1.0

1.1

1.25

4.5
5.0
5.6
6.3

2.8
3.2
3.6
4.0

1.4

2.5
2.2
2.0
1.8

1.6

MICROCOPY RESOLUTION TEST CHART
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REPORT NO. NADC-79125-60

LEVEL II 12

FAULT-TOLERANT ACTUATION CONCEPT
FOR A RESEARCH TEST AIRCRAFT

AD A093113

BELL HELICOPTER TEXTRON
P. O. Box 482
Fort Worth, Texas 76101

OCTOBER 1980

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Prepared for:
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Failure-Tolerant Actuator	Redundancy Level
Failure Tolerance Level (FTL)	Quadruplex
Single Fail-Operate	Triplex
Dual Fail-Operate	Failure Management
	Electrohydraulic Servovalve (EHSV)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The fault-tolerant actuation system uses 4 active electrical control paths to control a dualized hydraulic actuator. A simple failure management system operates in conjunction with some of the inherent features of the basic system to provide a failure tolerance level of dual fail-operate for the electrical control paths. The concept is characterized by its fundamental simplicity and inherent ability to tolerate failures. The concept has application to fixed wing as well as rotary wing aircraft.

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FOREWORD

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TABLE OF CONTENTS (Concluded)

LIST OF ACRONYMS AND ABBREVIATIONS

AFCS	Automatic Flight Control System
BITE	Built-In Test Equipment
EHSV	Electrohydraulic Servovalves
FBW	Fly-By-Wire
FCS	Flight Control System
FTL	Failure Tolerance Level
LGS	Landing Guidance Sensor
LVDT	Linear Variable Differential Transformer
MTBF	Mean Time Between Failure
SW	Switch
TP	Test Point
T/QIU	Triplex/Quadriplex Interface Unit
VDC	Volts DC

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1. SUMMARY

This report describes a technology program for an actuation concept that is considered to be a candidate system for a research test vehicle. In addition to covering the basic program, the report includes in the Appendices a detailed discussion of the actuation concept, copy of the Integration Test Plan, and a Reliability Analysis of the actuation concept prepared under a Bell Helicopter IR&D program.

1.1 SCOPE

This program included a preliminary design study of a 4-axis fault-tolerant actuation system and also the design, fabrication, testing, and evaluation of a laboratory model of the actuation system for use in a potential test helicopter. The actuation concept used in this program was a derivative of the 4-valve Fly-By-Wire (FBW) actuation system that was conceptually developed and tested under a Bell Helicopter funded program. The 4-valve concept is summarized later in Section 2 and covered in more detail in Appendix A.

The 4-axis fault-tolerant actuation system was predesigned for operation with a triplex Automatic Flight Control System (AFCS) as well as to accommodate the installation requirements in the test helicopter. Each actuator assembly consists of a dual, series-type, AFCS actuator interfaced with a single-piston primary actuator in a manner to produce an output that is the summation of pilot and AFCS inputs. Two electrical and hydraulic power supplies were used to provide a failure tolerance level (FTL) of single fail-operate. The system was also configured so that in the event of a total loss of hydraulic and/or electrical power, the test aircraft could be flown manually. The AFCS was interfaced with the associated sensors and electrical control paths to effect a quadruplex control path system with an FTL of dual fail-operate. The preliminary design of the 4-axis control system is defined in Section 2.

The laboratory model of the actuation system was designed and fabricated using existing equipment from the Bell IR&D program when feasible. Hence, the laboratory model was functionally the same as the preliminary system but not physically the same. This equipment was installed on a existing test stand that was modified to accommodate the installation and test of the fault-tolerant AFCS actuator, primary actuator, load actuator, and the associated electronics. Integration tests were conducted to assure operational suitability. Simulated failures were inserted to validate the failure/management circuitry. This effort is discussed further in Section 2.

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1.2 CONCLUSIONS

The 4-valve actuation system has been evaluated within the scope of this program and is recommended as a valid candidate for a fault-tolerant actuation system in a selected test helicopter. This recommendation is based on the pertinent attributes listed below.

- Simplicity - functionally, as well as low parts count, relates to good reliability, low cost, and low weight.

- Unique failure/management - more than satisfies fault-tolerance requirements; has a control path FTL of dual fail-operate and power supply/basic actuator FTL of single fail-operate.

- Unique multiple-path tracking feature - makes the system less sensitive to tolerance problems associated with control path elements.

- Easily retrofitted - actuator output can be differentially mixed with the pilot control or can replace the primary actuator and used as a FBW actuator.

The concept can also be extended to encompass a variety of other aircraft.

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2. INTRODUCTION

2.1 GENERAL BACKGROUND

Current hovering aircraft capabilities demand considerable
visual contact flight before final landing, with the pilot
providing most of the attitude-stabilizing, position-fixing,
height-controlling and deck motion compensating functions.
Pilot workload, even in clear weather operations, is
excessive. This places additional demands of considerable
magnitude upon the pilot and the flight control capabilities
of the hovering vehicle. The development of an advanced,
precise, and highly reliable flight control/guidance system
concept to meet operational goals is a prime requirement. The
manual and automatic modes of the flight control system must
have sufficient authority to perform their required functions
during the critical vertical take-off and landing operations.
This implies that the conflict between automatic control
authority and flight safety must be resolved by incorporating
fail-safe and fault-tolerant features in the Flight Control
System (FCS).

An SH-2F helicopter was chosen as the study vehicle for the
integration and evaluation of the 4-vlave concept. The an-
ticipated FCS requirements will consist of a single fail-
operational capability. The AFCS is anticipated to be a high
(50 percent) authority system. During landings on small
ships, all ship kinematics, aircraft range, and range rate
information will be transmitted to the helicopter via the
Landing Guidance Sensor (LGS) data link. All computations of
the flight control laws required for execution of the landing
task will be performed by the flight control computers.

The actuation system is recognized as a critical technology in
the development of a research flight test vehicle. It is for
a dual fail-operate requirement that the 4-valve actuation
system has been evaluated.

2.2 SUMMARY DESCRIPTION OF THE 4-VALVE ACTUATION SYSTEM

A summary description of the 4-valve actuation concept has
been included in this section to facilitate the presentation
of the material in the other sections. A more detailed de-
scription of the concept is provided in Appendix A.

The 4-valve actuation system uses four active electrical control paths to control a dualized hydraulic actuator. A simple failure management unit operates in conjunction with some of the inherent features of the basic system to provide an FTL for the control paths of dual fail-operate. This actuation system is characterized by fundamental simplicity and its inherent ability to tolerate failures; it is in essence a forgiving-type system.

The electrical control paths can be analog or digital and use electrohydraulic servovalves (EHSV) for a direct interface with the two links (2 per piston), four electronic drivers, four quasi-isolated failure/management units, and a dual primary hydraulic actuator (tandem or parallel). In a flight test model, all control channels would be operated with a control/reporting panel located in the cockpit.

This system offers the following features:

- Single fail-operate is inherent (without failure management).

- Dual fail-operate provided by adding a simple failure/management system.

- Electrohydraulic servovalves provide a direct interface between the electrical links and the power cylinder (no drive actuation function required).

- Provides automatic tracking of the multiple electrical control links.

- Includes unique feature for protection against intermittent type inputs (e.g., electrical transients) that could effect an unwarranted disengagement.

- Can be easily retrofitted using existing power cylinder installation.

- Has application to high-performance airplane controls as well as helicopter controls.

A simplified schematic of a tandem dual actuator and the driving circuit is shown in Figure 1. All electrical control paths operate simultaneously and are automatically tracked to provide the desired stiffness at null. The tracking signals are inherently generated in the failure sensing circuitry in the failure/management system.

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PORTING STAGE
POSITION TRANSDUCER

ACTUATOR
POSITION
FEEDBACK

PORTING STAGE
POSITION TRANSDUCER

ACTUATOR
POSITION
FEEDBACK

PORTING STAGE
POSITION TRANSDUCER

FAILURE LOGIC

FAILURE LOGIC

PORTING STAGE
POSITION TRANSDUCER

OUTPUT

LVDT'S

LVDT'S

R P

VALVE 2a

VALVE 2b

R P

VALVE 1a

VALVE 1b

FAILURE LOGIC

FAILURE LOGIC

AMPL 2a

AMPL 1a

AMPL 1b

AMPL 2b

2a
1a
1b
2b

PILOT
CONTROL
INPUT

E2a
E1a
E1b
E2b

AUTO
TRACT
SIGNALS

Figure 1. 4-Valve Actuation Concept.

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The failure/management system uses position sensors on the porting stage of the EHSV (see Figure 1) to provide the intelligence needed for the failure logic. The failure circuitry uses a simple logic for failure detection and has the intelligence to differentiate between an inert-type failure and a hard-type failure. Protection against an unwarranted disengagement of a control path (i.e., apparent intermittent failure) has been included for protection against induced transients.

Figure 2 is a photograph of the laboratory test model of the 4-valve actuation system configured for dual fail-operate application. As described later, this hardware was used in the program to simulate the series-type AFCS fault-tolerant actuator.

MECHANICAL INPUT

4-VALVE CONTROL HEAD

4-VALVE ACTUATOR

4-VALVE CONTROL MOTION INPUT

BOOST ACTUATOR

CONTROL ELECTRONICS FOR LOAD ACTUATOR

SYSTEM ELECTRONICS FOR 4-VALVE ACTUATOR

Figure 2. Laboratory test hardware.

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3. WORK PERFORMED

The objective of the work items described in this section was to confirm the validity of the 4-valve actuation system as a viable control system for a research test helicopter. These tasks are discussed in terms of what was accomplished, how, and the final results.

3.1 PRELIMINARY DESIGN OF A 4-AXIS ACTUATOR SYSTEM
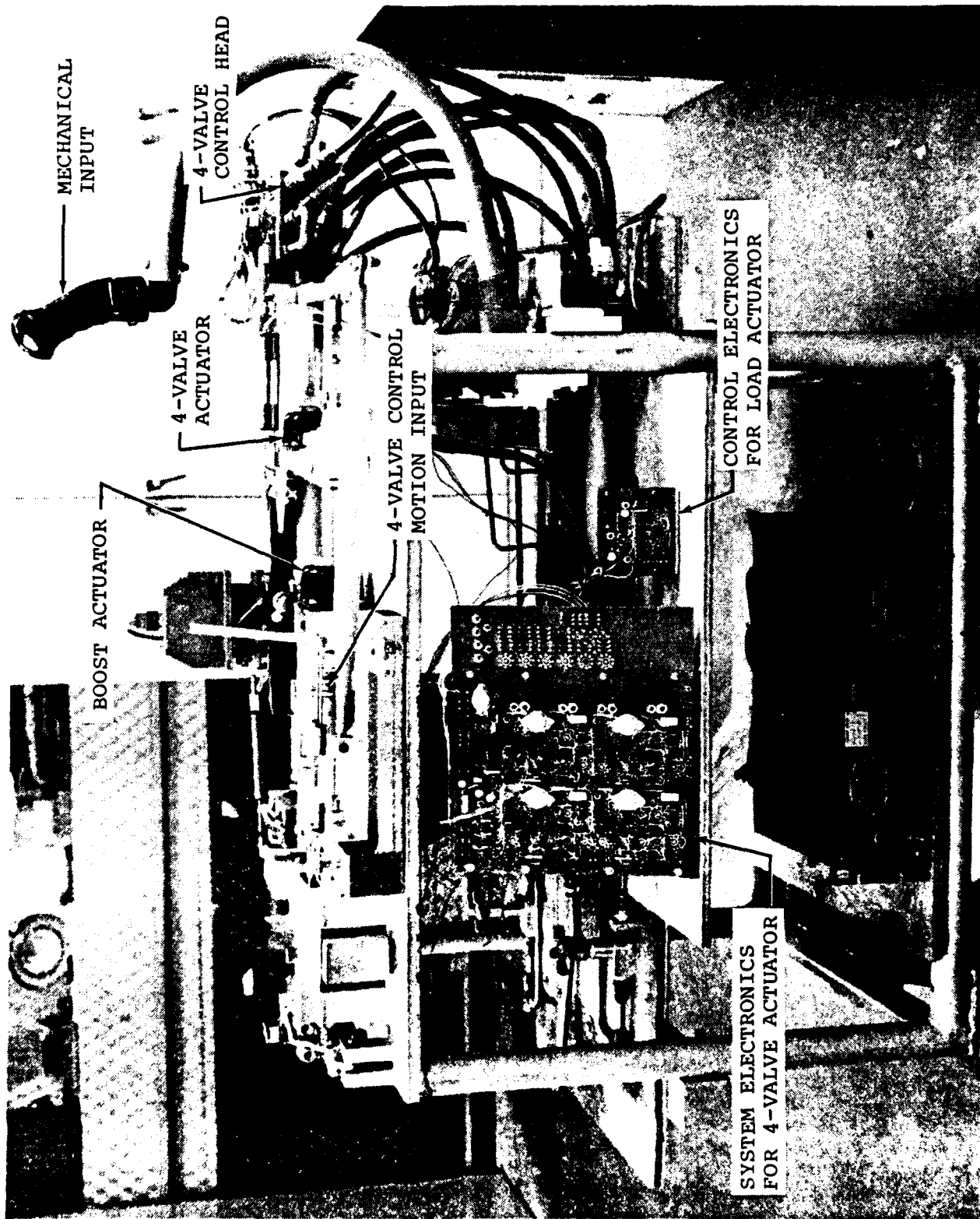
The 4-axis actuation system has been designed in accordance with the requirements for a potential test helicopter. It consists of four single primary actuators; four dual, fault-tolerant AFCS actuators; four electronic units that provide the electrical mixing and drive signal for the AFCS actuators and the redundancy management; and a control/annunciator panel. This equipment can be synthesized into a system by referring to Figure 3, a schematic of one control path of a control channel. As shown, the AFCS actuator mechanically sums with the pilot's mechanical controls to effect a series-type control input to the primary actuator. The AFCS actuator is controlled by the electronic unit which is interfaced with, and hence controlled by, a triplex AFCS computer system. Hence, the primary actuator can be driven by the pilot, the AFCS, or a combination of both.

The system has been designed to provide an AFCS with an FTL of dual fail-operate up through the EHSVs that port fluid into the dual cylinders of the AFCS actuators. The electrical and hydraulic power supplies are single fail-operate. For a dual electrical or hydraulic failure, the AFCS actuator will be automatically centered at a controlled rate; the actuation system will then revert to full manual control.

The control/annunciator panel was not designed only to consist of electrical and hydraulic power switches, automatic preflight test switches, and condition indicators (e.g., soft fail, hard fail, and disengage). A more detailed design of the total system should be accomplished before the central/annunciator panel design can be finalized. The other major components are summarized below.

3.1.1 Triplex/Quadruplex Interface Unit

As shown in Figure 3, this unit transposes the triplex AFCS signals into quadruplex signals for compatibility with the

PRESSURE OPERATED VALVING

HYDRAULIC SUPPLY NO.1 P1 R1

PRIMARY ACTUATOR

SEE DETAIL ACTUATOR SCHEMATIC FIG

MAIN CONTROL VALVE

SP
CENT

4 LVDT's   4 EHSV's   4 LVDT's

MANAGEMENT & SENSOR INPUTS

PILOT PLUS TRIM INPUT

FB2b FB2a FB1b   D1b D2a D2b   V1b V2a V2b

TRIPLEX DIGITAL AFCS

ANALOG CONTROL SIGNALS

ACTUATOR FEEDBACK

V1a

A3 A2 A1

SEE FIG

TRIPLEX/QUADRUPLEX INTERFACE

DEMODULATOR   FB1a

EHSV DRIVE SIGNAL

EHSI

A2b A2a A1b

A1a

AMPL   D1a

LEAD-LAG NETWORK   DEMODULATOR   V1a

V1a

SEE DETAIL ELECTRICAL SCHEMATIC FIG

LAG NETWORK

AUTO-TRACK SIGNAL

3. SEE DETAIL SCHEMATICS FOR SUPPLEMENTAL INFORMATION.
2. F/M UNIT 4 ONLY, PROVIDES A COMMON POINT FOR E4a,E1b,E2a,E2b.
1. E1b,E2a,E2b ARE FROM RESPECTIVE F/M UNITS.
NOTES:

AN2b AN2a AN1b

SEE FIG

ANNUNC PANE

Figure 3.   Simplified system schematic for contr

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LVING

P₂ HYDRAULIC
R₂ SUPPLY NO.2

→ CONTROL OUT

VALVE

SPRING
CENTERING

4
LVDT's

FAULT TOLERANT
AFCS ACTUATOR

V1b V1 V2b

TO EHSV 1a

DISENGAGE
SOLENOID

HYDRAULIC
SUPPLY

ELECTRONIC UNIT

EHSV FEEDBACK

AUTO-DISENGAGE
SIGNAL

SEE NOTE 1

E1b E2a E2b

V1a

SEE FIG

FAILURE/MANAGEMENT
UNIT 1a

NAL

AN2a AN1b AN1a

E/D1a E/D1b E/D2a E/D2b

ENGAGE/DISENGAGE
SIGNALS

ANNUNCIATOR
PANEL

CONTROL
PANEL

SEE FIG

control path 1a.

1

quadruplex AFCS actuation system. Figure 4 is a simplified
schematic of the Triplex/Quadruplex Interface Unit (T/QIU). A
cross-strap approach was considered for the interface function
but was voted out in preference of the scheme shown in Figure
4 that has some failure mode advantages.

The selected approach developed a "dummy" control path by sum-
ming the three AFCS signals into a high impedance amplifier
through FET switches that are operated by the quadruplex failure/
management system. This implementation provides a dual fail-
operate capability to the AFCS inputs. For example, if triplex
signal A_3 fails, failure/management unit 2b will open the re-
spective FET switch S_wA_3 and after the prescribed time delay,
will disengage control path 2b. A second AFCS failure would
operate in a similar manner and leave the remaining AFCS con-
trol path and the dummy path driving the AFCS actuator. If
the first or second failure had been the dummy control path,
control path 1a would have disengaged leaving the other paths
driving the AFCS actuator.

This circuit approach is simple and appears to be compara-
tively less vulnerable to failures.

3.1.2 Electronic Unit

The major components in the unit are the failure/management
unit and the drive circuitry. In addition to the basic mix-
ing of the input signals to the drive amplifier, the electronic
unit has two EHSV loops: the direct feedback loop and the auto-
tracking loop. The direct feedback loop is to improve the
linearity of the EHSV, i.e., minimize the variation from unit
to unit. The autotracking loop uses a signal that is in-
herently developed in the failure/management error sensing
circuitry and is used to track the control paths. The lag
network is used to effect a track only in the low-frequency
spectrum, e.g., below 60 radians per second. The lead-lag net-
work was included to maintain loop stability. A detailed de-
sign of the circuitry for the electronic unit is shown in
Figure 5. This design is a step toward developing a flight
test model of the actuation system.

3.1.3 Actuator Assembly

The actuator assembly in each control channel consists of a
primary actuator, an AFCS actuator, and hydraulic switching
valves. A simplified version of the arrangement is shown in
Figure 3. Figure 6 is a schematic of the hydraulic system.
As shown, it uses two pump units in conjunction with switching
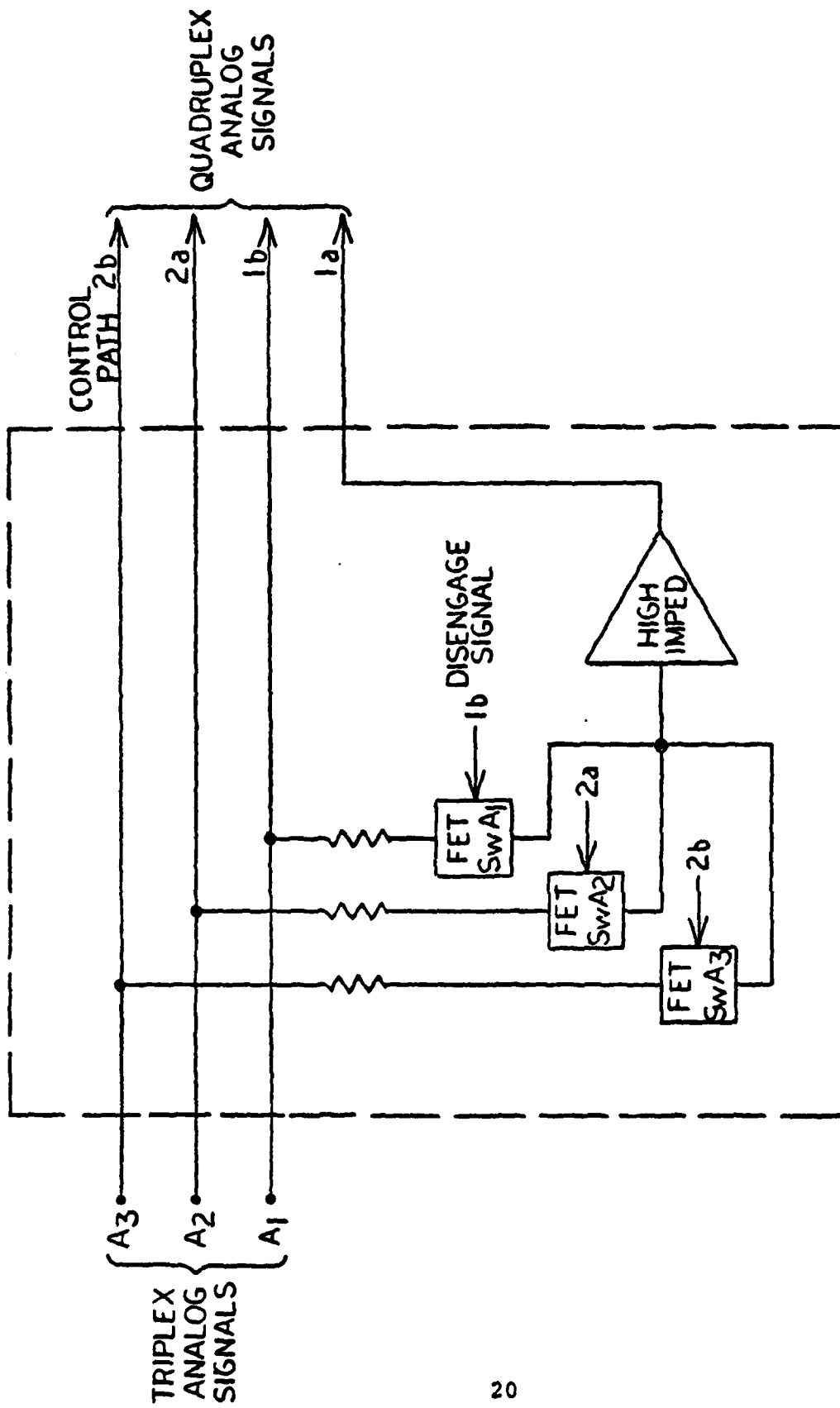valves to provide the primary actuator with an FTL of single

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Figure 4. Triplex/quadruplex interface unit.

