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SEPTEMBER 1969

HYDRAULIC CIRCUIT BREAKER FOR AIRCRAFT HYDRAULIC SYSTEMS

N.J. PIERCE

INTERIM TECHNICAL REPORT NO. 2

PART I

This document is subject to special export controls for each transmittal to foreign governments or foreign nationals may be made only with the prior approval of the Air Force Aero Propulsion Laboratory (APFL), Wright-Patterson Air Force Base, Ohio 45433

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FOREWORD

This report was prepared by N. J. Pierce, Senior Design Specialist, Hydraulics Staff, McDonnell Aircraft Company, McDonnell Douglas Corporation. The work reported herein was carried out under Contract No. F33615-69C-1510, Project No. 3145, "Hydraulic Circuit Breaker for Aircraft Hydraulic Systems" and was administered by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. The period covered by this report is 25 June 1969 to 25 September 1969.

Messrs., C. T. Thurston, G. E. Amies, R. S. Andrews

assisted in the performance of this work.

This report contains no classified information extracted from other classified documents.

Publication of this report does not constitute Air Force approval of the report findings or conclusions. It is published only for the exchange and stimulation of ideas.

ABSTRACT

Automatic failure isolation in aircraft hydraulic systems, to reduce the probability of a single hit causing the loss of the complete system, can be accomplished by a number of methods. Reservoir level sensing, (RLS) senses a loss of fluid from the total system, and initiates a search for the failed subsystem. Flow sensing and comparison senses a loss of fluid from the subsystem, and shuts off the supply. Subsystem isolation allows transfer of power but prevents fluid transfer between the system and subsystem. Miscellaneous methods enable a loss of fluid to be sensed and shut off. In addition, there are several combinations of concepts that are attractive. The first phase of the program has been carried out. The object of this part of the program was to collect and tabulate all the available data related to the subject from government and industry sources. The tabulated data was then used to compare the various techniques with the requirements for F-4 and F-15 type aircraft in the second phase of the study. A decision has been made as to which techniques merit further investigation. The best concept from each of the three basic categories (RLS, Flow Comparison, Isolation) was selected. Working prototypes for experimental verification of analytical predictions are being procured and will be evaluated.

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SECTION I

INTRODUCTION & SUMMARY

The need for automatic failure isolation in aircraft hydraulic systems has become more pronounced as military aircraft have become subject to high performance requirements and high risk combat situations. Many aircraft are lost because a single hit or operational failure has caused the loss of the entire hydraulic control system or systems. If it were possible to reliably seal off that portion of the system in which the failure has occurred, the remainder of the hydraulic system would remain operative. The isolation of a hydraulic failure would make possible the return of the aircraft and pilot or at least enable the pilot to fly the aircraft to friendly territory for ejection purposes. The isolation device must be of such reliability that its insertion into the hydraulic system does not significantly reduce the overall system reliability because of inadvertent closure.

An Air Force sponsored and funded program, under the direction of the Aero Propulsion Laboratory, for the development of a working hydraulic circuit breaker system, is under way at the McDonnell Aircraft Division of the McDonnell Douglas Corporation.

The program is being carried out in three phases: (1) will define the required parameters and performance of such a system and recommend units which should be designed and manufactured for further development and evaluation; (2) will be the manufacturing and testing of the selected units; (3) will be a final evaluation on the basis of the experimental results and recommendations of the type of system which should be used on future aircraft.

The first half of phase (1), the preliminary evaluation, was covered by Interim Technical Report No. 1. Interim Technical Report No. 2 covers the completion of phase (1) and the period from 25 June 1969 to 25 September 1969. The analysis of the candidate concepts has been completed and a concept from each of the basic categories has been selected for fabrication and test. The categories are reservoir level sensing, flow comparison, and subsystem isolation.

The Hydraulic Circuit Breaker (HCB) potential has been assesed as follows:

Combat -

- o Survivability
  - F-4 - Increase hit tolerance by one (3 vs. 2 for the same percent of kills).
  - Advanced Aircraft - Increase hit tolerance by two (5 vs. 3 for same percent of kills).
- o Can reduce chances of catastrophic hydraulic fires by limiting the amount of fluid dumped.

Non Combat -

- Increase in Aircraft Reliability
  - F-4 - 20% reduction in aircraft losses.
  - Advanced Aircraft - 70% reduction in aircraft losses.
- Reduction in aircraft losses due to dual system failures (11 F-4 losses out of approximately 3,000 in service - approximately $20,000,000.00).
- Reduction in pump replacement costs and maintenance due to system loss. (Approximately 70 pumps per year based on reported system losses in the last 3 1/2 years. Approximately 64% of the central system losses would have been eliminated by HCB).

The weight and cost penalties associated with the above noted potential for an advanced aircraft are:

- Reservoir Level Sensing - 15 to 20 lb. - $1500 to $1800
- Flow Comparison - 9 to 54 lb. - $630 to $4500
- Isolation - 45 lb. - $3000

Part I of this report presents the information not considered proprietary. Part II of this report presents the information considered proprietary. Therefore, only the Air Force Aero Propulsion Laboratory will have access.

SECTION II

THEORETICAL ANALYSIS RESULTS

1.0 SUMMARY

The theoretical analysis is essentially complete. Subsequent paragraphs contain a detailed review of each aspect evaluated. In general, the analysis indicated incorporation of an effective HCB would substantially increase hydraulic system survivability in combat, and system reliability during all types of normal system operation. This is primarily because HCB incorporation would:

(a) Reduce vulnerable area which could cause aircraft "kill" due to single or multiple combat hits.

(b) Decrease the number of "single-point" operational failures which would cause system loss.

(c) Reduce the fire hazard associated with the amount of fluid dumped over board.

(d) Reduce the need of a third redundant system or power pack units to attain high survivability.

In addition, the HCB will produce a decrease in maintenance costs and aircraft down-time due to system failures incurred by leaking subsystems. In general, few significant differences in weight and cost exist in the various concepts evaluated. Exceptions to this were the APM Flow Comparator design (lightest and least expensive) and the Abex and Vickers Motor Pumps (heaviest and most expensive).

2.0 SURVIVABILITY

An evaluation was conducted to determine the effects on hydraulic system survivability due to the addition of an HCB in each system branch circuit.

The evaluation was conducted for each selected configuration based on the occurrence of one through four combat hits on the hydraulic system. This was accomplished by a computer program which allowed all possible hit combinations to occur and computed the total probabilities of kill, abort and mission continuation in accordance with the ground rules of Paragraph 2.1.

The results shown in Table II.2-1 represent the effects of incorporating HCB where no armor protection is incorporated. As shown significant decreases in kill probability are realized with HCB incorporated. It should be noted that the probability of abort tends to become greater with HCB incorporated for multiple hit conditions. In this case the damage which would be a kill condition without HCB is converted to an abort condition when HCB is incorporated. As one would intuitively expect, the probability of mission continuation decreases as the number of hits on the system increases.

The effects of adding armor in conjunction with HCB are shown in Table II.2-2. The armor is assumed to be incorporated on the advanced aircraft similar to the present F-4. That is, the stabilator actuators and the central portion of the hydraulic system are protected against 50 caliber AP ammunition. However, for this study the armor is assumed to provide protection against all types of ammunition. With HCB and armor incorporated as described above, the probability of kill is reduced to significantly low levels for both aircraft. The probability of abort for the advanced aircraft is also significantly reduced. This is primarily because the critical failure areas (stabilator and control system) are protected by armor. This armor protection is also true for the F-4, however, the wing control surfaces are not protected by armor but are required for landing.

Table II.2-3 presents probabilities for the present F-4 with both partial armor and the electrical power pack (EPP) to stabilator incorporated. Again, kill and abort probabilities are substantially reduced with HCB incorporated.

In addition to the above, several important aspects of the survivability analysis are revealed regarding the number of hydraulic systems to power control surfaces.

(a) Two-system aircraft, e.g., original F-4, with HCB incorporated is more survivable than a three-system aircraft, e.g., present F-4 and advanced aircraft without HCB (Ref. Table II.2-1).

(b) The present F-4 with partial armor and HCB (Ref. Table II.2-2) is more survivable than the same aircraft with electrical power pack, but without HCB. (Ref. Table II.2-3).

Based on the above, the addition of HCB provides as much or more protection than adding another system in the loop.

Consideration to date has involved only the hydraulic system vulnerable areas, and the effects of a given hit. Total aircraft vulnerability is being considered

TABLE II.2-1 SURVIVABILITY – NO ARMOR PROTECTION

Configuration		Probability of Kill				Probability of Abort				Probability of Mission Continuation			
	No. Hits	1	2	3	4	1	2	3	4	1	2	3	4
Original F-4	Without HCN	0.06	0.56	0.79	0.90	0.94	0.44	0.21	0.10	0	0	0	0
	With HCB	0.01	0.09	0.22	0.38	0.41	0.74	0.73	0.61	0.58	0.17	0.05	0.01
Present F-4	Without HCB	0.01	0.20	0.41	0.57	0.60	0.65	0.53	0.41	0.39	0.15	0.06	0.02
	With HCB	0.01	0.07	0.18	0.35	0.35	0.68	0.73	0.62	0.64	0.25	0.09	0.03
Advanced Aircraft	Without HCB	0.02	0.04	0.27	0.48	0.30	0.73	0.65	0.49	0.68	0.23	0.08	0.03
	With HCB	0.02	0.03	0.09	0.19	0	0.27	0.50	0.59	0.98	0.70	0.41	0.22

TABLE II.2-2 SURVIVABILITY – WITH PARTIAL ARMOR PROTECTION

Configuration		Probability of Kill				Probability of Abort				Probability of Mission Continuation			
Present F-4	No. Hits	1	2	3	4	1	2	3	4	1	2	3	4
	Without HCB	0	0.08	0.20	0.32	0.40	0.57	0.59	0.55	0.60	0.35	0.21	0.12
	With HCB	0	0.01	0.02	0.06	0.15	0.33	0.51	0.62	0.85	0.66	0.47	0.32
Advanced Aircraft	Without HCB	0	0.00	0.06	0.15	0.15	0.40	0.55	0.61	0.85	0.60	0.39	0.24
	With	0	0	0.00	0.01	0	0.06	0.16	0.27	1.00	0.94	0.84	0.72

TABLE II.2–3 SURVIVABILITY – PRESENT F–4 WITH PARTIAL ARMOR AND ELECTRICAL POWER PACK INCORPORATED

Configuration	Probability of Kill				Probability of Abort				Probability of Mission Continuation			
No. Hits	1	2	3	4	1	2	3	4	1	2	3	4
Without HCB	0	0.02	0.10	0.21	0.41	0.63	0.70	0.67	0.59	0.35	0.20	0.12
With HCB	0	0.00	0.01	0.03	0.05	0.16	0.29	0.42	0.95	0.84	0.70	0.56

and the results will be presented in the next Interim Report. This will include three vs. two system areas and their relation to the total aircraft vulnerable area.

