Pressure

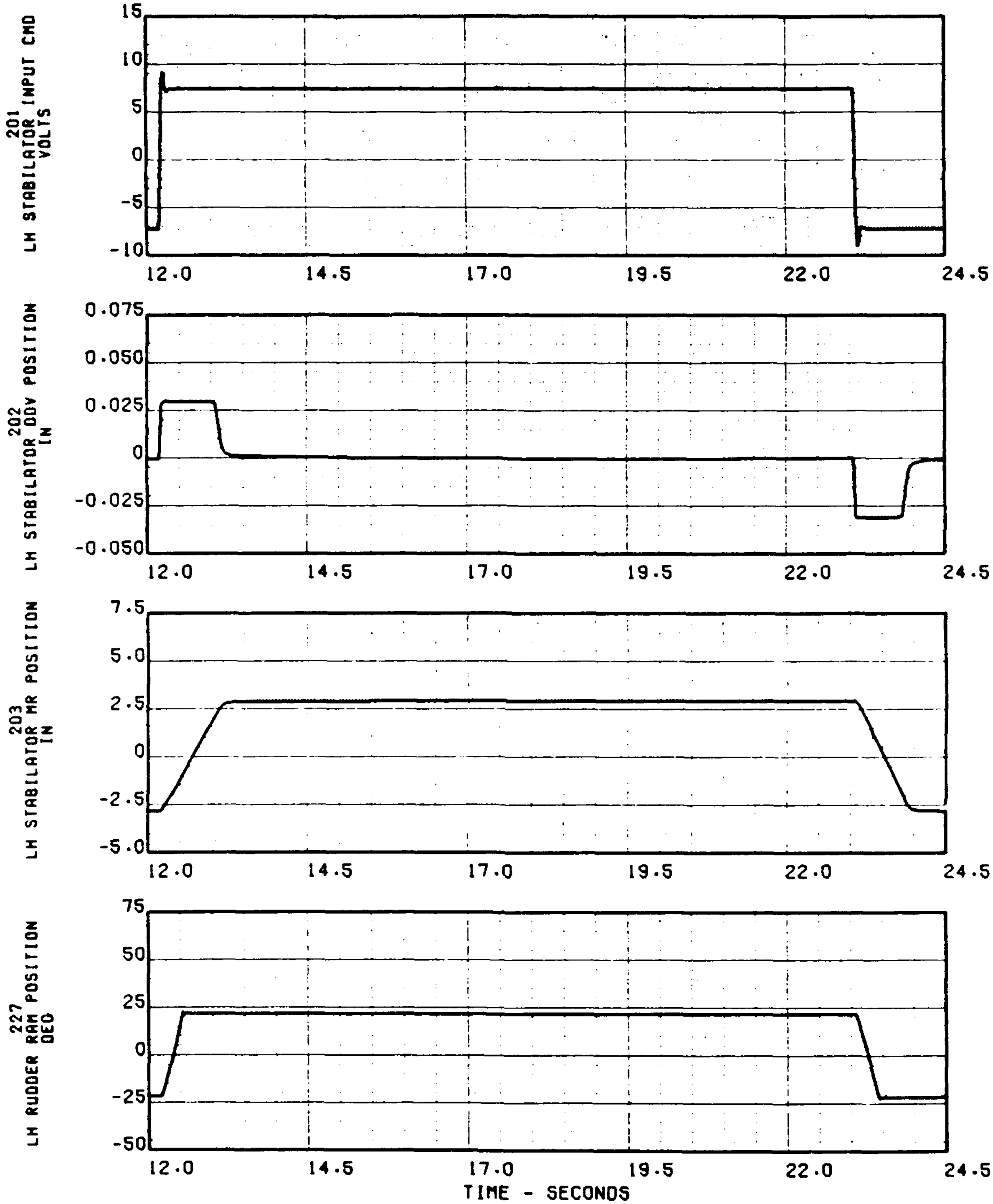


Figure 92. (Continued) Flight Controls Step Response
Variable Pressure

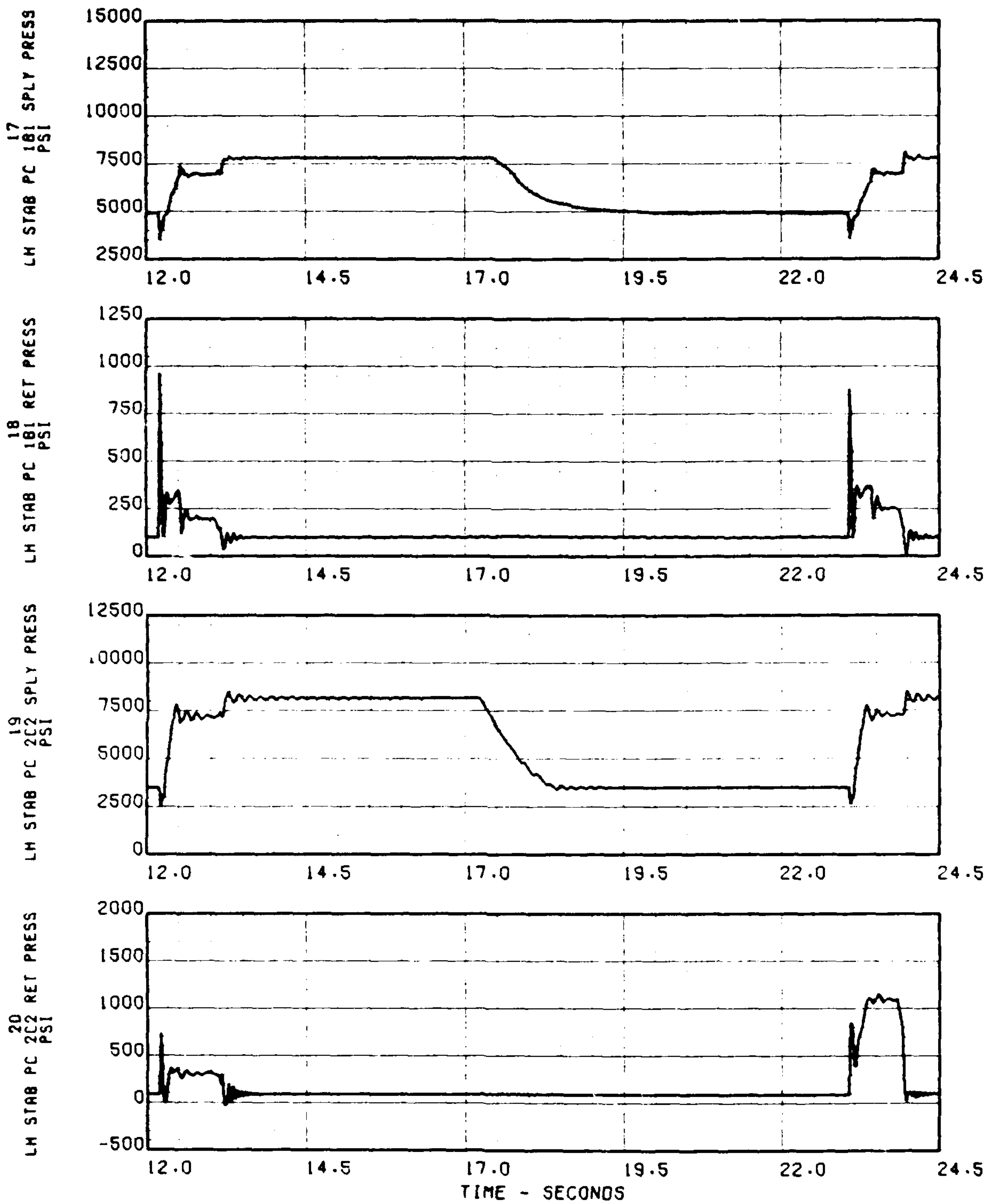


Figure 92. (Continued) Flight Controls Step Response
Variable Pressure

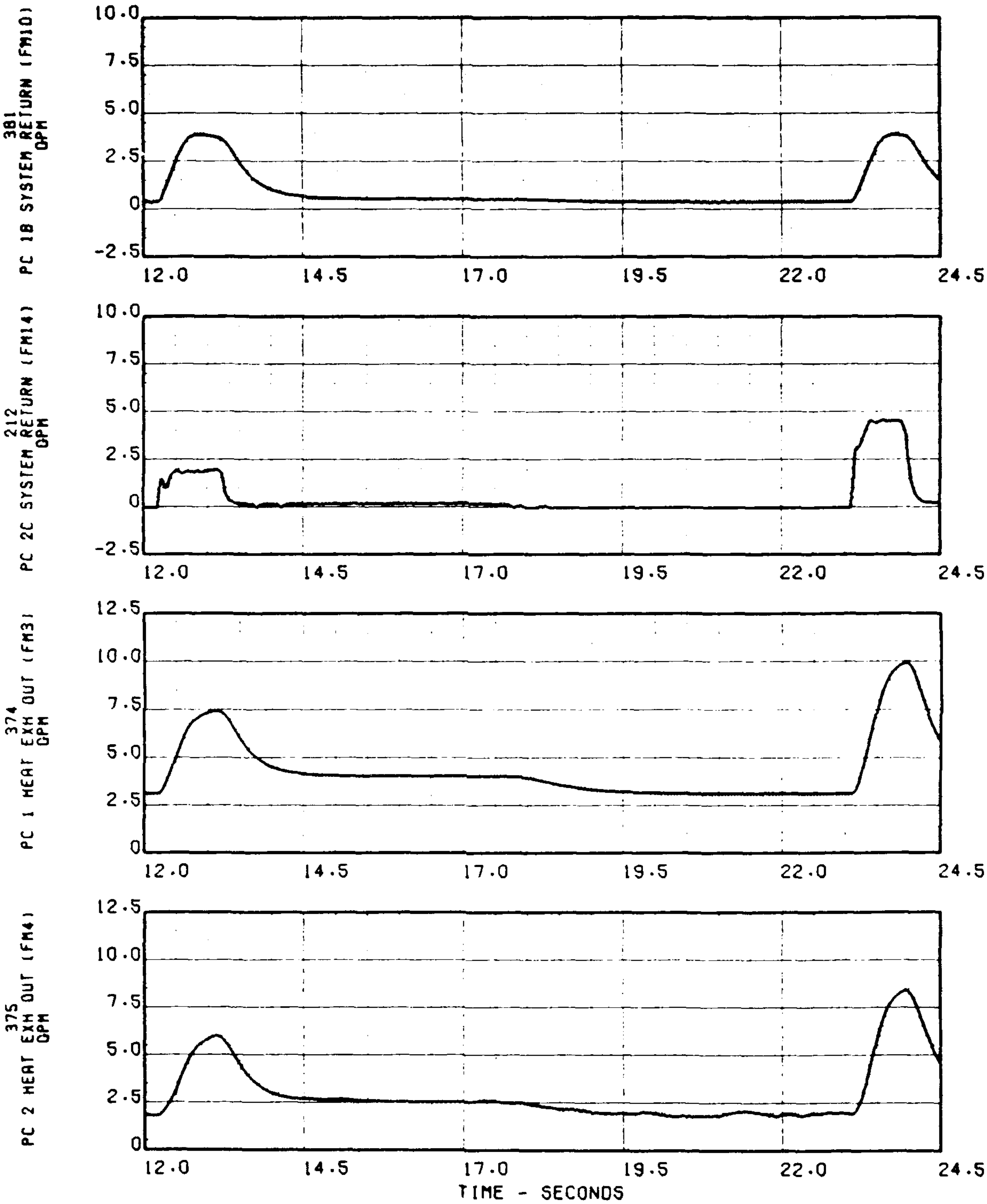


Figure 92. (Concluded) Flight Controls Step Response
Variable Pressure

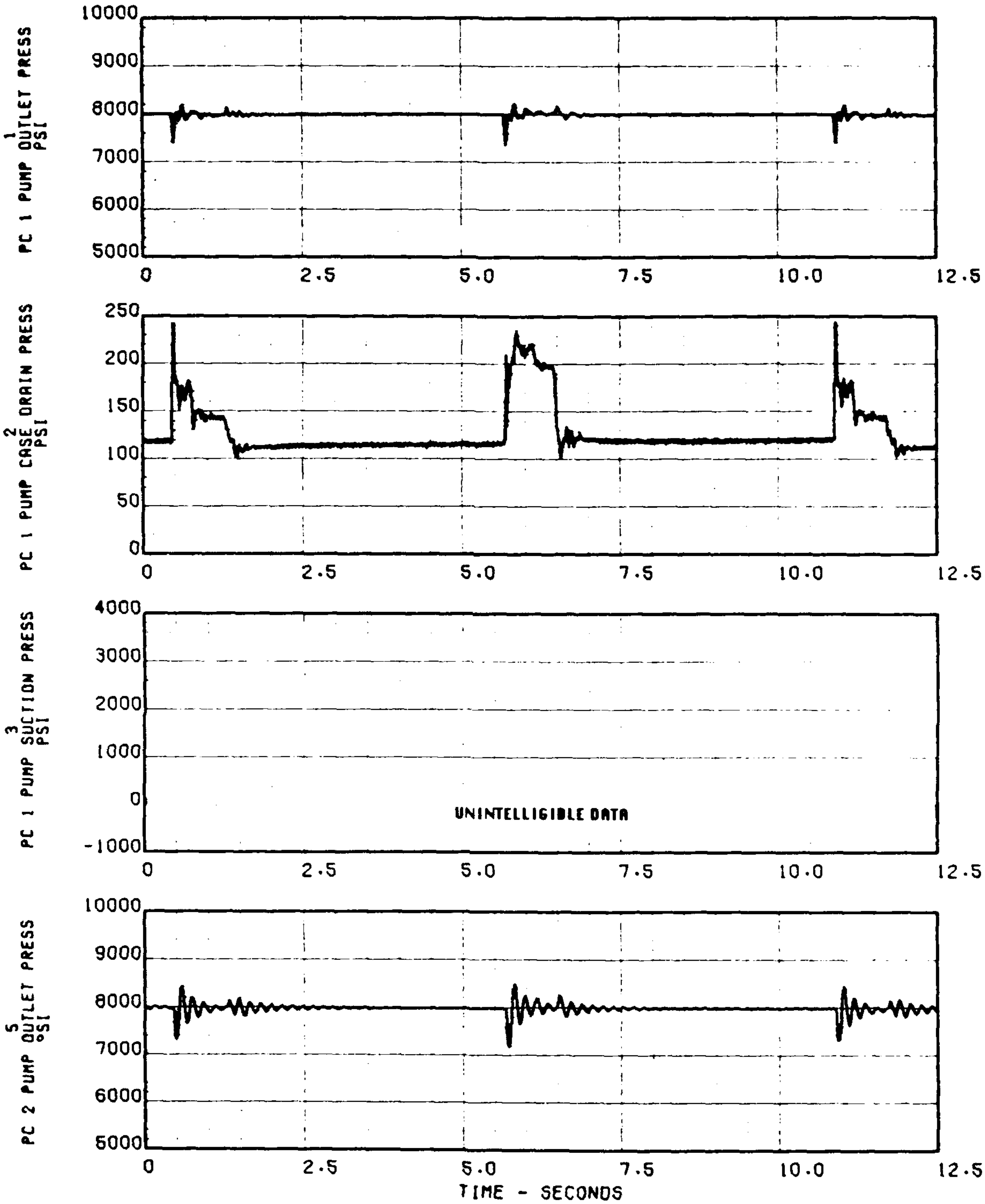


Figure 93. Flight Controls Step Response
Constant Pressure

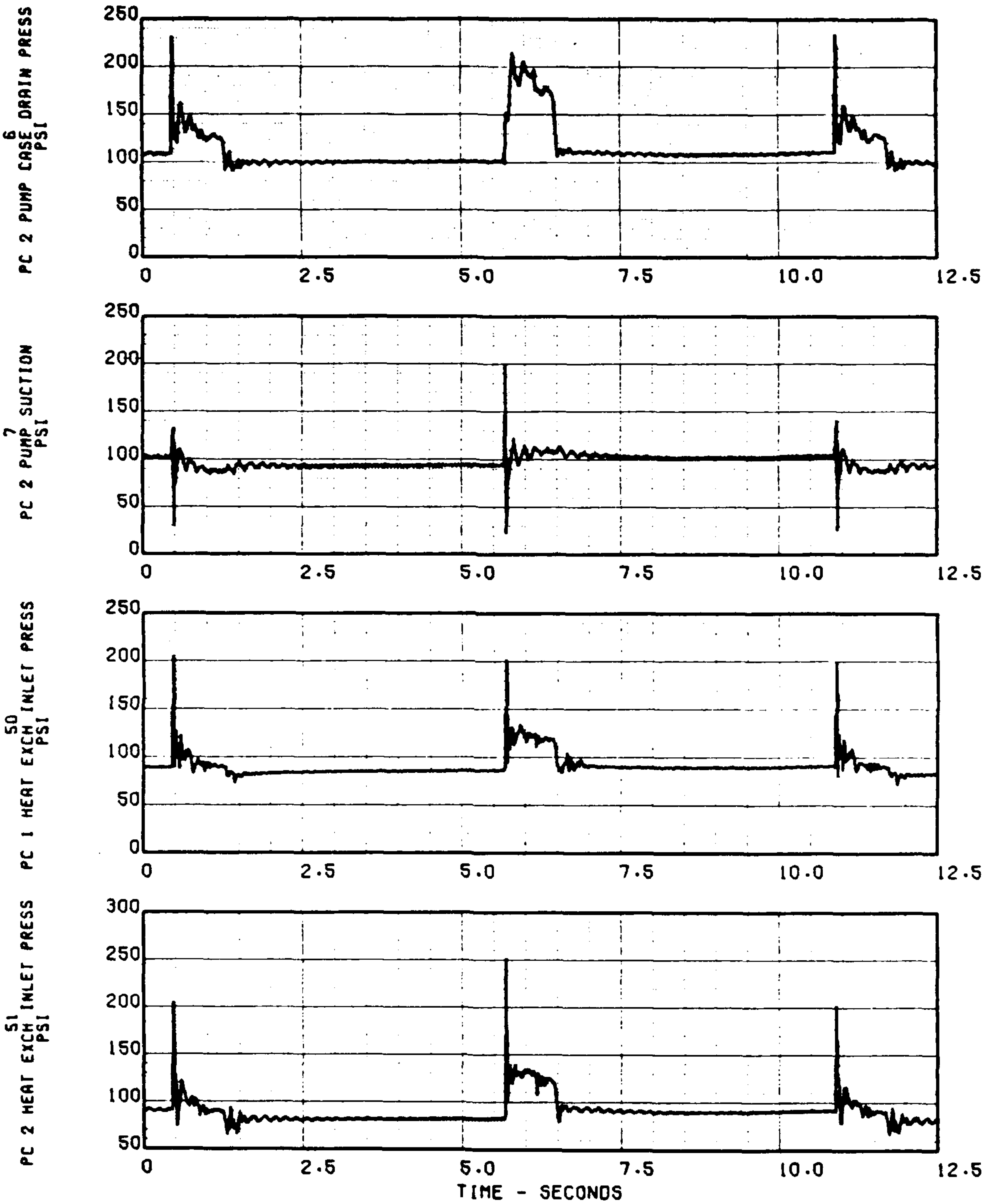


Figure 93. (Continued) Flight Controls Step Response
Constant Pressure

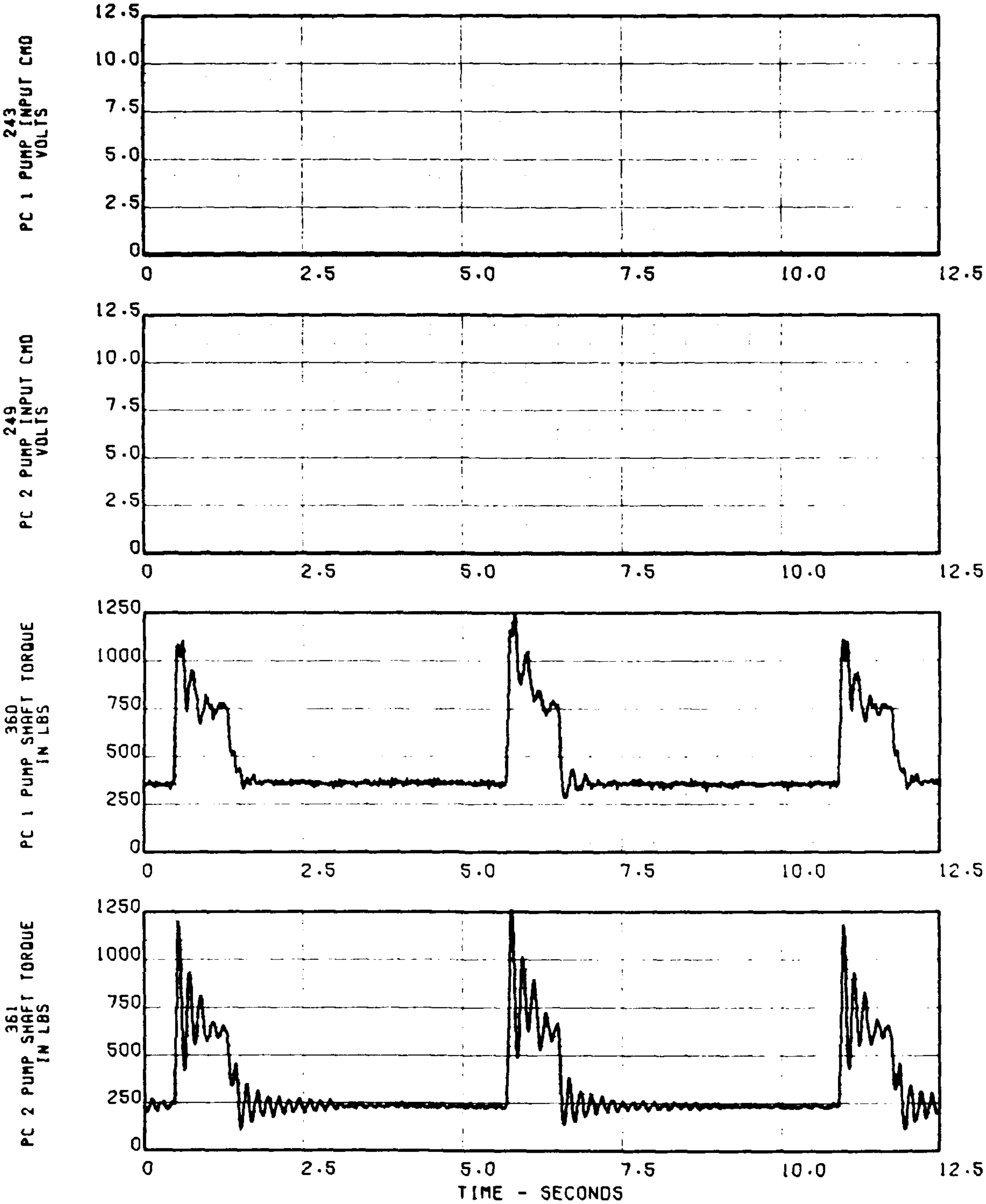


Figure 93. (Continued) Flight Controls Step Response
Constant Pressure

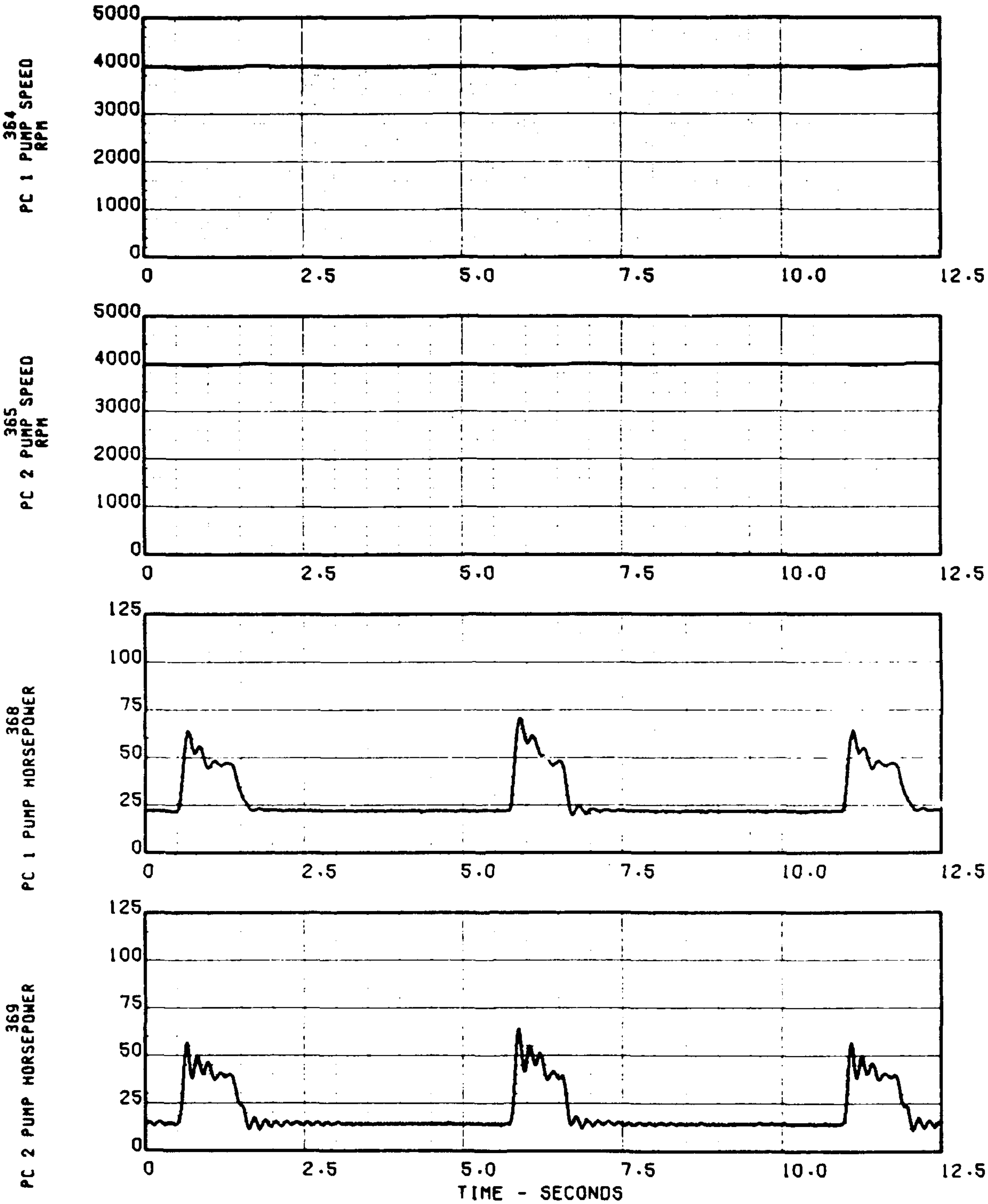


Figure 93. (Continued) Flight Controls Step Response
Constant Pressure

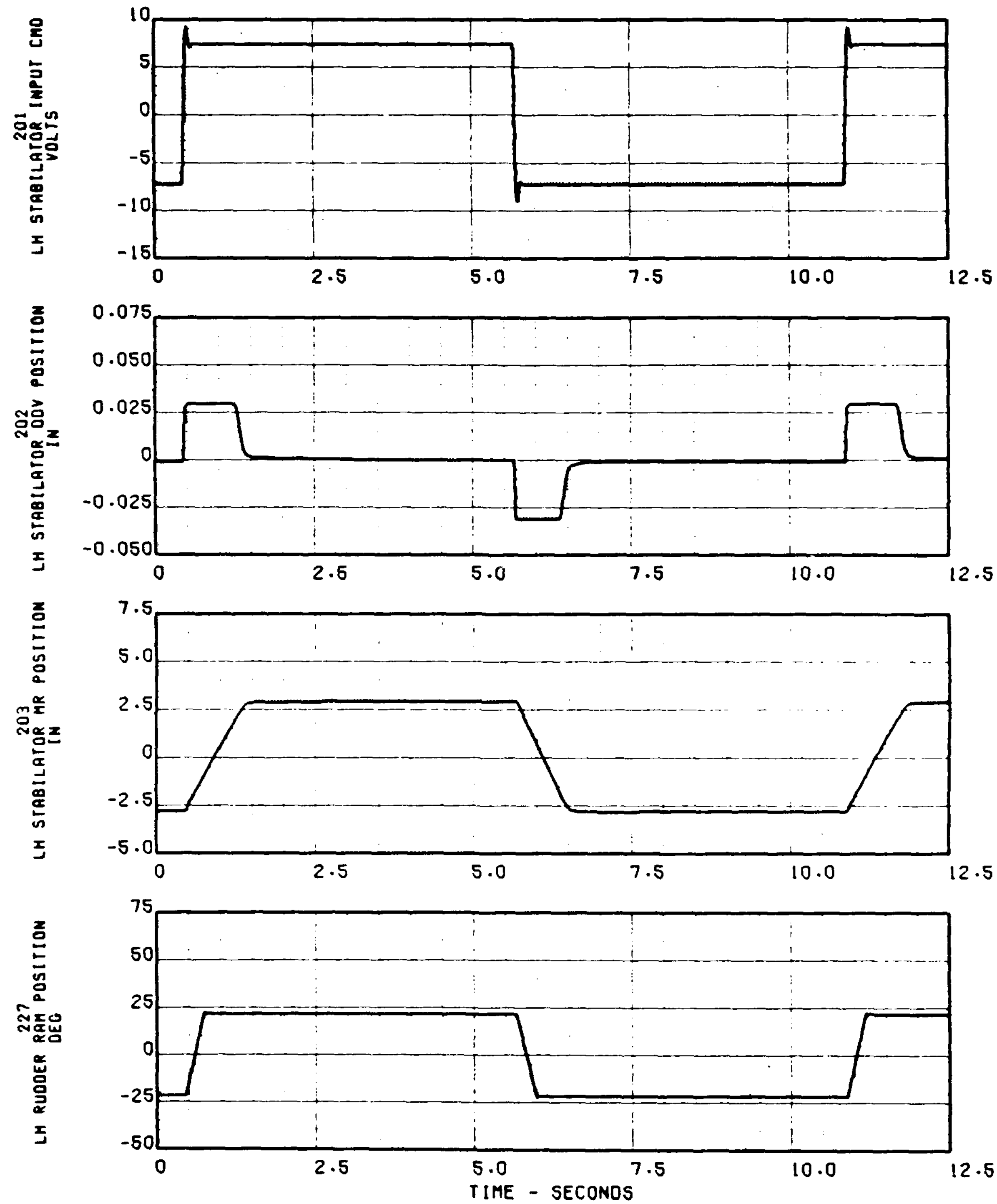


Figure 93. (Continued) Flight Controls Step Response
Constant Pressure

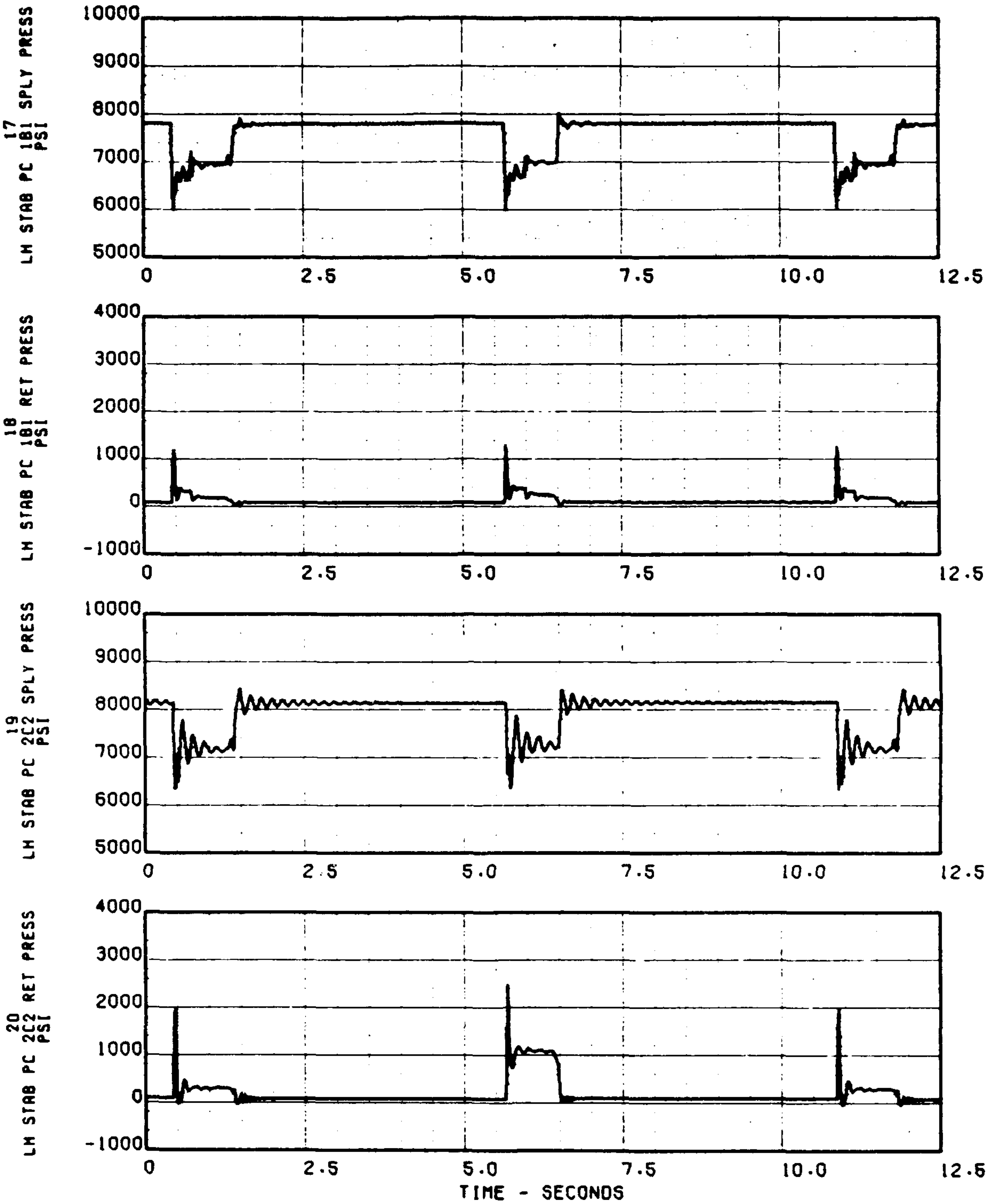


Figure 93. (Continued) Flight Controls Step Response
Constant Pressure

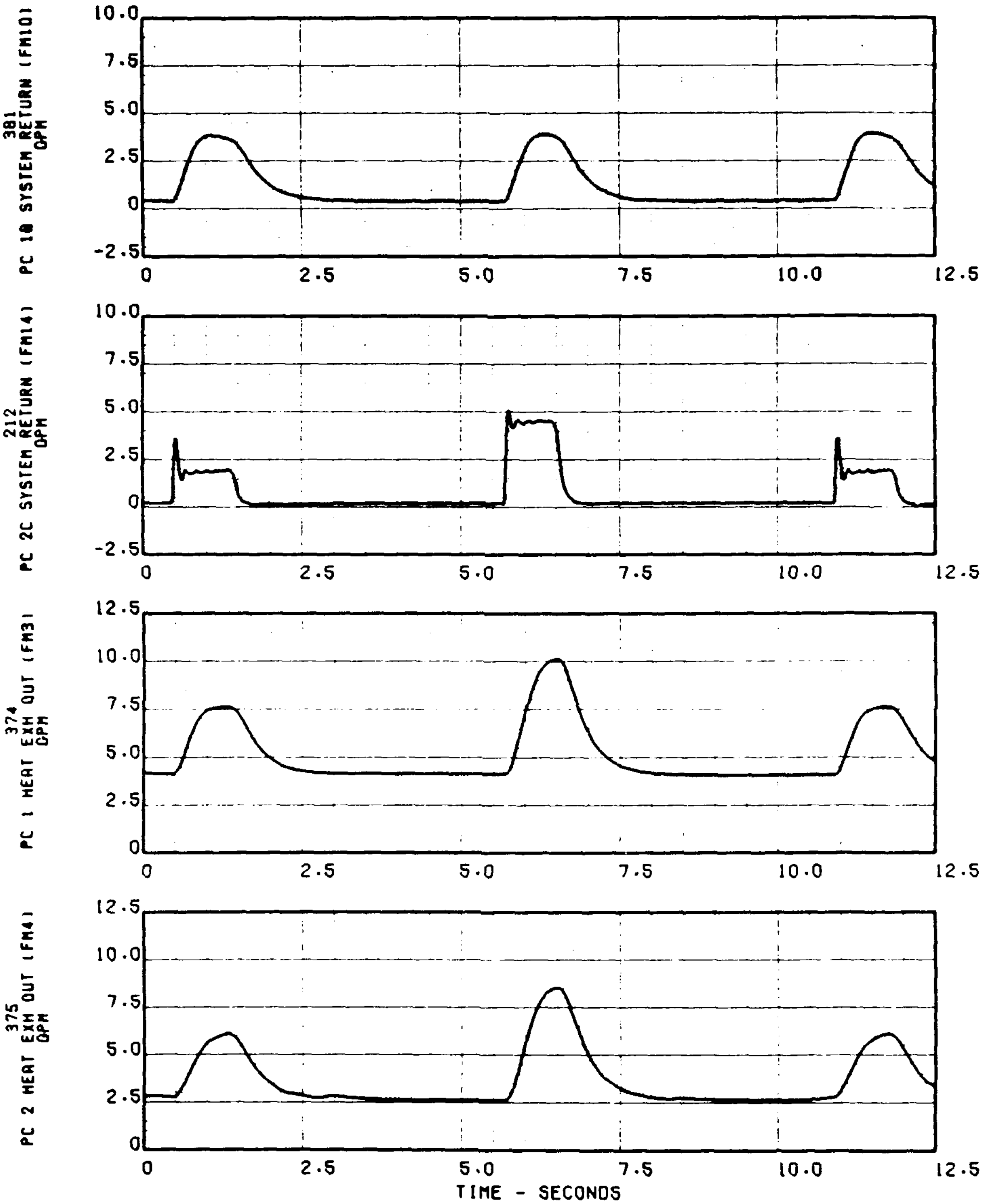


Figure 93. (Concluded) Flight Controls Step Response
Constant Pressure

Parameters 1 and 5 (PC pump outlet pressures) of Figure 92 show the variable pump outlet pressure with a 2-second time constant for pressure decay. The pump pressure commands are shown as parameters 243 and 249; it should be noted that with variable pressure enabled a 10-volt command corresponds to 8000 psi and 0 volts corresponds to 3000 psi. With variable pressure disabled, pressure reverts to 8000 psi. Pump shaft torque was recorded in parameters 360 and 361, and pump horsepower in parameters 368 and 369.

Parameter 369 in Figure 92 shows the power reduction between 8000 and 3000 psi operation during quiescent flow conditions; pump power reduces from 14 hp to 4 hp. Pressure conditions at the actuators were measured similarly. The L/H stabilator command, DDV position, and ram position are shown in parameters 201 through 203. Each of the actuators in the system were commanded identically.

Parameters 17 through 20 show the stabilator supply and return pressures for each system. Parameter 20 shows a substantially lower return pressure spike with variable pressure than with constant pressure. Stabilator return flows were recorded in parameters 212 and 381 and heat exchanger flows were recorded in 374 and 375. A reduction in quiescent flow occurs during lower pressure operation.

The response of the convergent flap actuator, in the utility system, to a 75% stroke step command is shown in Figure 94. Similarly the response of the divergent flap actuator is illustrated in Figure 95. The UT-1 and UT-2 pump outlet pressures were at 8000 psi constant pressure; these and additional pump parameters are shown. Parameters for the distribution pressures and flows show the unique characteristic of the regenerative divergent flap actuator; very little return flow is measured during the extend cycle.

Local velocity reduction (LVR) and flow augmentation techniques were shown to be effective during the program. LVR kept pressure spikes below 8800 psi during stabilator maximum rate valve reversals. Load recovery valves embedded in the stabilator and canard actuators reduced system flow demand during aiding loads; rates above 12 inches per second were recorded without any increase in central system flow demand. Central system flow demand was also reduced 25% - 30% during no load - maximum rate actuation with flow augmentation.