20

+28

3.01k
1k
15k
150k
4.7k

6
4
5

8038
1
7

250

X

12
10

39k
.01

2

4 K.C.

1
31.2k
10k

6.8
.001

4 K.C. Oscillator

220Ω

2
.015

10k
100k

200k
2

X

+14

1k
10k

EHSV (LVDT)

Control Path 2a

10K

Control Path 1b
10K
10K
Control Path 1a

10K

Control Path 2b

10K

+28

7   8

3
6
+14.00

4
723
9

9.53k

2
1k

5
10K

Regulated Power Supply

To Triplex
F.E.T. Switch
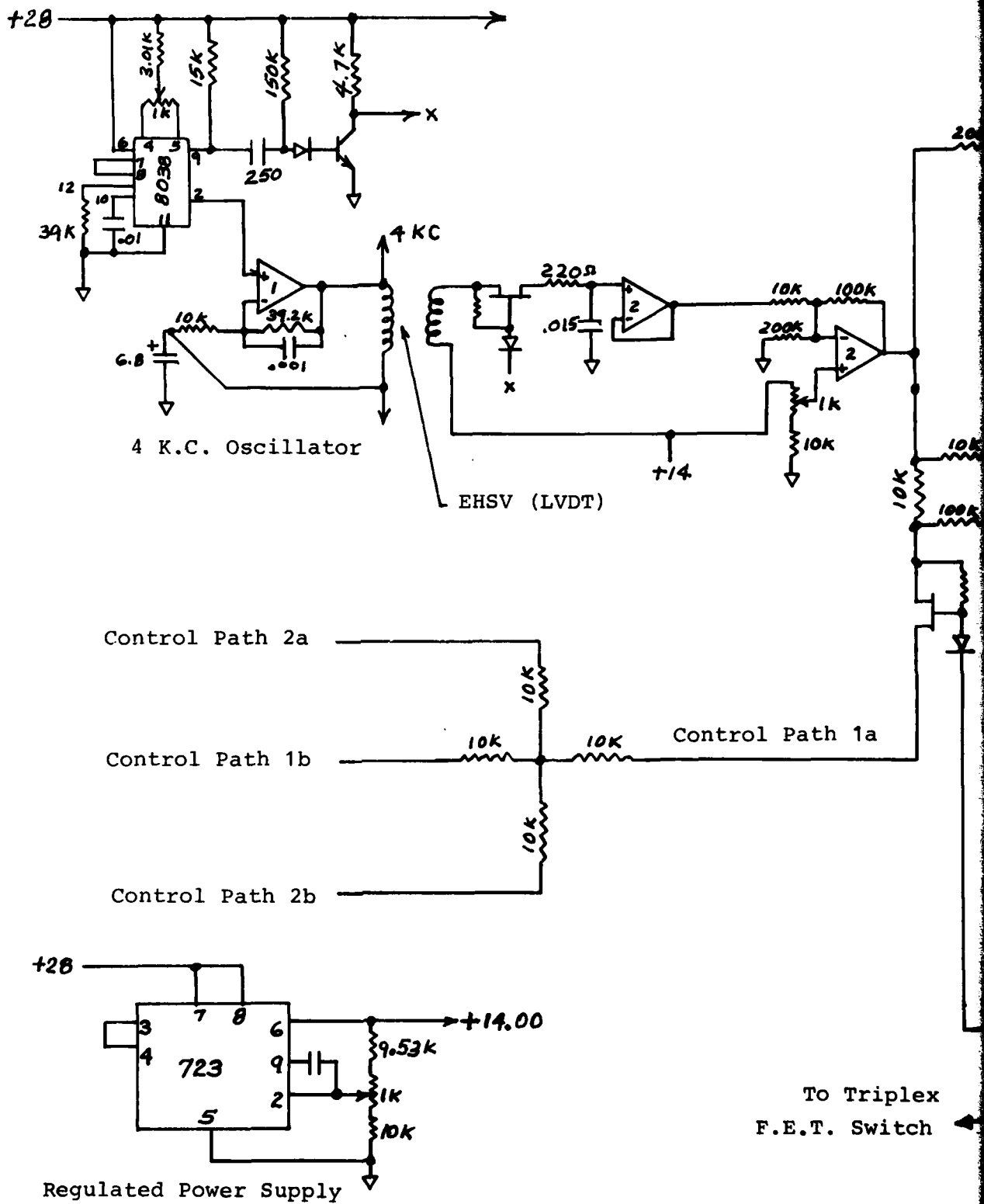
Figure 5. Detail circuit schematic of ēlectronic unit.

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Pilot Input (LVDT)

TO EHSV

Open EHSV Protection

Failure Management
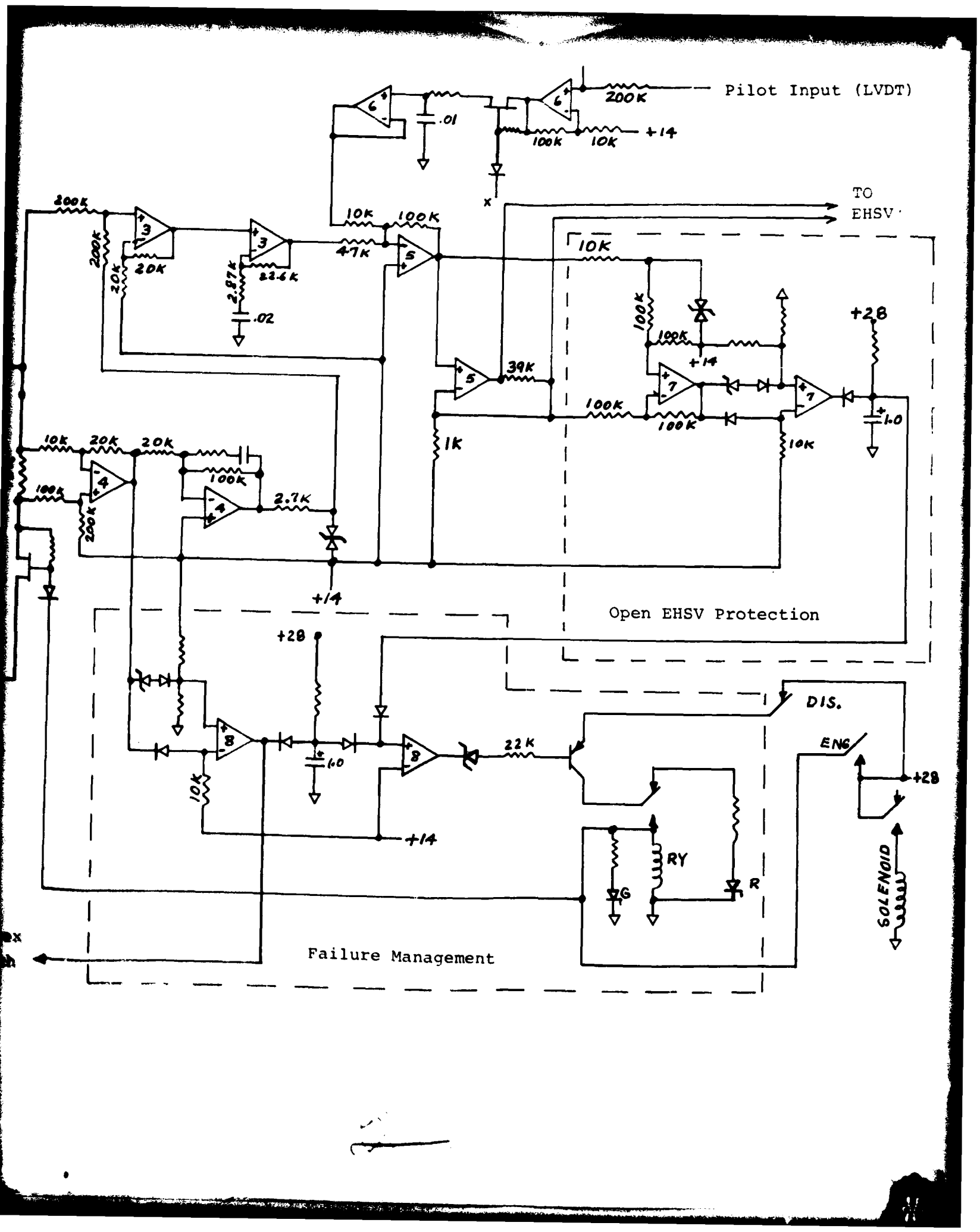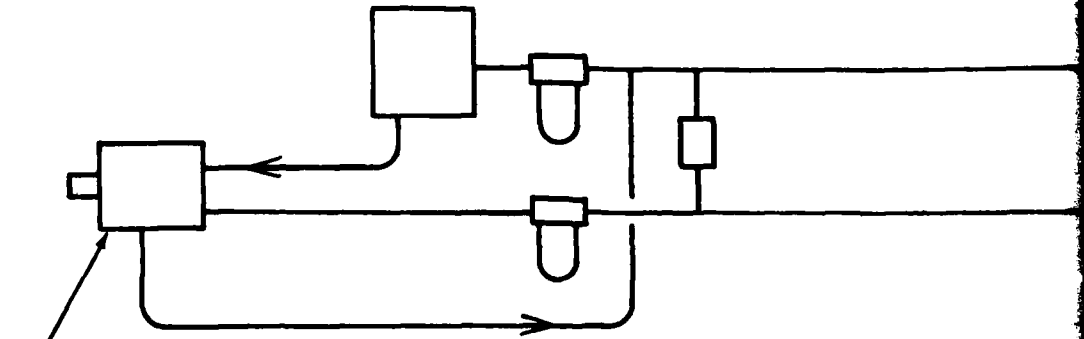
ADDED PUMP - TRANSMISSION
DRIVEN IF PAD AVAILABLE.
ELECTRIC MOTOR DRIVEN
IF PAD NOT AVAILABLE.

ADDED SYSTEM - PC - 2

RESERVOIR

RETURN FILTER

RETURN

RELIEF VA

SUCT

PUMP

PRESS

CASE DRAIN

PRESS FILTER
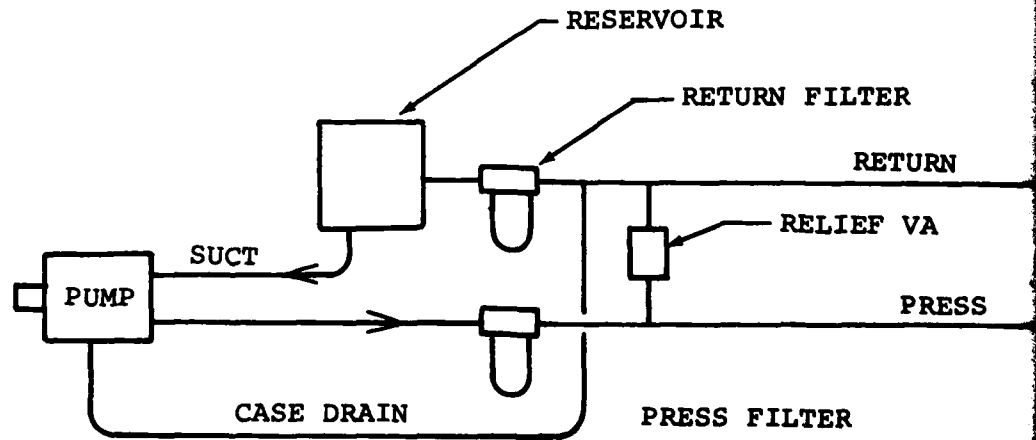
EXISTING SYSTEM - PC - 1

Figure 6. Schematic of hydraulic syste

DIRECTIONAL

LONGITUDINAL CYCLIC

COLLECTIVE

AFCS SERVO
ACTUATOR

MECHANICAL
SERVO ACTUATOR

LATERAL CYCLIC

SWITCHING VALVE
NORMALLY BIASED TO
PC-1 SWITCHES TO
PC-2 IF PC-1 FAILS
CONTAINS SOLENOID
TO TURN OFF PC-1
& PC-2 FOR MANUAL
FLIGHT CONTROL
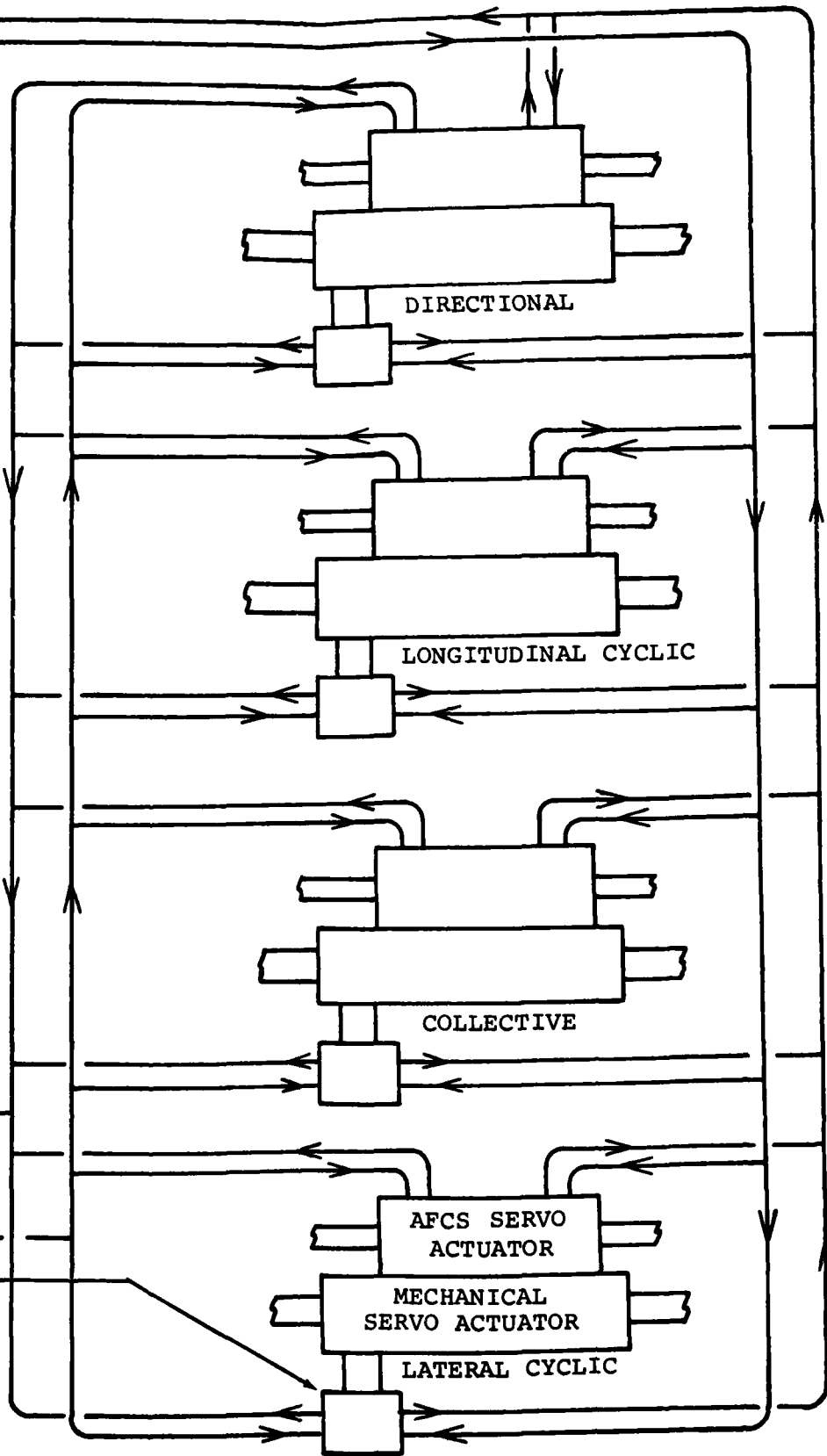
fail-operate. An FTL of single fail-operate is provided to the dual AFCS actuator by connecting each half to a separate pump.

A detailed schematic of the basic actuator assembly is shown in Figure 7. It consists of four EHSVs, four isolation valves, two bypass valves, dual AFCS cylinders, centering and locking mechanisms, switch valve, mechanical linkages, and the primary actuator that includes a mechanical control valve and a bypass valve. The mixing linkages are representative of how the pilot's input is mixed with the AFCS actuator to effect a series-type summation.

3.2 CONSTRUCTION OF A LABORATORY MODEL OF THE ACTUATION SYSTEM FOR ONE CONTROL CHANNEL

Figure 8 is a schematic of the laboratory test model of the fault-tolerant actuation system. Reference should also be made to Figure 2, which is a photograph of the laboratory model. The system was designed using existing equipment where possible. Hence, it is essentially the same functionally as the preliminary design but not physically the same. These functional differences are listed below.

- Triplex AFCS signals were simulated.

- Existing control panels were used and do not have an automatic preflight function.

- One hydraulic supply and valving were used to simulate dual supplies.

- One electrical supply and switches were used to simulate dual electrical supplies.

The remainder of the system is functionally the same.

3.3 DESIGN OF EQUIPMENT AND PREPARATION OF FAILURE TEST PLAN

The test system consists of a primary/AFCS actuator assembly; load actuator and associated control circuit; electronic control/failure management circuitry for the AFCS (4-valve) actuator; and a failure simulation panel. These equipments were designed for installation on a laboratory test stand equipped with hydraulic and electrical supplies that were configured to simulate dual supplies. As shown in Figure 8, either hydraulic supply will operate the primary actuator through a pressure-operated selector valve. Hydraulic supply

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PC-2
R P

CENTERING & LOCKING
MECHANISM (RATE
LIMITED)

SWITCHING VALVE
BIASED TO PC-2
FOR NORMAL OPERATION
IF PC-2 OFF OR FAILED
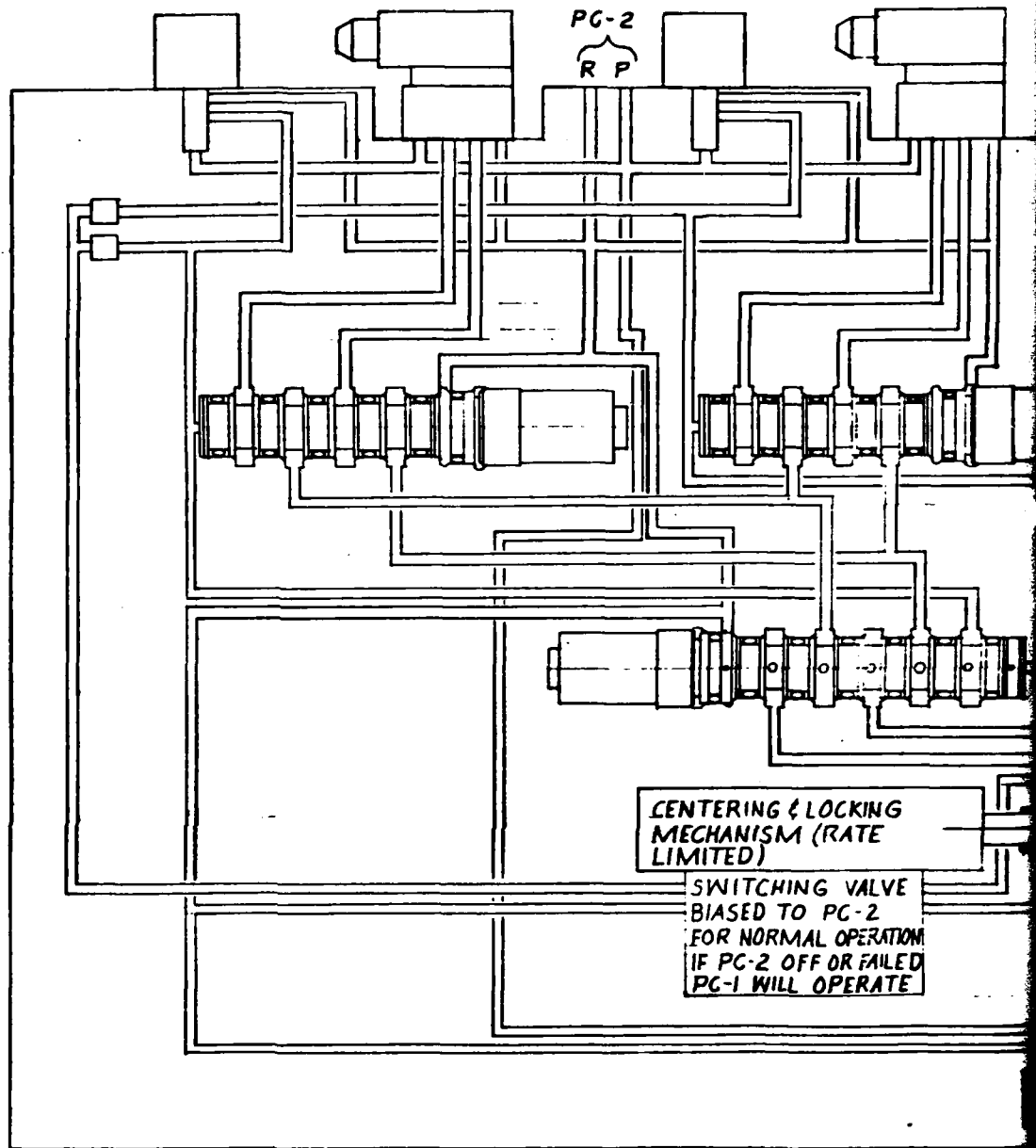PC-1 WILL OPERATE

CONTROL OUTPUT

Figure 7. Detail schematic of basic actuator assembly.

PG-1

R   P

SOL VA
(4) REQ'D

EH SERVO VA
(4) REQ'D

BLOCKING VALVE
(4) REQ'D

BY-PASS VALVE (2) REQ'D

MECHANICAL INPUT FROM PILOT

BY-PASS VALVE

SWITCHING VALVE BIASED TO PC-1 FOR
NORMAL OPERATION. SWITCHES TO PC-2
IF PC-1 FAILS. CONTAINS SOLENOID TO
TURN OFF PC-1 & PC-2 FOR MANUAL
FLIGHT CONTROL

PRESSURE OPERATED VALVING

HYDRAULIC   P₁
SUPPLY NO.1   R₁

BOOST ACTUATOR

BOOST VALVE

SP
CENT

PILOT MECH
INPUT

| 4 POTS | 4 EHSV's | 4 LVDT's |

FB2b FB2a FB1b   D1b D2a D2b   V1b V2a V2b

MANUAL SIMULATION
TRIPLEX AFCS
SIGNALS

ANALOG CONTROL
SIGNALS

A3   A2   A1

SEE FIG

ACTUATOR
FEEDBACK

V1a

TRIPLEX/QUADRUPLEX
INTERFACE

DEMODULATOR   FB1a

EHSV
DRIVE SIGNAL

EHSV

A2b   A2a   A1b

A1a

D1a

AMPL

EHSV

SEE DETAIL ELECTRICAL
SCHEMATIC FIG

LEAD-LAG
NETWORK

DEMODULATOR   V1a

LAG
NETWORK

AUTO-TRACK SIGNAL

2. F/M UNIT 1a ONLY, PROVIDES A COMMON POINT FOR E1a,E1b,E2a,E2b.
1. E1b,E2a,E2b ARE FROM RESPECTIVE F/M UNITS.
NOTES:

Figure 8.   System schematic of laboratory test model.

CONT CIRCUITRY

P2 HYDRAULIC
R2 SUPPLY NO.2

POT | EHSV

LOAD
ACTUATOR

SPRING
CENTERING

4-VALVE SCAS
ACTUATOR

V2b

TO EHSV 1a

DISENGAGE
SOLENOID

HYDRAULIC
SUPPLY

EHSV FEEDBACK

AUTO-DISENGAGE
SIGNAL

SEE NOTE 1

E1b E2a E2b

FAILURE/MANAGEMENT
UNIT 1a

2 b

2 a

1 b

ELECTRICAL
SUPPLY

E/D1a E/D1b E/D2a E/D2b

ENGAGE/DISENGAGE
SIGNALS
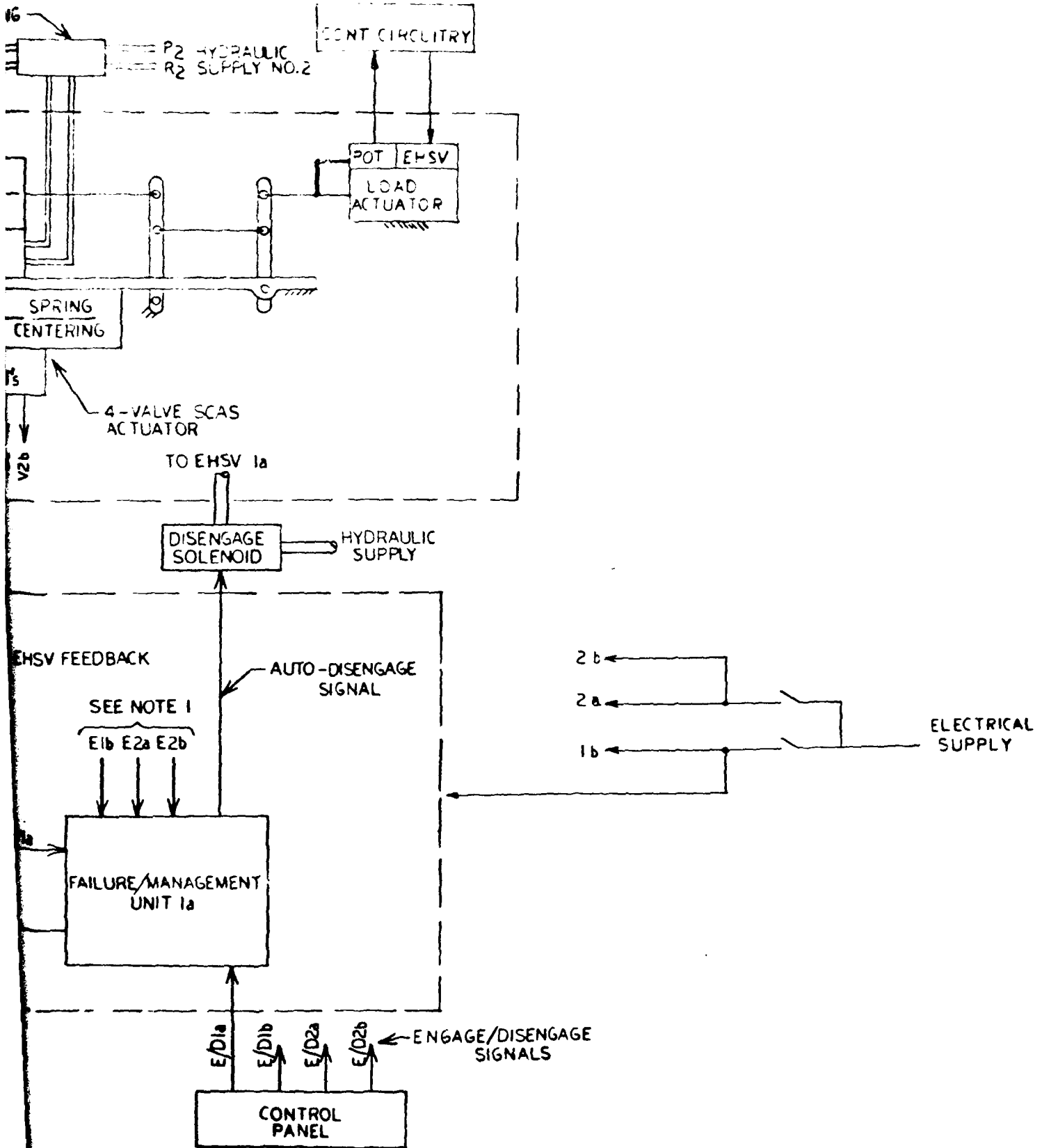
CONTROL
PANEL

No. 1 and Electrical Supply No. 1 provide power for Control Paths 1a and 1b while the No. 2 supplies provide power for Control Paths 2a and 2b. Figure 2 is a photograph of the equipment and the test stand.

