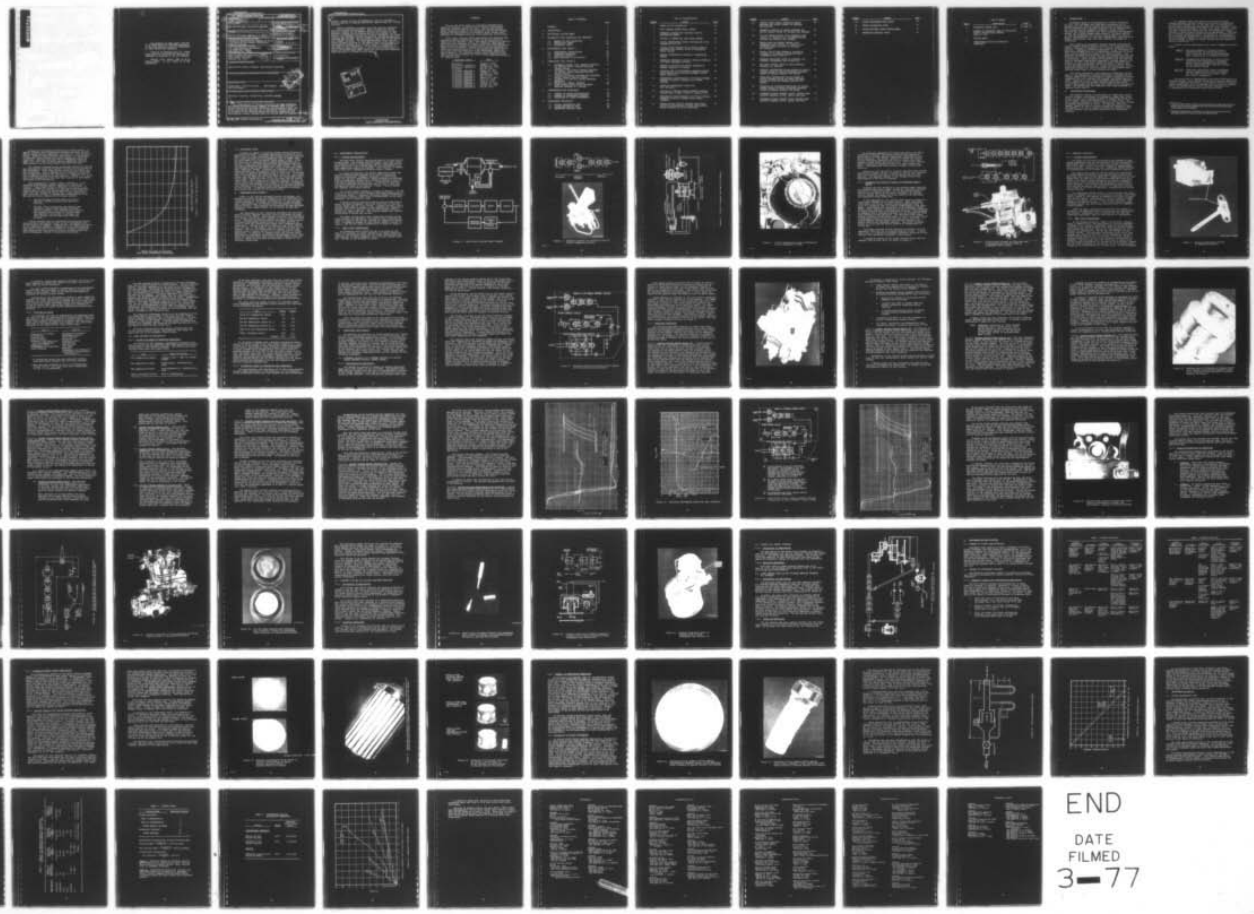
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An investigation of fluidic technology has been conducted ~~by AiResearch Manufacturing Company of Arizona~~. The initial program activities involved collecting and documenting data from early experimental applications of AiResearch fluidic controls. An analysis of the failures experienced during laboratory and experimental testing revealed that the failure mode of greatest NEXT Page

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concern, fluidic circuit contamination, did not represent a serious obstacle to seeking operational applications for fluidic controls.

Several production programs involving fluidic components were also studied and analyzed. These included the thrust reverser actuator on the General Electric CF6 engine for the McDonnell Douglas DC-10 airplane and for the European A.300B Airbus, the Lockheed S-3A ram air pressure regulator, the thrust reverser and secondary nozzle actuator for the BAC/Aerospatiale Concorde SST aircraft, and two pressure regulators on the Boeing E-3A (AWACS) aircraft. Of these applications, data from the thrust reverser actuator on the General Electric CF6 engine for the McDonnell Douglas DC-10 aircraft greatly overshadowed the remainder of the information. At the time of preparation of this report, these data showed a fluidic module reliability in excess of 600,000 hours MTBF, based on over 5,425,000 component operating hours in normal airline usage.



FOREWORD

This is the final report by AiResearch Manufacturing Company of Arizona, a Division of The Garrett Corporation, under HDL contract DAAG39-72-C-0092. The program reported herein involves a study of the reliability of fluidic devices, designed and manufactured by AiResearch, under actual field operation of aerospace vehicles, both commercial and military.

This report contains field operational data obtained from AiResearch fluidic experience during the entire period of Phase B of the contract. Also, this report contains reliability data that were collected from early AiResearch experimental applications and laboratory testing under activities defined as Phase A of the contract. Reports were issued periodically to cover the active monitoring of field operational experience as the fluidic devices moved out of the development phase into actual service. The following reports were submitted during this program which covered the period between April 11, 1972, and June 30, 1976.

AiResearch Report	Date
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AE-12213-R, Addendum 1	October 13, 1972
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73-410128, Addendum 1	August 16, 1973
73-410128, Addendum 2	November 8, 1973
73-410128, Addendum 3	February 14, 1974
73-410128, Addendum 4	May 7, 1974
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73-410128, Addendum 6	April 17, 1975
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73-410128, Addendum 8	October 30, 1975
73-410128, Addendum 9	January 20, 1976
73-410128, Addendum 10	May 14, 1976

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1. INTRODUCTION

AiResearch began an investigation of fluidic technology in 1964. This interest was stimulated principally by the anticipation that control systems using fluidic devices could provide substantially improved reliabilities, at reduced costs, for a unique line of AiResearch products. These products included gas turbine engines, air motor actuators, and pneumatic valves, all of which require some degree of intrinsic control. It also was considered that fluidic devices should be able to operate satisfactorily in very high temperatures, high vibration levels, high neutron flux, and other adverse environmental conditions.

Early efforts to synthesize control systems from discrete fluidic element modules quickly pointed up the stage-matching problem (matching of impedances) as a serious impediment to that approach. Subsequent efforts concentrated on the development of monolithic systems built up of laminations containing all necessary circuit elements and joined by a bonding process. The processes and practices resulting from this program now form the basis for all fluidic control systems designed and manufactured by AiResearch. Since no amount of laboratory work can take the place of extensive operational experience, program emphasis was shifted (in 1967) from basic technology toward designing and installing some experimental fluidic controls in actual operational environments of interest. These control devices, and the experience gained with them, constitute the experimental data reported under Phase A of this reliability study.

This early experience, plus continuing technology improvements in the laboratory, provided sufficient confidence in the fluidic capabilities thus developed to permit proposing fluidics components for use in several new aircraft and engine applications. Starting in 1969, these proposals resulted in contracts for a number of fluidic control systems applications which entered operational status during the course of this reliability study. The operational data resulting from these programs is reported under Phase B.

2. ANTICIPATED FAILURE MODES

The specific method of construction of monolithic fluidic control systems, as developed by AiResearch, makes them insensitive to some of the normal stresses of operational usage such as endurance, shock, and temperature to at least 1350F. (To date, however, AiResearch fluidic applications have been limited to maximum temperatures of 500F.) In addition, since the dynamic forces at work in fluidic devices are relatively high, as compared to the force gradients induced by vibration, most fluidic elements also are quite insensitive to vibrational stresses.

In a general sense, the nature of monolithic fluidic systems precludes the most common failure modes of mechanical or electronic systems and, at the same time, re-introduces a primary failure mode long since solved for these systems. Thus, the remaining environmental stresses (salt spray, humidity, sand and dust) constitute a major part of the spectrum of failure stresses to which fluidic devices may be susceptible. These can all be broadly classified under the heading of "contamination." The avoidance and elimination of contamination is considered to be the principal problem in the reliability of fluidic devices. This conclusion is shared by others researching the question of fluidic reliability.[1,2]

Fluidic circuit contamination has three fundamental failure modes:

Type I - Particles capable of altering circuit performance may be inadvertently built into the device during the manufacturing, test, calibration, or assembly processes.

Type II - Contamination sufficient to alter circuit performance may accumulate or aggregate within circuit passages from particles and/or condensates which can pass through the filtration system.

Type III - Sufficient particulate and/or condensate matter trapped by the filtration system may clog the filter and thereby render the circuit inoperative.

The first type of contamination noted above obviously is a factory problem. This problem can be solved through appropriate internal procedures including 1) discovering areas or locations where contaminants can be introduced into the fluidics elements during the manufacturing through assembly processes, and 2) systematically eliminating these possibilities.

---

1 NASA Report CR-61849, "Procedure For Obtaining Fluid Amplifier Reliability Data," November, 1965, J. N. Shinn, et al. Prepared for the Astrionics Laboratory, Marshall Space Flight Center, National Aeronautics and Space Administration, Huntsville, Alabama, under Contract NAS8-5408.

2 USAAVLABS Technical Report 68-36, "Fluidic Reliability," June, 1968, H. Ogren, et al. Prepared for U.S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, under Contract DAAJ02-67-C-0003.

The second and third types of contamination relate to extreme operational conditions, the characteristics of which are largely unknown at this time, and to the effectiveness and capacity of the filtration system employed. It appears that this fluidic reliability study program is the first to develop firm data concerning the quantity and quality of particulate and condensible matter that is either ingested into or generated by aircraft gas turbine engines, and the ability of filtration systems to protect against these contaminants.

In any case, the major results of these types of failures probably will be a considerable evolution of fluidic filtration systems. Improved methods of filtration should then be the principal contributor to the desired growth in reliability of fluidic devices.

3. RELIABILITY DATA COLLECTION AND REPORTING

The AiResearch system used for collecting data and information and reported in this study is described in the following paragraphs.

3.1 METHODS OF DATA COLLECTION

3.1.1 Returned Units

For the bulk of the study period of this program, all units containing fluidic controls that were returned to AiResearch were for repair under warranty coverage. To ensure a thorough engineering evaluation of all failures involving the fluidic elements, appropriate internal procedures for analysis and investigation were established at AiResearch. To the extent that this information was available, the investigation included recording of the following items: symptoms of the device prior to removal, model and serial number of the vehicle on which installed, owner or operator, end unit identification, fluidic module identification, and operating time.

3.1.2 Findings on the Nature of the Failure

The detailed engineering evaluation provided technical information concerning the condition of the unit on teardown. Photographs were made and performance characteristics were recorded, as appropriate.

3.1.3 Best Estimate(s) of Cause

Because of the monolithic construction of the fluidic elements, the true case of a failure could, in some cases, only be inferred from other data.

3.1.4 Corrective Action and Results

Failed units virtually always were found to be repairable by backflushing with solvents and/or dry air. These data could be statistically relevant to future decisions regarding local maintenance actions.

3.1.5 Statistical Treatment of Failure Data

In the statistical sense of reliability data, only two items of information are relevant: confirmed failures and operating time. Since actual data on the length of life usually cannot be obtained from the operator's records, the alternate assumption most often employed is that the failures are randomly (exponentially) distributed. Since no "infant mortality" or "wearout" modes have been identified for fluidic devices, this assumption appears to be reasonable. Therefore, the data are presented graphically as a sequential analysis,[3] which plots accumulated confirmed failures versus total operating hours. In this manner, the anticipated growth in reliability (which is the natural outcome of design changes) is continuously displayed.

3.2 RELIABILITY GROWTH

Any device that is manufactured, tested, and used under unchanging conditions over a period of time may also be expected to show no change in reliability. For most significant components in aerospace applications, however, early failures are examined for cause and the corrective action changes the reliability of the device. In these cases, a growth in reliability from an initial value to a higher level occurs over a period of time. The growth experienced, and how soon it occurs, depends on the factors listed below.

1. Severity of the consequences of failure.
2. Customer attitude toward the level of reliability being experienced.
3. Complexity and cost of the corrective action required.
4. Time required for incorporation of modifications.
5. Number of units in service.

[3] MIL-STD-781B, "Reliability Tests: Exponential Distribution," U.S. Government Printing Office.

Because of the number and diversity of these factors, it appears unlikely that a meaningful mathematical model of reliability growth can be postulated "a priori" for a new device or system. However, where available data permit, it is possible to construct growth curves from prior systems as a basis for comparison. This has been done for an AiResearch auxiliary power unit (APU) that is widely used in commercial aircraft applications, and for which careful data have been kept.

The "events" recorded during operational service of the APU were unscheduled maintenance actions reported as attributable to APU performance. Thus, they relate to, but do not define, the APU reliability. This is because the APU "mission" could have been accomplished without the necessity of completing some of the maintenance actions that were reported. However, in a broad sense, the progression of the data over a period of time shows the growth in APU reliability.

This progression is clearly shown in Figure 1, if all unscheduled maintenance actions reported are counted as "events." This example shows a reduction in event rate (or increase in MTBF) by a factor of 5 over the four-year period. Although much of this gain was accomplished in the first two years, the gain during the fourth year is also significant. This large gain in MTBF is perhaps more characteristic of an APU than of fluidic devices for two basic reasons:

1. The APU has many failure modes that can be improved, whereas fluidics have basically only one.

2. The APU, with a relatively high failure rate initially, reveals many "pattern failures" early in service. This characteristic permits the required modifications to be determined much earlier in time than if, perhaps, its early failure rate had been only one-tenth as great.

Fluidic devices, with an inherently low beginning failure rate, may take considerably longer to show improvements than the APU used as an example. Nevertheless, the example may serve as an interesting standard of comparison as the data obtained from actual field service of fluidics in aerospace operations show opportunities for improving fluidic systems reliability and the consequent effects of modification programs.

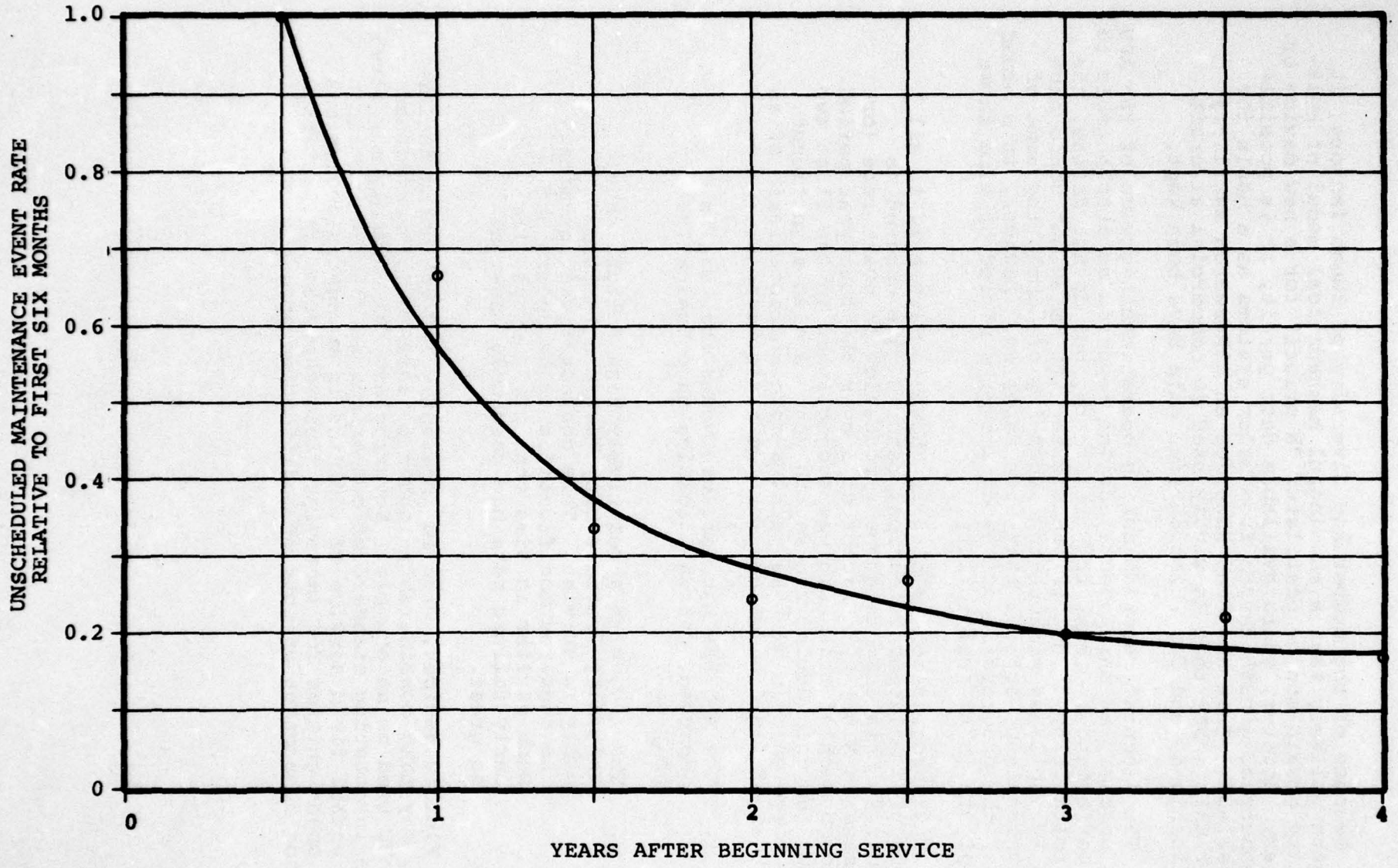


Figure 1. Growth in APU Reliability.

3.3 CONFIDENCE LIMITS

Because the number of verified fluidic system failures is expected to be small, it appears appropriate to identify confidence limits for the statistical data derived from the failures. The limits are based on the presumption that the sample data are distributed in a "chi-Square" manner about a mean. Since the mean will be changing due to design modifications over a period of time, the limits derived from accumulated data will no doubt be substantially skewed from "true" values. The best that presently may be said about the limits is that they represent "potential" values. Although any confidence level may be chosen arbitrarily, the scarcity of data appears to call for a two-sided, 80-percent confidence level at this time. This means that, on the basis of the data available, there is a ten percent change that the MTBF will be higher than the stated upper limit, and an equal probability that it will be lower than the stated lower limit. Thus, there is an 80-percent probability that the "true" value will be between the limits so defined. Because of the nature of the problem, such estimates derived from mathematical statistics have little utility except as general guidelines at this writing. As designs mature and experience lengthens, more weight may be given to this type of data.

4. EXPERIMENTAL DATA (PHASE A)

Early in the life of AiResearch fluidic technology, the predominant factor preventing acceptance of the technology as a standard design and production technique was the lack of operational experience. To answer this question, it was necessary that field experience be obtained using development or preproduction devices. This required the assistance of some equipment operators, since regular checks of the fluidic devices were necessary.

The assistance of four AiResearch customers was solicited: Delta Airlines, American Airlines, Pacific Southwest Airlines, and the U.S. Air Force. Delta agreed to monitor the performance of a fluidic control circuit installed on one of their DC-9 aircraft. American Airlines and Pacific Southwest Airlines agreed to permit experimental installations of fluidic controls on three of their gas turbine ground power carts (manufactured by AiResearch). One was a PSA unit located in San Diego, another was a PSA unit in Los Angeles, and the third was an AAL unit in Phoenix. The U.S. Air Force agreed to conduct a flight test program using a fluidic device in a C-141A aircraft in normal operations. In addition, a company-funded gas turbine engine developed for helicopter applications was equipped with an overspeed fuel shutoff valve which used a fluidic speed sensor and control. These installations are described in detail in the following subsections.

4.1 EXPERIMENTAL INSTALLATIONS

4.1.1 Airline Installations

The same basic fluidic control was used in all the airline installations. Gas turbine auxiliary power units (APUs) made by AiResearch utilize a temperature sensor to modulate the APU bleed load valve in an override mode so that permissible tailpipe temperatures cannot be exceeded. This function is customarily done with a temperature-sensing bimetal element.

For these experiments, the normal temperature sensor and control functions were replaced by a fluidic temperature-sensitive oscillator, frequency converter, and gain block. Except for the DC-9 installation, supply pressure was obtained from the compressor plenum via a 150-micron wash-by filter and a 25-micron absolute inline filter. A conventional pressure regulator controlled the supply pressure to 20±1.5 psig over the operating range of the control. Figure 2 block diagrams the complete load control system.

The fluidic sensor schematic is shown in Figure 3. It consists of an oscillator which converts the sensed temperature to a frequency signal, a frequency conversion package to generate a differential pressure output that is proportional to the input frequency, and an amplifier stage.

Although previous laboratory engine tests of this type of sensor had been successful, the first field test of this particular sensor was not in an engine. A sensor was built into a package, also shown in Figure 3, and installed on a Delta DC-9 aircraft so that it operated from the environmental control system main supply duct air. The pressure gauges were checked periodically to detect any failure.

The other airline field test evaluations involved actual engine control and operation. The sensor output operated the bleed air valve on the APU and limited the exhaust gas temperature. A schematic diagram of this control system is shown in Figure 4 and the APU engine installation is shown in Figure 5.

4.1.2 USAF C-141A Installation

An AiResearch Model GTCP85-106 APU is utilized on the USAF C-141 aircraft in ground operations to supply hydraulic, electric, and pneumatic power for all normal ground uses, and additionally, to supply pneumatic power for main engine starting. The APU is not utilized in flight.

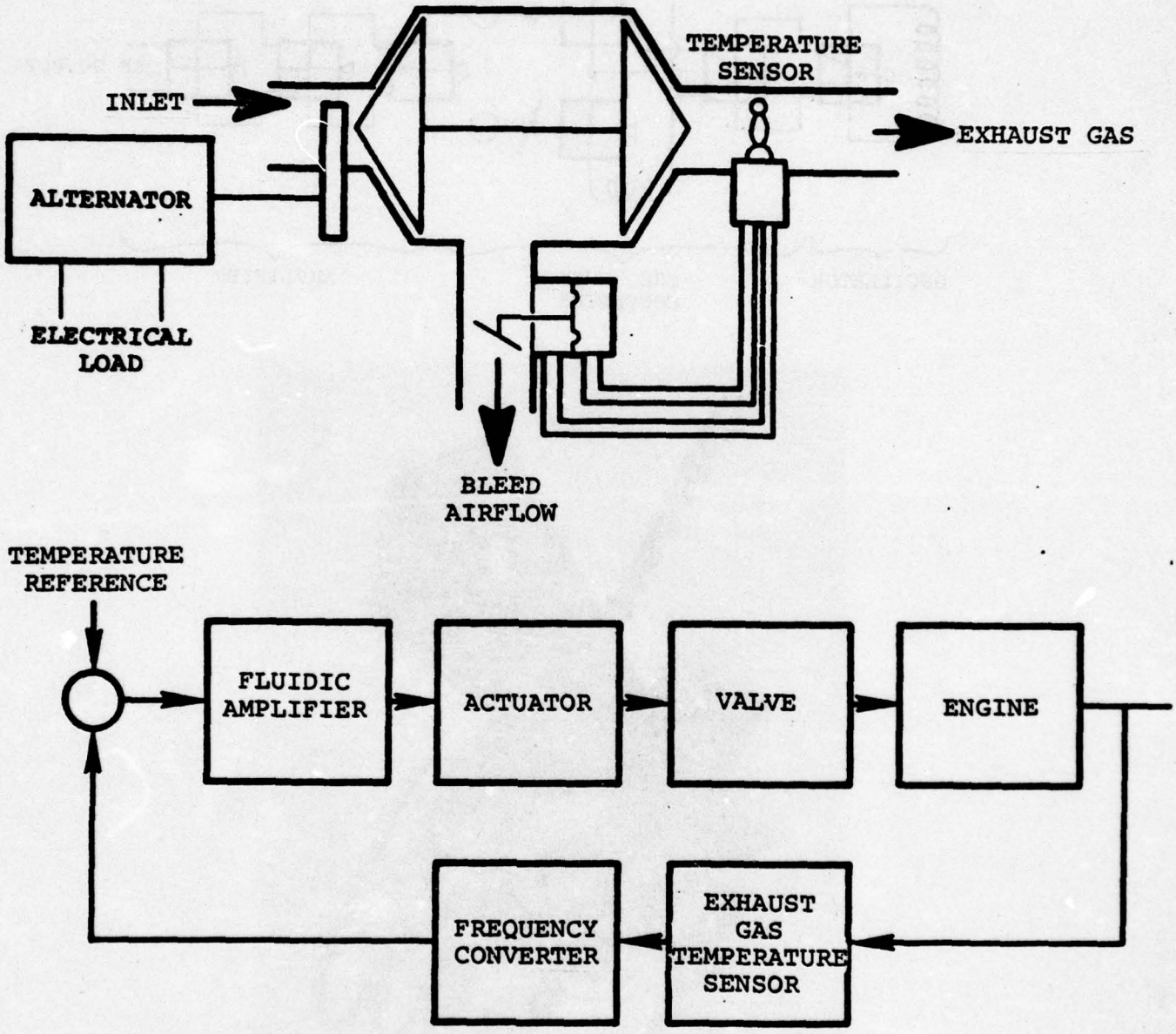
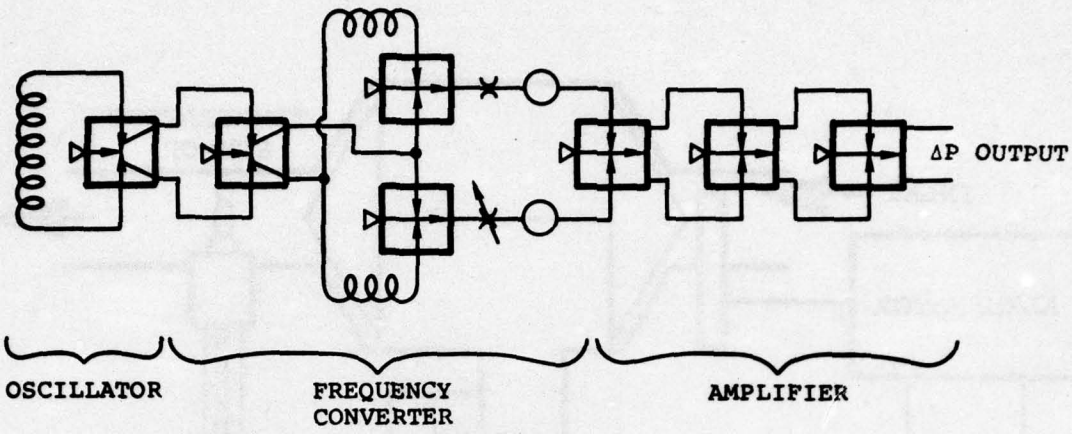


Figure 2. Load Control System Block Diagram.