2.1 Ground Rules and Assumptions

The ground rules and assumptions necessary to conduct this evaluation are itemized below:

(a) The basic aircraft configurations considered in the evaluation are:

- Original F-4 - Power Control (P.C.) Systems No. 1 and No. 2 supply power for the spoiler and aileron actuators in both wings, and the stabilator actuator. Utility system supplies power for all other hydraulic functions. (Ref. Figure II.2-4)
- Present F-4 - P.C. No. 1 supplies power to left wing spoiler and aileron actuators and the stabilator actuator. P.C. No. 2 supplies power to the right wing spoiler and aileron actuators and the stabilator actuator. Utility system supplied power to spoiler and aileron actuators in both wings and remaining functions except stabilator. (Ref. Figure II.2-5)
- Advanced Aircraft - P.C. No. 1 and No. 2 to ailerons in both wings and both differential stabilators. Also utility supplies the stabilators and remainder of hydraulic functions except the ailerons. (Ref. Figure II.2-6)
- System distribution to power control surfaces:

	P.C. No. 1			P.C. No. 2			Utility			
Aircraft	Left Wing	Right Wing	Stab.	Left Wing	Right Wing	Stab.	Left Wing	Right Wing	Stab.	HCB No.
Original F-4	X	X	X	X	X	X	-	-	-	6
Present F-4	X	-	X	-	X	X	X	X	-	X
Advanced Aircraft	X	X	X	X	X	X	-	-	X	8

NOTES: HCB's are incorporated in the P.C. systems only.
Adv. A/C incorporates two stabilator actuators and two aileron actuators in each wing (no spoilers).

(b) The probability definitions applicable to the study are:

- Probability of Kill - Loss of landing capability.
- Probability of Abort - One more branch circuit failure would cause loss of landing capability.