3.3.1 Primary/AFCS Actuator Assembly

The AFCS (4-valve) actuator was interfaced with the primary actuator (see Figure 9) to effect a differential mixing with the pilot's input. Hence, the output of the primary actuator is a summation of the pilot's control input and the AFCS input. Some friction in the pilot's control was used to prevent motion of the actuator from being felt in the pilot's controls that could have occurred because of the short linkage arrangement.

The AFCS actuator has a displacement authority of about ±50 percent of the total displacement of the primary actuator. Hard stops were located on the output of the primary actuator to prevent overtravel of the control system. The spring centering device was logically interfaced with the AFCS actuation system so that it would center and lock in the absence of hydraulic pressure or electrical power on at least one solenoid valve.

The primary/AFCS actuator assembly was designed using existing hardware. The stroke of the AFCS actuator was limited to about 0.6 inch to allow an existing spring centering device to be used to center and mechanically lock the AFCS actuator when it is disengaged or in the event of total loss of electrical or hydraulic power. This configuration satisfies the functional requirements as planned. To evaluate it in the proper perspective, however, thresholds, failure effects, etc., have been evaluated in terms of percent of full stroke capability since the EHSV flow gains and associated loop gains were designed for compatibility with the actuator size and flow requirements. Also, the pilot's mechanical input to actuator output gain was mechanized so that full pilot stroke produced about 1.2 inches of actuator stroke; this ratio needs to be considered when qualitatively appraising the "feel" of the mechanical controls.

3.3.2 Load Actuator and Control Circuitry

The load actuator can be identified in Figure 9 as the actuator connected to the end of the pivoted beam. As shown, it was connected in parallel with the primary actuator so that it can be used for simulating reactionary loads from the output control elements e.g., the swashplate. The load actuator

CENTERING MECHANISM

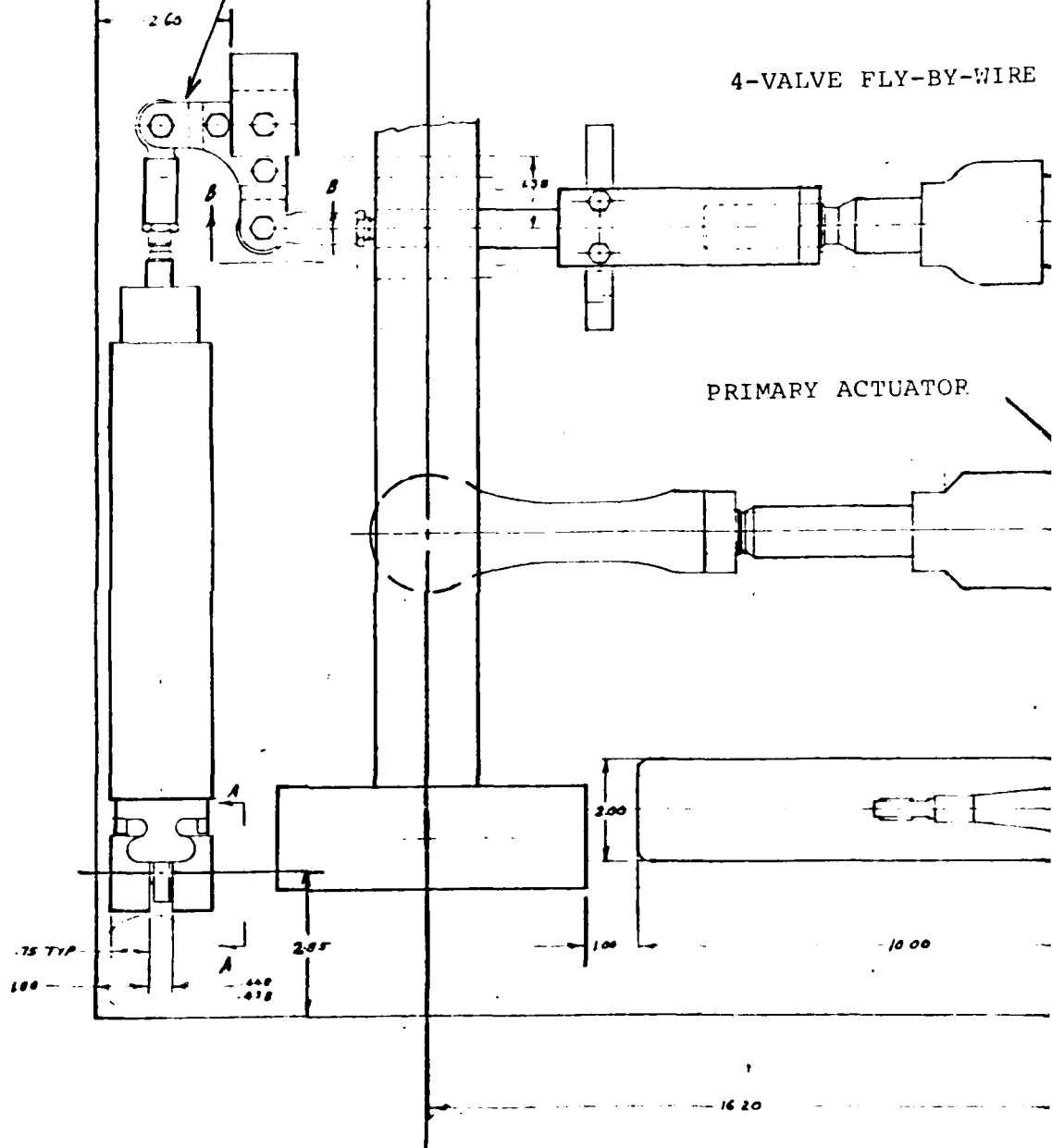LOAD ACTUATOR
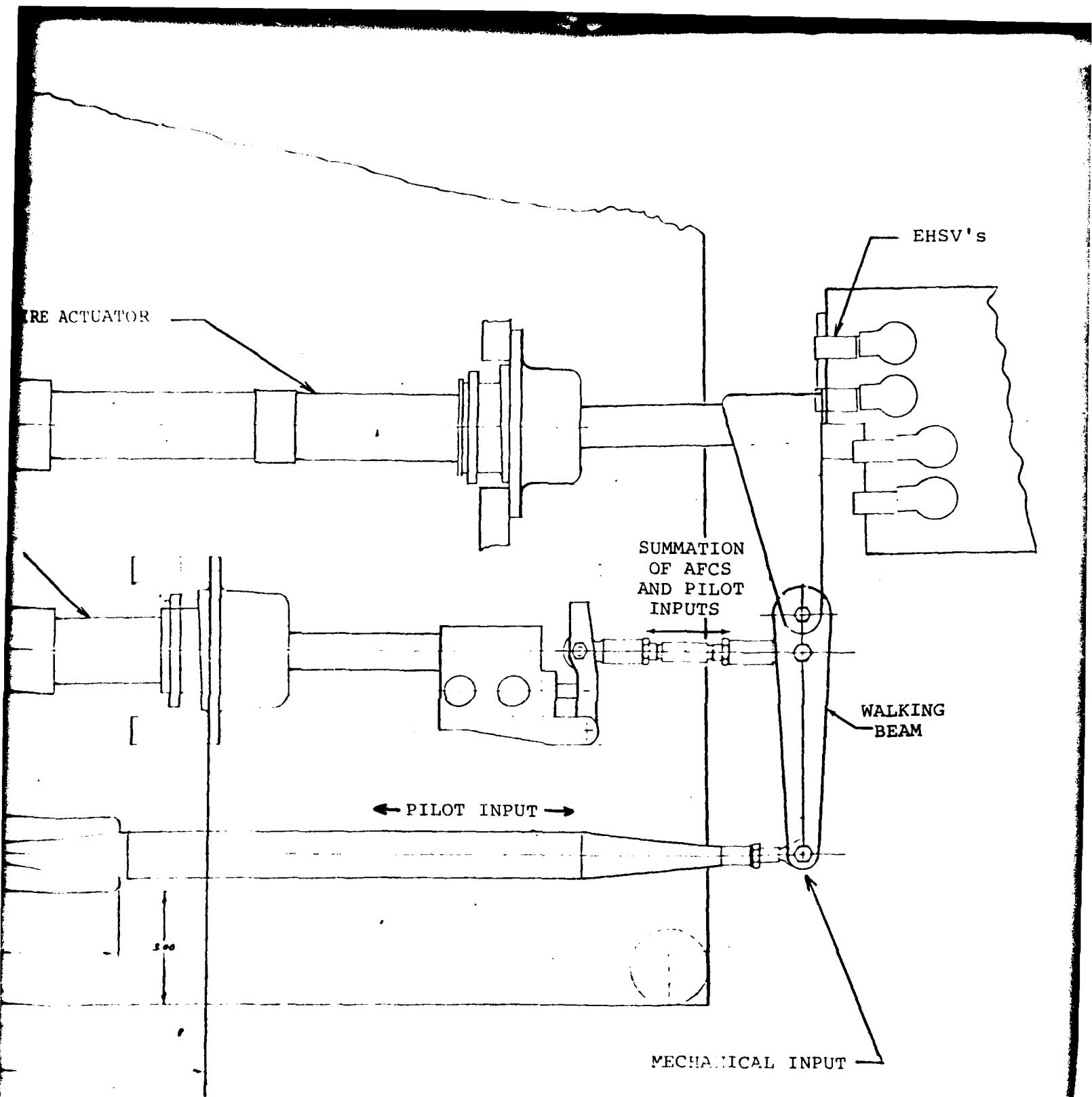
4-VALVE FLY-BY-WIRE

PRIMARY ACTUATOR

Figure 9. Plan layout of the actuator/control assembly.

EHSV's

IRE ACTUATOR

SUMMATION
OF AFCS
AND PILOT
INPUTS

WALKING
BEAM

← PILOT INPUT →

MECHANICAL INPUT

was controlled by the control circuitry, which can be identi-
fied in Figure 2 as the small circuit board on the lower
right. The circuitry was connected to the actuator to effect
a closed loop. A gain potentiometer was used to provide a
means for controlling the magnitude of the load. This
actuator and circuitry existed and was used without any mod-
ifications.

2.3.3   Electronic Control and Failure Management Circuitry

Figure 10 is a schematic of the failure management and elec-
tronic control circuitry as well as the test circuitry for
simulating failures. This circuitry is also shown in Figure
2. Each of the squares on the large circuit board and the as-
sociated drive signal constitutes a control path from the
T/QIU. The T/QIU is located on the lower portion of the
circuit board, which is immediately to the right of the large
board in the photo, and also schematically shown in Figure 10.
AFCS inputs were simulated manually with the lightweight
control stick shown in Figure 2, and schematically shown in
Figure 10, as the three potentiometers that provide a driving
signal for the T/QIU. A "sine wave" electrical signal was
also provided as an alternate means of driving the T/QIU. A
technical discussion of this unit is included in Appendix A.

3.3.4   Failure Simulation Panel

The Failure Simulation Panel is located immediately above the
T/QIU circuitry (see Figure 2) and is schematically shown in
Figure 10 for Control Path 1a. The switching circuitry pro-
vides the capability of simulating the following failure modes
for each control path.

- Transient input (pulse)

- Hard control path failure

- Hard and open failure in two triplex links (A1 and A2)

- Open EHSV coil

- Inert failure

3.3.5   Test Plan

An operational and failure mode test plan was prepared to pro-
vide a means of evaluating the operational and failure protec-
tion characteristics of the 4-valve actuation system and,
hence, to determine the validity of the system for use as an
AFCS actuation in a research test helicopter. This document
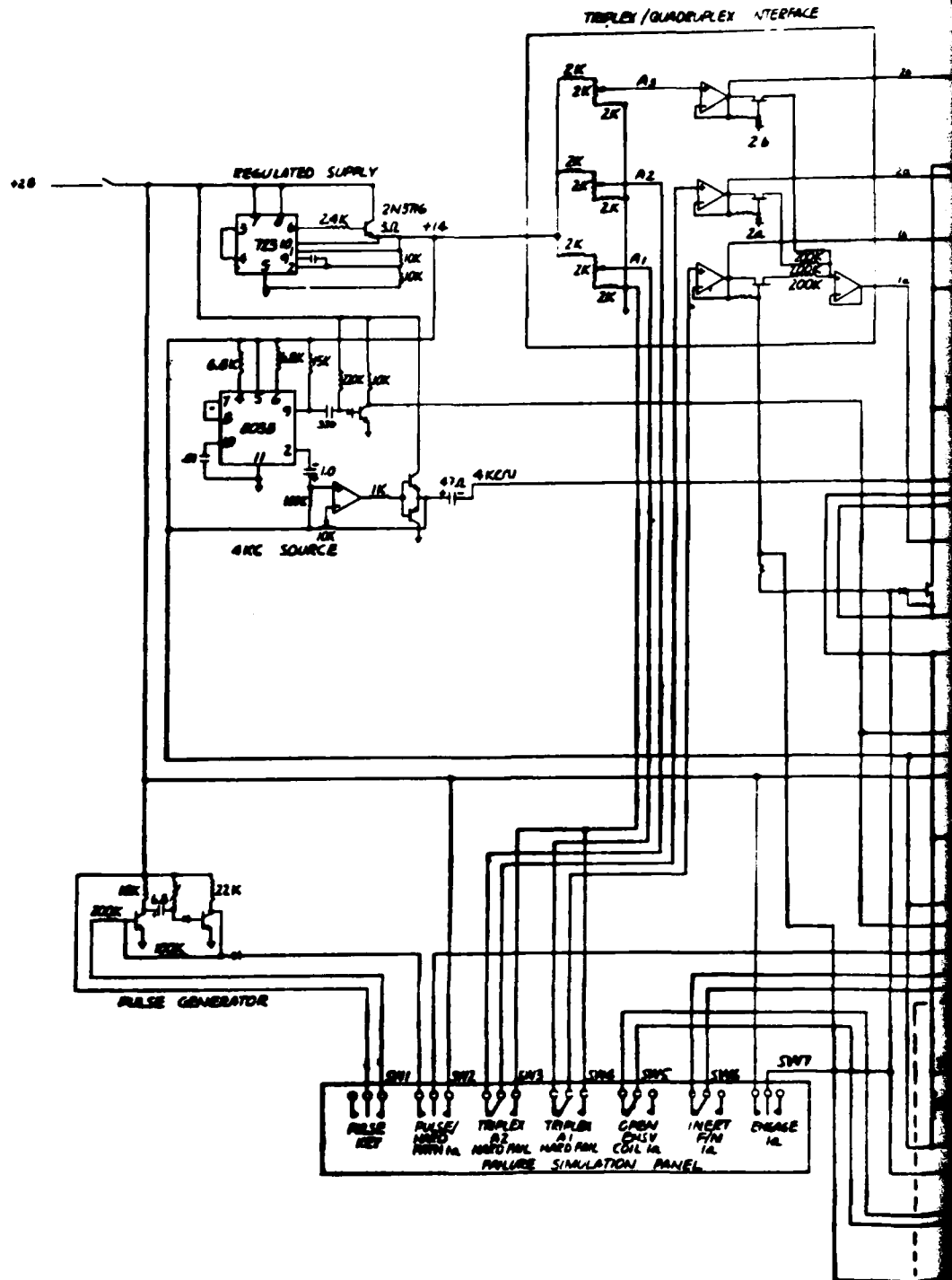is provided as a section in the appendices.

Figure 10. Schematic of the laboratory test model of the elect

lectronic unit.

3.4 FABRICATION PROGRAM

Most of the equipment for this program has been used previously in a Bell IR&D FBW program and only minor modifications were required. The most significant changes were associated with the configuration and interconnection of the actuators. The fabrication of these changes and others are discussed below.

3.4.1 Test Stand

The test stand depicted in Figure 11 existed and was provided by Bell. It was modified as required to accommodate the actuator/control assembly installation. As shown, the cyclic control stick and control tubes were added to provide the mechanical pilot input.

3.4.2 Actuator Assembly

The actuator assembly consists of a single piston primary actuator, 4-valve fault-tolerant actuator, centering actuation unit, and load actuator. All of these actuators existed and were used without modifications with the exception of the centering actuation unit. This unit was a modified AH-1G Cobra SCAS actuator. Bell provided the load and 4-valve actuators and Hydraulic Research Textron provided the primary, single-piston actuator, and the modified SCAS actuator. The actuators were fabricated into the configuration shown in Figure 9.

3.4.3 Electronic Circuitry

Some additional electronic circuitry was fabricated for use with existing circuit hardware. Figure 12 is a photograph of the existing circuit. Figure 11 shows this circuitry plus the added circuitry, which is the board on the right with the switches at the top. The T/QIU circuitry and failure simulation circuitry are fabricated on this board. The small circuit board, separate and on the right, is the electronic drive circuitry for the load actuator. It existed and was used without modifications.

3.4.4 Electrical/Hydraulic Power Supplies

Electrical and hydraulic switches were used in conjunction with laboratory power supplies to simulate redundant supplies. No fabrication was required.
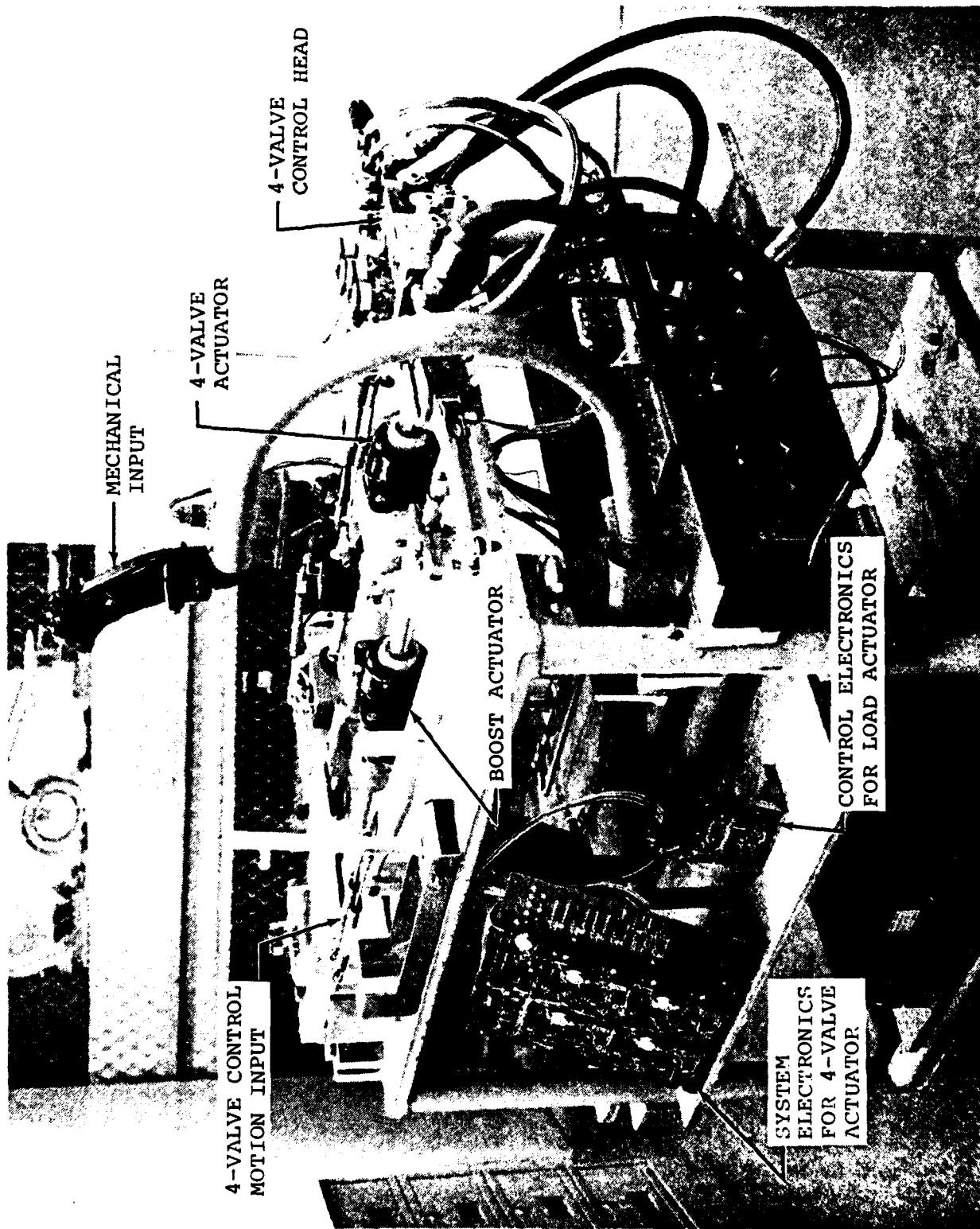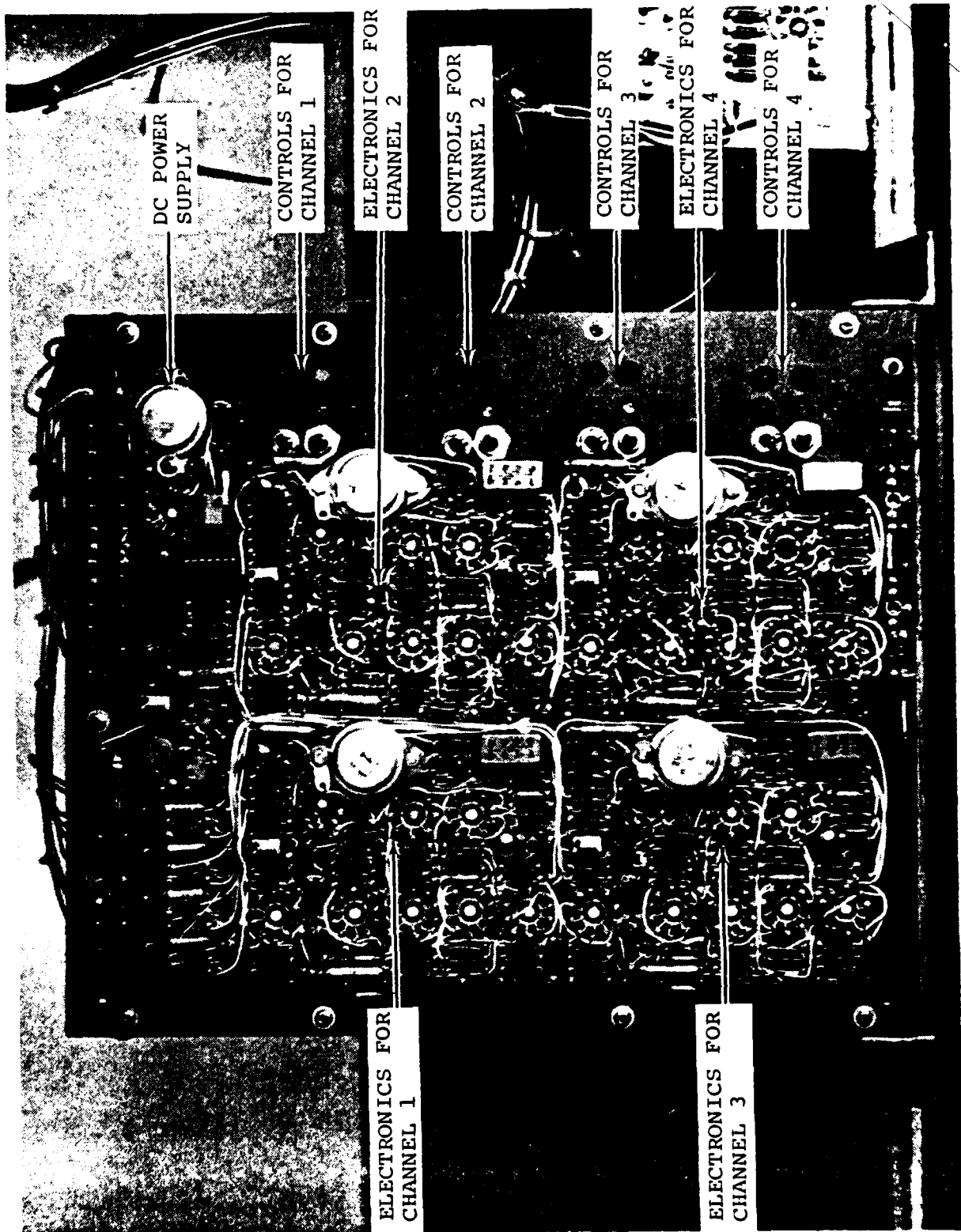
Figure 11. Laboratory test hardware.