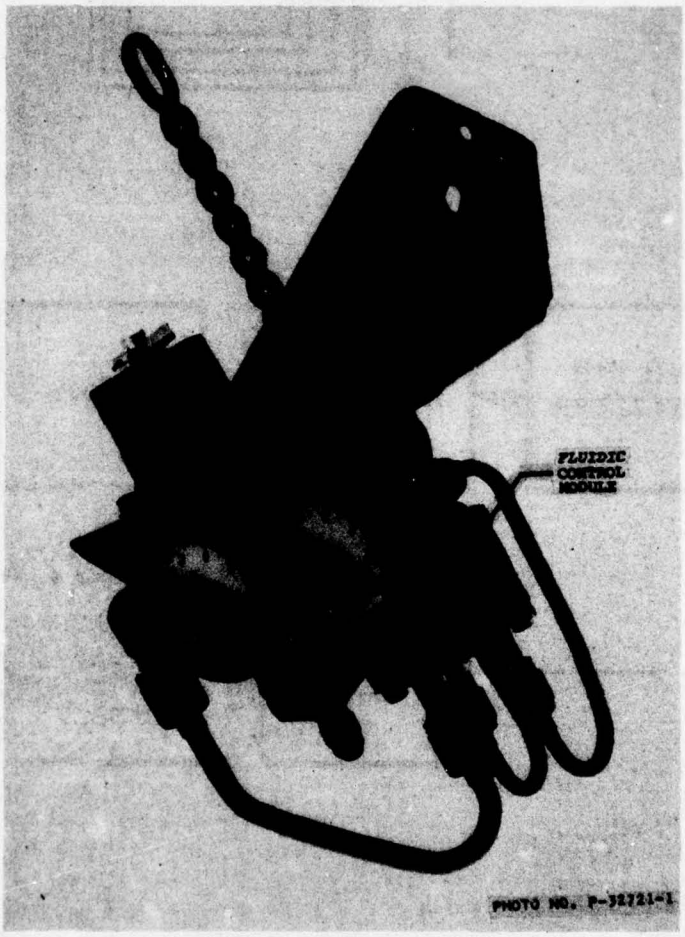


Figure 3. Schematic Diagram and Pictorial View of Fluidic Temperature Sensor.

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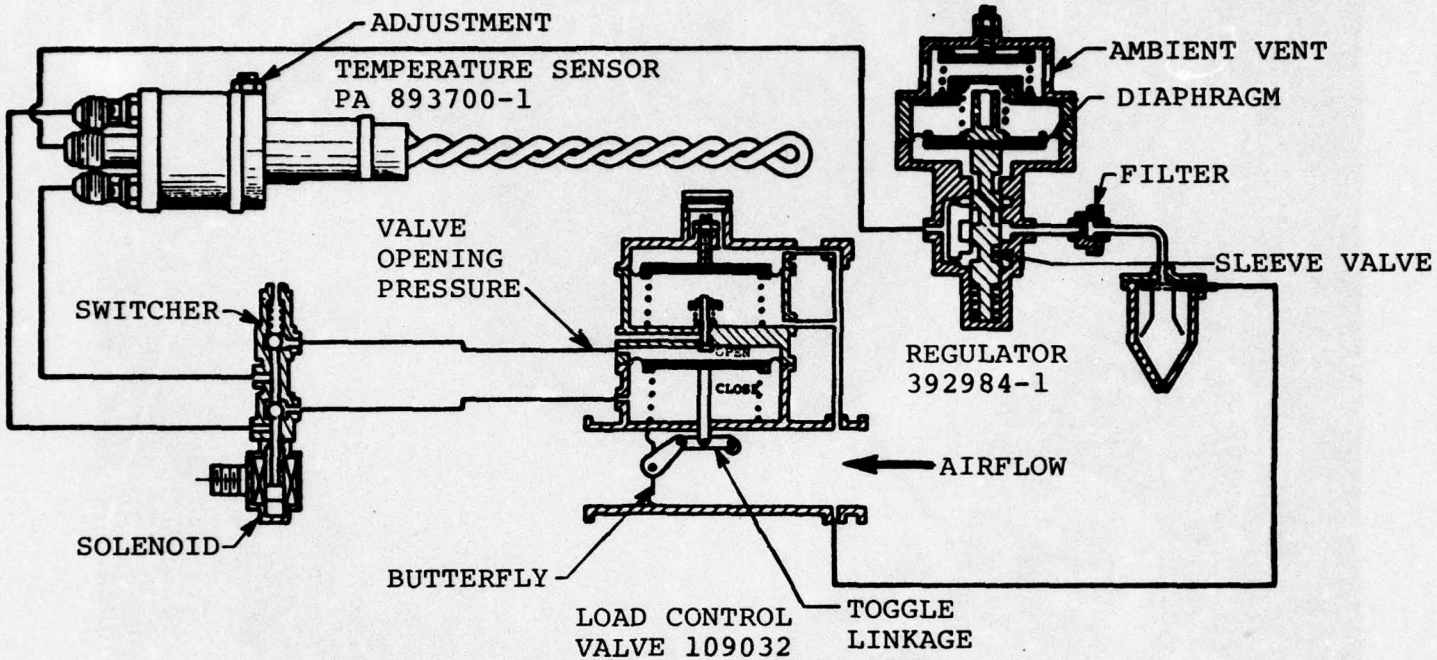


Figure 4. Fluidic T_5 Sensor and Load Valve System.

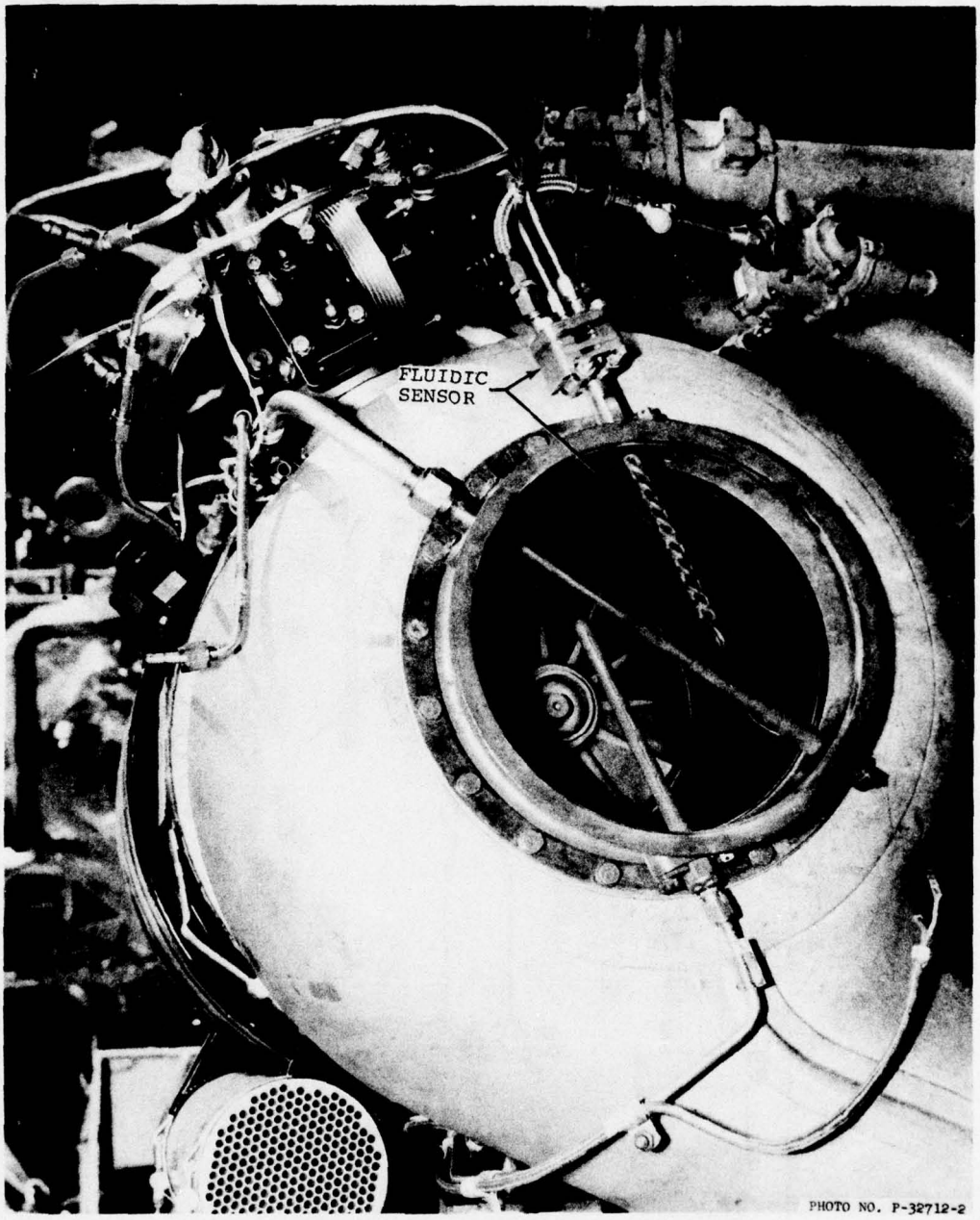


Figure 5. Fluidic Temperature Sensor Installation on an AiResearch 95-2 APU.

MP-35220

As previously described for ground cart APU's, the APU's installed on aircraft also require exhaust gas temperature monitoring to protect against inadvertent overloading during engine starting. The fluidic temperature sensor and control circuit previously described was used to replace the normal pneumatic bleed sensor and control valve. The fluidic control module contained an adjustment screw for valve closure set point. Instrumentation was provided to detect a system malfunction.

Control air for the fluidic circuits was taken from the APU discharge and passed through a separator, filter, and regulator. The in-line filter size was 10 micron nominal and 25 micron absolute. The smallest passage in the fluidic circuit was approximately 0.024 inch in diameter.

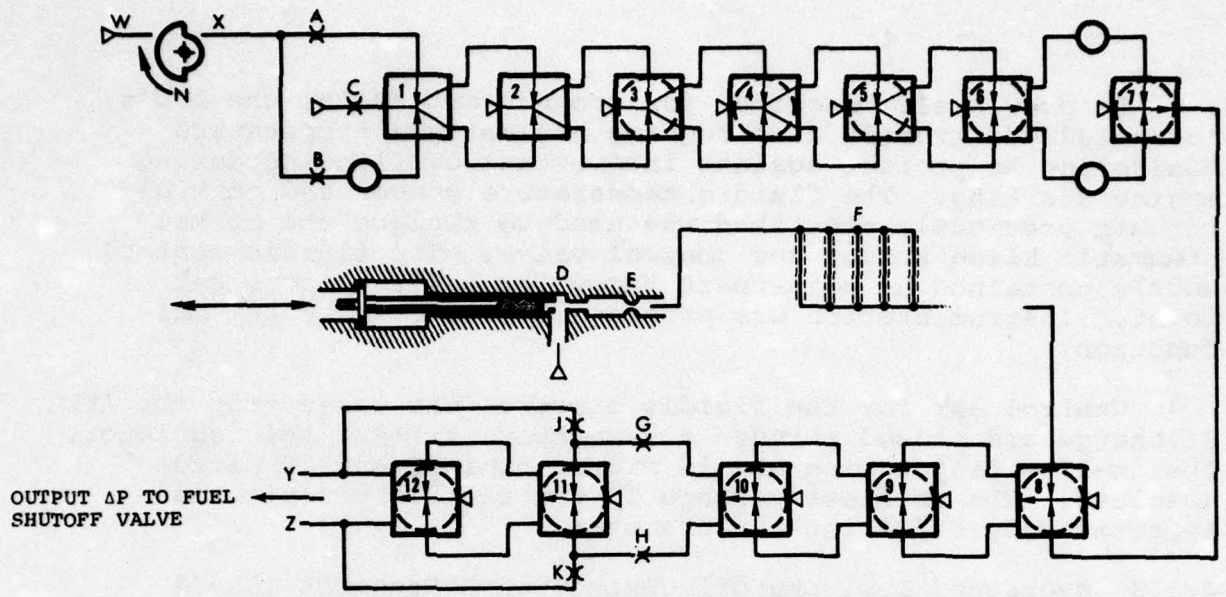
4.1.3 Overspeed Fuel Shutoff Control on AiResearch TSE231 Engine

Although the fuel control of a gas turbine engine controls to a maximum speed under normal conditions, redundant overspeed protection is usually provided. It was decided to employ a fluidic control device on the TSE231 overspeed fuel shutoff control because the sensor was to be located in an area where the temperature would reach 800F.

In this application, the turbine shaft speed is sensed by a lobed wheel attached to the power turbine. This lobed wheel interrupts a jet of air, thereby causing pneumatic pulses to occur at a frequency that is directly proportional to the shaft speed. These pulses are transmitted to an integrated fluidic package which contains a frequency-to-analog converter producing an output pressure that is proportional to speed. This pressure is compared with a reference pressure and the differential pressure obtained is then amplified. The amplified error signal drives a bistable output stage which, in turn, is applied across a diaphragm to move a valve and shut off engine fuel flow. A ground checkout feature resets the reference pressure for a ground check of the overspeed function. The actual overspeed occurs at 53,000 rpm and ground checkout is accomplished at 38,000 rpm.

The supply pressure for the fluidics is obtained from the compressor bleed air via a 25-micron absolute filter. A spool-type bleed air differential pressure regulator referenced to the fluidic vents maintains a constant 15 psid output.

A schematic diagram of the latest fluidic circuit and the complete fuel shutoff valve are shown in Figure 6.



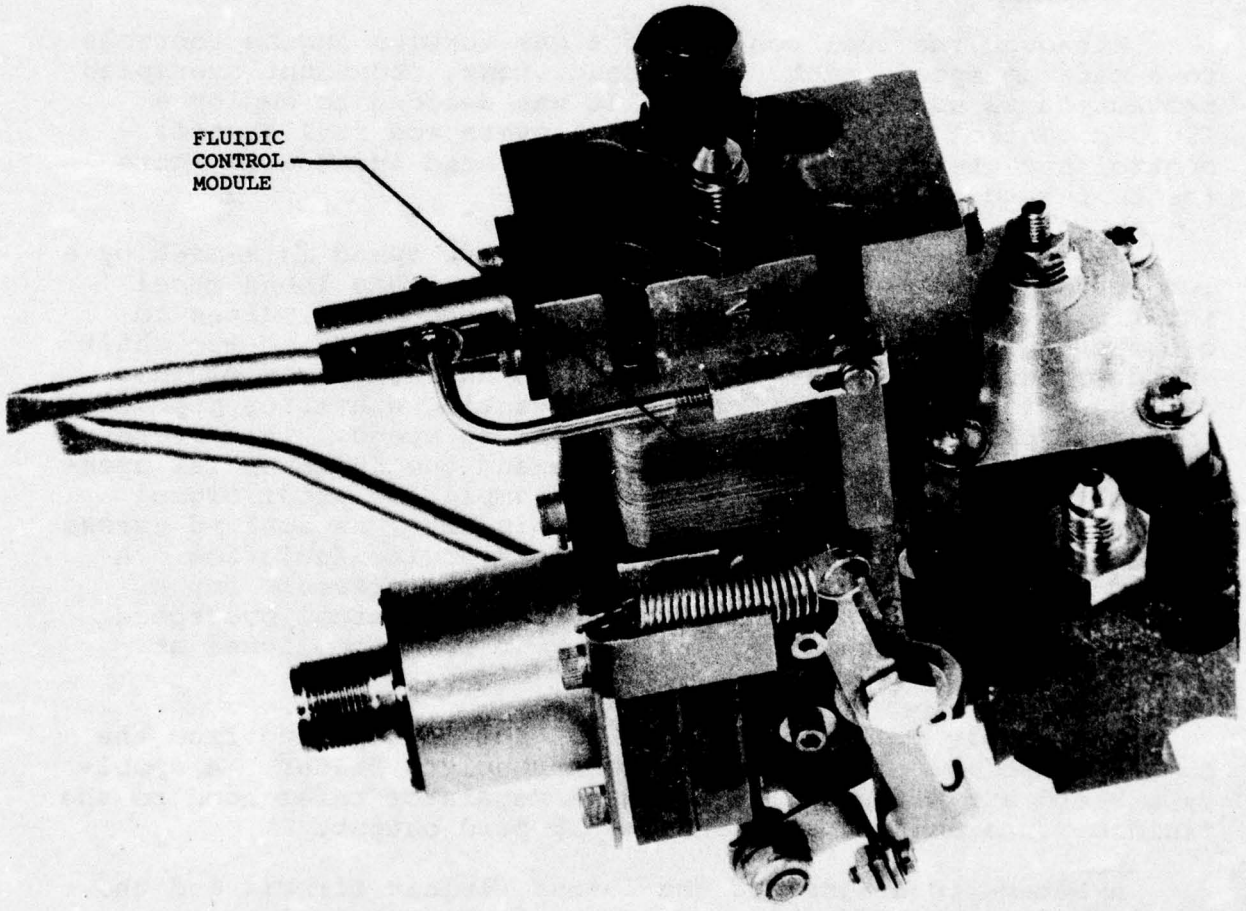


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Figure 6. Fluidic Block Diagram and Pictorial View of Overspeed Fuel Shutoff Valve on AiResearch TSE231 Engine.

MP-35221

4.2 OPERATING EXPERIENCE

4.2.1 Airline Installations

The Delta DC-9 fluidics installation was powered by main engine compressor bleed air and operated for 1600 hours without maintenance before blockage of the filter caused its removal. This filter was a coarse, wire-wound element of approximately 250-micron mesh, installed in-line. Subsequent checks revealed no deterioration of the fluidic circuits themselves, however.

The temperature sensor of the AAL ground cart APU failed in Phoenix after a period of three months which involved 230 hours and 1400 cycles of APU operation. Examination of the unit showed that the tube wall of the sensor probe was 0.004 inch thick at the failure point instead of the design thickness of 0.010 inch. Thus, the failure was established as a manufacturing problem. The fluidic circuits showed no deterioration. This unit had previously been subjected to laboratory testing for a total of 109 hours of operation, encompassing 404 cycles, without failure.

The temperature sensor of one of the PSA ground cart APU's failed in Burbank (this unit was originally located in San Diego) after a period of five months, encompassing 102 hours of operation and 447 cycles. Examination of the unit showed a delamination of the sensor due to a faulty bonding operation. This condition is shown on Figure 7. The fluidic circuits showed no deterioration, and the failure was attributed to a manufacturing problem.

After one year, involving 448 hours and 1556 cycles of operation, the remaining PSA APU installation was removed without failure. Subsequent tests indicated that the unit was completely functional, with no deterioration in performance.

4.2.2 USAF C-141 Installation

On the program involving a USAF C-141 aircraft, testing began in February 1970, and compilation of data was completed in August 1970. However, additional running time was accumulated until the end of December 1970, when the fluidic control was removed from the APU. During the test program, and until removal, no malfunction of the APU was attributable to the fluidic control. The principal discrepancy noted during this program was a shift of 50C (90F) in the temperature set point which occurred between April 10 and May 11 of 1970. After program termination, the unit was completely disassembled and examined. The set point shift was attributed to sensitivity of the variable adjustment, in conjunction with lockwire tension and the loss of preload on the jam nut of the adjustment screw caused by the deterioration of a rubber seal. It was considered

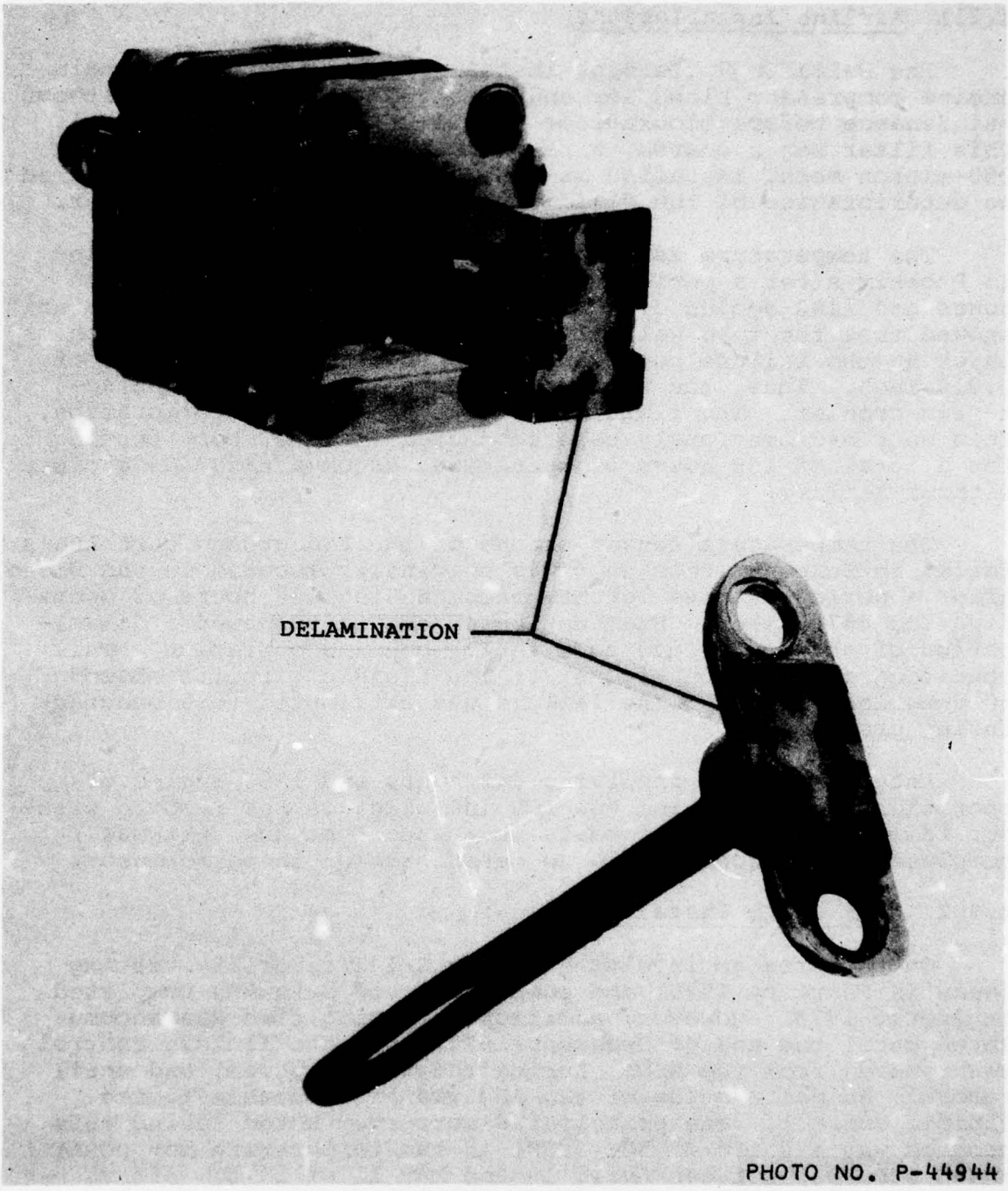


Figure 7. Bonding Delamination Failure of Temperature Sensor.

that no discernible shift in fluidic circuit characteristics other than the variable adjustment could be suspected as a basic cause of the discrepancy. Satisfactory operation of the fluidic control was logged for a total of 97.6 hours of APU time, including 364 start cycles of the APU.