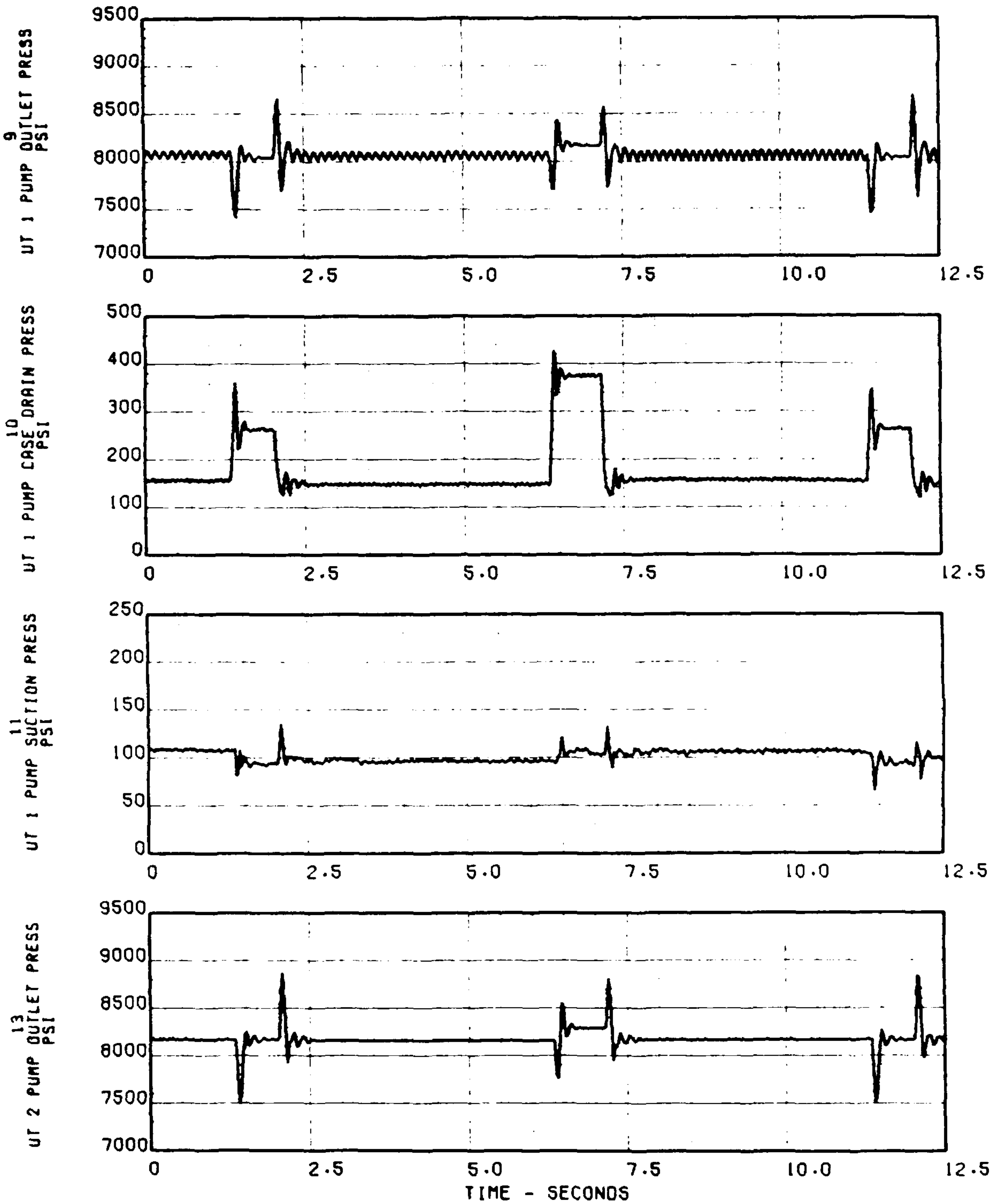


Figure 94. Convergent Flap Step Response

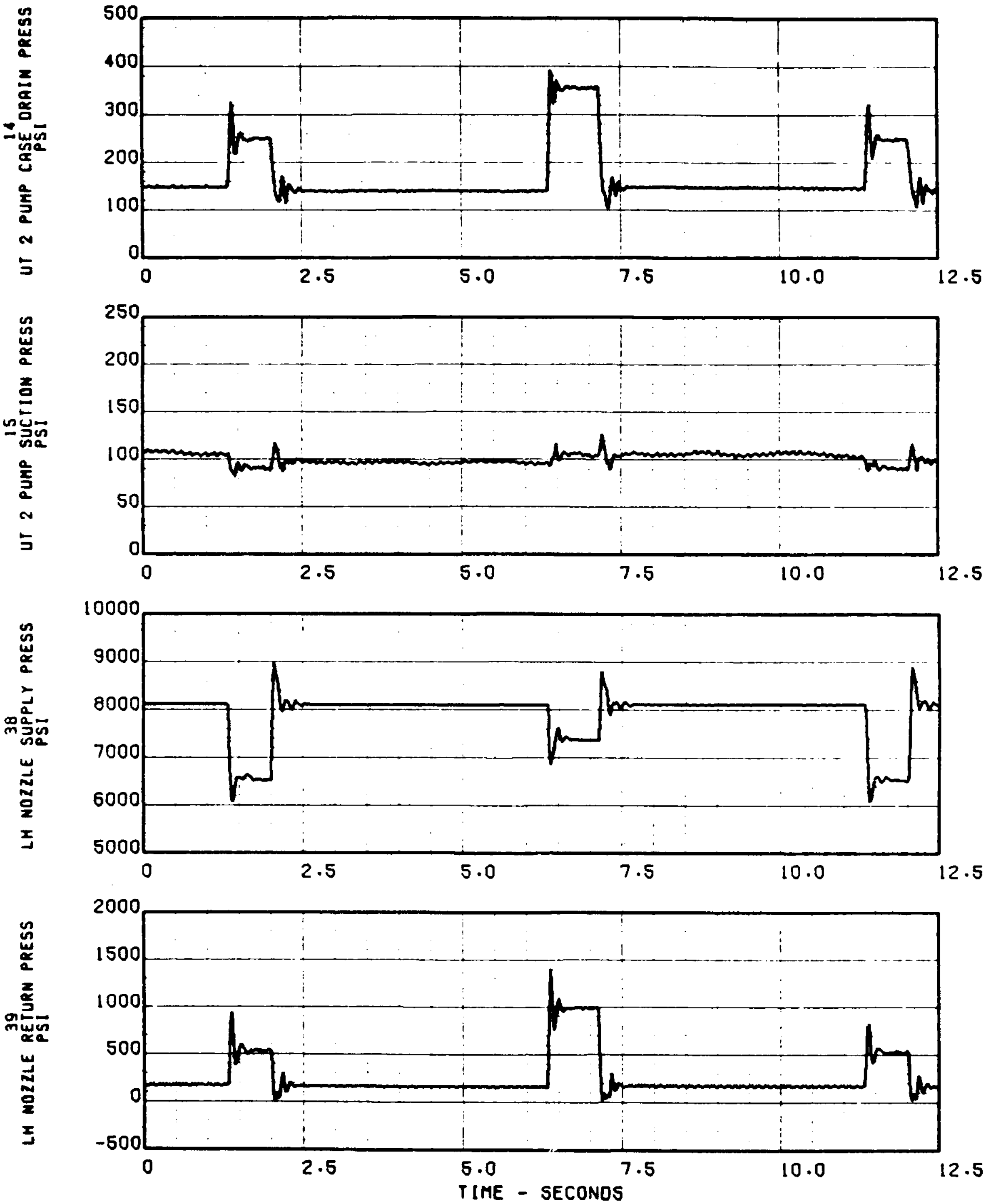


Figure 94. (Continued) Convergent Flap Step Response

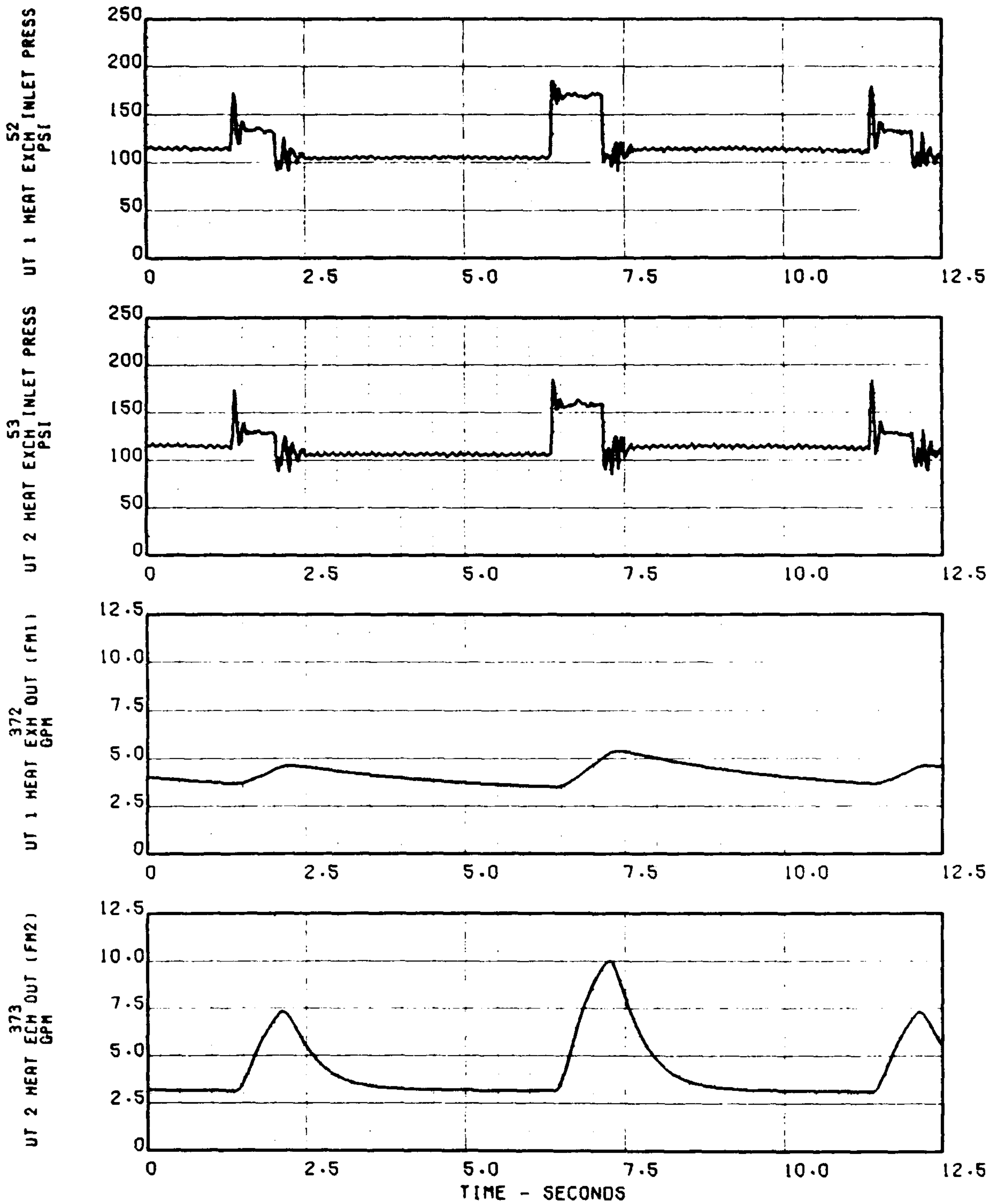


Figure 94. (Continued) Convergent Flap Step Response

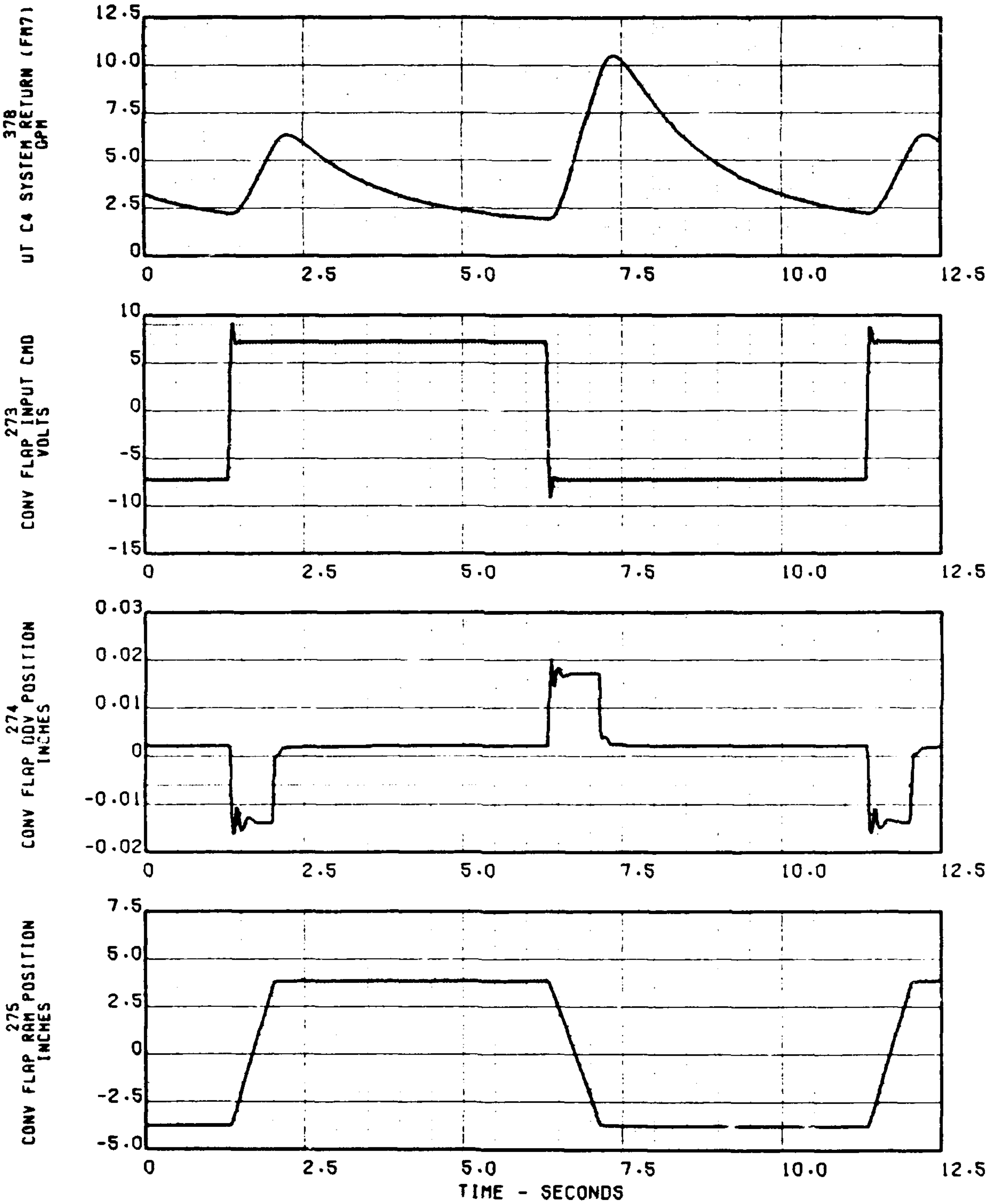


Figure 94. (Concluded) Convergent Flap Step Response

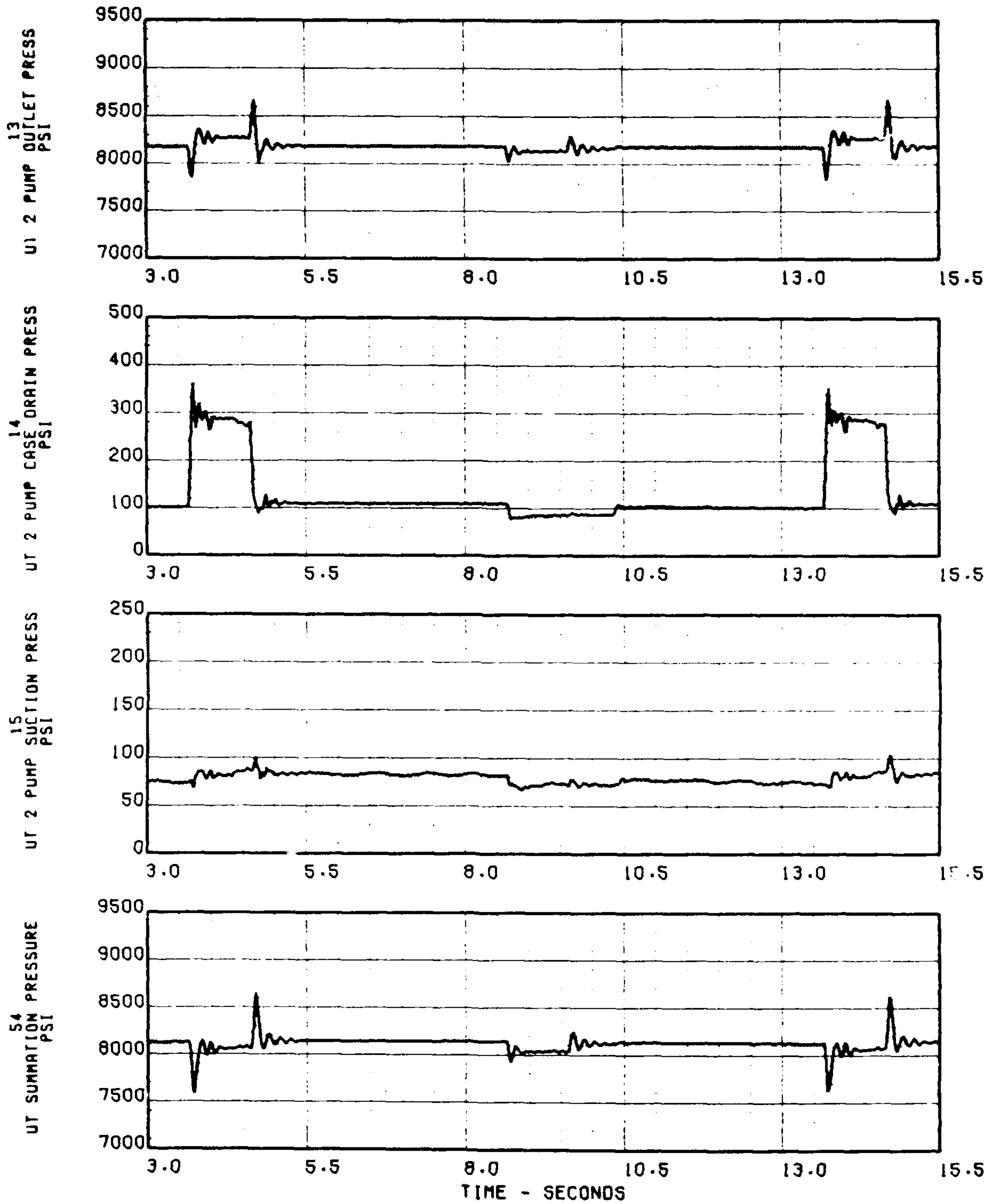


Figure 95. Divergent Flap Step Response

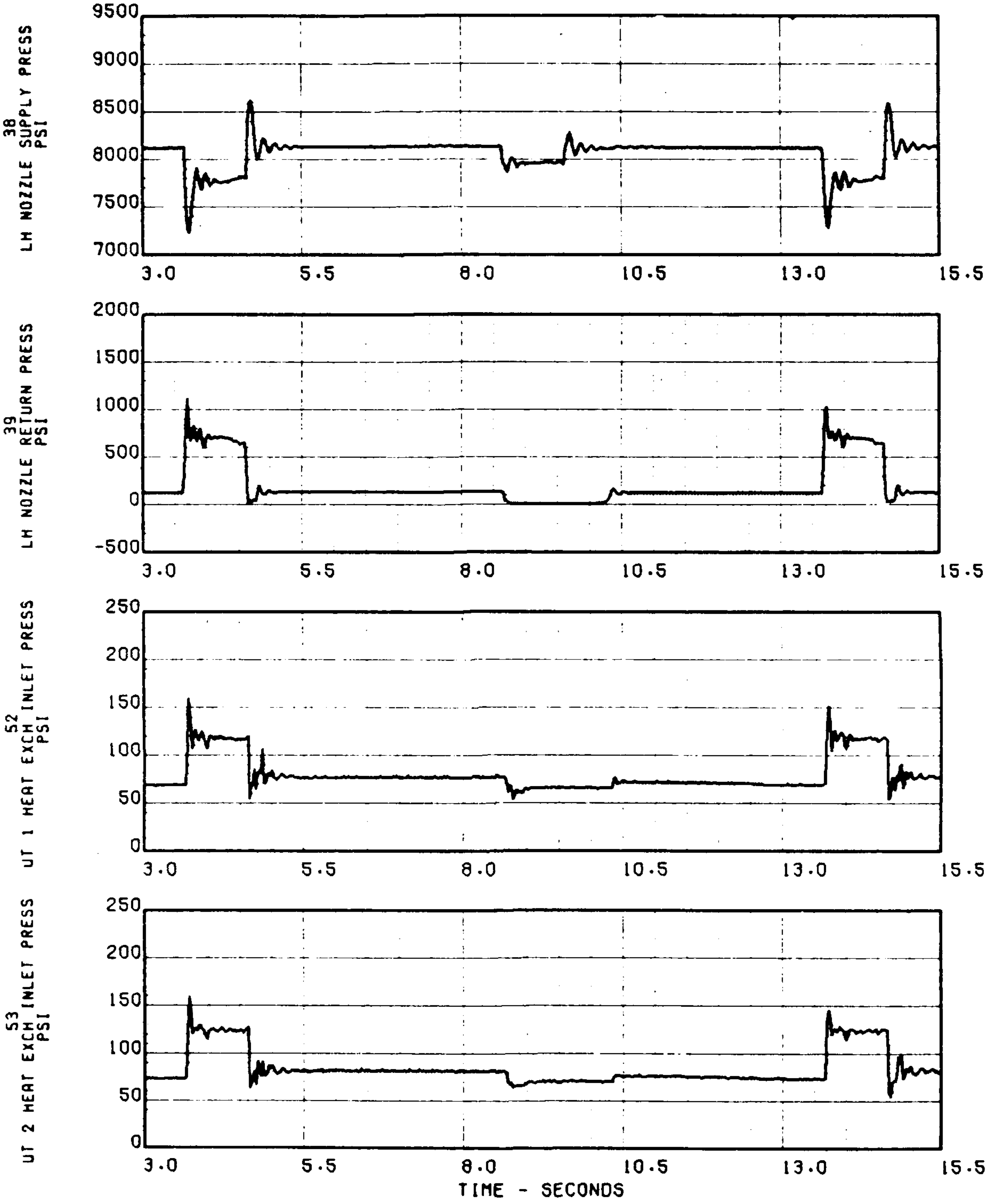


Figure 95. (Continued) Divergent Flap Step Response

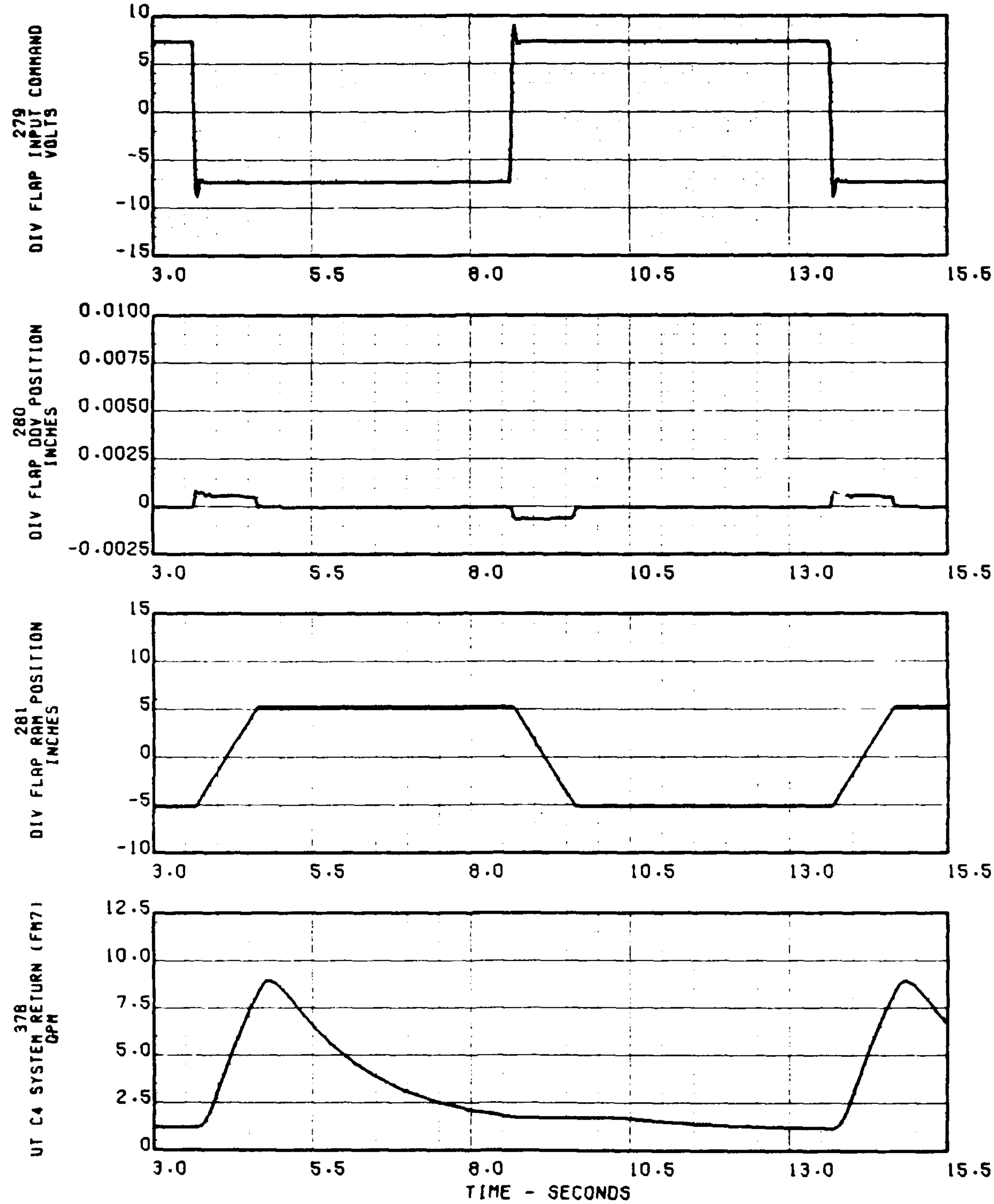


Figure 95. (Continued) Divergent Flap Step Response

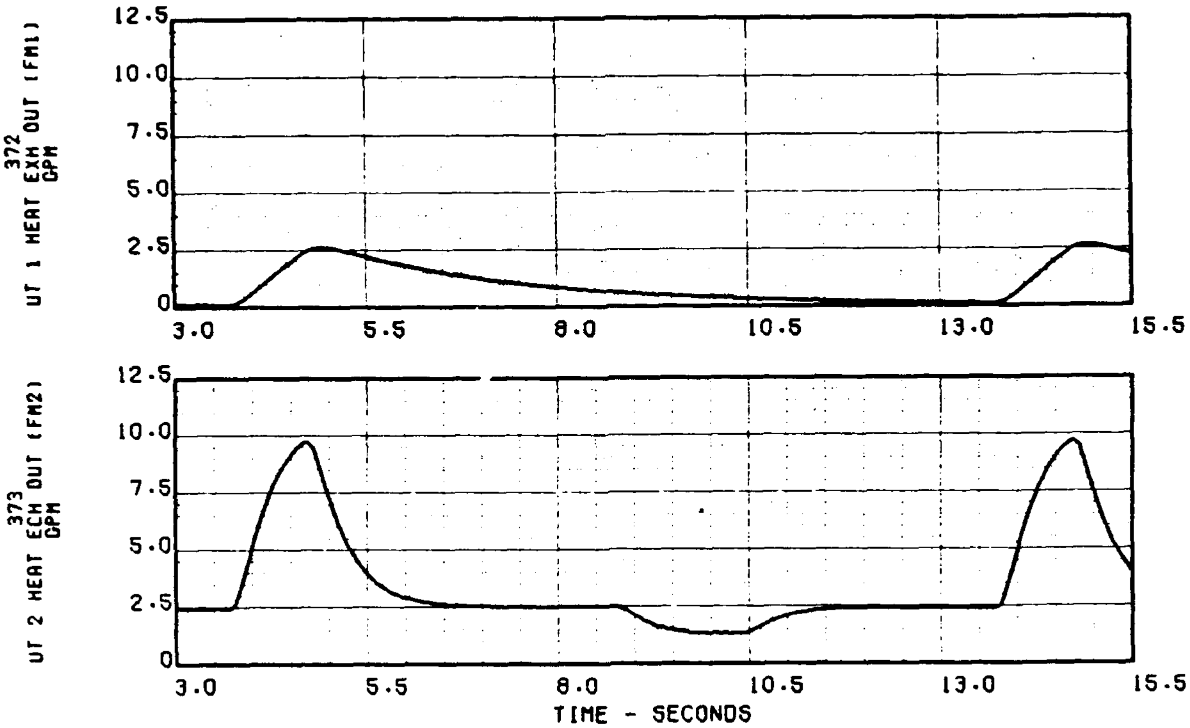


Figure 95. (Concluded) Divergent Flap Step Response

5.3 VERIFICATION OF COMPUTER SIMULATIONS

Computer simulation work performed in Phase II of the program is presented in Volume I. This effort was directed toward sizing of the distribution system lines and equipment ports. This effort proved successful in that rates and pressure transients were at acceptable levels everywhere in the system except the heat exchangers. Heat exchanger flow was achieved by using a bypass relief valve to set flow through the heat exchangers. Further simulation work showed a need to increase the size of the heat exchanger flow path to reduce transients generated by the flight control actuators. It was not necessary to add any restrictors or change any other line sizes in the course of the test program. The computer simulation comparisons presented herein with actual test data are the result of using measured parameters from the LTD in simulation models with line lengths and component parameters updated to match the LTD. Most of the comparisons match in characteristics; however, some steady state pressure levels differ. Program termination precluded doing any further work to improve the simulation data file.

5.3.1 Steady State Flow Analysis (SSFAN) - The updated SSFAN model was created from the HYTRAN (Hydraulic Transient Analysis) model with a file conversion program. The HYTRAN model had been updated to reflect the correct line lengths and heat exchanger plumbing used on the LTD. Figure 96 presents a comparison between the SSFAN simulation and data taken during a system-wide, no-load rate response test. The predicted pressure levels are within 250 psi in the return circuits, and within 600 psi in the supply circuits. No-load rates and return circuit flows were matched as closely as possible for the comparison.

5.3.2 Hydraulic Transient Analysis (HYTRAN) - A series of valve reversals were used on the stabilator actuators to test the local velocity reduction (LVR) technique for reducing water hammer as well as to verify computer simulations. Figure 97 presents LTD central system and stabilator data taken during one of these valve reversals. With LVR, pressure transients at the stabilator supply were below 9000 psi. Figure 98 shows the HYTRAN simulation results of valve reversal shown in Figure 97. The HYTRAN simulation was plotted to the same scale and with the same format as the LTD data for direct comparison. As can be seen, the transient response was predicted very accurately. As with SSFAN, there are some differences in steady state levels.

5.3.3 Hydraulic System Frequency Response (HSFR) - HSFR predictions are presented in Volume I. Because of the high pump pulsations predicted, attenuators were added to the baseline system. Due to the late development of the large pumps, system level test data are not available for comparison.

5.4 ENDURANCE TEST RESULTS

The endurance test logs are presented in Figure 99 for the PC systems and in Figure 100 for the Utility system. Test hours and pertinent comments for system operation and failures are discussed herein.

5.4.1 Servoactuators - Of the 550 hours of endurance testing which was originally required by the statement of work, 324 hours were completed. The duty cycle which was used in this demonstration is shown in Appendix B. The actuator summary for the endurance test shown in Figure 101 includes the total cycles, loaded cycles and hours operated.

5.4.2 Pumps - Difficulties encountered in the endurance tests included failures of the 15 gpm variable pressure pumps. It was necessary to substitute constant pressure pumps into the utility system in order to have variable pressure pumps in the primary control systems. Figure 102 shows a summary of all 15 gpm pump test work. It should be noted that the pumps which accumulated over 300 hours were operated with variable pressure.

Circuit Location	Predicted	Measured
Pressure	**(psig)**	**(psig)**
PC - 1 Pump Outlet	8025	8000
Case Drain	170	165
Suction	108	95
H/X Inlet	139	100
PC - 2 Pump Outlet	8025	8000
Case Drain	171	145
Suction	108	95
H/X Inlet	136	105
L/H Flaperon		
PC-1 B Supply	7510	7600
PC-1 B Return	502	250
PC-2 A Supply	7688	7600
PC-2 A Return	202	150
L/H Stabilator		
PC-1 B Supply	7510	6900
PC-1 B Return	525	350
PC-2 C Supply	7758	7300
PC-2 C Return	450	330
R/H Stabilator		
PC-1 C Supply	7825	7600
PC-1 C Return	422	280
PC-2 B Supply	7350	7500
PC-2 B Return	375	380
Return Circuit Flow	**(gpm)**	**(gpm)**
PC-1 A	1.2	2.0
PC-1 B	4.2	4.0
PC-1 C	2.8	2.0
PC-1 H/X	9.1	9.0
PC-2 A	1.0	0.7
PC-2 B	5.3	4.3
PC-2 C	2.5	2.0
PC-2 H/X	9.7	8.0