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Figure 12. Electronic test circuitry.

3.5 TEST AND DEMONSTRATION PROGRAM

The test plan was prepared as a contracted item and has been
included as such in the appendices. The test instructions
from this plan have been integrated into this section and
presented along with the associated results of each test.
Figures 8 and 10 can be used, if necessary, to supplement the
following stated tests and results. The tests were conducted
in accordance with the test plan with some noted minor
variations.

Scope

The objective of the Integrated Test Program was to provide a
means of appraising the 4-valve actuation system as a candidate
actuation concept for use in the control system of a potential
test vehicle. It allows the actuation concept to be evaluated
in terms of operational suitability and its ability to tolerate
failures.

The following sections describe the test procedures and
results.

3.5.1 Functional Test

3.5.1.1 Primary/Load Actuator Configuration

Hydraulics OFF. With adjustable friction set for a minimum,
move pilot's control from stop to stop and check for freedom
of motion and interferences.

Results. System moved freely with no interferences.

Hydraulics ON. Move pilot's controls from stop to stop and
qualitatively check for operational suitability; note dead
spots, thresholds, breakout forces, etc. Turn off Supply
No. 1; Supply No. 2 should automatically take over. Apply
pressure to load actuator and with an appreciable amount of
load, move primary actuator from stop to stop to assure
proper operation.

Results. Primary actuator operated in a normal manner.
Motion was smooth with no appreciable dead spot. Loss of
hydraulic Supply No. 1 resulted in automatic transfer of
primary actuator to Supply No. 2, as was expected.

3.5.2 Fault-Tolerant AFCS Actuation System Alignment

The basic electronic circuitry was used on a previous pro-
gram and, hence, it was assumed that all the closed loops

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were stable. The control paths, however, were realigned to assure proper operation. Each control path was aligned and tested separately under the conditions stated below. Reference should be made to Figure 10 for supplemental information. It is pointed out that the operational amplifiers are operated at +28 VDC to ground with +14 VDC used as common.

3.5.2.1 Alignment and Test of Control Paths

Control Path 1a

  Conditions: • Hydraulic power on
           • Electrical power on
           • All solenoid valves disconnected
           • EHSV coil shorted across
           • TP5 shorted to +14 VDC
           • Control path 1a engaged

EHSV Tracking Loop

The purpose of the loop is to maintain EHSV track with the other EHSVs.

• Adjust "Pot 1" to null "TP1" (reference +14 VDC). This operation assumes the mechanical null of the EHSV is correct and aligns the tracking loop accordingly. The mechanical null is accurate to ±2 percent, which is considered an adequate reference since the second stage of the EHSV has an overlap of ±10 percent.

Results. Nulled tracking loop.

EHSV Feedback Loop

  Conditions: Same as above.

The purpose of this loop is to improve the linearity of the EHSVs and to help maintain the null alignment. This operation also assumes the mechanical null of the EHSV is correct and aligns the linearity loop accordingly.

• Adjust "Pot 2" to null "TP2" (referenced to +14 VDC).

Results. Nulled feedback loop.

These instructions were followed for all four paths with satisfactory results. When all channels had been aligned and the system returned to normal operation (all channels engaged), outputs from some of the tracking loops were higher than expected. With additional investigation, an alternate

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alignment procedure was developed with improved results. The alternate method consisted of the following procedure.

- All solenoid valves disconnected

- All EHSV coils shorted across

- All inputs to tracking loops shorted to +14 VDC

- All channels engaged

- Electrical and hydraulic power on

- All actuator position FB signals aligned (within 3 mv)

- All control signals aligned (within 11 mv)

New Results. All TP1s were nulled with their associated "Pot 1." All "TP2s" were nulled with their associated "Pot 2." With all shorts removed, all solenoids connected, and all control paths engaged, the tracking loops maintained outputs very near their nulled output (2 mv maximum).

Frequency Response Test

    Conditions: · Hydraulic power on (1300 psi)

                · Electrical power on

                · Solenoid valves disconnected

                · Shorts across EHSVs removed

                · Control paths engaged

                · Open SW4 and connect a frequency source across the normally closed contact to effect a series input

                · Short on TP 5 removed

- Adjust AFCS input to effect a null at TP5.

- Conduct frequency response of the control path and EHSV using the LVDT as the output element.

Results. The input signal was adjusted to drive the LVDT approximately 25 percent of maximum.

Control paths dynamically tracked well, and demonstrated a flat response to 50 Hz, and were down 6dB at approximately 140 Hz.

3.5.2.2 Alignment of Electrical Mechanical Transducers

Actuator Feedback Transducers

Conditions: • Hydraulic power on
             • Electrical power on
             • Solenoid valves connected
             • Control paths engaged

• Use AFCS simulation controller and position 4-valve actuator in increments and determine sensitivity in terms of volts per inch of actuator travel.

Results. 3.32 volts of AFCS signal produced one inch of actuator travel. Ratio of the AFCS signal to feedback signal is one.

• Use controller and drive 4-valve actuator in increments and measure track error from stop to stop.

Results. The maximum tracking error was 0.201 volt. This measurement was made at TP1, which is the output of an amplifier with a stage gain of ten. This amounts to about 1.5 percent of valve displacement and 0.06 percent of total pilot control authority.

• Trim feedback transducers using la as reference.

Results. The basic transducers are dual element potentiometers with 0.5-percent linearity. The end points did not mechanically coincide. To improve tracking, a trimpot was added to each pair of elements. All feedback transducers were adjusted for zero difference at the center position. This adjustment resulted in a maximum deviation of 40 mv over the total travel.

AFCS Simulation Control Transducers

Conditions: Same as above.

• Use same procedure as above on triplex controller for control paths A1, A2, and A3.

Results. The triplex simulated input utilizes the same type potentiometer as the feedback transducers. Alignment was accomplished by the same procedure used for the feedback transducer with equal results.

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• If necessary, trim the gain of summing amplifier in interface unit to make control path 1a track with other 3 paths.

Results. Control path 1a is derived by summing signal outputs from A1, A2, and A3. No trimming was required.

3.5.2.3 Auto Tracking Loop Test

Conditions:
- Hydraulic power on
- Electrical power on
- All solenoid valves disconnected
- All control paths disengaged

• Short TP5 to +14 VDC in all control paths to isolate the control input. Engage control path 2a, then the other paths, one at a time. Use pulse key on Failure Simulation Panel and apply pulse to control path 2a. Qualitatively observe the output of LVDT on an oscilloscope and note characteristics.

Results. Test indicated tracking loops were well damped.

• Disengage control path 2a, remove short from TP5 in all control paths. Connect path 2a solenoid. Engage control path 2a, 4-valve AFCS actuator will track simulated AFCS input. Drive AFCS actuator from stop to stop and examine for interferences over the complete range of the pilot's mechanical input. The friction unit on the pilot's controls will probably have to carry some friction because of the short link arrangements.

Results. Very little friction is necessary and no interference noted.

• Repeat with some load applied by the load actuator. Apply step input to AFCS actuator and observe stability characteristics with oscilloscope.

Results. Actuator loop was well damped.

• Engage all control paths and drive the AFCS actuator in increments over full travel and check tracking of each control path at TP6. This is the signal that is used through the limiting diodes at TP1 for autotracking as well as for a signal to the failure management circuitry.

Results. Data for automatic tracking are shown in Table 1. Maximum tracking error was 0.32 percent in terms of actuator travel.

TABLE 1. CONTROL PATH TRACKING DATA

% Travel Transducer	Control Path	Transducer Control Volts	Actuator Feedback	TP1	TP2	TP3	TP6
0	1a	-7.98	-6.04	+0.124	+0.112	-0.05	0.082
0	2a	-8.00	-5.99	+0.042	+0.007	+0.08	0.083
0	1b	-7.99	-6.00	+0.078	+0.029	-0.72	0.067
0	2b	-7.95	-6.00	-0.044	-0.092	-0.52	0.076
25	1a	-7.61	-6.39	+0.094	+0.094	+0.03	0.067
25	2a	-7.63	-6.36	+0.057	+0.014	+0.06	0.082
25	1b	-7.62	-6.37	+0.120	+0.072	-0.72	0.061
25	2b	-7.58	-6.37	-0.039	-0.087	-0.60	0.070
50	1a	-7.02	-6.96	+0.005	-0.013	-0.01	0.00
50	2a	-7.02	-6.96	+0.042	-0.012	+0.03	0.00
50	1b	-7.03	-6.96	+0.096	+0.025	+0.80	0.00
50	2b	-7.02	-6.96	+0.093	+0.020	-0.48	0.00
75	1a	-6.61	-7.36	-0.012	-0.008	-0.21	0.066
75	2a	-6.63	-7.37	+0.123	+0.090	+0.12	0.080
75	1b	-6.63	-7.36	+0.092	+0.050	+0.14	0.062
75	2b	-6.59	-7.37	+0.045	-0.002	-0.48	0.070
100	1a	-6.30	-7.66	-0.048	-0.058	-0.09	0.065
100	2a	-6.32	-7.68	-0.138	+0.087	+0.20	0.080
100	1b	-6.31	-7.65	+0.048	-0.010	-0.87	0.061
100	2b	-6.28	-7.68	+0.045	-0.055	-0.52	0.070

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3.5.3 Composite Test

The composite test is a quick check to assure that simultaneous operation of the primary actuator and AFCS actuator does not create any mechanical interferences or objectionable "feel" in the pilot's controls.

    Conditions: · Electrical power on
                      · Hydraulic power on
                      · 4 control paths engaged

  · Simultaneously apply a varying input to the AFCS actuator while the primary actuator is being driven throughout its displacement range.

Results. No mechanical interferences.

If any mechanical interferences or objectionable pilot "feel" characteristics are present, they should be cleared before proceeding to the Operational Suitability Test. It is pointed out that the pilot will feel the motions of the AFCS actuator when the sum of the AFCS actuator and his input exceeds the downstream stops. This should be recognized as a normal cue that the controls are against the stops.

3.5.4 Operational Suitability Test

This test is similar to the above functional composite test with the exception that the operating conditions will be varied and some parameters will be measured and recorded. The purpose of this test is to provide information pertinent to the judging of the operational suitability of the 4-valve actuation concept.

3.5.4.1 Characteristics Under Normal Conditions

    Conditions: · Electrical power on
                · Hydraulic power on
                · 4 control paths engaged
                · Load actuator adjusted for typical static load

  · Measure displacement threshold of pilot controls in terms of inches at top of stick. This will actually show up as a "dead spot" in the controls. For this to be meaningful, the measurement should be corrected to reflect the difference in the short linkage control ratio and control ratio in the test helicopter.

<u>Results</u>. The corrected threshold was ±0.09 inch.

- Measure the AFCS input threshold in volts required from the simulated inputs to effect a displacement of the 4-valve actuator. As in the above case, this measurement should be corrected to read in terms of percent of the actual capable travel of the 4-valve actuator.

<u>Results</u>. The AFCS actuator displacement is mechanized to operate the primary actuator valve. Unless loads on the primary actuator exceed its capability, the AFCS actuator is essentially unloaded at all times. Under the above-stated conditions, ±4 mv of input signal was adequate to move the 4-valve actuator. This test was performed by observing the feedback voltage and moving the control motion transducer until a noticeable change was produced in the feedback voltage. The 4-valve actuator has a total travel of 4.0 inches but was restricted to 0.50 inch. This scaling was necessary due to the actuator-centering mechanism. In terms of limited actuator travel, the deadband represented 0.24 percent of 0.50 inch; in terms of total actuator travel, the deadband represented 0.03 percent.

- Qualitatively evaluate pilot and AFCS characteristics while both are operating simultaneously. Observe objectionable "dead spot" effects that may occur when the direction of the AFCS actuator is reversed.

<u>Results</u>. There were no apparent dead spots in the pilot's controls.

3.5.4.2 <u>Characteristics Under Single Failure Conditions</u>

<u>Conditions</u>:
- Same as 3.5.4.1 except with control
- Path la disengaged.

<u>Procedure</u>:   Same as 3.5.4.1.

<u>Results</u>. Hydraulic flow gain and, hence, the bandwidth was reduced to some degree in the 4-valve actuator; however, there was no apparent change in the pilot's controls. Force gain remained the same.

3.5.4.3 <u>Characteristics Under Dual Failure Conditions</u>

<u>Two Companion Control Paths</u> (shares same piston)

<u>Conditions</u>:   Same as 3.5.4.1 except with control Paths la and lb disengaged.

<u>Procedure</u>:   Same as 3.5.4.1.

Results. Flow gain remained unchanged but force gain was re-
duced by 0.5. No apparent change in pilot's control, however.

Two Control Paths not Sharing Same Piston

Conditions: Same as 3.5.4.1 except with control paths
                 1a and 2a disengaged.

Procedure: Same as 3.5.4.1.

Results. Flow gain reduced by 0.5, but force gain remained
the same. No apparent change in pilot's control.

One Control Path And Associated Failure Management Circuit

Conditions: Same as 3.5.4.1 except with control path
                 1a failed "hard" and failure management
                 circuit 1a inoperative.

Procedure: Same as 3.5.4.1.

Results. The system was stable. Control path 1a EHSV was
completely open, which resulted in an increased deadband of
±20 mv and a static displacement of 0.04 inch.

3.5.4.4 Characteristics Under Failure of One Electrical
         Supply

Conditions: Same as 3.5.4.1 except electrical supply
                 to control paths 1a and 1b off.

Procedure: Same as 3.5.4.1.

Results. Control paths 1a and 1b were automatically dis-
engaged. Operation was same and with same results as for
failure of two companion control paths when 1a and 1b channels
were disengaged. The deadband was ±2 mv.

3.5.4.5 Characteristics under Complete Failure of Electrical
         and Hydraulic Power

Conditions: Same as 3.5.4.1 except all electrical and
                 hydraulic power supply turned off.

Procedure: Same as 3.5.4.1 except no test required on
                 AFCS.

Results. AFCS actuator automatically centered. No restric-
tions in mechanical or hydraulic system were experienced other
than normal friction load.

3.5.5 Failure Modes and Effect Test

The tests in this section cover the basic type of failures
that can occur. The intent was to validate the 4-valve actua-
tion concept as a viable fault-tolerant actuation system. The
AFCS control paths, up to and including the EHSV's, were
tested to assure an FTL of dual fail-operate for the worst
conditions. The electrical and hydraulic power systems were
tested to assure that the failure effects on the total system
would result in an FTL of single fail-operate and dual fail-
safe. The failure modes covered in the subsequent
subsections were simulated using the switches on the Failure
Simulation Panel, four electrical power switches, two
hydraulic hand valves, and combinations of these input
devices. Pertinent parameters were measured and recorded to
define failure effects. The measurements were made using an
oscilloscope. Except as noted, all initial conditions were
for all control paths and power supplies to be operating.

3.5.5.1 Control Paths and Failure Management System

Transient Disturbances

The purpose of this test was to show tolerance to EMI-type
disturbances.

Short Pulse - Control Path 1a Only

- Position SW2 to Pulse position and use SW1 momentarily to
  apply pulse (about 0.2 sec). Applied pulse should result
  in a short duration jump of the actuator. Control path
  1a should tolerate this disturbance and not disengage.

Result. The 0.2-second disturbance to the actuator resulted
in a jump of 0.044 inch and restored to original position.

- Adjust pulse width to approximately 0.4 second and apply
  pulse to path 1a (disengage delay time set for 0.35
  second).

Result. Control path 1a disengaged and the system restored.

- Reengage control path 1a.

First Hard Failure

This test is to demonstrate the ability of the system to manage
hard failures.

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- Position SW2, control path 1a to HARD to simulate a hard
  failure. Use oscilloscope and measure and record actu-
  ator displacement and time required for recovery.

Result. Control path 1a disengaged. First hard failure
displaced the actuator 0.044 inch and the system restored after
the control channel was disengaged after a time delay of 0.35
second, which was arbitrarily established for the test model.

Second Hard Failure

This test is to demonstrate the ability of the system to manage
dual hard failures.

- Position SW2, control path 2a, to HARD to simulate a
  second hard failure. Control path 2a should disengage.
  Measure and record actuator displacement and time
  required for recovery.

Result. Control path 2a disengaged. The second failure re-
quires a higher disagreement between the EHSV's than for the
first failure, which assures a more positive failure. First
failure requires a faulty path to cause a disagreement of about
40 percent (of total EHSV displacement) with the other EHSVs
to effect a disengagement. The second failure requires a
disagreement of 45 percent. The remaining two control paths
continued to operate in a normal manner.

The recovery time was 0.35 second as was expected; the dis-
placement was 0.1 inch.

- Reengage control paths 1a and 2a.

Single Inert Control Path Failure

This test is to demonstrate the ability of the system to sense
inert-type failures without requiring large valve displacements.

- Position SW5, control path 1a to OPEN to simulate an open
  EHSV coil. Simulate an AFCS input; control path 1a
  should disengage immediately.

Results. SW5 opened the EHSV coil that controls the LVDT
feedback signal in a high gain negative feedback loop. Unless
the control path under test is perfectly nulled, the open coil
will be detected immediately and the respective control paths
will disengage with no actuator jump. Under no condition was
an AFCS signal greater than ±2 mv required to effect a disen-
gagement.

- Reengage control path 1a.

Dual Inert Control Path Failure

This test is to demonstrate the ability to manage two inert failures. If these are not properly managed, a "two-and-two" vote condition can occur. This system recognizes the condition and will disengage both faulty control paths.

- Position SW5, control paths la and lb to OPEN to simulate two open EHSV coils. Simulate an AFCS input, control paths la and lb should both disengage. Measure the magnitude of the AFCS signal required to effect the disengagement.

Result. At no time during demonstration did the two channels fail to disengage. Disengagement occurred instantly when the two switches were opened.

- Reengage control paths la and lb.

Failure/Management Circuitry Failure Plus Associated Control Path Failure

This test is to demonstrate the capability of the system to operate with one control path failed and not isolated by the normal disengagement.

- Open SW6, control path la, to simulate an inert Failure Management System. Position SW2, control path la, to HARD to simulate a hard failure. The hard failure should not effect a disengagement since the associated failure management circuitry is inoperative; the fault-tolerant actuation system should still be operable but with a slight static offset. Measure and record this offset.

Result. The offset was recorded to be 0.044 inch of actuator. System functioned in a normal manner. Threshold was ±2 mv.

- With the pilot's control locked, record the stall load for this condition in terms of pressure on load actuator.

Result. 500 psi was required to effect a stall condition. The primary actuator stalled at a pressure less than 500 psi.

- Close SW6; control path la should disengage.

<u>Results</u>. Control path 1a disengaged in the normal delay time after SW6 was closed.

- Disengage control path 1b.

- With the pilot's mechanical controls locked, measure stall load. This should be about the same as for the above dual failure condition.

<u>Results</u>. 500 psi hydraulic pressure on the load actuator stalled the AFCS as was expected. This indicated that for the preceding test condition, the affected piston was essentially bypassed by the operation of the hard failed EHSV and the companion EHSV.

First Failure of Triplex Control Path

This test is to demonstrate the capability of managing two failures in the Triplex AFCS ahead of the interface unit.

- Position SW4 to OFF to simulate a failure in the triplex control path A1. Control path 1b should disengage. Control path 1b has a shorter time delay than 1a and operates the 1b disengagement solid state switch in the interface unit before control path 1a can disengage. After the switch has operated to effect an open to A1, control path 1a will restore itself to correctly track with control paths 2a and 2b.

<u>Results</u>. Loss of signal A1 caused EHSV coil 1b to have a hard signal and the system reacted the same as for a hard failed signal. The control path automatically disengaged after the failure management delay time.

Second Failure of Triplex Control Path

This test is to demonstrate that the system will tolerate two failures on the triplex control paths and still operate.

- Position SW3 to OFF to simulate a failure in triplex control path A2. Control path 2a should disengage. As in the above condition, control path 1a will temporarily be out of track until control path 2a is disengaged.

<u>Results</u>. The temporary disruption in the first failure caused the actuator to jump more than normally experienced for a first hard failure. Due to the triplex/quadruplex design, a failure in either of the triplex signals created a failure in the dummy control path 1a as well as the failed control path. Control path 1a has a longer delay than control paths

2a, lb, or 2b and did not disengage; however, on the second
failure, two additional control paths would trip out. Cir-
cuitry was added to immediately switch out the failed signal
with the FET switch that is connected to the dummy channel.
This immediately allows the dummy control path to track pro-
perly again as well as to reduce the actuator jump. This addi-
tional circuitry allows two control paths of the 4-valve sys-
tem to work properly after two of the triplex signals have
failed and allow control path la to track properly at all
times. The dual fail-operate exceeds the single fail-operate
requirement.

- Returned SW3 and SW4 to ON position and reengaged con-
  trol paths lb and 2a.

3.5.5.2 Electrical Power Supply

Single Failure

This test is to demonstrate the capability of the actuation
system to continue operating after one electrical power supply
has failed. Power Supply No. 1 provided power to control paths
la and lb while Supply No. 2 provided electrical power to
control paths 2a and 2b. The existing power switches on the
engage/disengage panel were used to simulate electrical power
supplies No. 1 and 2.

- Position power switches for control paths la and lb to
  OFF.

Result. Control paths la and lb disengaged. Control paths
2a and 2b continued to operate in a normal manner. The loss
of the two control paths does not change the "flow gain" of
the actuator; however, the force gain was reduced to one-
half of the normal gain.

Dual Failure

Purpose of this test is to demonstrate that if both electrical
supplies fail, the AFCS actuator will automatically center at
an acceptable rate and mechanically lock and provide a pivot
for the pilot's mechanical control input. The second failure
is fail-safe in that the pilot can still fly with boosted
manual controls.

- With the AFCS actuator fully extended in one direction,
  position the power switches for the two power supplies to
  the OFF position. Measure time required for the AFCS
  actuator to center.

<u>Result</u>. All control paths disengaged and the AFCS actuator centered and mechanically locked. Actuation system reverted to boosted manual controls. Normal time was approximately one second for actuator centering.

- Position all electrical power switches to ON.

3.5.5.3 <u>Hydraulic Power Supply</u>

<u>Single Failure</u>

This test is to demonstrate that the system will tolerate a hydraulic supply failure and continue operating.

- Close the No. 1 manual valve to simulate a failure of Hydraulic Supply No. 1.

<u>Result</u>. The pressure-operated/spring-return bypass valve across Piston No. 1 opened to the bypass position so that Piston No. 2 operated unrestricted. Control paths 1a and 1b did not disengage because of a "two-and-two" vote condition. This is a plus since it demonstrates the AFCS actuator is not vulnerable to hydraulic transients. In addition, the pressure-operated valve on the primary actuator operated to connect Hydraulic Supply No. 2 to the primary actuator.

<u>Dual Failure</u>

This test was to demonstrate that the actuation system was fail-safe after two hydraulic failures in that it will revert to manual control.

- Close the No. 2 manual valve to simulate a failure of Hydraulic Supply No. 2.

<u>Result</u>. The pressure-operated/spring-return bypass valve across Piston No. 2 moved to the bypass position and allowed the centering unit to center and lock the AFCS actuator. This provided a fixed pivot for the pilot's input. In addition, the pressure-operated/spring-return valve across the primary actuator operated to effect a bypass on the piston to allow freedom of movement and, hence, revert to unboosted controls.