FIGURE II.2-4 ORIGINAL F-4; SCHEMATIC – POWER CONTROL HYDRAULIC SYSTEM WITH HCB INCORPORATED

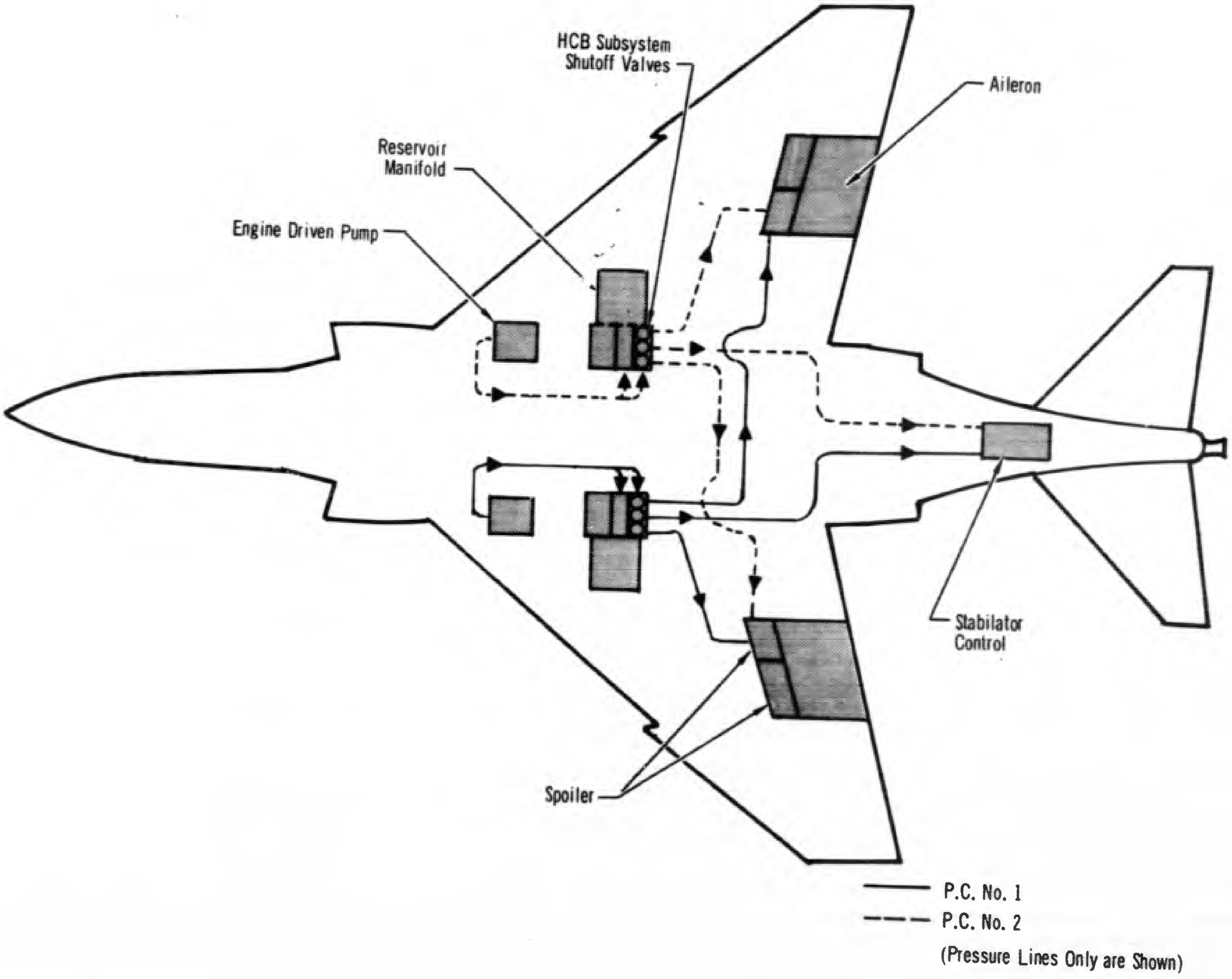


FIGURE II.2-5 PRESENT F-4; SCHEMATIC – POWER CONTROL HYDRAULIC SYSTEM WITH HCB INCORPORATED

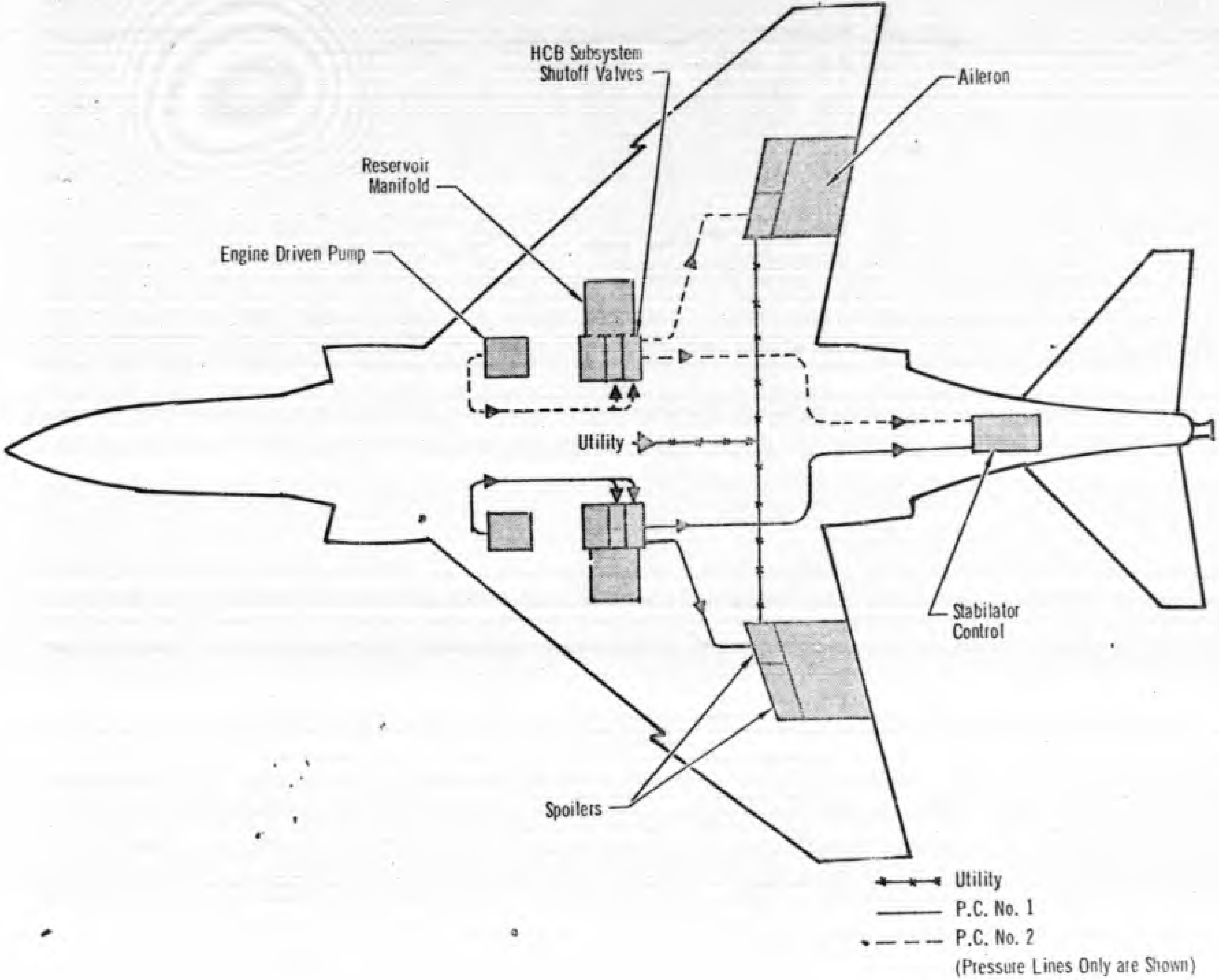
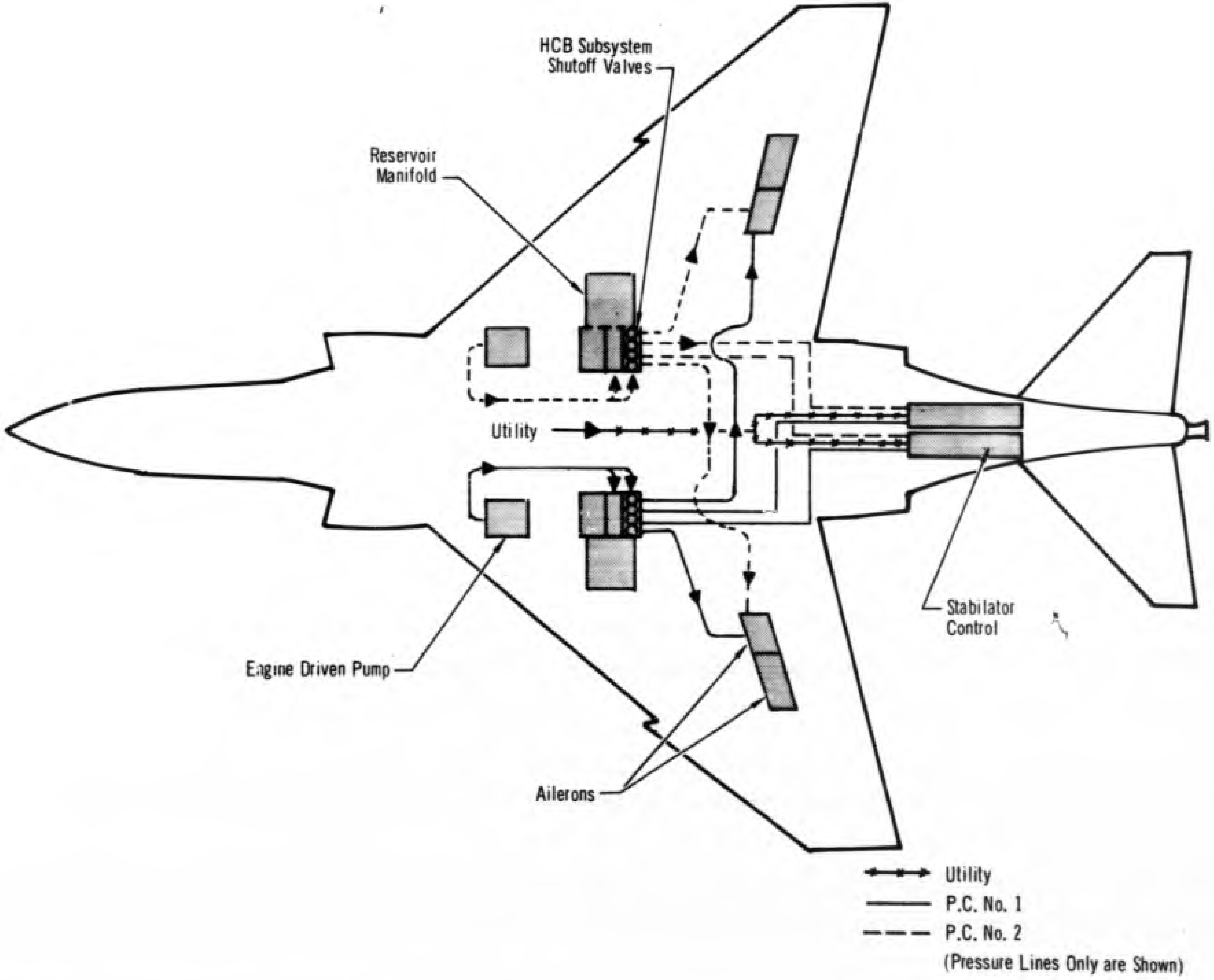


FIGURE II.2-6 ADVANCED AIRCRAFT; SCHEMATIC – POWER CONTROL HYDRAULIC SYSTEM WITH HCB INCORPORATED



- Probability of Mission Continuation - Combat hit(s) do not result in either of the above conditions.

- Probability of Survival = (1 - Prob. of Kill) = (Prob. of abort + Prob. of mission continuation).

(c) Landing capability for the F-4 configurations require at least control of the stabilator <u>and</u> either spoiler and aileron on one wing, spoilers in both wings <u>or</u> ailerons in both wings. For the advanced aircraft configuration landing capability requires at least control of both stabilators.

(d) A hit is defined as a single combat hit which causes loss of that portion of the system where it occurs on the hydraulic system only.

(e) The probability of the HCB device being hit is not included in the evaluation, i.e., Prob. (HCB survival) = 1.0.

(f) Each Power Control (P.C.) is divided into the following portions:

Central System - Pumps, Reservoir, Manifold, Accumulator, etc.
Left Wing - Aileron(s) and Spoilers
Right Wing - Aileron(s) and Spoilers
Stabilator

An HCB device is assumed to isolate each system portion above except the central system. Hit(s) in any portion causes total loss of that portion of the particular system. Hit(s) in the central system causes loss of the total system. The system breakdown described above includes associated lines and components.

(g) Similarly, the Utility system is divided into:

Central System
Left Wing (Present F-4 only)
Right Wing (Present F-4 only)
Stabilator (Advanced Aircraft only)
Utility Functions (Flaps, Landing Gear, etc.)

(h) The central portion of each system is assumed partially protected by virtue of its location in the aircraft. A single hit on any tandem actuator is considered to cause loss of one hydraulic branch circuit to that actuator 90% of the time and loss of all branch circuits 10% of the time.

3.0 CATASTROPHIC FIRE PREVENTION

Incorporation of HCB would significantly reduce the amount of fluid which could be dumped onto adjacent equipment due to external leakage. This is important from the standpoint of the combat fire hazard associated with leaking hydraulic fluid. Each HCB concept allows some amount of fluid to be dumped prior to shutoff. To provide some feel for the effects of this condition, a thermodynamic evaluation was conducted to determine the amount of leaking fluid required to create potential fire damage to an F-4E aircraft. Based on the study results, it is believed that a minimum volume of 25 to 40 in^3 must burn to produce failing structural temperatures. It is important to recognize that these values are based on one selected set of flight conditions and one particular aircraft compartment. A more rigorous investigation may have revealed that other flight conditions or localized compartment would have been more or less critical than that evaluated. The following paragraphs present a detailed description of this analysis.

3.1 Method of Analysis and Results

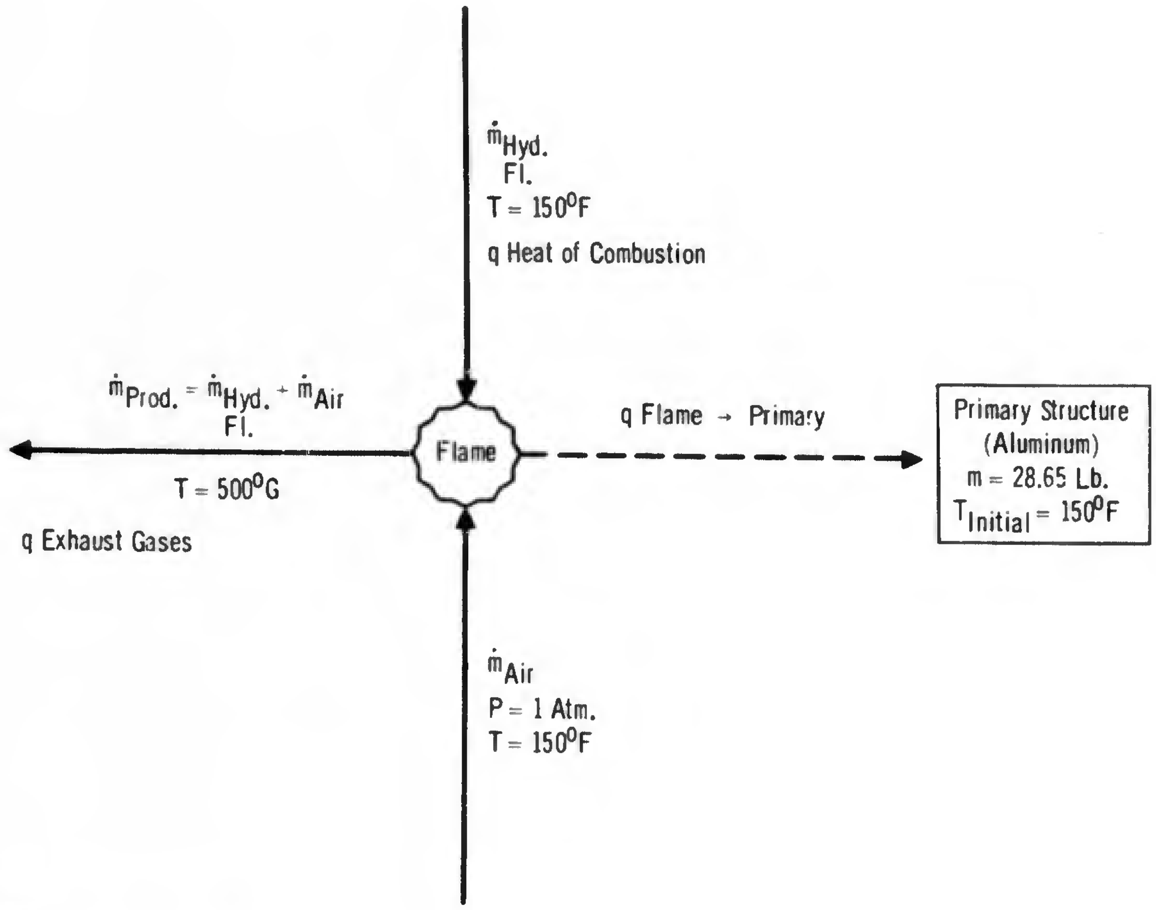
It was assumed that a fire could be started by an incendiary bullet hitting a hydraulic line. Two types of failures were initially considered in the wing in the vicinity of the hydraulic line to the aileron actuator. One was over heating of the fuel tank and the other overheating of structure. It was decided that a structural failure near the inboard spoiler actuator is more likely due to better air ventilation. It was assumed that the fluid was supporting a fire in a wing compartment, housing the inboard spoiler actuator. The compartment is bounded at the forward end by the main rear spar of the wing, at the aft end by the spoiler hinge support, by ribs on each side, and by the wing skins on the top and bottom.