Figure 96. SSFAN Simulation and System Comparison

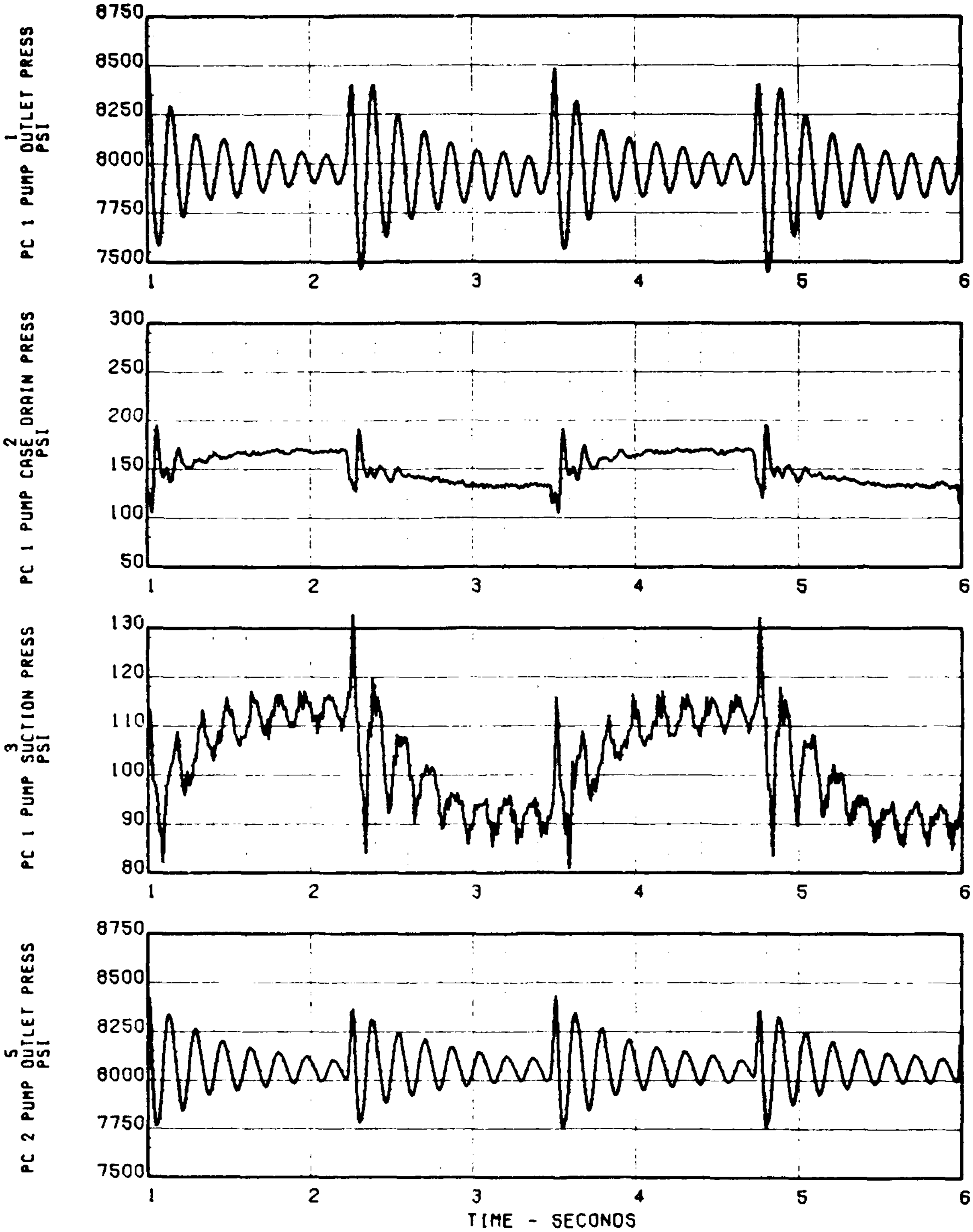


Figure 97. System Test Results for Valve Reversal

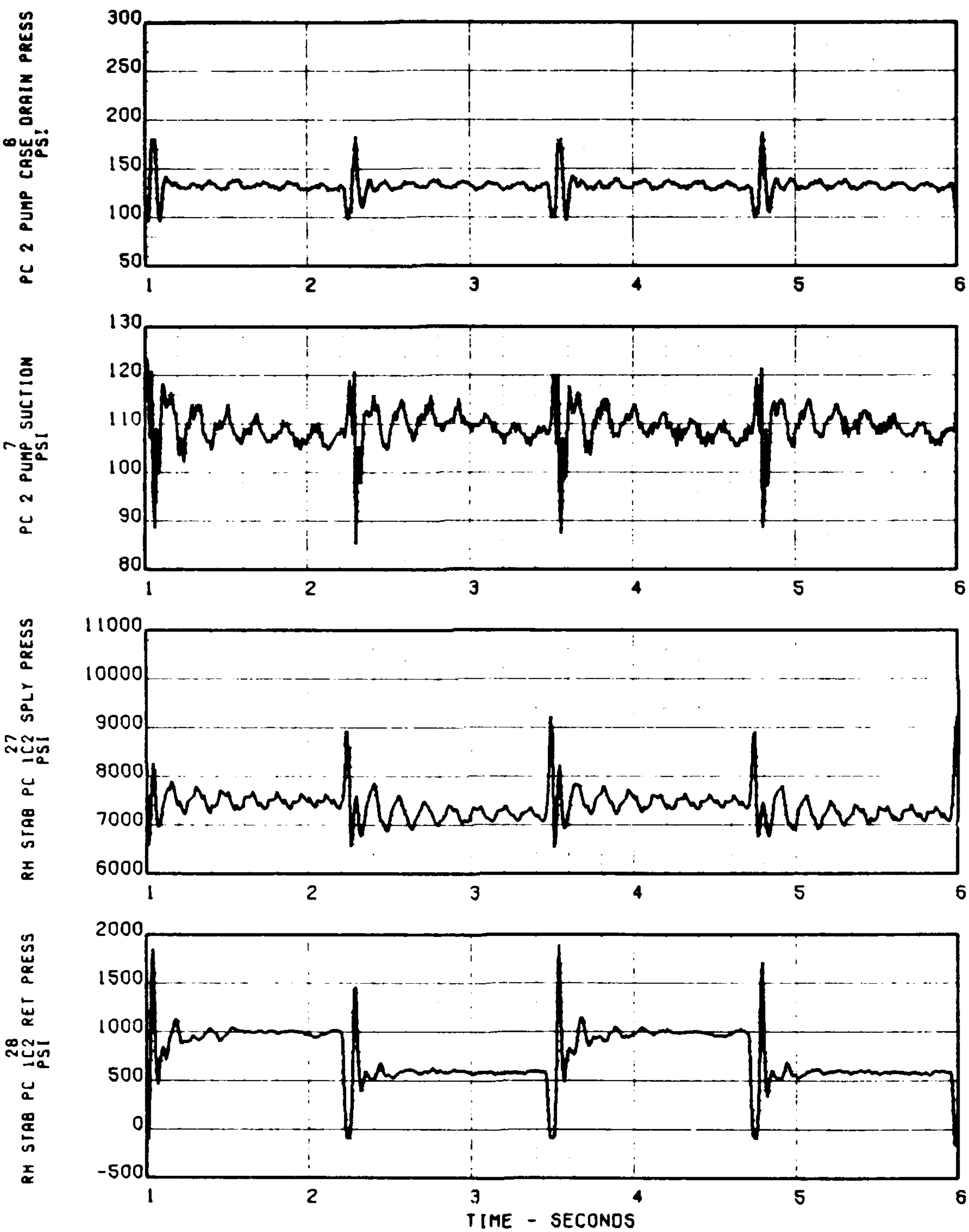


Figure 97. (Continued) System Test Results for Valve Reversal

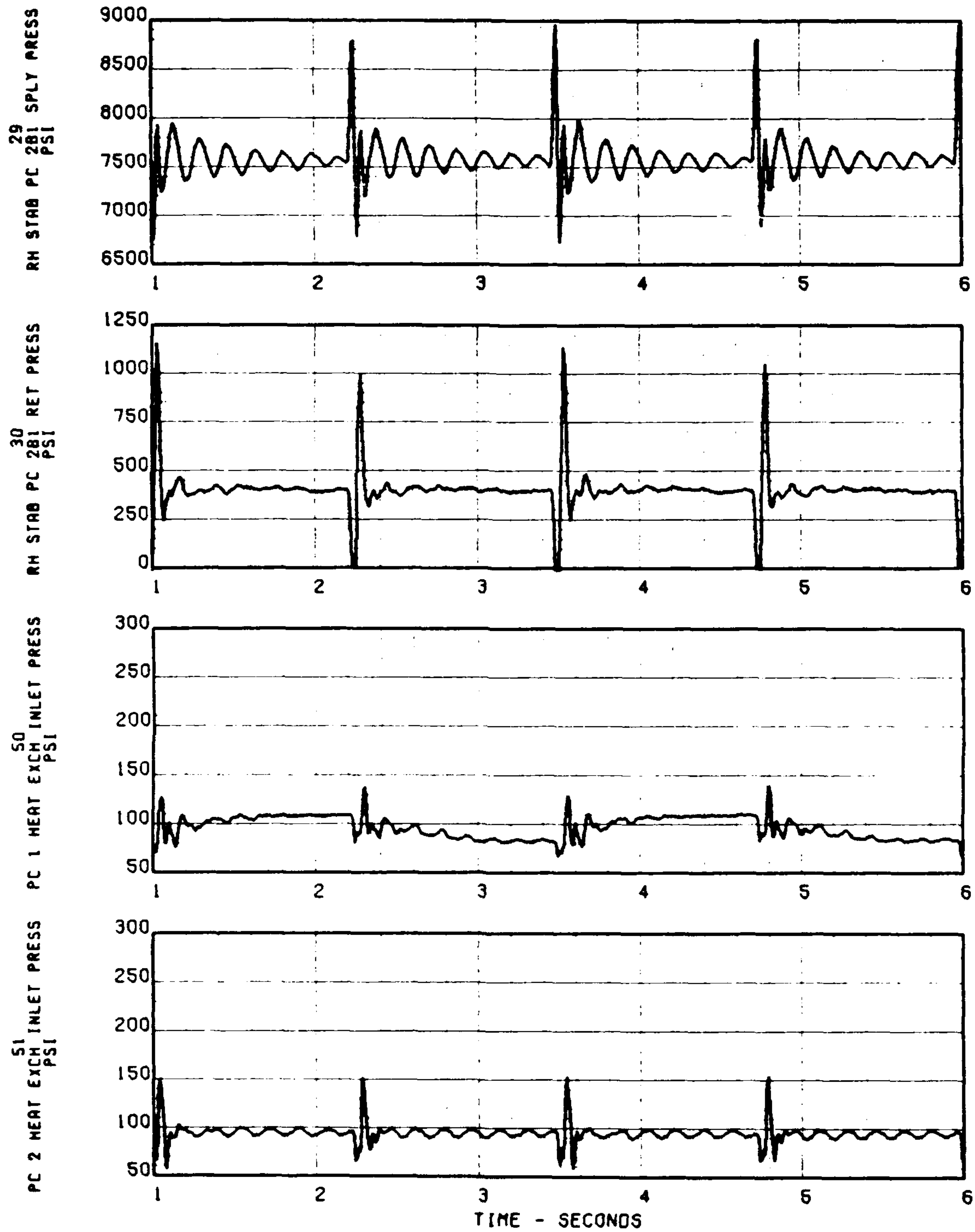


Figure 97. (Continued) System Test Results for Valve Reversal

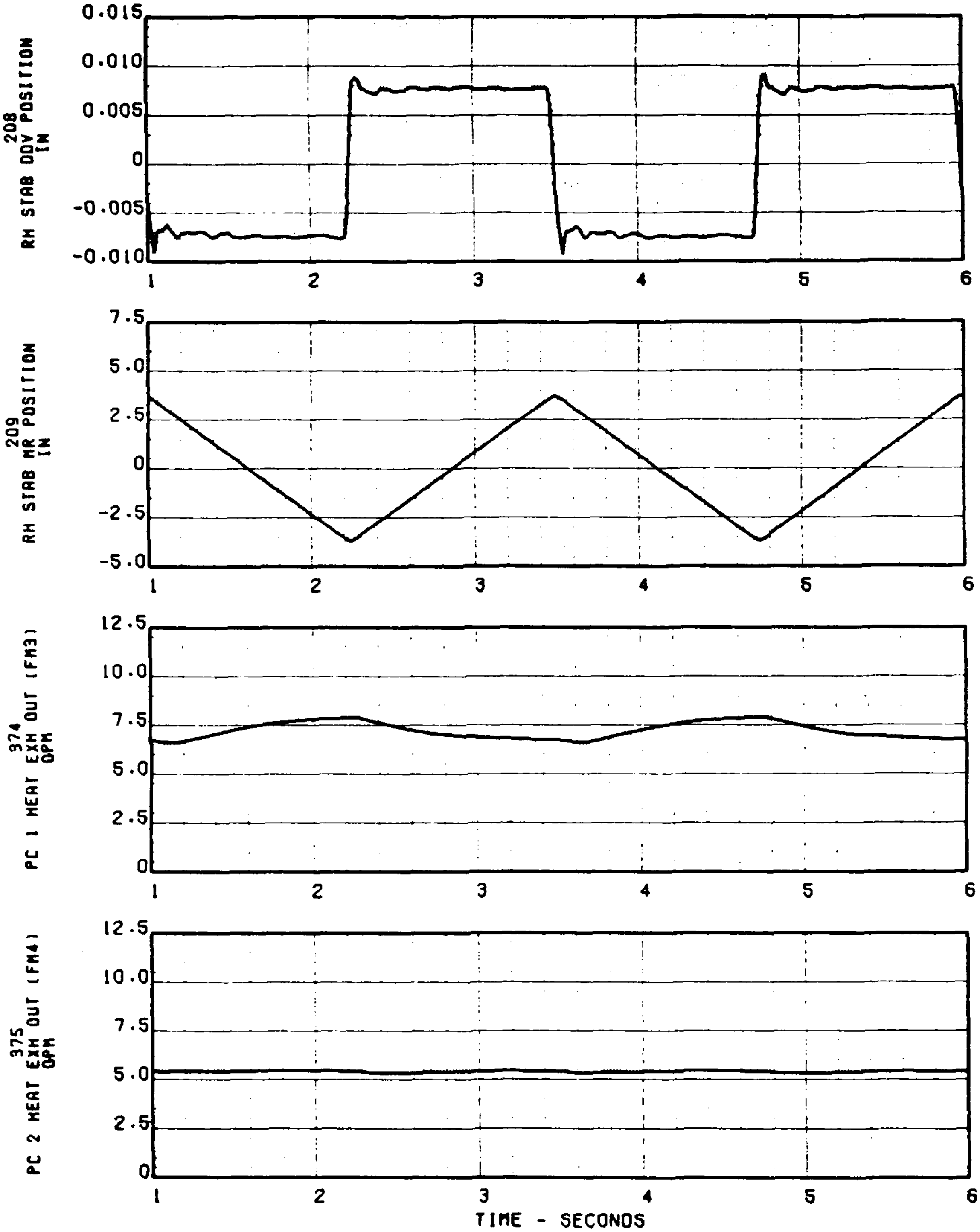


Figure 97. (Concluded) System Test Results for Valve Reversal

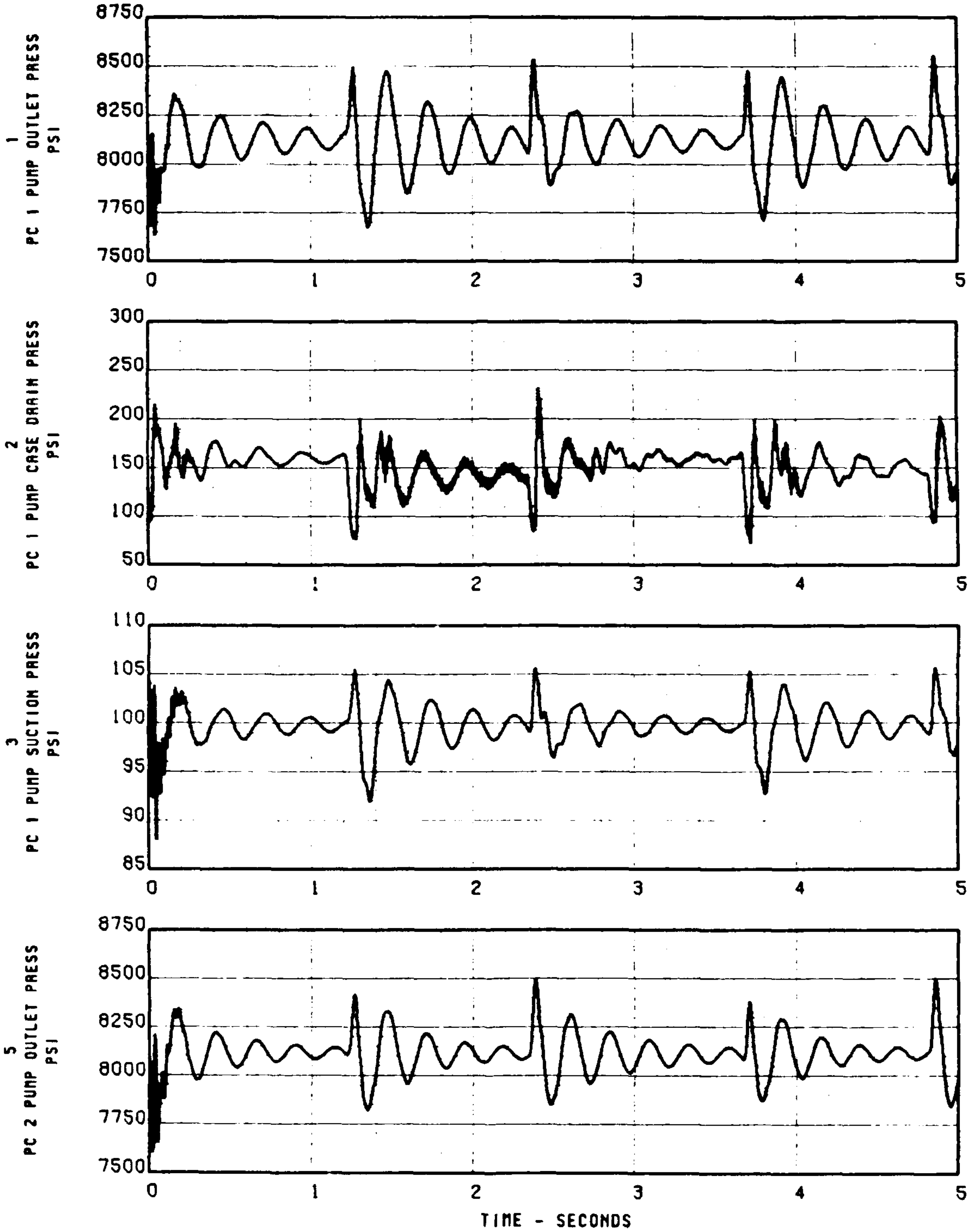


Figure 98. HYTRAN Simulation for Valve Reversal

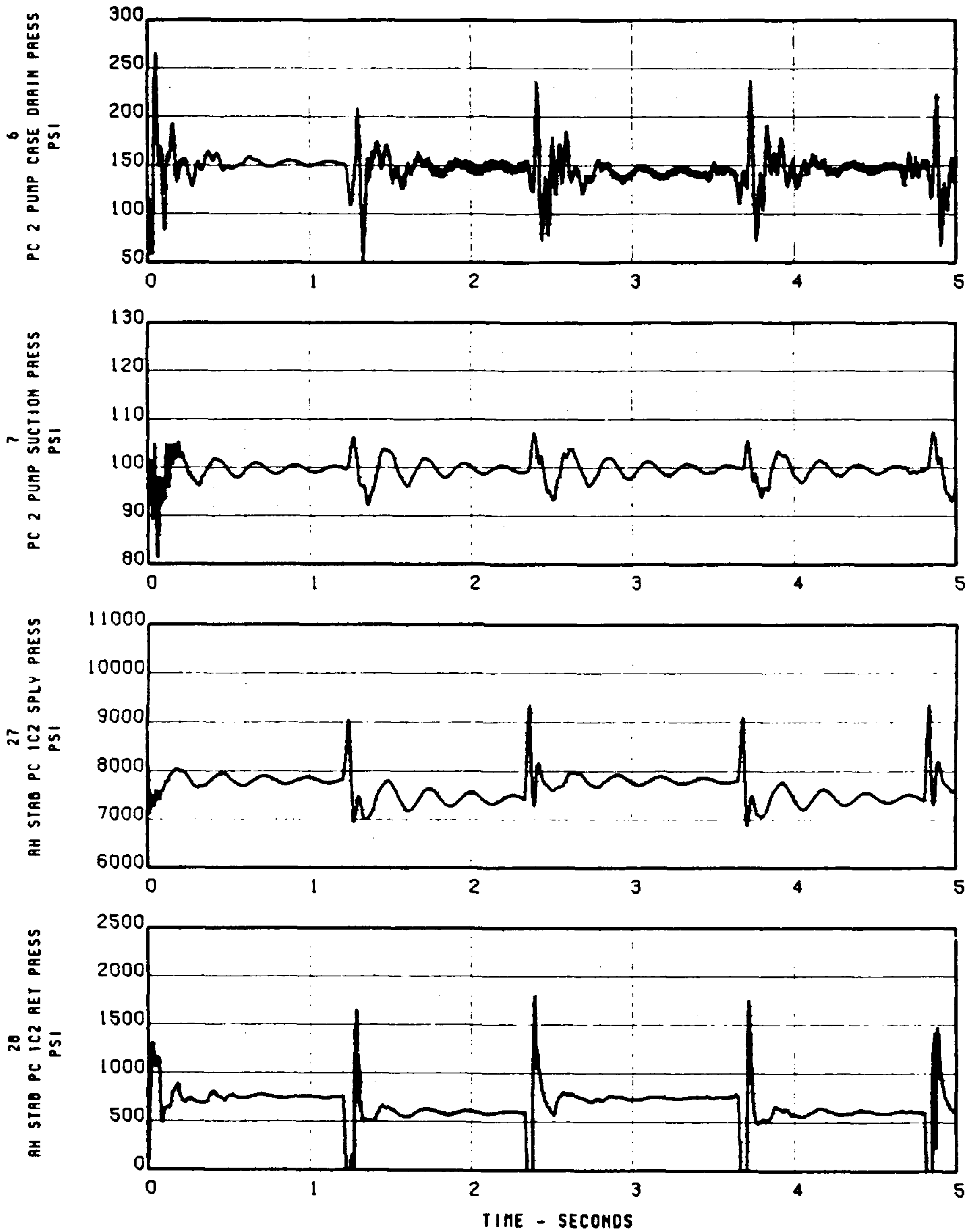


Figure 98. (Continued) HYTRAN Simulation for Valve Reversal

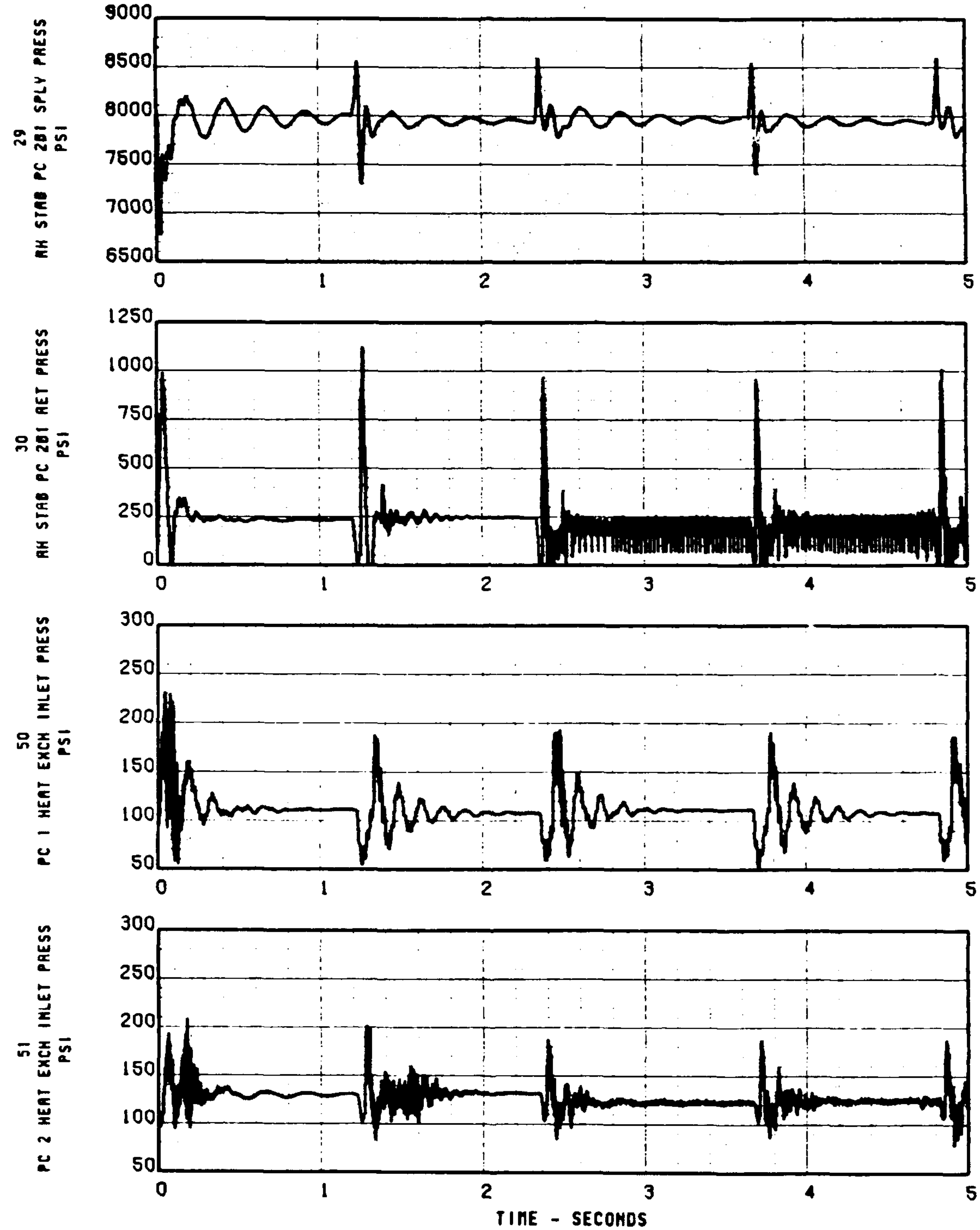


Figure 98. (Continued) HYTRAN Simulation for Valve Reversal

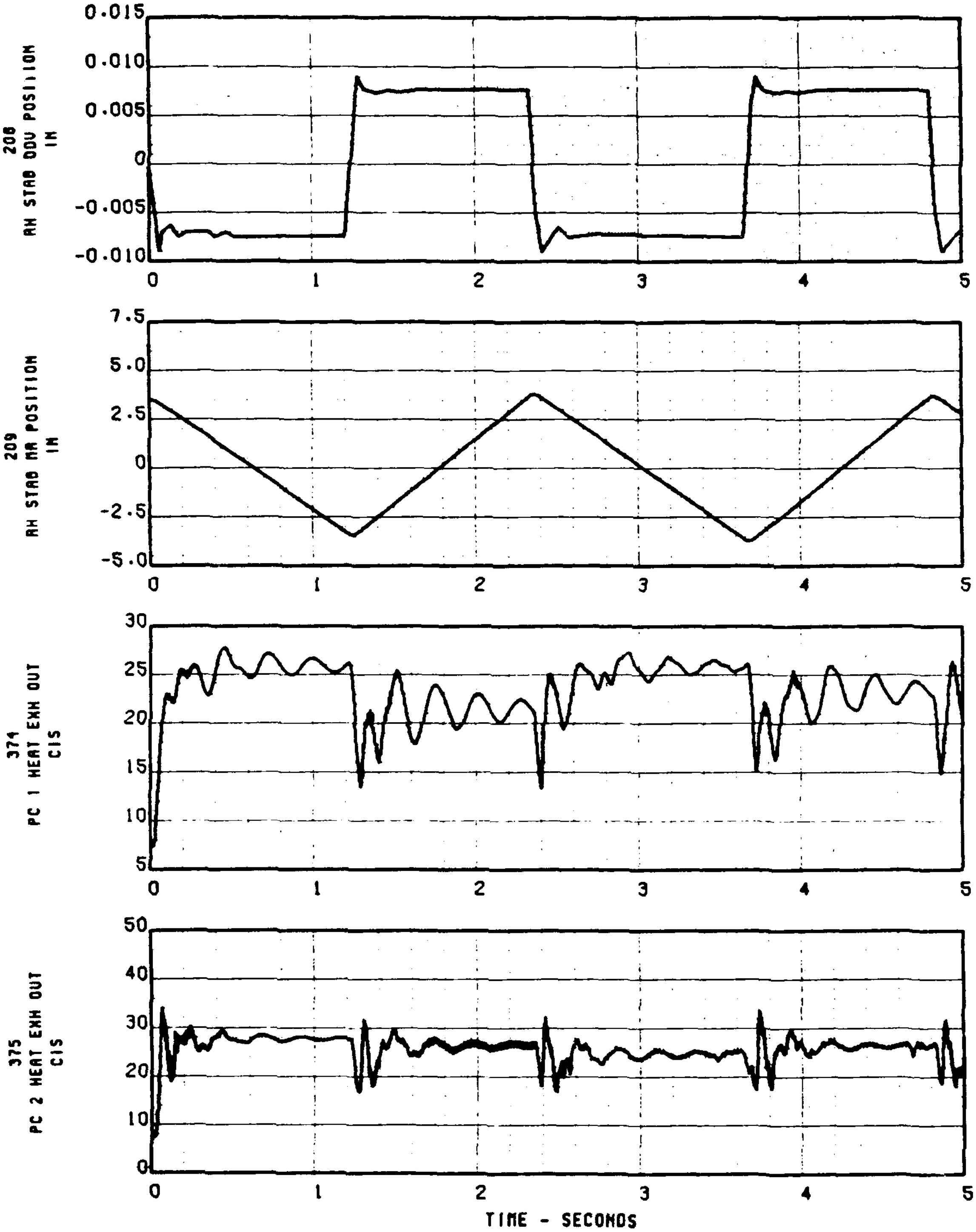


Figure 98. (Concluded) HYTRAN Simulation for Valve Reversal

Date	Endurance Elapse Time Start	Endurance Elapse Time Stop	Hourmeter Reading PC-1 Start	PC-1 Stop	PC-2 Start	PC-2 Stop	Comments
8 Dec 89	0	1.4.38	78.1	79.3	53.1	54.2	No Load PC -1 @ 7000 psi PC-2 @ 8000 psi
9 Dec 89 7:58 am	1.4.38	2.0.0	79.3	80.25	54.2	55.3	
9:26 am	2.0.0	2.20.51	80.25	80.6	55.3	55.6	PC-2 Pump Outlet Fitting Leaked, System was Shut Down for Repair
10:34 am	2.20.51	3.16.43	80.6	81.6	55.6	56.6	RH Arc Valve Leaked, System was Shut Down for Repair
12:53 pm	3.16.43	4.0.0	81.6		55.6		
1:20 pm	4.0.0	8.0.0	82.4	86.4	57.4	61.4	System Continued for 4 Hours with no Cooling Down Period PC-1 & PC-2 Temp @ 160°F
11 Dec 89 8:57 am	8.0.0.	10.0.0	86.4	88.4	61.4	63.4	PC-1 & 2 Temp OK. Shut Down System to Check Motor Vibration
1:08 pm	10.0.0	10.31.42	88.6	89.1	63.5	64.1	High Pressure Line in the LH Nozzle Actuator Leaked at the Fitting. PC-1 System Shut Down. Tightened up Fitting.
	10.31.42	12.0.0	89.1	90.6	64.1	65.5	
3:50 pm	12.0.0	14.0.0	90.8	92.8	65.6	67.6	
2 Dec 89 2:08 pm	14.0.0	16.0.0	93.7	95.7	67.9	70.0	R/H Stab + L/H Flap have Full Load. Peak Temp ~195° PC-1 RLSA Triped, had to Refill
12 Dec 89 4:20 pm	16.0.0	18.0.0	95.7	97.8	70.0	72.0	Start Temp = 122° Peak @ Combat = 200°

Figure 99. Endurance Test Log – PC System

Date	Endurance Elapse Time		Hourmeter Reading				Comments
			PC-1		PC-2		
	Start	Stop	Start	Stop	Start	Stop	
13 Dec 89 1:50 pm	18.0.0	20.0.0	98.6	100.7	72.1	74.1	Fluid Sample Taken
4:35 pm	20.0.0	22.0.0	100.7	102.7	74.1	76.2	Start Temp: 122° Combat Temp: 195°
14 Dec 89 2:45 pm	22.0.0	24.0.0	102.8	105.0	76.3	78.5	Combat Temp: 198° Peak
5:15 pm	24.0.0	26.0.0	105.0	107.0	78.5	80.6	Start Temp: 115° (130° in Warm up) Combat Temp: 198° (PC-2) 196° (PC-1)
15 Dec 89 8:20 am	26.0.0	28.0.0	107.0	109.1	80.6	82.6	Start Temp - 81° (PC-1 Hx 1.98 gpm) (PC-2 Hx 1.86 gpm) Stol 1 - 135° (Peak) Combat - 197° PC-1 TRQ = 235 @ 11% Cruise 1 PC-2 TRQ = 230 @ 11% Cruise 1
12:00 pm	28.0.0	30.0.0	109.1	111.1	82.6	84.7	Took Load off Flaperon Combat: 197°
3:00 pm	30.0.0	32.0.0	111.1	113.1	84.7	86.7	Start 117° Combat 197°
16 Dec 89 7:43 am	32.0.0	42.0.0	113.1	123.2	86.7	96.7	Start Temp: 114° PC-1 TRQ 170 in-lbs PC-2 TRQ 120 in-lbs End of Combat: PC-1 Temp = 195° PC-2 Temp = 196° Fluid Sample Taken During Taxi 2 at 39 hrs.
18 Dec 89 9:15 am	42.0.0	44.0.0	123.2	125.2	96.7	98.8	Start Temp: 118° Combat: 198° PC-1 5° Warmer than PC-2 (Descent)
12:53 pm	44.0.0	46.0.0	125.2	127.2	98.8	100.8	Start Temp: 110° Combat: 192°

Figure 99. (Continued) Endurance Test Log – PC System

Date	Endurance Elapse Time Start	Endurance Elapse Time Stop	Hourmeter Reading PC-1 Start	PC-1 Stop	PC-2 Start	PC-2 Stop	Comments
18 Dec 89 2:53 pm	46.0.0	48.0.0	127.2	129.3	100.8	102.9	Start Temp: 140° Combat: 193°
4:53 pm	48.0.0		129.3	129.7	102.9	103.3	Start Temp: 140° Canard Leaked Thru Rod End,
		50.0.0	129.7	131.3	103.3	104.9	Capped off and Continued.
29 Jan 90 1:25 pm	50.0.0	52.0.0	142.9	145.0	130.4	132.4	PC-1 & 2 Running with Variable Pressure
3:35 pm	52.0.0	54.0.0	145.0	147.1	132.4	134.5	
5:54 pm	54.0.0	56.0.0	147.1	149.2	134.5	136.7	Disconnected Ground Cart; QD Leaked after Disconnected.
7:55 pm	56.0.0	58.0.0	149.2	151.2	136.7	138.7	Added ~1 gal. to PC-1
30 Jan 90	58.0.0	64.26.55	151.6	158.1	139.6	146.1	Added Fluid to PC-1 @ 66 hrs.
	64.26.55	68.0.0	158.1	161.7	146.1	149.8	
31 Jan 90	68.0.0	76.0.0	161.7	169.8	149.8	157.9	Took Fluid Samples @ 70 hrs. Refilled Reservoirs
	76.0.0	80.0.0	169.8	174.0	157.9	162.1	R/H Rudder not Run for 2 Hrs.
1 Feb 90	80.0.0	84.0.0	174.0	178.2	162.1	166.4	Stopped to Reinstall the L/H Rudder Actuator
	84.0.0	90.0.0	178.5	184.9	166.5	172.7	L/H Rudder Included @ 86 hrs. Combat: PC-1: 191° UT-1: 206° PC-2: 187° UT-2: 187° Descent: UT-1: 208° UT-2: 187° PC's: 160° Stol 2: UT-1: 227° UT-2: 198°
2 Feb 90	90.0.0	100.0.0	184.9	195.0	172.8	183.0	
3 Feb 90	100.0.0	108.0.0	195.0	203.1	183.0	190.9	Replaced Intensifier Inlet Hose at 103.7 hrs. Added Fluid to PC-2

Figure 99. (Continued) Endurance Test Log – PC System

Date	Endurance Elapse Time Start	Endurance Elapse Time Stop	Hourmeter Reading PC-1 Start	Hourmeter Reading PC-1 Stop	Hourmeter Reading PC-2 Start	Hourmeter Reading PC-2 Stop	Comments
5 Feb 90	108.01	112.44.27	203.1	208.1	190.9	195.9	Refilled PC-1 Reservoir Pressure Intensifier Inlet Line Broke
	112.44.27	115.8.27	208.3	211.3	195.9	198.5	
6 Feb 90	115.8.27	118.0.0	211.0	215.0	198.5	202.0	
	118.0.0	122.0.5	215.0	218.6	202.0	205.7	Start @ 42% Cruise
	122.0.5	126.0.4	218.6	222.7	205.7	209.7	
7 Feb 90	126.0.4	128.48.0	222.8	225.6	209.7	212.6.5	Start @ 1% Cruise 2 Intensifier Inlet Line Broke, Removed Intensifier from Circuit
	128.48.0	135.16.0	225.6	232.2	212.6.5	219.5	
	135.16.0	136.0.0	232.2	233.0	219.8	220.6	
8 Feb 90	136.0.0	138.0.0	233.0	235.1	220.6	222.8	
	138.0.0	140.59.0	135.1	238.3	222.8	226.3	
9 Feb 90	140.59.0	142.57.0	238.4	240.4	226.3	228.3	Start @ Cruise 2
	142.57.0	154.0.0	240.4	251.6	228.3	239.6	Start @ Cruise 2 - 21%
12 Feb 90	145.0.0	155.14.0	251.6	252.9	239.6	240.9	
14 Feb 90	155.14.0	156.0.0	258.9	259.8	246.9	247.7	Start @ 63% Cruise 2
15 Feb 90	156.0.0	162.0.2	259.9	267.7	247.8	255.6	
	162.0.2	164.0.0	267.7	269.9	255.6	257.8	
16 Feb 90	164.0.0	168.0.0	269.9	–	257.8	–	
2nd Shift	168.0.0	174.0.0	–	280.2	–	268.2	
17 Feb 90	174.0.0	182.0.0	280.2	288.4	268.2	276.4	
19 Feb 90	182.0.0	190.0.0	288.4	296.7	276.4	284.7	
	190.0.0	192.0.0	296.7	299.1	284.7	287.1	

Figure 99. (Continued) Endurance Test Log – PC System

Date	Endurance Elapse Time Start	Endurance Elapse Time Stop	Hourmeter Reading PC-1 Start	Hourmeter Reading PC-1 Stop	Hourmeter Reading PC-2 Start	Hourmeter Reading PC-2 Stop	Comments
20 Feb 90	192.0.0	200.0.0	299.2	308.2	287.2	296.2	
	200.0.0	202.0.0	308.2	310.2	296.2	298.2	
21 Feb 90	202.0.0	208.41.3	310.3	317.1	298.3	305.1	
22 Feb 90	208.41.3	218.0.0	321.1	330.5	305.3	314.7	Start @ 32% Combat
23 Feb 90	218.0.0	224.41.27	330.5	337.7	314.7	322.0	
26 Feb 90	224.41.27	234.0.0	337.7	347.4	322.1	331.7	Start @ 35% Combat
27 Feb 90	234.0.0	246.0.0	347.4	359.6	331.7	343.9	No Inertia on L/H Rudder
28 Feb 90	246.0.0	260.0.0	359.6	374.0	343.9	358.2	
1 Mar 90	260.0.0	262.0.0	374.0	376.0	358.2	360.2	Switched PC-1 & UT-1 Pump
	262.0.0	269.0.0	376.0	383.2	360.3	367.6	
2 Mar 90	269.0.0	280.0.0	383.3	394.7	367.6	378.9	Flaperon Transfer Tube Hold-down Clamp Broke-seal Blew
5 Mar 90	280.0.0	288.8.52	394.7	403.0	378.9	387.2	Disconnected L/H Rudder @ 283.3 Hr.
6 Mar 90	288.8.52	296.0.0	403.0	411.3	387.3	395.6	
7 Mar 90	296.0.0	304.0.0	411.3	421.9	395.6	406.2	
8 Mar 90	304.0.0	306.0.0	422.8	424.8	407.1	409.1	Shut Down PC-2 Pump Servo Valve Leaked
	306.0.0	314.0.0	425.1	433.8	409.4	418.2	
9 Mar 90	314.0.0	324.0.0	433.8	444.6	418.2	429.0	Switched PC-2 & UT-2 Pumps

Figure 99. (Concluded) Endurance Test Log – PC System

Date	Endurance Elapse Time		Hourmeter Reading				Comments
			UT-1		UT-2		
	Start	Stop	Start	Stop	Start	Stop	
10 Jan 90 9:38 am	0.0.0	2.0.0	31.5	33.6	10.0	12.1	Start Temp: UT-1: 127° @ Taxi UT-2: 155° @ Taxi Cruise Start 170° 210° UT-2 ~ 250 in-lb More than UT-1 During Cruise
4:08 pm	2.0.0		33.9	34.6	12.4	13.0	UT-1 150° @ Taxi UT-2 168° @ Taxi R/H Rev Vane Seal Leaked (on Left)
5:20 pm			34.6	36.0	13.0	14.4	58% Descent: Two -5 Fittings Backed off and Began Leaking on the Convergent Actuator
11 JAN 90 1:50 pm	4.0.0	6.0.0	36.2	36.6	14.8	15.1	UT-1: 144°, UT-2: 88° Start Temp Arc Valve Seal Blew. Replaced it &
			36.6	38.2	15.1	16.7	Took Fluid Sample During Cruise 1 (50%)
12 Jan 90 12:00 pm	6.0.0	8.0.0	39.1	41.1	17.5	19.6	UT-1: 123° (Start) UT-1 & 2 Torque ~Same UT-1: 152° @ Cruise 2 (0%)
2:35 pm	8.0.0	10.0.0	41.1	43.1	19.6	21.6	UT-1: 156° UT-2: 175° @ End of Climb
13 Jan 90 7:40 am	10.0.0	12.0.0	43.2	45.2	21.6	23.6	Start Temp: 87°
10:00 am	12.0.0	14.3.25	45.4	47.5	32.9	25.9	R/H Arc Valve Leaked, RLS A Shut Down
	14.3.25	16.0.0	47.5	49.5	26.0	28.0	
2:50 pm	16.0.0	18.0.0	49.5	51.5	28.0	30.0	
15 Jan 90 9:00 am	18.0.0	20.0.0	51.7	53.8	30.0	32.0	UT-2 Pressure Switch (Top of Filter) Leaked thru Blow out Hole. Replaced Switch

Figure 100. Endurance Test Log – UT System

Date	Endurance Elapse Time		Hourmeter Reading				Comments
			UT-1		UT-2		
	Start	Stop	Start	Stop	Start	Stop	
15 Jan 90 1:30 pm	20.0.0	22.0.0	53.9	56.2	32.2	34.4	
3:35 pm	22.0.0	24.0.0	56.2	58.2	34.4	36.4	UT-1: 129° UT-2: 144° @ Start
16 Jan 90 12:35 pm	24.0.0	26.0.0	58.2	60.2	36.4	38.4	
2:35 pm	26.0.0	28.0.0	60.2	62.2	38.4	40.4	UT-1: 135° UT-2: 147°
	28.0.0	28.53.59	62.3	63.1	40.5	41.4	UT-1: 131° @ Stop - 14% Cruise UT-2: 144° @ Stop - 14% Cruise
	28.53.59	30.0.0	63.2	64.3	41.4	42.6	UT-1: 130° (Start) 14% Cruise UT-2: 143° (Start) 14% Cruise
17 Jan 90	30.0.0	32.0.0	64.3	66.4	42.6	44.6	
	32.0.0	34.0.0	66.4	68.4	44.6	46.6	
2:30 pm	34.0.0	37.0.49	68.4	71.3	46.7	49.6	UT-2 Pressure Switch Leaked – RLSA Shutdown
	37.0.49	38.0.0	71.5	72.5	49.7	50.7	UT-1 Smart Pump Starting to have Problem Holding 8K - Started @ 4K (But got it up to 8K) at End was Down to 7.5K
	38.0.0	41.15.2	72.9	76.1	50.8	54.1	Switched UT-1 Pump Installed (S/N 193200)
	41.15.2	50.0.0	76.1	84.9	54.1	62.9	Fluid Sample @ 40 Hrs.
29 Jan 90	50.0.0	52.0.0	85.0	85.0	62.9	65.0	UT-2 Pump Operation Only UT-1 not Operated Due to Missing Torque Sensor
1:25 pm	52.0.0	54.0.0	85.0	87.1	65.0	67.1	Start up with UT-1 & 2 both Operational
3:35 pm	54.0.0	56.0.0	87.1	89.2	67.1	69.3	
5:54 pm	56.0.0	58.0.0	98.2	91.2	69.3	71.3	

Figure 100. (Continued) Endurance Test Log – UT System

Date	Endurance Elapse Time Start	Endurance Elapse Time Stop	Hourmeter Reading UT-1 Start	Hourmeter Reading UT-1 Stop	Hourmeter Reading UT-2 Start	Hourmeter Reading UT-2 Stop	Comments
30 Jan 90	58.0.0	64.26.55	92.6	99.1	72.6	79.1	Start up Leak on L/H Nozzle Divergent (55% Cruise 1) Capped off Lower Div and Continued. Actuator Seal Failure
	64.26.55	68.0.0	99.1	102.8	79.1	82.8	
31 Jan 90	68.0.0	76.0.0	102.8	110.9	82.8	91.0	Fluid Samples Refilled Reservoirs Replaced Lower Div. Nozzle Actuator @ 76 Hrs.
	76.0.0	80.0.0	110.9	115.1	91.0	95.1	
1 Feb 90	80.0.0	84.0.0	115.1	119.3	95.1	99.4	Stopped to Plumb in the L/H Rudder Actuator
	84.0.0	90.0.0	119.3	125.5	99.4	105.6	
2 Feb 90	90.0.0	100.0.0	125.5	135.5	105.6	115.6	
3 Feb 90	100.0.0	108.0.0	135.5	143.7	115.6	123.8	
5 Feb 90	108.0.0	112.44.27	143.7	148.6	123.8	128.8	
	112.44.27	115.8.27	148.6	151.1	128.8	131.3	
6 Feb 90	115.8.27	–	151.1	–	131.3	–	
	118.0.0	122.0.5	154.5	158.3	134.8	138.5	Start @ 42% Cruise
	122.0.5	126.0.4	158.3	162.4	138.5	142.6	
7 Feb 90	126.0.4	128.48	162.5	165.2.5	142.7	145.5	Start @ 1% Cruise 2
	128.48	135.16	165.2.5	171.8	145.5	152.1	
	135.16	136.0.0	171.8	172.8	152.1	152.8	

Figure 100. (Continued) Endurance Test Log – UT System

Date	Endurance Elapse Time Start	Endurance Elapse Time Stop	Hourmeter Reading UT-1 Start	Hourmeter Reading UT-1 Stop	Hourmeter Reading UT-2 Start	Hourmeter Reading UT-2 Stop	Comments
8 Feb 90	136.0.0	138.0.0	172.6	174.7	152.8	155.1	UT-2 Pump Sounding Bad Rev Vane Seal Blew
	138.0.0	140.59	174.7	177.9	155.1	158.3	R/H Nozzle "Off"
9 Feb 90	140.59	142.57	177.9	179.9	158.4	160.3	Started @ Cruise 2
	142.57	154.0.0	179.9	191.1	160.3	171.6	Started @ Cruise 2 - 21%
12 Feb 90	154.0.0	155.14	191.1	192.4	171.6	172.9	UT-1 Pump Failed
14 Feb 90	155.14	156.0.0	195.4	196.2	176.2	177.0	Started @ 63% Cruise 2
15 Feb 90	156.0.0	162.0.2	197.1	205.3	177.1	185.3	
	162.0.2	164.0.0	205.3	207.5	185.3	187.5	
16 Feb 90	164.0.0	168.0.0	207.5	–	187.5	–	
2 nd Shift	168.0.0	174.0.0	–	215.7	–	197.8	
17 Feb 90	174.0.0	182.0.0	218.7	226.9	197.8	206.0	
19 Feb 90	182.0.0	190.0.0	226.9	236.6	206.0	214.7	
	190.0.0	192.0.0	236.6	239.5	214.7	217.1	
20 Feb 90	192.0.0	200.0.0	239.6	248.6	217.2	226.2	
	200.0.0	202.0.0	248.6	251.5	226.2	228.3	
21 Feb 90	202.0.0	208.41.3	251.5	258.4	228.3	235.2	UT-2 Pump Failed
22 Feb 90	208.41.3	218.0.0	259.1	268.5	235.4	244.8	Start @ 32% Combat
23 Feb 90	218.0.0	224.41.27	268.5	276.1	244.8	252.5	Ran with UT-1 Pump Only Cycling Limited to 10%
26 Feb 90	224.41.27	234.0.0	276.2	285.8	252.5	252.5	
27 Feb 90	234.0.0	246.0.0	286.1	298.3	252.5	252.5	
28 Feb 90	246.0.0	260.0.0	298.3	312.6	252.5	252.5	

Figure 100. (Continued) Endurance Test Log – UT System

Date	Endurance Elapse Time Start	Endurance Elapse Time Stop	Hourmeter Reading UT-1 Start	UT-1 Stop	UT-2 Start	UT-2 Stop	Comments
1 Mar 90	260.0.0	262.0.0	312.6	314.6	252.5	252.5	Switched PC-1 & UT-1 Pump
	262.0.0	269.0.0	314.7	321.9	252.5	252.5	UT @ 8K Pump
2 Mar 90	269.0.0	28.0.0	322.0	333.4	252.5	252.5	
5 Mar 90	280.0.0	288.5.52	333.4	341.7	252.5	252.5	UT Pump Went Bad
6 Mar 90	288.8.52	296.0.0	341.7	341.7	252.5	263.5	Replaced UT Pump & Continued
7 Mar 90	296.0.0	304.0.0	341.7	341.7	263.5	274.8	Shut Down to Replace PDU
8 Mar 90	304.0.0	306.0.0	341.7	341.7	275.4	277.4	
	306.0.0	314.0.0	341.7	341.7	278.2	287.6	
9 Mar 90	314.0.0	324.0.0	341.7	346.0	287.7	299.3	190174 Installed on UT-1 @ 341.7 Switched UT-2 & PC-2 Pump

Figure 100. (Concluded) Endurance Test Log – UT System

	Number of Cycles					
Actuator	No load	1/2 Load	Full Load	Total Cycles	Total Hours	Surface Inertia
E-Systems:						
R/H Stabilator	895,600	555,272		1,450,872	324	N
L/H Stabilator	895,600	555,272		1,450,872	324	Y
Bendix:						
L/H Rudder	644,832	420,932	223,900	1,289,664	288	Y
HR Textron:						
R/H Rudder	671,700	555,272		1,226,972	274	N
Parker Bertea:						
L/H Canard	205,000	N/A	N/A	205,000	48.5	Y
L/H Reverser Vane	67,716	N/A	N/A	67,716	324	Y
R/H Reverser Vane	28,842	N/A	N/A	28,842	138 (1)	N
R/H Arc Valve	206,241	N/A	N/A	206,241	138 (1)	N
Moog:						
L/H Flaperon	896,600	507,476		1,404,076	313	Y
Convergent Nozzles	373,625	110,593		484,218	324 (2)	Y
Divergent Nozzles:						Y
S/N 001,002&004	373,625	110,593		484,218	324 (2)	
S/N 003(chrome rod)	113,582			113,582	76	
S/N 005(tung.carb. rod)	260,043	110,593		370,636	248 (2)	
Cadillac Gage:						
Diffuser Ramp	484,218			484,218	324	N
Sundstrand:						
Leading Edge Flap		37,902		37,902	10.8	N

(1) Hours limited to 138 to reduce flow demand on 15 gpm backup pumps

(2) Includes 100 hours of cycling limited to 10% strokes to reduce flow demand

Figure 101. Actuator Endurance Hours/Cycles

Serial Number		Pressure Control	Ownership	Location	Total Test Hours	
					Utility	PC
192336	(1)	Variable	Air Force	McAir	5.7	302.6
192337		Variable	Air Force	Abex	50.7	—
192343		Constant	McAir	McAir-PC-2	42.8	4.5+
192369		Constant	Air Force	McAir	17.7	—
192370		Constant	Air Force	Abex	8.5	—
192413		Variable	Air Force	McAir-UT-2	22.0+	121.4
193074	(2)	Variable	Air Force	Abex	27.1	364.2
193174		Variable	McAir	McAir-UT-1	4.8+	11.5
193175		Variable	McAir	McAir-PC-1	78.1	69.5+
193198		Constant	McAir	McAir	82.4	—
193199		Constant	McAir	McAir	138.3	—
193200		Constant	McAir	McAir	102.2	—

(1) Of the 308.3 total hrs, about 250 hrs were with variable pressure.
(2) Of the 391.3 total hrs, about 300 hrs were with variable pressure.

Figure 102. 15 gpm Pump Log

5.4.3 Heat Rejection and Power Consumption - Assuming turbulent flow, CTFE convective heat transfer coefficient for the same flow condition is approximately 10 percent better than that of MIL-H-83282. Conversely, the thermal mass (fluid density times specific heat) of CTFE is approximately 21 percent less than that of MIL-H-83282. To transfer the same amount of heat, materials with higher heat transfer coefficients require less heat exchanger area, while materials with lower thermal mass require more heat exchanger area. The higher heat transfer coefficient of CTFE is not expected to overcome the effect of lower fluid thermal mass; thus, it is expected that the heat exchanger area would be somewhat larger for a CTFE based system with all other system heat rejection characteristics being equal. It must be noted that for laminar flow, the convective heat transfer coefficient for CTFE is approximately 42 percent lower than that for MIL-H-83282. This may impose significant heat exchanger sizing penalties if the heat exchanger is designed at laminar flow conditions. Heat exchanger sizing performed in Phase III of this contract and reported in Reference 1 was done to assure the adequacy of the F-15E heat exchangers used for Phase V. Due to termination of the program, specific testing to verify heat exchanger requirements could not be performed.