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4. RECOMMENDATIONS

This program and the BHT IR&D program have confirmed the
validity of the 4-valve actuation concept for use in applica-
tions that require fault-tolerant actuation systems. Hence,
it is recommended that further steps be taken toward obtain-
ing a flight test model of a control system using this con-
cept. In a subsequent program, it is recommended to go to a
full FBW control system and to use the 4-valve actuator as
the primary actuator. This approach would afford a "smart"
control system and also delete the mechanically driven primary
actuator as well as the associated mechanical interface. It
is pointed out, however, that during the development flight
test of such a system, the mechanical controls could be re-
tained as a backup control system for the safety pilot. At
some later date after the reliability of the FBW control
system has been validated, the mechanical controls could be
removed. The objective of this follow-up effort would be to
validate a flight test model.

The objective could be obtained in the three-phase program
outlined below.

4.1 PHASE I

This phase would be to develop circuit and actuator configura-
tions suitable for use in a flight test model. This would in-
clude designing, fabricating, and testing a laboratory model
of the circuitry and the FBW actuator with the auxiliary me-
chanical backup controls.

4.2 PHASE II

Prototype hardware for the flight test model would be fabri-
cated and qualified under this phase to the extent necessary
for safety of flight. Phase II should also include a system
integration bench test.

4.3 PHASE III

The flight test model of the 4-valve FBW control system with
the auxiliary mechanical backup control would be validated
in this phase. It would include installation, ground test,
ground run, and flight test. Extensive failure mode testing
would be accomplished during ground test and ground run.
The ground run test would also include a prescribed number
of hours with all the controls being moved periodically. A
minimum of twenty hours of flight time would be required.

After the developmental flight test program, it is recommended that the aircraft be assigned to duty in an area where cognizant personnel could maintain the control system and provide quality maintenance records. After the system had been qualified to a specified maintenance program as well as a specified number of flight hours, the 4-valve FBW control system would be considered validated and subject to being used in production aircraft.

APPENDIX A

TECHNICAL DISCUSSION OF A 4-VALVE ACTUATION CONCEPT

INTRODUCTORY COMMENTS

This section describes the basic 4-valve actuation concept as
it relates to the basic control elements. It provides a con-
ceptual description of the electrical links, electrohydraulic
interface, power actuators, and failure management system.
The actuator configuration may be a redundant tandem piston or
a parallel actuator configuration. To facilitate the descrip-
tion of the concept in the subsequent subsections, a conven-
tional dual tandem piston configuration will be used (see
Figures A1 and A2).

To provide a viable fault-tolerant control system, it is
necessary to have an adequate number of reliable control paths
and actuators for each control channel and, also, a com-
patible, secure failure management system. The system
described in the following material satisfies the control
channel requirement and includes a unique concept for sensing
and isolating a failed and/or degraded control path.

DESCRIPTION OF CONCEPT

Summary. The basic fault-tolerant actuation system consists
of dual hydraulic primary actuators, quadruplex electrical
control paths, and a failure management system. Two electri-
cal control paths are used for each piston. The failure
management system is mechanically interfaced with the elec-
trical control paths to provide maximum security. It provides
automatic disengagement of a control path and also provides
track error signals that are used in the control paths for
automatic alignment of the four valves.

A flight test model of this system would include a master
control panel and an annunciator panel. The control panel
would provide the necessary control functions, preflight
checkout capability, and a manual reset for each control
channel. The annunciator panel would indicate the operating
condition of the control paths and would operate in conjunc-
tion with the control panel for the preflight checkout.

FBW Control Paths. A control axis of the basic 4-valve actu-
ation concept consists of four FBW control paths and a dual
piston power cylinder. The four control paths connect the
AFCS signals to the power actuator cylinder and include the
four electrohydraulic servovalves as shown in Figure A2.

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MECHANICAL
CONTROL HEAD

TYPICAL HYDRAULIC BOOST ACTUATOR

ELECTROHYDRAULIC SERVOVALVES

MANIFOLD ASSEMBLY
(REPLACES MECHANICAL
CONTROL HEAD)
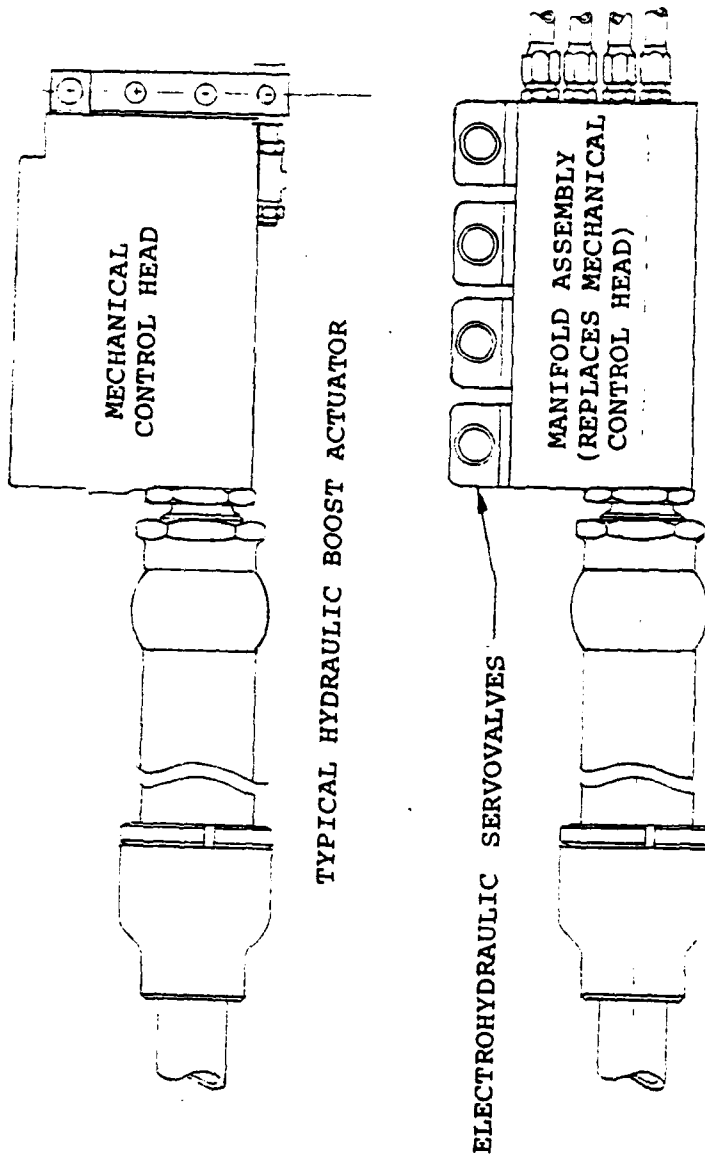
BOOST CYLINDER MODIFIED TO FLY-BY-WIRE CONFIGURATION

Figure A1. Conventional hydraulic boost actuator and proposed fly-by-wire actuator.
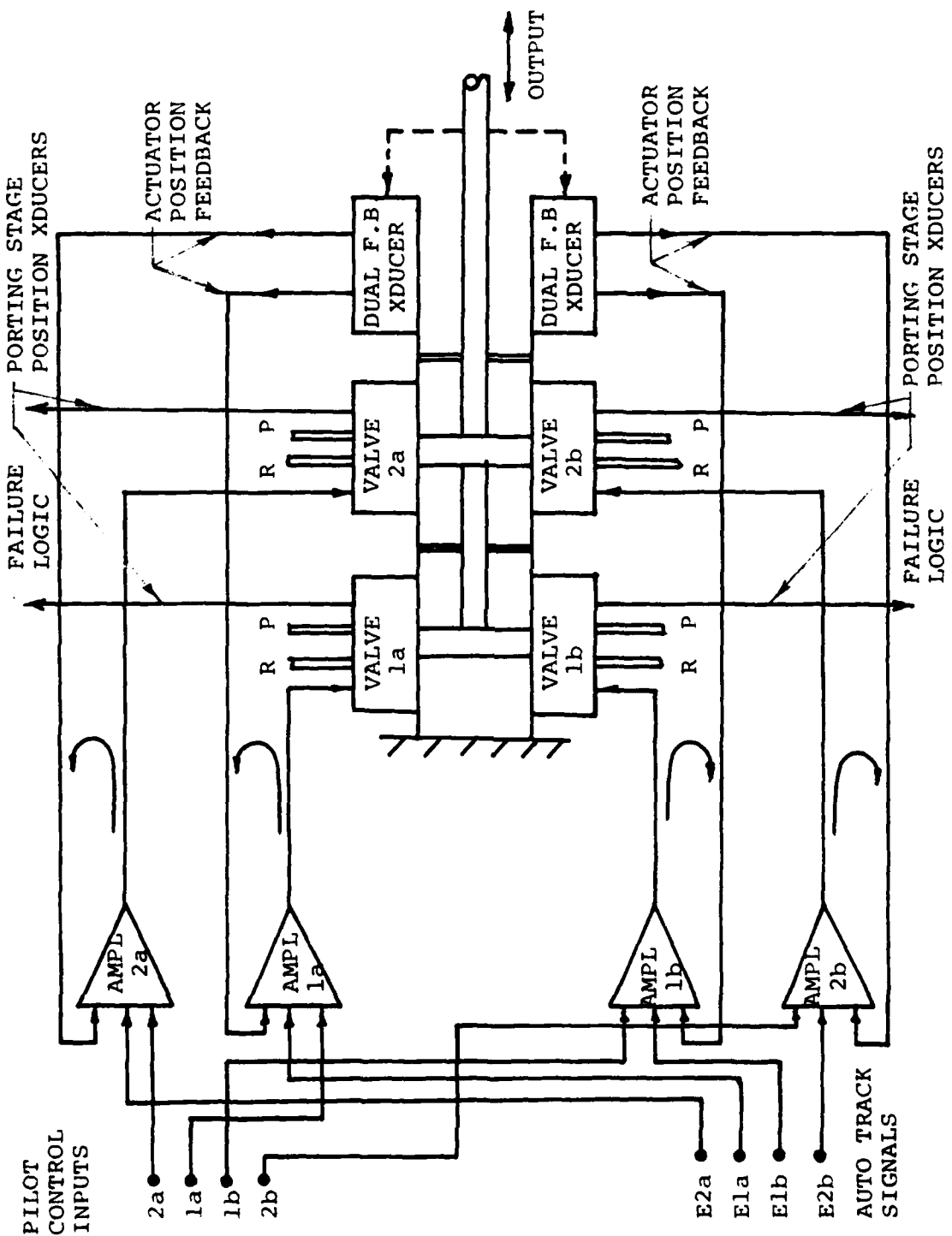
Figure A2. Dual fail-operate FBW concept for dual boost configuration.

The dual actuator schematically depicted is conventional, except that the control head (spool valve assembly) has been replaced with the four electrohydraulic servovalves.

Figure A2 is a functional schematic of the follow-up system; i.e., the dual boost actuator is slaved to the AFCS control inputs. All control paths are identical and operate simultaneously. A control input to the amplifiers proportionally opens the valves and drives the actuator until the dual feedback transducers provide feedback signals that cancel the command signals at the amplifier, which closes the valves and hence stops the actuator at a new position. The four valves are continuously and automatically aligned by a limited authority signal that is inherent in the failure management system (this feature is discussed in more detail later). The dual feedback transducers can be single elements and separately located to reduce vulnerability to battle damage if desired. The response of the actuator can be shaped to improve handling qualities as required.

The failure logic for the system shown in Figure A2 operates in the following manner. If a control path fails (e.g., path 1a), the path is automatically disengaged and Valve 1a is cut off to prevent leakage of fluid from one side of the piston to the other. A second path failure will be disengaged in the same manner. If the second failure should be path 1b, the logic circuitry will automatically engage a pressure-operated hydraulic bypass across the common piston so that the failure will not restrict the operation of the other piston. It is pointed out that if a first failure should disable the failure management system (described in the next section), the control path system, shown in Figure A2, has the inherent capability of absorbing a second failure. This is possible because, for example, if Valve 1a should fail and remain hardover, the other three valves will go in the opposite direction to oppose the actuator motion. This will effect a bypass around the piston common to Valves 1a and 1b and, hence, will allow the other piston to operate without any appreciable degradation. This inherent feature appreciably improves the overall reliability of the system and allows a comparatively simple failure management system to be used in place of a conventional voting scheme.

Failure Management System

The failure management system complements the control paths to provide a control system with a failure tolerance level of dual fail-operate. It also includes an inherent signal that is used to effect a limited authority and an automatic alignment function for the control paths, which compensates for differences in component tolerance build-up. The failure

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management system consists of a failure-sensing function and an automatic disengage function. These functions are conceptually described in the following paragraphs.

The addition of an LVDT-type position transducer to the porting stage of the servovalves (second stage on conventional servovalves) allows the failure management circuitry to be mechanically interfaced with the control paths. This feature affords a more secure means of sensing a failed or degraded control path without reducing the reliability of the control path and, hence, the transducer can be used to cover failures up to the power piston. Several other ways to provide a valve feedback signal for this failure monitor concept were considered. For example, differential pressure across the second stage of a conventional servovalve can be used. Also, the current flow through the first stage (flapper valve coil) can be used and is more economical. However, neither of these approaches will provide 100 percent failure coverage and were discarded in favor of the valve position transducer approach. Valves of this type are currently available.

The basic failure sensing function for each power actuator channel is provided simply by using four equal value resistors in conjunction with the 4-valve position transducers. Connection of the resistors as shown in Figure A3 constitutes a very simple and reliable logic concept that allows each control path to comparatively monitor itself, determine a failure, and disengage itself.

Figure A3 is a simplified schematic of the basic concept for sensing a failure. For normal operation, the voltage across the valve position transducers should be the same. Since the voltages across the transducers are the same regardless of valve position, there will be no appreciable current in the resistors. Current will flow only in the resistors when the valve positions are not in agreement. If one control path has a "hard" failure, the respective porting stage will fully displace while the others will partially displace in the opposite direction. The voltage differences will cause a current in the resistor associated with the failed control path that is several times higher than the current in the other resistors, thus providing a means for identifying the failed path. For example, if Valve 2b is hardover, the other three will be displaced a small amount (depending on the actuator load and the loop gain of the control paths) in the opposite direction and each will produce a transducer output voltage. The equivalent circuit would be as shown on the following page.
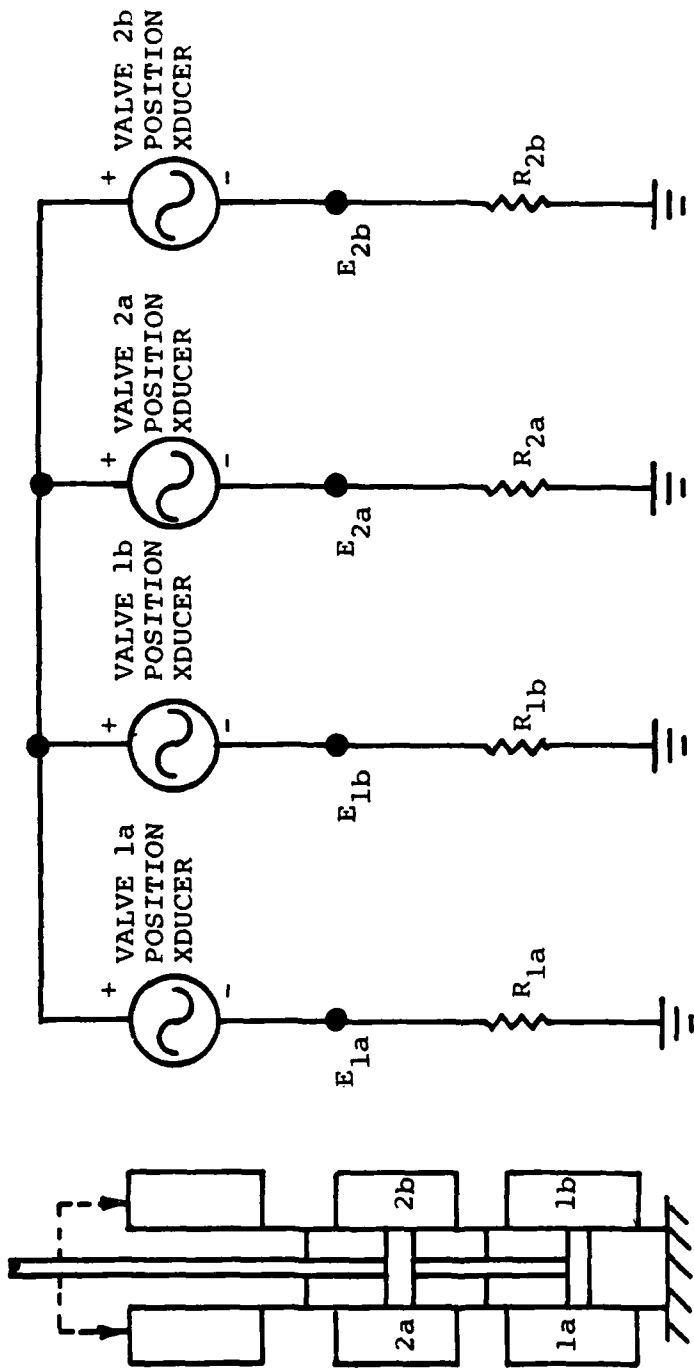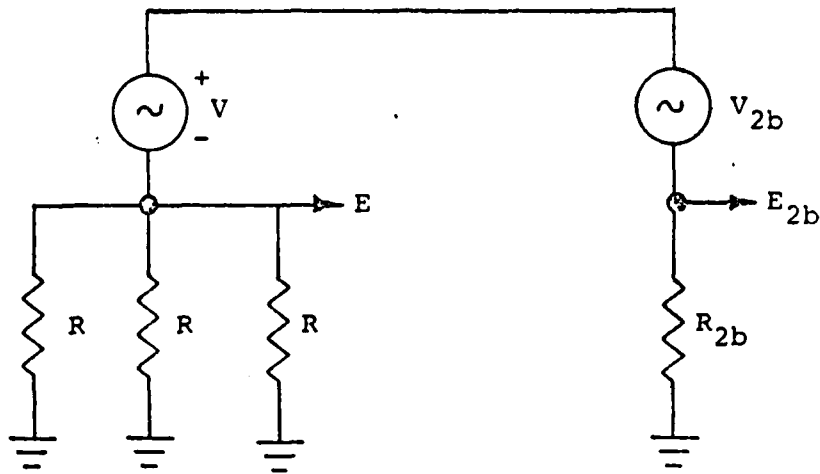
Figure A3. Fault detection concept.

As indicated in the equivalent circuit, the voltage from the valve transducer in the failed control path is opposite in polarity from the other three transducers and, in effect, is in series and will be additive.

The current $I_{2b} = \dfrac{(V-V_{2b})}{R/3+R}$ Where: $R_{1a} = R_{1b} = R_{2a} = R_{2b} = R$

$$= \frac{3}{4} \frac{(V-V_{2b})}{R}$$

The current in each of the other three resistors would be

$$\frac{1}{4} \frac{(V-V_{2b})}{R}$$

or 1/3 the current in R_{2b}. A second failure would produce the following current condition (assuming the second failure is in path E_{1b} and the switch, S_{2b}, has opened):

$$I = \frac{(V-V_{1b})}{R/3+R} = \frac{2}{3} \frac{(V-V_{1b})}{R}$$

The current in the other two resistors would be $1/3 \dfrac{(V-V_{1_b})}{R}$ or one-half the current in the resistor of the failed path.

In both cases, the failure current associated with the failed path is high enough (compared to the other currents) to provide a means of positive identification of a failure or degraded condition.

Several approaches for detecting failures were considered. One approach was to simply compare the magnitude of the failure voltages across each resistor with a set threshold. This approach is simple, straightforward, and is valid. The second approach was to use a comparison technique for determining failure. This approach is not quite as simple as the first approach, but it appeared to be more tolerant of failures and was used in the BHT FBW program. Subsequent studies have indicated that the first approach offers some advantages and will be used in future systems.

The automatic disengage function is the part of the failure management system that makes the decision if a failure has occurred, disengages the failed control path if required, or as an adjunct, provides a soft-fail (e.g., high null) indication to the pilot but does not produce a disengagement. The soft-fail feature is a cautionary device for the pilot and also can be used as Built-In Test Equipment (BITE).

The automatic disengage function for each control path uses a unique comparison technique to detect a failure and a threshold circuit to effect a disengagement of the failed control path. The detection concept is based on the failure signal from the failed control path being three times higher than the other failure signals for a first failure and two times higher for a second failure. The failure threshold for automatic disengage can be judiciously established. A time-inhibit circuit has been included to require the failure to exist for a predetermined time period (perhaps 0.5 second) to effect a disengagement. The purpose of this is to provide a more positive indication of a failure.

As shown in Figure A4, the Valve 2b failure signal is negative-peak detected and applied to the noninverting input of the threshold amplifier. If the failure signal is negative and larger than the threshold voltage, the output of the threshold amplifier will swing from a hard negative voltage to a hard positive voltage, which is applied to the time-inhibited, fast-recovery, control path disengage switch. If the failure exists for the required time period, the solid-state switch will disengage the control path and will also
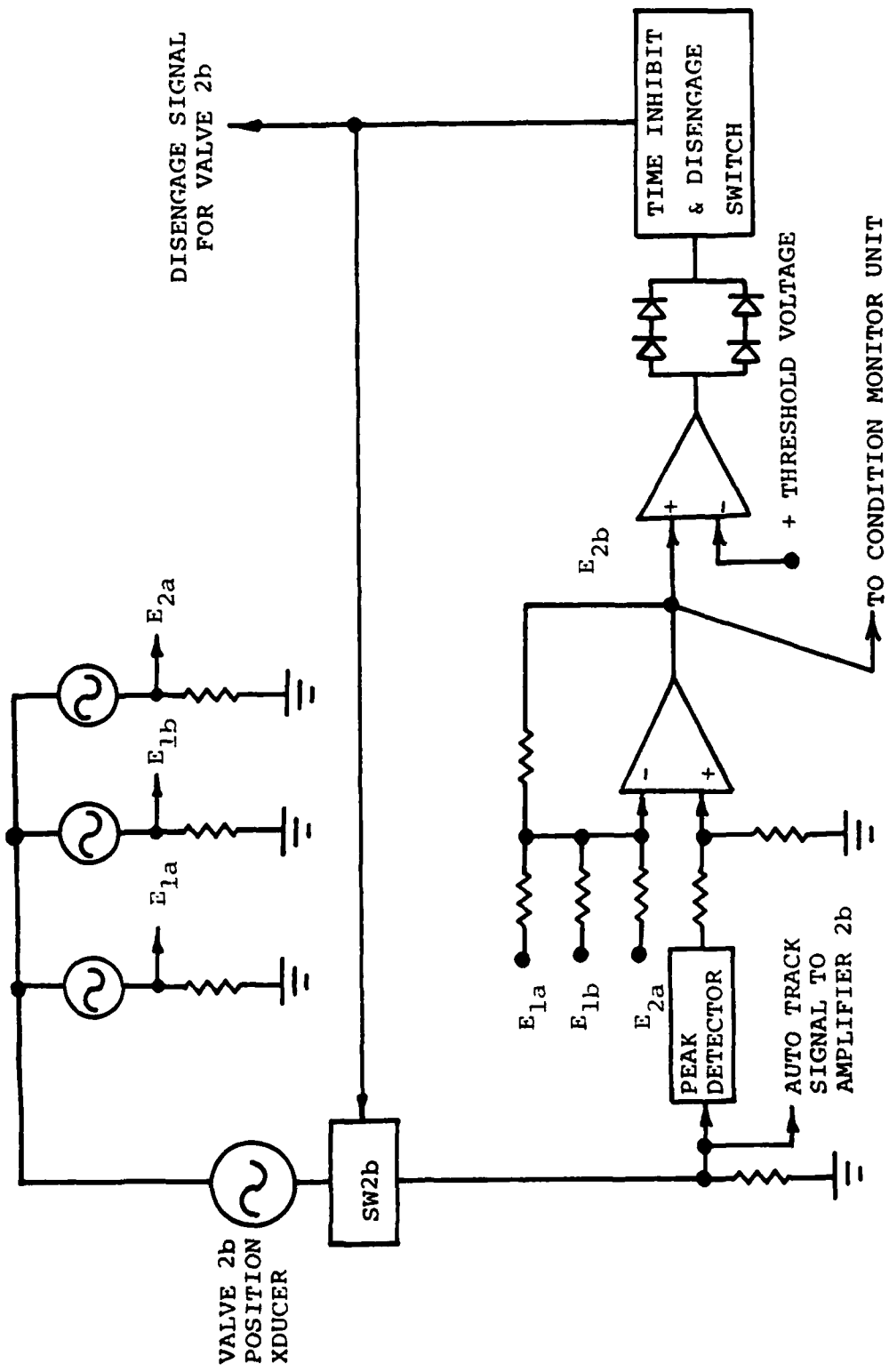
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Figure A4. Failure sensor and automatic disengage concept.