The flight condition used as criteria in the failure analysis is slightly subsonic at sea level in an ICAO Standard Day atmosphere. The resulting stagnation air temperature of 150°F is used as the initial structural temperature prior to initiation of a fire. Heating of the structure to 500°F is believed to result in an immediate catastrophic failure.

Two analyses were conducted to determine the required leakage of 5606 hydraulic fluid necessary to cause a structural failure in the wing compartment as described above. The first analysis is a simplified baseline approach which predicts an absolute minimum quantity of fluid which may result in failure. A more realistic transient analysis shows higher quantities of hydraulic fluid are necessary.

The thermal model of the simplified analysis is shown in Figure II.3-1. The primary structure consists of the compartment walls as defined above. The mass of the walls and the attached actuator valve are considered as a single isothermal heat sink node with a combined mass of 28.6 pounds. The stoichiometric air/fuel ratio and specific heat of the exhaust gases are based on an assumed formula of $C_{15}H_{32}$ for the hydraulic fluid. Instantaneous stoichiometric burning (Stoichiometric burning indicates that ideal mixing occurs whereby every molecule of hydraulic fluid combines with the proper amount of air and all the oxygen and fluid burns.) within the compartment is assumed whereby the total heat of combustion (17,000 BTU per pound) generated in the flame mode is divided between that transferred to the structure and that retained in the exhaust gases. An infinite heat transfer coefficient is considered which results in the final tem-

FIGURE II.3-1 SIMPLIFIED THERMAL MODEL



Note:
q – Heat Transfer Rate
ṁ – Mass Flow Rate

peratures of the exhaust gases and the primary structure being the same. Starting with the initial structural temperature of 150°F, the quantity of hydraulic fluid required to produce the 500°F, failure temperature is 4.5 cubic inches.

The minimum quantity of hydraulic fluid versus airflow rate to produce a structural failure is shown in Figure II.3-2. This condition occurs for stoichiometric burning whereby the leakage rate into the compartment is equal to the burning rate. The minimum volume of hydraulic fluid on the stoichiometric burning curve is approximately 17 in^3 and occurs at an air flow rate of 0.7 ft^3/sec and a fluid burning rate of 0.003 lbs/sec. The curve goes to an infinite volume at an air flow rate of 0.51 ft^3/sec. This indicates that at lower air flow rates or at fluid burning rates of less than .0022 lbs/sec, a failure temperature of 600°F cannot be produced. The other leg of the curve shows that as the fluid burning rate and the air flow rate increase, the required volume of fluid to produce a failure continues to rise. A 500°F structural failure cannot be produced at any point below the stoichiometric burning curve since all of the hydraulic fluid and oxygen burn completely to produce maximum heat. Required amounts of hydraulic fluid to produce a 500°F structural failure above this curve are discussed in the following paragraphs.

The transient analysis is based on an expansion of the simplified thermal model (see Figure II.3-3). The primary structure is thermally linked by a conduction path to surrounding secondary structure. The mass of the secondary structure is also considered as a single isothermal heat sink. The primary and secondary structures are connected thermally to the free air stream passing across the wing. A conventional turbulent boundary layer heat transfer coefficient of 90 BTU/Hr ft^2°F was utilized to calculate the heat transfer between the skin and the air stream. Determination of the heat transfer coefficient between the burning gases and the primary structure is more complex. Since the air velocities within the compartment are expected to be relatively low and uniform, both free convection and forced convection coefficients were evaluated. Linearized radiation coefficients were determined to account for radiant heat transfer from the water vapor, and carbon dioxide for both rich and lean burning mixtures. Variation in the convective and radiative coefficients resulted in a total heat transfer coefficient ranging from 4 to 15 BTU/Hr ft^2°F. An intermediate value of 10 is used in the analysis.

The heat input to the flame node within the compartment is based on the burning rate of the leaking hydraulic fluid. Heat transfer to the primary structure is a function of air flow rate into the compartment, the temperature of the primary structure, and the heat transfer coefficient between the flame and the structure. The effective flame temperature is considered to be uniform throughout the compartment and is used as the exhaust temperature of the combustion products. This temperature is utilized in evaluating the heat transfer from the flame node via the gases.

The results are depicted in the curves of Figure II.3-4 which represent various burning rates extending from stoichiometric burning conditions at the lower ends of the curves, to leaner mixtures as the air flow rates increase. Lean burning occurs when the air/fuel mixture consists of more than enough oxygen necessary for total combustion of all the fluid. As the mixture becomes leaner, the required volume of fluid increases because more of the heat of combustion is transferred to extra air and less is available to heat the structure. The maximum air flow rates depicted at infinite fluid volume show a limiting air flow

FIGURE II.3-2 REQUIRED LEAKAGE OF 5606 HYDRAULIC FLUID TO PRODUCE 500°F STRUCTURAL TEMPERATURE FOR STOICHIOMETRIC BURNING