Variable pressure operation has proven to effectively reduce heat rejection and power consumption. Figures 103 and 104 compare pump outlet, case drain and suction temperatures for variable and constant 8000 psi operation. These temperatures were typical for both the PC-1 and PC-2 systems. Variable pressure operation reduces pump temperatures significantly when compared to constant pressure. During the cruise phases of the duty cycle, pump outlet and case drain temperatures are 35 to 40 deg F cooler with variable pressure. Figure 105 presents pump temperatures typical of the utility system during variable pressure operation. Heat rejection and system flow data typical of both the PC-1 and PC-2 systems is presented in Figures 106 and 107. Comparison between these two figures shows a considerable reduction (as much as 50%) of both quiescent leakage and heat rejection during variable pressure operation in the less active phases of the duty cycle. Figure 108 shows substantial savings in the utility system heat rejection and system flow during variable pressure operation.

Pump shaft power and system pressure was recorded during an entire 2 hour duty cycle for the PC systems during both variable and constant pressure operation. Figure 109 presents average pressure and shaft power during each mission phase for both variable and constant pressure operation. During variable pressure operation, the pumps were commanded to 8000 psi during 28% of the duty cycle, 3000 psi for 51% of the time and the balance between 3000 and 8000 psi as determined by the smart pump controller. The time averaged pump pressure and pump shaft power during variable pressure operation was about 5070 psi and 14.2 hp respectively. The time averaged pump shaft power during constant pressure operation was 23.3 hp. Figure 110 presents an energy consumption comparison between the two pressure modes. Pump shaft power was integrated over the entire 2 hour duty cycle and showed a 39% reduction in pump shaft power. These results are dependent on the severity of the duty cycle. The pump controller parameters were programmed to produce 8000 psi operating pressure at least 25% of the duty cycle. If the time required at 8000 psi could be reduced, the power consumption and heat rejection during variable pressure operation would be much less.

5.4.4 Fluid Samples - Figure 111 shows the results of the CTFE fluid samples analyzed at Material Laboratory of the Wright Research and Development Center at Wright-Patterson AFB throughout the endurance test. Viscosity, water content and acid levels are all within the acceptable limits for the fluid. The only noticeable sign of degradation is the darkening of the fluid which is not in any way detrimental to the fluids performance. Fluid samples taken during previous test efforts had several problems with water and acid levels. These are discussed in Appendix C.

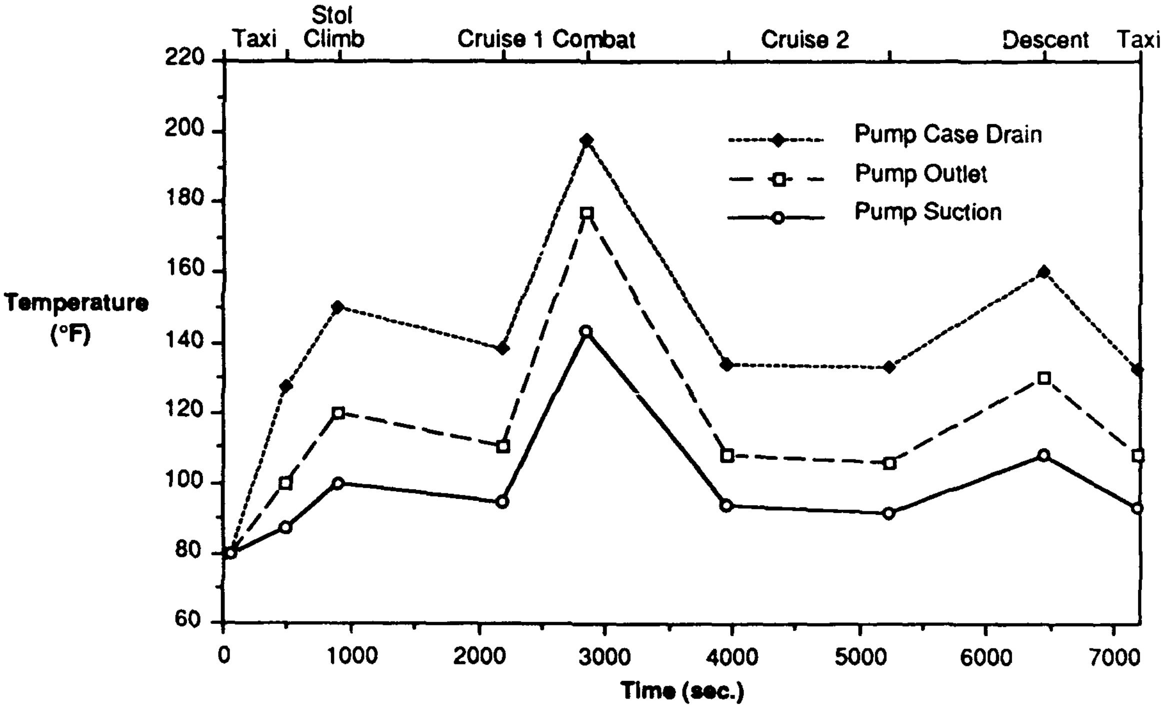


Figure 103. PC Pump Temperature
Variable Pressure

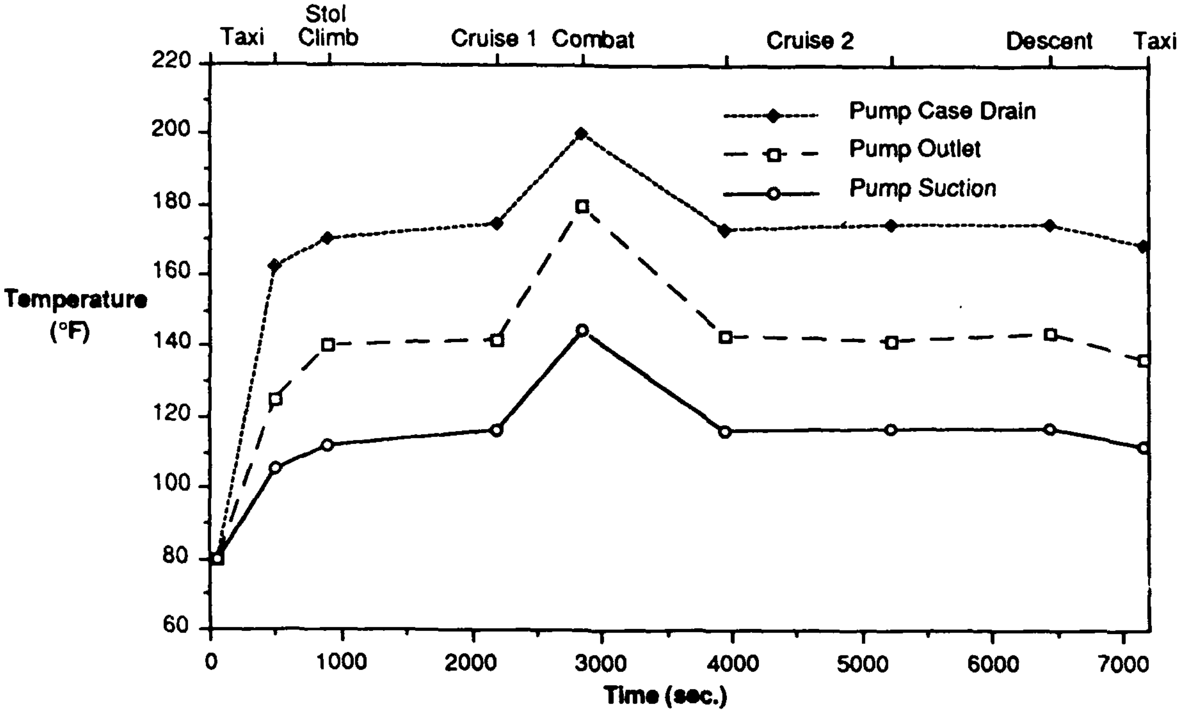


Figure 104. PC Pump Temperature
Constant Pressure

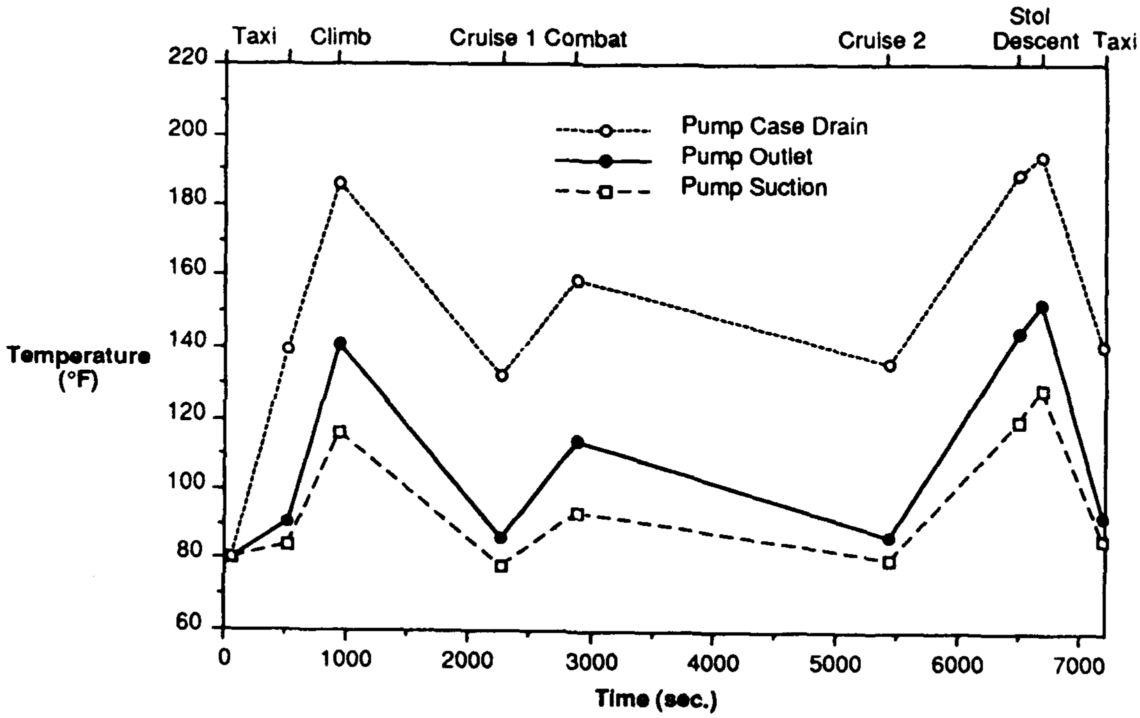


Figure 105. UT Pump Temperature
Variable Pressure

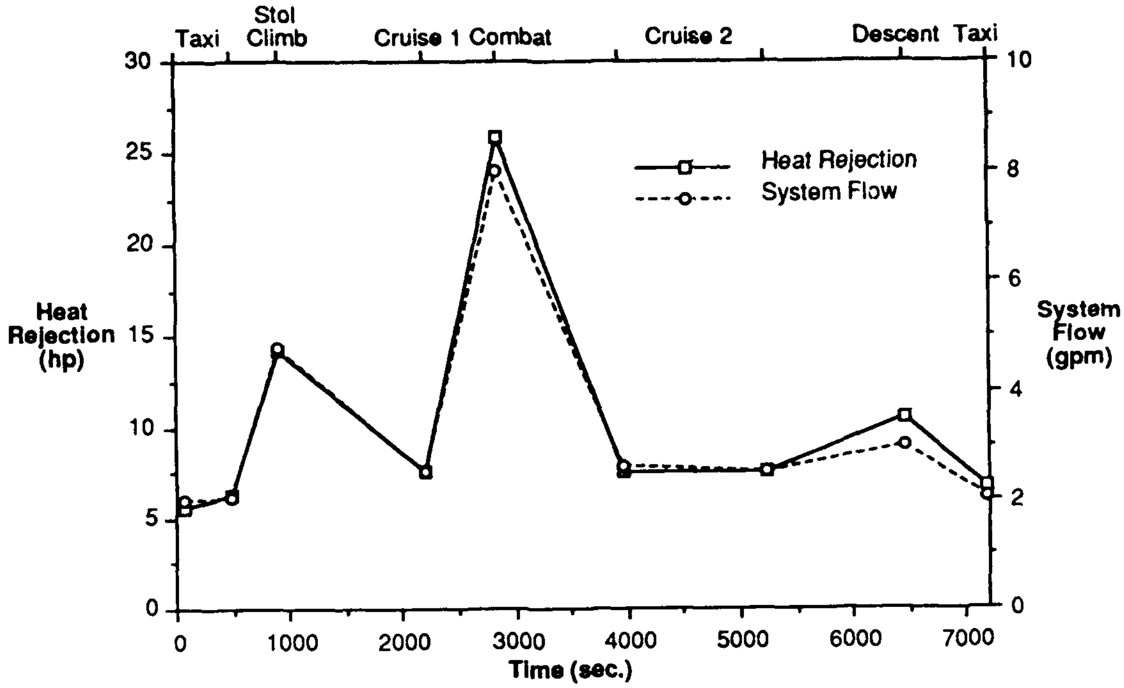


Figure 106. PC System Heat Rejection
Variable Pressure

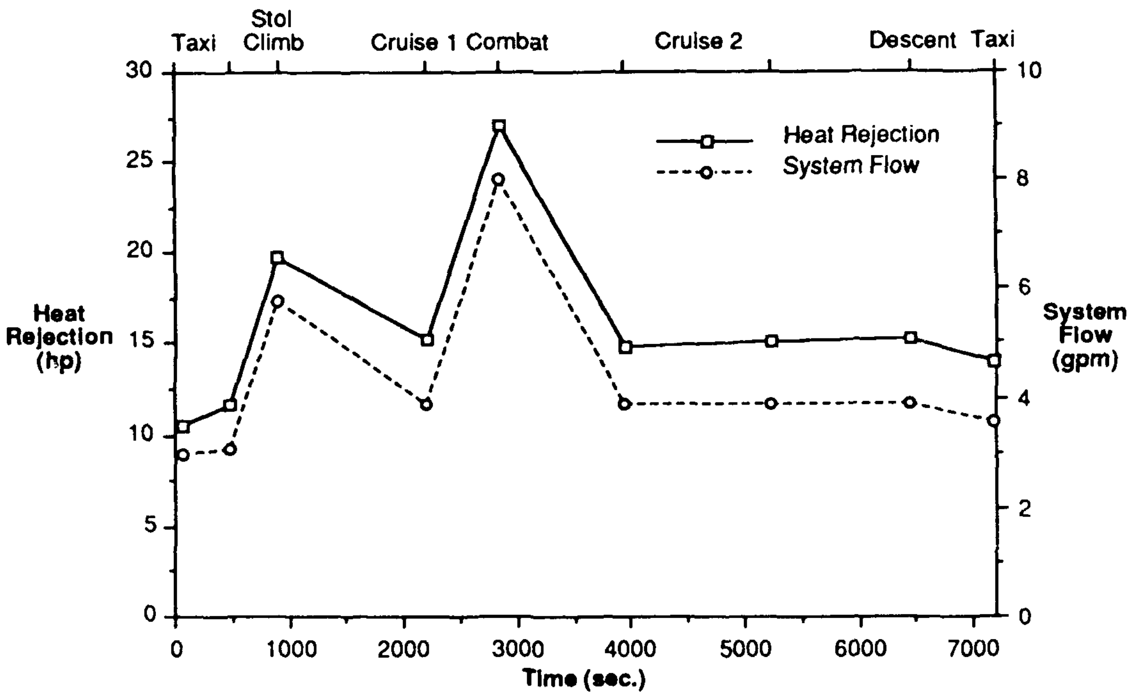


Figure 107. PC System Heat Rejection
Constant Pressure

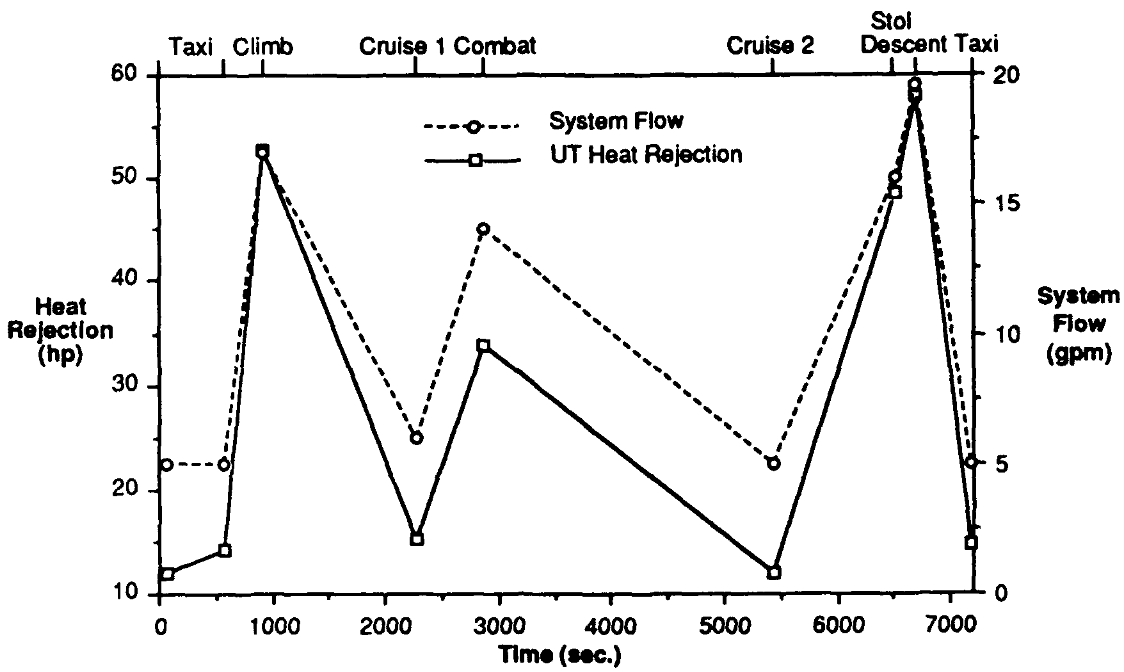


Figure 108. UT System Heat Rejection
Variable Pressure

	Time (sec)	Average Pressure (psi)		Average Pump Horsepower			
		Variable Pressure		Variable Pressure		8000 psi	
		PC-1	PC-2	PC-1	PC-2	PC-1	PC-2
Warm-up	60	3225	3317	6.2	4.4	15.3	15.3
Taxi 1	450	3339	3442	6.5	4.9	17.3	17.4
Stol Climb	416	6825	6951	21.2	21.1	25.3	25.3
Cruise 1	1336	4354	4557	12.3	11.0	23.7	22.9
Combat	612	7958	7985	36.8	35.8	36.8	35.8
Cruise 2	2557	4054	4190	11.0	8.9	22.9	21.7
Descent	1072	6861	7103	18.0	17.8	21.6	21.2
Stol 2	180	7998	8015	32.7	32.3	33.2	32.8
Reverse Taxi 2 Cool Down	517	3128	3200	6.5	3.8	18.8	18.1
Total Time	7200 (2hr)						
Time Average (2hr duty cycle)		5000	5144	15.0	13.5	23.7	23.0

Figure 109. PC Power Consumption
Variable Pressure vs Constant Pressure

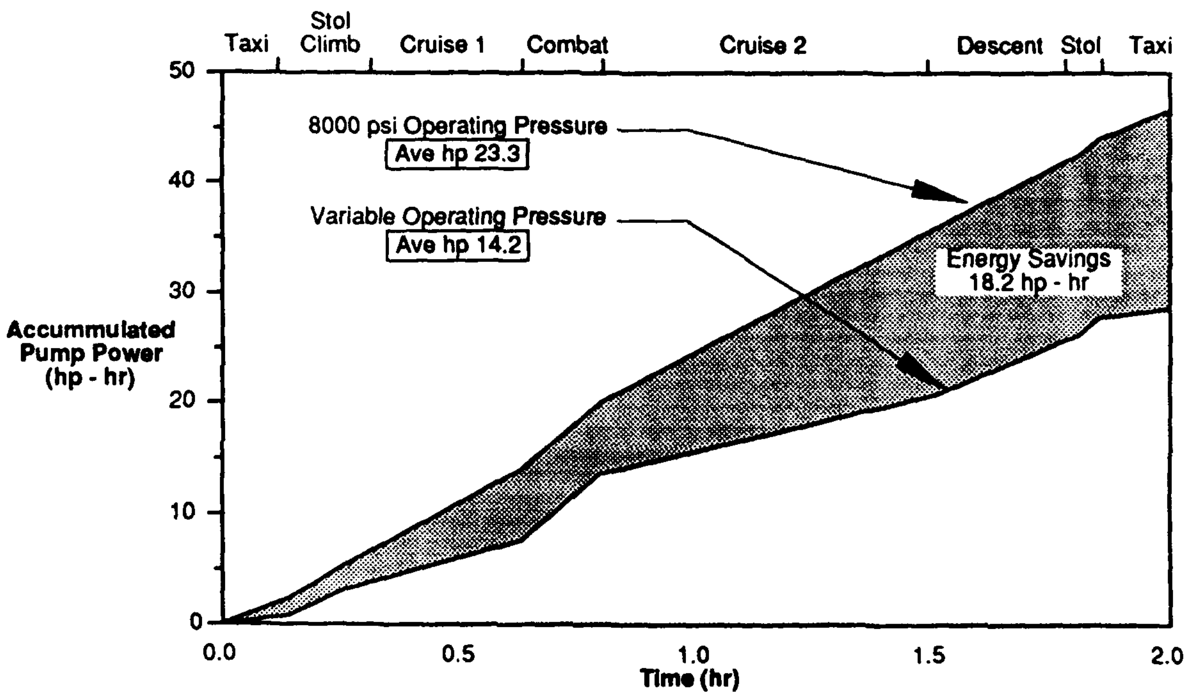


Figure 110. PC System Energy Consumption and Savings

Samples Received From MCAIR Starting 1 JAN 90						
MLO Number	Appearance of Sample	System Hours	VISC. (cSt) 100°F	VISC. (cSt) 210°F	Water (ppm)	ACID Nr [mg KOH/gm)
Unstressed						
89-369 b	Amber Clear	0.0	3.10	1.03	56	0.09
89-322 c	Amber Clear	0.0	2.96	1.00	31	0.00
Stressed						
90-13	Amber Clear	Abex Stand	3.02	1.13	278	0.35
90-17	Amber Clear	100.7 PC-1	3.10	1.03	a	0.23
90-19	Amber Clear	111.1 PC-1	3.12	1.04	a	0.22
90-21	Amber Clear	131.3 PC-1	3.13	1.03	114	0.31
90-23	Amber Clear	104.9 PC-2	3.12	1.03	127	0.27
90-24	Amber Clear	84.7 PC-2	3.11	1.24	a	0.23
90-26	Amber Clear	61.0 PC-2	3.10	1.04	a	0.22
90-27	Amber Clear	36.7 UT	3.13	1.03	131	0.23
90-28	Amber Clear	66.3 PC-1	3.13	1.04	a	0.19
90-29	Amber Clear	31.5 Utility	3.14	1.04	130	0.17
90-30	Brown Clear	Abex Stand	2.99	0.98	369	0.42
90-138	Amber Clear	80 Utility	3.17	1.05	129	0.29
90-139	Amber Clear	60 Utility	3.14	1.04	a	0.32
90-140	Amber Clear	70 PC-1	3.18	1.04	a	0.32
90-141	Amber Clear	60 PC-2	3.16	1.03	a	0.26
90-142	Golden Clear	70 PC-2	3.16	1.05	a	0.36
90-143	Golden Clear	90 Utility	3.15	1.06	125	0.42
90-144	Golden Clear	70 Utility	3.16	1.04	a	0.33
90-145	Golden Clear	80 PC-1	3.14	1.04	a	0.37
90-147	Golden Clear	162.1 PC-2	3.16	1.04	135	0.64
90-150	Lt Amber Clear	43.0 Utility	3.14	1.05	a	0.27
90-151	Amber Clear	74.8 Utility	3.16	1.04	a	0.37
90-152	Dk Amber Clear	84.9 Utility	3.16	1.04	a	0.36
90-154	Dk Amber Clear	64.3 Utility	3.15	1.07	a	0.32
90-155	Dk Amber Clear	247.5 PC-1	3.16	1.04	a	0.43
90-156	Dk Amber Clear	195.0 PC-1	3.16	1.05	a	0.39
90-157	Dk Amber Clear	135.5 Utility	3.16	1.06	128	0.40
90-158	Lt Amber Clear	183.0 PC-2	3.14	1.04	a	0.40
90-159	Dk Amber Clear	214.9 Utility	3.14	1.03	a	0.37
90-160	Dk Amber Clear	156.2 Utility	3.14	1.05	a	0.39
90-161	Dk Amber Clear	166.4 Utility	3.15	1.04	a	0.42
90-163	Dk Amber Clear	248.6 Utility	3.14	1.04	a	0.40
90-164	Lt Amber Clear	184.8 PC-1	3.16	1.03	a	0.39
90-166	Lt Amber Clear	226.8 PC-1	3.16	1.05	122	0.41
90-167	Dk Amber Clear	308.2 PC-1	3.17	1.04	a	0.44
90-168	Dk Amber Clear	276.4 PC-1	3.14	1.04	a	0.44
90-170	Lt Amber Clear	203.5 PC-2	3.14	1.05	a	0.40
90-171	Lt Amber Clear	296.2 PC-2	3.13	1.04	a	0.48
90-172	Dk Amber Clear	264.4 PC-2	3.13	1.04	a	0.45
90-174	Dk Amber Clear	172.6 PC-2	3.13	1.03	122	0.40

a - Not determined
b - Contains antiwear + Barium Dinonylnaphthalene Sulfonate fluid additives
c - Contains antiwear fluid additive only

Figure 111. CTFE Fluid Sampling Results

5.5 PROGRAM RELIABILITY GOALS

The statement of work required that the reliability goal be three times the best aircraft reliability of those currently in the field. During the first phase of the program, the F-14, F-15 and F-16 reliability records were analyzed and the F-16 was shown to have the highest reliability of the three. After the hydraulic equipment roster was adjusted to the size of the baseline hydraulic system, the F-15 S/MTD, the reliability goal for the program endurance test became 177 hours MTBF. The hours completed of the scheduled 500 hour endurance test were not adequate to demonstrate that the system reliability goal could be met.

5.6 RELIABILITY ASSESSMENT CRITERIA

To provide consistent classification of system failures, the following definition for reliability terms and conditions are presented.

5.6.1 Failure Classification Process - System failures were classified as either relevant or non-relevant depending on whether the failure could be expected in field service. All system failures were reviewed and classified by a review group which include individuals from design, test and evaluation, and supportability engineering.

(a) Relevant Failures - A system failure was relevant when it could occur or recur during the operational life of an item in field service. Because this was a closed end program with limited time and resources available to effect the development approach of test, analyze and fix (TAAF), certain failures which would recur were justified non-relevant when a positive design correction was identified but not implemented.

(b) Non-Relevant Failures - A system failure was non-relevant when it was determined that one or more of the following conditions applied. In addition, the letter code preceding the condition description was used as the non-relevant code for system failure recording.

(CODE)	DESCRIPTION
(A)	Failures occurring during troubleshooting after system shutdown.
(B)	Failures caused by test operator error, accidental damage, or test equipment malfunction.
(C)	Failures induced by installation checks or repair verification tests.
(D)	Failures induced by bench test or off system repair.
(E)	Failures resulting from neglect or incorrect maintenance.
(F)	Failures of fluid leakage which are corrected by tightening and which do not prevent the system from performing its operating requirement.

5.6.2 Reliability Analysis and Assessment - A summary of the 42 failures identified during the 324 hours accomplished in the endurance test is provided in Appendix D. Seventeen of the failures listed therein were classified as relevant. Only the first occurrence of a given relevant failure was used in the analysis (since corrective action would not be forthcoming); this reduced the number of failures being examined to seven. Figure 112 shows the analysis of this failure data in tabular form and Figure 113 shows the data graphically.

Failure Number	Endurance (hrs)		Reliability Estimate (hrs)		
	Actual Time	Adjusted Time	Lower Limit	Upper Limit	Estimated MTBF
1	16	48	16	932	48
2	50	150	32	422	75
3	50	150	24	183	50
4	50	150	19	110	38
5	50	150	16	76	30
6	64	193	18	74	32
7	284	851	72	259	122

Figure 112. Failure Data for Reliability Analysis

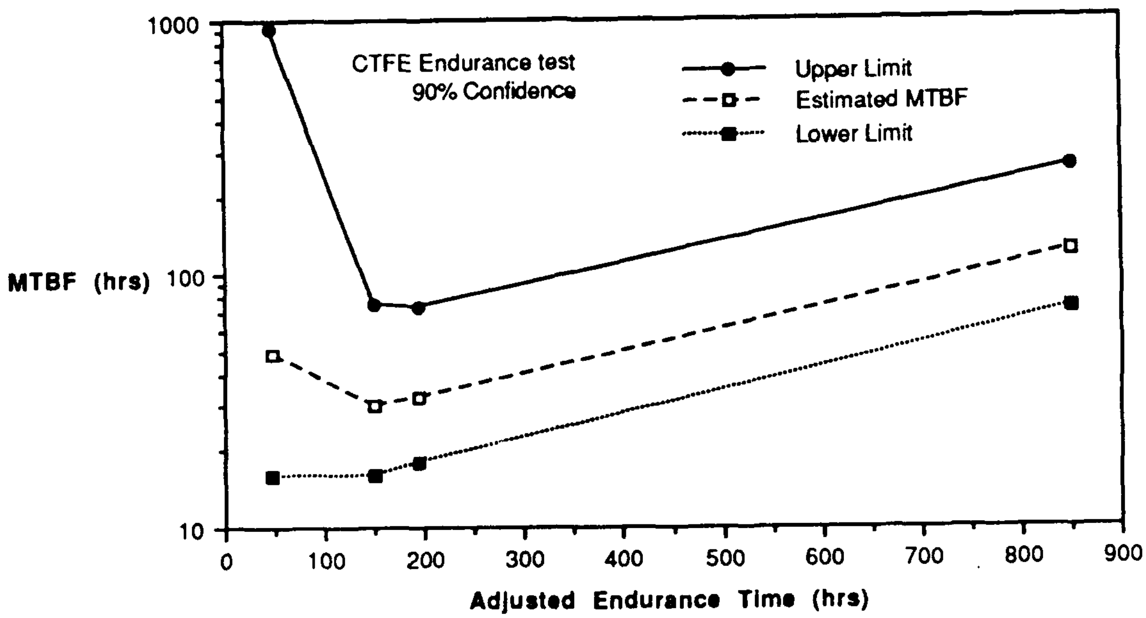


Figure 113. Reliability Achievement

The cumulative test time at which a failure occurred was modified to account for the differences between endurance test conditions and those which would be typical of field usage. One hour of test time was considered equivalent to three hours of field usage (adjusted endurance time ref.). The instantaneous MTBF was calculated by dividing the adjusted endurance time by the cumulative number of failures up to that point. System failures were assumed to be distributed exponentially. A chi-square distribution was used to calculate upper and lower limits for the instantaneous MTBF at a confidence level of ninety percent.

At the end of the test, corresponding to an adjusted endurance time of 972 hours, the estimated MTBF is 122 hours with a 90 percent level of confidence that the MTBF is between 72 and 259 hours. The original goal was 177 hours which was derived from an analysis of the F-14, F-15, F-16 and F-18 aircraft reliability records (See Volume I). Three factors are present which cloud these results: (1) Curtailment of 40 gpm pump development, (2) inability to implement corrective actions because of time restrictions and (3) stoppage of the endurance test at 324 hours due to program termination.

5.6.3 Maintenance Assessment - Maintenance actions consisted of removal and installation of equipment, filter element changes, reservoir servicing, air bleeding and hydraulic line repairs. Several hydraulic seal changes were made in place as well. Hydraulic line repairs were handled very routinely because of the variety of fitting stock on hand from the many suppliers. All of the maintenance performed was either equivalent to or less time consuming than similar activities on current technology systems would entail; particularly hydraulic line repairs.

Of all the maintenance activities, air bleeding the systems was the most difficult task. This was attributed to two primary factors. An Enerpac power supply was used early on in the program, and the flow rate was inadequate to provide an "fluid sweep" of the systems. The other factor was the design of the distribution tubing installations; all of the trunk lines were run on overhead panels. This made the installations less prone to damage and easy to observe for leaks. It also made all of the other equipment easier to access. Running overhead, however, produced high spots for trapped air. Satisfactory bleeding was accomplished once the 15 gpm ground power supply was brought on line.

5.7 AIRCRAFT BATTLE DAMAGE REPAIR (ABDR) EVALUATION

This task was not performed due to contract termination.

5.8 EQUIPMENT DISASSEMBLY AND INSPECTION

Disassembly and inspection of the equipment was not performed on any equipment other than items returned to suppliers for repair. There was no unusual wear or damage to be reported which hadn't been revealed in previous test efforts with CTFE fluid. This includes corrosion and discoloration of copper bearing alloys and carbon steels, low durometer seal fretting in threaded boss glands and excessive wear of chrome plated rods.

5.9 PHASE V FINAL ORAL PRESENTATION

The Statement of Work required that an oral presentation of the program be held at MCAIR at the conclusion of the program. This presentation was held on March 15, 1990 and attended by personnel from the Army, Air Force, Navy, several aircraft manufacturers and representatives from the hydraulic equipment supplier industry. The attendance was well in excess of 150 people. This presentation consisted of a management overview and test program details. Following the presentation, tours of the laboratory facility were given for all of the attendees. The laboratory technology demonstrator was operated for the morning and afternoon tour groups. Many compliments were received, citing the large selection of equipment in the demonstrator and the high quality of workmanship.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

OVERVIEW

After the demonstration facility was completed, the equipment performance established and the endurance testing started, the successful points in the program could be identified as well as the more salient problems. The overwhelming conclusion was that the operating pressure level of 8000 psi presented no effort over that which would be required for any other system pressure level. There were also no problems in the laboratory with the fluid; rather problems related to pumping the fluid. Pumps (40 gpm, CTFE) proved to be the major shortfall in the program. If there were but one ongoing contracted activity in support of nonflammable fluid technology, it should be the continued development of high power pumps. Any technology improvements could likely be applied in conventional fluid pumps resulting in significant improvements in reliability and service life.

Even though there were few difficulties with the fluid in the laboratory, several suppliers experienced abnormal degradation of the fluid; more specifically the rust inhibitor, BSN. This additive has been superseded by a zinc based inhibitor which has been tested by the Materials Lab (WRDC/MLBT) but not in time to be used in this program. This Air Force test included a 930 hour pump (3000 psi) test at 275°F operating temperature, which is the upper operating temperature of the pump.

This design experience with CTFE permits one obvious conclusion. A design activity cannot make fluid trades considering nonflammabilty alone. An 8000 psi CTFE system can be weight competitive with a 3000 psi system with conventional fluid, but this is irrelevant. When only weight is considered, an 8000 psi system with CTFE cannot compete with an 8000 psi system with conventional fluid. While the LTD 8000 psi, CTFE system was 14 percent lighter than a 3000 psi equivalent system utilizing conventional fluid system, this weight savings converts to a 9 percent weight penalty when the LTD weight analysis was performed with conventional fluid. This weight penalty must be justified through improved survivability and reduced life cycle costs. The weight penalty for nonflammability is reduced as operating pressure increases. The weight savings potential of 8000 psi over 3000 psi, both with conventional fluid, is substantial: 22% for the demonstrated F-15 SMTD system.

Demonstration of variable pressure operation on a multi-system level was a significant accomplishment of the program. Variable pressure operation was expected to present many operating anomalies but actually presented none of any consequence. Of all of the power efficient technologies which have been studied in recent years, variable pressure is the most effective approach, reducing hydraulic system power consumption by as much as half depending on the duty cycle.

The hydraulic equipment suppliers had little difficulty with the design of the equipment; stainless steel and titanium were used almost exclusively for pressure vessels. Seals did not present difficulties except in three instances; all of which were special cases. Otherwise, conventional seal glands and running clearances were used in every item without incidence. Direct drive valve configurations used in the servoactuators included linear single stage, linear two stage, rotary-linear single stage and rotary single stage. The only noted preference is for rotary-linear based on manifold packaging flexibility.

Fabrication of the distribution system using a wide variety of high pressure fittings as well as odd size tubing for pressure supply proved to be the most routine of all the activities. Line breaks which did occur were no more dramatic than at lower pressure. None of the line breaks were attributed to high pressure; rather improper fitting installation or excessive pressure transient cycling induced by unstable servovalve control. The facility was found to be the "driest" of any assembled at MCAIR. There were no leaks in any permanent fitting or any separable fitting which had been properly installed.

Conclusions and recommendations are put forward in the following sections related to the many technical focal points in the overall technology demonstration.

6.1 CTFE A02 HYDRAULIC FLUID

There were, without exception, no fluid related problems encountered during the demonstrator testing relating to the extensive use of corrosion resistant materials. Nearly all of the metals exposed to CTFE were corrosion resistant. Three suppliers experienced difficulties from fluid degradation and/or contamination which require explanation. Suppliers who had difficulties had test setups which contained commercial grade carbon steel and components which had been used previously and the past history and cleanliness was questionable.

Several investigators noted a sticky residue on "dry" component parts. This residue was a high molecular weight constituent of the fluid which did not evaporate. It is not present in all batches of CTFE which have been manufactured, but could be controlled, if required. No harmful effects were observed from this residue.

Pump cavitation causes local heating and extremely high temperatures and erosion of material surfaces. Disassociation of CTFE due to heating which could form acids during cavitation has also been considered as possibly being relevant in this process. Acid level has been shown to increase through use at the pump suppliers which is due to the thermal degradation of the BSN additive. As long as the acid level does not exceed 1.0 mg KOH/gm, the fluid is considered serviceable. Low thermal conductivity and specific heat are also characteristics of CTFE fluid which have an adverse affect on pump design compared to conventional fluids.

Discoloration of carbon steels and copper bearing alloys has occurred after being wetted with CTFE. This discoloration when removed revealed surface corrosion and minor pitting of the component. After parts were rinsed with Stoddard solvent, corrosion would reoccur after a short time. Any non-CRES component should remain submerged in a rust inhibited fluid or be reworked prior to reassembly. The corrosion inhibitor is ineffective after air drying. Use of CRES materials and plating of non-CRES materials is essential for success. In many cases, structural requirements designate the material to be used and surface treatment is the only solution. One supplier (Abex) used ion implantation successfully on several internal parts to their pump and control valve. Similarly, valve spools which were discolored and sticking, worked smoothly after ion implantation.

6.1.1 Barium Dinonylnaphthalene Sulfonate (BSN) Rust Inhibitor - Most of the difficulties have been directly related to the rust inhibitor additive, BSN. If water content is not carefully controlled, the additive is sure to form a precipitant which has been referred to as "snow" because of its appearance, particularly at lower temperatures.

Experience has shown that water content must be maintained below 250 ppm to avoid precipitation. Certain metallic elements tend to accelerate the effect. Existence of the precipitant causes clogging of filter elements and gumming of close tolerance valves. Heating of the fluid and precipitant to 160^{o}F has usually resulted in the precipitant returning to solution.

At the high end of the operating temperature range, the rust inhibitor has been found to form a dark sticky precipitant which has caused jamming of close tolerance parts. Darkening of the fluid had been noted in previous programs, however this is of no consequence as long as the fluid remains translucent and does not become cloudy. This problem has been more prevalent in pump test circuits. As this program concluded, the Air Force had successfully demonstrated high temperature stability and operating capability of a formulation with a zinc based rust inhibitor. Time and resources did not permit introduction of this formulation into the program. The Air Force should continue efforts with the zinc base inhibited fluid.

6.1.2 Component Wear - During the program several of the actuators were found to have accumulated a greenish gel-like substance at the piston rod end. When first observed, this appeared to be rod seal leakage. Several years ago TRW (Reference 3) discovered a similar substance to be a product resulting from CTFE-A08 fluid reacting with the chrome and removing the plating from the surface. Analysis performed by MCAIR showed the green material to be 8,000 to 10,000 ppm Chromium and that after 400,000 cyles, of less than 10% stroke, diametral wear was measured to be approximately .001 inches. Therefore, if normal plating thickness was .005, the life of the rod would be less than 4 million cycles instead of the required 10 million.

These findings, along with recent incentives in California to reduce chromium emissions from plating facilities, would indicate that alternate platings or coatings should be developed. One other coating system was demonstrated with satisfactory results during this program; Tungsten Carbide/Cobalt applied by a detonation process (Union Carbide). This coating was used on one MOOG engine nozzle actuator identical to the one analysed above. The fluid accumulated at the end of this rod was analyzed and found to contain only 78 ppm Tungsten. By comparison with the chromium plate wear evident on a previous nozzle actuator the Tungsten Carbide/Cobalt shows a good potential of meeting full life requirements.

6.2 HYDRAULIC PUMPS

The demonstrator testing was accomplished using 15 gpm capacity, variable pressure pumps (Abex). A program goal was to develop four 8000 psi, variable pressure hydraulic pumps of 40 gpm capacity which would be endurance tested to 2000 hours with CTFE. Two of the pump suppliers (Abex and Garrett) succeeded in performing limited endurance testing. Test levels of about 100 hours were achieved, far short of the 2000 hour goal.

The low lubricity and poor thermal transport properties of CTFE has required redesign in several areas to reduce bearing stresses. Garrett showed that wear could be reduced in orders of magnitude if cooler fluid at higher case flow is provided at the expense of efficiency. High pressure pulsations and cavitation have been a concern with 8000 psi CTFE pumps and measures were taken at the onset of the program to increase base pressure to preclude cavitation. Attenuators were also added to reduce the pulsation levels.

The lack of long life pumps is a shortfall which keeps nonflammable fluid technology in a position of high risk. More development work is needed to reduce pressure pulsations in 8000 psi pumps to avoid the weight penalty of pulsation attenuators.

6.2.1 Variable Pressure Pumps - The variable pressure pump is heavier than its constant pressure counterpart but it can reduce hydraulic power consumption by as much as one-half depending on the duty cycle. Failure modes have a direct bearing on whether or not variable pressure can or should be considered. If the mission requires that the system fail to high pressure with loss of control, there is an implication that the heat rejection capability must be as if it were for a constant pressure system. The potential for heat exchanger weight savings is erased.

6.3 SYSTEM DESIGN FOR 8000 PSI

It would be difficult to relate all of the design information which has been developed in the past several years so it must be restricted to those subjects which have been addressed in this program. In general, CTFE did not present any additional influence in component design other than requiring larger valves and CRES materials.