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switch open the valve position transducer circuit to the resistor, as shown, to isolate the failure from further interacting with the failure management system.

As an adjunct to the above described basic concept, an additional feature was incorporated in the design of the failure sensing circuitry that affords it the intelligence to differentiate between an inert-type failure and a hard-signal failure. This feature was tested in the BHT FBW laboratory model and proved to be an asset to the concept. The EHSV drive circuitry has been designed so that any open circuit up to the valve coil would create a hard failure. Hence, the most probable cause of an inert failure in a control path would be an "open" in the EHSV coil.

During a cruise condition, and especially in calm air, the EHSV's displacements are comparatively small. Hence, if one path becomes inert, the disagreement between the inert control path and the operating paths may not be of sufficient magnitude to overcome the set threshold and effect a disengagement. This suggests that an open EHSV coil failure could exist for some time without disengaging the respective channel. Hence, a simple circuit was included as a part of the failure/management system to monitor the EHSV coil (see Figure A5). It simply relates the EHSV coil current with input signal to determine an open EHSV coil and, in turn, disengages the respective control path.

In addition to providing a method of failure detection and automatic disengage, the failure management system provides a signal for each control path that is used to automatically keep the servovalves aligned (in-track). The four valves, as shown in Figure A2, will normally be out of track to some degree because of circuit component tolerances and mechanical misalignments. The disagreement between the valves will degrade the force gain of the actuator for small inputs about a null position. The voltage signals across the resistors shown in Figure A3 can be used directly with the control path circuitry to make the valves track. That is, voltage signals (prior to peak detection) E_{1a}, E_{1b}, E_{2a}, and E_{2b} can be used directly as driving signals to their respective control path amplifiers to effect an alignment of the valves. This function is made fail-safe by limiting the control authority of the signal.
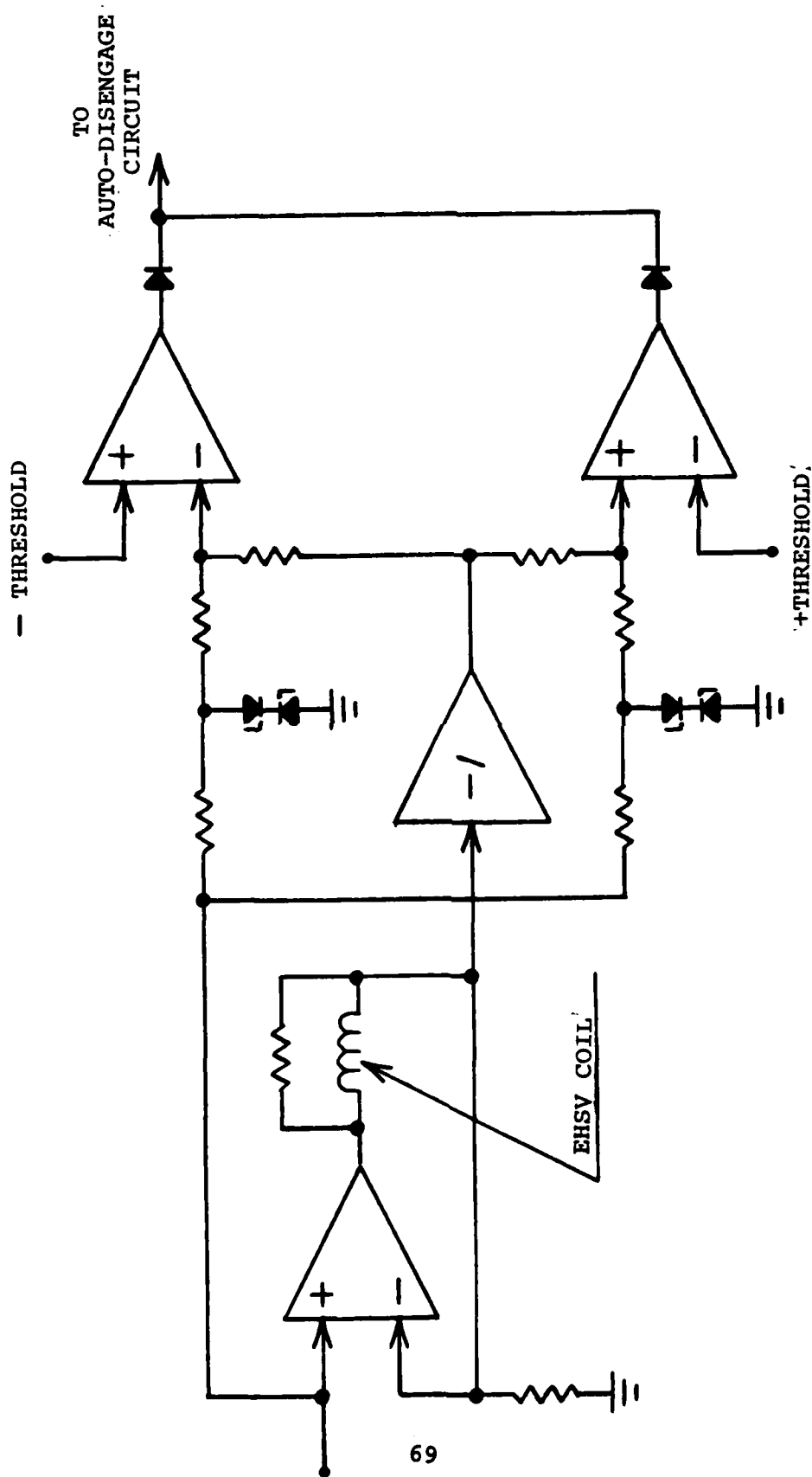
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Figure A5. Inert failure monitor for driver state and coil - 1 required per piston.

APPENDIX B

INTEGRATION TEST PLAN FOR FAULT-TOLERANT
ACTUATION CONCEPT FOR A RESEARCH TEST AIRCRAFT

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TABLE OF CONTENTS (Concluded)

LIST OF ILLUSTRATIONS

1. SCOPE

The objective of the Integrated Test Program is to appraise the 4-valve actuation system as a candidate actuation concept for use in the control system of a test vehicle. The plan has been devised to evaluate the actuation concept in terms of operational suitability as well as its ability to tolerate failures.

The following sections describe the subject equipment, test stand, auxiliary equipment, procedures for integrating the equipment, and means for determining operational suitability, failure mode testing, and failure effects.
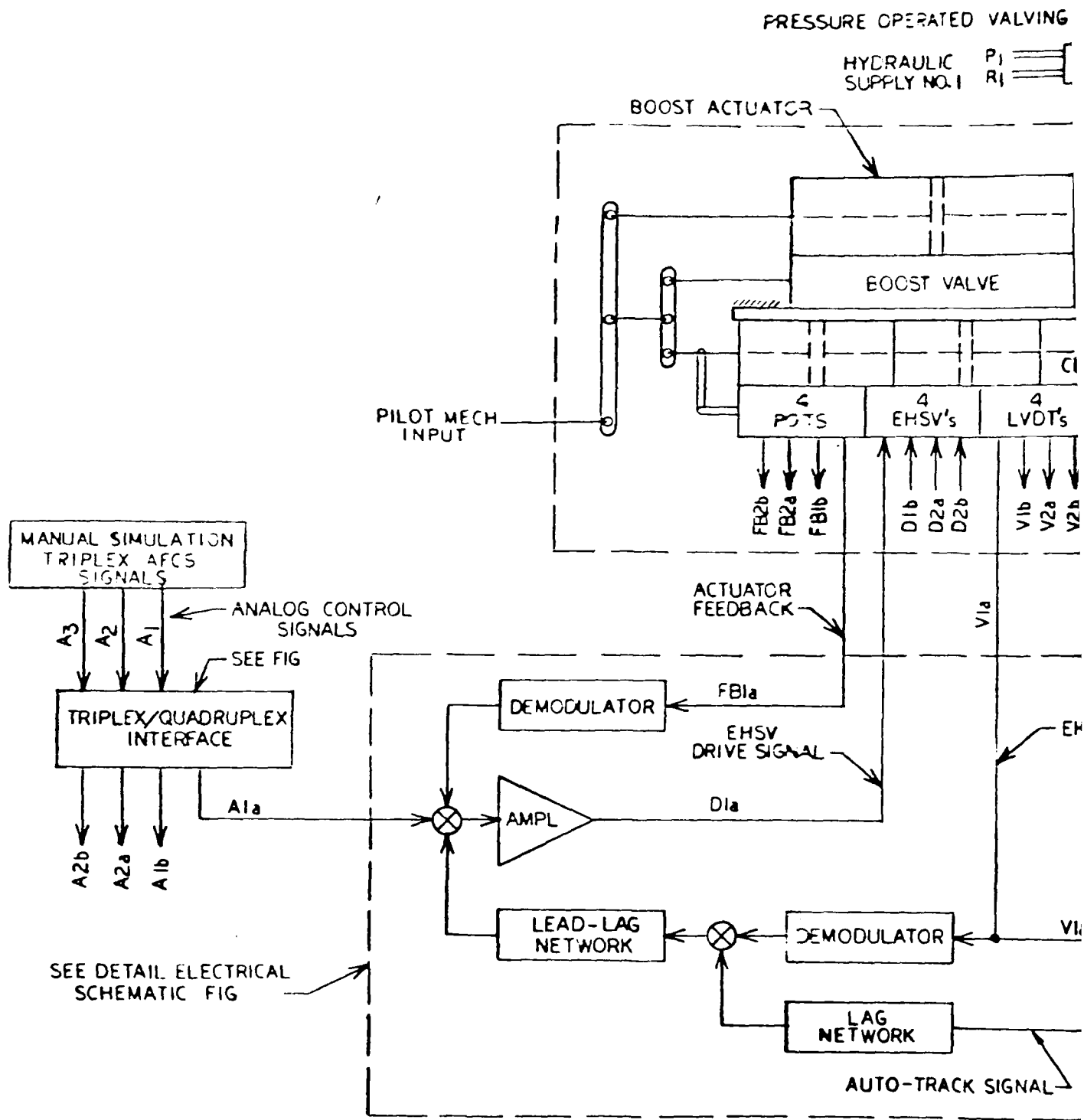
2. DESCRIPTION OF HARDWARE

2.1 GENERAL DESCRIPTION

The test system consists of a primary/AFCS actuator assembly; load actuator and control circuitry; failure management and electronic control circuitry for AFCS (4-valve) actuator; and a failure simulation panel. These equipments are installed on a laboratory test stand having hydraulic and electrical supplies that are configured to simulate dual supplies. Either hydraulic supply will operate the primary actuator through a pressure-operated selector valve. Hydraulic Supply No. 1 and Electrical Supply No. 1 provide power for control paths 2a and 2b. Figure 11 is a photograph of the equipment and the test stand. Figure B1 is a schematic of the system.

2.2 PRIMARY/ARCS ACTUATOR ASSEMBLY

The AFCS (4-valve) actuator is interfaced with the primary actuator (see Figure 11) to effect a differential mixing with the pilot's input. Hence, the output of the primary actuator is a summation of the pilot's control input and the AFCS input. Some friction in the pilot's control will probably be required to prevent motion of the actuator from being felt in the pilot's controls that may occur because of the short linkage arrangement.

The AFCS actuator has a displacement authority of about ±50 percent of the total displacement of the primary actuator. As shown, hard stops are located on the output of the primary actuator to prevent overtravel of the control system. The spring centering device is logically interfaced with the AFCS actuation system so that it will center and lock in the absence

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Figure B1.   Schematic of laboratory model of actuation system.

SPRING
CENTERING

4-VALVE SCAS
ACTUATOR

TO EHSV

V1b V2a V2b

DISENGAGE
SOLENOID

HYDRAULIC
SUPPLY

CONTROL CIRCUITRY

E-SV

EHSV FEEDBACK

AUTO-DISENGAGE
SIGNAL

SEE NOTE

V1a

AIRLOAD MANAGEMENT

ENGAGE/DISENGAGE
SIGNALS

CONTROL
PANEL

2 b
2 a
1 b
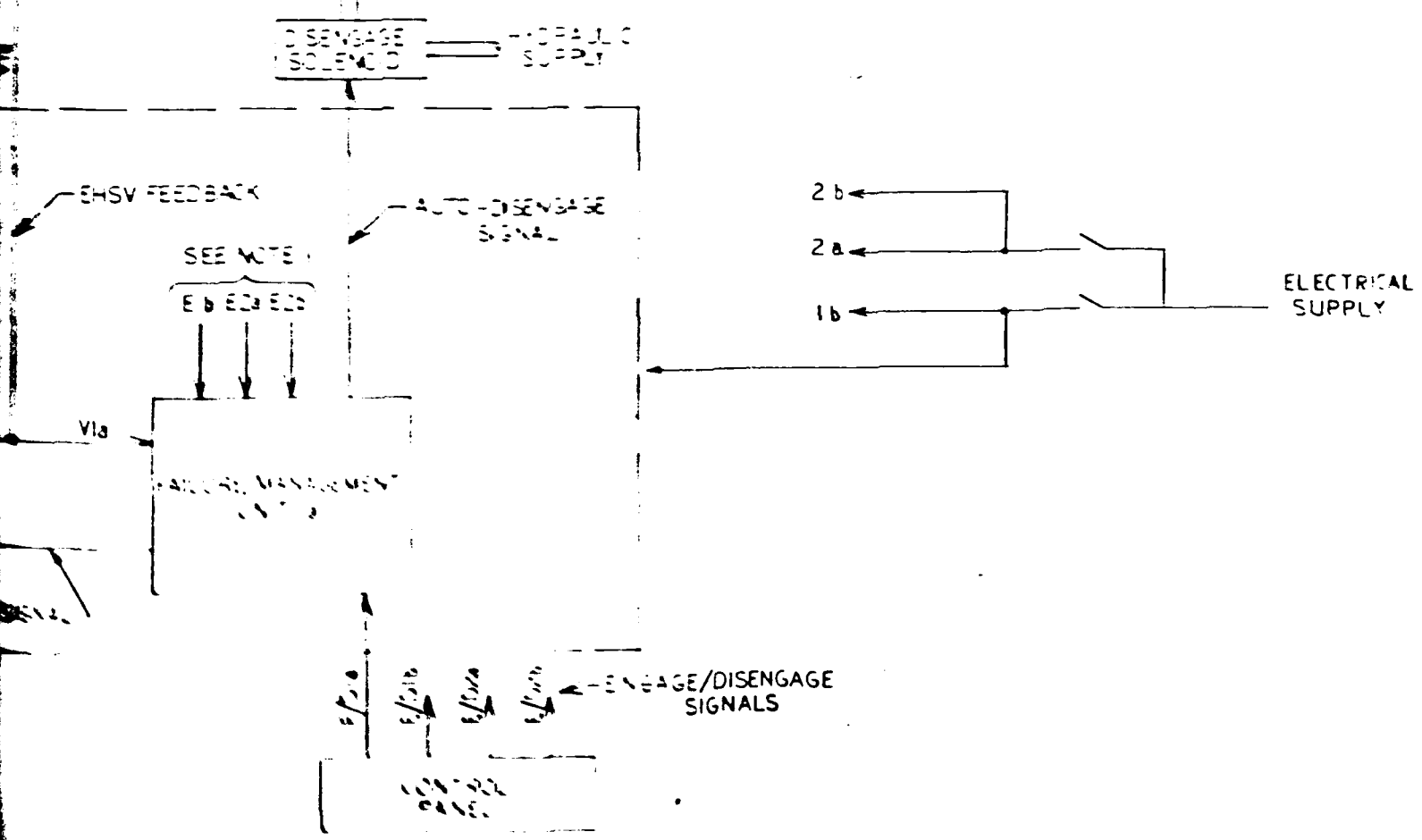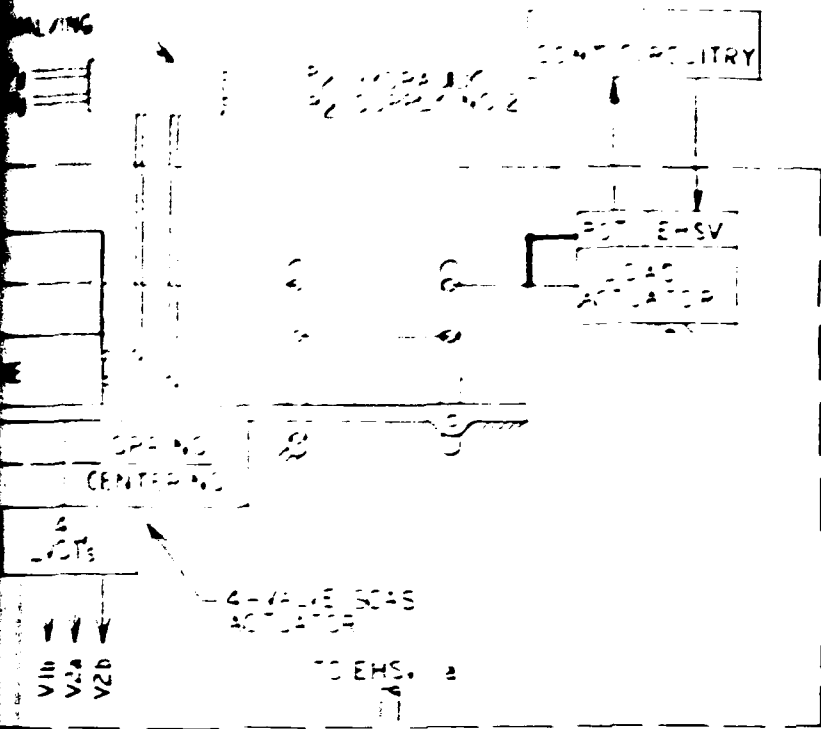
ELECTRICAL
SUPPLY

Figure B2.   Schematic of electronic circuitry for fault-tolerant AFC

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AFCS actuator.

of hydraulic pressure or electrical power on at least one solenoid valve.

The primary/AFCS actuator assembly has been designed so that existing hardware could be used where practical. Accordingly, the stroke of the AFCS actuator has been limited to about 0.6 inch to allow an existing spring-centering device to be used to center and mechanically lock the AFCS actuator when it is disengaged or in the event of total loss of electrical or hydraulic power. This configuration will satisfy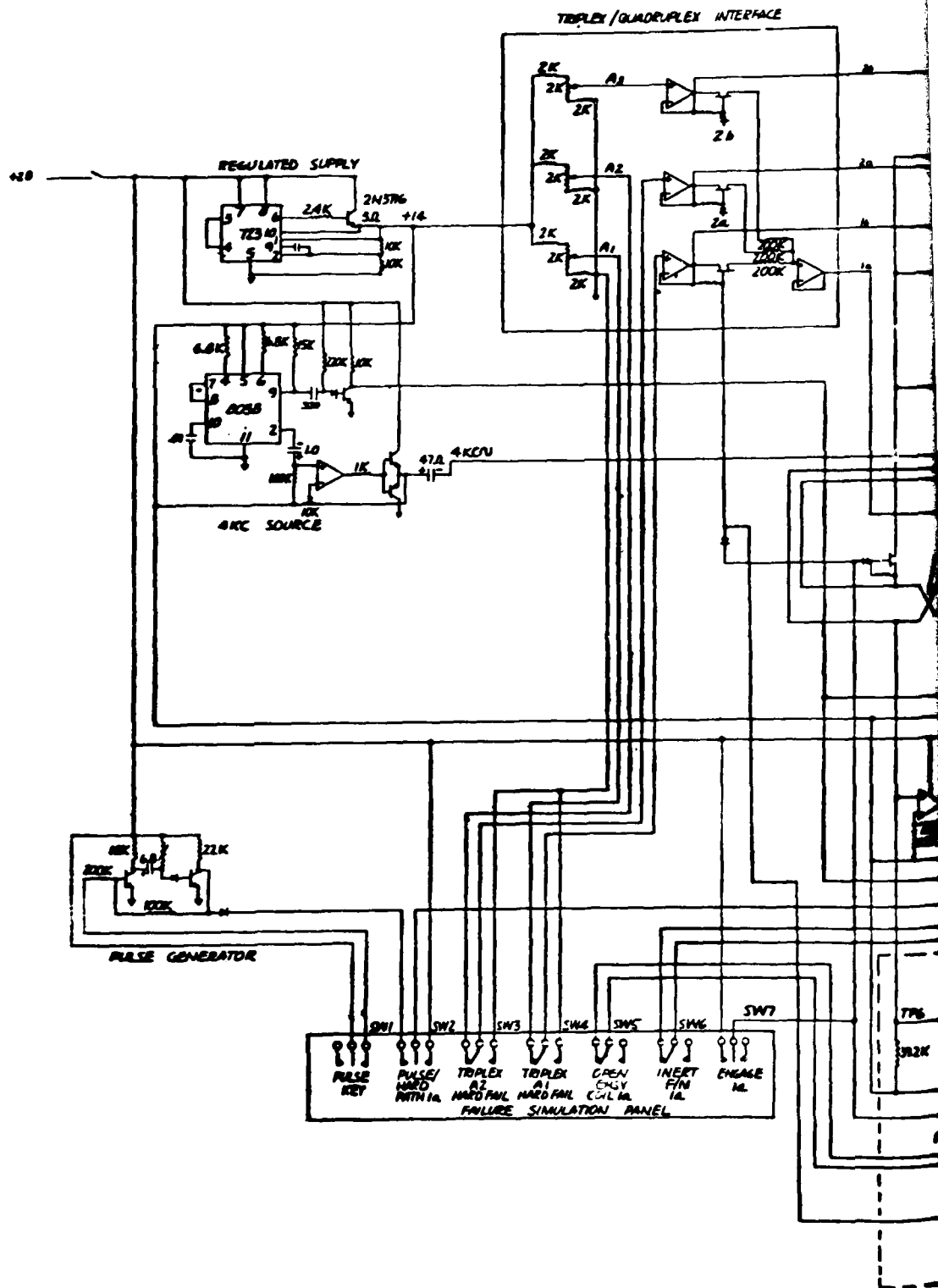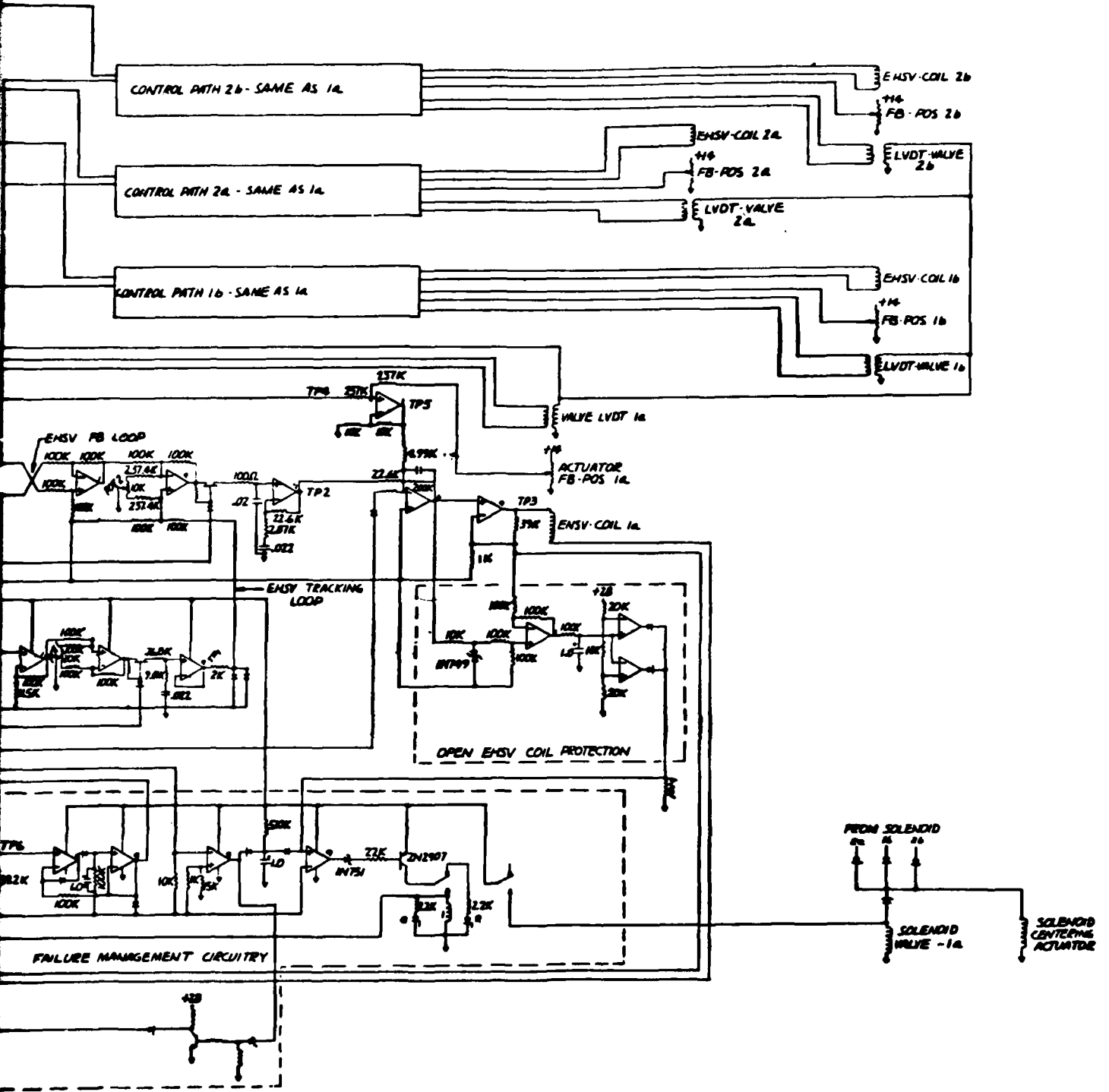 the functional requirements as planned. To evaluate it in the proper perspective, however, thresholds, failure effects, etc., should be evaluated in terms of percent of full stroke capability since the EHSV flow gains and associated loop gains have been designed for compatibility with the actuator size and flow requirements. Also, the pilot's mechanical input to actuator output gain has been mechanized so that full pilot stroke produces about 1.2 inches of actuator stroke. This ratio needs to be considered when qualitatively appraising the "feel" of the mechanical controls.