4.2.3 Overspeed Fuel Shutoff Control on AiResearch TSE231 Engine

The TSE231 overspeed control accumulated only two hours of operation on a helicopter engine before it exhibited a calibration shift and was removed. Testing indicated that a particle of some undetermined material had found its way into the unit during either assembly or test operations before the unit was protected by its filtration system. Migration of the particle to a location causing a change in amplifier gain after installation on the helicopter is considered to be the only credible cause of the symptoms observed. (The circuit was subsequently redesigned to preclude the failure mode believed to be the cause of this incident.)

Prior to use in the engine installation on the helicopter, prototype and preproduction units of the fluidic control device had accumulated a total of approximately 135 hours of operation on the TSE231 engine in test cell runs without failure. Since these units were powered by normal engine bleed air, this time may be counted as experimental operational experience from a contamination standpoint.

4.3 LABORATORY TESTING

4.3.1 Type of Information Available

Considerable test time and cycles have been accumulated on fluidic devices in the various stages of development testing of new products. By its very nature, however, this kind of test experience accumulation is useless in the statistical aspects of reliability determination. Configuration changes are constantly in process and are addressed to the question of whether a system can be made to meet the basic performance requirements.

Although reliability is usually not directly considered during the development testing phase, it is during this part of the design cycle that many things are discovered that are concerned with the eventual reliability of the product. Some examples of this nature that have been discovered in development testing of fluidic devices at AiResearch are listed below.

1. The need for laboratory air supplies at least as clean as the air supply of the anticipated application.

2. The need for special handling and assembly techniques to avoid Type I (built-in) contamination.

3. Complete avoidance, if at all possible, of adjustable orifices.

Although many such items seem self-evident after their discovery, the solutions to the problems they pose seldom are.

From the viewpoint of reliability data, the only laboratory testing of possible usefulness is that derived in qualification testing. Major design features are usually frozen prior to the start of qualification testing, and it is the intent of buyer and seller alike that qualification test units be of the configuration intended for production and delivery to the user.

Under these conditions, qualification test experience may be included in the totality of reliability data. At the time of the initial report, only the qualification test results from the thrust reverser actuation system on the General Electric CF6 engine of the McDonnell Douglas DC-10 airplane and the ram air cooling pressure regulator on the Lockheed S-3A airplane had been documented. Thus, this information is included in this report as laboratory data assembled under Phase A of this contract. Subsequent qualification test results were not excerpted and reported under this contract for two reasons.

1. Phase A was a single, noncontinuous task to compile prior data.

2. Field operational experience from fluidic systems now in the field has completely dominated all other sources of data.

4.3.2 Fan Thrust Reverser Actuation System on General Electric CF6 Engine

The General Electric CF6 fan thrust reverser actuator containing the fluidic control elements was subjected to environmental certification tests in the following sequence.

Performance
Proof Pressure/Load
Humidity
Vibration
Salt Fog
Sand and Dust
Temperature

In addition, system and subsystem endurance tests were run. Three separate actuators were used in the tests, but not all tests were run on all actuators.

The test program resulted in generation of six discrepancy reports which were forwarded to General Electric during the course of the program. None of the observed discrepancies involved the fluidic control system.

Qualification test requirements involved a total number of "deploy" and "stow" cycles well in excess of 20,000. Since each direction of stroke activates and depends upon the fluidic control circuit for proper low speed control and torque limiting at end of stroke, this testing may properly be regarded as including over 40,000 total fluidic system cycles without malfunction.

4.3.3 S-3A Ram Air Valve

The Lockheed S-3A ram air augmentation and emergency shutoff valve for the air conditioning and pressurization system is controlled in the automatic mode by a fluidic module. The complete valve assembly is supplied by AiResearch and two units were used in the qualification test program. The valves were subjected to the qualification tests listed below.

Unit A	Unit B
Examination of Product	Examination of Product
Performance*	Performance Record
Pressure Loss	Proof Pressure
Proof Pressure	Vibration
Endurance (including high and low temperature)	Mechanical Shock
Temperature Shock	Acceleration
Disassembly and Inspection	Sand and Dust
Burst Pressure	Salt Spray
	Humidity
	Disassembly and Inspection
	Supplemental Torque Motor Correlation**

*A performance record test was conducted following each test except pressure loss and burst pressure.

**This test was conducted on the -2-1 configuration of Part 898524. All other tests were accomplished on the -1-1 configuration.

The test program resulted in observance of four discrepancies, two of which involved the fluidic module. During vibration testing, incorrect modulation of the valve by the fluidic control was observed. Investigation revealed partial blockage of the fluidic supply port screen by chips and lint. Proper operation was restored by cleaning the filter and supply regulator, and testing was resumed. Following completion of vibration testing, the performance test showed that the regulator output pressure was slightly above the specification limit. Examination again revealed the presence of lint and other contamination; however, the supply filter was found to be clean. After cleaning, the unit again performed satisfactorily. The nature and location of the contaminants in both cases indicated that the contaminant particles had been built into the assembly (Type I) and/or were due to improper cleaning of the valve body, and had become dislodged by the vibration test.

The remaining discrepancy occurred at the completion of the salt spray test on Unit B when it was found that the fluidic control operated improperly due to crystallized salt. The salt spray was found to have entered the module through open vent passages in the module design. A design change eliminated the exposed vent passages, and retesting verified the ability of the new design to pass the salt spray test.

The total qualification test program involved more than 10,000 valve actuation cycles, approximately 7000 cycles of which were run in the automatic control mode.

4.4 EARLY ESTIMATE OF RELIABILITY

4.4.1 Reliability Based on Operating Experience

An analysis of the foregoing experimental evaluation data covering actual service operating experience shows four failures attributable to the fluidics elements. The failures were from various causes which are listed below.

Unit	Cause of Failure
DC-9 Temperature Sensor	Clogged filter - Type III contamination
APU Temperature Sensor	Broken probe - manufacturing error
APU Temperature Sensor	Bond delamination - manufacturing error
TSE231 Overspeed Control	Type I contamination

Of the four failures, only the first one listed was clearly related to the operating environment, which was the purpose of the testing. Furthermore, the environmentally induced failure occurred on the only unit that was protected by only a single inline filter. An evaluation of the reliability of fluidic devices based on the results of these tests (using all the failures and the short time accumulated) might have indicated that fluidic technology was not yet ready for the high reliability applications of aerospace. However, closer examination of the data revealed that no state-of-the-art advances were necessary to eliminate the manufacturing problems encountered.

The total hours and number of cycles of operating experience accumulated on the various fluidic controls are indicated in the following tabulation.

Unit	Hours	Cycles
Delta DC-9 Temperature Sensor	1600	--
AAL APU Temperature Sensor	339	1804
PSA APU Temperature Sensor No. 1	102	447
PSA APU Temperature Sensor No. 2	448	1556
USAF C-141 APU Temperature Sensor	98	364
TSE231 Overspeed Control	137	--
TOTALS:	2724	4171

If it could be assumed that a properly designed and maintained filtration system could limit random clogging to a value of from 10 to 20 percent of that observed in these experimental field trials, then present fluidics systems could be expected to shown an MTBF due to contamination (the failure mode of greatest concern) of from 5500 to 240,000 hours, using 80 percent confidence limits for the single observed failure. At the time that these tests were concluded, contamination of fluidic elements from operational environments changed from that of being an unknown factor into one which appeared to be an acceptable technical and management risk for new commercial and military aerospace applications.

4.4.2 Reliability Based on Laboratory Test Experience

The qualification test experience of the CF6 thrust reverser actuator added confidence to the foregoing. If the endurance cycles encountered during that test program had been accumulated

in service, they would have represented approximately 8700 hours of operational flight time. With no failures attributable to the fluidic elements encountered during the qualification endurance testing, this operating time would reprresent a "worst case" lower limit of 5400 hours MTBF, using an 80 percent, single-sided confidence limit. (Double-sided confidence limits are not appropriate for the case of zero observed failures.)

The qualification data from the S-3A unit is somewhat ambiguous on the point of environmental contamination. Although a salt spray failure was experienced, the failure resulted in a design change and the changed design subsequently passed the test. However, as previously noted, qualification test data can provide little more than general guidance concerning the ability of fluidic systems to survive the contaminants encountered in actual operation, particularly if laboratory air is used for the fluidic power supply instead of a power supply that simulates the anticipated operational conditions.

Thus, the early data compiled in this phase of the study provided no definitive answers to the question of fluidic system reliability. It was anticipated that this question would be answered much more accurately under Phase B of this contract. Actual operational experience and the resulting reliability encountered were reported under Phase B on a continuing basis.

5. OPERATIONAL DATA (PHASE B)

The analysis and reporting of field experience with fluidic devices was a progressive task under this study contract, and covered a period of approximately four years. At the beginning of the program, only the fluidic control module for the thrust reverser actuator (air motor) for the McDonnell Douglas DC-10 aircraft (General Electric CF6 engine) was in active service, with some time also accumulated on the ram air cooling pressure regulator of the Lockheed S-3A aircraft. During the latter part of the program, the A.300B Airbus, the Concorde SST, and the Boeing E-3A aircraft became operational. These fluidic applications and AiResearch experience with them are detailed in the following paragraphs.

5.1 MCDONNELL DOUGLAS DC-10 (GENERAL ELECTRIC CF6 ENGINE) THRUST REVERSER ACTUATOR CONTROL SYSTEM

5.1.1 Description of Application

This system is required to operate at maximum deployment speed until just before the end of stroke. The actuator must then stop and proceed into the limit at approximately 4 percent of full speed, snubbing at the end of the stroke to limit the torque on the actuator. This provides the aircraft with quick

response of the thrust reverser mechanism in both directions, yet limits the end-of-stroke forces to levels acceptable from a structural impact standpoint. The actuator and its attached controls must operate in an ambient temperature range from minus 40F to plus 350F and with an air supply at a maximum temperature of 600F. Fluidic control is an obvious candidate for such an application.

During actuation, the air motor runs at full speed (approximately 25,000 rpm) for slightly over 90 percent of the actuation stroke, after which a limit switch signals the fluidic low speed control to assume control of the system. Since the actuator torque must also be limited at the end of the stroke, fluidic logic is provided to control the input to the air motor from either limiting condition. To achieve system stability and accuracy, a fluidic operational amplifier, providing lag-lead compensation, accepts the speed or torque-limiting signal and drives the mechanical servovalve which then actuates the snubbing valve and motor brake as required to maintain control.

The fluidic circuitry of the CF6 thrust reverser actuator is shown in Figure 8. The speed control function is performed by the circuit indicated on the figure. A four-bladed interrupter is mounted on the shaft of the air motor and cuts two jets of air which are positioned such that one is interrupted by the blade while the second is wide open. This results in pulses at four times shaft speed which are applied to the buffer amplifier via orifice impedances. The buffer amplifier has positive feedback paths for its output-to-input connections through orifice impedances. A second amplifier accepts the output frequency and provides a constant amplitude output for the signal regardless of the frequency.

The constant amplitude frequency passes through two volumes which are charged as the pressure increases and discharged as it decreases. The volumes have a fixed charge and discharge rate, with the charge rate greater than the discharge rate. Therefore, as the input frequency increases, the volumes retain a greater charge and the difference between the fixed amplitude of the output of the second amplifier and the charge of the volumes decreases as the frequency increases. Thus, the third amplifier has a decreasing input differential amplitude as the frequency increases. Therefore, the output swing of the third amplifier is decreased and the power jet remains for progressively greater lengths of time over the output channel. The output is therefore an increasing pressure with increasing input frequency. This output signal is applied to a summing junction where the motor torque override signal is added.

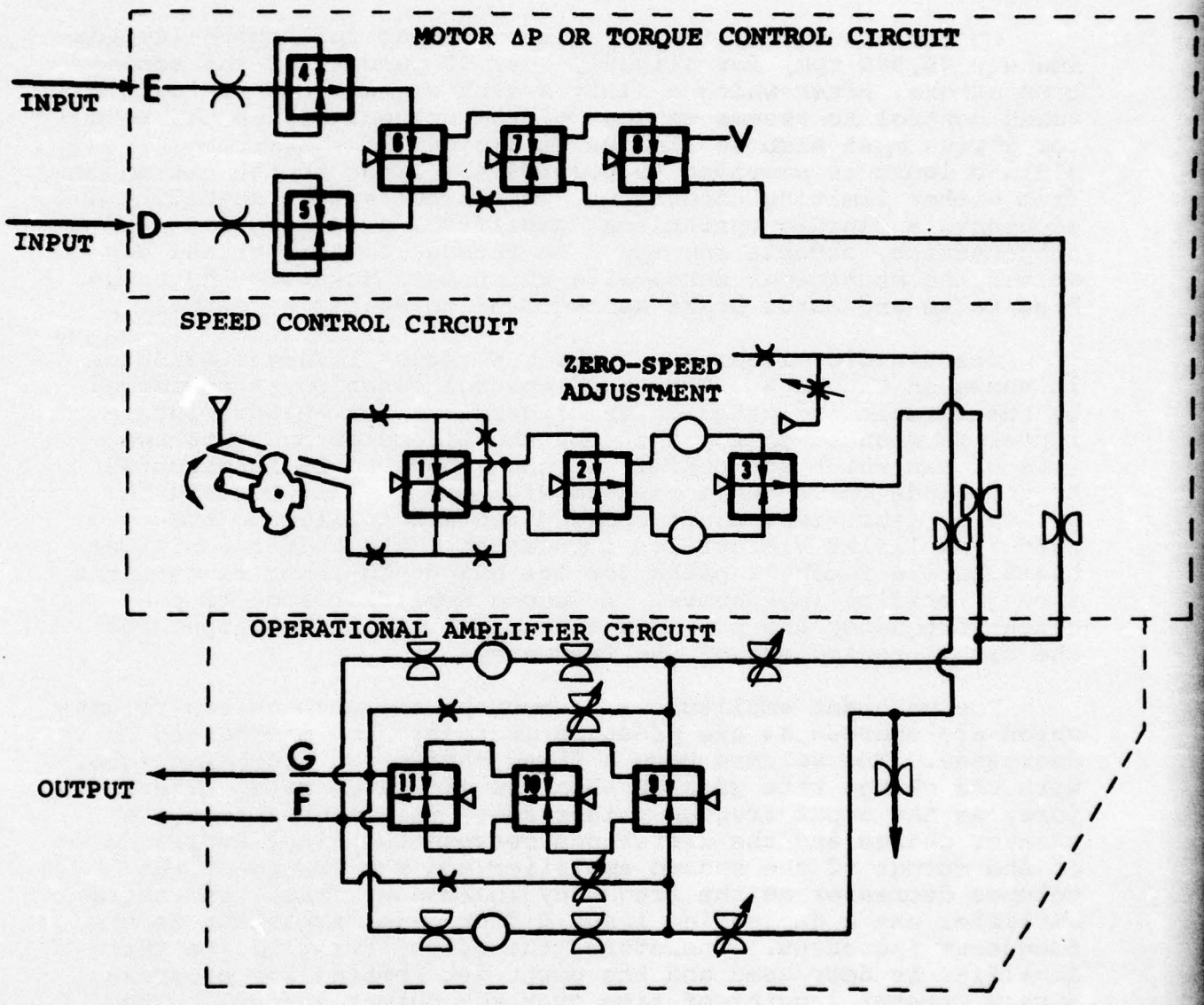


Figure 8. Schematic Dagram of Fluidic Control System on CF6 Thrust Reverser Actuator

This torque signal is derived from the motor ΔP which is sensed in the motor differential pressure or torque control circuit at input Ports E and D on the schematic diagram of Figure 8. The orifices shown are of the vortex type and consist of six chambers in each path. Amplifiers 4 and 5 are used for impedance matching and Amplifiers 6, 7, and 8 scale the signal to the desired value for addition with the speed signal.

Signal addition is achieved in capillary orifice summation circuits. Each orifice consists of a long passage. The summed signals are used as an input to the operational amplifier circuit shown in Figure 8. The input signal is scaled by the adjustable orifices which are of variable length. The operational amplifier consists of a three-stage gain block, with negative feedback via one impedance path, and positive feedback via another. Adjustment of the orifices is such that the unit has a bistable output by making the negative feedback slightly less than the positive feedback. The output at Ports F and G is transmitted to the air motor actuator servo control valve to operate the brake and snubber valve on the air motor. The complete actuator assembly is shown in Figure 9.

5.1.2 Operating Experience

The following paragraphs describe in detail the events recorded to date which are associated with the fluidic control system on the AiResearch pneumatic actuator used on the thrust reverser of the General Electric CF6 engine on the McDonnell Douglas DC-10 airplane. The following material is presented generally in the sequence in which the incidents occurred; no attempt was made to arrange the units according to the type of malfunction noted.

5.1.2.1 Fluidic Control Module Serial 104 - Fluidic Control Module Serial 104 (installed in Pneumatic Actuator Serial AEX-10003 on the first flight test aircraft) was returned intact with the air motor actuator because the motor would not operate on low speed control after the snubbing action. The malfunction was believed to be caused by an obstruction in the fluidic circuit due to ingested contamination. The circuit was submerged in solvent in an ultrasonic tank and backflushed. The fluid used for flushing was collected and an analysis was made on the contamination that was removed from the circuit. After backflushing, the circuit was retested and was found to be functioning properly. A comparison with backflushing results of some other units, including a new unit in an "as-bonded" condition, led to the conclusion that most of the contamination observed in unit Serial 104 could have been due to the manufacturing and handling practices being followed at that time. (Refer to Section 6 of this report for additional details.)

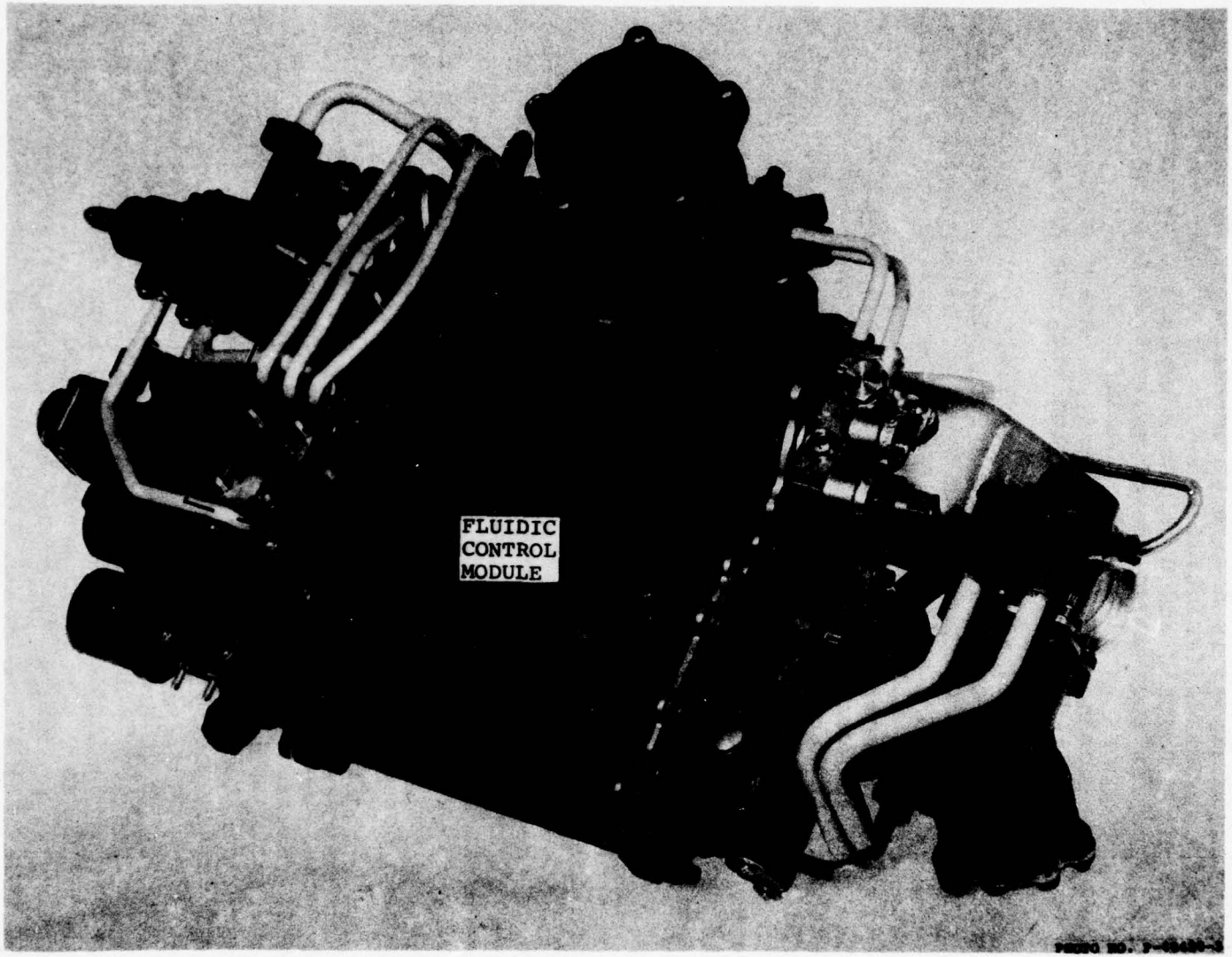


Figure 9. Pneumatic Actuator for Thrust Reverser on General Electric CF6 Engine (AiResearch Part 126366-1-1).

To prevent a recurrence of these problems, the following corrective measures were taken.

1. "Last Chance" screens were added to the circuit to reduce the possibility of entrance of contamination into the circuit after assembly.

2. Handling procedures during assembly were modified to prevent building contamination into the circuit.

   a. More strict control of cleanliness during assembly was instituted.

   b. Circuits were kept in plastic bags and special protective containers during handling.

   c. A furnace enclosure was built to prevent furnace-induced contamination during bonding.

3. Filtration was added to the test equipment to prevent contamination during testing.

4. All detail laminations and subassemblies were cleaned and stored in plastic bags prior to use.

5.1.2.2 Fluidic Control Module Serial 271 - The complete air motor (Pneumatic Actuator Serial AEX-10108) was returned by United Airlines because the unit was shearing flexible drive shafts. The air motor and control circuit were contaminated with dirt and dust. The fluidic control circuit was removed, examined, and placed on a test stand. Excessive oil and dirt were noted in the circuit. Considerable dirt and other contamination was present on all the screens covering the openings. When tested, the output of the circuit was far below normal limits. When the intermediate second stage "drop-in" screen on the inlet to the circuit was removed, the circuit output saturation increased to near normal limits. The fluidic supply pressure regulator was sticking and the regulator was unstable and oscillated at high inlet pressures.

Malfunction of the fluidic circuit was attributed to excessive oil and dirt contamination which plugged the circuit input screens.

A design change had been previously initiated to substantially increase this filter area. No further action was initiated as a result of this failure.

5.1.2.3 Fluidic Control Module Serial 272 - The air motor with this fluidic control circuit (Pneumatic Actuator Serial AEX-10109) was returned from the customer with extreme external sand and dust contamination. The drive unit assembly was tested and it was found that the air motor would operate at high speed but would not operate at low speed on the fluidic control. The fluidic supply pressure regulator was checked and found to be functioning properly. The pressure supply tube was removed and the circuit "drop-in" screen was checked. The screen was replaced with a new clean one and the unit was retested. Operation of the unit was very nearly normal. The low speed set point was slightly low, which could be attributed to factors other than the contamination. To insure that the clogged screen was causing the problem, it was re-installed in the circuit and retested. The test results were essentially the same as the initial test run, thus verifying the conclusion that the clogged screen was causing the malfunction. The particles appeared to have a tendency to adhere to the screen and to each other.

A design change had been previously initiated to substantially increase the area of the filter. No further action was initiated as a result of this failure.

NOTE: Subsequent evaluation of filter systems determined that a coarse screen filter may be plugged by fine particles due to electrostatic charging of the particles as they pass through an upstream depth-media filter.

5.1.2.4 Fluidic Control Module Serial 242 - The unit (Pneumatic Actuator Serial AEX-10093) was removed from a National Airlines DC-10, Serial 62, and returned for repair of a broken mounting lug and other external damage. The unit was noted to be exceptionally dirty, both externally and internally. A calibration check showed that the speed set point for the fluidic circuit was out of limits on the low side. Examination of the unit disclosed substantial plugging of the filter in the motor downstream pressure sensing port by carbonaceous-type particles. Similar material plus metal chips were found on the secondary filter screen in the air supply line. Detailed testing of the fluidic circuit showed that the vent pressure was approximately 0.5 psi higher than the original calibration. However, removal of all filter screens had no discernible effect on this pressure, nor did a subsequent backflushing with Dowclene under a pressure of 40 psi. The adjustment screws were then removed and the variable orifices examined. No contamination was found. The unit was recalibrated and returned to service.