6.3.1 Direct Drive Servovalves - Direct drive servovalves are used on 3000, 4000 and 5000 psi systems and will find even more applications in 8000 psi systems to reduce quiescent flow to a minimum. All of the servo-devices in this program used direct drive valves except for the subsititute 15 gpm pumps, which had electrohydraulic servovalves for variable pressure control. In this instance the quiescent flow loss had minimum effect since the pumps were operating at 3000 psi a large portion of the time. Direct drive valve experience has been very positive on this program in that all design approaches performed well. Of the various force motor-valve arrangements tested (linear-linear, rotary-rotary, and rotary-linear) the only preference that can be expressed is for rotary-linear. The rotary force motor, linear valve approach appears to have more design flexibility for manifold packaging than the other arrangements.

6.3.2 Servoactuator Dynamic Stiffness - Actuators designed for higher pressure systems have less fluid column stiffness because of their reduced piston area. An 8000 psi actuator is only three-eighths as stiff as an equally powerful 3000 psi actuator. Some actuators are sized to provide a required stiffness to an excitation air load. If an actuator is stiffness critical when sized for 3000 psi, it can be made no smaller by going to a higher pressure. This "oversizing" of actuators for stiffness is reflected throughout the hydraulic power and distribution system sizing and results in large system weight penalties.

Electronic enhancement is the most viable alternate to minimize the required fluid column stiffness. It improves control performance in the servovalve to make the actuator capable of reacting excitation loads at higher frequencies. This problem is a fundamental issue in high pressure technology, and complete development of this approach is needed. This approach is consistent with fly-by-wire flight control systems which depend on redundant electronics for safety.

6.3.3 Hydraulic Component Structural Materials - The material selection process had two criteria; fatigue strength at an 8000 psi system level and CTFE compatibility. It was recognized in past efforts by the suppliers and others that conventional aluminum alloys have an upper system operating limit of 5500 psi. This has been reinforced several times by suppliers recently developing equipment for 5000 psi systems who have abandoned aluminum in favor of titanium. The pressure transient limit for 5000 psi systems has been 6750 psi where the limit for 8000 psi systems is 9600 psi. The demonstrator distribution system was sized to limit pressure transients to 8800 psi; however, test data showed that 9200 psi was sometimes reached.

Titanium has been used successfully in 8000 psi equipment. Since most grades are damage tolerant, there are further savings available because rip stop construction may not be required. Corrosion resistant steels were used in all other pressure vessel applications except for one item; the Cadillac Gage Diffuser Ramp Actuator used a manifold machined from an aluminum metal matrix material. The pump suppliers relied heavily on steel alloys with superior hardness to stainless steels This did not present a problem because of the low water content in the CTFE fluid.

The suppliers impulse tested several items to failure and none of the failures were unique. Failures encountered started in thread roots, tool marks and porting intersections. There were no conclusions drawn which are peculiar to either high pressure or CTFE fluid.

6.3.4 Hydraulic Component Seals - Hydraulic seals for 8000 psi and/or CTFE fluid are considered low risk. Seal materials which were applied most frequently and most successfully were Viton GLT for static seals and energizers and PEEK for dynamic seals. Some instances of rapid seal wear-out occurred where low durometer elastomer seals fretted from seal breathing. Several of the seals which leaked from fret failure were in threaded bosses. A review of past seal development literature has shown no development work applied to threaded boss gland configurations.

6.3.5 Distribution System Components - The distribution system was constructed as ODD-EVEN. Odd size tubes and fittings were used in the pressure supply lines and even sized (3000 psi) tubes and fittings were used in the return lines. Solid support from the many tube and fitting manufacturers made this effort possible. Construction of the distribution system proved to be one of the easier tasks. Each of the fitting suppliers provided assembly support at his facility or provided tooling for fitting installation on-site. There were no technical problems encountered with any of the fittings delivered for the program. The distribution system was not intended to be a technology focal point on the program; however, its exclusion would have prevented weight verification.

6.3.6 Filtration - Although not related directly to any program technical incentives, filtration technology proved to have some very interesting aspects. Both 1- and 5-micron elements were supplied by two different suppliers. During the program the 1-micron elements required more frequent replacement than the 5-micron elements; however, using 1-micron filters showed that sampling the system was futile, showing "1-micron" contamination levels because the sampling process introduced more contamination than existed in the fluid sample. It is conceivable based on this finding that with 1-micron filters, routine fluid sampling for particulate contamination could be eliminated and this maintenance saving could offset the more frequent element replacements.

6.4 POWER EFFICIENT TECHNOLOGY

Power efficient technologies which were demonstrated in this program included variable pressure operation, variable displacement hydraulic motors, flow augmentation in flight control actuators and overlapped valves. Pressure intensification was also demonstrated; however, severe pressure transients forced termination after continuing line failures.

6.4.1 Variable System Pressure - Variable operating pressure as demonstrated in this program has been intended for the sole purpose of reducing energy consumption and the heat rejection of the system. It is shown in Section V that the total energy consumption of the Primary Control (PC) systems on the Demonstrator for the entire duty cycle was 60 percent of what would be used when operating at constant pressure.

No operating anomalies were observed other than persistent intersystem leakage in the initial phase of the endurance test. This situation was aggravated by the occasional need to operate one system at constant pressure because of a shortage of operable variable pressure pumps. Every point where two systems interface must receive attention in the detail design of the component intersystem seal arrangements. Return to return interfaces across lapped lands is the best for controllong intersystem leakage. Bootstrap reservoir operation with variable pressure must be considered in intersystem leakage design.

There were several instances of the pumps on each system not providing the same pressure demanded; this applied to both the low as well as the high pressure command. Even when the command/discharge pressures are tracking closely, one system base pressure can be as much as 60 psi less than the other unless the power demands for both systems are in phase. All hydraulic control features which rely on sensing pressure or using pressure to perform a control function must consider variable pressure conditions, including intersystem leakage control.

As system power requirements increase, usually without any increase in available heat sink, variable pressure can be an enabling technology.

6.4.2 Actuation Duty Cycle With Variable Pressure - The actuator duty cycle used for this program resulted in the systems operating at 8000 psi approximately 28 percent of the time. The flight control duty cycle which is anticipated in a given design configuration has a direct bearing on the value of variable pressure operation. Stable aircraft may show that the highest system pressure is only required 5 percent of the time while an unstable aircraft may reside at high pressure over 50 percent of the time. Careful attention must be paid to heat generation and available heat sink throughout the mission profile.

6.4.3 Variable Displacement Hydraulic Motors (VDHM) - Varying the displacement of a motor to suit the torque requirement is as effective at reducing supply flow from the central system as flow augmentation. Added complexity and weight of the motor is an accompaniment. Conventional line loss distribution (1/3-1/3-1/3) is favored over asymmetric line loss in order to achieve low motor displacement and low flow at low load and maximum power transmission. VDHM's should be considered when a large reduction in flow demand at low load can result in downsizing the central system pump.

6.4.4 Flow Augmentation - Two flight control actuators on the Demonstrator were flow augmented with ejector pumps installed in the inlets. These pumps direct fluid leaving the cylinder back into the inlet under low load conditions. This results in the central system pumps having to supply only 60 percent of the fluid flow required to displace the actuator ram.

Cumulative weight effects are a concern. The added weight in the flow augmented actuator matched closely with the estimated weight saved if a smaller pump were used (7.3 vs. 7.4 lbs). Unfortunately, in this equipment roster, there were four pumps and four flow augmented actuators. Flow augmentation requires low pressure supply line loss and a low loss main control valve since pressure loss must be redistributed to the flow augmentor in order to drive the ejector efficiently. The net result in this instance is that weight which could be saved from downsizing filter manifolds must exceed a 7.0 lb weight increase in pressure tubing in order for the overall concept to save weight.

6.4.5 Overlapped Valve Lands - Several of the flight control actuators used overlap in the servovalves to reduce quiescent leakage at null. The weight associated with overlap is nil. The MOOG Flaperon Actuator was first tested in the Demonstrator with a servovalve having lands overlapped to 10 percent of valve stroke. This arrangement proved to have very poor performance and the valve was changed to 5 percent overlap. Five percent overlap has been found to be near optimum for the stabilator and canard actuators as well, and captures most of the potential leakage reduction.

Significant overlap would not be attempted in actuators with mechanical input; however, digital flight control technology can easily compensate for nonlinear effects such as overlap. A conclusion from the early trade studies in the program was that five percent overlap should be attempted; reducing overlap as required to meet performance. This conclusion has been verified by the demonstrator testing.

6.5 HYDRAULIC SYSTEM WEIGHT AT 8000 PSI

Weight comparisons have been presented in Section 4.0 for one primary control system compared with the baseline aircraft, the F-15 S/MTD aircraft. The comparison, which excludes power efficient technologies, shows that a weight reduction of 21 percent was achieved with 8000 psi operating pressure. The savings are less comparing CTFE at 8000 psi with MIL-H-83282 at 3000 psi; a savings of 14 percent was shown. This was less savings than predicted in previous studies; however, actual hardware can be expected to weigh more than analytically predicted, rarely less. Pump weight remained a prediction in this comparison since neither 15 nor 40 gpm pumps match the optimum power level of the baseline system.

6.5.1 Hydraulic Components - Hydraulic components for 8000 psi can weigh more or less than their (equivalent horsepower) 3000 psi counterparts. Fundamentally, a valve sized to control three-eights of the flow will have smaller flow passages and that the smaller passages will require less surrounding material for pressure containment. Technical requirements and practices which can cancel out the weight savings are low pressure loss, large design factors and low strength materials. The interaction of component sizing with distribution line sizing is discussed below. Valves designed for CTFE are required to be 50 percent larger because of higher fluid density.

6.5.2 Distribution Systems - Most of the weight savings stems from using smaller lines associated with lower flow rates. Higher source pressure allows more loss in fluid power transmission lines which permits further downsizing, other design criteria permitting.

Large pressure loss in supply lines ("asymmetric" line loss) is a fundamental approach if full weight savings are to be realized. Water hammer can be controlled by local velocity reduction instead of restricting flow velocity limits. When sizing return lines in an 8000 psi system, the designer must recognize that aiding loads or control reversals at high surface rates can produce very high pressure spikes in the return system. Any design activity should aggressively address pressure supply and return line pressure loss distribution in concert with component pressure loss requirements.

In theory, higher pressure saves weight. In practice, the savings can be diluted because of standard fractional line sizing and conventional approaches to setting component pressure loss requirements. Assign servovalve loss first; the goal being stable operation, low flow forces and minimum weight. Examine several arrangements of line sizes using all undistributed pressure loss. When a line sizing arrangement is borderline for being too small with low losses from the needed flow controls, it must be weight traded against the next largest line size with more loss allowances for the flow controls. Only with the greatest attention to detail will the minimum system weight be achieved.

REFERENCES

1. Greene, J. B., et al, "Nonflammable Hydraulic Power System For Tactical Aircraft" Vol. 1-Aircraft System Definition, Design and Analysis WRDC-TR-89-2026 McDonnell Aircraft Co. Contract F33615-86-C-2600, May 1989.

2. Schmidt J. L., "High Pressure Hydraulic Distribution System" NA-86-1672 Rockwell International, Contract F33615-86-C-2634

3. Martin J. W., "Nonflammable Hydraulic System Seal Materials" AFWAL-TR-84-4097 TRW Electronics and Defense Sector, Contract F33615-81-C-5092, September 1984.

APPENDIX A

SYSTEM SCHEMATICS

HYDRAULIC
SYSTEM SCHEMATICS

FOR

NONFLAMMABLE HYDRAULIC POWER
SYSTEMS FOR TACTICAL AIRCRAFT
(8000 PSI. - CTFE)

PREPARED BY

J. J. Sheahan
Senior Engineer - Design

APPROVED

J. A. Wieldt
Design Specialist

MCDONNELL AIRCRAFT COMPANY SAINT LOUIS, MISSOURI MCDONNELL DOUGLAS CORPORATION	SIZE A	FSCM NO. 76301	DWG NO. 71J136949
	SCALE:	REV D 11/29/9	SHEET

MAC 1201BD (REV 11 MAR 77)

INDEX

SHEET NO.	SYSTEM DESCRIPTION	REV LTR	SHEET NO.	SYSTEM DESCRIPTION	REV LTR
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2	LEFT HAND SIDE FLIGHT CONTROLS	D			
3	POWER CONTROL SYSTEM NO. 2	D			
4	RIGHT HAND SIDE FLIGHT CONTROLS	D			
5	UTILITY CENTRAL SYSTEM	D			
6	ENGINE NOZZLES INTERCONNECT	D			
7	ENGINE NOZZLES ACTUATION	D			
8	UTILITY SYSTEM FUNCTIONS	D			
9	GROUND SERVICE UNIT				

(C) PED 7/15/8	(D) DEB 11/29/9	MODEL NHPSTA	TITLE INDEX
(B) JJS 10/30/7		SIZE B	FSCM NO. 76301
(A) MRE 6/15/7		DESIGN DATA DRAWING NO. 71J136949	
DWN JBW 5/14/6		SCALE	REV D
MCDONNELL AIRCRAFT COMPANY SAINT LOUIS MISSOURI	MCDONNELL DOUGLAS CORPORATION	SHEET i	

MAC 1701AB(REV 23 AUG 77)

NOTES

1. RESTRICTOR FLOW RATE AT 100 PSI ΔP AT 90° ± 30°F FLUID TEMPERATURE.

2. RESTRICTOR FLOW RATE AT 1100 PSI ΔP AT 90° ± 30°F FLUID TEMPERATURE.

3. P PRESSURE TRANSDUCER

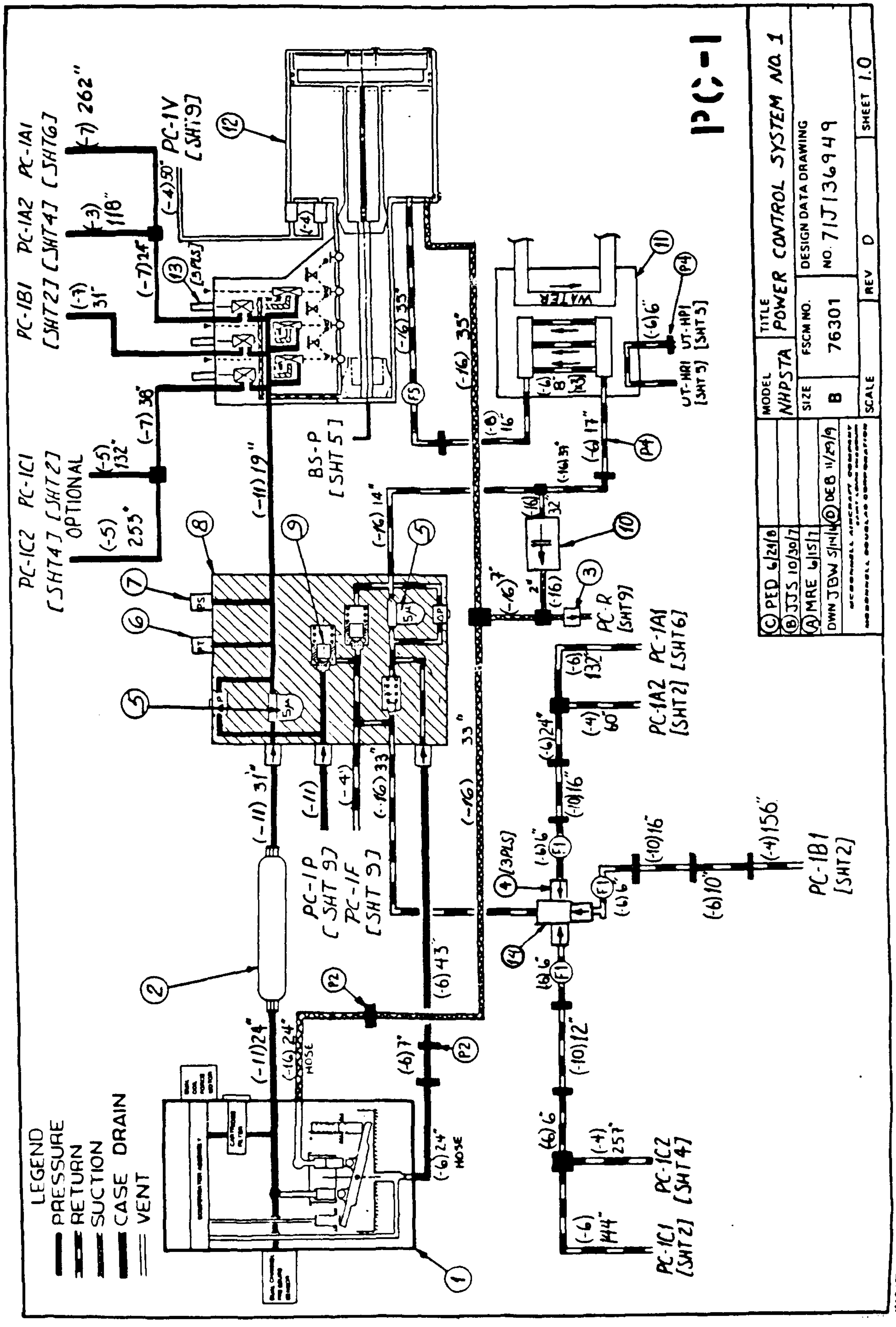
P1	0-15000 PSI
P2	0-3000 PSI
P3	0-5000 PSI
P4	0-2000 PSI

F FLOW METER

F1	1.76-16 GPM
F2	.823-5.031 GPM
F3	3.26-26.94 GPM
F4	.419-2.635 GPM
F5	2.5-29 GPM

B DEB 12/13/9	MODEL NHPSTA	TITLE NOTES		
A MRE 6/15/7	SIZE B	FSCM NO. 76301	DESIGN DATA DRAWING NO. 71J136949	
DWN JBW 5/14/6				
MCDONNELL AIRCRAFT COMPANY / SAINT LOUIS, MISSOURI / MCDONNELL DOUGLAS CORPORATION	SCALE	REV B	SHEET 11	

MAC 1301A(REV 23 AUG 77)


PC-1
LEGEND
PRESSURE
RETURN
SUCTION
CASE DRAIN
VENT
WATER
MODEL NHPSTA
TITLE POWER CONTROL SYSTEM NO. 1
SIZE B
FSCM NO. 76301
DESIGN DATA DRAWING
NO. 71J136949
SCALE
REV D
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OPTIONAL
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[SHT9]
BS-P
[SHT 5]
PC-1P
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(-6)7"
(-6) 43"
(-16) 33"
(-16) 35"
(-6) 35"
(-16) 14"
(-4)(3PLS)
(-10)16
(-4)156"
(-10)12"
(-6)10"

(1) PUMP - HYDRAULIC, VARIABLE PRESSURE AND DELIVERY

(2) ACOUSTIC FILTER, PULSCO P/N 840 40111

(3) VALVE - HYDRAULIC, CHECK (LOW PRESSURE)
ST7M262-16

(4) VALVE - HYDRAULIC, CHECK (LOW PRESSURE)
ST7M261-6

(5) FILTER ELEMENT. 5 MICRON ABSOLUTE
P/N 71-136910-209, APM P/N AC-B655F-12

(6) TRANSMITTER - HYDRAULIC, PRESSURE
P/N 71-136931-101, CONDEC P/N 415G252

(7) SWITCH - HYDRAULIC, PRESSURE
P/N 71-136930-101, ITT NEO-DYN P/N 1203P0018

(8) MANIFOLD - HYDRAULIC, FILTER, 5 MICRON ABSOLUTE
P/N 71-136910-101, APM P/N AE-B655-12

(9) VALVE - HYDRAULIC, PRESSURE RELIEF
P/N 71-136925-101, CIRCLE SEAL P/N RY57-29

(10) VALVE - HYDRAULIC, PRESSURE RELIEF
CIRCLE SEAL P/N 5132T-16TB-70

(11) HEAT EXCHANGER - HYDRAULIC, CTFE/WATER
UAP P/N UA538795-3

(12) RESERVOIR - HYDRAULIC, PRECHARGE
P/N 71-136939-101, PARKER P/N 3850080

(13) SWITCH - HYDRAULIC, PRESSURE
P/N 71-136930-103, ITT NEO-DYN P/N 1203P0023

(14) MANIFOLD ASSEMBLY, RETURN
MCAIR P/N ADP-M2

PC-1

(C) PED 6/24/8	MODEL NHPSTA	TITLE POWER CONTROL SYSTEM No. 1		
(B) JJS 10/30/7				
(A) MRE 6/15/7	SIZE B	FSCM NO. 76301	DESIGN DATA DRAWING NO. 71J136949	
DWN JBW 5/14/6				
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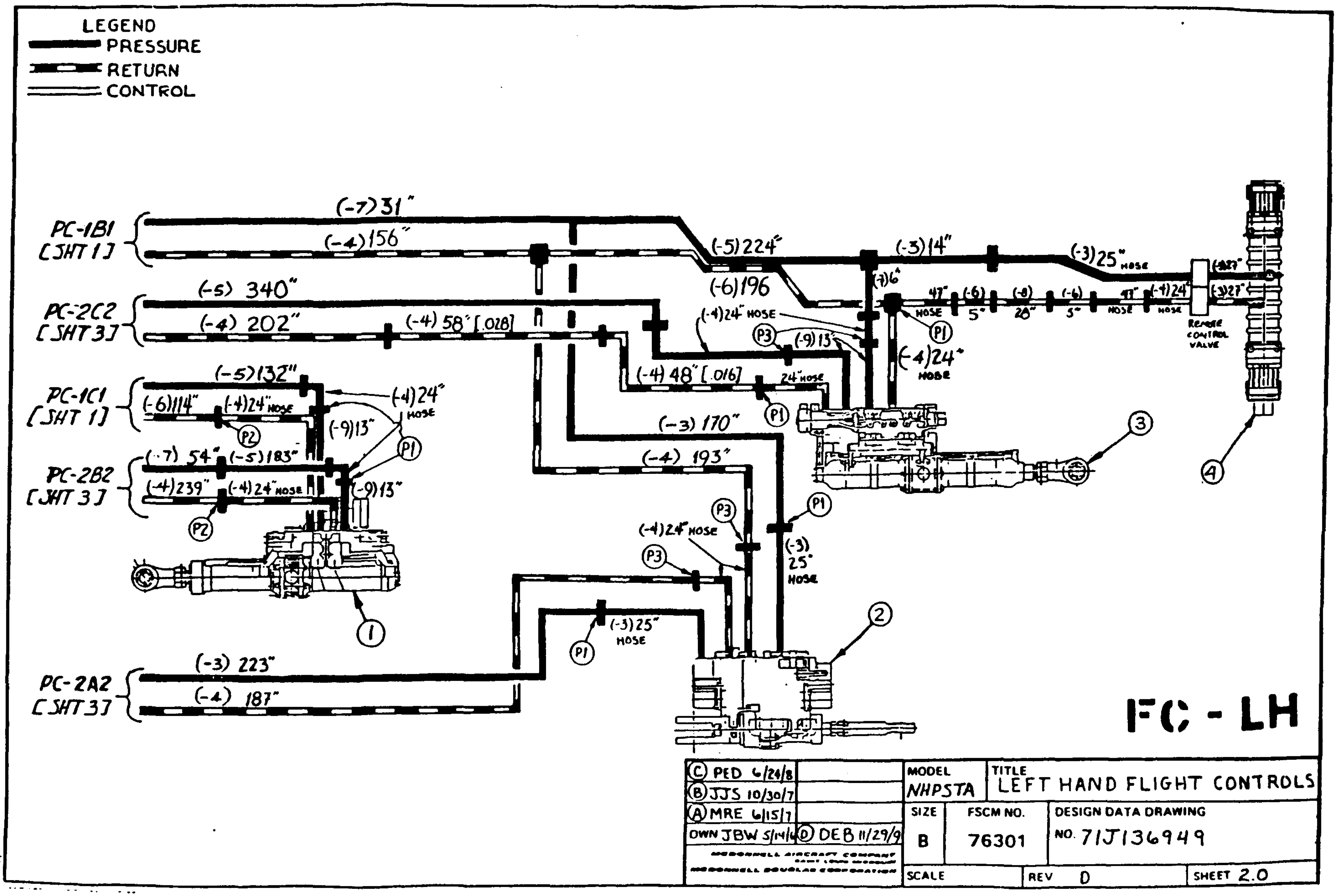
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PRESSURE
RETURN
CONTROL
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PC-2C2 [SHT 3]
PC-1C1 [SHT 1]
PC-2B2 [SHT 3]
PC-2A2 [SHT 3]
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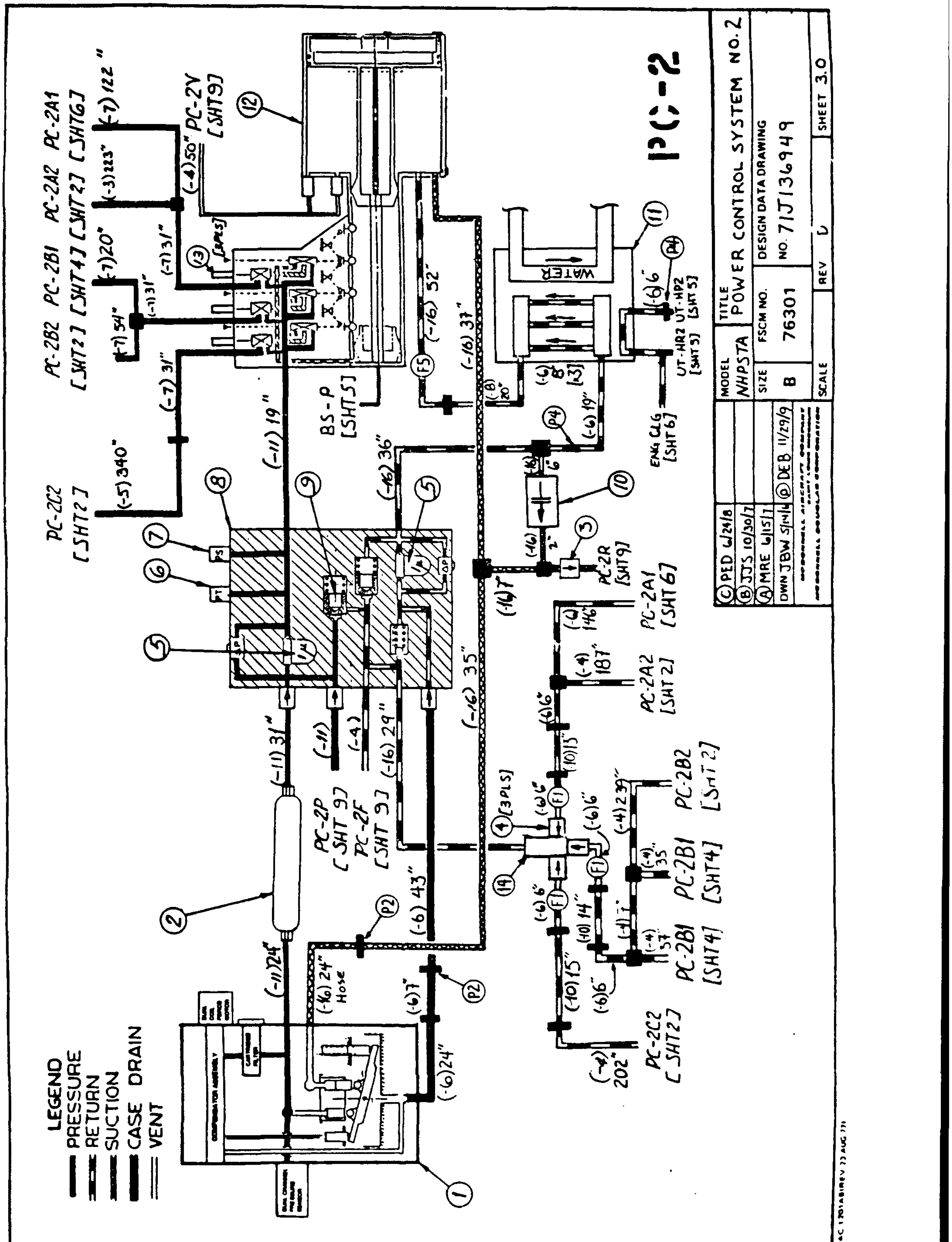
(-4) 193"
(-4) 24" HOSE
(-3) 25" HOSE
(-3) 25" HOSE
(-3) 223"
(-4) 187"
5"
26"
5"
REMOTE CONTROL VALVE
P1
P2
P3
1
2
3
4
FC - LH
C PED 6/24/8
B JJS 10/30/7
A MRE 6/15/7
DWN JBW 5/14/4
D DEB 11/29/9
MODEL NHPSTA
TITLE LEFT HAND FLIGHT CONTROLS
SIZE B
FSCM NO. 76301
DESIGN DATA DRAWING NO. 71J136949
SCALE
REV D
SHEET 2.0

1. SERVOCYLINDER - HYDRAULIC, CANARD
   PARKER BERTEA (LECHT ACTUATOR)
2. SERVOCYLINDER - HYDRAULIC, FLAPERON
   P/N 71-136901-101, MOOG P/N L4797
3. SERVOCYLINDER - HYDRAULIC, STABILATOR
   P/N 71-136934-101, E-SYSTEMS P/N 186000-100
4. HINGE - HYDRAULIC, RUDDER
   P/N 71-136937-101 BENDIX P/N 3337026

FC-LH

	MODEL	TITLE	
(B) JJS 10/30/7	NHPSTA	LEFT HAND FLIGHT CONTROLS	
(A) MRE 6/15/7	SIZE: B	FSCM NO.: 76301	DESIGN DATA DRAWING NO. 71J136949
DWN JBW 5/14/4	SCALE	REV B	SHEET 2.1
MCDONNELL AIRCRAFT COMPANY / MCDONNELL DOUGLAS CORPORATION			

MAC 1201AB (REV 21 AUG 71)


LEGEND
PRESSURE
RETURN
SUCTION
CASE DRAIN
VENT
PC-2
MODEL
NHPSTA
TITLE
POWER CONTROL SYSTEM NO. 2
SIZE
B
FSCM NO.
76301
DESIGN DATA DRAWING
NO. 71J136949
SCALE
REV D
SHEET 3.0
WATER

(1) PUMP - HYDRAULIC, VARIABLE PRESSURE AND DELIVERY

(2) ACOUSTIC FILTER, PULSCO P/N 840 40111

(3) VALVE - HYDRAULIC, CHECK (LOW PRESSURE)
P/N ST7M262-16

(4) VALVE - HYDRAULIC, CHECK (LOW PRESSURE)
P/N ST7M261-6

(5) FILTER ELEMENT, 5 MICRON ABSOLUTE
P/N 71-136910-209, APM P/N AC-B655F-12

(6) TRANSMITTER - HYDRAULIC, PRESSURE
P/N 71-136931-101, CONDEC P/N 415G252

(7) SWITCH - HYDRAULIC, PRESSURE
P/N 71-136930-101, ITT NEO-DYN P/N 1203P0018

(8) MANIFOLD - HYDRAULIC, FILTER, 5 MICRON ABSOLUTE
P/N 71-136910-101, APM P/N AE-B655-12

(9) VALVE - HYDRAULIC, PRESSURE RELIEF
CIRCLE SEAL P/N RV 57-29

(10) VALVE - HYDRAULIC, PRESSURE RELIEF
CIRCLE SEAL P/N 5132T-16TB-70

(11) HEAT EXCHANGER - HYDRAULIC, CTFE/WATER
UAP P/N 53B795-3

(12) RESERVOIR - HYDRAULIC, PRECHARGE
P/N 71-136939-101, PARKER P/N 3850080

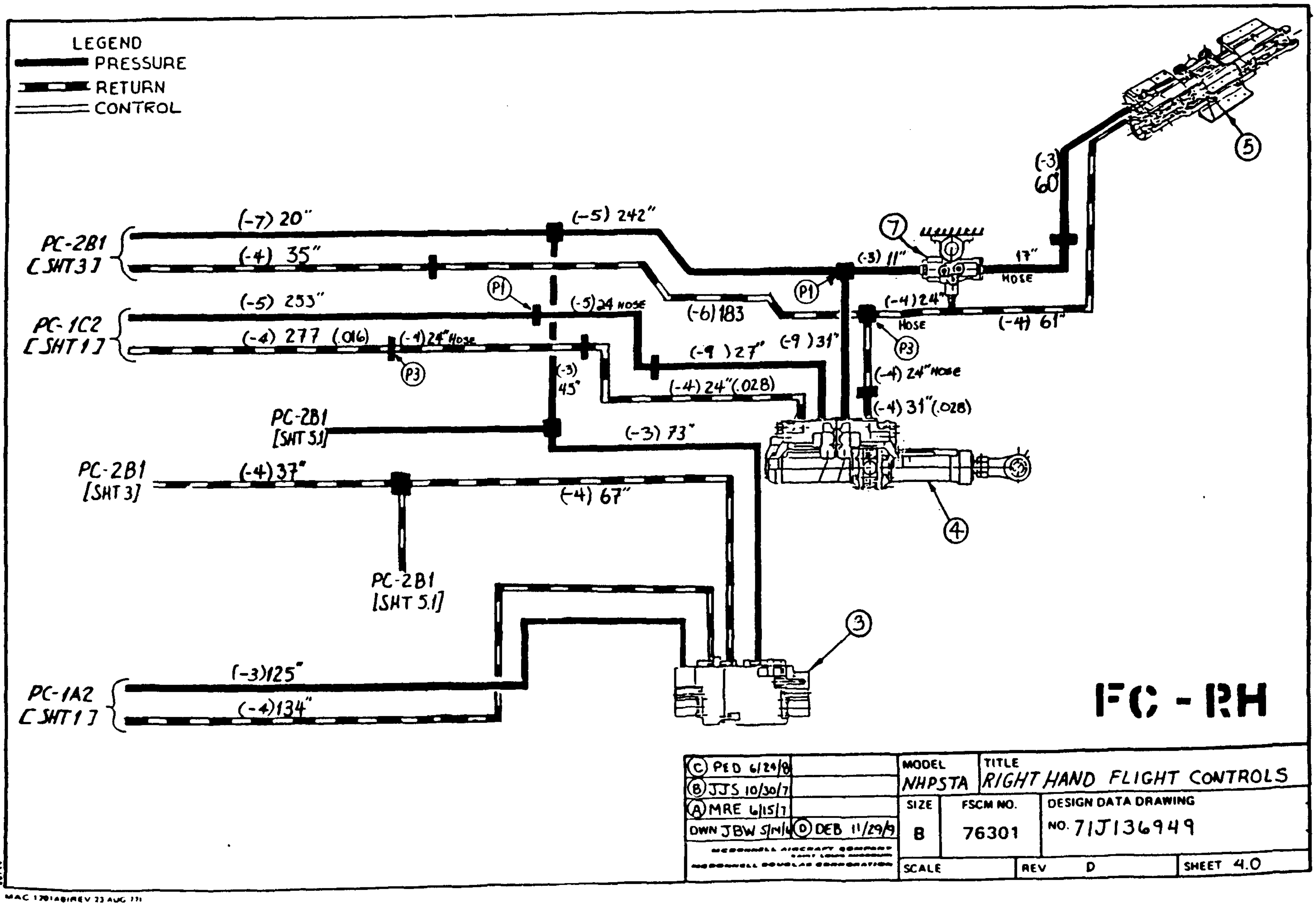
(13) SWITCH - HYDRAULIC, PRESSURE
P/N 71-136930-103, ITT NEO DYN P/N 1203P0023

(14) MANIFOLD ASSEMBLY, RETURN
MCAIR P/N ADPM2

PC-2

(C) PED 6/24/0	MODEL NHPSTA	TITLE POWER CONTROL SYSTEM No. 2		
(B) JJS 10/30/7	SIZE B	FSCM NO. 76301	DESIGN DATA DRAWING NO. 71J136949	
(A) MRE 6/15/7				
DWN JBW 5/14/4				
MCDONNELL AIRCRAFT COMPANY / MCDONNELL DOUGLAS CORPORATION	SCALE	REV C	SHEET 3.1	

MAC 1701AB(REV 23 AUG 71)


LEGEND
PRESSURE
RETURN
CONTROL
PC-2B1 [SHT 3]
PC-1C2 [SHT 1]
PC-2B1 [SHT 5.1]
PC-2B1 [SHT 3]
PC-2B1 [SHT 5.1]
PC-1A2 [SHT 1]
(-7) 20"
(-4) 35"
(-5) 242"
(-5) 253"
(-4) 277 (.016)
(-4) 24" HOSE
(-5) 24 HOSE
(-6) 183
(-3) 45"
(-9) 27"
(-9) 31"
(-4) 24" (.028)
(-3) 73"
(-4) 37"
(-4) 67"
(-3) 125"
(-4) 134"
(-3) 11"
17" HOSE
(-3) 60"
(-4) 24" HOSE
(-4) 61"
(-4) 24" HOSE
(-4) 31" (.028)
P1
P3
3
4
5
7
FC - RH
C PED 6/24/8
B JJS 10/30/7
A MRE 6/15/7
DWN JBW 5/14/4 D DEB 11/29/9
MCDONNELL AIRCRAFT COMPANY
MCDONNELL DOUGLAS CORPORATION
MODEL NHPSTA
TITLE RIGHT HAND FLIGHT CONTROLS
SIZE B
FSCM NO. 76301
DESIGN DATA DRAWING NO. 71J136949
SCALE
REV D
SHEET 4.0
MAC 1701A(REV 23 AUG 71)

1 DELETED

2 DELETED

3 SERVOCYLINDER-HYDRAULIC, FLAPERON SIMULATOR
P/N 71-136901-103, MOOG P/N A14628

4 SERUOCYLINDER-HYDRAULIC STABILATOR
P/N 71-136934-101, E-SYSTEMS P/N 186000-100

5 HINGE - HYDRAULIC, RUDDER
P/N 71-136937-101, HR TEXTRON P/N 41007097

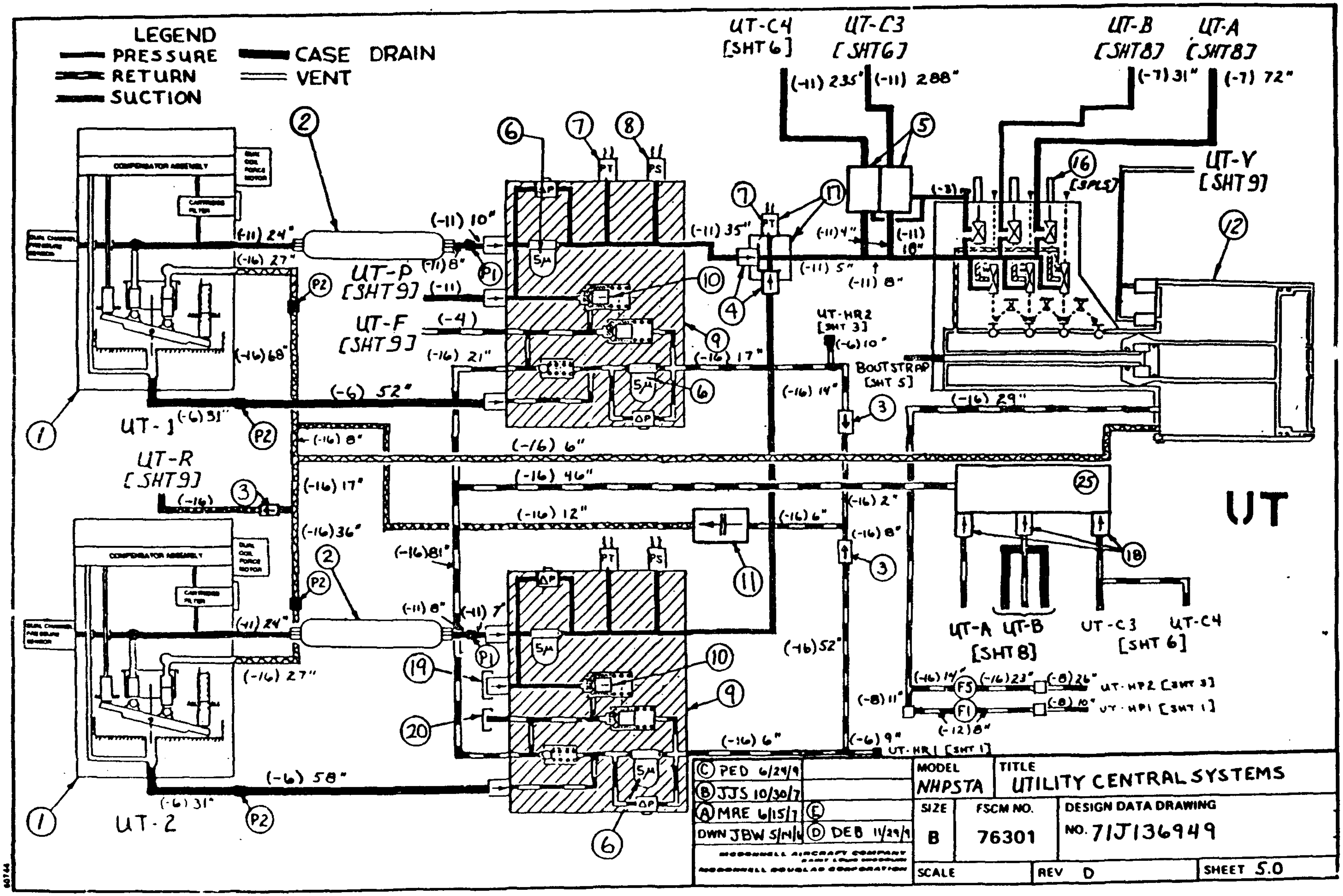
6 DELETED

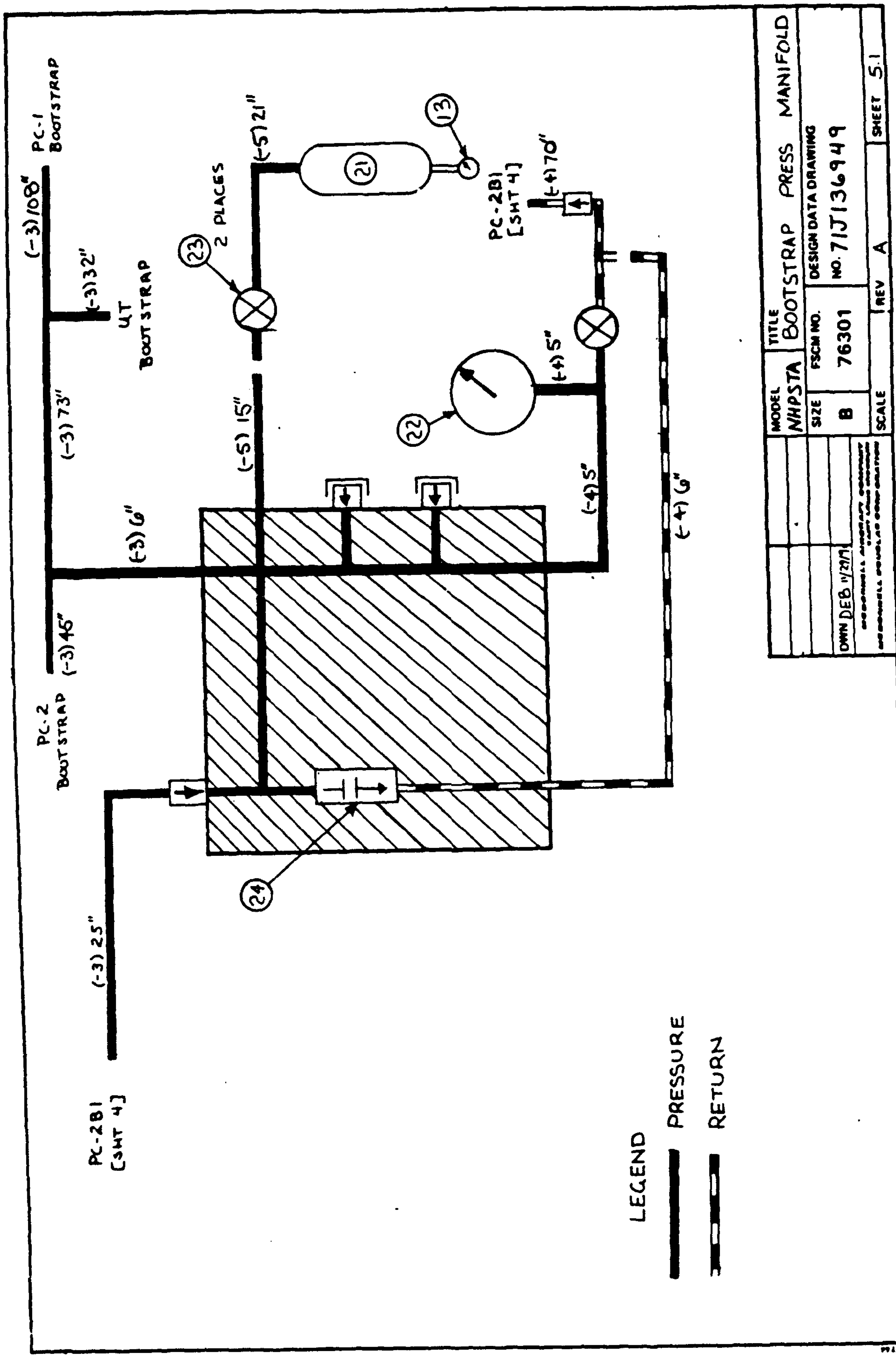
7 ~~INTENSIFIER - HYDRAULIC, PRESSURE~~ REMOVED AFTER 91 HOURS
P/N 71-136922-101, PARKER P/N 3850126