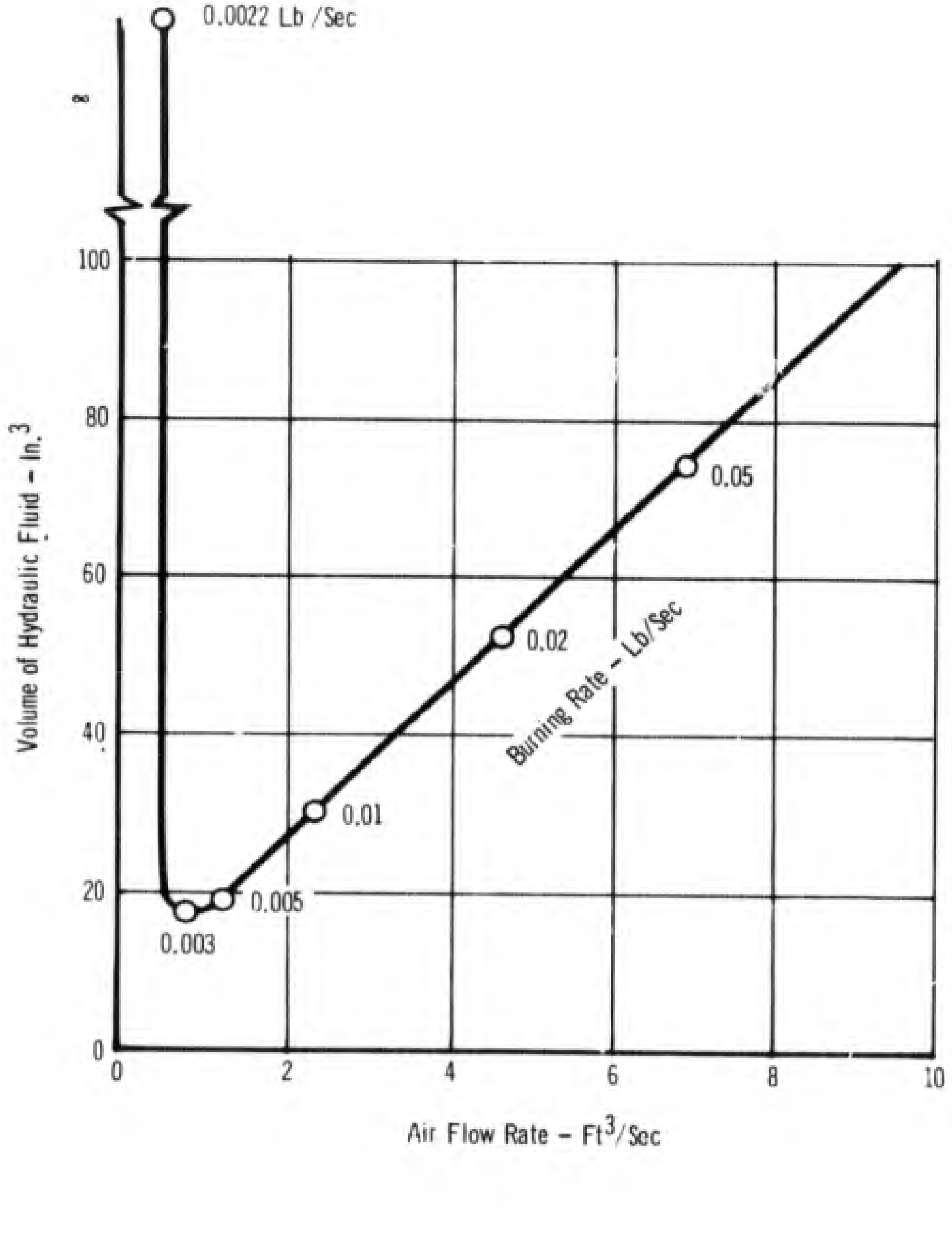


FIGURE II.3-3 TRANSIENT THERMAL MODEL

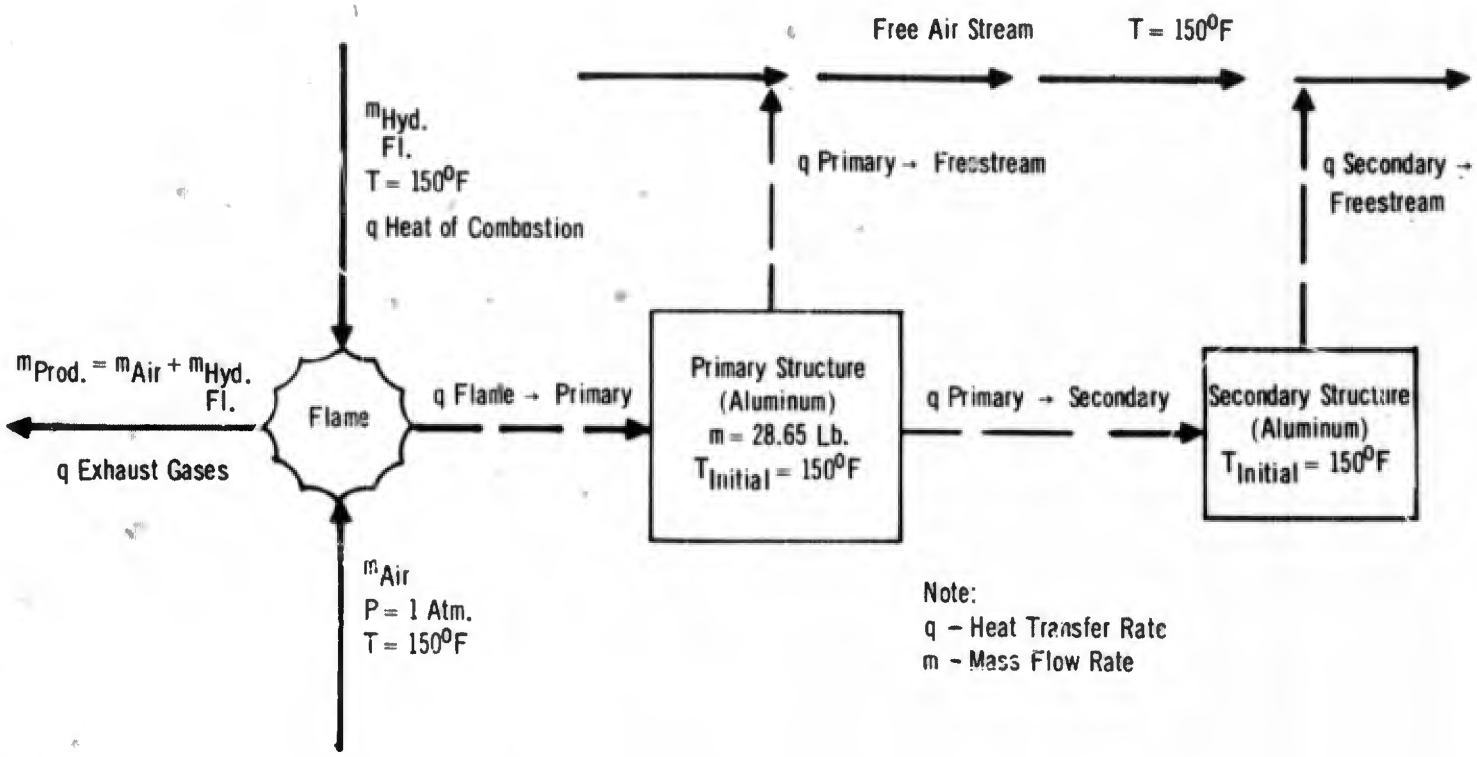
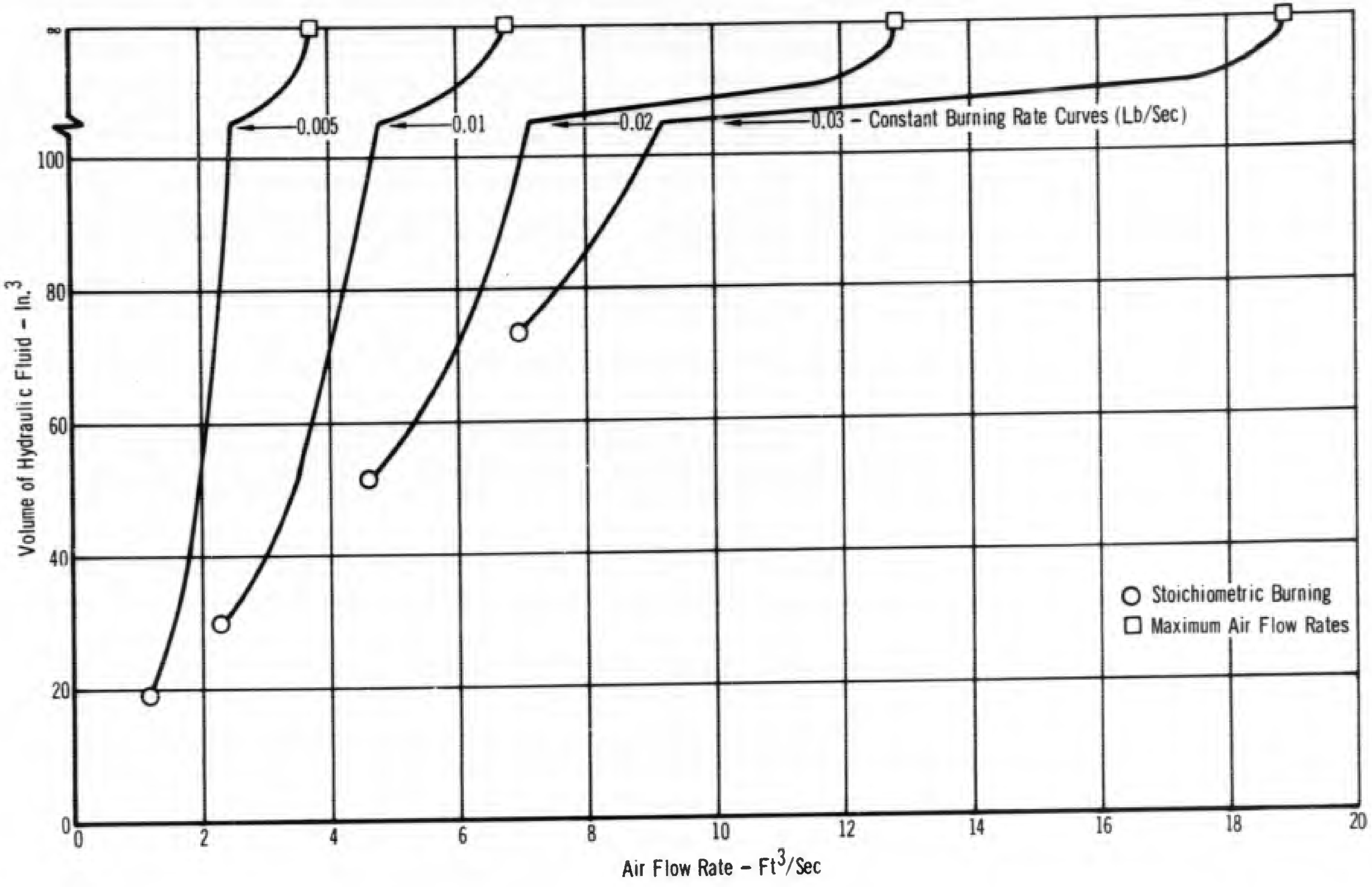


FIGURE II.3-4 REQUIRED LEAKAGE OF 5606 HYDRAULIC FLUID TO PRODUCE 500°F STRUCTURAL TEMPERATURE FOR LEAN BURNING



rates depicted at infinite fluid volume show a limiting air flow rate for each burning rate beyond which a 500°F failure will not occur regardless of how long the fire burns. In each of the above cases, the leakage rate of hydraulic fluid into the compartment is assumed to be equal to the burning rate of the fluid. These data also can represent conditions where the leakage rate into the compartment is greater than the burning rate. However, it must be assumed that this extra fluid remains in the liquid state and no heat is transferred to it (i.e., it leaks out of the aircraft wing at the same temperature as it leaks into the compartment.

A rich burning mixture is a condition where all of the oxygen content of the air burns with an excess of fluid available. Results of the rich burning analysis are shown in Figure II.3-5. Four burning rates are considered (vertical curves) in conjunction with various fluid leakage/burning rate ratios (inclined curves). This ratio extends from a stoichiometric mixture where the leakage rate is equal to the burning rate up to a point where the leakage is twice as large as the burning rate.