Although significant evidence of contamination was present on the filter screens, internal contamination of the fluidic circuit is an unlikely candidate for the cause of this discrepancy since removal of the screens, plus a solvent high pressure flush, failed to change the circuit characteristics. The most likely cause is considered to be a shift in the set point of the supply regulator due to contamination.

A source of regulated fluid pressure is necessary for every fluidic system. However, since the required regulated pressure is often available due to other system requirements, it is not necessarily appropriate to charge a failure of the regulator against the fluidic portion of the system. In fact, on the basis of current practice in reliability apportionment at AiResearch, a regulator is considered as separate and distinct from the fluidic circuit it supplies even if that is its only function. Inasmuch as the primary purpose of this study is to establish the susceptibility of fluidic circuits to contamination failures, and since the shift in regulation set point was so slight that it would have gone unnoticed in routine operations, this event has not been counted as a confirmed fluidic failure. However, failures such as this one, which are attributable to peripheral elements of the fluidic system, will continue to be reported in this study.

It is of interest to note that the original regulator design incorporated in this unit was subsequently changed to reduce its susceptibility to contamination-induced "stiction".

5.1.2.5 Fluidic Control Module Serial 439 - The complete actuator (Pneumatic Actuator Serial AEX-10233) was removed from a National Airlines DC-10 as inoperative in the low-speed mode. Disassembly of the unit revealed a small aluminum chip lodged between the poppet and seat of the differential pressure relief valve. This valve creates a bias pressure in the differential pressure control circuit. The effect of this failure mode is shutdown of the actuator so that low-speed operation cannot occur. Careful examination of the components revealed that the chip had been shaved from the relief valve inlet port by misaligned installation of the steel inlet pressure line. This probably occurred during a previous field modification of the unit. Thus, the failure was attributed to mishandling, and cannot be counted as a verified failure of the fluidic circuit. A photograph of the chip is shown in Figure 10.

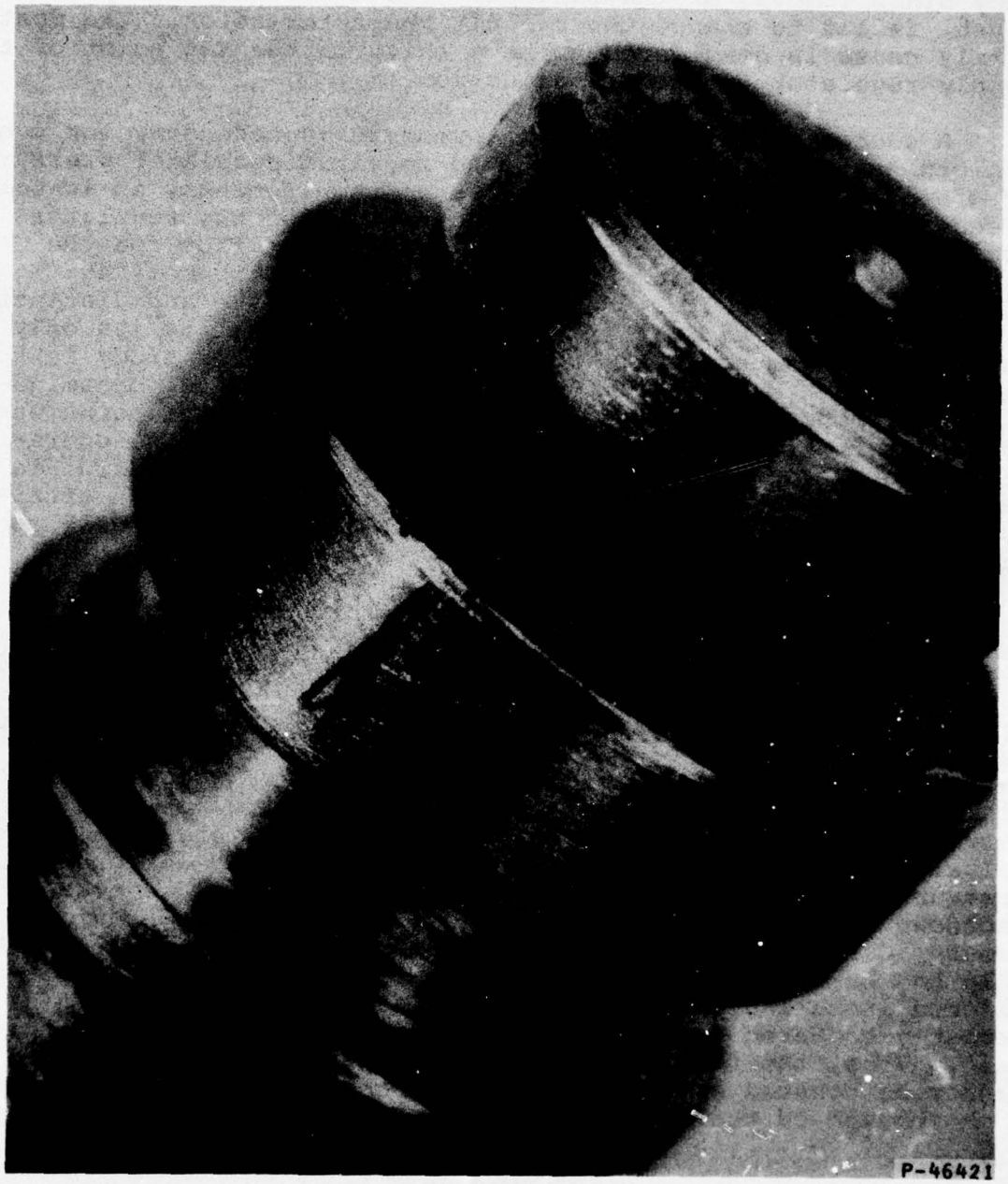


Figure 10. Aluminum Chip in Differential Pressure Relief Valve Removed From Actuator Assembly 126366, Serial AEX-10233, Thrust Reverser on General Electric CF6 Engine.

5.1.2.6 Fluidic Control Modules Serials 140, 171, 161, and 177 - Four actuators returned as inoperative proved to have clogged inlet filters. All of the units were from American Airlines, indicating the possibility of some unique element of their DC-10 operations. A check of the pressure drop across the four inlet filters showed their condition as indicated in the following tabulation.

Pneumatic Actuator Serial Number	Filter Obstruction percent	Fluidic Control Module Serial Number
AEX-10027	99	140
AEX-10039	94	171
AEX-10043	92	161
AEX-10045	96	177

In each case, the fluidic module was removed and checked separately. The fluidic modules of all four actuators were within specified performance limits in the "as-received" condition.

In this particular application, a progressive deterioration in supply pressure will incapacitate the actuator before the fluidic controls become inoperative. Although the fluidic circuit will operate with pressures down to about 5 psig, the brake on the actuator motor will not release below about 6 to 8 psig. However, the inlet filter failure mode counts as Type III contamination. (Refer to Section 2 for classification of failure types.)

5.1.2.7 Fluidic Control Module Serial 175 - The actuator (Pneumatic Actuator Serial 10047) was removed from a DC-10 airplane, Serial 008, at the Long Beach plant of McDonnell Douglas. Investigation disclosed a marked shift in the characteristics of the fluidic module due to some form of internal contamination. As received, the unit had a low set point on speed and high hysteresis. Although the speed calibration was reset, the hysteresis remained and the performance characteristics of the unit were not very repeatable. Backflushing made some change in the circuit characteristics; however, the unit still exhibited evidence of internal contamination. A final attempt was made to remove this contamination by placing the unit in the bonding furnace and subjecting it to a formal

bonding temperature cycle under vacuum conditions. This treatment solved the problem, and the unit was successfully recalibrated and returned to service.

After all the evidence was evaluated, it was concluded that the most likely source of this contaminant was a loose particle of material that was generated in the original bonding operation and became attached to two or more adjacent laminates. The particle evidently broke loose from its original location sometime after initial calibration and test of the unit. Consequently, a change in bonding procedures was initiated to preclude further difficulty from this inferred source.

5.1.2.8 Fluidic Control Module Serial P-238 - This actuator (Pneumatic Actuator Serial AEX-10013) was returned from General Electric because of instability. The unit had been used in a test program at General Electric and therefore was not subjected to the operational environment of an airline. Tests of the actuator at AiResearch confirmed the instability. It was found that the instability vanished when the fluidic module adjustments were changed to reduce the low speed set point to approximately 10 percent. The fluidic module was cleaned, modified to the latest configuration, recalibrated, and reinstalled on the actuator. However, retesting of the actuator showed it to be unstable again due to the loss of the speed chopper signal. Retest of the fluidic module showed that the vent pressure was intermittent in the range of 1.2 to 3.6 psi. The normal vent pressure is 1.2 to 1.3 psi. This indicated the presence of a particle in the vent nozzle inside the module. The module was recleaned in an ultrasonic solvent bath and backflushed through the vents. Further attempts to calibrate the module indicated that, although the particle was no longer in the same location, it was still present in the module; therefore, it was decided to scrap the module.

Subsequent tests of this actuator with a new fluidic module revealed that the initial instability was due to a faulty servovalve, and not to the fluidics. Therefore, it has been concluded that the loose particle was probably a small ball of metal formed in the bonding process which became dislodged from a laminate during the ultrasonic cleaning process. The possible formation of such particles was discovered early in the production program (refer to paragraph 5.1.2.7 above), and changes in materials and processes were implemented to eliminate this possibility. The module in question was manufactured prior to these changes.

On the basis of the foregoing analysis, this event was considered to be due to Type I contamination.

5.1.2.9 Fluidic Control Module Serial 148 - The actuator (Pneumatic Actuator Serial AEX-10029) was returned to AiResearch by American Airlines. The fluidic module was found to be low in speed set point (500 rpm instead of an original value of 1100 rpm) and low in ΔP set point (16 psi instead of an original value of 27 psi for the supply input). Ultrasonic cleaning and backflushing had no effect on these characteristics. The needle valves for adjustment of these two set points were removed and examined. No evidence of internal contamination was found on the valve needles. On re-installation of the needles, it was found that the module could be calibrated to nearly within its original characteristics. However, since the fluidic module was an early design which could not meet present test requirements, the module was scrapped and a new unit installed on the actuator.

5.1.2.10 Fluidic Control Module Serials P-229, P-511, P-232, P-720, and P-164 - Several DC-10 thrust reverser actuators were returned for repair because they had been subjected to extreme overtemperature conditions. In each case, the probable cause of the incident was failure of the upstream shutoff valve in the open position, thereby allowing a continuous bleed of high temperature compressor air into the actuator during maximum power operation. The normal temperature of the actuator is less than 350F, whereas the overtemperature units may have experienced temperatures ranging up to 700F. The resulting degradation of elastomeric materials used in the design caused failure of the actuators. It is interesting to note, however, that the failure mode resulting from these overtemperature conditions was somewhat gradual, as opposed to an abrupt cessation of operation. These incidents were not counted as fluidics failures since the primary cause of failure was exposure to temperature in excess of the design limits.

As a result of the overtemperature damage noted above, the actuators were largely scrapped. The fluidic modules of all the actuators were removed and inspected. Some of the modules could not be tested because of excessive damage. The test results of those units tested are discussed in the following paragraphs.

(a) Fluidics Control Module P-227 - The external appearance of this unit showed metallic discoloration from the high temperature experienced. It was also assumed that the O-ring seals used in mounting the fluidic module on its base plate were no longer effective as sealing elements.

When installed on the test bench, the unit operated with a speed control point of about one-half of the normal setting. Although other control parameters were also degraded, the unit

would have provided satisfactory control functions to the actuator if the actuator had been operable. After replacing the O-ring seals, it was found that the unit could be recalibrated to within required limits. This module was not returned to service.

(b) Fluidic Control Module P-511 - This unit was similar in external appearance to the unit described above. During testing, the unit was found to be low in gain and integration rate. With the module in the condition as removed, it probably would not have provided satisfactory control for the actuator. After cleaning and replacement of the seals, it was found that the module could be recalibrated to the required limits. This module was not returned to service.

(c) Fluidic Control Module P-232 - The external appearance of this module showed metallic discoloration from the high temperature experienced. It was also assumed that the O-ring seals used in mounting the fluidic module on its base plate were no longer effective as sealing elements.

When installed on the test bench, the module operated with an excessively wide hysteresis band. The nominal speed set point was high at approximately 1800 rpm. The diaphragms in the pressure regulator and all of the O-rings in the unit were brittle because of the overtemperature. The reason for the wide hysteresis band and associated increase in speed set point was determined to be loss of the negative feedback signal in the operational amplifier. The loss of signal was due to leakage past an O-ring as a result of loss of elasticity in the O-ring.

(d) Fluidic Control Modules P-720 and P-164 - Both of these fluidic modules showed external evidence of exposure to overtemperature conditions. Elastomeric materials in the units were badly degraded. One of the units (P-164) used a mechanical pressure regulator of an earlier configuration and was found to be in the poorest condition due to regulator malfunction. However, both units exhibited the same basic problem, namely, excessive width of the hysteresis band caused by the imbalance of positive and negative feedback around the operational amplifier. Leakage from the elastomeric

seals in the negative feedback path were the cause of this problem. The units were subsequently repaired and returned to service. Repair of the units consisted of replacement of all elastomeric materials and cleaning with solvent.

5.1.2.11 Fluidic Control Modules Serials P-291 and P-256 - Two fluidic controllers were returned for inspection following failure. The first controller was involved in a failure which occurred immediately upon installation in the aircraft. The second controller experienced a gradual degrading of performance until the unit would not meet specified requirements during operation. These incidents are discussed in the following paragraphs.

The first unit (Serial P-291) was originally returned to AiResearch for update modification and repair. At this time, the fluidic circuit was disassembled and cleaned, although it was still functioning properly. The unit was then recalibrated, tested, and returned to service. The actuator was functioning properly at the time of shipment from AiResearch. However, upon installation at National Airlines, the unit was found to be inoperative. Upon return of the unit to AiResearch, the failure was attributed to the fluidics elements. The fluidic circuit was backflushed with solvent; however, only a minor amount of background particles was collected. Performance of the unit was unchanged.

Further analysis of the test data indicated that the problem was due to contamination in the positive feedback orifices of the lag-lead circuit. Due to the small area of these orifices, removal of particles with simple flushing and ultrasonic vibration is extremely difficult. Therefore, the unit was subjected to high pressure (3000 psig) air. This again did not remove the contamination. Flushing and ultrasonic cleaning were again attemped; however, the contamination was still present and the unit could not be recalibrated. Analysis of the assembly showed that there was only one possible source for this type of contamination of the circuit. Contamination of this type could occur either during or after the cleaning operation that is performed on all circuits returned to AiResearch. Failure of this unit was therefore considered to be due to a factory operation (Type I failure).

The second fluidic circuit failure also occurred with a modified and repaired unit (Serial P-256). After modification, the unit was returned to the airline and had been in service for approximately 200 hours. The mode of failure involved a depression of the speed set point to a value of 300 rpm. At this time, operation of the unit became so sluggish that the unit appeared to have experienced total failure on the aircraft.

Investigation of the fluidics circuit supported the findings of both operation on the aircraft and laboratory test data on the actuator. The speed set point adjustment needle valve was removed; however, no evidence of contamination was found. The unit was then flushed and a small but insignificant amount of material was obtained from within the unit. After further test, the unit showed no change in the performance characteristics. Further ultrasonic cleaning and flushing made no difference in the operation of the unit.

When the needle valve was reset to a slightly further open position, the unit was immediately capable of being recalibrated to its original, as-shipped condition. During this operation, it was noted that the adjustment was more sensitive than it should have been as compared to the general production run of units. No valid reason (such as dimensional tolerances, stackup, etc.) could be found for this performance. There was a possibility that the adjustment could have moved in service even though it was checked and found to be locked tight upon receipt of the unit at AiResearch.

This left the conclusion regarding the cause of the failure open to the possibilities of either mechanical failure or contamination failure, neither of which could be totally substantiated. However, the failure was classified as due to contamination during service (Type II failure).

5.1.2.12 Fluidic Control Module Serial P-554 - During one reporting period, a total of 48 units were returned from the airlines due to suspected malfunction of the pneumatic motor-driven actuator. Of these 48 units, 27 were overheated due to a system malfunction. A test of the fluidic assembly of all of these units was not possible due to damage of the elastomeric materials contained in the assembly. All of these units were subsequently cleaned and refurbished for return to service with the refurbished actuators. The remaining 21 units were subjected to testing, with six units exhibiting some form of minor malfunction. Although none of the units were inoperable, all would have affected actuator performance to some degree. Of these six units, five were analyzed and found to contain oil from the actuator. Further examination of the air motors revealed that the seals had failed within the actuator, thus allowing the lubricating oil from the actuator to seep into the area of the speed pulse generator. The oil was then ingested into the signal ports to the fluidics, and then into the fluidics circuits. These five units, therefore, were classed as secondary failures and were not counted.

The sixth unit had suffered a severe primary performance degradation in service. This unit, Serial P-554, was returned by Continental Airlines. Test of the air motor actuator showed that the speed of the actuator was excessive under deploying conditions and slow under retracting conditions. Upon removal of the fluidic package from the actuator, no oil or dust was noted at the interface. The fluidic circuit was subjected to tests with the performance characteristics shown in the traces of Figure 11. For comparison, the specified characteristics are shown in Figure 12. As evident by the traces, hysteresis bands (or hitches) caused by latching of this airflow in the amplifiers occurred. This is most apparent on the transient gain curves, but is also indicated on the steady-state speed traces as an indecisiveness of set point around the center of the operating range. Another effect is that of decreased gain on the steady-state curve. Since both the motor differential pressure and gain curves show this characteristic, the degradation of performance occurred in the common output operational amplifier portion of the circuit. Figure 13 shows the circuit diagram and indicates the area where the problem occurred. The suspected condition of failure was therefore contamination buildup on the control points or splitters of one of the amplifiers.

The circuit was then cleaned. The cleaning process involved removal of the pressure regulator and volume tank assembly. The adjustment orifices were not touched. The unit was then immersed in Triethane solvent in the ultrasonic cleaner for 10 minutes with a 90-degree rotation of the unit every minute. This was followed by a high pressure solvent flush and another three minutes of ultrasonic cleaning. The unit was then reassembled and retested. The results are shown on Figure 14. Although there was some degree of improvement, the unit was considered to be permanently contaminated. Analysis of the residual in the solvent used for flushing showed no large quantities or sizes of particles, thus confirming that the particulate matter was still within the unit.

It should be noted that the failure of this unit was not catastrophic in nature. The failure represented only a decline in performance.

5.1.2.13 United Airlines Maintenance Centers Records - During the reporting period which ended on May 30, 1975, arrangements were made with the United Airlines Maintenance Center to record all data for the CF6/DC-10 fluidic controls returned for any reason. United Airlines presently has a contract with most of the major airline operators in the country for maintenance of these units.