FC-RH

		MODEL	TITLE	
C PED 6/24/8		NHPSTA	RIGHT HAND FLIGHT CONTROLS	
B JJS 10/30/7		SIZE	FSCM NO.	DESIGN DATA DRAWING
A MRE 6/15/7		B	76301	NO. 71J136949
DWN JBW 5/14/4	D DEB 11/29/9			
MCDONNELL AIRCRAFT COMPANY / MCDONNELL DOUGLAS CORPORATION		SCALE	REV D	SHEET 4.1

MAC 1301A(REV 23 AUG 77)


LEGEND
PRESSURE
RETURN
SUCTION
CASE DRAIN
VENT
UT-1
UT-2
UT-P [SHT 9]
UT-F [SHT 9]
UT-R [SHT 9]
UT-C4 [SHT 6]
UT-C3 [SHT 6]
UT-B [SHT 8]
UT-A [SHT 8]
UT-Y [SHT 9]
UT-HR2 [SHT 3]
BOOTSTRAP [SHT 5]
UT-A UT-B [SHT 8]
UT-C3 UT-C4 [SHT 6]
UT-HP2 [SHT 3]
UT-HP1 [SHT 1]
UT-HR1 [SHT 1]
UT
MODEL NHPSTA
TITLE UTILITY CENTRAL SYSTEMS
SIZE B
FSCM NO. 76301
DESIGN DATA DRAWING
NO. 71J136949
SCALE
REV D
SHEET 5.0
MCDONNELL AIRCRAFT COMPANY
MCDONNELL DOUGLAS CORPORATION


PC-1
BOOTSTRAP
(-3)108"
(-3)32"
UT
BOOTSTRAP
(-3)73"
(-3)6"
(-3)45"
PC-2
BOOTSTRAP
(-3)25"
PC-2B1
[SHT 4]
(-5)15"
(-5)21"
23
2 PLACES
21
13
PC-2B1
[SHT 4]
(-4)70"
22
(-4)5"
(-4)5"
(-4)6"
24
LEGEND
PRESSURE
RETURN
MODEL
NHPSTA
TITLE
BOOTSTRAP PRESS MANIFOLD
SIZE
B
FSCM NO.
76301
DESIGN DATA DRAWING
NO. 71J136949
SCALE
REV
A
SHEET
5.1
DWN DEB 11/29/77

(1) PUMP - HYDRAULIC. VARIABLE PRESSURE AND DELIVERY

(2) ACOUSTIC FILTER, PULSCO P/N 840 40111

(3) VALVE - HYDRAULIC, CHECK (LOW PRESSURE)
ST7M262-16

(4) VALVE - HYDRAULIC, CHECK (HIGH PRESSURE)
CRISSAIR P/N 4C4634

(5) RLS AUXILIARY VALVE
GARKENYON P/N 95754

(6) FILTER ELEMENT, 5 MICRON ABSOLUTE

P/N 71-136941-209, PUROLATOR P/N 7590139-102

(7) TRANSMITTER - HYDRAULIC, PRESSURE
P/N 71-136931-101, CONDEC P/N 415G252

(8) SWITCH - HYDRAULIC, PRESSURE
P/N 71-136930-101, ITT NEO-DYN P/N 1203P0018

(9) MANIFOLD - HYDRAULIC. FILTER. 5 MICRON ABSOLUTE

P/N 71-136941-101, PUROLATOR P/N 7590095-101

(10) VALVE - HYDRAULIC, PRESSURE RELIEF
P/N 71-136925-101, CIRCLE SEAL P/N RV57-29

(11) VALVE - HYDRAULIC, PRESSURE RELIEF
CIRCLE SEAL P/N 5132T-16TB-100

(12) RESERVOIR - HYDRAULIC, BOOTSTRAP
P/N 71-136939-101, PARKER F/N 3850080

(1) SEE NOTES PAGE ii

(13) VALVE - PNEUMATIC, FILL, GAUGE
CIRCLE SEAL P/N GP10-80

(14) DELETED

(15) HEAT EXCHANGER - HYDRAULIC, CTFE/WATER

(16) SWITCH - HYDRAULIC, PRESSURE
P/N 71-136930-103, ITT NEO DYN P/N 1203P0023

(17) MANIFOLD - HYDRAULIC (HIGH PRESSURE)
GAR-KENYON P/N

(18) VALVE - HYDRAULIC, CHECK (LOW PRESSURE)
ST7M261-8

(19) CAP, ST7M235T4

(20) CAP, ST7M235T16

(21) ACCUMULATOR - HYD, CYL, 8000 PSI
P/N 71-136936-101 PARKER P/N 3860012

(22) HELICOIL PRESSURE GAGE

(23) MANUAL DUMP VALVE

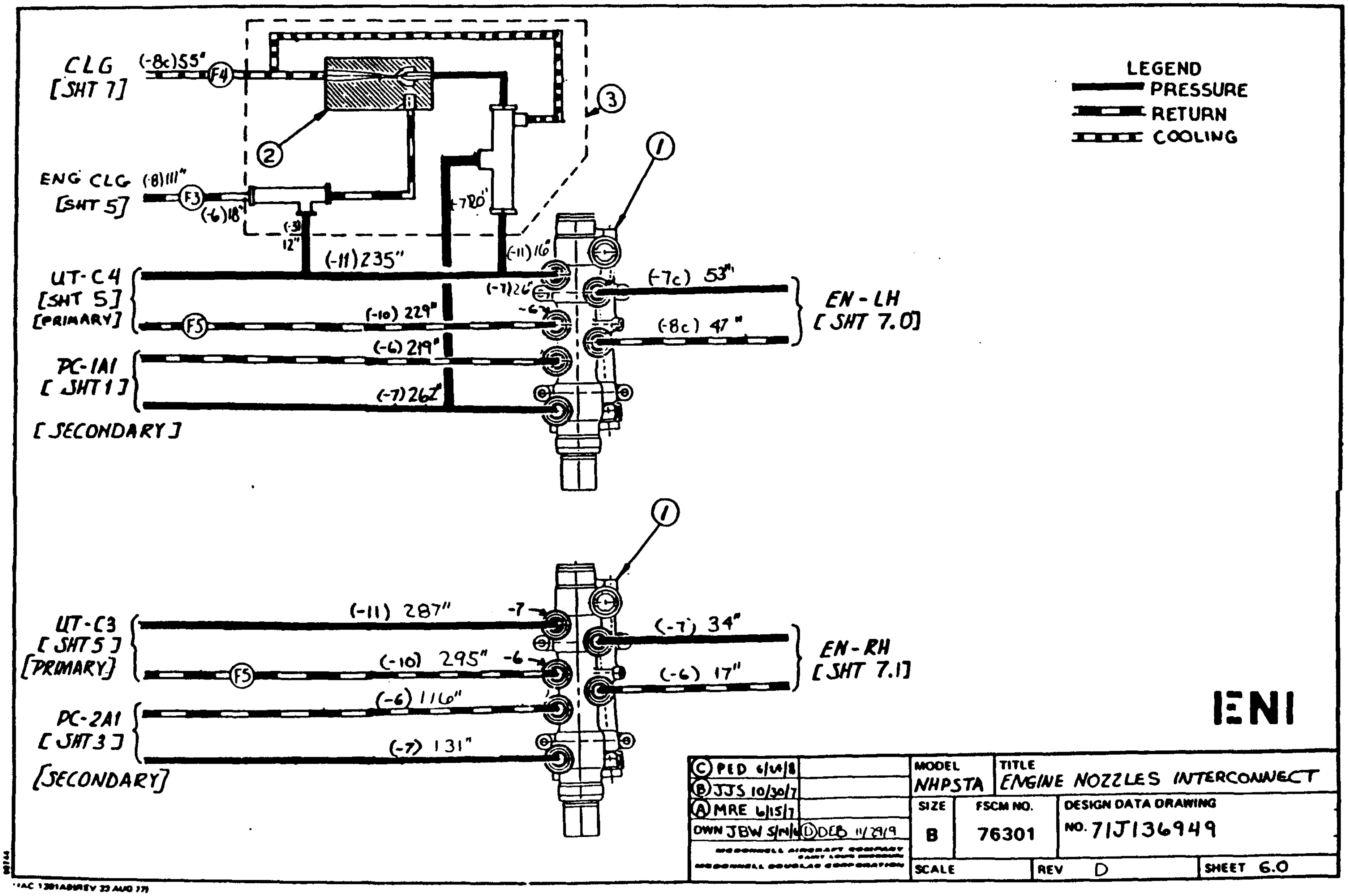
(24) VALVE - HYDRAULIC, PRESSURE RELIEF
LEE P/N: PHTX 0500050BA

(25) MANIFOLD ASSY, RETURN

UT

(C) PED 6/24/9	MODEL NHPSTA	TITLE UTILITY CENTRAL SYSTEMS		
(B) JJS 10/30/7				
(A) MRE 6/15/1	SIZE B	FSCM NO. 76301	DESIGN DATA DRAWING NO. 71J136949	
DWN JBW 5/14/ (D) DEB 4/29/9				
MCDONNELL AIRCRAFT COMPANY SAINT LOUIS MISSOURI / MCDONNELL DOUGLAS CORPORATION	SCALE	REV D		SHEET 5.2

AC 1701 A8 (REV 73 AUG 19)


LEGEND
PRESSURE
RETURN
COOLING
CLG
[SHT 7]
(-8c) 55"
F4
ENG CLG
[SHT 5]
(-8) 111"
F3
(-6) 18"
(-3) 12"
(-7) 20"
(-11) 235"
(-11) 16"
(-7) 26"
-6
UT-C4
[SHT 5]
[PRIMARY]
F5
(-10) 229"
PC-1A1
[SHT 1]
(-6) 219"
(-7) 262"
[SECONDARY]
(-7c) 53"
(-8c) 47"
EN-LH
[SHT 7.0]
UT-C3
[SHT 5]
[PRIMARY]
(-11) 287"
-7
(-10) 295"
-6
PC-2A1
[SHT 3]
(-6) 116"
(-7) 131"
[SECONDARY]
(-7) 34"
(-6) 17"
EN-RH
[SHT 7.1]
ENI
C PED 6/14/8
B JJS 10/30/7
A MRE 6/15/7
DWN JBW 5/14/6 D DEB 11/29/9
MODEL NHPSTA
TITLE ENGINE NOZZLES INTERCONNECT
SIZE B
FSCM NO. 76301
DESIGN DATA DRAWING NO. 71J136949
SCALE
REV D
SHEET 6.0

① VALVE - HYDRAULIC, SHUTTLE
P/N 71-136928 -101, PARKER P/N 3860017

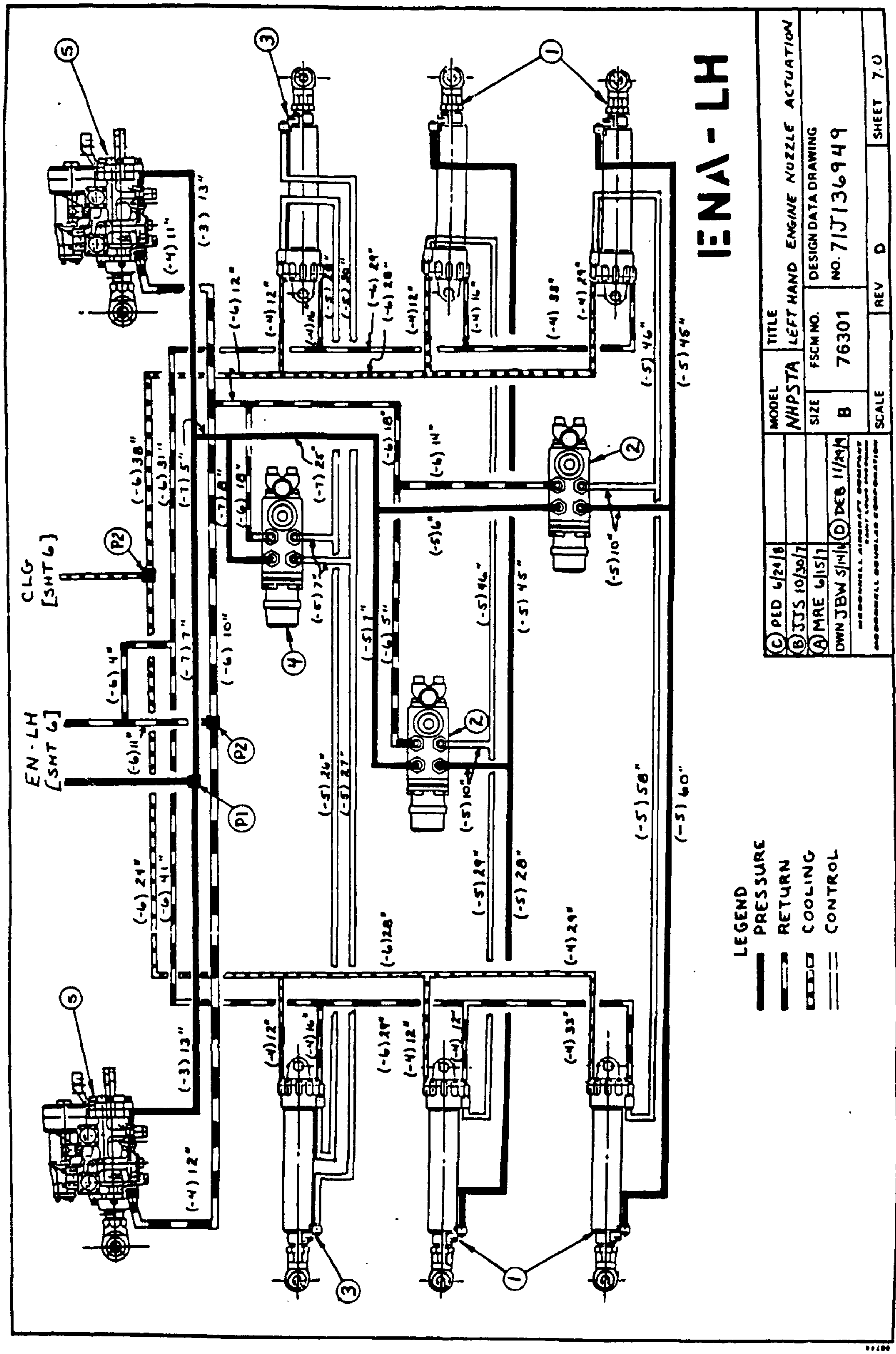
② EDUCTOR - HYDRAULIC
MCAIR P/N ADP-07

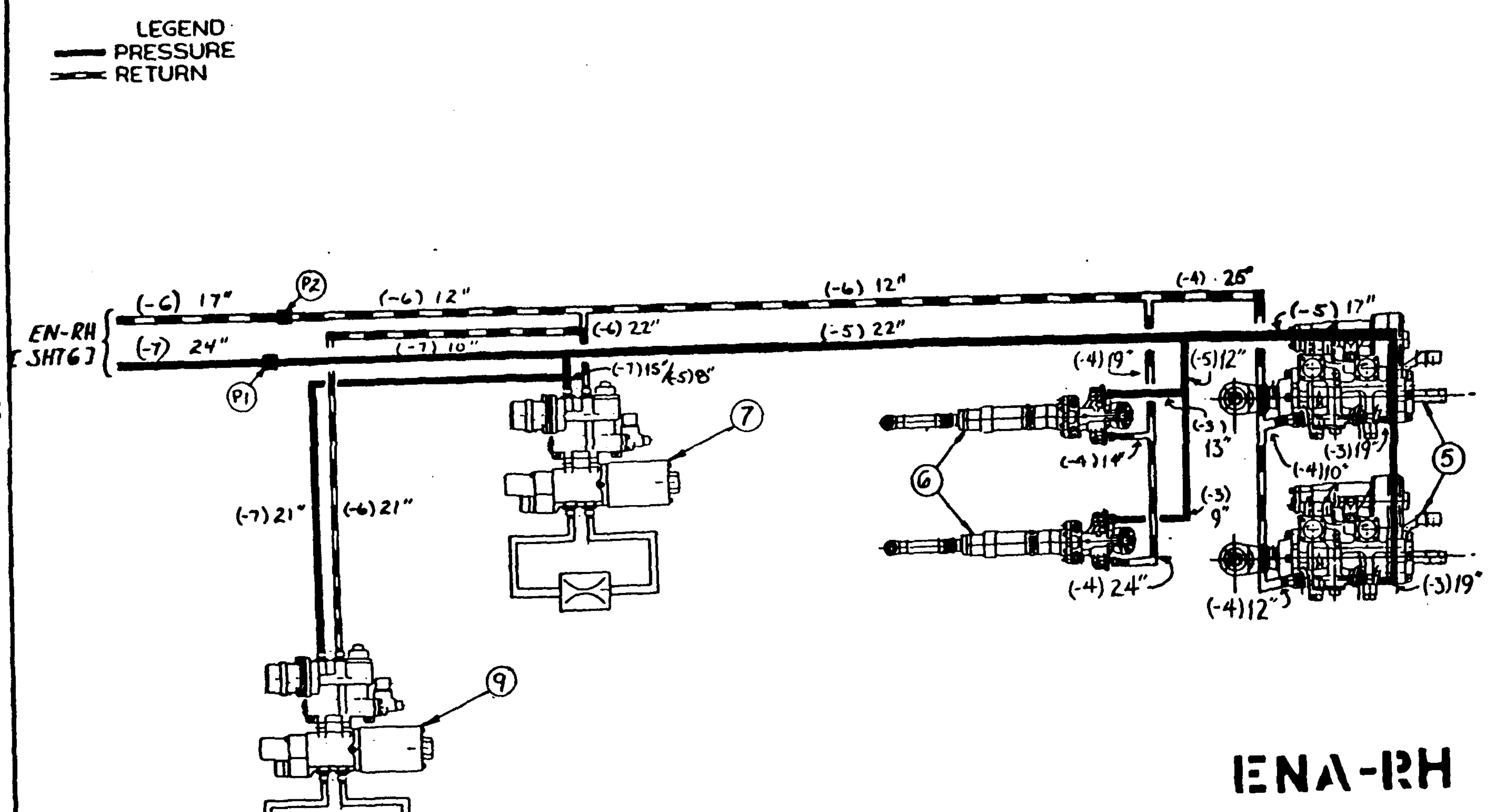
③ AUGMENTED COOLING / SHUTTLE
VALVE + GAR-KENYON P/N : 95771

ENI

Ⓒ PED 6/24/8	MODEL NHPSTA	TITLE ENGINE NOZZLES INTERCONNECT		
Ⓑ JJS 10/30/7				
Ⓐ MRE 6/15/7	SIZE B	FSCM NO. 76301	DESIGN DATA DRAWING NO. 71J136949	
DWN JBW 5/11/6				
	SCALE	REV C		SHEET 6.1

MAC 1381A86REV 22 AUG 77


ENA-LH
LEGEND
PRESSURE
RETURN
COOLING
CONTROL
EN-LH [SHT 6]
CLG [SHT 6]
P1
P2
MODEL
NHPSTA
TITLE
LEFT HAND ENGINE NOZZLE ACTUATION
SIZE
B
FSCM NO.
76301
DESIGN DATA DRAWING
NO. 71J136949
SCALE
REV D
SHEET 7.0
C PED 6/24/8
B JJS 10/30/7
A MRE 6/15/7
DWN JBW 5/14/4
D DEB 11/29/4



(C) PED 6/24/8		MODEL NHPSTA	TITLE RIGHT HAND ENGINE NOZZLE ACTUATION		
(B) JJS 10/30/7					
(A) MRE 4/15/87		SIZE B	FSCM NO. 76301	DESIGN DATA DRAWING NO. 71J136949	
DWN JBW 5/4/6	(D) DEB 11/29/9				
MCDONNELL AIRCRAFT COMPANY SAINT LOUIS MISSOURI MCDONNELL DOUGLAS CORPORATION		SCALE	REV D		SHEET 7.1

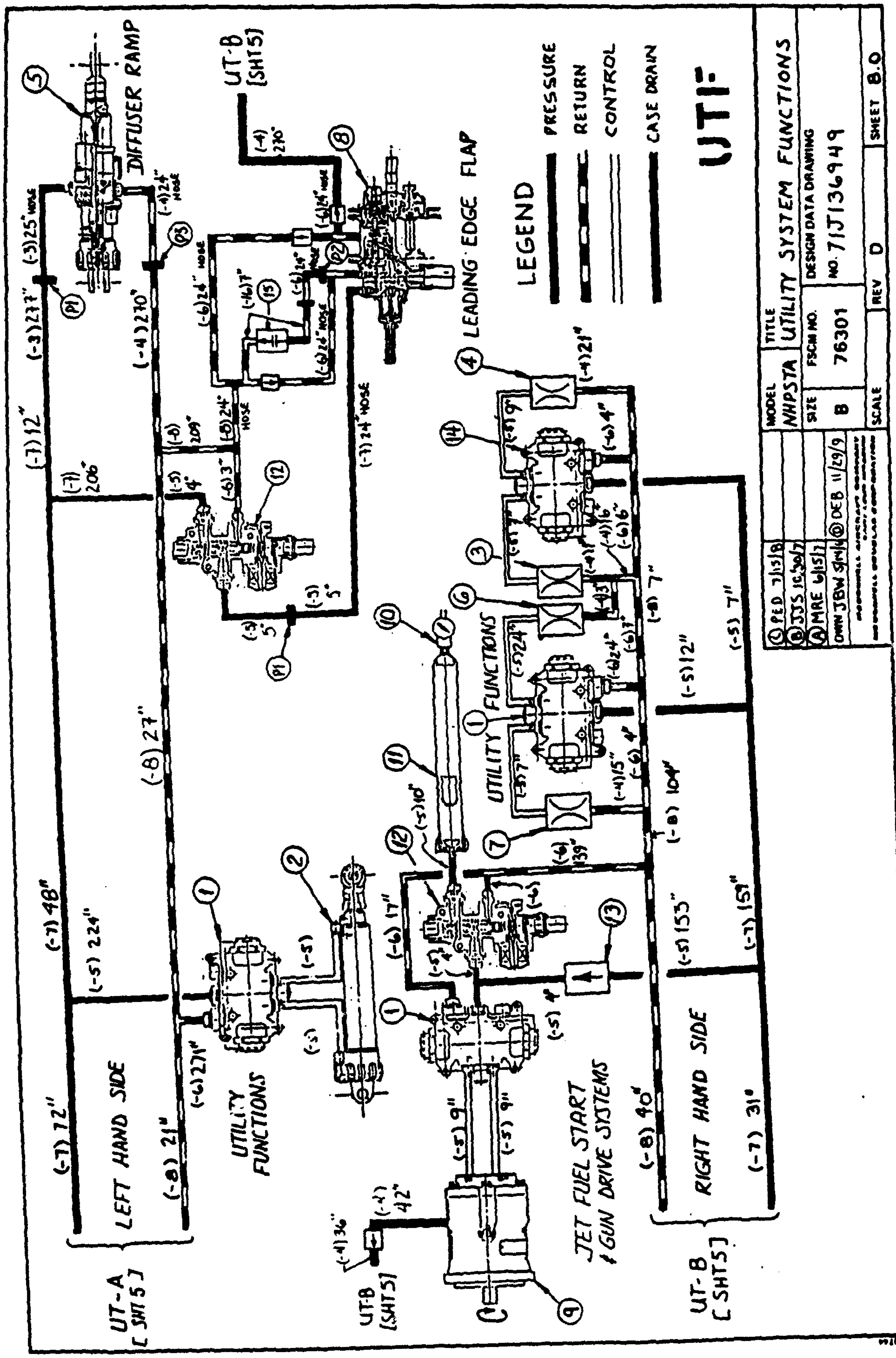
1. OUTPUT RAM - HYDRAULIC, DIVERGENT FLAP
   P/N 71-136907-205, MOOG P/N A-79210
2. SERVOCONTROL UNIT - HYDRAULIC, DIVERGENT FLAP
   P/N 71-136907-201, MOOG P/N A79225
3. OUTPUT RAM - HYDRAULIC, CONVERGENT FLAP
   P/N 71-136907-207, MOOG P/N A-79207
4. SERVOCONTROL UNIT - HYDRAULIC, CONVERGENT FLAP
   P/N 71-136907-203, MOOG P/N A-79222
5. SERVOCYLINDER - HYDRAULIC, REVERSER VANE
   P/N 71-136938-101, BERTEA P/N 314000
6. SERVOCYLINDER - HYDRAULIC, ARC VALVE
   P/N 71-136938-103, BERTEA P/N 324300
7. SIMULATOR - HYDRAULIC, DIVERGENT FLAP
   P/N 71-136907-209, MOOG P/N A79225
8. RESTRICTOR FLUID FLOW
9. SIMULATOR - HYDRAULIC, CONVERGENT FLAP
   P/N 71-136907-207, MOOG P/N A79222

△2 SEE NOTES PAGE ii

ENA

(B) JJS 10/30/7	MODEL NHPSTA	TITLE ENGINE NOZZLES ACTUATION		
(A) MRE 6/15/7	SIZE B	FSCM NO. 76301	DESIGN DATA DRAWING NO. 71J136949	
DWN JBW 5/14/	SCALE	REV B	SHEET 7.2	
MCDONNELL AIRCRAFT COMPANY / MCDONNELL DOUGLAS CORPORATION				

MAC 1381A8 (REV 23 AUG 71)


DIFFUSER RAMP
UT-B [SHT 5]
LEADING EDGE FLAP
LEGEND
PRESSURE
RETURN
CONTROL
CASE DRAIN
UTF
LEFT HAND SIDE
UTILITY FUNCTIONS
RIGHT HAND SIDE
JET FUEL START & GUN DRIVE SYSTEMS
UT-A [SHT 5]
UT-B [SHT 5]
MODEL NHPSTA
TITLE UTILITY SYSTEM FUNCTIONS
SIZE B
FSCM NO. 76301
DESIGN DATA DRAWING NO. 71J136949
REV D
SHEET 8.0

(1) VALVE - HYDRAULIC, LINEAR, DIRECTIONAL CONTROL, 4W-3P
P/N 71-136915-101, PARKER P/N 3860029

(2) CYLINDER - HYDRAULIC, UTILITY
CADILLAC GAGE P/N 3001300

(3) RESTRICTOR - FLUID FLOW

(4) RESTRICTOR - FLUID FLOW

(5) SERVOCYLINDER - HYDRAULIC, DIFFUSER RAMP
P/N 71-136904-101, CADILLAC GAGE P/N 3001000

(6) RESTRICTOR - FLUID FLOW

(7) RESTRICTOR - FLUID FLOW

(8) POWER DRIVE UNIT - LEADING EDGE FLAP
P/N 71B136940-201, SUNDSTRAND P/N EP2847-8

(9) MOTOR - HYDRAULIC, UTILITY
P/N 71-136912-101, ABEX P/N AM2CH-1

(10) VALVE - PNEUMATIC, FILL, GAUGE
P/N 71-136932-101, CIRCLE SEAL P/N GP10-80

(11) ACCUMULATOR - HYDRAULIC, CYLINDRICAL, 8000 PSI
P/N 71-136936-101, PARKER P/N 3860012

(12) VALVE - HYDRAULIC, LINEAR, DIRECTIONAL CONTROL 3W-2P
P/N 71-136917-101, PARKER P/N 3850073

(13) VALVE - HYDRAULIC, CHECK (HIGH PRESSURE)

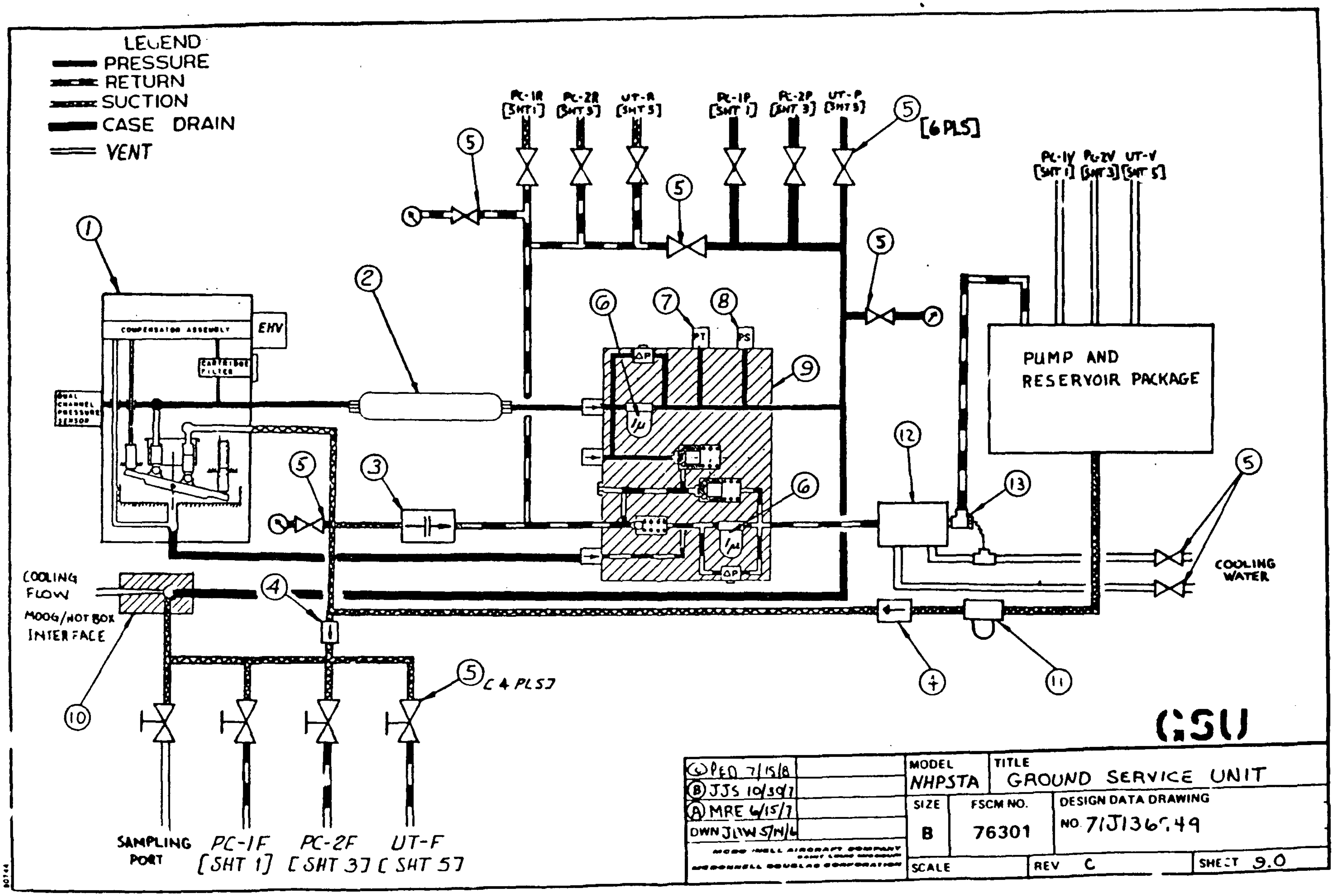
(14) VALVE - HYDRAULIC, LINEAR, DIRECTIONAL CONTROL, 4W-3P
MC AEROSPACE P/N MC 12966

(15) VALVE - HYDRAULIC, PRESSURE RELIEF
CIRCLE SEAL P/N 5132T-16TB-100

UTF

(C) RED 7/15/0	MODEL NHPSTA	TITLE UTILITY SYSTEM FUNCTIONS		
(B) JJS 10/30/7				
(A) MRE 6/15/7	SIZE B	FSCM NO. 76301	DESIGN DATA DRAWING NO. 71J136949	
DWN JBW 5/14/ (D) DEE 11/29/9				
MCDONNELL AIRCRAFT COMPANY SAINT LOUIS MISSOURI MCDONNELL DOUGLAS CORPORATION	SCALE	REV 0	SHEET S.1	

MAC 1701A8 (REV 23 AUG 71)


LEGEND
PRESSURE
RETURN
SUCTION
CASE DRAIN
VENT
PC-1R [SHT 1]
PC-2R [SHT 3]
UT-R [SHT 5]
PC-1P [SHT 1]
PC-2P [SHT 3]
UT-P [SHT 5]
[6 PLS]
PC-1V [SHT 1]
PC-2V [SHT 3]
UT-V [SHT 5]
COMPENSATOR ASSEMBLY
EHV
CARTRIDGE FILTER
DUAL CHANNEL PRESSURE SENSOR
PT
PS
ΔP
PUMP AND RESERVOIR PACKAGE
COOLING WATER
COOLING FLOW
MOOG/HOT BOX INTERFACE
[4 PLS]
SAMPLING PORT
PC-1F [SHT 1]
PC-2F [SHT 3]
UT-F [SHT 5]
GSU
C PED 7/15/8
B JJS 10/30/7
A MRE 6/15/7
DWN JLW 5/11/6
MODEL NHPSTA
TITLE GROUND SERVICE UNIT
SIZE B
FSCM NO. 76301
DESIGN DATA DRAWING NO. 71J13649
SCALE
REV C
SHEET 9.0

1. PUMP-HYDRAULIC, VARIABLE PRESSURE AND DELIVERY
   ABEX P/N APGVH -
2. ACOUSTIC FILTER, PULSCO P/N 840 40111
3. VALVE-HYDRAULIC, PRESSURE RELIEF [100PSI]
   CIRCLE SEAL P/N 5132-16TB-100
4. VALVE-HYDRAULIC, CHECK (LOW PRESSURE)
5. VALVE-HYDRAULIC, NEEDLE CONTROL
6. FILTER ELEMENT, 1 MICRON ABSOLUTE
   P/N 71-136941-233,
7. TRANSMITTER-HYDRAULIC, PRESSURE
   P/N 71-136931-101, CONDEC P/N 41SG252
8. SWITCH-HYDRAULIC, PRESSURE
   P/N 71-136930-101, ITT NEO-DYN P/N 1203P0018
9. MANIFOLD-HYDRAULIC, FILTER, 1 MICRON ABSOLUTE
   P/N 71-136941-101, APM P/N AE 8655-12
10. EDUCTOR-HYDRAULIC
    MCAIR P/N ADP - 8
11. MANIFOLD-HYDAULIC, FILTER, 1 MICRON ABSOLUTE
    APM
12. PRATT AND WHITNEY
    STAINLESS STEEL OIL COOLER
    P/N F-100
13. PENN TEMP CONTROL VALVE
    I.B. CABINET

GSU

(C) PED 7/15/8	MODEL	NHPSTA	TITLE	GROUND SERVICE UNIT	
(B) JJS 10/30/7	SIZE	B	FSCM NO. 76301	DESIGN DATA DRAWING NO. 71J136949	
(A) MRE 6/15/7					
DWN JBW 5/14/6					
MCDONNELL AIRCRAFT COMPANY / MCDONNELL DOUGLAS CORPORATION	SCALE		REV C	SHEET 9.1	

MAC 1701A (REV 23 AUG 77)

APPENDIX B

DEMONSTRATOR DUTY CYCLE

PC CYCLES, FREQUENCY, SYSTEM PRESSURE VS. PHASE

Actuator \ Mission Phase	Warm Up	Taxi	STOL	Climb	Cruise	Combat	Cruise	Descent	STOL	Reverse	Taxi	Cool Down
Stabilator	0	2-100%	2-80% 2-70%	30-50% 30-30% 400-2%	500-10% 2000-2%	6-100% 6-90% 30-80% 68-70% 80-50%	1000-10% 3500-2%	90-50% 70-30% 1000-2%	2-90% 8-80% 30-70% 100-2%	0	0	0
Freq. (Hz)		.448	.235	1.153	1.871	.31	1.76	1.082	.777			
Canard	0	2-90% 200-0%	2-80% 2-70%	30-50% 30-30% 600-2%	700-10% 1600-2%	14-90% 30-80% 68-70% 80-50%	1300-10% 2800-2%	90-50% 70-30% 1200-2%	8-80% 30-70%	0	0	0
Freq. (Hz)		.448	.235	1.654	1.572	.313	1.603	1.269	.211			
Flaperon	0	2-100%	2-100% 10-80%	2-90% 100-70% 50-50% 100-30%	500-10% 1750-2%	2-100% 50-80% 150-70% 150-30% 1000-10%	1000-10% 3250-2%	4-90% 250-70% 200-50% 250-30%	2-100% 2-90% 140-80%	0	0	0
Freq. (Hz)		.56	.705	.631	1.684	2.209	1.662	.656	.8			
Rudder	0	2-100%	2-80% 2-70%	30-50% 30-30% 400-2%	500-10% 2000-2%	6-100% 6-90% 30-80% 68-70% 80-50%	1000-10% 3500-2%	90-50% 70-30% 1000-2%	2-90% 8-80% 30-70% 100-2%	0	0	0
Freq. (Hz)		.704	.235	1.153	1.871	.31	1.76	1.082	.777			
Total Time (Sec)	60	450	17	399	1336	612	2557	1072	180	7	450	60
Cum. Time (sec.)	60	510	527	926	2262	2874	5431	6503	6683	6690	7140	7200
Ave Pump Pressure (psi)	3000	3150	8000	6800	4200	8000	4000	6900	8000	3000	3000	3000

UTILITY SYSTEM CYCLES, FREQUENCY, SYSTEM PRESSURE VS. PHASE

Engine Actuators \ Mission Phase	Warm Up	Taxi	STOL	Climb	Cruise	Combat	Cruise	Descent	STOL	Reverse	Taxi	Cool Down
Divergent Flap	0	2-100% 10-10%	2-50% 10-10%	2-80% 120-30% 50-2%	150-10% 525-2%	3-90% 8-80% 40-70% 11-50% 175-2%	280-10% 1000-2%	10-80% 48-50% 200-30% 250-2%	1-100% 1-90% 20-70% 20-50%	1-50%	10-10%	0
Freq. (Hz)		.471	.705	.481	1.104	.403	.891	.483	.233	.857	.466	
Convergent Flap	0	2-100% 10-10%	2-50% 10-10%	2-80% 120-30% 20-10% 34-2%	150-10% 525-2%	3-90% 8-80% 40-70% 11-50% 172-2%	280-10% 1000-2%	10-80% 48-50% 200-30% 210-2%	1-100% 1-90% 20-70% 20-50%	1-50%	10-10%	0
Freq. (Hz)		.357	.705	.441	1.104	.398	.891	.445	.233	.714	.466	
Reverser Vanes	0	2-100% 25-10%	1-100% 1-50% 15-2%	0	0	2-90% 6-70% 8-50% 15-30% 130-2%	0	0	1-100% 2-90% 8-80% 4-70% 5-50% 5-30% 155-2%	1-50% 5-30%	2-80% 25-10%	0
Freq. (Hz)		.448	1.0			.263			1.0	.857	.282	
Arc Valve Actuator	0	2-100% 10-10%	2-50% 10-10%	3-80% 120-30% 25-2%	150-10% 1400-2%	3-90% 8-80% 40-70% 11-50% 175-2%	280-10% 1000-2%	10-80% 48-50% 200-30% 250-2%	1-100% 1-90% 20-70% 20-50%	1-50%	10-10%	0
Freq. (Hz)		.471	.705	.481	1.104	.403	.891	.483	.233	.857	.466	
Total Time (Sec)	60	450	17	399	1336	612	2557	1072	180	7	450	60
Cum. Time (Sec.)	60	510	527	926	2262	2874	5431	6503	6683	6690	7140	7200

UTILITY SYSTEM CYCLES, FREQUENCY, SYSTEM PRESSURE VS. PHASE (cont.)