2.3 LOAD ACTUATOR AND CONTROL CIRCUITRY

The load actuator can be identified in Figure 11 as the actuator connected to the end of the pivoted beam. As shown, it is connected in parallel with the primary actuator so that it can be used for simulating reactionary loads from the output control elements; e.g., the swashplate. The load actuator is controlled by the control circuitry that can be identified in Figure 11 as the small circuit board on the lower right. The circuitry is connected to the actuator to effect a closed loop. A gain potentiometer is used to provide a means for controlling the magnitude of the load.

2.4 FAILURE MANAGEMENT AND ELECTRONIC CONTROL CIRCUITRY

Figure B3 is a schematic of the failure management and electronic control circuitry as well as the test circuitry for simulating failures. This circuitry is shown in Figure 11. Each of the squares on the large circuit board and the associated drive signal constitutes a control link from the T/QIU. The T/QIU is located on the lower portion of the circuit board that is immediately to the right of the large board in the photograph and also schematically shown in Figure B2. AFCS inputs will be simulated manually with the lightweight control stick shown in Figure 11 and schematically shown in Figure B2 as the three potentiometers that provide a driving signal for the triplex/quadruplex interface unit.

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2.5 FAILURE SIMULATION PANEL

The Failure Simulation Panel is located immediately above the
T/QIU circuitry (see Figure 11) and is schematically shown in
Figure B2 for control path 1a. The switching circuitry pro-
vides the capability of simulating the following failure modes
for each control path.

- Transient input (pulse)
- Hard control path failure
- Hard and open failure in two triplex links (A1 and A2)
- Open EHSV coil
- Inert failure management system

3. INTEGRATION TEST OF EQUIPMENT

3.1 FUNCTIONAL TEST

3.1.1 Primary/Load Actuator Configuration

3.1.1.2 Hydraulics ON. Move pilot's controls from stop to
stop and qualitatively check for operational suitablity. Note
dead spots, thresholds, breakout forces, etc. Turn off Supply
No. 1; Supply No. 2 should automatically take over. Apply
pressure to load actuator and with an appreciable amount of
load, move primary actuator from stop to stop to assure proper
operation.

3.1.2 Fault-Tolerant AFCS Actuation System

The basic electronic circuitry was used on a similar program
and therefore it can be assumed that all the closed loops are
stable. The control paths, however, will be realigned to
assure proper operation. Each control path will be aligned
and tested separately under the conditions stated below.
Reference should be made to Figure B2 for supplemental infor-
mation. It is pointed out that the operational amplifiers are
operated at +28 VDC to ground with +14 VDC used as common.

3.1.2.1 Alignment and Test of Control Paths

Control Path 1a

	Conditions:	• Hydraulic power ON
		• Electrical power ON
		• All solenoid valves disconnected
		• EHSV coil shorted across
		• TP5 shorted to +14 VDC
		• Control Path 1a engaged

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EHSV Tracking Loop

The purpose of the loop is to maintain EHSV track with the other EHSVs.

- Adjust "Pot 1" to null "TP1" (reference +14 VDC). This operation assumes the mechanical null of the EHSV is correct and aligns the tracking loop accordingly. The mechanical null is accurate to ±2 percent, which is considered an adequate reference since the second stage of the EHSV has an overlap of ±10 percent.

EHSV Feedback Loop

The purpose of this loop is to improve the linearity of the EHSVs and to maintain the null alignment.

- Adjust "Pot 2" to null "TP2" (reference +14 VDC). This adjustment aligns the output of the feedback with the assumed mechanical null of the EHSV.

Frequency Response Test

Conditions:
- Hydraulic power ON
- Electrical power ON
- All solenoid valves disconnected
- Short across EHSV 1a removed
- Control path 1a engaged
- Open SW4 and connect a frequency source across the normally closed contacts to effect a series input
- Short on TP5 removed

- Adjust AFCS input to effect a null at TP5.

- Conduct frequency response of the control path and EHSV using the LVDT as the output element.

Control Paths 1b, 2a, and 2b

Same as control path 1a. Only the control path in test should be engaged.

3.1.2.2 Alignment of Electromechanical Transducers

Actuator Feedback Transducers

Conditions:
- Hydraulic power ON
- Electrical power ON
- Solenoid valves 1a (only) connected
- Control paths 1a engaged

- Use AFCS simulation controller and position 4-valve actuator in increments and determine sensitivity in terms of volts per inch of actuator travel.

- Use controller and drive 4-valve actuator in increments and measure track error from stop to stop.

- Trim feedback transducers using transducer la as reference.

AFCS Simulated Control Transducers

Conditions: Same as above

- Use same procedure as above on triplex controller for control paths Al, A2, A3.

- If necessary, trim the gain of summing amplifier in interface unit to make control path la track with other paths.

3.1.2.3 Autotracking Loop Test

Control Path la

Conditions: - Hydraulid power ON
                 - Electrical power ON
                 - 4 solenoid valves disconnected
                 - All control paths disengaged

- Short TP5 to 14 VDC in all control paths to isolate the control input.

- Engage control path la, then the other paths one at a time.

- Use pulse key on failure simulation panel and apply pulse to control path la. Qualitatively observe the output of LVDT la on an oscilloscope and not stability characteristics.

- Remove short from TP5 in all control paths.

- Connect path la solenoid.

- Engage control path la; 4-valve AFCS actuator will now track simulated AFCS input.

- Drive AFCS actuator from stop-to-stop and examine for interferences over the complete range of the pilot's mechanical input. The friction unit on the pilot's controls will probably have to carry some friction because of the short link arrangements.

- Repeat with some load applied by the load actuator. Apply step input to AFCS actuator and observe stability characteristics on oscilloscope.

- Drive AFCS actuator in increments over full travel and check tracking of each control path by recording voltage on TP6. This is the signal that is used through the limiting diodes at TP1 for autotracking as well as for a signal to the failure management circuitry.

- Tracking is expected to be within 0.05 when measured in terms of total actuator displacement capability.

- Connect solenoids for control paths 1b, 2a, and 2b.

- Engage control path 1b.

- Apply step input to AFCS actuator and qualitatively observe stability characteristics.

- Engage control paths 2a and 2b.

- Apply step input to AFCS actuator and qualitatively observe stability characteristics.

- Drive AFCS over full travel in increments.

- Record tracking errors in each path at TP6.

3.1.3 Composite Test

The composite test is a quick check to assure that simultaneous operation of the primary actuator and AFCS actuator does not create any mechanical interferences or objectionable "feel" in the pilot's controls.

Conditions: Electric power ON
                Hydraulic power ON
                4 control paths engaged

- Simultaneously apply a varying input to the AFCS actuator while the primary is being driven throughout its displacement range.

- If any mechanical interferences or objectionable pilot "feel" characteristics are present, they should be cleared before proceeding to the Operational Suitability Test.

- It is pointed out that the pilot will feel the motions of the AFCS actuator when the sum of the AFCS actuator and his input exceeds the downstream stops. This should be recognized as a normal cue that the controls are on the stops.

3.2 OPERATIONAL SUITABILITY TEST

This test is similar to the above functional composite test with the exception that the operating conditions will be varied and some parameters will be measured and recorded. The purpose of this test is to provide information pertinent to the judging of the operational suitability of the 4-valve actuation concept for use in the NAVTOLAND test helicopter.

3.2.1 Characteristics Under Normal Conditions

Conditions: Electrical power ON
              Hydraulic power ON
              4 control paths engaged
              Load actuator adjusted for typical static
                 load

- Measure displacement threshold of pilot controls in terms of inches at top of stick. This will actually show up as a "dead spot" in the controls. For this to be meaningful, the measurement should be corrected to reflect the difference in the short linkage control ratio and control ratio in the test helicopter.

- Measure the AFCS input threshold in volts required from the simulated inputs to effect a displacement of the 4-valve actuator. As in the above case, this measurement should be corrected to read in terms of percent of the actual capable travel of the 4-valve actuator.

- Qualitatively evaluate pilot and AFCS characteristics while both are operating simultaneously. Observe objectionable "dead spot" effects that may occur when the direction of the AFCS actuator is reversed.

3.2.2 Characteristics Under Single-Failure Conditions

Conditions: Same as 3.2.1 except control path
              1a is disengaged.

Procedure: Same as 3.2.1.

3.2.3 <u>Characteristics Under Dual Failure Conditions</u>

3.2.3.1 <u>Two Companion Control Paths</u> (share same piston)

<u>Conditions</u>:   Same as 3.2.1 except control paths 1a and
                     1b are disengaged.

<u>Procedures</u>:   Same as 3.2.1.

3.2.3.2 <u>Two Control Paths not Sharing Same Piston</u>

<u>Conditions</u>:   Same as 3.2.1 except control paths 1a and
                     2a are disengaged.

<u>Procedures</u>:   Same as 3.2.1.

3.2.3.3 <u>One Control Path And Associated Failure Management
         Circuit</u>

<u>Conditions</u>:   Same as 3.2.1 except control path 1a is
                     failed "hard" and Failure Management cir-
                     cuit 1a is inoperative.

<u>Procedure</u>:   Same as 3.2.1.

3.2.4 <u>Characteristics Under Failure of One Electrical Supply</u>

<u>Conditions</u>:   Same as 3.2.1 except electrical supply to
                     control paths 1a and 1b are off.

<u>Procedures</u>:   Same as 3.2.1.

3.2.5 <u>Characteristics under Complete Failure of Electrical
       and Hydraulic Power</u>

<u>Conditions</u>:   Same as 3.2.1 except all electrical and
                     hydraulic power supply turned off.

<u>Procedure</u>:   Same as 3.2.1 except no test required on
                     AFCS actuation unit.

4. FAILURE MODES AND EFFECT TEST

The tests in this section cover the basic type of failures
that can occur. The intent is to validate the 4-valve actu-
ation concept as a viable fault-tolerant actuation system.
The AFCS control paths, up to and including the EHSVs, will

be tested to assure a failure tolerance level (FTL) of dual fail-operate for the worst conditions. The electrical and hydraulic power systems will be tested to assure that the failure effects on the total system will result in an FTL of single fail-operate and dual fail-safe.

The failure modes covered in the subsequent subsections will be simulated using the switches on Failure Simulation Panel; four electrical power switches, two hydraulic hand valves, and combinations of these input devices. Pertinent parameters will be measured and recorded to define failure effects. The measurements will be made using an oscilloscope. Except as noted, all initial conditions will be for all control paths and power supplies will be operating.

4.1 CONTROL PATHS AND FAILURE MANAGEMENT SYSTEM

4.1.1 Transient Disturbances

The purpose of this test is to show tolerance to EMI-type disturbances.

4.1.1.1 Short Pulse - Control Path 1a Only

- Position SW2 to PULSE position and use momentary SW1 application to apply pulse (about 0.2-second pulse).

- Applied pulse should result in a short duration jump at the actuator. Control path 1a should tolerate this disturbance and not disengage.

- Adjust pulse width to about 0.4 second and apply pulse. Control path 1a should disengage.

- Reengage control path 1a.

4.1.2 First Hard Failure

This test is to demonstrate the ability of the system to manage hard failures.

- Position SW2, control path 1a, to HARD to simulate a hard failure.

- Control path 1a should disengage.

- Use oscilloscope and measure and record actuator displacement and time required for recovery.

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4.1.3 Second Hard Failure

This test is to demonstrate the ability of the system to manage dual hard failures.

- Position SW2, control path 2a, to HARD to simulate a second hard failure.

- Control path 1a should disengage.

- Measure and record actuator displacement and time required for recovery.

- Reengage control paths 1a and 2a.

4.1.4 Single Inert Control Path Failure

This test is to demonstrate the ability of the system to manage inert-type failures without requiring large actuator displacements to create an error signal.

- Position SW5, control path 1a, to OPEN to simulate an open EHSV coil.

- Simulate an AFCS input; control path 1a should disengage immediately.

- Measure the magnitude of the AFCS required to effect a disengagement.

- Reengage control path 1a.

4.1.5 Dual Inert Control Path Failure

This test is to demonstrate the ability to manage two inert failures. If these are not properly managed, a "two-and-two" vote condition can occur. This system recognizes the condition and will disengage both faulty control paths.

- Position SW5, control paths 1a and 1b, to OPEN to simulate two open EHSV coils.

- Simulate an AFCS input; control paths 1a and 1b should both disengage.

- Measure the magnitude of the AFCS signal required to effect the disengagement.

- Reengage control paths 1a and 1b.

4.1.6 Failure Management Circuitry Failure Plus Associated Control Path Failure

This test is to demonstrate the capability of the system to operate with one control failed and not isolated by the normal disengagement.

- Open SW6, control path 1a, to simulate an inert Failure Management System.

- Position SW2, control path 1a, to HARD to simulate a hard failure.

  The hard failure will not effect a disengagement since the associated failure management circuitry is inoperative; the fault-tolerant actuation system will still be operable but with a slight static offset.

- Measure and record this offset.

- Measure and record the stall load for this condition in terms of pressure on load actuator.

- Close SW6; control path 1a should disengage.

- Disengage control path 1b.

- Measure stall load; this should be about the same as for the dual failure conditions.

4.1.7 First Failure of Triplex Control Path

This test is to demonstrate the capability of managing failures in the triplex AFCS ahead of the interface unit.

- Position SW4 to OFF to simulate a failure in the triplex control path A1.

  Control path 1b should disengage. Control path 1b has a shorter time delay than 1a and operates the 1b disengage solid state switch in the interface unit before control path 1a can disengage. After the switch has operated to effect an open to A1, control path 1a will restore itself to correctly track with control paths 2a and 2b.

4.1.8 Second Failure of Triplex Control Path

This test is to demonstrate that the system will tolerate two failures on the triplex control paths and still operate.

- Position SW3 to OFF to simulate a failure in triplex control path A2.

  Control path 2a should disengage. As in the above condition, control path 1a will temporarily be out of track until control path 2a is disengaged.

- Return SW3 and SW4 to ON position and reengage control paths 1b and 2a.

4.2 ELECTRICAL POWER SUPPLY

4.2.1 Single Failure

This test is to demonstrate the capability of the actuation system to continue operating after one electrical power supply has failed. Power Supply No. 1 provides power to control paths 1a and 1b while Supply No. 2 provides electrical power to control paths 2a and 2b. The existing power switches on the Engage/Disengage Panel will be used to simulate Electrical Power Supplies Nos. 1 and 2.

- Position power switches for control paths 1a and 1b to OFF.

  Control paths 1a and 1b will disengage. Control paths 2a and 2b will continue to operate in a normal manner. The loss of the two control paths will not change the "flow gain" of the actuator; however, the "force gain" will be one-half of the normal gain.

4.2.2 Dual Failure

The purpose of this test is to demonstrate that if both electrical supplies fail, the AFCS actuator will automatically center at an acceptable rate and mechanically lock and provide a pivot for the pilot's mechanical control inputs. The second failure is fail-safe in that the pilot can still fly with boosted manual controls.

- With the AFCS actuator fully extended in one direction, position the power switches for control paths 2a and 2b to OFF position.

  Control paths 2a and 2b will disengage and the AFCS actuator will center and mechanically lock. Actuation system has now reverted to boosted manual controls.

- Measure time required for the AFCS actuator to center.

- Position all electrical power switches to ON.

4.3 HYDRAULIC POWER SUPPLY

4.3.1 Single Failure

This test is to demonstrate that the system will tolerate a hydraulic supply failure and continue operating.

- Close the No. 1 manual valve to simulate a failure of Hydraulic Supply No. 1.

  The pressure-operated/spring-return bypass valve across Piston No. 1 will open to the bypass position so that Piston No. 2 can operate unrestricted. Control paths 1a and 1b will not disengage because of a "two-and-two" vote condition. This is a plus since it demonstrates that the AFCS actuator is not vulnerable to hydraulic transients. In addition, the pressure-operated valve on the primary actuator will operate to connect Hydraulic Supply No. 2 to the primary actuator.

4.3.2 Dual Failure

This test is to demonstrate that the actuation system is fail-safe after two hydraulic failures in that it will revert to manual control.

- Close the No. 2 manual valve to simulate a failure of Hydraulic Supply No. 2.

  The pressure-operated/spring-return bypass valve across Piston No. 2 will move to the bypass position, which allows the pilot to manually (no boost) control the aircraft. In addition, the pressure-operated/spring-return valve across the primary actuator will operate to effect a bypass on the piston to allow freedom of movement. The loss of both supplies to the centering device allow it to center and lock the AFCS actuator.

4.4 SUMMARY DISCUSSION ON FAILURE MODE TESTING

Supplemental discussions will be included covering the test and the results as well as any peculiarities that may occur during the tests.

APPENDIX C

FAULT-TOLERANT ACTUATOR CONCEPT RELIABILITY
ANALYSIS

1. INTRODUCTION

An analysis was performed to provide prediction reliability
values for the FBW actuator concept. The concept uses a dual
hydraulic power actuator (2 single actuators), four electro-
hydraulic control paths (2 per piston), and one failure manage-
ment unit per control path. The failure management system
consists of a failure sensing function and an automatic dis-
engage function for each of the four control paths. Each
power actuator is electrically controlled by EHSV receiving
commands from the pilot's input and from actuator feedback
sensors. The FBW system is a predominately dual fail-operate
system and includes the following components per control path:

Component	Quantity
EHSV Feedback Loop Circuitry	4
EHSV Tracking Loop Circuitry	4
EHSV Open Coil Protection Circuitry	4
Failure Management Circuitry	4
Triplex/Quadruplex Circuitry	1
On/Off Switch	4
Power Supply Circuitry	4
Electrohydraulic Servoactuator	1
Solenoid Switch	4
Control Motion Sensor	4
Feedback Sensor	4

The reliability analysis covers an estimate of the system,
mission, and flight safety reliability.

2. DEFINITIONS

Dual fail-operate system - A system that can tolerate a like failure in any two of its control paths and still operate undegraded. Any two of the four control paths are adequate to maintain safety-of-flight to a 100 percent probability.

Failure - The inability of an item to perform within its specified limits.

Time (for reliability values in the analysis) - Flight hours measured from time of lift-off until aircraft touchdown.

Mean-Time-Between-Failure - The average operational flight hours between independent failures.

Mission - A time period that starts after preflight checkout has been completed and the system is determined to be operationally ready, measured from aircraft lift-off until aircraft touchdown.

System Reliability - The probability that an operationally ready mission-configured system of the aircraft will complete a one-hour mission without a failure requiring corrective maintenance.

Mission Reliability - The probability that an operationally ready mission-configured system of the aircraft can perform all mission functions successfully during a one-hour mission.

Flight Safety Reliability - The probability that the aircraft system will operate for a one-hour mission without the occurrence of an in-flight equipment malfunction/failure that results in injury to the crew that would preclude them from performing their mission or will not permit a controlled landing given that the aircraft is operationally ready at the start of the mission.

3. ANALYSIS

The analysis was prepared following the procedures and using information given in Sections 2 and 3 of MIL-HDBK-217B.

Failure rate data for components not covered by MIL-HDBK-217B were derived from Navy Maintenance, Material and Management system data (3-M) or obtained from the component manufacturer. A system breakdown in terms of a series of block diagrams was used in the analysis procedure. The component tree for the FBW actuator concept is presented in Figure C1. The system block diagram is presented in Figures C2 through C5.

4. RELIABILITY ANALYSIS

The analysis was performed to estimate the reliability of the FBW system on a per-control-path basis and for the system. (For the purpose of this analysis, the system is defined as one power actuator and the four control paths with their associated control circuitry.)

The mission analysis was performed using the sources referenced in Section 3. The mission failure rates were determined after first performing a limited failure modes and effects analysis for each of the FBW components. The components were analyzed to determine which type failure modes could cause loss of a function that would affect the mission and that would be observable by the crew in flight, such as degraded performance or an actuator hardover. Each type failure mode that could be experienced by each component was assigned a percent of occurrence. For example, a capacitor has two primary failure modes, short and open. Approximately 80 percent of the failure occurrences for a capacitor would be a shorted mode. Therefore, if the short mode of the capacitor would be noticeable by the crew or affect the operation or the aircraft, the capacitor failure mode failure rate would be obtained by multiplying the component failure rate by the failure mode factor of 0.80. Next, the product of the component failure rate and the failure mode factor are summed. This procedure was followed for each component of the FBW actuator to obtain the mission analysis results.