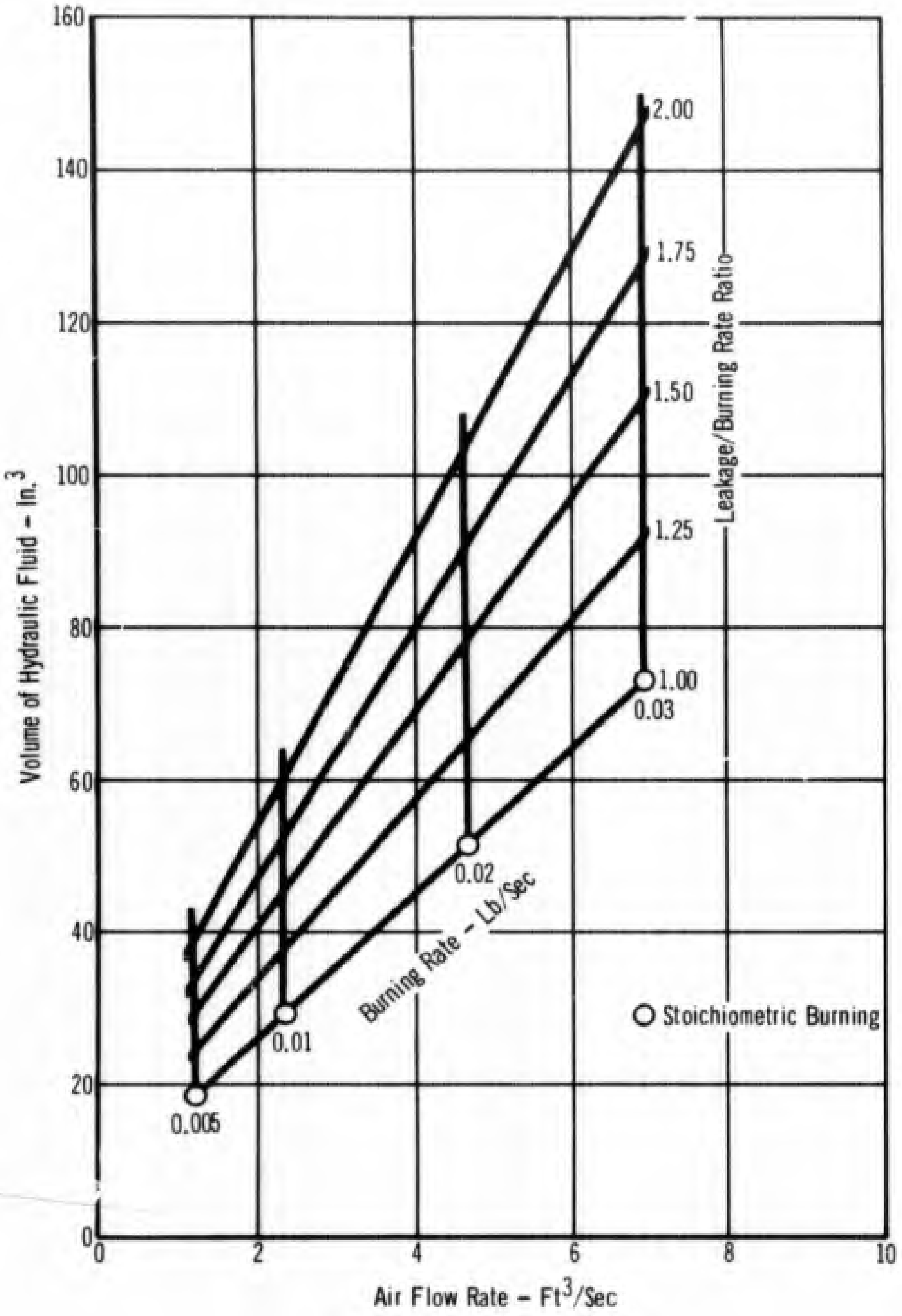
Three conditions of the excess fluid are considered in the rich burning analysis. First, the excess fluid is assumed to remain in the liquid state with zero heat being transferred to it. Next, the excess fluid is assumed to remain in the liquid state but heated to a higher temperature before leaking out of the aircraft. The difference in required hydraulic fluid to produce a 500°F structural temperature between the above two conditions is negligible. In the third condition the most critical assumption is made whereby the excess fluid is vaporized and its temperature raised to that of the exhaust combustion gases. Comparison of the third condition with the first indicates less than a ten percent rise in required hydraulic fluid at a leakage/burning rate ratio of two. The difference diminishes to zero at a ratio of one. Thus, the results of the first condition only are presented in Figure II.3-5.

3.2 Conclusions

It is concluded that the simplified approach which gives a required volume of only 4.5 in^3 of hydraulic fluid is conservatively low primarily due to the assumed infinite heat transfer coefficient between the hot gases and the primary structure. The minimum volume of 17 in^3 of hydraulic fluid indicated in the transient analysis also appears conservatively low for two reasons. First, stoichiometric burning requires very thorough mixing with the air, a process more likely to be approached with a highly volatile fluid. The subject 5606 hydraulic fluid has a very low vapor pressure. Secondly, the probability of having the proper air flow rate at low burning rates is low. This is indicated by the nearly vertical burning rate curves at low air flow rates in Figure II.3θ4. In light of the above rationale, the minimum volume of hydraulic fluid required to produce a 500°F structural failure is believed to be between 25 and 40 in^3.

This analysis is based on one flight condition and one localized aircraft compartment. A more thorough investigation may have revealed that another flight condition and localized compartment would have been more critical.

FIGURE II.3–5 REQUIRED LEAKAGE OF 5606 HYDRAULIC FLUID TO PRODUCE 500°F STRUCTURAL TEMPERATURE FOR RICH BURNING



4.0 RELIABILITY

An analysis was conducted to determine the reliability of each HCB device and the effect of each on hydraulic system reliability. Reliability estimates were conducted for three cases:

- Probability of HCB failure during normal system operation, e.g., inadvertant closure.
- Probability of HCB failure during emergency system operation, i.e., failure to sense and shut off leaking subsystem.
- Percent reduction in aircraft aborts and aircraft losses with HCB incorporated.

One typical HCB design was selected from each of the four basic concepts (RLS, Flow Comparator, Isolation and Isolation Reversion). The evaluation covered two aircraft configurations, present F-4 and an advanced aircraft configuration. The results as presented in Table II.4-1 indicate the RLS and Isolation Reversion devices are most reliable during normal system operation due to their relatively passive nature. In the case of emergency system operation the isolation devices are better since they simply cease functioning after a subsystem leak occurs. However, it should be recognized that some form of switch-off device may be required.

Evaluation of the system probability of failure with and without HCB incorporated indicate significant percent reductions in aborts and aircraft losses with each HCB except in the case of the Isolation device. In this case, the effect on the present F-4 is very small and in fact shows an increase in percent aborts. Also, for the advanced aircraft the isolation device ranks a poor fourth although significant reductions do result. The Isolation concept's contribution to system success is to a great extent offset by its own probability of failure during normal operation.

F-4 malfunction data was reviewed to determine the number of power control system losses due to leakage which could have been averted by an HCB device. The results are summarized in Table II.4-2. As shown, 64% of the leakage which caused system loss occurred due to leakage in a branch circuit. Assuming HCB protection in each branch circuit and that the HCB device would be effective 100 percent of the time, this represents a significant number (104) of system losses which could have been averted. It is also significant to note that this represents 38 percent of hydraulic system losses due to all reasons; component and subsystem mechanical/electrical failures, as well as leakage.

4.1 GROUND RULES AND ASSUMPTIONS

Ground rules and assumptions used in the reliability analysis are presented below:

(a) Failure rate estimates for the HCB concepts are based on piece part count and engineering evaluation of failure rates obtained from FARADA (Failure Rate Data Handbook, BuWeps). Hydraulic system component failure rates are based on AFM 66-1 reporting for F-4C/D/E and RF-4C from January 1968 through 31 December 1968.

TABLE II.4–1 RELIABILITY

			With HCB Incorporated			
Hydraulic Circuit Breaker Configuration	Failures During Normal System Operation Per 10^6 Missions	Failures During Emergency System Operation Per 10^6 Missions	% Reduction in Aircraft Aborts Due to Hydraulic System Failures		% Reduction in Aircraft Loss Due to Hydraulic System Failures	
			Present F–4	Advanced Aircraft	Present F–4	Advanced Aircraft
RLS – Mechanical, Pilot Operated; Poppet Shut-Off	1	45	12	94	19	73
Flow Comparator – Fixed Orifice Type	47	47	10	84	18	62
Isolation – Hydraulic Operated Motor Pump	300	1	3 (Increase)	32	2	36
Isolation Reversion – Normally Bypassed; Oscillating Pistons During Emergency	1	107	18	94	20	71

Notes: 1 The above do not include failures due to combat damage.
2 Abort – One more subsystem failure would cause loss of landing capability.
3 Aircraft Loss – No landing capability remaining.

TABLE II.4-2 LEAKAGE FAILURES EXPERIENCED IN F-4 POWER CONTROL SYSTEMS WHICH CAUSED SYSTEM LOSS

1 January 1966 Thru 30 June 1969

Losses Caused by Leakage	Total Losses	Percent Due to Leakage in Branch Circuits
System Losses	162	64
Losses Causing Flight and Ground Aborts	89	55
Losses Causing Flight Aborts	55	73

Notes:

- Leakage failures counted in above do not include those caused by combat damage.
- Branch circuit leaks could have been protected by HCB.

(b) The reliability estimates represent the likelihood of equipment operational failures where the fault originated with the equipment. This excludes failures due to combat damage.

(c) System duty cycle time per mission = 1.5 hours.

(d) The present F-4 and Advanced Aircraft configurations evaluated are as defined in Section 2.1.

(e) The definitions of aircraft loss and abort are as defined in Section 2.1.

5.0 MAINTAINABILITY

An analysis was conducted to determine the maintainability aspects for the various HCB concepts. Table II.5-1 shows the results for two types of estimates; maintenance manhours per flight hour (MMH/FH) and average time to repair (ATTR). Based on this evaluation the hydraulic-operated motor pumps are considered the least maintainable. This is primarily due to the relative complexity and number of dynamic elements.

(a) The estimates were derived from AFM 66-1 maintenance data for the F-4C collected in the period 1 October 1968 to 21 December 1968 and covering 26,926 hours of operation. The data were applied on a piece part and similar component basis to arrive at an overall value for each HCB device. Maintenance manhours to repair are those manhours used in maintenance actions such as a malfunction correction, inspection or servicing relative to the particular HCB device. This time includes such actions as access removal, item repair, replacement, adjustment and test applicable to the aircraft. Therefore, the average time to repair represents the average aircraft down-time necessary to maintain the particular component.

(b) It is important to note that the HCB maintenance time added may be offset by a decrease in total aircraft maintenance and hardware replacement cost. On the present F-4 a branch circuit leakage failure will in turn cause pump degradation or failure due to a cavitation and over heating. These type failures would be largely eliminated by HCB incorporation. As stated in Section 4, 104 system losses occurred due to power control system branch circuit leaks. In most of these cases, the system hydraulic pump likely required replacement.

TABLE II.5-1 MAINTAINABILITY

HCB Type	Maintenance Man Hours Per 1000 Flight Hours (MMH/FH) x 10^3	Average Time to Repair (ATTR)
Reservoir Level Sensing and Subsystem S/O RLS (MCAIR)		
Pilot-Operated, Poppet S/O	9.3	4.2
Direct-Operated, Spool S/O	4.5	5.5
Pilot-Operated, Spool S/O	7.8	3.6
Electrical (Sol. S/O)	8.2	2.7
Flow Comparison		
Fixed Orifice (Hyd. Res.)	5.8	3.1
Variable Orifice (Weston)	3.9	2.8
Flow Rod (Transonics)	10.2	3.4
Fixed Orifice, Summing Lever (H.R.)	10.2	3.1
Capillary, W/Bypass (APM)	4.3	2.6
Isolation		
Pulsating Pistons (Barber-Coleman)	18.8	4.9
Pulsating Pistons (Sprague)	6.6	2.6
Hyd-Hyd Motor Pump (Vickers)	85.8	4.0
Other		
Return Pressure Sensing (MCAIR)	1.3	3.2

6.0 WEIGHT AND COST

Weight and production unit cost estimates were obtained from each proposing company. MCAIR concepts were evaluated in-house to determine weight and cost. The results are tabulated in Table II.6-1. The estimates are based on six HCB devices per aircraft. As shown, the APM Flow Comparator and MCAIR Return Pressure Sensing device are relatively low weight and cost, while the Vickers and Abex Hydraulic Motor mps are relatively high. It should be noted that the Return Pressure Sensing unit is primarily applicable to utility type functions where flow is not continuous. Although weight and cost are considered important aspects of this study, they are not weighted as heavily as performance, survivability or reliability parameters.