Mission Phase / Misc. Utility	Warm Up	Taxi	STOL	Climb	Cruise	Combat	Cruise	Descent	STOL	Reverse	Taxi	Cool Down
Diffuser Ramps	0	2-100% 2-50% 5-10%	1-30%	3-50% 3-30% 10-10%	260-10%	3-90% 8-80% 3-70%	2590-2%	14-50% 30-30%	1-100% 1-90% 2-70%	1-10%	50-10%	0
Freq. (Hz)		.02	.058	.04	.194	.022	1.013	.041	.022	.142	.188	
Leading Edge Flap	0	3-100%	2-100% 4-80%	5-90% 50-70% 50-50% 100-30%	400-10% 1400-2%	44-70% 120-30% 800-10%	800-10% 2600-2%	10-90% 100-70% 200-50% 225-30%	3-100% 6-90% 84-80%	0	0	0
Freq. (Hz)		.502	.471	.514	1.346	1.575	1.328	.449	.683			
Ave Pump Pressure (psi)	3400	3700	7900	6500	3000	7600	3000	6400	8000	8000	3500	3000
Total Time (Sec)	60	450	17	399	1336	612	2557	1072	180	7	450	60
Cum Time (Sec.)	60	510	527	926	2262	2874	5431	6503	6683	6690	7140	7200

APPENDIX C

CTFE A02 HYDRAULIC FLUID CHARACTERISTICS AND EXPERIENCES

CTFE A02 HYDRAULIC FLUID CHARACTERISTICS AND EXPERIENCES

Introduction - Several observations have been made on CTFE A02 hydraulic fluid properties and characteristics such as density, bulk modulus, dissolved air, water, toxicity and other issues such as additive stability and corrosion phenomenon. A compendium of CTFE fluid properties is included herein. CTFE has one principle advantage over conventional fluid and that is nonflammability. This should be the primary consideration for any application considered. All other fluid properties can be accommodated by design. There are some attributes when compared to individual fluids, however. CTFE A02 has also presented certain challenges which have been addressed over the past several years and measures have been identified which must be taken to minimize the risk of placing this nonflammable fluid in the field.

CTFE A02 Fluid Formulation - CTFE A02 fluid includes two additives. An anti-wear additive which is a proprietary product of the 3M Company is included at 0.05 percent by volume. An anti-corrosion additive, BSN is included at 0.5 percent by volume. An original goal for the A02 formulation was 350°F operating temperature. A02 has not been able to meet this goal due to thermal degradation of BSN at the upper temperature extreme. However, the Air Force has developed a 350°F formulation using a different rust inhibitor, but it was developed too late to use in this program.

Nonflammability - The full impact of having a nonflammable hydraulic fluid may not be fully appreciated by the designer. There are several other design attributes which accompany the elimination of any possibility of a hydraulic fire and its reflection into the statistical improvement in peacetime as well as combat survivability. It does not require any concessions in how hydraulic lines are installed in fire zones. They may be routed through bomb bays, bays which contain electrical distribution equipment and avionics bays. Concerns over fluid collected from minor hydraulic leaks and maintenance are eliminated because the fluid will evaporate.

Density - CTFE is approximately 2.2 times as dense as conventional hydraulic fluids; weighing roughly 15.2 lb/gal. In order to be weight competitive for future aircraft, it requires an operating pressure of 8000 psi to be competitive with a 3000 psi MIL-H-83282 from a weight standpoint. The use of other shear stable fluids at 8000 psi operating pressure will always result in a lighter system if the requirement for nonflammability is not considered. Past programs have addressed the density issue. CTFE's high density causes water and nonmetallic debris to float. With conventional hydraulic fluids, water and debris disappear to the bottom of the reservoir. The high density presents some handling problems. A 5-gallon container is the largest quantity that should be handled manually. Packaging of four such containers on a pallet is a convenient quantity (20 gallons) for storage and forklift handling.

Bulk Modulus - CTFE fluid bulk modulus is 15 to 20 percent lower than that of MIL-H-83282 fluid. The bulk modulus data which is currently available for CTFE is believed to be conservative since some test data shows better performance than the analytical predictions for parameters affected by bulk modulus such as actuator column stiffness.

Technical disciplines concerned with flight control actuator performance and flight control surface structural dynamics use a conservative fluid bulk modulus in analysis efforts, typically 120,000 to 131,000 psi for MIL-H-5606 and MIL-H-83282. These values are based on maximum fluid temperature (275^{O}F) and minimum pressure (zero). The conservative approach can be justified during preliminary analysis efforts; however, values closer to actual conditions should be used to avoid the weight penalty of stiffness critical actuators.

Dissolved Air - Any fluid can hold large quantities of air in solution at high pressures and at 8000 psi CTFE holds 500 times its volume of standard atmospheric air. Since air content is most critical in the low pressure side of a closed hydraulic system (return, reservoir, pump suction), these are the points of concern. Pump airlock and loss of discharge pressure can occur with air in the system. Where critical flight control surfaces are powered by two independent systems, dissimilar pump suction system design relative to "g" sensitivity should be implemented. Trapped bootstrap or gas pressurized reservoirs can also eliminate airlock.

All fluids hold air in solution; the actual amount depends on the equilibrium pressure. Air in solution has no measurable effect on bulk modulus. Free air evolved from reduction in pressure produces the sponginess often mistaken for dissolved air. MIL-H-83282 "in the can" typically contains 12 percent air in solution. CTFE holds about 18 percent. The designer is concerned with the amount of air contained in fluid at normal return pressure or reservoir pressure. Excess air can appear as foamy fluid, reservoir venting at startup/shutdown and noisy return lines. Normally, open loop cart bleeding can be expected to reduce dissolved air to about 1.5 times the amount held at atmospheric pressure. This is more than adequate for eliminating any air related anomalies during system operation.

Pump cavitation potential is increased by excess air in the system and can be very damaging to pumps and piping alike. The heavier the fluid and the higher the operating speed of the pump, the more base pressure is required to avoid cavitation. Conventional systems typically require a base reservoir pressure of 35 to 85 psi for tactical aircraft and over 100 psi with larger aircraft with significant longer suction lines from the reservoirs to the pumps. CTFE requires a minimum of 100 psi in comparison and depending on the pump operating speed could require much higher net positive suction head to avoid cavitation. This, however does not present a significant weight penalty in the central system.

Air in the system can be reduced by "open loop" bleeding of the systems with a ground power cart. "Open loop" refers to powering the aircraft hydraulic systems while circulating fluid through the cart reservoir which is vented to atmosphere. After open loop air bleeding, the aircraft system will contain about 1.5 times the amount of air which would be dissolved at atmospheric pressure. Fluid purifiers are commercially available which can remove 100 percent of the dissolved air. These are not in wide use simply because most systems, properly designed, are very tolerant of dissolved air. CTFE ground power cart design should consider including the capability to close the reservoir by some means to prevent evaporation and water intrusion but which could be opened for open loop air bleeding.

The final consideration regarding dissolved gases is system operating temperature. If the maximum operating temperature exceeds the normal rated fluid temperature of 275 degrees F, serious consideration should be given to nitrogen inerting to improve thermal stability and inhibit corrosion.

Dissolved Water - Water on the order of several hundred parts per million promotes corrosion in hydraulic systems. Rust inhibited hydraulic fluids are used in stationary test benches and for storage of components. The rust inhibited fluids are not used in flight systems because they have an upper thermal stability limit below maximum system operating temperatures. Because CTFE does not provide a barrier film on surfaces for corrosion protection, it was deemed essential from the onset of development to include a rust inhibitor in the flight fluid formulation.

The major problem with CTFE has been its anti-corrosion additive, BSN. Excess water is prone to stratify on top of the high density CTFE fluid instead of disappearing to the bottom of a containment vessel. The additive then combines with the water to form a wax like material which appears as "snow" and collects at the top of the fluid at room temperature. When heated above 160°F, this precipitant will dissolve and will not reappear when temperatures are reduced. Understanding this phenomenon and implementing a solution will be crucial to implementing the usage of CTFE in service. The most undesirable characteristic of the fluid formulation has been the build up of this precipitant on close tolerance surfaces in servovalves which can render them inoperative. Another drawback of CTFE is the formation of a corrosion product on non CRES and copper bearing alloys when left exposed to the atmosphere after having been wetted with CTFE. This can be avoided by preventing exposure to atmosphere or with the expanded use of CRES materials and newer surface treatments such as ion implantation.

Alcohols are surfactants which allow many fluids to hold significantly more water when contaminated with even trace amounts. Anyone working with CTFE should take great care to avoid introducing any form of alcohol into the system. Alcohol has been used to flush systems following water/acid cleaning. The interaction of CTFE, water and alcohol is not well researched or otherwise documented and caution is advisable.

Pump Performance and Life - The most difficult problem at present and the area of greatest concern is hydraulic pump performance and life. Even though several pumps have worked well with CTFE, the design of the central system is viewed as the key factor as to how well any given pump performed and lasted. More endurance work by pump suppliers is needed. Most pump time (and poor reliability) has been demonstrated on other 8000 psi "test" programs which were likely more severe than a typical aircraft duty cycle.

Pump Pressure Pulsations - MCAIR conducted a significant amount of testing to evaluate the affects of air on pump and system pulsation characteristics using MIL-H-5606 and MIL-H-83282 fluids. The results showed that the magnitude of the pulsations increased significantly and caused catastrophic line and component failures if the amount of air in the system was increased beyond an acceptable level; typically 20 percent. Open loop bleeding would normally produce an air content of 1.5 times the atmospheric value of 18 percent. The criteria used for

CTFE fluid at 8000 psi was based on this work. Subsequent tests showed that the maximum acceptable dissolved air volume was 30 percent. Open loop bleeding of this test rig resulted in 22 to 25 percent as compared to the 18 percent measured in the supply can at ambient pressure.

Pump "Airlock" - Conventional pumps are not designed to handle air. They are not compressors and a bubble of air can cause pump airlock and loss of system pressure. Aircraft have been lost because of airlocked pumps in a negative "g" maneuver. This is further aggravated in bootstrap systems where loss suction head will immediately follow loss of pump discharge pressure. CTFE must be used in a closed system unlike MIL-H-83282 and SKYDROL. MIL-H-83282 is typically used in closed systems because of negative "g" maneuvers. CTFE when operated hot and at inadequate reservoir pressure may have "vapor lock" potential regardless of air content.

CTFE Toxicity - CTFE 3.1 fluid, composed primarily of the trimer and tetramer of CTFE, produced little or no acute toxicity, but caused extensive liver damage in 90 day inhalation exposure studies with rats. The pattern of toxicity with 3.1 fluid was similar to other chemicals -- such as clofibrate (a hyperlipidemia drug), phthalate plasticizers, and polychlorinated normal paraffins -- that produce chronic liver damage in rodents which can progress to liver cancer. However, these rodent liver effects are not observed when monkeys or humans are treated with some of the same chemicals. Therefore, the rodent response is not believed to be a reliable predictor of human hazard for these chemicals.

In subsequent studies performed to assess the relevance of the rodent toxicity to humans, 3.1 fluid did not produce the same liver toxicity in rhesus monkeys and was non-mutagenic. Higher molecular weight components of the 3.1 fluid were found to be more toxic in rats than lower molecular weight components. Acid metabolites of CTFE oligomers are probably responsible for the toxicity.

To put the relative risk associated with the use of CTFE-based fluids in perspective, repeated dosing studies were performed with other in-use (MIL-H-5606 and -83282) and proposed (LT-83282) hydraulic fluids. All of these hydrocarbon-based fluids also produced significant toxicity in subchronic dosing situations, but the nature of the toxicity was different than for 3.1 fluid. These fluids caused kidney damage of a kind associated with kidney cancer in male rats. Once again this toxicity, which has been observed for many hydrocarbon-based fluids including gasoline, is not believed to be a reliable predictor of human response.

In summary, all of the hydraulic fluids examined show some degree of toxicity in rats and would be likely to cause tumors in the liver or kidney of exposed rats if a lifetime cancer study were to be performed. Although target tissue in the rodent is different to CTFE-based fluids than for the hydrocarbon-based fluids, neither of the two responses are considered likely to be predictive of human risk. The use of CTFE-based hydraulic fluids is therefore not expected to cause a significantly increased hazard compared to other in-use and proposed hydraulic fluids. However, because the rodent data do at least suggest the potential to be toxic, both CTFE-based and hydrocarbon-based hydraulic fluids should be handled prudently, with appropriate industrial hygiene precautions taken to minimize inhalation exposure as well as skin contact.

Industry Experience - Experience with using CTFE in the industry varies from good to bad. Contributing to either result are features in the test facilities or the manner in which it was used in a test system. A side (but potentially related) issue is the success with hydraulic pumps used at the various using facilities. Several observations have been made by the operators at several facilities.

Best experience has occurred when the test circuits are constructed from corrosion resistant materials and other materials which have known chemical compatibility. Diatomaceous and sintered aluminum filter elements should be avoided. Typically, the fluid has been used successfully in systems with low fluid volume and aircraft quality materials and components. Fluid sampled from large systems using industrial pumps have had a translucent dark brown color or an opaque brown coffee color when water is present. The color is attributed to thermal stressing and water contamination. Systems should be closed; reservoirs which are open to the atmosphere are inadvisable.

MCAIR Experience - The Flight Controls Laboratory at MCAIR has been conducting Air Force contracted program work with CTFE since December 1983. The most time accumulated in any one period of time was a 750 hour endurance test run between December 1983 and October 1984 on the Flight Worthiness of Fire Resistant Hydraulic Systems which was the first program at MCAIR to use CTFE fluid technology. This effort was followed by a contracted effort to research two significant shortfalls found in the initial program; high pump pulsations and reduced dynamic stiffness of flight control actuators. This effort spanned from October 1984 through December 1986. The Flight Worthiness programs were followed by the Low Energy Hydraulic Consumption Techniques program which was structured on using CTFE at 8000 psi operating pressure and was also capped by an endurance test phase from May 87 through March 88 which accumulated approximately 245 operating hours.

MCAIR's experience with the CTFE fluid has been neither extremely positive or negative, having had the same experiences with the fluid as other researchers but with less severity. The waxy deposit referred to as "snow" as well as dark filmy deposits has appeared in test systems having close tolerance parts of non-corrosion resistant steel and bronze but has not hampered test efforts.

The following tables and graphs showing CTFE fluid properties were generated using the SSFAN computer program (Reference Technical Report AFAPL-TR-76-43, Volume VI). The validation of the prediction method was discussed in Volume I of this report. Additional data has been used to further validate these predictions. The data was developed through a cooperative IRAD with the Monsanto Corporation. The testing included measurement of isothermal secant bulk modulus, density, and viscosity at extremes of temperature and pressure. Vapor pressure versus temperature was supplied by WRDS/MLBT. Thermal conductivity data are not shown but are presented in Volume I of this report.

[illegible] FLUID TYPE: CTFE-AO2

[illegible] PRESSURE IS 0.0 P.S.I.G.

[illegible]	VISCOSITY (CS)	DENSITY (GM/ML)	BULK MODULUS ADIAB TAN (PSI)	HEAT CAPACITY (BTU/LB DEG F)	SONIC VELOCITY (FT/SEC)
-65.0	1200.000	1.9399	360041.	0.1937	3713.
-60.0	798.031	1.9353	353335.	0.1939	3682.
-50.0	382.944	1.9260	340024.	0.1941	3621.
-40.0	202.000	1.9168	326914.	0.1943	3559.
-30.0	114.060	1.9076	314074.	0.1946	3497.
-20.0	69.121	1.8983	301557.	0.1948	3435.
-10.0	44.475	1.8891	289405.	0.1950	3373.
0.0	30.114	1.8799	277649.	0.1953	3312.
10.0	21.295	1.8706	266310.	0.1955	3252.
20.0	15.628	1.8614	255402.	0.1957	3192.
30.0	11.841	1.8521	244931.	0.1960	3134.
40.0	9.220	1.8429	234900.	0.1962	3077.
50.0	7.352	1.8337	225304.	0.1964	3021.
60.0	5.984	1.8244	216137.	0.1967	2966.
70.0	4.959	1.8152	207389.	0.1969	2913.
80.0	4.175	1.8060	199049.	0.1971	2861.
90.0	3.564	1.7967	191103.	0.1974	2811.
100.0	3.080	1.7875	183537.	0.1976	2762.
110.0	2.682	1.7783	176335.	0.1978	2714.
120.0	2.360	1.7690	169482.	0.1981	2668.
130.0	2.095	1.7598	162963.	0.1983	2623.
140.0	1.875	1.7506	156762.	0.1985	2579.
150.0	1.689	1.7413	150863.	0.1988	2537.
160.0	1.532	1.7321	145251.	0.1990	2496.
170.0	1.397	1.7229	139913.	0.1992	2456.
180.0	1.280	1.7136	134833.	0.1995	2417.
190.0	1.179	1.7044	129998.	0.1997	2380.
200.0	1.089	1.6952	125396.	0.1999	2344.
210.0	1.010	1.6859	121014.	0.2002	2309.
220.0	0.940	1.6767	116840.	0.2004	2275.
230.0	0.877	1.6675	112863.	0.2006	2242.
240.0	0.820	1.6582	109072.	0.2009	2210.
250.0	0.769	1.6490	105458.	0.2011	2179.
260.0	0.723	1.6398	102010.	0.2013	2150.
270.0	0.681	1.6305	98721.	0.2016	2121.
280.0	0.642	1.6213	95580.	0.2018	2093.
290.0	0.608	1.6121	92581.	0.2020	2065.
300.0	0.575	1.6028	89716.	0.2023	2039.
310.0	0.546	1.5936	86977.	0.2025	2013.
320.0	0.519	1.5843	84359.	0.2027	1989.
330.0	0.494	1.5751	81854.	0.2030	1965.
340.0	0.471	1.5659	79457.	0.2032	1941.
350.0	0.449	1.5566	77162.	0.2034	1919.

HYDRAULIC FLUID TYPE: CTFE-A02
FLUID PRESSURE IS 3000.0 P.S.I.G.

TEMP (DEG F)	VISCOSITY (CS)	DENSITY (GM/ML)	BULK MODULUS ADIAB TAN (PSI)	HEAT CAPACITY (BTU/LB DEG F)	SONIC VELOCITY (FT/SEC)
-65.0	1516.300	1.9589	409258.	0.1935	3939.
-60.0	1079.810	1.9546	400549.	0.1936	3901.
-50.0	575.838	1.9461	383707.	0.1938	3827.
-40.0	324.699	1.9376	367629.	0.1941	3754.
-30.0	180.955	1.9291	352298.	0.1943	3683.
-20.0	114.228	1.9206	337697.	0.1945	3614.
-10.0	74.837	1.9122	323802.	0.1947	3546.
0.0	50.792	1.9038	310590.	0.1949	3481.
10.0	35.633	1.8954	298031.	0.1952	3417.
20.0	25.775	1.8870	286100.	0.1954	3356.
30.0	19.171	1.8787	274768.	0.1956	3296.
40.0	14.623	1.8704	264005.	0.1958	3238.
50.0	11.409	1.8621	253785.	0.1960	3182.
60.0	9.085	1.8538	244079.	0.1963	3127.
70.0	7.367	1.8456	234861.	0.1965	3074.
80.0	6.071	1.8374	226105.	0.1967	3023.
90.0	5.077	1.8292	217786.	0.1969	2974.
100.0	4.301	1.8210	209881.	0.1971	2926.
110.0	3.832	1.8129	202366.	0.1973	2879.
120.0	3.288	1.8048	195220.	0.1975	2834.
130.0	2.850	1.7966	188423.	0.1978	2791.
140.0	2.491	1.7886	181955.	0.1980	2749.
150.0	2.195	1.7805	175797.	0.1982	2708.
160.0	1.948	1.7724	169933.	0.1984	2668.
170.0	1.740	1.7644	164346.	0.1986	2630.
180.0	1.562	1.7564	159021.	0.1988	2593.
190.0	1.409	1.7484	153943.	0.1990	2557.
200.0	1.277	1.7404	149099.	0.1992	2522.
210.0	1.162	1.7324	144475.	0.1994	2489.
220.0	1.060	1.7245	140061.	0.1996	2456.
230.0	0.970	1.7165	135843.	0.1998	2424.
240.0	0.889	1.7086	131813.	0.2001	2394.
250.0	0.817	1.7007	127959.	0.2003	2364.
260.0	0.750	1.6928	124272.	0.2005	2335.
270.0	0.685	1.6849	120745.	0.2007	2307.
280.0	0.642	1.6771	117367.	0.2009	2280.
290.0	0.608	1.6692	114132.	0.2011	2254.
300.0	0.575	1.6614	111031.	0.2013	2228.
310.0	0.546	1.6535	108059.	0.2015	2203.
320.0	0.519	1.6457	105209.	0.2017	2179.
330.0	0.494	1.6379	102475.	0.2018	2156.
340.0	0.471	1.6301	99850.	0.2020	2133.
350.0	0.449	1.6223	97329.	0.2022	2111.

HYDRAULIC FLUID TYPE: CTFE-A02
FLUID PRESSURE IS 5500.0 P.S.I.G.

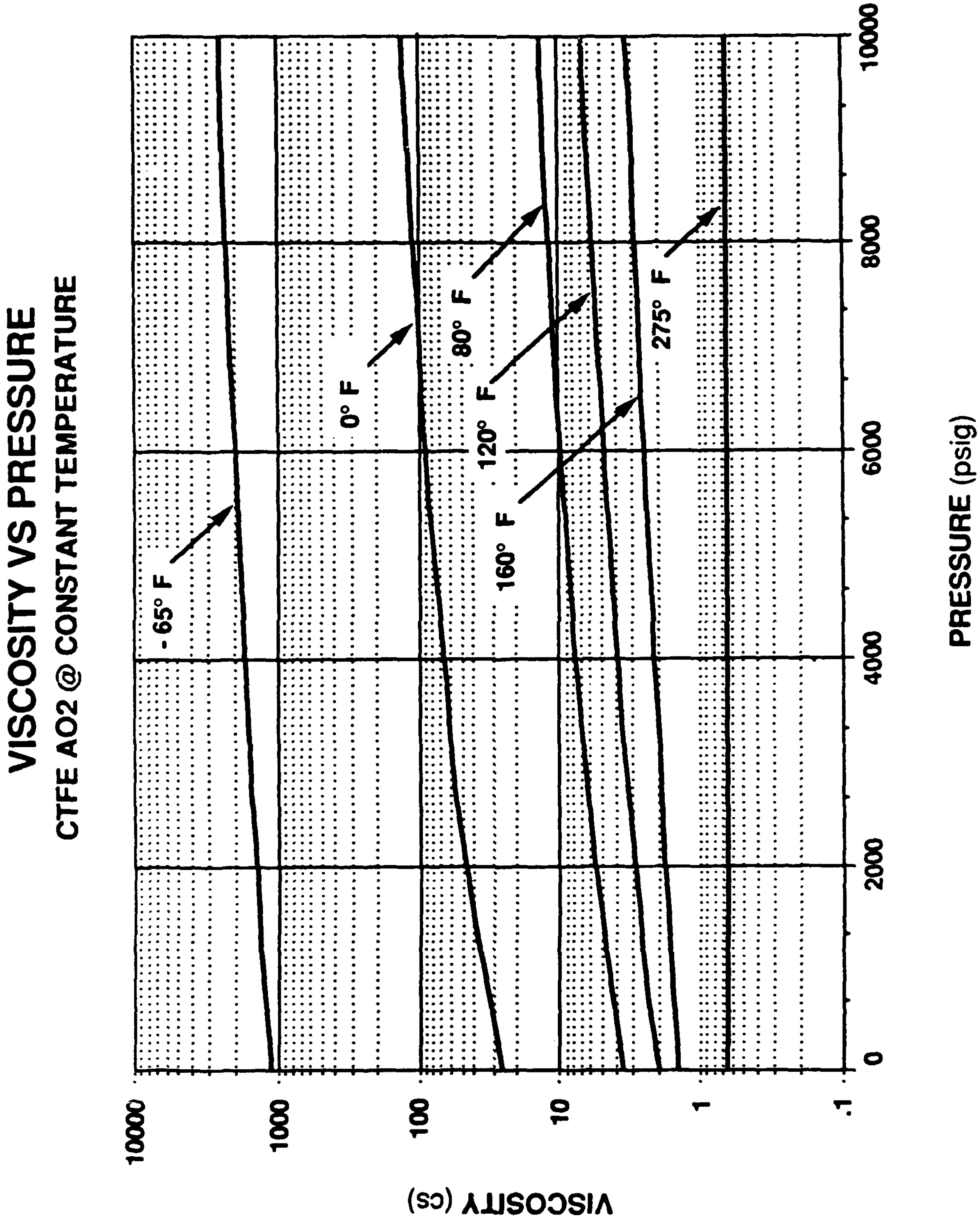
TEMP (DEG F)	VISCOSITY (CS)	DENSITY (GM/ML)	BULK MODULUS ADIAB TAN (PSI)	HEAT CAPACITY (BTU/LB DEG F)	SONIC VELOCITY (FT/SEC)
-65.0	1842.701	1.9730	462575.	0.1935	4173.
-60.0	1389.272	1.9689	451655.	0.1936	4128.
-50.0	808.980	1.9609	431005.	0.1938	4040.
-40.0	482.232	1.9530	411815.	0.1941	3957.
-30.0	265.829	1.9450	393949.	0.1943	3879.
-20.0	173.610	1.9371	377284.	0.1945	3803.
-10.0	115.463	1.9293	361715.	0.1947	3732.
0.0	78.522	1.9215	347145.	0.1949	3663.
10.0	54.724	1.9137	333490.	0.1951	3598.
20.0	39.108	1.9060	320674.	0.1954	3535.
30.0	28.643	1.8983	308628.	0.1956	3475.
40.0	21.475	1.8906	297292.	0.1958	3417.
50.0	16.455	1.8830	286609.	0.1960	3362.
60.0	12.865	1.8754	276531.	0.1962	3309.
70.0	10.244	1.8678	267012.	0.1964	3258.
80.0	8.294	1.8603	258011.	0.1966	3210.
90.0	6.818	1.8527	249491.	0.1968	3163.
100.0	5.682	1.8453	241418.	0.1970	3117.
110.0	5.158	1.8378	23376[illegible]	0.1972	3074.
120.0	4.336	1.8304	22[illegible]	0.1974	3032.
130.0	3.683	1.8230	219587.	0.1976	2991.
140.0	3.157	1.8156	213019.	0.1978	2952.
150.0	2.731	1.8083	206768.	0.1980	2914.
160.0	2.380	1.8010	200813.	0.1982	2878.
170.0	2.088	1.7937	[illegible]	0.1984	2843.
180.0	1.843	1.7864	189721.	0.1986	2809.
190.0	1.636	1.7792	184552.	0.1988	2776.
200.0	1.458	1.7719	179613.	0.1990	2744.
210.0	1.305	1.7647	174892.	0.1992	2713.
220.0	1.172	1.7576	170376.	0.1994	2683.
230.0	1.055	1.7504	166053.	0.1996	2654.
240.0	0.952	1.7432	161913.	0.1998	2626.
250.0	0.859	1.7361	157946.	0.2000	2599.
260.0	0.773	1.7290	154143.	0.2001	2573.
270.0	0.688	1.7219	150494.	0.2003	2548.
280.0	0.642	1.7148	146992.	0.2005	2523.
290.0	0.608	1.7078	143629.	0.2007	2499.
300.0	0.575	1.7007	140398.	0.2008	2476.
310.0	0.546	1.6937	137293.	0.2010	2454.
320.0	0.519	1.6867	134306.	0.2012	2432.
330.0	0.494	1.6797	131434.	0.2014	2411.
340.0	0.471	1.6727	128669.	0.2015	2390.
350.0	0.449	1.6657	126007.	0.2017	2370.

HYDRAULIC FLUID TYPE: CTFE-A02
FLUID PRESSURE IS 8000.0 P.S.I.G.

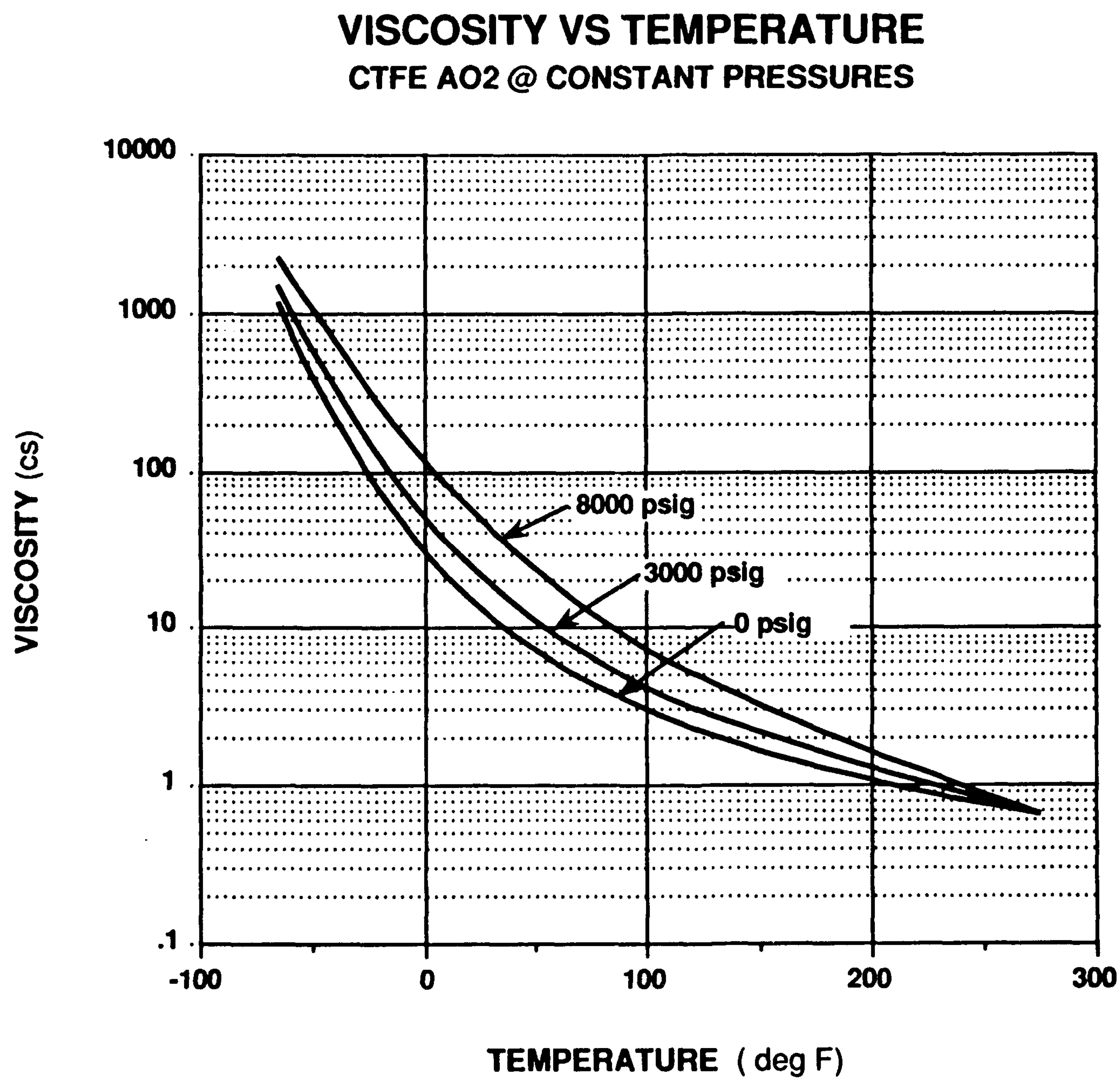
TEMP (DEG F)	VISCOSITY (CS)	DENSITY (GM/ML)	BULK MODULUS ADIAB TAN (PSI)	HEAT CAPACITY (BTU/LB DEG F)	SONIC VELOCITY (FT/SEC)
-65.0	2239.364	1.9853	532714.	0.1936	4464.
-60.0	1787.423	1.9815	518741.	0.1937	4409.
-50.0	1136.516	1.9740	492951.	0.1939	4307.
-40.0	716.194	1.9666	469687.	0.1942	4212.
-30.0	390.510	1.9592	448597.	0.1944	4124.
-20.0	263.862	1.9518	429394.	0.1946	4042.
-10.0	178.145	1.9445	411840.	0.1948	3966.
0.0	121.392	1.9372	395733.	0.1950	3895.
10.0	84.043	1.9299	380905.	0.1952	3829.
20.0	59.338	1.9227	367211.	0.1954	3766.
30.0	42.796	1.9155	354529.	0.1956	3708.
40.0	31.538	1.9084	342753.	0.1958	3652.
50.0	23.732	1.9013	331792.	0.1960	3600.
60.0	18.217	1.8942	321567.	0.1962	3551.
70.0	14.245	1.8871	312007.	0.1964	3504.
80.0	11.331	1.8801	303052.	0.1966	3460.
90.0	9.156	1.8731	294649.	0.1968	3418.
100.0	7.505	1.8661	286749.	0.1970	3378.
110.0	6.944	1.8592	279312.	0.1972	3340.
120.0	5.716	1.8523	272298.	0.1974	3304.
130.0	4.759	1.8454	265676.	0.1976	3270.
140.0	4.002	1.8386	259414.	0.1978	3237.
150.0	3.397	1.8317	253486.	0.1980	3206.
160.0	2.907	1.8249	247868.	0.1982	3176.
170.0	2.506	1.8181	242537.	0.1984	3148.
180.0	2.175	1.8113	237475.	0.1986	3120.
190.0	1.898	1.8046	232662.	0.1987	3094.
200.0	1.665	1.7979	228082.	0.1989	3070.
210.0	1.466	1.7912	223721.	0.1991	3046.
220.0	1.296	1.7845	219565.	0.1993	3023.
230.0	1.148	1.7778	215601.	0.1994	3001.
240.0	1.018	1.7712	211818.	0.1996	2980.
250.0	0.903	1.7645	208206.	0.1998	2960.
260.0	0.797	1.7579	204755.	0.1999	2941.
270.0	0.692	1.7513	201455.	0.2001	2923.
280.0	0.642	1.7447	198300.	0.2003	2905.
290.0	0.608	1.7381	195280.	0.2004	2889.
300.0	0.575	1.7315	192391.	0.2006	2873.
310.0	0.546	1.7250	189624.	0.2007	2857.
320.0	0.519	1.7184	186974.	0.2009	2843.
330.0	0.494	1.7119	184436.	0.2010	2829.
340.0	0.471	1.7054	182004.	0.2012	2815.
350.0	0.449	1.6988	179674.	0.2013	2803.

HYDRAULIC FLUID TYPE: CTFE-A02
FLUID PRESSURE IS 10000.0 P.S.I.G.

TEMP (DEG F)	VISCOSITY (CS)	DENSITY (GM/ML)	BULK MODULUS ADIAB TAN (PSI)	HEAT CAPACITY (BTU/LB DEG F)	SONIC VELOCITY (FT/SEC)
-65.0	2617.343	1.9939	607041.	0.1937	4755.
-60.0	2186.649	1.9904	589603.	0.1938	4691.
-50.0	1491.715	1.9833	558108.	0.1940	4572.
-40.0	982.767	1.9762	530457.	0.1942	4465.
-30.0	531.198	1.9692	506009.	0.1944	4369.
-20.0	368.823	1.9622	484260.	0.1946	4281.
-10.0	252.021	1.9553	464807.	0.1948	4202.
0.0	172.006	1.9483	447324.	0.1951	4129.
10.0	118.457	1.9414	431546.	0.1953	4063.
20.0	82.831	1.9345	417252.	0.1955	4002.
30.0	59.009	1.9277	404259.	0.1957	3947.
40.0	42.889	1.9209	392416.	0.1959	3895.
50.0	31.811	1.9141	381592.	0.1961	3848.
60.0	24.063	1.9073	371678.	0.1963	3804.
70.0	18.544	1.9005	362580.	0.1965	3764.
80.0	14.543	1.8938	354216.	0.1967	3727.
90.0	11.591	1.8871	346517.	0.1969	3693.
100.0	9.376	1.8804	339422.	0.1970	3661.
110.0	8.808	1.8738	332880.	0.1972	3632.
120.0	7.132	1.8671	326842.	0.1974	3606.
130.0	5.843	1.8605	321270.	0.1976	3581.
140.0	4.837	1.8539	316128.	0.1978	3559.
150.0	4.045	1.8473	311383.	0.1980	3538.
160.0	3.412	1.8407	307009.	0.1981	3520.
170.0	2.901	1.8342	302981.	0.1983	3503.
180.0	2.483	1.8276	299278.	0.1985	3487.
190.0	2.138	1.8211	295879.	0.1987	3474.
200.0	1.851	1.8146	292769.	0.1988	3462.
210.0	1.610	1.8081	289931.	0.1990	3451.
220.0	1.404	1.8016	287353.	0.1991	3442.
230.0	1.228	1.7951	285023.	0.1993	3434.
240.0	1.075	1.7887	282931.	0.1995	3428.
250.0	0.940	1.7822	281068.	0.1996	3422.
260.0	0.817	1.7758	279426.	0.1998	3419.
270.0	0.694	1.7693	277999.	0.1999	3416.
280.0	0.642	1.7629	276781.	0.2001	3415.
290.0	0.608	1.7565	275768.	0.2002	3415.
300.0	0.575	1.7500	274955.	0.2003	3416.
310.0	0.546	1.7436	274342.	0.2005	3418.
320.0	0.519	1.7372	273925.	0.2006	3422.
330.0	0.494	1.7308	273704.	0.2007	3427.
340.0	0.471	1.7244	273679.	0.2008	3433.
350.0	0.449	1.7180	273852.	0.2010	3441.