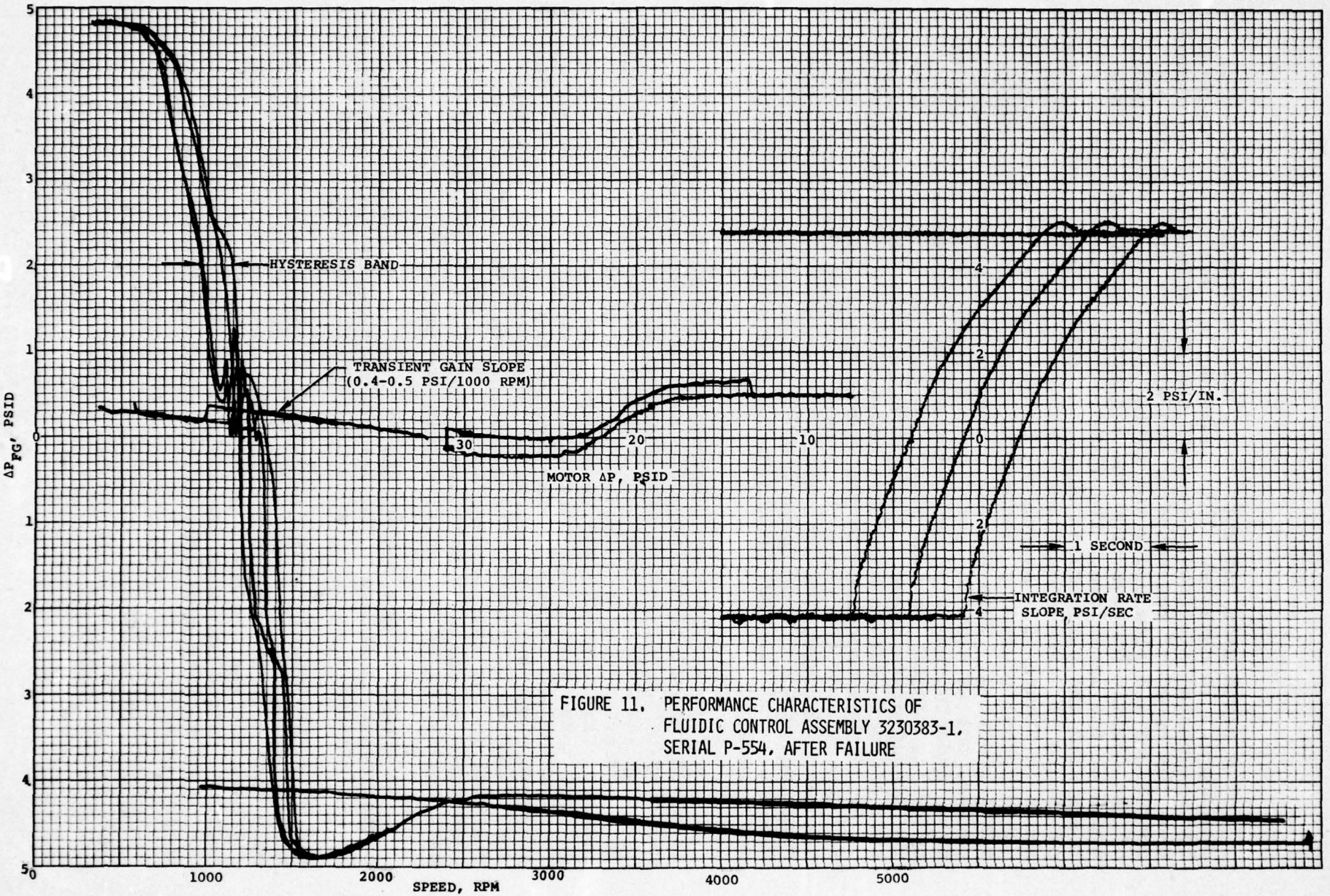


FIGURE 11. PERFORMANCE CHARACTERISTICS OF FLUIDIC CONTROL ASSEMBLY 3230383-1, SERIAL P-554, AFTER FAILURE

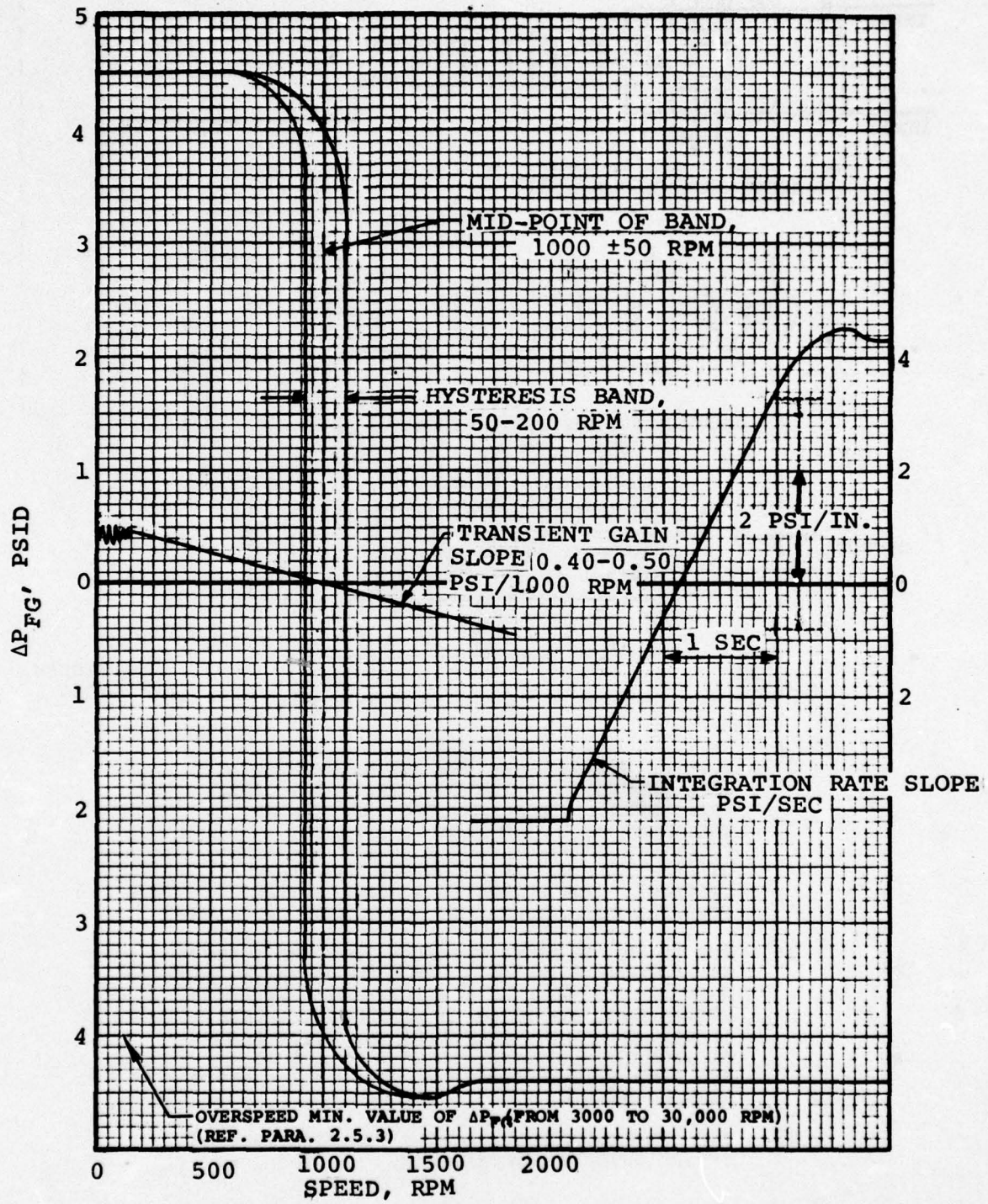
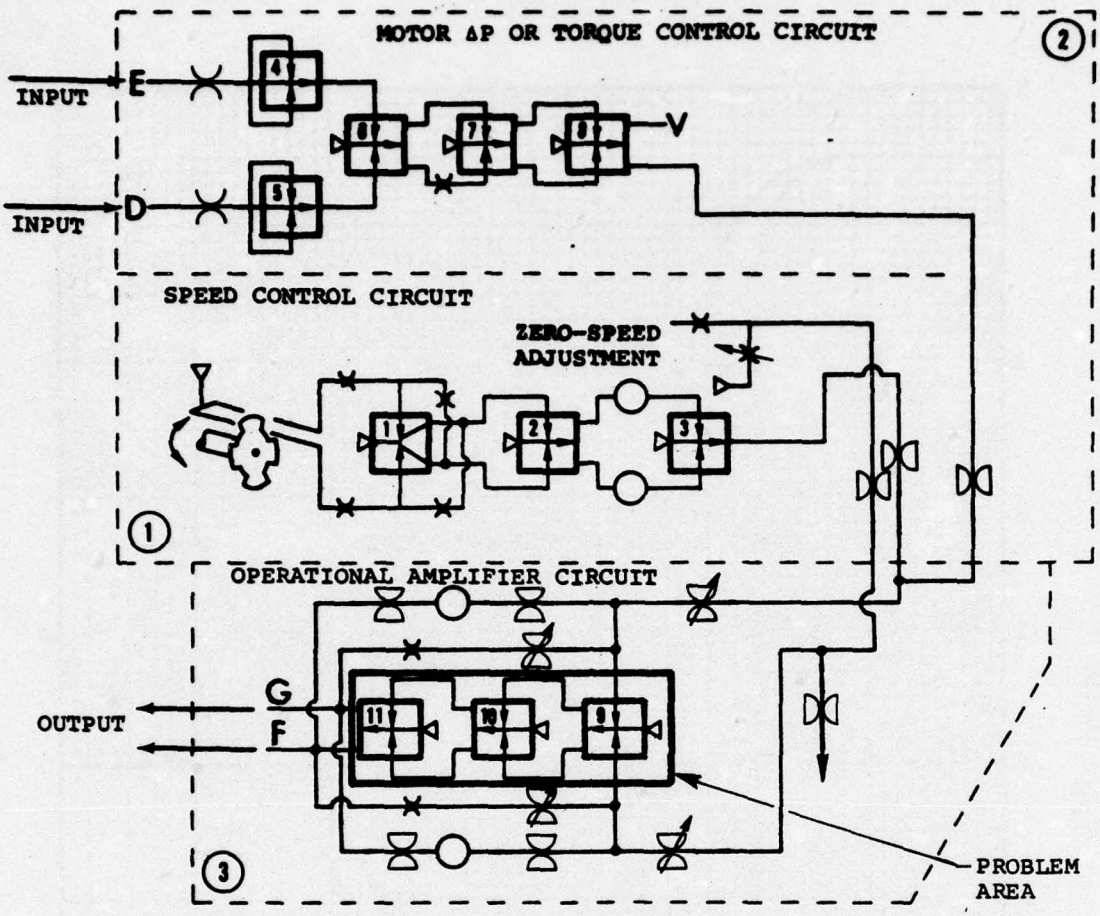


Figure 12. Specified Performance Limits for Part 3230383-1.



① A PULSE GENERATOR OF THE JET INTERRUPTER TYPE PROVIDES A PULSE FREQUENCY AT 4 TIMES SHAFT SPEED. THIS FREQUENCY IS USED AS THE INPUT TO A FREQUENCY-TO-PRESSURE CONVERTER CONSISTING OF A BUFFER AMPLIFIER, DISCRIMINATION, RECTIFICATION AND FILTER CIRCUITS. THE OUTPUT IS A DIFFERENTIAL PRESSURE PROPORTIONAL TO MOTOR RPM.

② THE ΔP SENSOR ACCEPTS INPUTS FROM THE INLET AND OUTLET OF THE GEAR MOTOR TO GENERATE A SIGNAL TO OVERRIDE THE LOW-SPEED CONVERTER SIGNAL WHEN THE MOTOR IS STATIONARY. THIS LIMITS THE TORQUE OUTPUT OF THE MOTOR TO PROVIDE THE NECESSARY LOADING OF THRUST REVERSER INTO THE AIRCRAFT STRUCTURE WITHOUT CAUSING DAMAGE.

③ THE COMPENSATION AND OUTPUT CIRCUITS PROVIDE SYSTEM DYNAMIC COMPENSATION.

Figure 13. CF6 Fluidic Control System Schematic Showing Problem Area in Part 3230383-1, Serial P-554

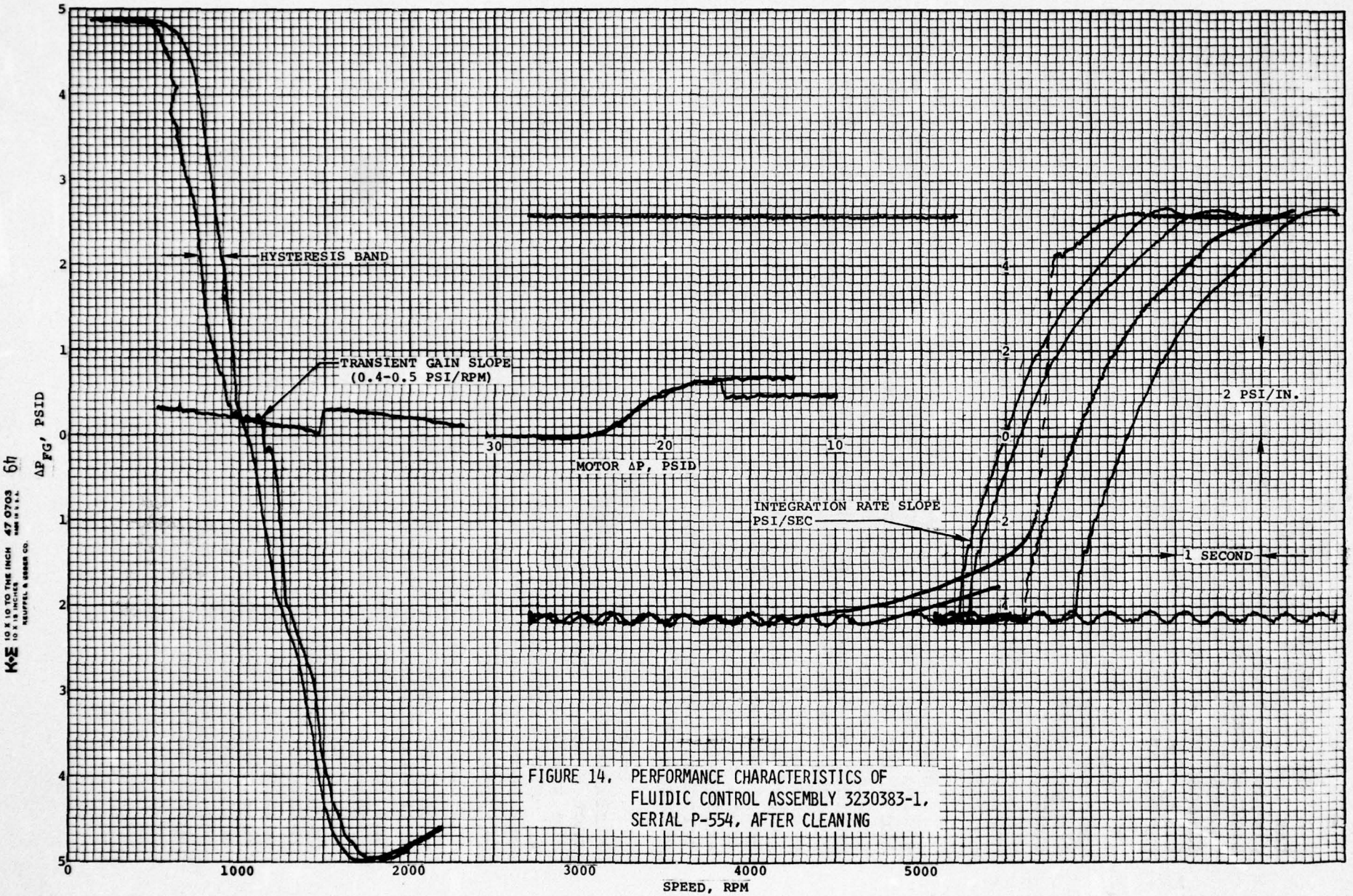


FIGURE 14. PERFORMANCE CHARACTERISTICS OF FLUIDIC CONTROL ASSEMBLY 3230383-1, SERIAL P-554, AFTER CLEANING

Of the units returned from the field since that time, by far the largest number of actual malfunctions were traced to plugged filters. On the first confirmed fluidic failure investigated under this new arrangement, detailed data was not recorded of the actual cause of failure. The failed unit was cleaned by backflushing and then returned to service. At this time, the decision was made to return all fluidic circuits suspected of failure to AiResearch for detailed evaluation.

One of the failed fluidic circuits was returned from American Airlines via the United Airlines Maintenance Center. The photograph on Figure 15 shows the last chance screen on the supply port of the circuit. This screen was totally plugged with contaminant. Removal of the contaminant from the screen corrected the failed condition and returned the fluidic control to full working condition.

Analysis of the contaminant showed that the particles were silica (sand) which had passed through the main filters. Metallic chips and a small trace of hydrocarbons were also found. A similar failure had occurred earlier, apparently due to the buildup of silica on the drop-in screen of a circuit. This buildup was surmised as being caused by an electrostatic charging of the silica particles which subsequently were collected by the screen. Consultation with filter manufacturers has revealed the validity of this analysis. The two upstream depth media filters used to clean the supply air act as electron strippers when the small micron and submicron particles pass through, thereby providing the source of the electrostatic charged particles.

In another instance, two units were returned by the United Airlines Maintenance Center for failure to operate at the correct speed. The first unit examined showed excessive spread in the speed-operating point with the load varied. Air leakage was detected between the laminations and machined ports. The bond was found to be defective and leakage paths which caused the failure developed during operation of the unit.

The second returned unit had operated at very low speed with a minimum limit speed below 400 rpm. Examination of the unit disclosed that the lockwire on the speed adjustment orifice was loose. The unit was pressure flushed and ultrasonically cleaned in solvent to confirm that this was the cause of failure. No change in the performance characteristics was noted. Upon readjustment of the speed set point orifice, the unit returned to the original calibration limits. During the recalibration, it was observed that this particular unit was more sensitive to the adjustment needle position than the average unit, which confirmed that the small amount of movement due to the looseness of the lockwire was a probable cause for the low speed operation of the unit.

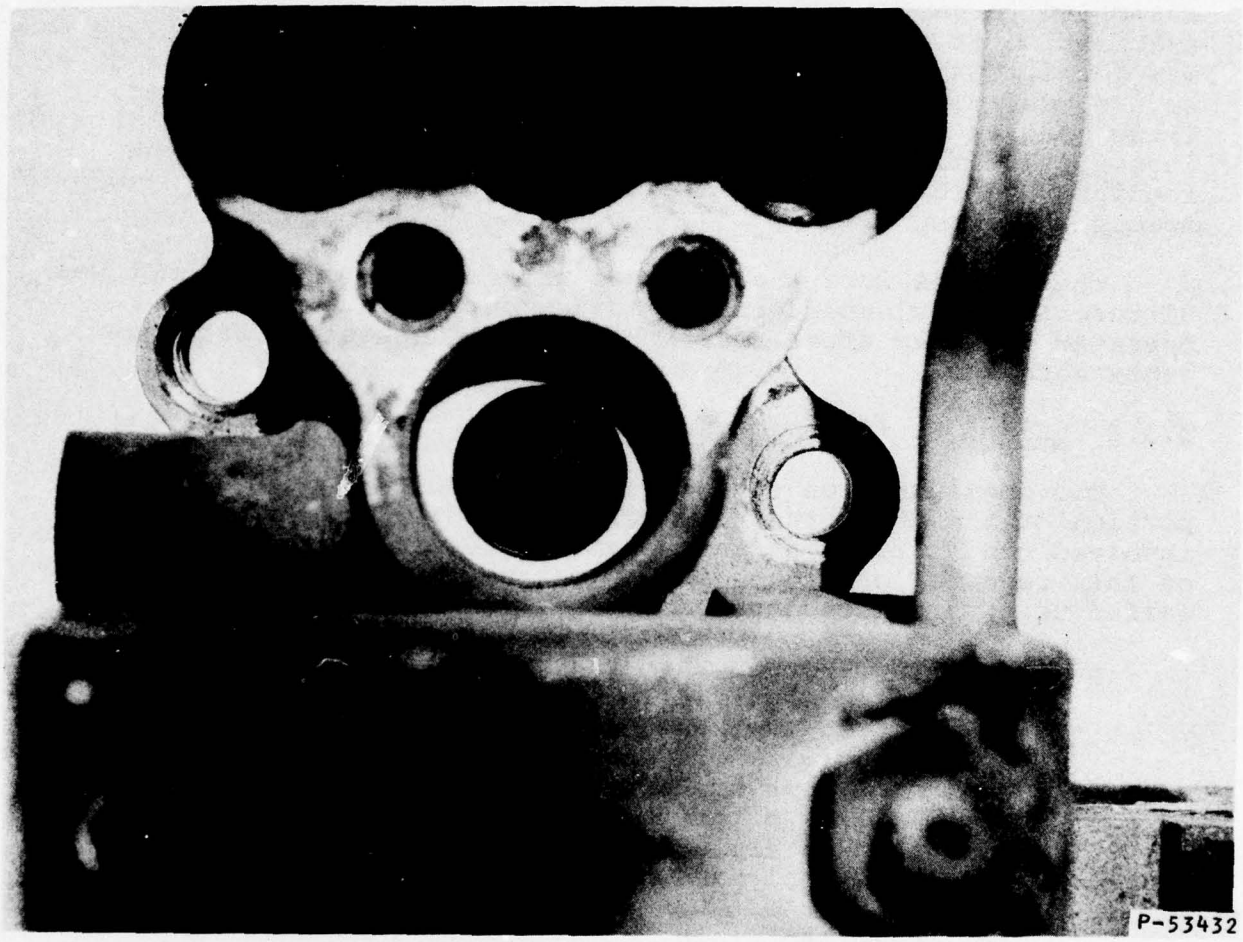


Figure 15. Failed Fluidic Circuit Returned from Field Depicting Contamination Caused From Electrostatic Charging of Silica Particles.

P-51756

One fluidic control unit was returned from the AiResearch maintenance facility. This unit (Serial P-460 from Actuator Serial AEX-10799) was completely inoperative in that the recorded vent pressure was excessively high and the supply pressure could not be regulated. The unit was partially disassembled to remove all parts made from rubber and to permit examination of the regulator. However, no evidence of failure was found. Examination of the fluidic vent nozzles disclosed severe contamination due to oil and other particulate matter. These nozzles were found to be plugged to such an extent that insufficient flow was obtained through the unit to allow the regulator to reach the required differential operating pressure across the circuit.

The nozzles were then flushed with solvent and the unit was ultrasonically cleaned with no adjustments made. The unit operated normally after reassembly and all operating requirements were met.

5.1.3 Unique Configuration or Conditions

Two configuration changes were instituted in the fluidic portion of the CF6 thrust reverser actuator. Both of them involved the filtration system and are described in Section 6 of this report. Other conditions unique to the first three failed units are listed below.

- Cleaning - Other than the normal cleaning operations involved in photoetching and bonding the circuit laminations, no special cleaning operations were originally specified for this control. However, experience has shown the desirability of performing a backflushing operation on all units with a solvent after module assembly and bonding operations have been completed. None of the units which have failed in the field thus far were subjected to this cleaning procedure.

- Assembly - No special precautions were taken in Serial 104. Serial 271 was assembled in a controlled clean area. Serial 272 was assembled in the same clean area, and was bonded in a special furnace to eliminate furnace contamination. In addition, the unit was transported in special containers and in plastic bags throughout the assembly process.

- o Test - No special protective measures were taken with Serial 104 to prevent contamination during testing. For Serials 271 and 272, circuit modules were kept in plastic bags before and after testing to protect against handling contamination. For these two units, the supply air on the test stand was passed through a 10-micron filter and a desiccant chamber was used to remove moisture and oil vapors.

5.2 EUROPEAN A.300B AIRBUS (GENERAL ELECTRIC CF6 ENGINE) THRUST REVERSER ACTUATOR CONTROL SYSTEM

5.2.1 Description of Application

The description of operation is identical to that previously described for the DC-10 application in that the A.300B Airbus utilizes two General Electric CF6 main engines with identical thrust reversers.

5.2.2 Operating Experience

The Airbus is operated on short haul, high density air routes. The ratio of flight hours to landings for this application is 1.4, which represents a ratio of 2.8 thrust reverser cycles to each flight hour. As of June 30, 1976, 19 aircraft were in service with a total operating time of 27,265 hours, accumulating at a current rate of about 1650 flight operating hours per month and representing 3300 component flight hours and 4610 cycles of operation each month. The A.300 application has no recorded failures to date.

5.3 CONCORDE SST THRUST REVERSER AND SECONDARY NOZZLE ACTUATOR CONTROL SYSTEM

5.3.1 Description of Application

An air motor is used to drive a variable area nozzle on the exhaust of each engine. In flight, this variable geometry exit is used to optimize engine efficiency, and is modulated continuously in response to altitude and Mach number signals. This same actuator is used to operate the thrust reversers. The temperature environment for this application ranges from minus 65F to 500F which again makes a fluidic control system an obvious candidate.

A fluidic speed control, consisting of a pulse generator, frequency converter, and gain block, is used to maintain a constant speed of operation of the actuator while repositioning the

nozzle. The fluidic circuit schematic diagram is shown in Figure 16. The pulse generator consists of a two-lobed wheel on the shaft of the air motor which interrupts the flow of air from two nozzles to two receivers. The receivers are located so that one nozzle/receiver is interrupted while the second is not. The pulses of air pressure enter the fluidic circuit and switch the input amplifier stages. The cascade of amplifiers upstream of the two volumes ensures a constant amplitude pulse signal. These constant amplitude pulses pass through the two volumes which are charged as the pressure increases and discharged as the pressure decreases. The volumes have a fixed charge and discharge rate, with the charge rate greater than the discharge rate. Therefore, as the input pulse frequency increases, the volumes retain a steadily increasing charge and the difference between the minimum charge level of the volume and the constant amplitude signal decreases, thereby gradually decreasing the swing of the power jet of the next amplifier and allowing its output to increase. This output is compared to a reference pressure that is generated from the supply source. The difference, or error signal, is amplified to drive the control servo for the air motor actuator. A photograph of the complete actuator assembly is shown in Figure 17. This application uses four actuators per aircraft.

5.3.2 Operating Experience

The Concorde airplane is currently flying with AiResearch actuators installed in the thrust reverser and nozzle control application. Only a few SST aircraft are operational with an estimated 3000 hours accumulated to date and no primary failures have been reported. A single reported secondary failure is discussed in the following paragraph.

5.3.2.1 Concorde Secondary Nozzle Actuator - One actuator (Part 126404-1-1, Serial P-111) was returned from Concorde production aircraft Number 02 as inoperable after approximately 100 hours of operation on the aircraft. The external condition of the actuator showed that the system had been exposed to large quantities of oil on which dirt had accumulated.

The actuator would not function when tested. The malfunction was traced to several areas including the fluidic speed control. The set point of the fluidic control module was depressed below zero speed; however, by proper adjustment, the set point could be raised to meet the requirements.

The fluidic module was then backflushed and a sample of the contaminant was examined. The millipore sample is shown in Figure 18. These samples consisted of an oil residue and some fine black carbon particles. Retest of the unit after backflushing showed no significant change in the characteristics of the circuit.

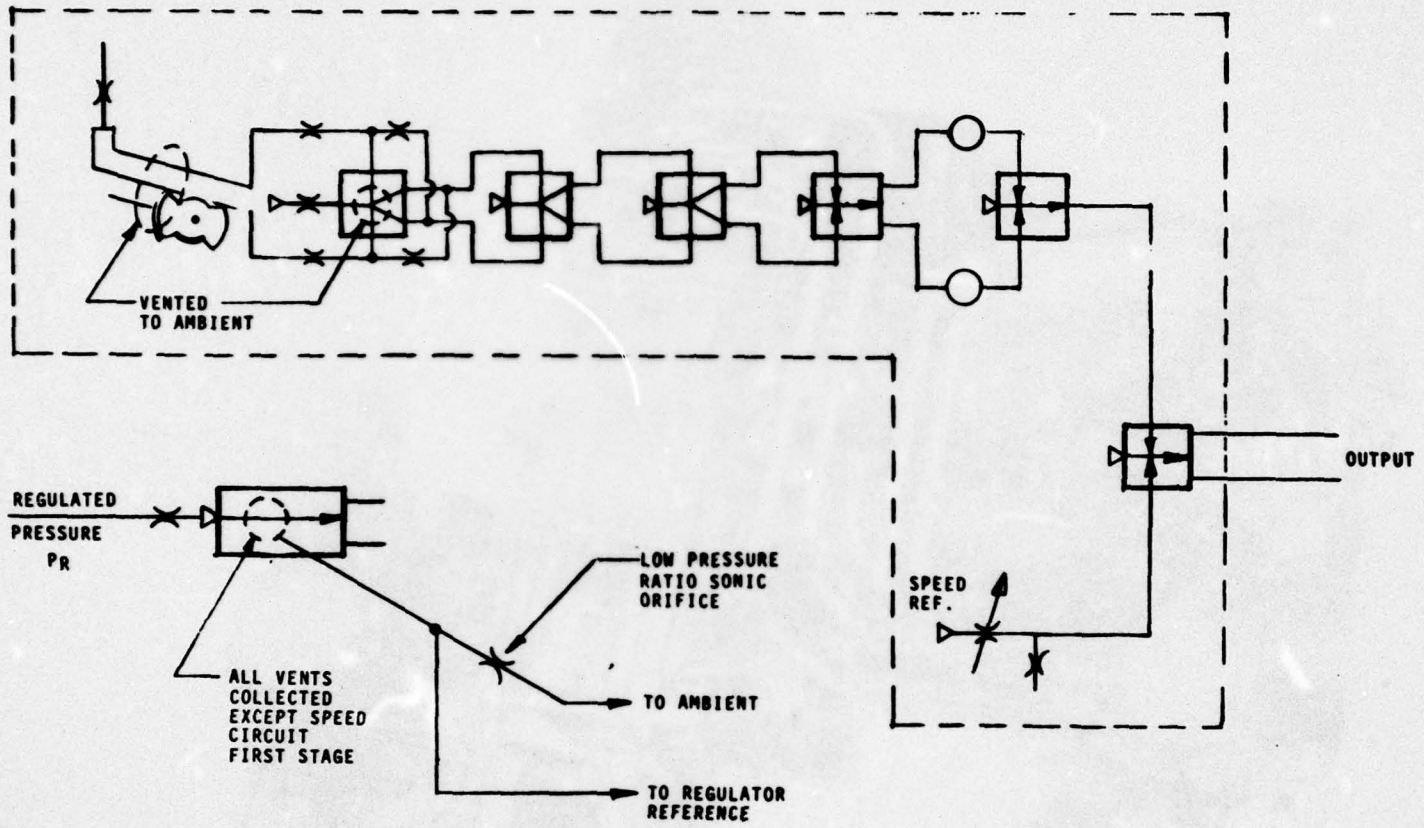


Figure 16. Fluidic Speed Control System on Thrust Reverser and Nozzle Control of Concorde SST Aircraft.