In addition to the mission analysis, a flight safety analysis was also performed by examining each component failure mode. This analysis was conducted to determine which component failure modes could result in complete loss of function of
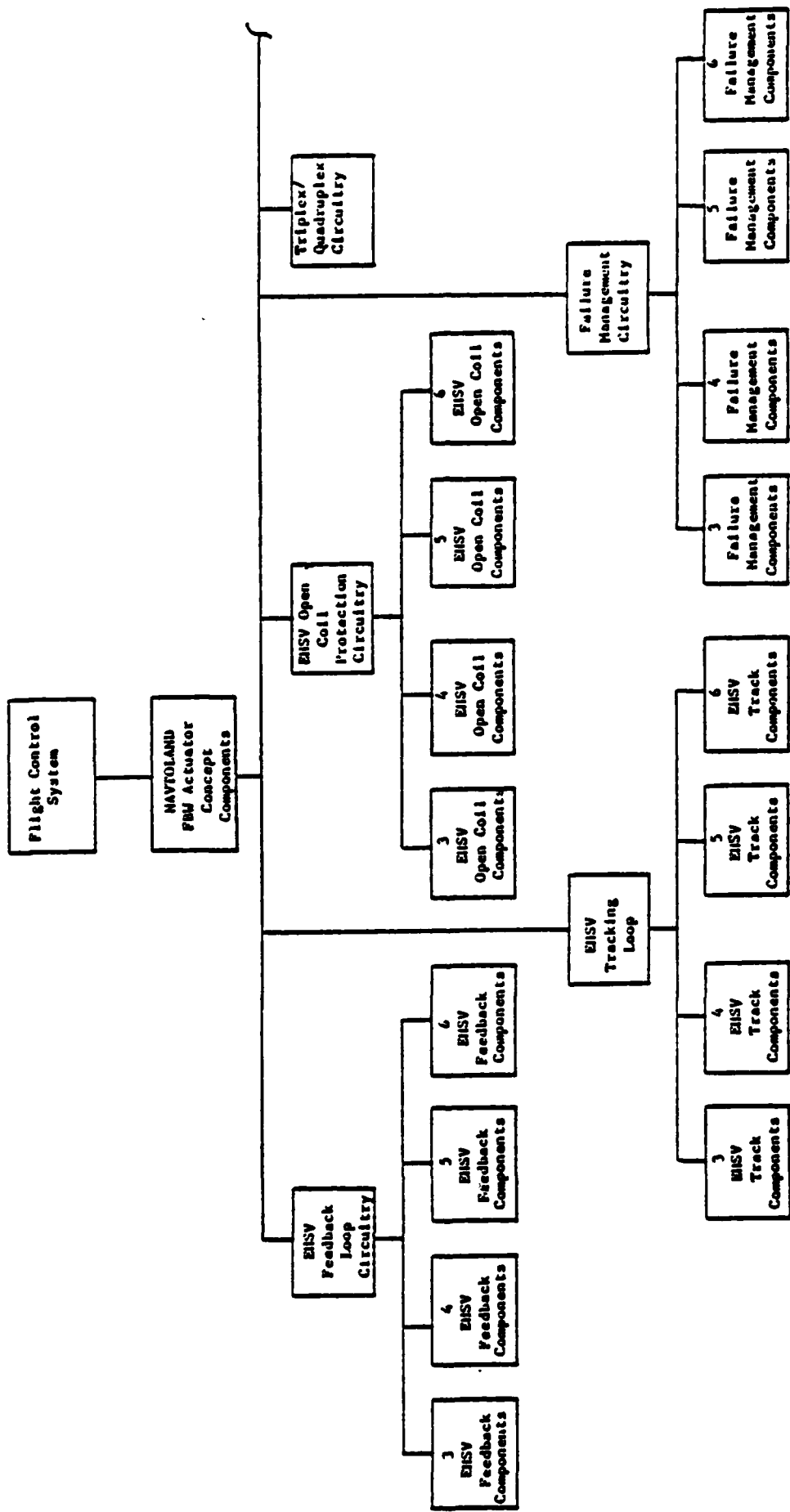
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Flight Control System

NAVTOLAND FBW Actuator Concept Components

EHSV Feedback Loop Circuitry

EHSV Open Coil Protection Circuitry

Triplex/Quadruplex Circuitry

Failure Management Circuitry

1 EHSV Feedback Components

4 EHSV Feedback Components

5 EHSV Feedback Components

6 EHSV Feedback Components

3 EHSV Open Coil Components

4 EHSV Open Coil Components

5 EHSV Open Coil Components

6 EHSV Open Coil Components

3 Failure Management Components

4 Failure Management Components

5 Failure Management Components

6 Failure Management Components

EHSV Tracking Loop

3 EHSV Track Components

4 EHSV Track Components

5 EHSV Track Components

6 EHSV Track Components

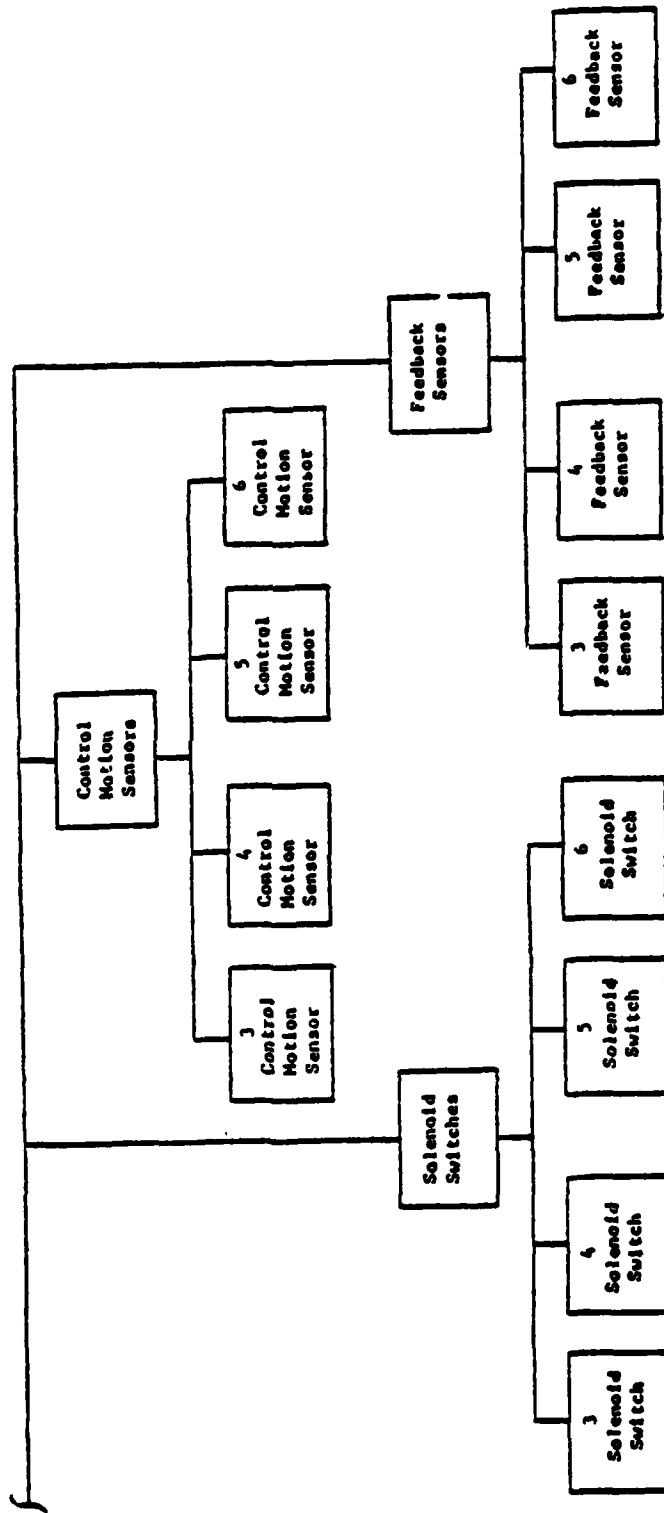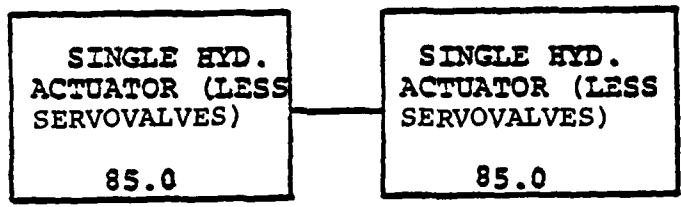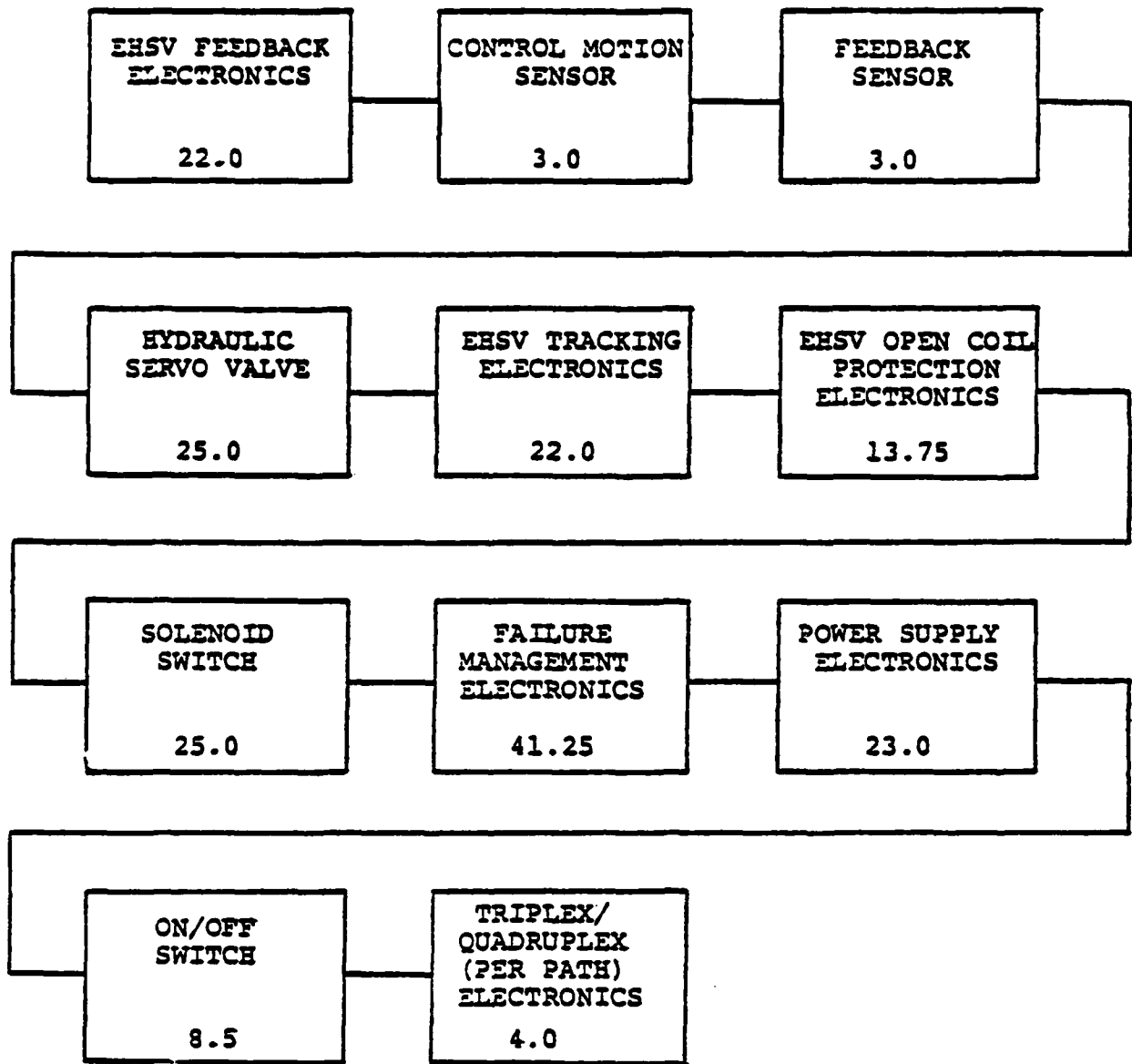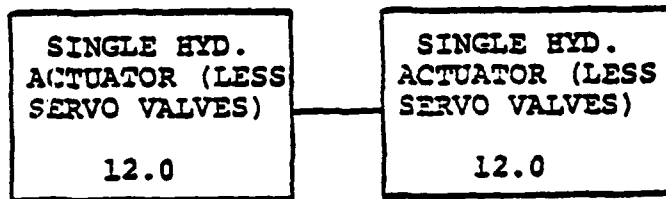Figure C1. FBW actuator concept component tree.
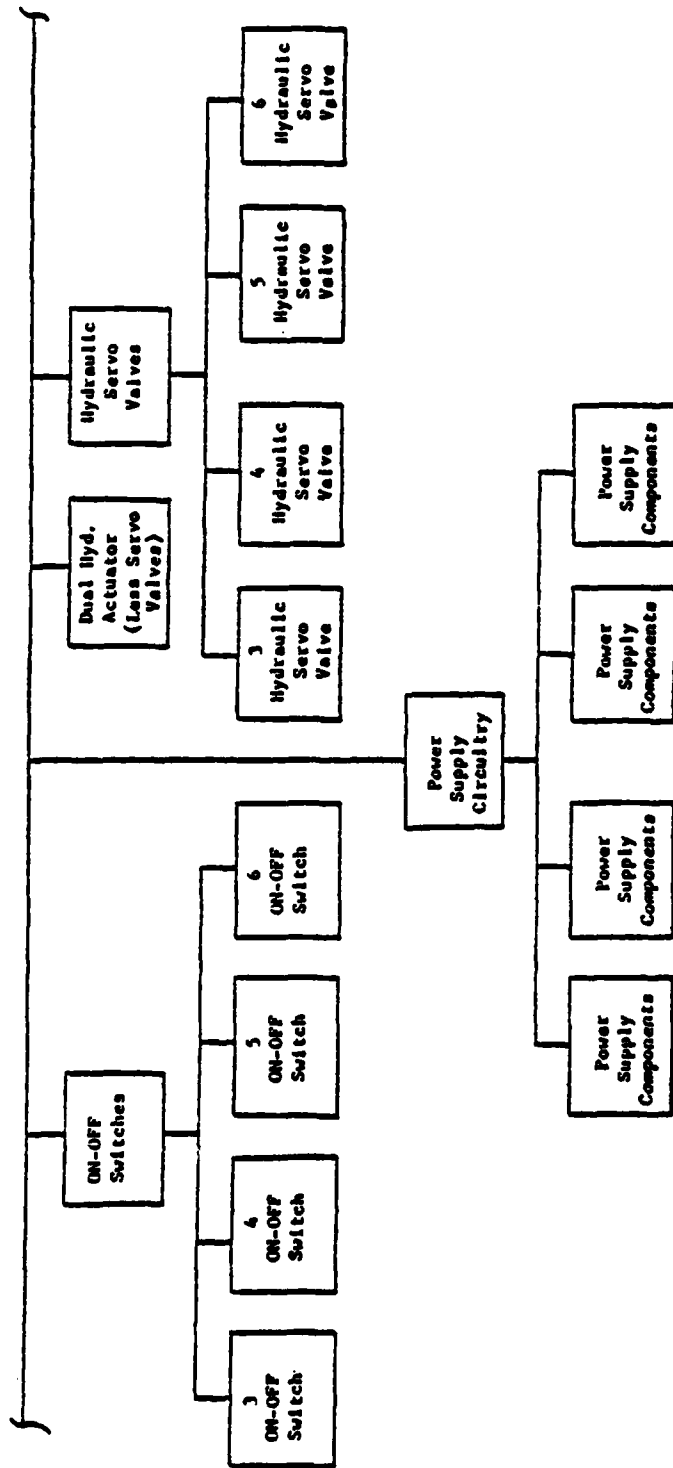
Figure C1. Continued.

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Figure C1. Concluded.

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$$R_{S_1} = \pi \, R_{S_i} = e^{-t \, \Sigma \, \lambda_{S_i}}$$

Figure C2. System reliability block diagram of the FBW actuator concept common components and corresponding failure rates (λ_{S_i}).
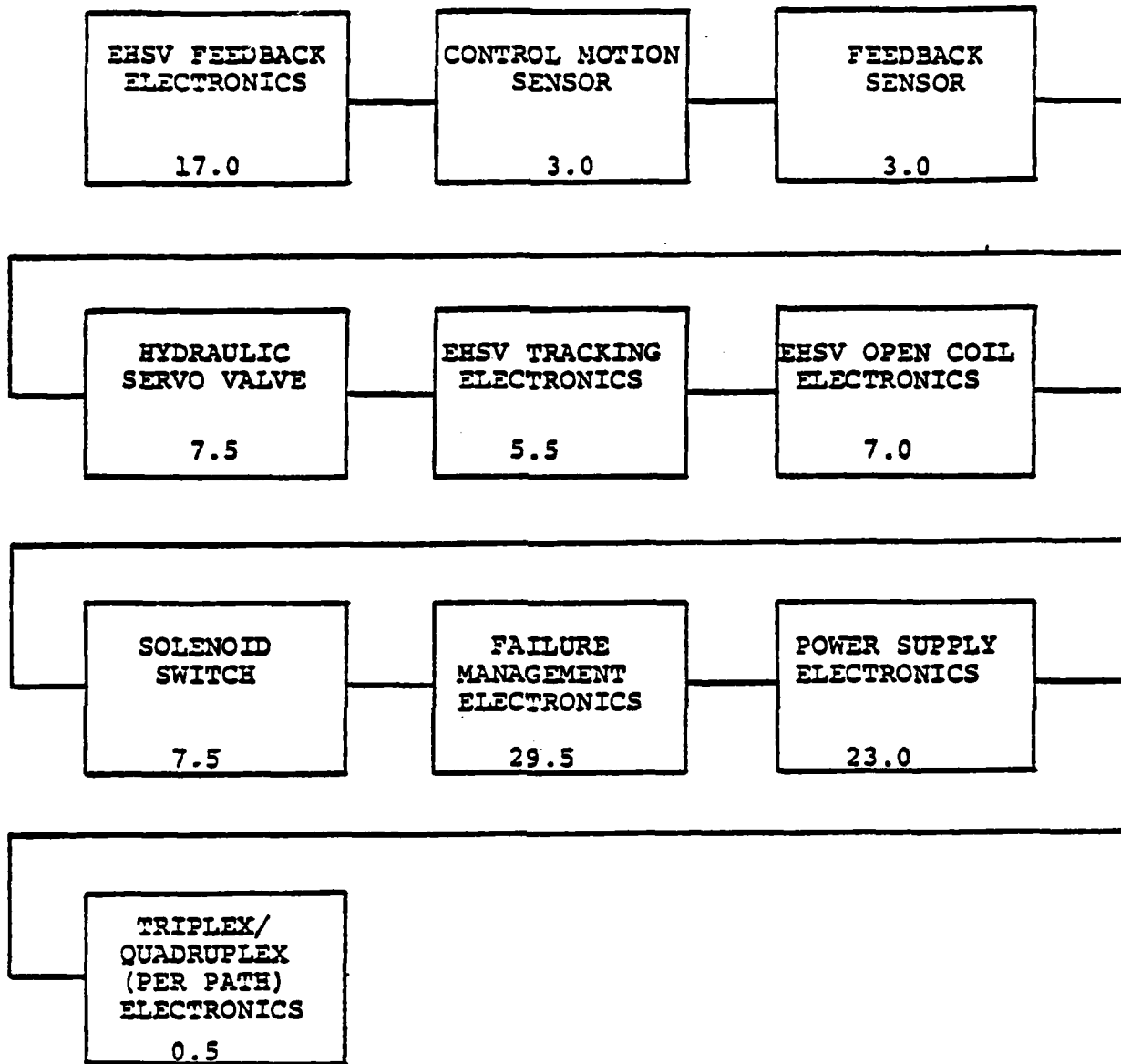
Figure C3. System reliability block diagram of one of the four
FBW actuator concept control paths and corresponding
component failure rates (λ_{S_j}) (failures per 10^6 flight
hours).

$$R_{S_3} = R_{S_4} = R_{S_5} = R_{S_6} = \pi R_{S_j} = e^{-t \Sigma \lambda_{S_j}}$$

$$R_{M_1} = R_{M_i} = e^{-t \, \Sigma \lambda_{M_i}}$$

Figure C4.   Mission reliability block diagram of the FBW actuator
concept common components and corresponding mission
failure rates (λ_{M_i}) (failures per 10^6 flight hours).

$$R_{M_3} = R_{M_4} = R_{M_5} = R_{M_6} = \pi R_{M_j} = e^{-t\Sigma \lambda_{M_j}}$$

Figure C5.   Mission reliability block diagram one of the four
FBW actuator concept control paths and corresponding
component failure rates (λ_{M_j}) (failures per 10^6 flight
hours).

the FBW actuator. Similar to the mission analysis, the failure mode failure rates for each component causing actuator function loss was summed to obtain the flight safety analysis results.

The component success probabilities for one hour of mission time were computed using the exponent reliability equation:

$$R = e^{-\lambda t} \tag{1}$$

where,

e = exponential distribution value

λ = failure rate failures per flight hour

t = the one hour of mission time

R = the probability that no failure will occur during time t

Failure probabilities (Q) were computed using the equation:

$$Q = 1-R \tag{2}$$

where,

R = the reliability using equation (1)

The next step in analysis was to determine the success path for:

- one path surviving

- two paths surviving

- three paths surviving

- for all paths surviving

The probability of successful operation of the system with all paths surviving is equal to the product of each item reliability:

$$R_S = R_{S_1} R_{S_2} R_{S_3} R_{S_4} R_{S_5} R_{S_6} \tag{3}$$

where,

R_S = the system reliability

$R_1 = R_2 =$ the reliability of each single actuator

$R_3, R_4, R_5, R_6 =$ the reliability of each of the four control paths

The probability of at least three of the four paths surviving a one hour mission is:

$$R_M(3) = w \, R_{M_1} \, (4R_{M'}^3 - 3R_{M'}^4) \tag{4}$$

where,

$R_{M_1} = R_1 = R_2 =$ the probability of success of one of the single actuators

$R_{M'} = R_3 = R_4 = R_5 \, R_6 =$ the probability of success of one of the four control paths

The probability of at least two of the four paths surviving a one hour mission is:

$$R_M(2) = R_{M_1}^2 \, (6R_{M'}^2 - 8R_{M'}^3 + 3R_{M'}^4) + (2R_{M_1} - 2R_{M_1}^2) \, R_{M'}^2 \tag{5}$$

The probability of at least one of the four paths surviving a one hour mission is:

$$R_M(1) = R_{FS} = (2R_{M_1} - R_{M_1}^2)(4R_{M'} - 6R_{M'}^2 + 4R_{M'}^3 - 4R_{M'}^4) \tag{6}$$

5. RESULTS

The results of the system reliability analysis are shown in Table C1. This table presents the failure rate, MTBF, and one hour reliability for each component and for the total system.

The results of the mission reliability analysis are shown in Table C2. This table also presents the failure rate, MTBF, and one hour mission reliability for each major component and for the total system.

Table C3 presents the results of the per path analysis for mission and flight safety reliability. This table shows the probability of no failures, 3-path survival, 2-path survival, and 1-path survival.

TABLE C1.   PREDICTED SYSTEM RELIABILITY OF THE
FLY-BY-WIRE ACTUATOR CONCEPT

	Failure Rate (Failures per 10^6 Flight Hours)	Mean Time Between Failures (Flight Hours)	Reliability (One Hour)
System	932	1073	.999069
EHSV Feedback Loop Circuits (4)	88	11364	.999912
EHSV Tracking Loop Circuits (4)	88	11364	.999912
EHSV Open Coil Protection Circuits (4)	55	18182	.999945
Failure Management Circuits (4)	165	6061	.999835
Triplex/Quadruplex Circuits (1)	16	62500	.999984
ON-OFF Switch (4)	34	29412	.999966
Power Supply Circuits (4)	92	10870	.999908
Control Motion Sensors (4)	12	83333	.999988
Feedback Sensors (4)	12	83333	.999988
Dual Hydraulic Actuator (1)	270	3704	.999730
Solenoid Switches (4)	100	10000	.999900

	1.0		2.8	2.5
			3.2	2.2
	1.1		3.6	2.0
			4.0	1.8
	1.25	1.4		1.6
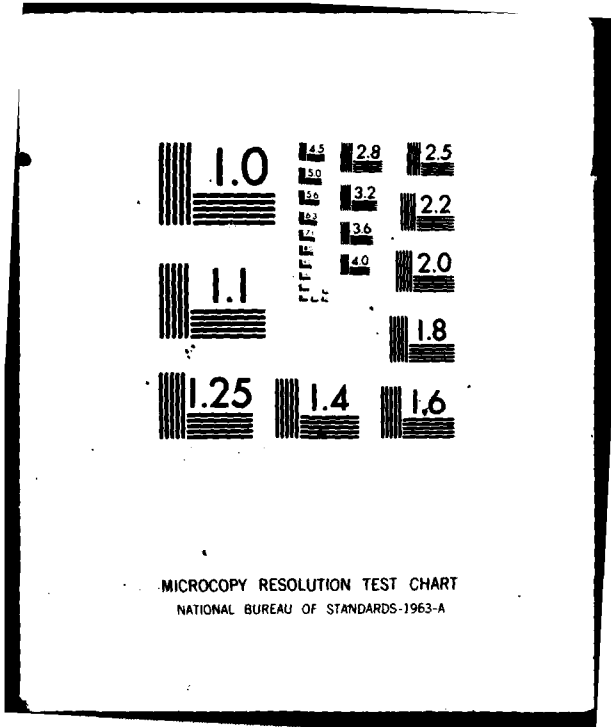
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TABLE C2. PREDICTED MISSION RELIABILITY OF THE
FLY-BY-WIRE ACTUATOR CONCEPT

	Failure Rate (Failures per 10^6 Flight Hours)	Mean Time Between Failures (Flight Hours)	Reliability (One Hour)
System	438	2283	.999562
EHSV Feedback Loop Circuits (4)	68	14706	.999932
EHSV Tracking Loop Circuits (4)	22	45454	.999987
EHSV Open Coil Protection Circuits (4)	28	35714	.999972
Failure Management Circuits (4)	118	8475	.999882
Triplex/Quadruplex Circuits (1)	2	500000	.999998
Power Supply Circuits (4)	92	10870	.999908
Control Motion Sensors (4)	12	83333	.999988
Feedback Sensors (4)	12	83333	.999988
Dual Hydraulic Actuator (Less Valves) (1)	24	41667	.999976
Hydraulic Servovalves (4)	30	33333	.999970
Solenoid Switches (4)	30	33333	.999970

TABLE C3. PATH PROBABILITY ANALYSIS

	No Failures	(One Hour Reliability) 3-Path Survival	2-Path Survival	1-Path Survival
Mission (Includes Hardovers)	.999562	.9999759	.999999992	
Flight Safety				.999999999857

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In performing this analysis, a few basic assumptions were made:

- The FBW system will use components with an established reliability history.

- All components will be subjected to a burn-in test to eliminate infant mortality failures and stabilize failure rates.

- All components will be tested to the expected operating limits in the true installation environment during development.

- Cooling air will be used whenever the system is energized to eliminate heat related problems.

- The design cycle will include a Test, Analyze, and Fix (TAAF) program for reliability growth and evaluation.

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