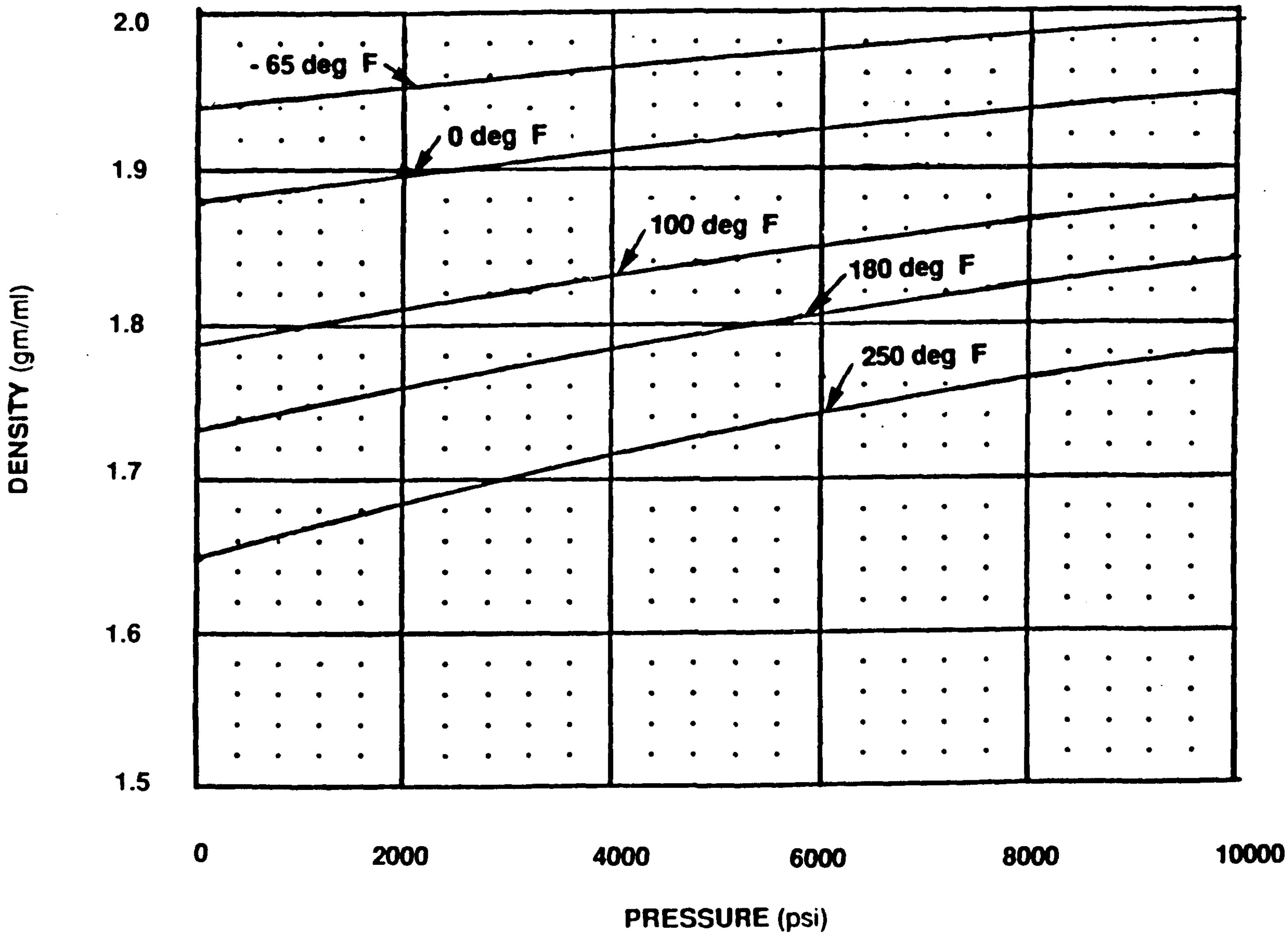


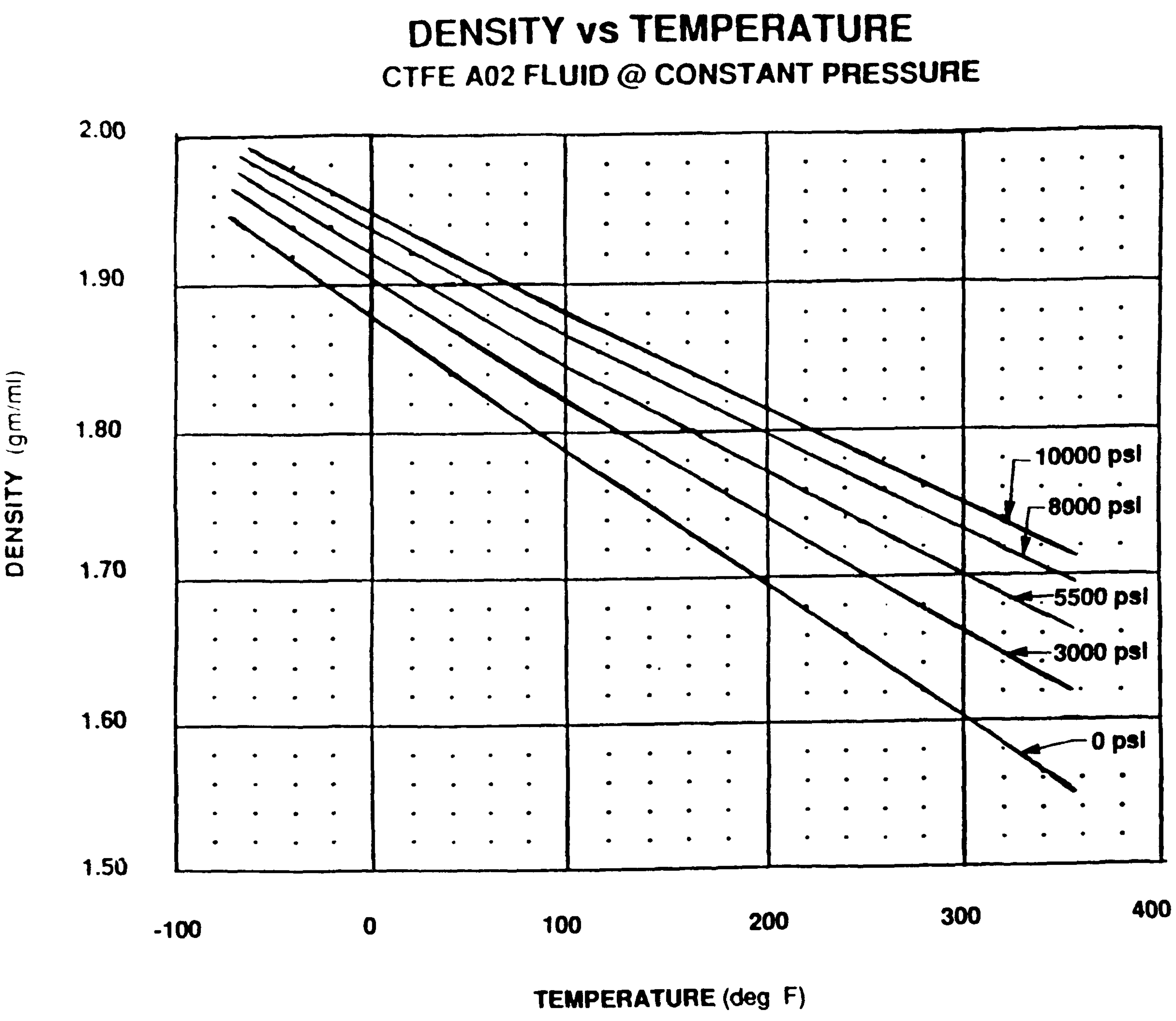
VISCOSITY VS PRESSURE
CTFE AO2 @ CONSTANT TEMPERATURE
- 65° F
0° F
80° F
120° F
160° F
275° F
10000
1000
100
10
1
.1
VISCOSITY (cs)
0
2000
4000
6000
8000
10000
PRESSURE (psig)


VISCOSITY VS TEMPERATURE
CTFE AO2 @ CONSTANT PRESSURES
10000
1000
100
10
1
.1
-100
0
100
200
300
8000 psig
3000 psig
0 psig
VISCOSITY (cs)
TEMPERATURE (deg F)

DENSITY vs PRESSURE

CTFE A02 FLUID @ CONSTANT TEMPERATURE

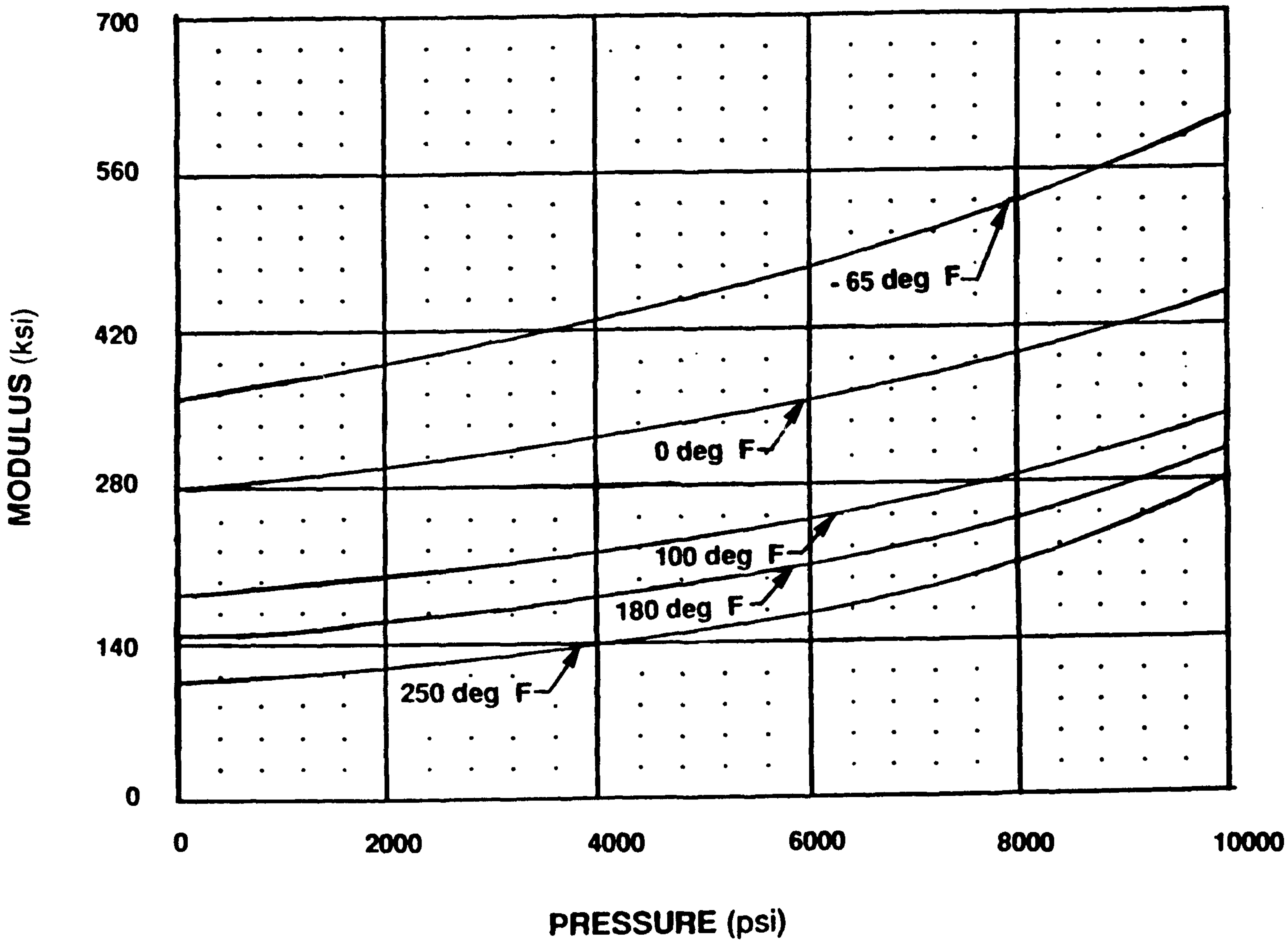




DENSITY vs TEMPERATURE
CTFE A02 FLUID @ CONSTANT PRESSURE
2.00
1.90
1.80
1.70
1.60
1.50
DENSITY (gm/ml)
-100
0
100
200
300
400
TEMPERATURE (deg F)
10000 psi
8000 psi
5500 psi
3000 psi
0 psi

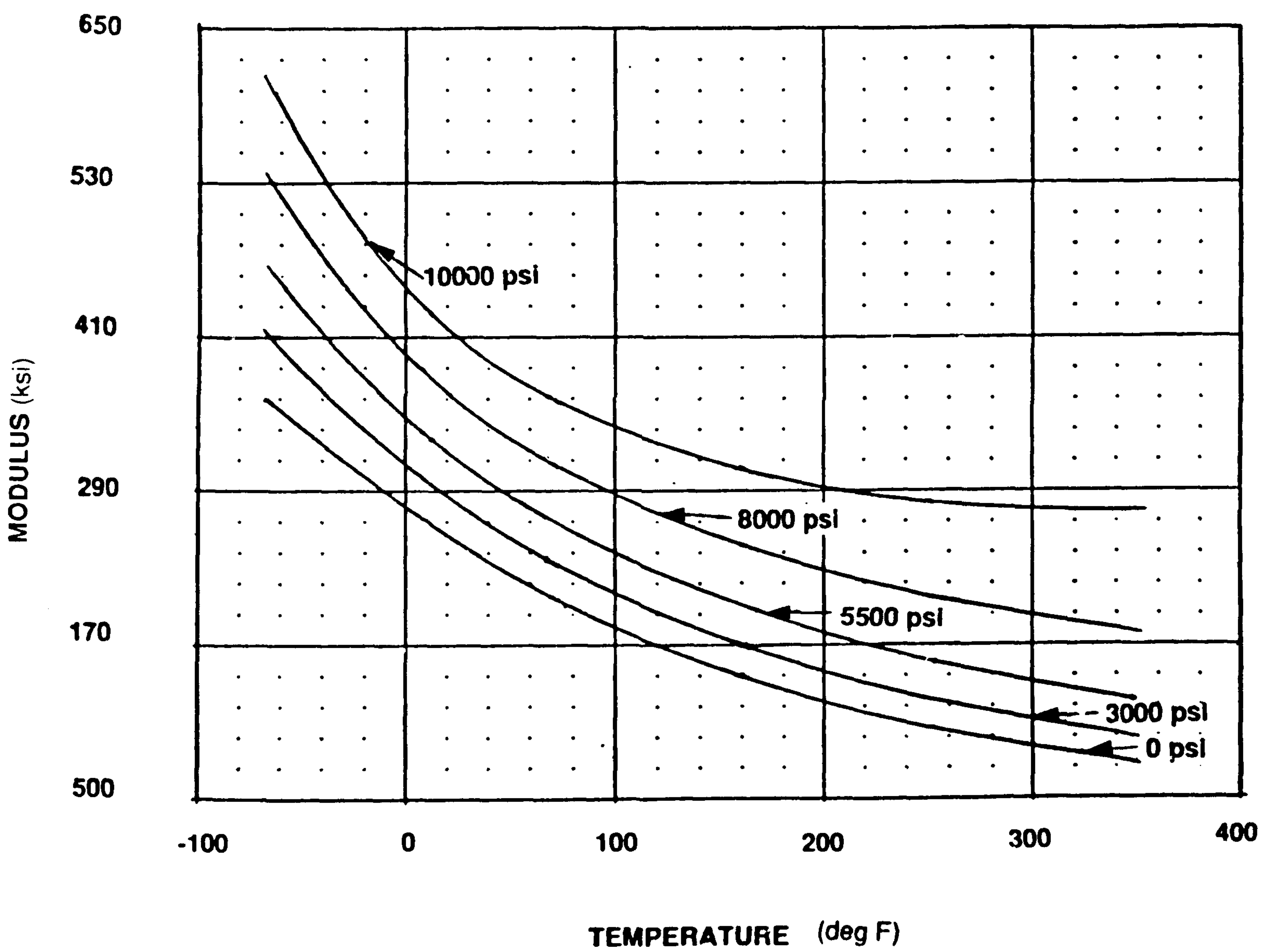
ADIABATIC TANGENT BULK MODULUS vs. PRESSURE

CTFE A02 FLUID @ CONSTANT TEMPERATURE

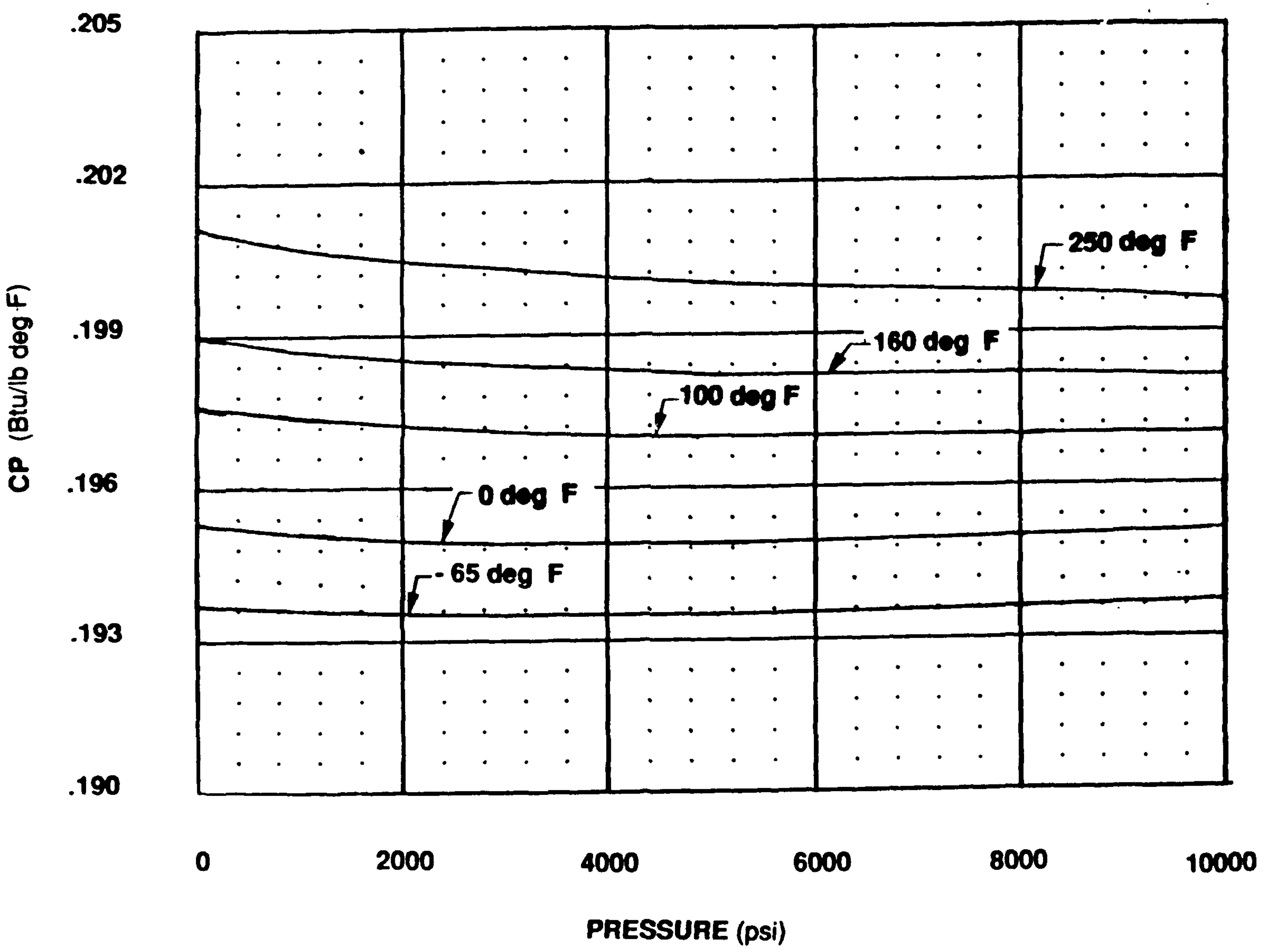


ADIABATIC TANGENT BULK MODULUS vs TEMPERATURE

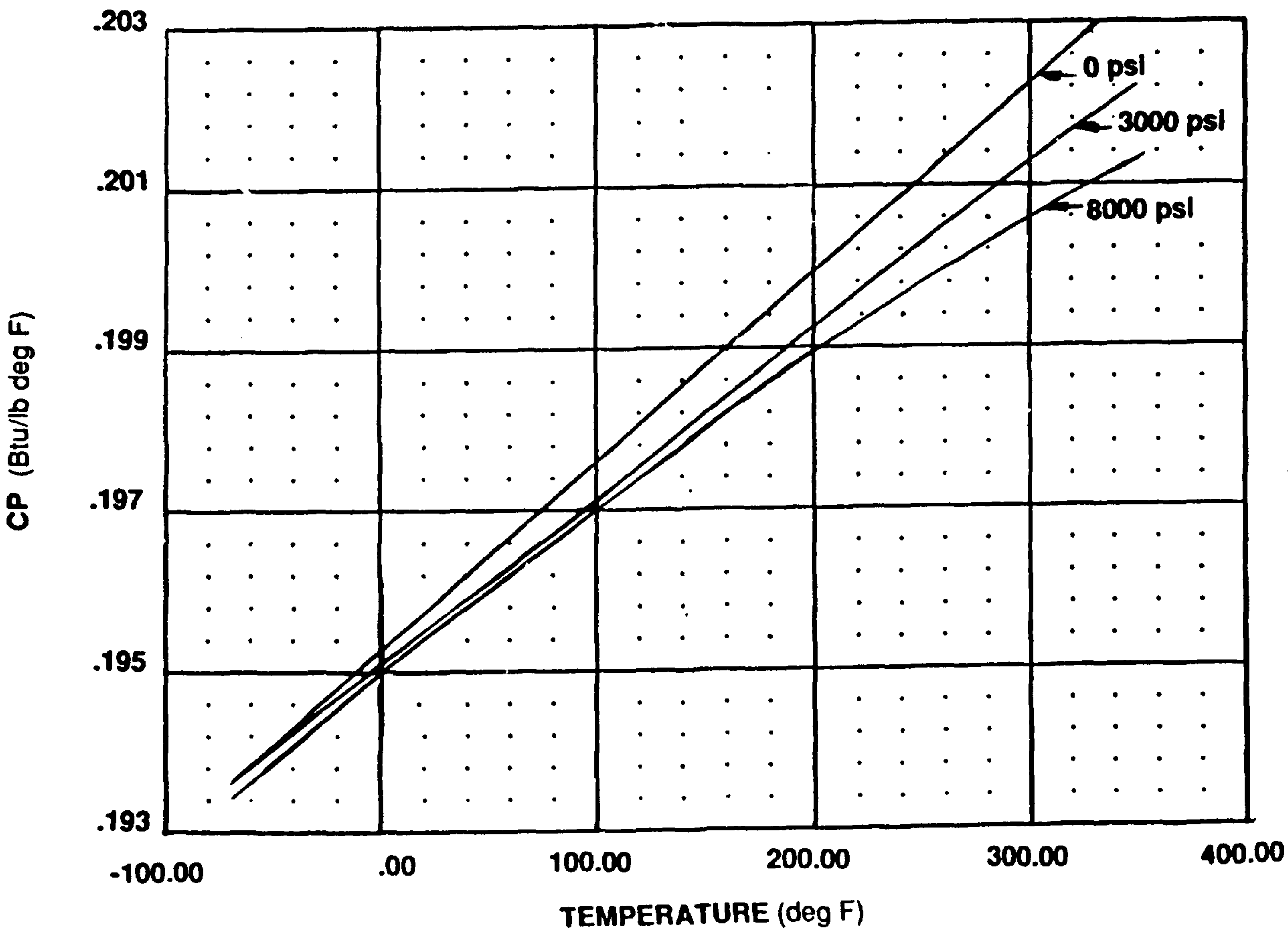
CTFE AO2 FLUID @ CONSTANT PRESSURE

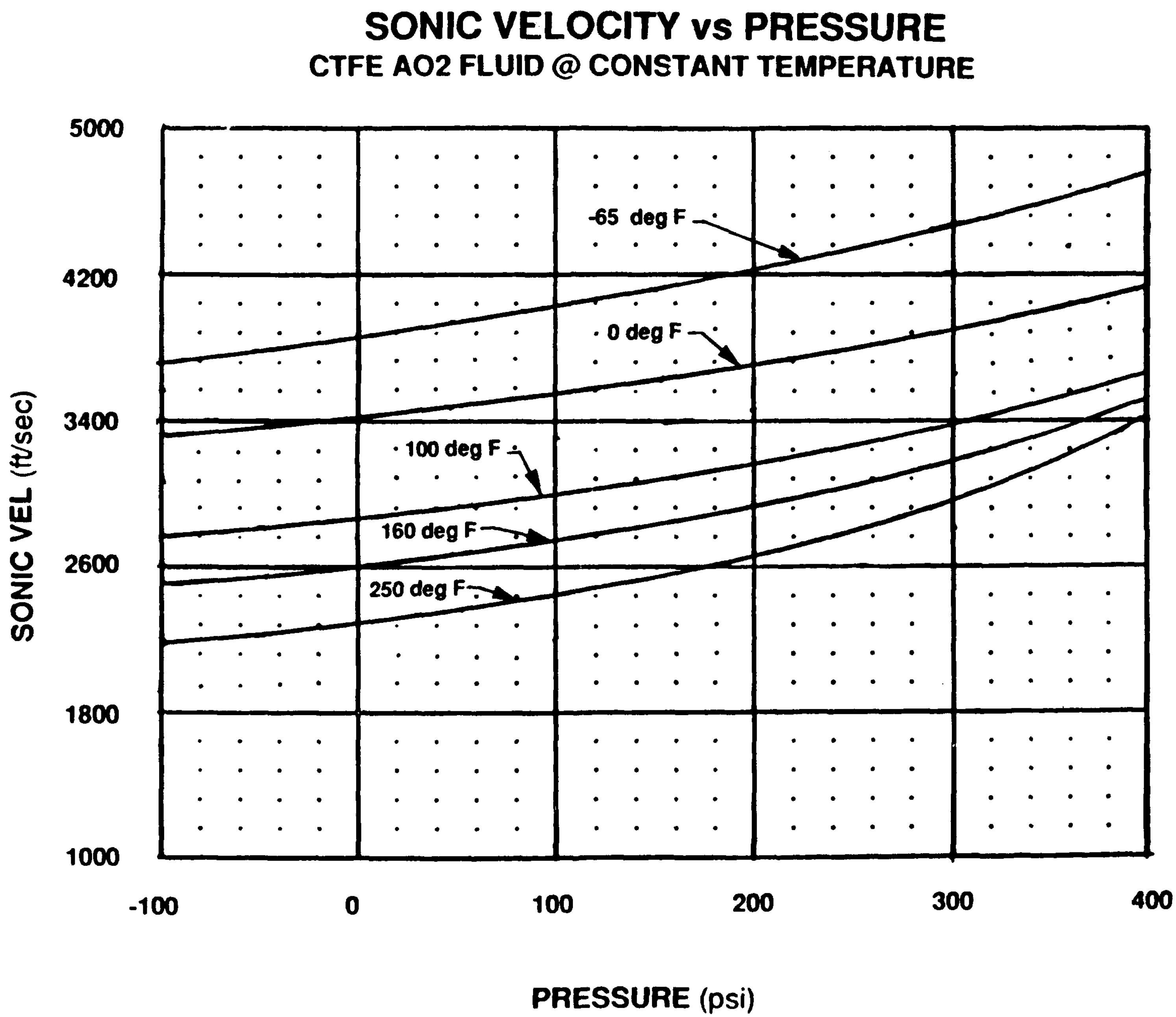


SPECIFIC HEAT vs PRESSURE
CTFE A02 FLUID @ CONSTANT TEMPERATURE



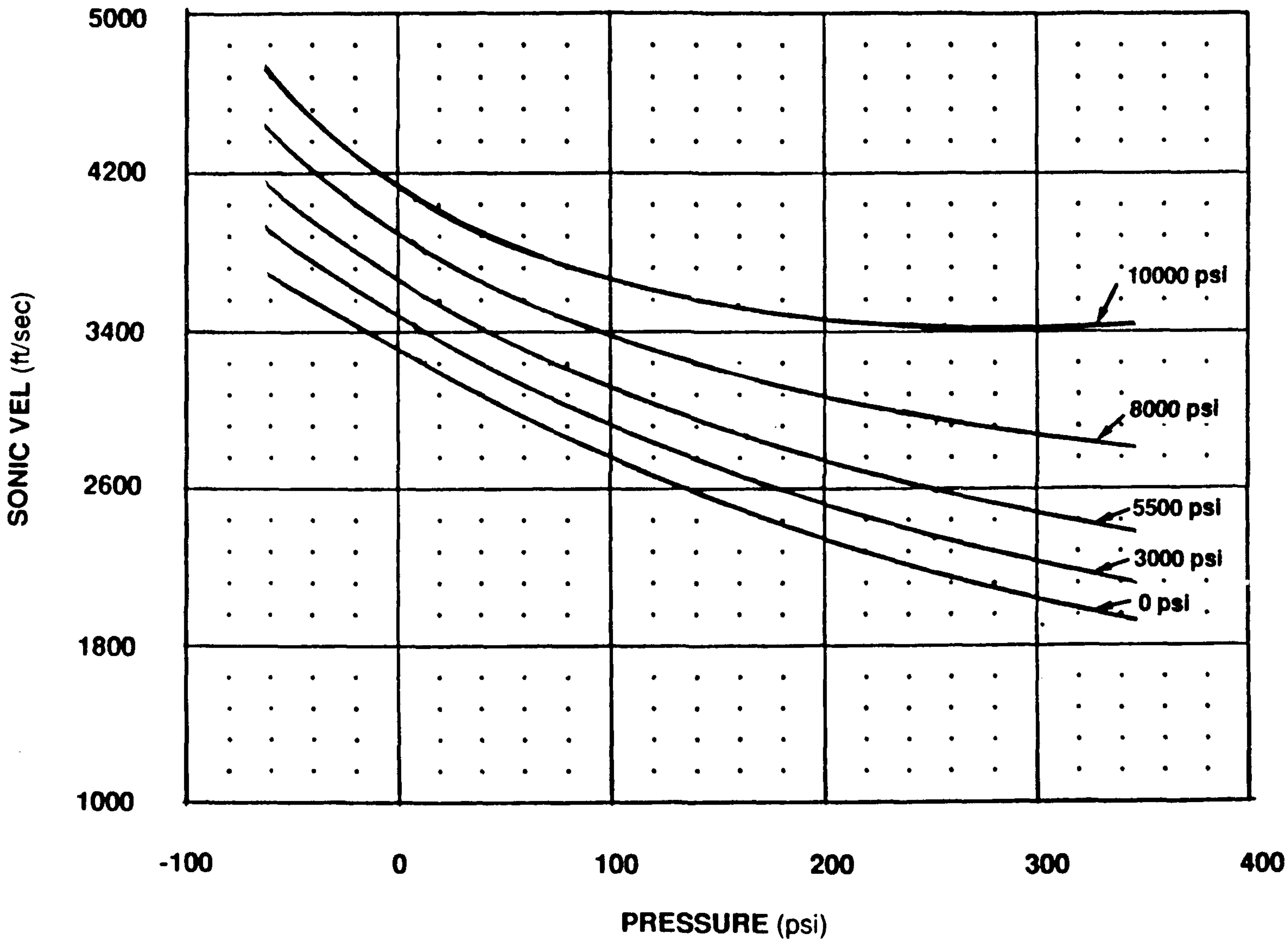
SPECIFIC HEAT vs TEMPERATURE
CTFE A02 FLUID @ CONSTANT PRESSURE




SONIC VELOCITY vs PRESSURE
CTFE AO2 FLUID @ CONSTANT TEMPERATURE
5000
4200
3400
2600
1800
1000
-100
0
100
200
300
400
-65 deg F
0 deg F
100 deg F
160 deg F
250 deg F
SONIC VEL (ft/sec)
PRESSURE (psi)

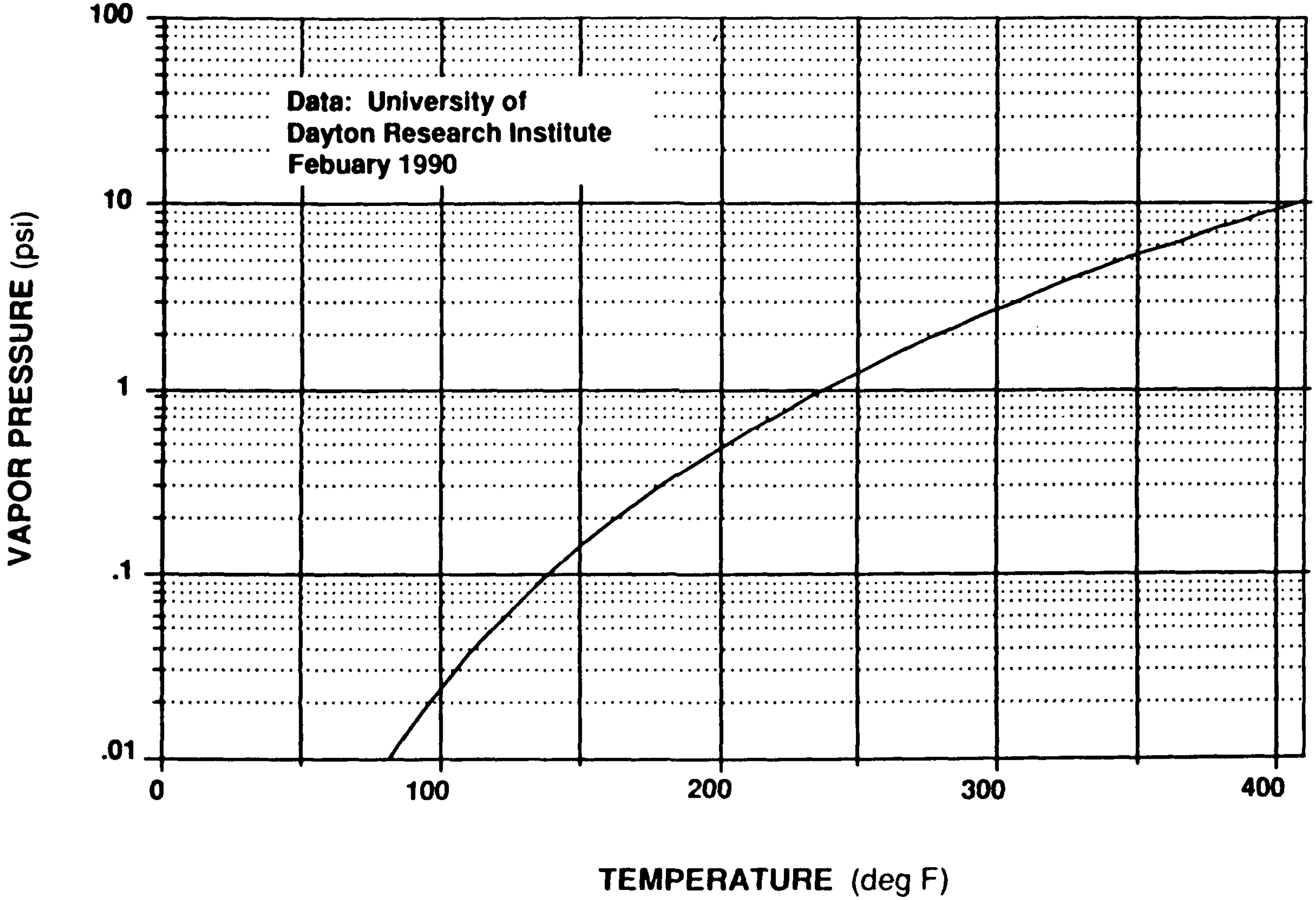
SONIC VELOCITY vs TEMPERATURE

CTFE AO2 FLUID @ CONSTANT TEMPERATURE



VAPOR PRESSURE vs TEMPERATURE

CTFE A02



APPENDIX D

FAILURE ANALYSIS

8000 PSI Endurance Test

Reliability Failure Log

FR No.	Fail Date	Failed Part	Part No.	Cum Test Time hrs	Failure Description	Failure Status	Failure Category	Remarks/Comments
FR No.	Fail Date	Failed Part	Part No.	Cum Test Time hrs	Failure Description	Failure Status	Failure Category	Remarks/Comments
1	12-12-89	L/H Nozzle AM2P shuttle valve.	3070089-101	16	Valve stopped shuttling.	Physical failure analysis in progress by Vendor.	R1	2nd failure. Test Time is ave 14 to 18
2	12-13-89	-5T Line.	?	18	Line cracked behind Ring-lock fitting.	This is 2nd failure caused by pre-test instability.	NR	
3	12-14-89	PC1 Reservoir.	3070060-101	22	*** No Failure ***	*** No Failure ***	NR	Item removed for modification by Vendor.
4	12-18-89	L/H Canard Actuator.	330400ADP-1005	50	Leaks thru rod end.	Returned to Vendor.	R2 -	
5	12-20-89	Upper L/H Nozzle control valve.	?	50?	*** No Failure ***	*** No Failure ***	NR	Switched upper and lower valves to isolate instability.
6	12-20-89	Lower L/H Nozzle control valve.	?	50?	*** No Failure ***	*** No Failure ***	NR	Switched upper and lower valves to isolate instability.
7	12-20-89	R/H Stab/Canard Actuator.	P871-136934-A	50?	Unstable, does not run with PC-2 (only)	Returned to Vendor.	NR	Item received unstable from Vendor.
8	01-03-90	L/H Rudder Control valve.	3337000	50?	High leakage.	Failure induced by test equipment.	NR	
9	01-03-90	L/H Rudder Actuator.	3337104	50?	Seal deteriorated.	Returned to Vendor.	R3	
10	01-04-90	L/H Diffuser Actuator.	10237-3001	50?	*** No Failure ***	*** No Failure ***	NR	Removed for modification.

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Enclosure 1, Pg 1 of 4

8000 PSI Endurance Test

Reliability Failure Log

FR No.	Fail Date	Failed Part	Part No.	Cum Test Time hrs	Failure Description	Failure Status	Failure Category	Remarks/Comments
11	01-09-90	O-Ring Seal.	?	58?	O-Ring Seal Deteriorated.	Suspect design flaw.	R4	
12	01-10-90	PC-1 Pump.	66120	58?	*** No Failure ***	*** No Failure ***	NR	Used pump torque sensor on UT-2 pump.
13	01-10-90	UT-2 Pump.	63149-01	58?	Leaks and would not hold pressure.	Cracked port plate.	NR	Pump is not of production configuration (40 GPM).
14	01-11-90	O-Ring Seal.	?	58?	Repeat of FR NO.11.	Repeat of FR NO.11.	Repeat R4	
15	01-13-90	O-Ring Seal.	?	58?	Repeat of FR NO.11.	Repeat of FR NO.11.	Repeat R4	
16	01-15-90	Pressure Switch.	98087-1203P0010	58?	Leaking thru blow hole.	Physical failure analysis in progress by Vendor.	R5-	
17	01-17-90	Pressure Switch.	98087-1203P0010	58?	Repeat of FR NO.16.	Repeat of FR NO.16.	Repeat R5	
18	01-18-90	UT-1 Pump.	65195	58?	Pump will not produce more than 6000 PSI.	Installed new pump.	NR	Pump is not of production configuration (40 GPM).
19	01-23-90	UT-1 Pump.	63149-01	58?	*** No Failure ***	*** No Failure ***	NR	Used pump torque sensor on PC-1 pump.
20	01-23-90	Bootstrap Accumulator.	3060012-101	58	*** No Failure ***	*** No Failure ***	NR	Item changed-out to incorporate specified design.
21	01-30-90	Actuator, lower divergent flap.	?	64.3	Suspect internal transfer tube seal failure.	Returned to MOOG for physical failure analysis.	R6	
22	02-02-90	-3T Line.	?	90	Line blew just behind fitting at intensifier inlet.	Under investigation by Test Team.	C1	
23	02-02-90	O-Ring Seal.	?	94	Repeat of FR NO.16.	Repeat of FR NO.16.	Repeat R5	

Prepared by the NAPD Supportability Team

Enclosure 1, Pg 2 of 4

8000 PSI Endurance Test

Reliability Failure Log

FR No.	Fail Date	Failed Part	Part No.	Cum Test Time hrs	Failure Description	Failure Status	Failure Category	Remarks/Comments
24	02-03-90	-3T High Pressure Hose.	?	103.7	Repeat of FR NO.22.	Repeat of FR NO.22.	Repeat C1	
25	02-05-90	-3T Line.	?	112.5	Repeat of FR NO.22.	Repeat of FR NO.22.	Repeat C1	
26	02-07-90	-3T Line.	?	135.16	Repeat of FR NO.22.	Repeat of FR NO.22.	Repeat C1	
27	02-08-90	R/H Arc Valve O-Ring	346600	136	Repeat of FR NO.11.	Repeat of FR NO.11.	Repeat R4	
28	02-08-90	UT-2 Pump.	63149-01	136	Pump Froze, Broke Shaft	Installed New Pump	NR	Pump Not Prod Configuration
29	02-08-90	UT-1 Pump.	63149-01	138	Running Hot, Making Noises	Installed New Pump	NR	Pump Not Prod Configuration
30	02-11-90	UT-1 Pump.	63149-01	155.14	Rear Shaft Seal Blown	Installed New Pump	NR	Pump Not Prod Configuration
31	02-17-90	R/H Reverser Vane O-Ring On HS Port	346500-902	174	Repeat of FR NO.16.	Repeat of FR NO.16.	Repeat R5	
32	02-22-90	UT-2 Pump.	63149-01	208.41	Making Noises	Installed New Pump	NR	Pump Not Prod Configuration
33	02-26-90	PC-2 Pump	65195	224.41	Low Pressure, Case Drain @ 4000 PSI		NR	Pump Not Prod Configuration
34	02-26-90	UT-2 Pump	66120	224.41	*** No Failure ***	*** No Failure ***	NR	Put On PC-2
35	02-26-90	R/H Arc Valve Metal C-Ring	346600-6	225.6	Deteriorated Seal		Repeat R3	
36	02-28-90	C-Ring	?	253	Repeat of FR NO.3.	Repeat of FR NO.3.	Repeat R3	Test Time Ave of 246-260
37	03-01-90	PC-1 Pump	66120	262	Will Not Go Below 6000 PSI	Switched With UT-1	NR	Pump Not Prod Configuration
38	03-01-90	UT-1 Pump.	63149-01	262	*** No Failure ***	*** No Failure ***	NR	Switched With PC-1
39	03-02-90	L/H Flaperon Actuator	MOD 33E347	277.7	Failed O-Ring and Forward Transfer Tube Bolt	Replaced	Repeat R4	

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8000 PSI Endurnce Test

Reliability Failure Log

FR No.	Fail Date	Failed Part	Part No.	Cum Test Time hrs	Failure Description	Failure Status	Failure Category	Remarks/Comments
40	03-05-90	UT-1 Pump.	63149-01	283.3	Low Pressure	Installed New Pump	NR	Pump Not Prod Configuration
41	03-05-90	L/H Rudder Actuator	3337104	283.6	Valve Leaking Blown Seal & Quill	Disconnected	Repeat R7	
42	03-05-90	L/H Rudder Control Valve.	3337008	283.6	Blown Seals Leaking Quills		* R7 *	

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Enclosure 1, Pg 4 of 4

le = Time

Enclosure (2) Pg 1 of 2

FR #	Rel FR #	Fail Time (Hrs)	Adj. Endur. Time (Hrs)	Orig Rel Fail Y/N	Cum # of Fail	Est. MTBF (Hrs)	Chi-square Distribution: Deg Of Fdm	Chi-square Distribution: 95% Prob	Chi-square Distribution: 5% Prob	Est. Limits MTBF: Lower Limit (Hrs)	Est. Limits MTBF: Upper Limit (Hrs)
1	1	16.0	48.00	Y	1	48.00	2	5.99	0.10	16.03	932.04
4	2	50.0	150.00	Y	2	75.00	4	9.49	0.71	31.61	421.94
9	3	50.0	150.00	Y	3	50.00	6	12.60	1.64	23.81	182.93
11	4	50.0	150.00	Y	4	37.50	8	15.50	2.73	19.35	109.89
14	4	50.0	150.00								
15	4	50.0	150.00								
16	5	50.0	150.00	Y	5	30.00	10	18.30	3.94	16.39	76.14
17	5	50.0	150.00								
21	6	64.3	192.90	Y	6	32.15	12	21.00	5.23	18.37	73.77
23	5	94.0	282.00								
27	4	136.0	408.00								
31	5	174.0	522.00								
35	3	225.6	676.80								
36	3	253.0	759.00								
39	4	277.7	833.10								
	7	283.6	850.80	Y	7	121.54	14	23.70	6.57	71.80	259.00
42	7	283.6	850.80								

Calculations

Adjusted Endurance Time

3 * Cum Test Time Hours

Lower and Upper Limits

2 * Adjusted Endurance Time / chi-squared value

MTBF

Adjusted Endurance Hours / Cum # of Failures

BIBLIOGRAPHY

List of Additional Papers and Reports on High Pressure Aircraft Hydraulic Systems and NonFlammable Hydraulic Fluid Systems

Hupp, R. V. and Haning, R. K., "Power Efficient Hydraulic Systems" NADC-88066-60 Rockwell International Corp. Contract N62269-85-C-0259, July 1988.

Raymond E. T., "Design Guide For Aircraft Hydraulic Systems and Components For Use With Chlorotrifluoroethylene Nonflammable Hydraulic Fluids" AFWAL-TR-80-2111 Boeing Military Airplane Co. Contract F33615-76-C-2064, March 1982.

Raymond E. T., et al, "Fire Resistant Aircraft Hydraulic Systems" AFWAL-TR-80-2112 Boeing Military Airplane Co. Contract F33615-76-C-2064, July 1982.

Alfoldy W. P., and Bonnell G. M., "Hydraulic System Performance Tests Using CTFE Hydraulic Fluid, Chlorotrifluoroethylene" Cadillac Gage Report No.88-101, Cadillac Gage Textron, February 1988.

Flippo R. V., "8000 psi Hydraulic System Seals and Material Test Program - Final Report" SAE 871895, HR Textron, October 1987.

Binns K. E., Campbell B., Wright-Patterson Air Force Base, Pierce N., Young R., McDonnell Aircraft Company, "Nonflammable Fluid and 8000 psi Technology for Future Aircraft Hydraulic Systems" SAE 851909, October 1985.

Snyder E., et al, "Nonflammable Aircraft Hydraulic Systems Development" SAE 821566, Air Force Wright Aeronautical Laboratories, October 1982.

Snyder E., et al, "Air Force Nonflammable Hydraulic System Materials Development" SAE 851908, Air Force Wright Aeronautical Laboratories and University of Dayton Research Institute, October 1985.

Kouns H., "Compatibility Test Report on 8000 psi Hydraulic Pump with A02(CTFE) Fluid" Abex Report No. AER-883, Abex Corporation, Aerospace Division, December 1983.

McDonnell Douglas Corp., 1983 Independent Research and Development Report, MDC Q0866-7, Vol. 1, Task IV - Fluid Leakage Characteristics; 26 Feb 1983.

McDonnell Douglas Corp., 1984 Independent Research and Development Report, MDC Q0871-7, Vol. 1, Task II - Application of Overlapped Control Valves, 15 Feb. 1984

McDonnell Douglas Corp., 1985 Independent Research and Development Report, MDC Q0874-7, Vol. 2, Task I - Computer Analysis Program Development; Pump - System Pulsation Attenuation; 15 Feb 1985.

McDonnell Douglas Corp., 1986 Independent Research and Development Report, MDC Q0877-7, Vol. 2, Task III - Actuator Stiffness Enhancement; 15 Feb 1986.

Harmon A., "High Technology Test Bed (HTTB)" SAE A-6 Lockheed Georgia Co., April 1987.

Greene, J. B., et al, "Low Energy Consumption Hydraulic Techniques" AFWAL-TR-88-2062 McDonnell Aircraft Co. Contract F33615-84-C-2417, August 1988.

Pierce, N. J., et al, "Flight Worthiness of Fire Resistant Hydraulic Systems" AFWAL-TR-84-2085 McDonnell Aircraft Co. Contract F33615-80-C-2074, December 1984.

Halat, "Hydraulic Pumps for High Pressure Non-Flammable Fluids" SAE 851911, Vickers Inc., October 1985.

Janczur Z. J., "High Pressure Hydraulic Seals" AFWAL-TR-89-2003 Parker Bertea Aerospace Group, Contract F33615-84-C-2416, September 1988.

McDonnell Douglas Corporation, Fluid Properties Data Manual, MDC IR 0386, 18 Dec. 1985.

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