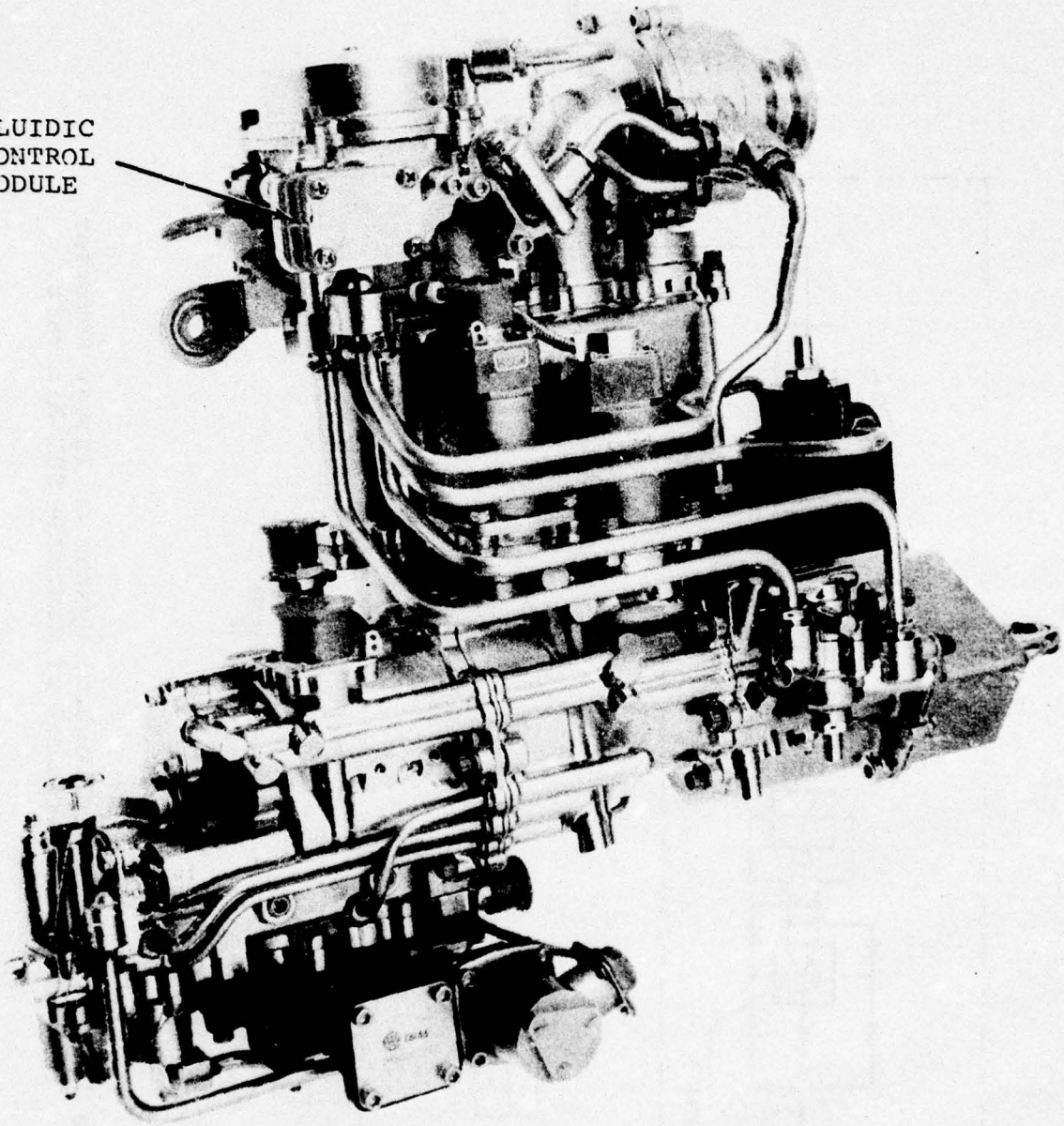
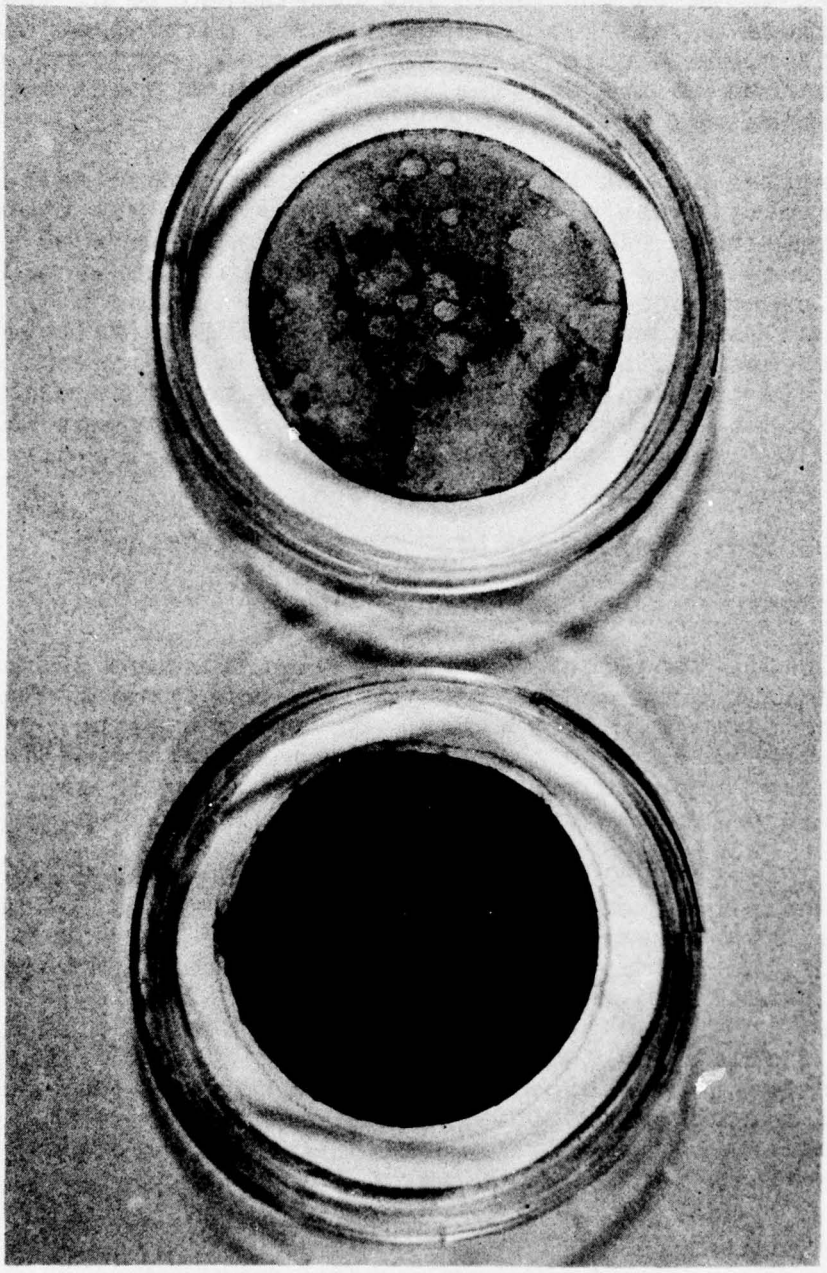


PHOTO NO. P-42148-2

Figure 17. Pneumatic Actuator of Thrust Reverser and Nozzle Control System of Concorde SST Aircraft.

MP-35225



P-49786-2

Figure 18. Oil and Carbon Residue from AiResearch Part 126404-1-1, Serial P-111, Secondary Nozzle Actuator on Concorde SST Aircraft.

MP-43715

The adjustment needle valve was then removed and examined. The condition of the needle is shown in Figure 19. The hard black deposit shown in the photo was determined to be the real cause of failure. This black deposit was a carbonized oil varnish. After the needle valve was replaced, performance of the unit returned to its original condition and operation within specified limits was provided.

This failure is not being counted as a primary failure since the primary cause of failure of the system was considered to be an excessively high leakage of oil from a damaged seal on the main engine. This oil leakage was greater than would normally be experienced in the application. Although this failure is not being counted as a fluidic circuit failure, it does show the susceptibility of needle valves to contamination. Because of this incident, the controller is being redesigned so that it no longer includes a needle valve. Adjustment will be accomplished by insertion of fixed orifices into the circuit during calibration.

5.4 LOCKHEED S-3A RAM AIR COOLING PRESSURE REGULATOR

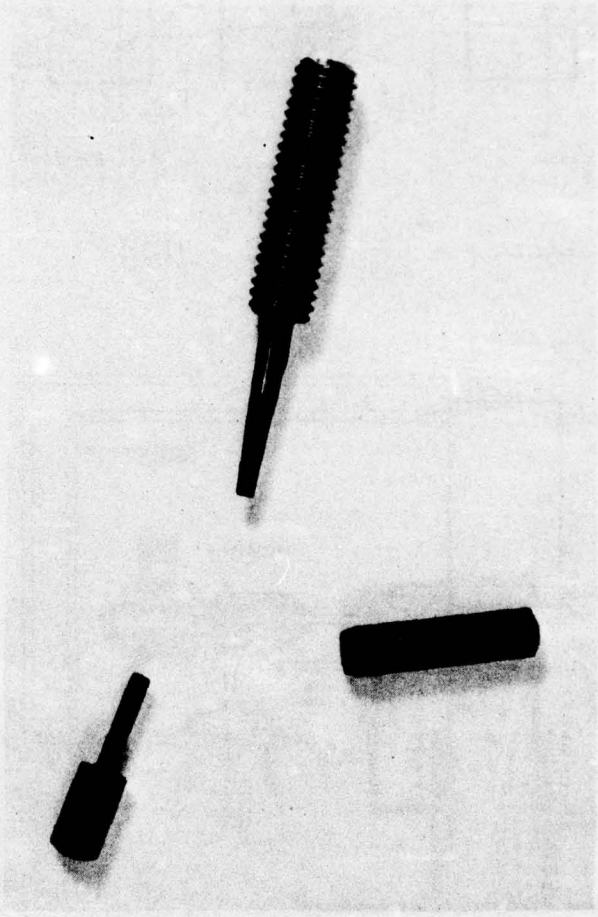
5.4.1 Description of Application

This fluidic application monitors the pressure differential between a ram air duct and an electronics compartment which is cooled by the ram air. Although an air cycle cooling system is the normal mode of cooling this compartment, an augmenting and emergency backup mode is provided by the fluidic ΔP regulator which controls a bypass valve.

The fluidic controller consists of a three-stage amplifier gain block which uses cabin pressure as a reference and compares the pressure downstream of the butterfly valve to this reference. The output of the circuit is a differential pressure which modulates the butterfly to maintain a difference of 6 to 9 inches of water between these two sensed pressures. Figure 20 shows both the fluidic circuit and the valve schematic diagram. Supply pressure for the valve is obtained from a conventional regulator that is used for other purposes in the aircraft system. The regulator obtains its supply from main engine bleed air via a filter. Figure 21 is a photograph of the unit.

5.4.2 Operating Experience

A total of 109 Lockheed S-3A aircraft were in service as of June 30, 1976, with an accumulated flying time of 50,959 hours at a current rate of 2650 flight hours per month. No fluidic failures have been reported for this application to date.



P-49786-1

Figure 19. Needle Valve Adjustment Removed from AiResearch Part 126404-1-1, Serial P-111, Secondary Nozzle Actuator on Concorde SST Aircraft.

MP-43714

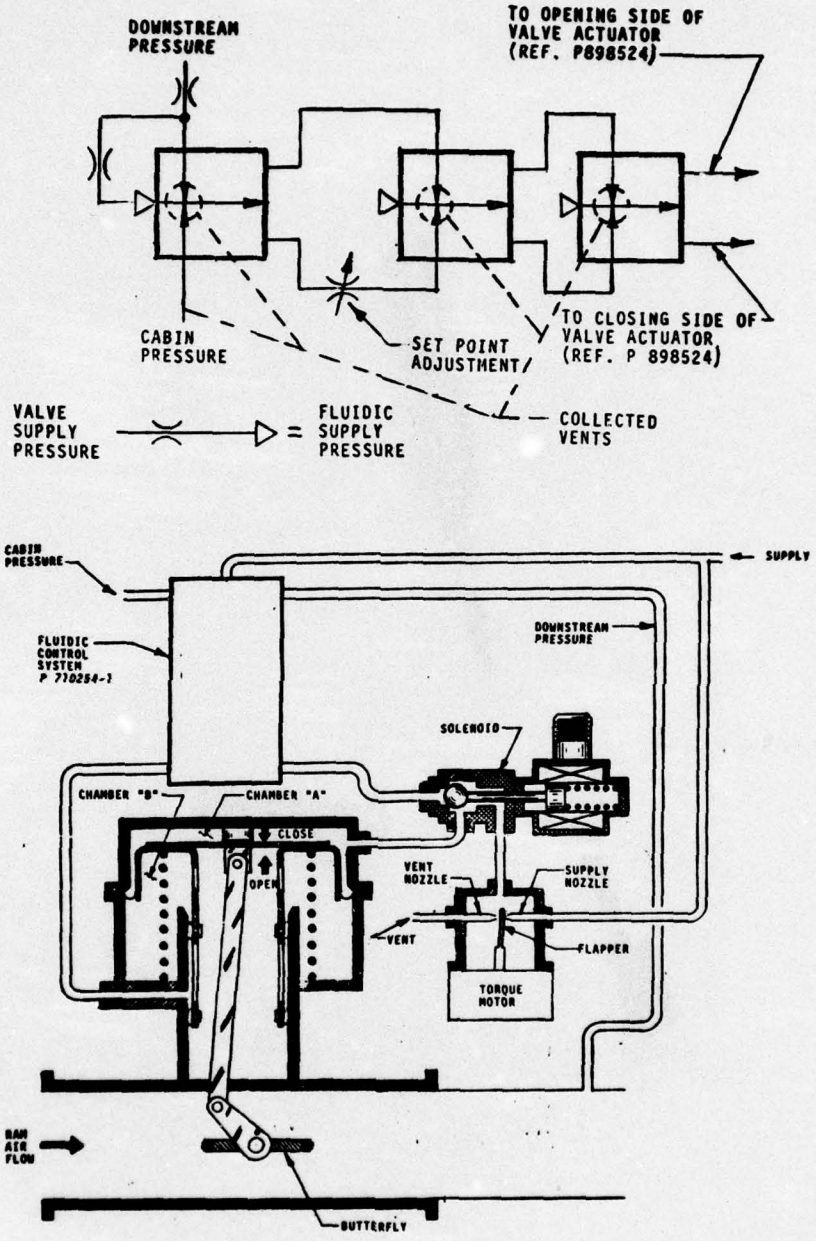


Figure 20. Fluidic Circuit and Schematic Diagram of Lockheed S-3A Pressure Regulating Valve (AiResearch Part 898524-1-1).



Figure 21. Pressure Regulating Valve of Lockheed S-3A Aircraft (AiResearch Part 898524-1-1).

5.5 BOEING E-3A (AWACS) AIRPLANE

5.5.1 Description of Application

The application on the Boeing E-3A aircraft is similar to that for the Lockheed S-3A, both in terms of function and fluidic circuitry. Two valves are used per aircraft. The fluidic circuits are identical in each valve but the flow areas of the valves are different, making two separate end item components.

5.5.2 Operating Experience

With only three of these aircraft operational as of June 30, 1976, the estimated total operating time is 800 hours; no failures have been reported.

5.6 SURGE CONTROL VALVE ON APU OF NORTH AMERICAN ROCKWELL B-1 AIRCRAFT

5.6.1 Description of Application

The auxiliary power unit for the North American Rockwell B-1 aircraft supplies compressor bleed air for main engine starting and for other ground power uses. To preclude load transients from causing APU compressor surge, a surge valve is provided to vent excess compressor flow. The surge valve and fluidic control circuits are shown schematically in Figure 22.

As shown, the surge valve butterfly is normally closed. The valve is modulated to an open position as a function of compressor inlet temperature and a ΔP signal representing total compressor airflow. Compressor inlet temperature is supplied to the system as an electric current, and a transducer converts this into a fluidic control pressure, which represents the desired airflow. The summing junction compares the control pressure with the ΔP signal representing actual flow to generate an error signal which is nulled by the surge valve. Butterfly position is fed back by a pin amplifier transducer to permit higher accuracy with stability. One APU and one control valve are used per aircraft.

5.6.2 Operating Experience

The B-1 airplane has only recently entered into the flight test program with an estimated 240 hours of operating time to date. No failures have been reported for this application.

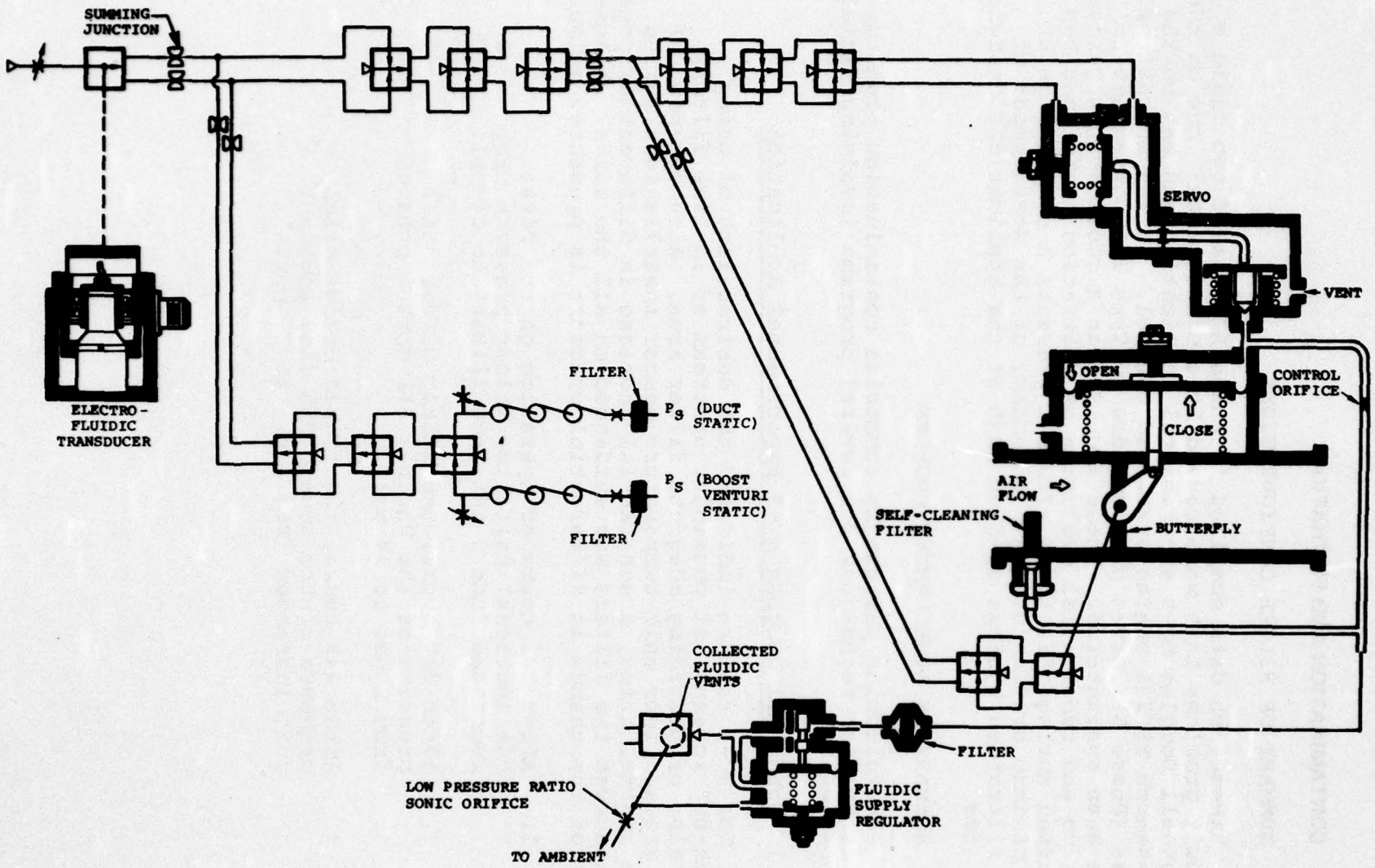


Figure 22. APU Surge Control Valve on North American Rockwell B-1 Aircraft

6. CONTAMINATION AND FILTRATION

6.1 SUMMARY OF FILTER CONFIGURATIONS

AiResearch data compiled in Phase A revealed two fluidic circuit problems that were caused by contamination: one on the McDonnell Douglas DC-9 experimental application and one on the AiResearch TSE231 engine overspeed control. In the operational phase (Phase B), seven problems due to Type III contamination have been encountered. These events span a considerable period of time and substantial evolution of filtration techniques has occurred during this time. Table 1 presents a compilation of the minimum orifice size and a summary of the development of the filtration systems used on each of the applications designed thus far.

6.2 SUMMARY OF DEVELOPMENT PROBLEMS

The following paragraphs summarize contamination problems and filtration techniques for several programs involving fluidics components.

6.2.1 McDonnell Douglas DC-9 Experimental Application

The DC-9 failure indicated the desirability of using "wash-by" screens, if possible, upstream of in-line filters, and also of providing adequate filter area. Although none of the ground power unit temperature sensor installations failed from contamination, a substantial increase in differential pressure across the filters was evidenced on all the units. A summary of the change in differential pressure is presented below.

1. After 102 hours of operation on the first PSA (Burbank) unit, the filter pressure drop increased from 2 psi (new filter) to 24 psi.

2. After 230 hours, the filter differential pressure of the Phoenix AAL unit increased from 2 psi to 24 psi.

3. After 448 hours, the filter differential pressure of the second PSA (Los Angeles) unit increased from 2 psi to 33 psi.

TABLE 1. FILTRATION SYSTEM DATA.

Fluidic Component and Application	Air Supply	Minimum Orifice Sizes	Filter Configuration	Maintenance Concept
Part 883700-1-1; Temperature sensor for McDonnell Douglas DC-9 experimental evaluation	Main engine bleed air supply, not previously filtered.	0.024-inch variable orifice 0.028-inch fixed orifice 0.040-inch by 0.030-inch etched capillary	Single, oblique wire-wound, inline filter installed just upstream of the supply pressure regulator. Screen area 3.5 square inches. Approximately 250-micron.	Inspect "on condition." Clean or replace as necessary.
Part 885550-3-1; Temperature sensor for APU experimental evaluation (AAL unit and first PSA unit)	APU compressor bleed air supply, not previously filtered.	Same as Part 883700-1-1 above, except circuit is a different configuration	Stage 1: Wash-by, wire mesh filter in air supply. Approximate screen area 1.5 square inches. 150-micron.	Inspect "on condition." Clean or replace as necessary.
			Stage 2: Inline, wire mesh filter installed just upstream of the supply pressure regulator. Screen area 3.5 square inches. 10-micron nominal, 25-micron absolute.	Inspect "on condition." Clean or replace as necessary.
Same as Part 885550-3-1, except this was the second PSA unit	Same as above.	Same as Part 885550-3-1	Stage 1: Same as Part 885550-3-1.	Same as Part 885550-3-1.
			Stage 2: Same as Part 885550-3-1, except filter was sintered stainless steel fiber material. Screen area 5.5 square inches. 15-micron nominal, 40-micron absolute.	Same as Part 885550-3-1.
Part 885550-4-1; Temperature sensor for Lockheed C-141 APU experimental evaluation	APU compressor bleed air supply, not previously filtered.	Same as Part 885550-3-1, except circuit is different by use of enclosed venting	Stage 1: Same as Part 885550-3-1.	Same as Part 885550-3-1.
			Stage 2: Same as second PSA unit, Part 885550-3-1.	Same as Part 885550-3-1.

TABLE 1. FILTRATION SYSTEM DATA.