TABLE II.6-1 WEIGHT AND COST

Configuration/Subcontractor	Weight (Lb) Based on Isolation of Six Subsystems	Production Cost $/Aircraft
RLS; Mechanical (MCAIR) RLS; Electrical (MCAIR)	15 to 20	1500 to 1800
Flow Comparator		
M.C. Manufacturing	51	3360
Hydraulic Research	30	2500
Weston	18	2400
Aircraft Porous Media	9	630
Bendix	30	4500
Bertea	43	3060
Isolation; Oscillating Pistons		
Barber Coleman	39	2550
Isolation; Hydraulics Motor Pumps		
Vickers	100	8400
Abex	180	7200
Isolation Reversion		
Barber Coleman	45	3000
Return Pressure Sensing (MCAIR)	2	150

SECTION III

CANDIDATE CONCEPTS

1.0 SUMMARY

Three primary HCB concepts were selected for design study at MCAIR and by various selected outside sources. These concepts are:

(a) Reservoir Level Sensing and Subsystem Shutoff

(b) Flow Comparison

(c) Subsystem Isolation

Another concept reviewed, return pressure sensing, is considered primarily applicable to utility type non-continuous functions. One design approach from each of the above concepts were selected for fabrication and test. The specific designs reviewed and their relative merits are discussed in the following paragraphs.

2.0 DESIGN OBJECTIVES & SYSTEM CHARACTERISTICS

The objectives and hydraulic system characteristics were discussed in detail in Interim Technical Report No. 1. This discussion is summarized here.

(a) Hydraulic Subsystem Characteristics

The combat survivability requirements demand that the flight control system be the primary area of effort for this study. Therefore, for the purposes of this study, subsystem actuators are assumed to have the following characteristics.

- Actuator rams are balanced.
- Bypass for dual main ram actuator in the event of failure.
- In-line return relief valve to contain fluid after failure.

The devices developed for the flight control systems can be used in a portion or all of the utility subsystems depending upon the concept. The HCB usage in the utility systems will be covered in detail in the final report.

(b) HCB Design Objectives

The design objectives of the HCB are as follows:

- External Leakage Sensitivity - 2 to 5 in^3/minute
- Volume Overboard - 50 in^3 maximum
- Essential - Sense and shutoff external leaks during subsystem steady state conditions (null or low flow).
- Desirable - Sense and shutoff external leaks during surface motion (medium to high flow).

The external leakage sensitivity is based on reservoir depletion versus mission duration. At leakage levels below 2 to 5 in^3/minute, the reservoir would likely not be at a dangerously low level prior to landing.

The maximum allowable volume overboard is an arbitrary point. It is based on an analysis made as a part of this study. The analysis used a specific area of the F-4 to determine the amount of hydraulic fluid that could be burnt in a fire without catastrophic consequences. The final determination of this point is beyond the scope of this study.

3.0 RESERVOIR LEVEL SENSING AND SUBSYSTEM SHUTOFF (RLS)

RLS makes use of the fact that an external leak of any magnitude in any subsystem branch circuit causes a decrease of the system reservoir supply. Depletion of this supply below a predetermined level will initiate automatic shutoff of each subsystem, in turn, until the leaking subsystem is shut off. In general, RLS provides a simple method of subsystem isolation which is insensitive to system pressure and flow dynamics. The passive nature of RLS essentially eliminates the likelihood of inadvertant closure. Also utilizing the reservoir level provides a most positive indication of system leakage. RLS does require more fluid in the reservoir to provide the leak search capability. However the total weight addition of fluid plus hardware compares favorably with other HCB concepts. Multiple subsystem shutoff capability becomes somewhat cumbersome for greater than three subsystems due to weight and complexity problems. However, the multiple shutoff capability does not substantially affect system survivability for a small number of damaging combat hits on the hydraulic system. From a reliability standpoint the likelihood of multiple subsystem equipment failures is relatively remote. It is therefore believed that single subsystem isolation capability provides adequate protection. Several RLS approaches were considered promising after an initial screening evaluation was conducted. These are listed in Table III.3-1 along with associated advantages and disadvantages. The mechanical, pilot operated, poppet shutoff was selected for fabrication and testing primarily because of its relatively low operating loads and quick, positive shutoff capability. A detailed operational description, schematic and performance curves are presented in Part 2 of this report.

TABLE III.3-1 RLS CONCEPT COMPARISON

RLS Concept	Advantages	Disadvantages
1. Mechanical, Direct Operated, Spool S/O	(a) Relatively simple. (b) Low operating loads. (c) Good emergency override capability.	(a) Not positive shutoff. (b) Slow shutoff for low leakage rates. (c) Contamination sensitive lapped fits. (d) Difficult to manually operate. (e) Unit tends to become lengthy and to outgrow reservoir envelope.
2. Mechanical, Direct Operated, Poppet S/O	(a) Simple (b) Positive shutoff. (c) Not contamination sensitive.	(a) High loads required to operate. (b) Slow shutoff response at low leakage rates. (c) Impossible to operate manually without mechanical advantage. (d) High preloaded spring necessary to avoid (1) effects of tolerance build-up between operating cam and seat, and (2) to allow reset capability. (e) Unit tends to become lengthy and outgrow reservoir envelope. (f) Poor emergency override capability.
3. Mechanical, Pilot Operated, Spool Shutoff	(a) Snap action shutoff. (b) Low operating loads. (c) Can be packaged into reservoir envelope. (d) Easily operated manually for cycling on ground on bench testing. (e) Ground and crew indication on value position easily incorporated. (f) Good emergency override capability. (g) Less distance required between sensing than (1) or (2), therefore less reservoir fluid volume required.	(a) More complex than (1) or (2). (b) Leakage in lapped shutoff valve would be problem. (c) Contamination sensitive.
4. Mechanical, Pilot Operated, Poppet Shutoff.	(a) Through (g) same as (3). (h) Not contamination sensitive. (i) More positively held open during normal operation than (3). (j) Positive seal when shutoff with negligible leakage.	(a) More complex than (1) or (2).
5. Electrical Initiated Shutoff.	(a) Negligible operating loads.	(a) Circuitry required for sensing and shutoff becomes relatively complex. (b) Additional power source must be available for operation. (c) Essentially no weight gain over mechanical approaches. (d) Chances of inadvertent operation greater due to switch or relay contact crossover, shorts, etc.

4.0 FLOW COMPARATORS

The flow comparator concept is based on measurement of flow into and out of a hydraulic system branch circuit. The difference in flow would be the leak rate. This difference is then transmitted into a signal to shut off the failed branch circuit.

Various methods of flow difference measurements were proposed, namely, ΔP values across fixed orifice, variable orifice and combinations of the two. These ΔP values in the pressure and return lines are then force summed on comparator pistons and the piston motion due to unbalanced forces used to shut off the branch circuit.

Some units incorporate by-pass features, that is, the unit is made non-functional and by-passed during normal system operation. A signal such as low reservoir level can initiate the operational mode. In general the units automatically reset after shutoff, when pressure is removed. Inflight pilot override is available in some units.

Flow comparison techniques have some potential for sensing at low external leakage flow levels. Also, they may have the potential of limiting the amount dumped into a fire to acceptable small amounts. Since each subsystem shut off operates independently, only the failed subsystem will be sensed and shut off. Low maintenance, medium weight and reasonable vulnerable area are potential advantages for flow comparators.

However, these concepts (other than by-pass type) are generally active and wear out, contamination, etc., may be a problem. Inadvertent operation is more likely due to system dynamics including inter system effects, change in characteristics due to wear out, and attempting to design for maximum performance. The concepts generally may not provide the necessary sensitivity.

The Bertea flow comparator was selected for fabrication and testing because its design concept was considered to be one of the best of those proposed.

The APM unit is being considered as a second flow comparator to be tested because of its low cost, low weight and simplicity of design.

Final proposed flow comparators descriptions are listed in Section III of Part 2 of this report with their associated advantages and disadvantages. The lack of detail in this section is due to the proprietary nature of the detail information. An effort is being made to get clearance to include more detail in the final report.

It should be noted that a Hydraulic Research & Manufacturing Company flow comparator has successfully completed a ground and flight test program. The test aircraft was an F-4E. The program was conducted by the Air Force Flight Dynamics Laboratory at Wright-Patterson Air Force Base, Ohio.

5.0 SUBSYSTEM ISOLATION

The Subsystem Isolation concept is based on the use of power transfer devices in each subsystem. This allows transfer of power from the central system to each subsystem without fluid interconnection of the two. A leak in a subsystem is therefore automatically isolated while the remaining subsystems continue operation. Three subcontractor proposals were evaluated for this concept. Abex and Vickers each proposed a hydraulic driven motor pump and Barber-Coleman proposed a hydraulic-driven oscillating piston pump. A detailed description of each are presented in Part 2 of this report.

Performance and reliability evaluation of the isolation concept indicates it can best be applied as an emergency standby mode of operation. This approach is called "Isolation Reversion". That is, the isolation device is bypassed during normal system operation allowing closed loop fluid flow through each subsystem via the central power portion of the system. If a subsystem leak occurs a low reservoir signal is provided to each isolation device closing the by-pass and initiating the isolation mode of operation. This eliminates the need for accepting the additional power loss required by the isolators during normal operation. Also the degradation of the isolator due to normal wear and/or functional failure is essentially eliminated since no operational time is accrued during normal system operation.