Fluidic Component and Application	Air Supply	Minimum Orifice Sizes	Filter Configuration	Maintenance Concept
Parts 109652-1-1 and 109712-1-1; Speed control for AiResearch TSE231 engine	Engine compressor bleed air supply, not previously filtered.	0.016-inch diameter circular orifice 0.010-inch by 0.017-inch capillary	Stage 1: Sintered stainless mesh pleated diaphragm inline filter located just upstream of pressure regulator. Approximate screen area 2 square inches. 10-micron nominal, 25-micron absolute.	Inspect "on condition." Clean or replace as necessary.
		Part 109652-1-1 had variable orifice with annulus approximately 0.0015-inch diameter	Stage 2: "Last Chance" etched screen filter built into fluidic module. Screen area 0.25 square inch, hole size 0.004-inch diameter (100-micron).	Inspect on disassembly. Clean if necessary by backflushing.
Part 3229099-2-1; General Electric CF6 thrust reverser actuator	Main engine bleed air supply, not previously filtered.	0.023-inch diameter fixed orifice 0.025-inch by 0.027-inch diameter adjustable needle seat 0.018-inch by 0.020-inch etched configuration	Stage 1: High capacity, sintered wire mesh, wash-by filter in supply line. Screen area 8.4 square inches. 15-micron nominal, 40-micron absolute. Stage 2: Not included in -2-1 configuration.	Inspect "on condition." Clean or replace as necessary.
Part 3229099-3-1; General Electric CF6 thrust reverser actuator	Same as Part 3229099-2-1.	Same as Part 3229099-2-1	Stage 1: Same as Part 3229099-2-1, Stage 1. Stage 2: New intermediate wire mesh screen filter between supply pressure regulator and fluidic module. Screen area 0.1 square inch. 40-micron.	Same as Part 3229099-2-1, Stage 1. Same as Part 3229099-2-1, Stage 1.

TABLE 1. FILTRATION SYSTEM DATA.

Fluidic Component and Application	Air Supply	Minimum Orifice Sizes	Filter Configuration	Maintenance Concept
Part 3229099-4-1; General Electric CF6 thrust reverser actuator	Same as Part 3229099-2-1.	Same as Part 3229099-2-1	Stage 1: Same as Part 3229099-2-1, Stage 1.	Same as Part 3229099-2-1, Stage 1.
			Stage 2: Intermediate wire mesh screen filter between supply pressure regulator and fluidic module. Screen area 0.1 square inch. 40-micron.	Same as Part 3229099-2-1, Stage 1.
			Stage 3: "Last Chance" screens built into fluidic module. Etched screen area 0.1 square inch, hole size 0.004-inch diameter (approximately 100-micron).	Inspect on disassembly. Clean by backflushing if necessary.
Part 3230383-1-1; General Electric CF6 thrust reverser actuator	Same as Part 3229099-2-1.	Same as Part 3229099-2-1	Stage 1: Same as Part 3229099-2-1, Stage 1.	Same as Part 3229099-2-1, Stage 1.
			Stage 2: Intermediate filter changed to 2 square inches. 15-micron nominal, 40-micron absolute.	Same as Part 3229099-2-1, Stage 1.
			Stage 3: "Last Chance" screens, same as Part 3229099-3-1.	Same as Part 3229099-3-1 "Last Chance" screens.
Parts 3150017-1-1 and -2-1; Lockheed S-3A pressure regulator	Main engine bleed air supply, previously filtered through a 40-micron mesh filter with 4.5 square inch area.	0.030-inch diameter circular orifice 0.015-inch by 0.025-inch minimum	Stage 1: Inline, wire mesh filter in supply line just upstream of the regulator. Screen area 4.5 square inches. 10-micron nominal, 25-micron absolute.	Inspect "on condition." Clean or replace as necessary.
			Stage 2: "Last Chance" screens built into fluidic module. Etched screen area 0.02 square inch, hole size 0.010-inch diameter. (250-micron.)	Inspect on disassembly. Clean by backflushing if necessary.

TABLE 1. FILTRATION SYSTEM DATA.

Fluidic Component and Application	Air Supply	Minimum Orifice Sizes	Filter Configuration	Maintenance Concept
Parts 3150703-1-1, -2-1, and -3-1; Concorde thrust reverser actuator	Main engine bleed air supply, not previously filtered.	0.0225-inch diameter circular orifice 0.015-inch by 0.025-inch minimum amplifier throat	Stage 1: Wash-by, wire mesh filter in supply line. Screen area 7.4 square inches. 10-micron nominal, 20-micron absolute.	Inspect "on condition." Clean or replace as necessary.
			Stage 2: "Last Chance" screens built into fluidic module. Screen area 0.04 square inch. Etched holes 0.010-inch diameter. (250-micron)	Inspect on disassembly. Clean by backflushing if necessary.
Part 109708-1; NR B-1 bomber APU surge valve	APU compressor bleed air supply not previously filtered.	Not yet defined	Stage 1: Wash-by, wire mesh filter in supply line. Screen area approximately 0.3 square inch. 30-micron nominal.	Inspect "on condition." Clean or replace as necessary.
			Stage 2: Inline wire mesh filter just upstream of fluidic supply regulator. Screen identical to Stage 1.	Same as Stage 1.
			Stage 3: "Last Chance" screens are to be defined.	

6.2.2 AiResearch TSE231 Engine Application

The contamination problem on the TSE231 engine overspeed control was investigated at some length because of the hazard potential inherent in this application. On disassembly, some signs of particulate contamination were in evidence on the "wrong" side of the filters as a result of backflushing. However, the amplifier gain change which was responsible for the failure could not be corrected by backflushing. A detailed failure modes and effects analysis conducted on the fluidic circuits concluded that the observed failure could only have occurred as a result of Type I (built-in) contamination which led to "beaver-damming" and partial plugging of a capillary orifice in the circuit. This failure is also clouded by the presence of a variable orifice on the original circuit design. These adjustment screws are considered by AiResearch to be prime suspects in the continuing generation of Type I contamination after final assembly and bonding. The circuit was subsequently redesigned to eliminate both the variable adjustment and the original amplifier circuit characteristics which permitted its gain to affect the system set point.

6.2.3 General Electric CF6 Thrust Reverser Application

The first CF6 contamination problem encountered in field operations was also established as due to manufacturing procedures. The fluidic unit of Serial 104 was subjected to test and a blockage was found in one of the circuits. The unit was backflushed with filtered alcohol. A retest revealed that the circuit was operating normally. The flushing effluent was collected, filtered, and evaluated to determine the type of contamination. The type and amount of this contamination was compared with that obtained by backflushing three other fluidic modules, one of which had failed on a laboratory motor. Another fluidic module in working condition had accumulated six hours on a test stand, and the third was newly returned from the bonding operation. In addition, several unbonded modules were disassembled and checked. Although the densities of contaminants on all the samples differed greatly, the presence of metal slivers and lint fibers in all samples clearly indicated the introduction of these and other contaminants through the manufacturing process (Type I). As a result of these findings, which were confirmed by an independent testing laboratory, many substantial changes were implemented in AiResearch manufacturing, handling, assembly, and test procedures to correct this problem. (Refer to paragraph 5.1.2.1 of this report.)

The second CF6 unit returned (Serial 271) revealed a problem which had been anticipated and for which a design change was already in process. The unit had a fluidic output that was far below normal. Investigation showed that the second stage filter was nearly blocked with oil and dust contamination. The large

area first stage filter for this unit is intended to provide all the necessary protection required from the particulate matter anticipated under normal conditions. The second and third stage filters in this unit are progressively smaller in area, and progressively larger in hole size. This is somewhat the reverse of standard filtration practice; however, the objectives here are different. The second and third stage filters were designed primarily for protection from particles generated by assembly operations, and were sized accordingly. As a result, the initial area of the second stage intermediate screen was set at 0.1 square inch. A subsequent design review identified the desirability of substantially increasing this filter area and a design change was initiated to provide two square inches of filter area in the intermediate location. This failure confirmed that judgment.

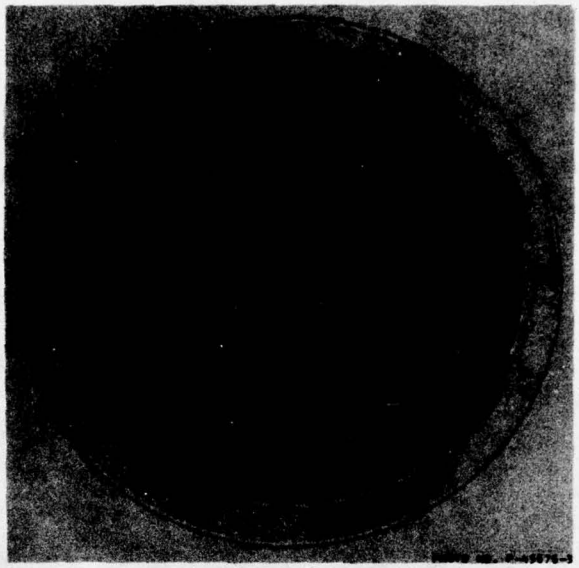
The third CF6 unit returned (Serial 272) would not operate in the low speed, end-of-stroke mode. Investigation showed complete plugging of the in-line, second stage intermediate filter screen between the pressure regulator and the fluidic supply input. Figure 23 shows the comparison between the plugged filter as removed and a new filter as installed.

An analysis of the contaminant found it to consist primarily of siliceous particles (sand) of an extremely fine nature. A few metal slivers of aluminum were also found, and were probably generated in the assembly process. The larger particles shown on the photomicrograph of Figure 23 are actually aggregations of the fine sand and particles.

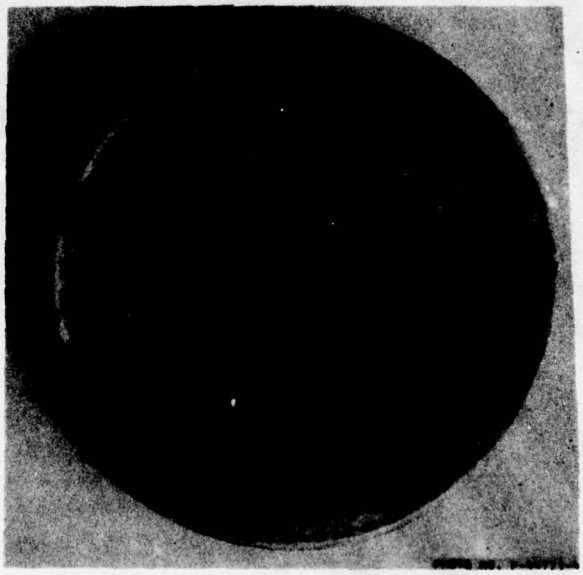
These failures were attributed to two factors: electrostatic charging of fine particles by the upstream filters and undersizing of the filter. The present design provides an increased flow area which is 65 times that of the original. This new intermediate stage filter element is shown oversize in Figure 24 to reveal the detail construction of the unit. Figure 25 shows the evolution of the filtration system for the CF6 unit up to the present time.

The remaining four filtration system contamination problems involved the main supply filter which is the filter failure mode normally expected in this application.

CLEAN FILTER



PLUGGED FILTER



ACTUAL FILTER OD: 0.450 INCH

Figure 23. Original Intermediate Filter Screen of Fluidic Control Module on Thrust Reverser Actuation System of General Electric CF6 Engine.

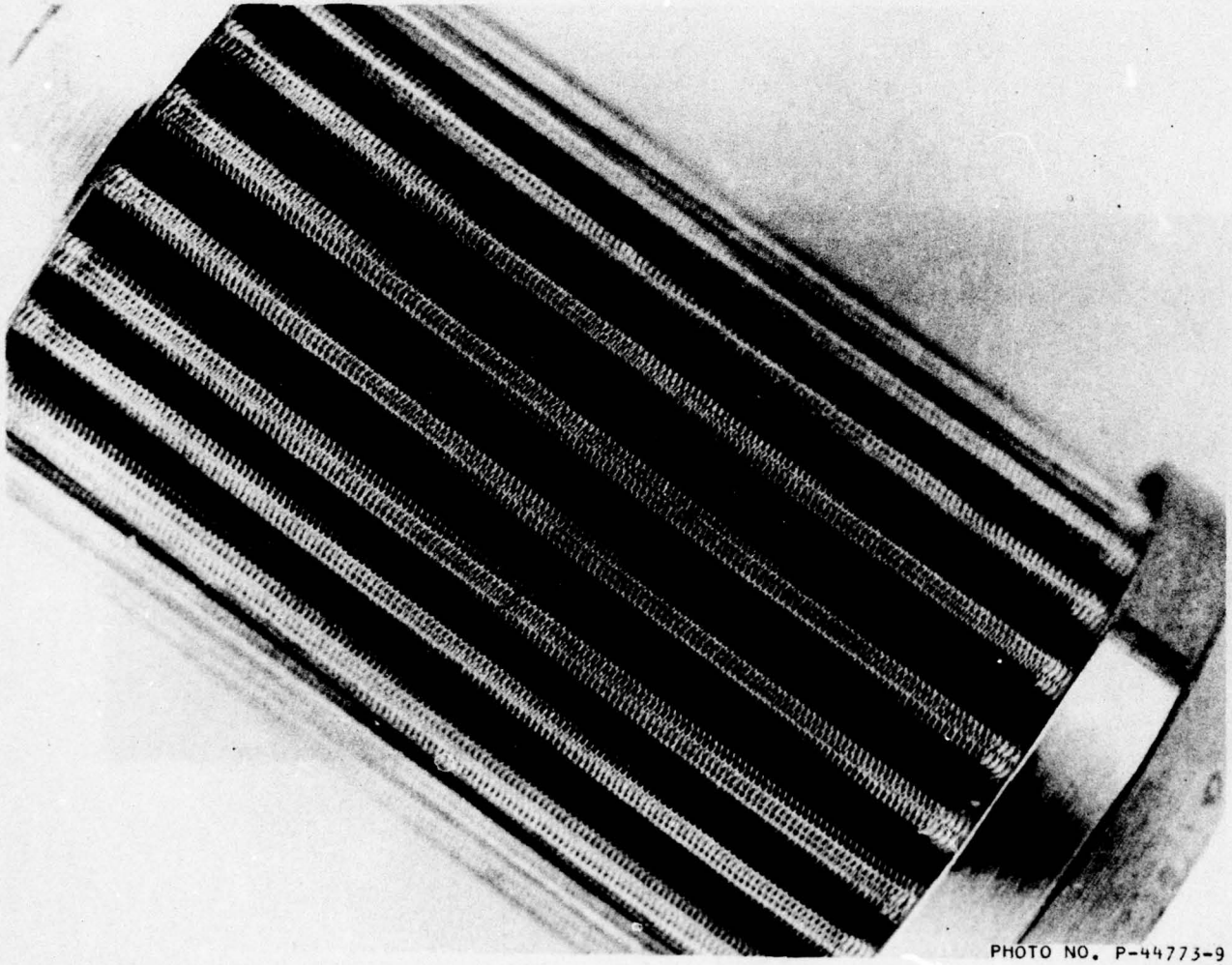


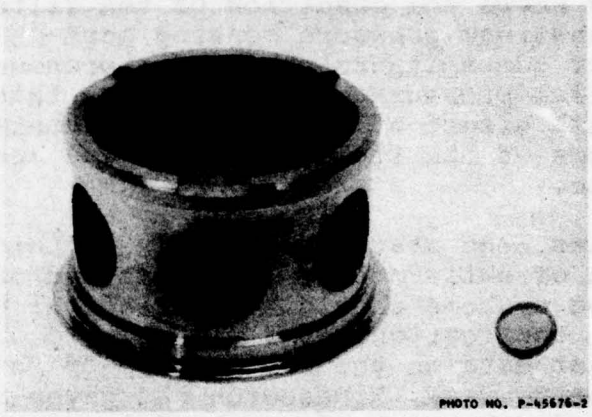
PHOTO NO. P-44773-9

Figure 24. Redesigned Intermediate Filter Screen of Fluidic Control Module on Thrust Reverser Actuation System of General Electric CF6 Engine.

SUPPLY FILTER
(ORIGINAL DESIGN)
PARTS 3229099-2
AND 3229099-3



SUPPLY FILTER WITH
INTERMEDIATE SCREEN
PART 3229099-4



SUPPLY FILTER
WITH NEW
INTERMEDIATE FILTER
PART 3230383-1

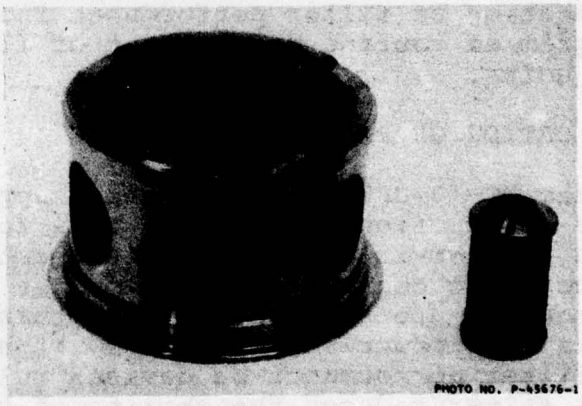


Figure 25. Evolution of Filtration Provisions of Fluidic Control Module on Thrust Reverser Actuation System of General Electric CF6 Engine.

6.2.4 Summary of Operational Experience

As originally anticipated, Type III contamination (refer to Section 2 for definition of types of contamination) proved to be the dominant event for the fluidic circuits monitored in this study. However, the internal circuit passages themselves seem to be quite tolerant of the contaminants which pass through the various filters in the system. For example, Figure 26 shows one of the small "drop-in" screens which provides secondary filtering of the supply air downstream of the primary filter. This particular screen is from actuator Serial AEX-10043, one of the four units reported in paragraph 5.1.2.6 herein. Although this screen appears to be obstructed over more than 50 percent of its area, the effect of the blockage on the performance of the fluidic circuit was found to be undetectable. Similarly, Figure 27 shows the condition of the filter removed from the motor downstream pressure sensing port on this same unit. The buildup of contaminants produced a pronounced increase in the differential pressure measured across this filter. However, the overall effect of this degree of contamination on the performance of the fluidic circuit was again found to be negligible.

It has been stated previously in this study, that the evolution of satisfactory long life and/or low maintenance filtration systems should be a principal product of these early aerospace applications of fluidics. To obtain statistically significant data on the performance of the various filter designs being used, AiResearch has given additional attention to 1) the development of meaningful criteria for measurement of the degradation of filter performance in operational usage, and 2) a program of routine measurement of filter performance on returned units.

6.3 EVALUATION OF FILTER PERFORMANCE

In the DC-10/CF6 thrust reverser application, the majority of filter obstructions identified thus far have been found in the large annular inlet filter, AiResearch Part 3229091-1. All of the pneumatic control elements on the actuator, including the fluidic module, are supplied through this filter. Therefore, since this is a power supply filter, it seemed logical that a test of filter performance be devised relating to the extent to which the filter reduces the ability of the flow of air to do work. In the DC-10/CF6 system, the supply pressure may vary from 10 psig up to 55 psig, and compressibility effects vary considerably over this range. However, a test procedure based on low supply pressures is desirable in this case, so that compressibility effects can be ignored. (For the test procedure described below, analysis has shown that the assumption of incompressible flow introduces an error of only a few percent over the range of interest.)

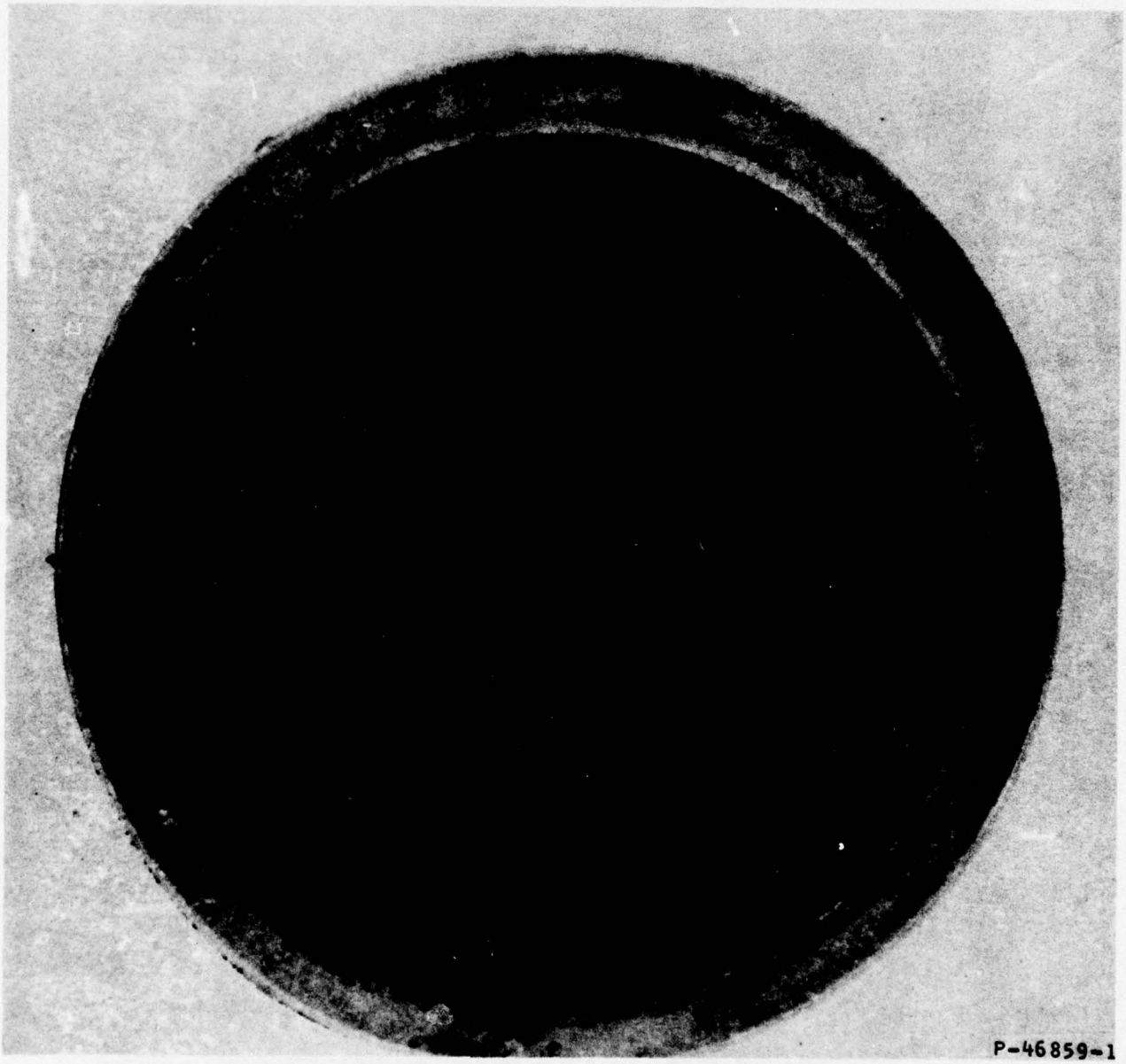


Figure 26. AiResearch Filter Element 3230163 Removed From Actuator Assembly 126366, Serial AEX-10043 Thrust Reverser on General Electric CF-6 Engine.

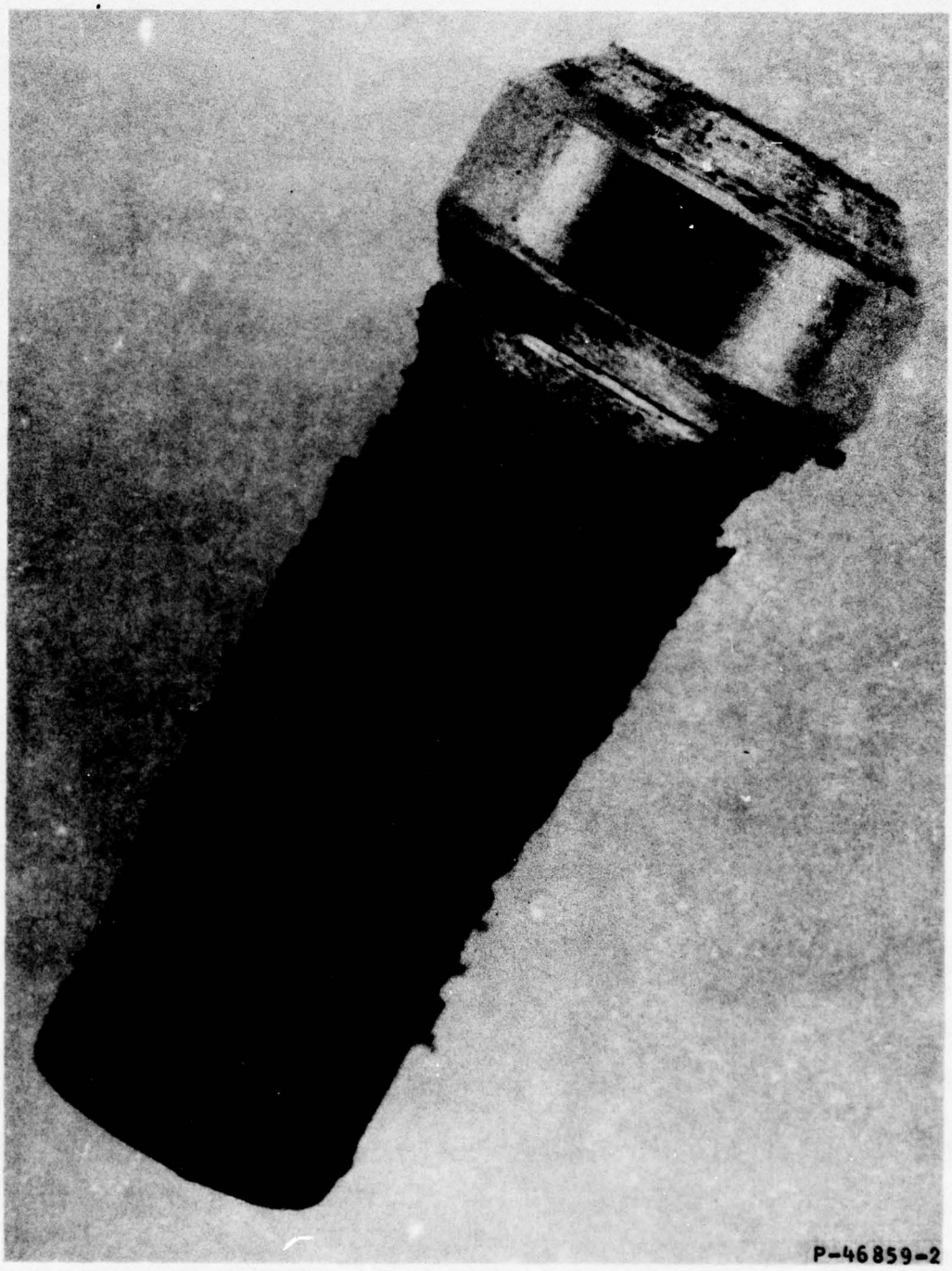


Figure 27. AiResearch Filter Element 882066 Removed From Actuator Assembly 126366, Serial AEX-10043 Thrust Reverser on General Electric CF-6 Engine.

The test setup devised by AiResearch for filter evaluation is shown in Figure 28. The filter under test is inserted in a holding fixture; air flows through the filter and then through a downstream orifice to ambient. Two pressure differentials are displayed: the ΔP across the filter and the ΔP across the downstream orifice. The test procedure requires that the inlet regulator be adjusted to establish a differential pressure of 4 in. Hg across the filter, at which the orifice differential pressure is recorded. (The orifice has been sized so that, with a clean filter, the airflow rate will be near the operating value of approximately 1.5 lb per min.)

In incompressible flow, the work available from a fluid stream is directly proportional to the available pressure differential. In this test, the total work available from the entering air is proportional to ΔP_{1-3}, and that extracted by the filter is proportional to ΔP_{1-2}. Therefore, the ratio $\Delta P_{1-2}/\Delta P_{1-3}$ is a reasonable measure of the "obstructance" of the filter in terms of work.

Several tests were run on this particular filter using strips of tape to block varying amounts of the filter area in a controlled manner to determine the effect on flow. These tests showed that a reasonably linear relationship existed between ΔP_{2-3} and the percentage of area of the filter blocked by the tape strips. In addition, it was found that a group of new filters (of the 15-micron nominal, 40-micron absolute configuration) produced ΔP_{2-3} readings ranging from 18 to 22 in. Hg.

These observations led to establishment of an arbitrary standard which has now been adopted for this filter. This standard is shown in Figure 29. If ΔP_{2-3} is less than 2.5 in. Hg, the filter is considered as "failed", since more than this degree of blockage will prevent the actuator from operating. Furthermore, if subsequent cleaning procedures cannot clear the filter sufficiently to raise the value of ΔP_{2-3} to a minimum of 15 in. Hg, the filter is not deemed suitable for re-installation in a unit.

Procedures have now been implemented so that the filter is removed from all returned units, tested, cleaned, and then re-tested. Re-installation of the filter in an actuator will occur only if the cleaned filter passes the final test described above. The results of these tests will be documented and analyzed to determine whether any statistically relevant conclusions can be drawn therefrom. Results of the tests will be presented in a subsequent report.

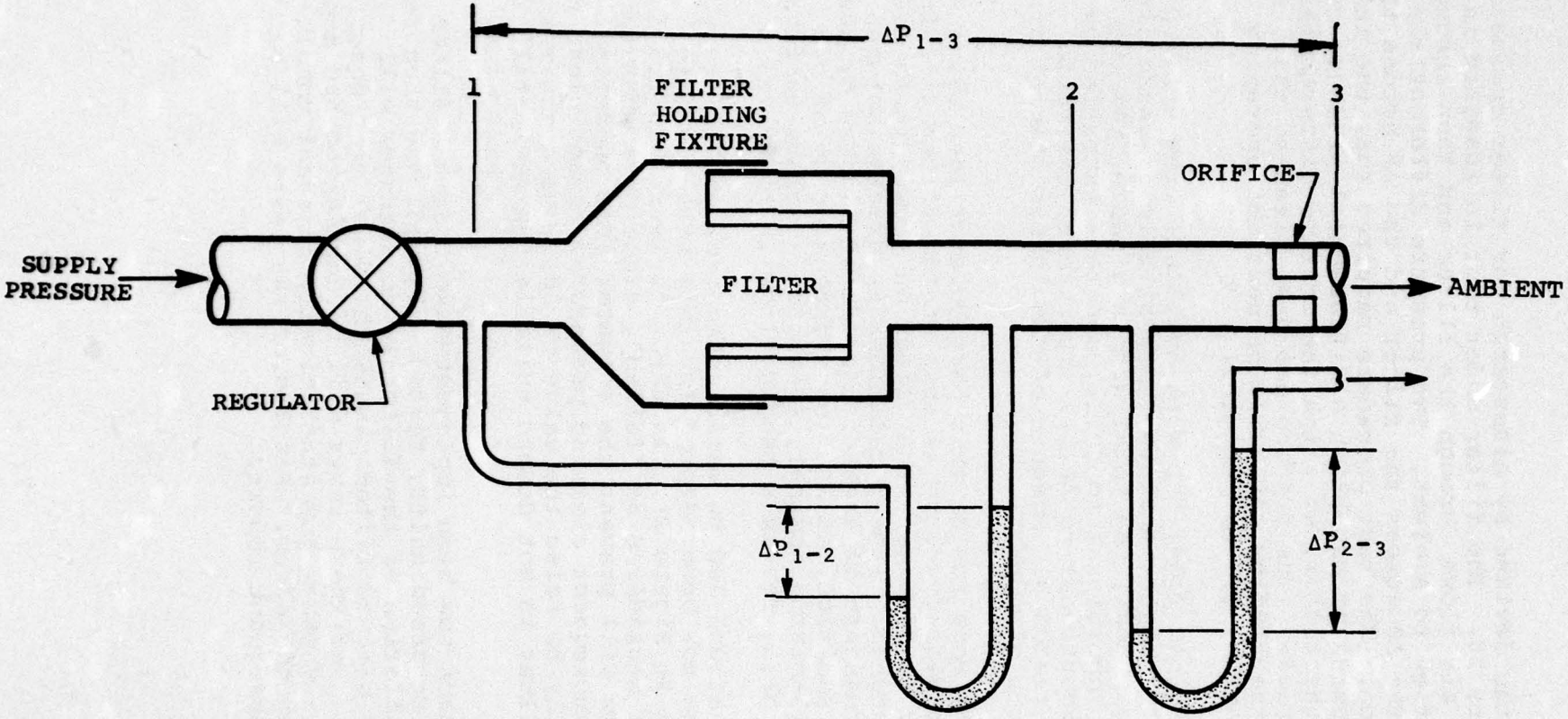


Figure 28. Filter Performance Test Setup.

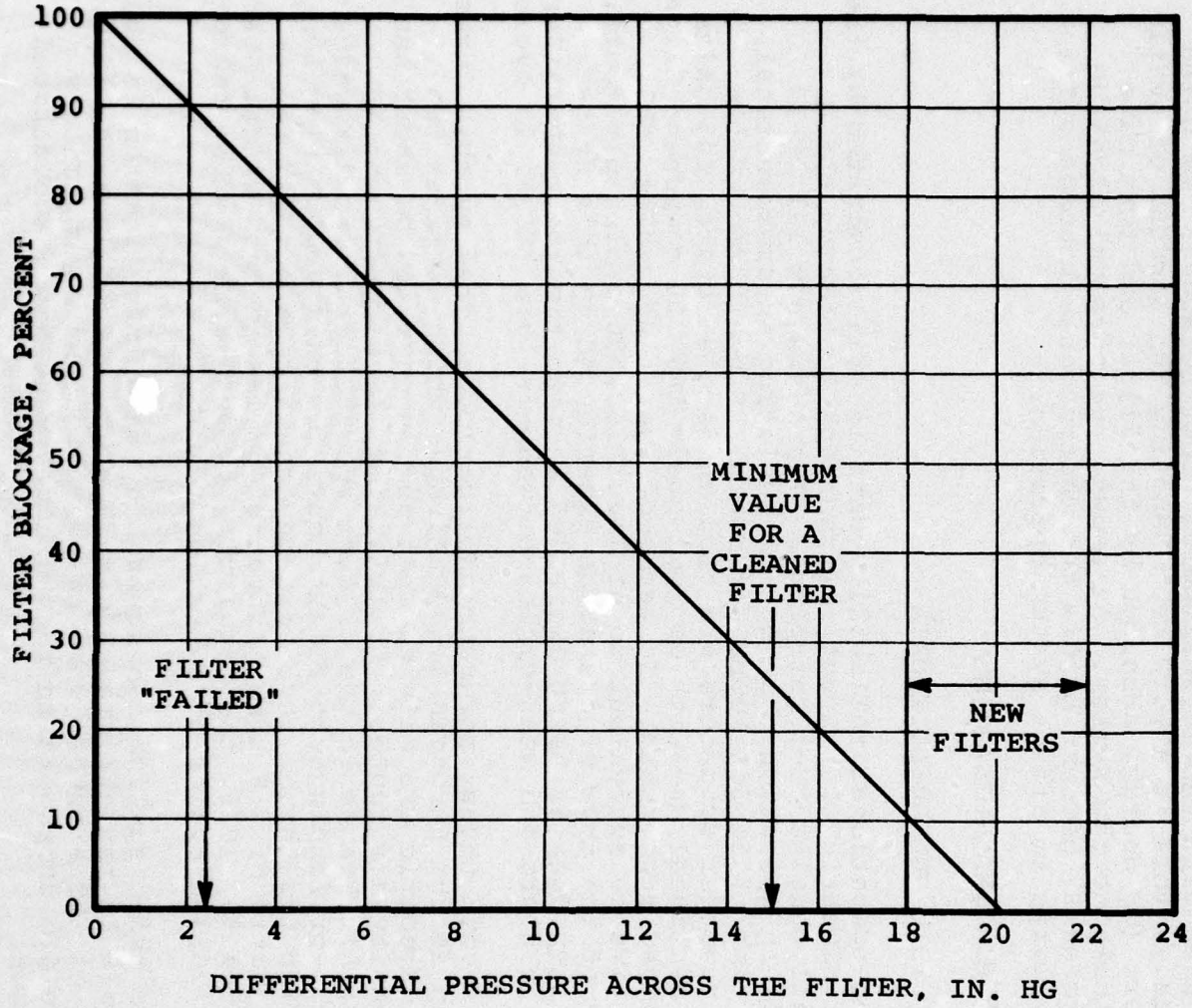


Figure 29. Filter Calibration Curve.

It is interesting to note that, although a new filter absorbs approximately 17 percent of the work energy available from the air supply in this test procedure, the filter must reach the point of absorbing over 60 percent of the input energy before it will prevent operation of the actuator. This is shown in Figure 30 which plots the percent of physical blockage of the filter area with the corresponding "obstructance". As noted previously, this is a work term denoting the percent of available work (or energy) absorbed by the filter and thus made unavailable to the system. As shown, the physical blockage must exceed 87 percent before the obstructance becomes sufficiently large to affect system operation.

7. OPERATIONAL RELIABILITY

7.1 FLUIDIC RELIABILITY DATA

The operational reliability data is still dominated by the General Electric CF6 thrust reverser application on the McDonnell Douglas DC-10 airplane. There are now 221 DC-10 aircraft in operation that are accumulating an average total flight time of 54,500 hours per month. Since three of the thrust reverser actuators are used on each aircraft, 663 units are in continual use with approximately 163,500 component flight hours added each month. In terms of operating cycles, this flight time is equivalent to at least 163,500 cycles per month. Because of the type of operation experienced by this system, reliability data is being expressed in mean-time-between-failure (MTBF) in hours and mean-cycles-between-failure (MCBF) in cycles.

A second thrust reverser application covered by this investigation is the European A.300B Airbus, which utilizes two General Electric CF6 main engines and is operated on short haul, high density air routes. At this time, 19 aircraft are in service; Air France is the biggest operator with six aircraft. The ratio of landings to flight hours for this application is 1.4. With two thrust reversers on each aircraft, this represents a ratio of 2.8 thrust reverser cycles to each flight hour. As of June 30, 1976, the total flight hours were 27,265, representing 76,342 cycles of operation.

The third application covered by this investigation is the Lockheed S-3A ram air pressure regulator. As of June 30, 1976, a total of 109 aircraft were in operation and approximately 2500 fluidic component operating hours were being accumulated each month.

The fourth application covered by this investigation is the thrust reverser and secondary nozzle actuator for the BAC/Aerospatile Concorde SST aircraft. This fluidic application is accumulating a limited number of operating hours since the airplane recently entered airline service.

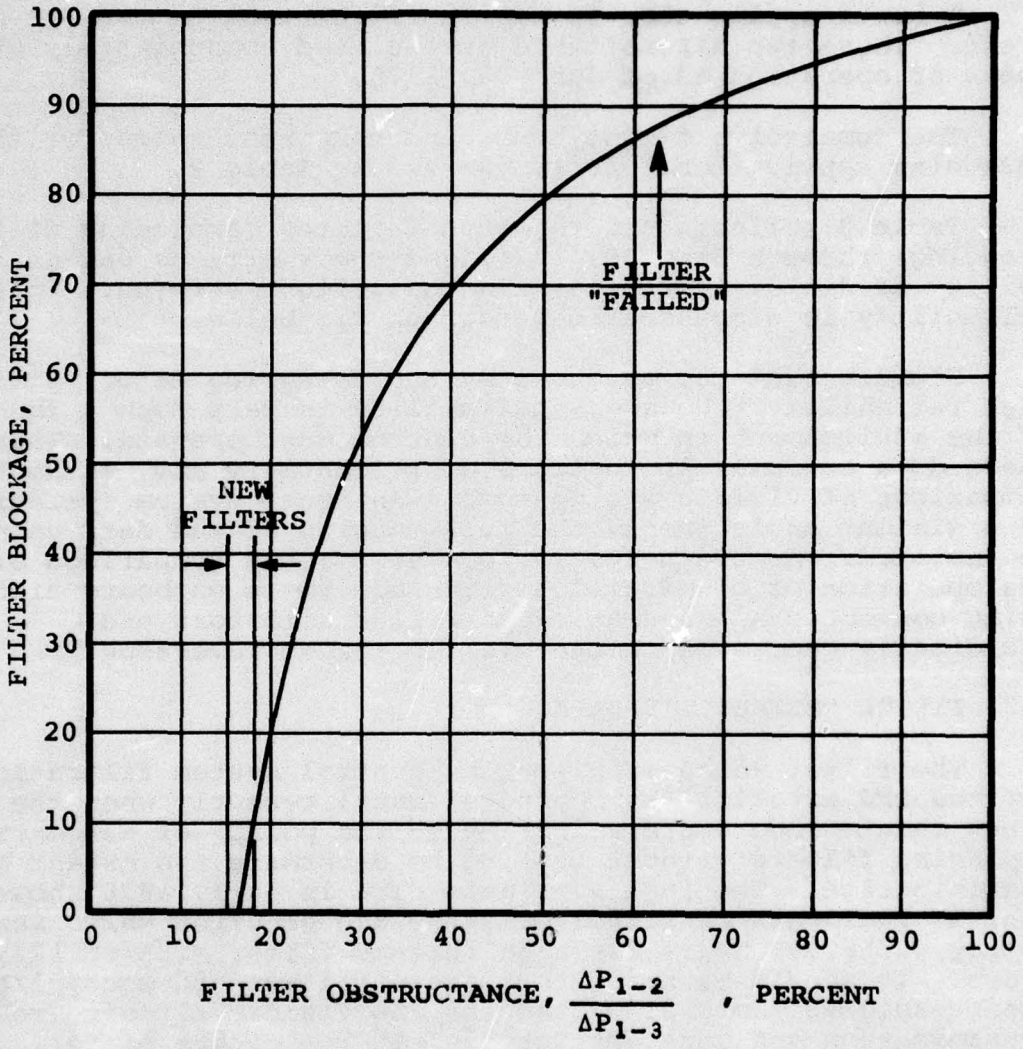


Figure 30. Filter Blockage Vs. Obstructance.

A fifth application has now entered service in the Boeing E-3A aircraft. The application is similar to that for the S-3A, both in terms of function and fluidic circuitry. Three aircraft are flying; they had accumulated approximately 800 hours of operation as of June 30, 1976.

A sixth application is now in flight test on two B-1 aircraft. These two aircraft had accumulated approximately 240 hours of operation as of June 30, 1976.

The cumulative flight hours and component hours for the foregoing applications are summarized in Table 2.

Table 3 reflects all reported failures (excluding filters clogging) through June 30, 1976, and their effects on the reliability of fluidic circuits in actual flight service. Filter reliability is discussed in paragraph 7.2 below.

Fluidic systems, as shown by the foregoing data, provide high reliability. However, reliability is very much a function of the environment in which the control must operate. Thus, these data are only indications of reliability and, without a comparison of fluidic system to conventional system operation in a similar environment, the full meaning of the data cannot be realized. Accordingly, Table 4 supplies a comparison of the operation of commercial airline equipment on board aircraft using conventional pneumatic-controlled actuators and fluidically controlled actuators for thrust reversing.

7.2 FILTER RELIABILITY DATA

The filter which supplies the control system filtration for the CF6 actuator was monitored until recently when the airlines maintenance centers introduced the policy of automatically replacing filters without testing to determine the extent of contamination. The last available data in early 1976 showed that 37 incidents of filter clogging had occurred while accumulating 4,356,006 hours for a calculated filter MTBF of 177,730 hours. It should be noted that these filters had accomplished their assigned tasks of protecting the fluidic circuit from contamination and were not actual failures of the filter. It would have been more appropriate to class them as mean-time-between-clogging rather than MTBF.

7.3 SEQUENTIAL ANALYSIS CHART

Figure 31 presents the final updated sequential analysis plot for the fluidic circuit and the filters. The plot of data points show the cumulative failures as a function of cumulative operating time through June 30, 1976.

TABLE 2. SUMMARY OF OPERATING TIMES OF PRODUCTION FLUIDIC APPLICATIONS THROUGH JUNE 30, 1976.

Application	Number of Aircraft Operational	Aircraft Operating Time hours	Component Operating Time hours	Number of Component Cycles
DC-10/CF6	221	1,783,176	5,349,528	5,349,528
A300B/CF6	19	27,265	54,530	76,342
S-3A	109	50,959	50,959	
E-3A	3	800	800	
Concorde	6 (est.)	3,000 (est.)	12,000	
B-1	2 (est)	240 (est.)		
		TOTAL:	5,467,817 hours	5,425,870 cycles

TABLE 3. FAILURE MODES.

Failure Mode	Cumulative Events
Fluidic Failures:	
Type I Contamination	3
Type II Contamination	6
TOTAL FLUIDIC FAILURES	9
Mechanical Failures:	2
TOTAL FAILURES	11

Reliability Calculations, Fluidic Failures Only

$$\text{Fluidics MTBF} = \frac{5,467,817}{9} = 607,535 \text{ hours}$$

$$\text{CF6 Fluidics MCBF} = \frac{5,425,870}{9} = 602,874 \text{ cycles}$$

Reliability Calculations,

$$\text{All Failures} = \frac{5,467,817}{11} = 497,074$$

Type I - Particles capable of altering circuit performance may be inadvertently built into the device during the manufacturing, test, calibration, or assembly processes.

Type II - Contamination sufficient to alter circuit performance may accumulate or aggregate within circuit passages from particles and/or condensates which can pass through the filtration system.

TABLE 4. CONVENTIONAL/FLUIDIC RELIABILITY COMPARISON.

System	MTBUR	Component Total Flight Hours
CONVENTIONAL PNEUMATIC		
Boeing 747 Fan Thrust Reverser	4035	16,028,680
Lockheed L-1011 Thrust Reverser	3742	2,252,589
FLUIDIC		
McDonnell Douglas DC-10 Thrust Reverser	9510	6,114,618

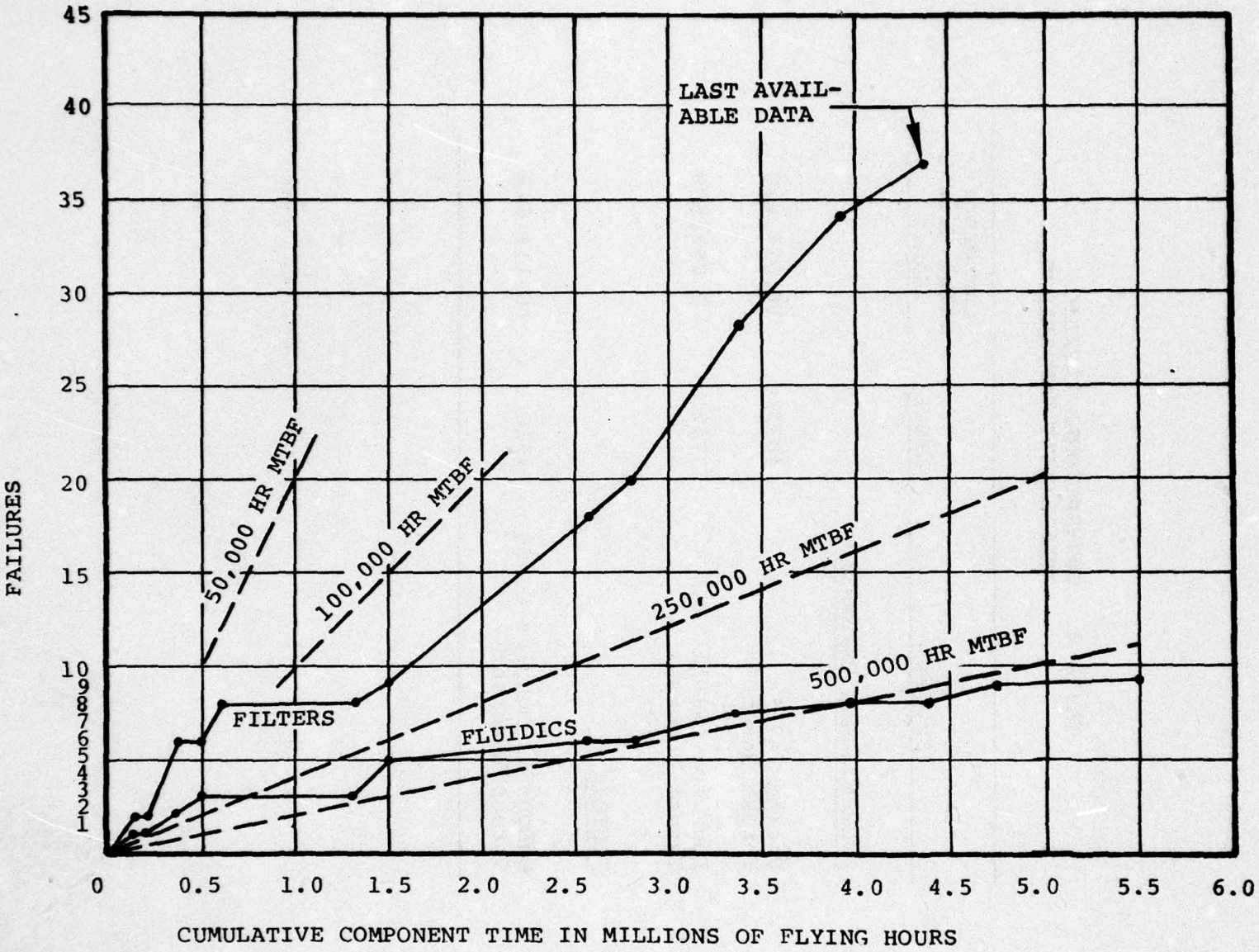


Figure 31. Sequential Analysis Chart.

It should be noted that the plot for the filters was terminated about the first of 1976 when filter data became unavailable.

The plot of fluidic circuit failures shows a MTBF growth from approximately 100,000 hours during early service to more than 600,000 hours as of June 30, 1976. There were no reported failures during the period from February 28 through June 30, 1976, while almost three quarters of a million hours were accumulated.

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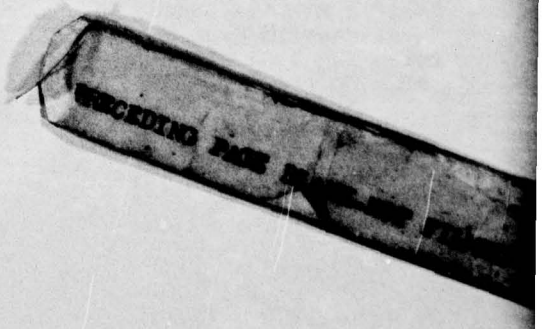
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