The Barber-Coleman design has been determined to be best suited for the isolation reversion system concept. This design is the best compromise from a weight and cost standpoint while providing a simpler method of subsystem operation. When the emergency mode of operation is initiated the isolator in the leaking subsystem is required to shut-off. The Barber-Coleman design automatically is deactivated after a small volume of fluid leaks overboard.

6.0 RETURN PRESSURE SENSING

The basic function of the return pressure sensor is to prevent flow through the selector valve if a leak occurs in the subsystem downstream of the selector valve. A leak causes a drop in the return pressure. This drop is used to shut off the supply passage in the selector valve. The return lines can be isolated from reverse flow by a check valve located at an optimum point in each subsystem return line. The return pressure sensing can be accomplished by (1) incorporating the device into the selector valve to shut off pressure to the valve pilot passages or (2) incorporate a pressure switch to open the electrical circuit to the valve solenoids.

While this concept has limited application in that it primarily can only be used in utility type, non-continuous flow subsystems, it also presents a low weight, normally passive, reliable, and efficient means of performing the function.

A detailed operational description and schematic are presented in Part 2 of this report.

7.0 PUMP ISOLATION

Pump isolation has merit for multi-pump systems and catastrophic fire prevention. Most pump systems incorporate check valves in pressure and case drain lines to prevent reverse flow. These can be placed strategically to protect the rest of the system from an external leak in the pump subsystem. The suction line is then the only area requiring a shutoff that need be operated by an external leak sensing device.

There are at least three sensing alternatives, which include flow comparison, pressure sensing and reservoir level sensing and shutoff.

Flow comparison is more complex than subsystem flow comparison. The pressure <u>and</u> case drain flows would have to be compared with the suction flow.

Pressure sensing would involve monitoring the pressure in the outlet and case drain lines. Any sustained absence or significant reduction in pressure would operate a valve to shut off the suction line.

Both of the concepts require active continuous monitoring and its associated potential problems with contamination, wear, system dynamics, startup problems, etc.

The third alternative would use a passive shutoff valve which would be operated by reservoir level sensing. This concept could allow larger quantities of fluid to be dumped overboard.

For single pump systems the reason for usage would be to minimize catastrophic fires by limiting the amount of fluid dumped into a fire.

The dual or multi-pump system would have an additional obvious reason, retention of the rest of the central system as a hydraulic power source.

A detailed operational description and schematic are presented in Part 2 of this report.

SECTION IV

EXPERIMENTAL EVALUATION

1.0 HARDWARE PROCUREMENT

A decision was made and coordinated with AFAPL regarding those HCB designs which show enough promise to warrant fabrication and test. The selected designs are:

- Reservoir Level Sensing and Subsystem Shut-Off (RLS) - Mechanical, Pilot-Operated, Poppet Shut-Off (MCAIR)
- Isolation Reversion - Normally bypassed, Activated by Low Reservoir Level (Barber-Coleman)
- Flow Comparator - Normally Passive, Activated by Low Reservoir Level (Bertea)
- Flow Comparator - Normally Active, (Aircraft Porous Media). Decision to procure this design is pending review of design revisions submitted by APM. This includes a revision incorporating a feature making design normally passive.

MCAIR also intends to fabricate and bench test a prototype Return Pressure Sensing unit. It is believed that this concept has considerable potential for use in "Utility" type systems, i.e., cyclic, noncontinuous flow.

2.0 TEST PLAN

A preliminary test plan was prepared and coordinated with AFAPL. The plan outlines bench and system level "Iron Bird" tests to be conducted on the HCB devices. This testing will include endurance test cycles, external leak simulation, system dynamic operation, air injection tests and performance measurements. The test plan is being finalized for formal submittal to AFAPL.

SECTION V

TASK STATUS

1.0 TECHNICAL EVALUATION & THEORETICAL ANALYSIS

Two additional proposals have been received and are being evaluated. Whittaker has proposed an electronic type flow comparitor. Hydraulic Research and Manufacturing has proposed an advanced flow comparitor. They are being evaluated and the results will be reported in the next interim report. The evaluation and analysis phase is essentially complete.

2.0 MILESTONE STATUS REPORT

The milestone status is shown in the chart in Figure V.2-1. The initiation of fabrication has been slipped to the last week in September due to the delay in concept selection for test.

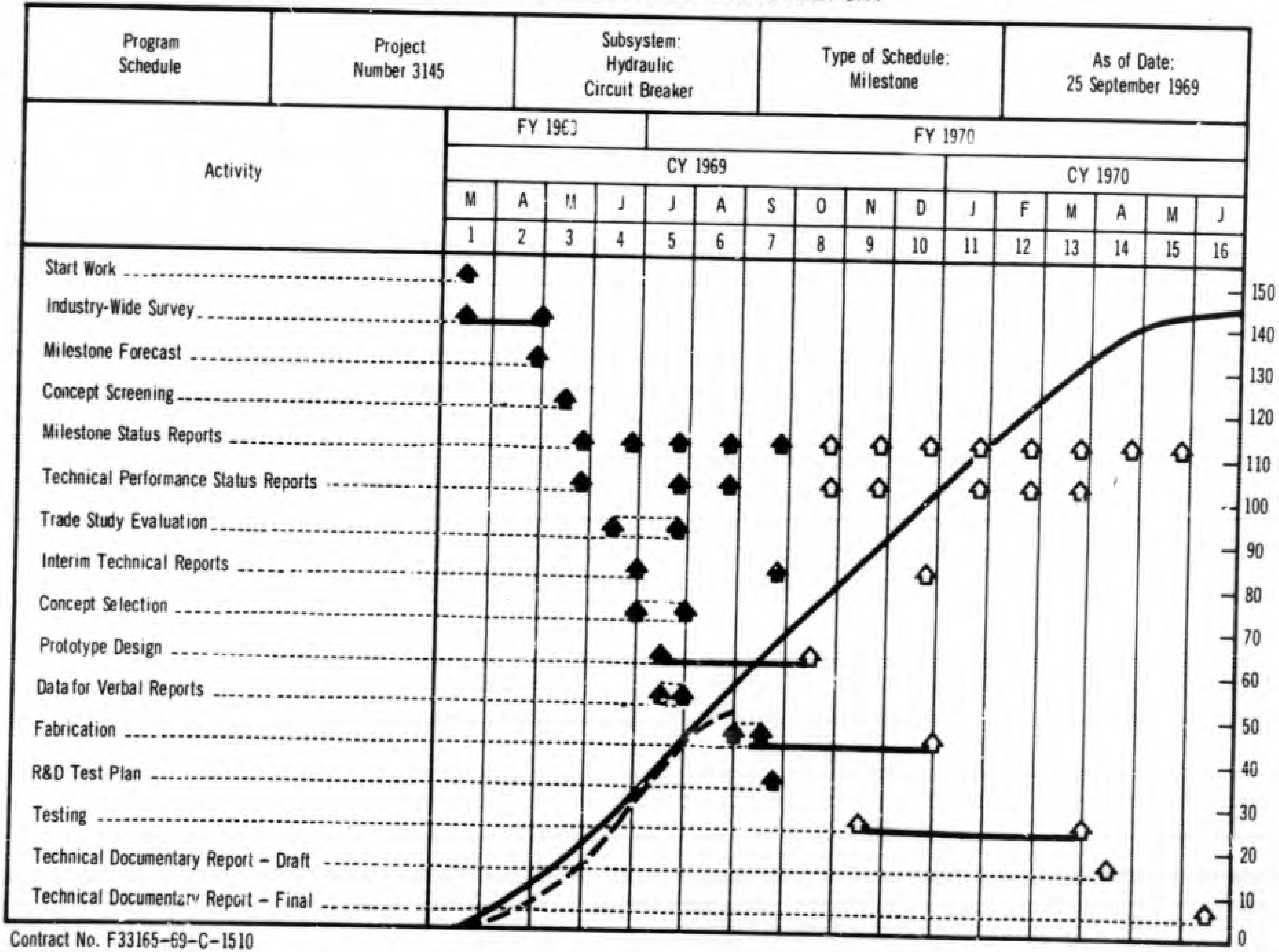
3.0 COORDINATION MEETINGS

For the period from 25 June to 25 September 1969, two meetings were held. On July 17 a meeting was held at MCAIR with Lt. J. Bambas and B. McFadden. The status of the program and trade-off study results to that date were reviewed. A formal presentation was made by N. J. Pierce and C. T. Thurston at Wright Field on 1 August regarding the results of the evaluation. In addition, preliminary plans for the fabrication and test phase of the study were coordinated with APL personnel, Lt. J. Bambas, E. Binns and B. McFadden.

4.0 PLANS FOR THE NEXT REPORTING PERIOD

Procurement of the test units is under way and initial deliveries and bench testing are scheduled during the next reporting period. Evaluation of the proposals just received will be completed.

FIGURE V.2-1 MILESTONE STATUSREPORT



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Note: Per agreement with ASD, the Milestone Status Reports will be included as part of the Technical Performance Status Reports or the Interim Technical Reports.

◇.....◇ ~ – Denotes milestone slip.

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13. ABSTRACT

Automatic failure isolation in aircraft hydraulic systems, to reduce the probability of a single hit causing the loss of the complete system, can be accomplished by a number of methods. Reservoir level sensing (RLS) senses a loss of fluid from the total system, and initiates a search for the failed subsystem. Flow sensing and comparison senses a loss of fluid from the subsystem, and shuts off the supply. Subsystem isolation allows transfer of power but prevents fluid transfer between the system and subsystem. Miscellaneous methods enable a loss of fluid to be sensed and shut off. In addition, there are several combinations of concepts that are attractive. The first phase of the program has been carried out. The object of this part of the program was to collect and tabulate all the available data related to the subject from government and industry sources. The tabulated data was then used to compare the various techniques with the requirements for F-4 and F-15 type aircraft in the second phase of the study. A decision has been made as to which techniques merit further investigation. The best concept from each of the three basic categories (RLS, Flow Comparison, Isolation) was selected. Working prototypes for experimental verification of analytical predictions are being procured and will be evaluated.

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Hydraulic Circuit Breaker Reservoir Level Sensing Hydraulic Fuse Hydraulic Leakage Detection Hydraulic Isolators Hydraulic Flow Comparator						

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