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HYDRAULIC SYSTEM SURVIVABILITY FOR MILITARY AIRCRAFT

INDEX

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1. Purpose: This document provides the fluid power design engineer with information and design considerations in regard to hydraulic system survivability under combat conditions.

2. Scope: This report supplies data on various survivability design approaches and techniques to provide a broad frame of reference for future fluid power designers. Before the designer embarks on the overall system design, a comprehensive understanding of the total hostile environment in which the air vehicle is to operate is mandatory. The overall approach is heavily dependent upon the level of threat, small arms versus medium, or heavy caliber antiaircraft projectiles, missile, single or multiple hit survivability and the projected angle of fire. Overall aircraft stability is a factor which dictates recovery speed from any given failure and limits the magnitude of transient disturbances in the control system. The designer should strive to achieve at a minimum a system which allows high performance type aircraft to obtain a quasi-stable period following total control loss to allow safe ejection of the air crew.

3. Definition:

Design information and guidelines are provided for the following topics:

Circuit Design	Redundancy Subsystem Arrangement Vulnerable Area Minimization Manual Reversion Flight Controls Structural Shielding Isolation Valving
Leakage Protection	Line Check Valves Reservoir Level Sensing Fuses Flow Differential Sensor Shut-Offs Transfer Valves Power Transfer Units
Control Jam Protection	Location of Hydraulic Equipment Tubing Material Selection Fluid Selection Hydraulic/Electrical Wiring Isolation
Detailed Component Consideration	"Crack-Stop"[1] Design for Pressure Vessels Material Selection Integration/Packaging Jam Resistant Actuator Design Gas Pressure Vessels

[1]Also referred to as "Rip-Stop."

4. Design Considerations:

4.1 Circuit Design:

The survivability requirements have a major impact on the development of the basic circuit arrangement. The requirements impact power source selection, isolation of circuits, plumbing routing, and fluid selection.

4.1.1 Redundancy:

Redundancy is necessary for flight-essential subsystems in modern high-performance aircraft. The actual number of redundant supply sources must be traded off against the increased weight, cost, and vulnerable area. The degree of redundancy also depends on the number of flight-essential services to be powered, the physical separation of flight control surfaces, availability of any backup control power (such as a manual control with degraded performance), and the availability of different surfaces that may be used to supply the same control axis (e.g. ailerons and spoilers or ailerons and differential speed brake). The major consideration in using redundancy (for survivability reasons) is to insure sufficient separation of the redundant components and/or subsystems to prevent simultaneous multiple damage and failure from a single hit, or total system failure.

Integrated Actuator Packages (IAP's) may be considered as a means of enhancing survivability where power requirements and space permit. The independent hydraulic power source provides for power supply redundancy. This is particularly true for large aircraft with long distances between control surfaces and/or power sources.

4.1.2 Subsystem Arrangement:

Survivability can be enhanced by the judicious arrangement of subsystems in relation to the supply sources. For example, if both speed brakes and flaps are hydraulically powered, an attempt should be made to power them from separate supply sources to ensure availability of one drag device in the event of a system loss. The same might be applied to normal and emergency operation of critical subsystems. Consideration should be given to secondary effects of damage such as linkage or mechanism jams or disconnects, hydraulic fluid loss, and open or shorted wiring. Degradation of aircraft performance may result from a loss of a subsystem. To minimize or eliminate the effect of a subsystem failure on overall performance, the designer must address this when establishing the overall system architecture. Fly-by-wire and optical control systems offer the designer increased flexibility to change the overall control laws to suit the particular requirement following loss of any subsystem.

4.1.3 Vulnerable Area Minimization: An important method of increasing survivability is to minimize the vulnerable area of the hydraulic system. Decisions in this area must be made during the initial system conception and development stage. The primary methods of minimizing the vulnerable areas are: 1) Simplification to reduce the number of required components: 2) Increased operating pressures to minimize line and component size. (Pressure levels of 8000 psi are achievable with current state of the art.) 3) Packaging of components to keep the total presented area to a minimum. (Modular packages offer a good approach to overall vulnerable area reduction.) 4) Component miniaturization.

4.1.4 Manual Reversion Flight Controls: A means of increasing flight control survivability is to revert to manual controls in the event of total hydraulic power loss. This approach is generally limited to the slower fixed wing aircraft or to small rotary wing aircraft. Generally, some type of retained cylinder damping is needed to maintain full stability of the control surface with loss of all hydraulic power.

4.2 Spatial Separation and Isolation: Serious consideration should be given to the needs for spatial separation and isolation of redundant circuits and/or flight-critical subsystems.

4.2.1 Separation of Redundant Circuits: To gain the maximum benefit of redundant circuits or subsystems, it is important that they be sufficiently separated to prevent loss of both circuits or subsystems from a single hit. This must be considered for the maximum designated threat. Ideally, this separation should be in all potential planes of impact.

One common rule of thumb for separation of redundant systems is 18 inches. However, caution must be taken to avoid standardizing on such separation distances. When locating redundant lines and components, both separation and standoff distances from predicated detonation points must be considered.

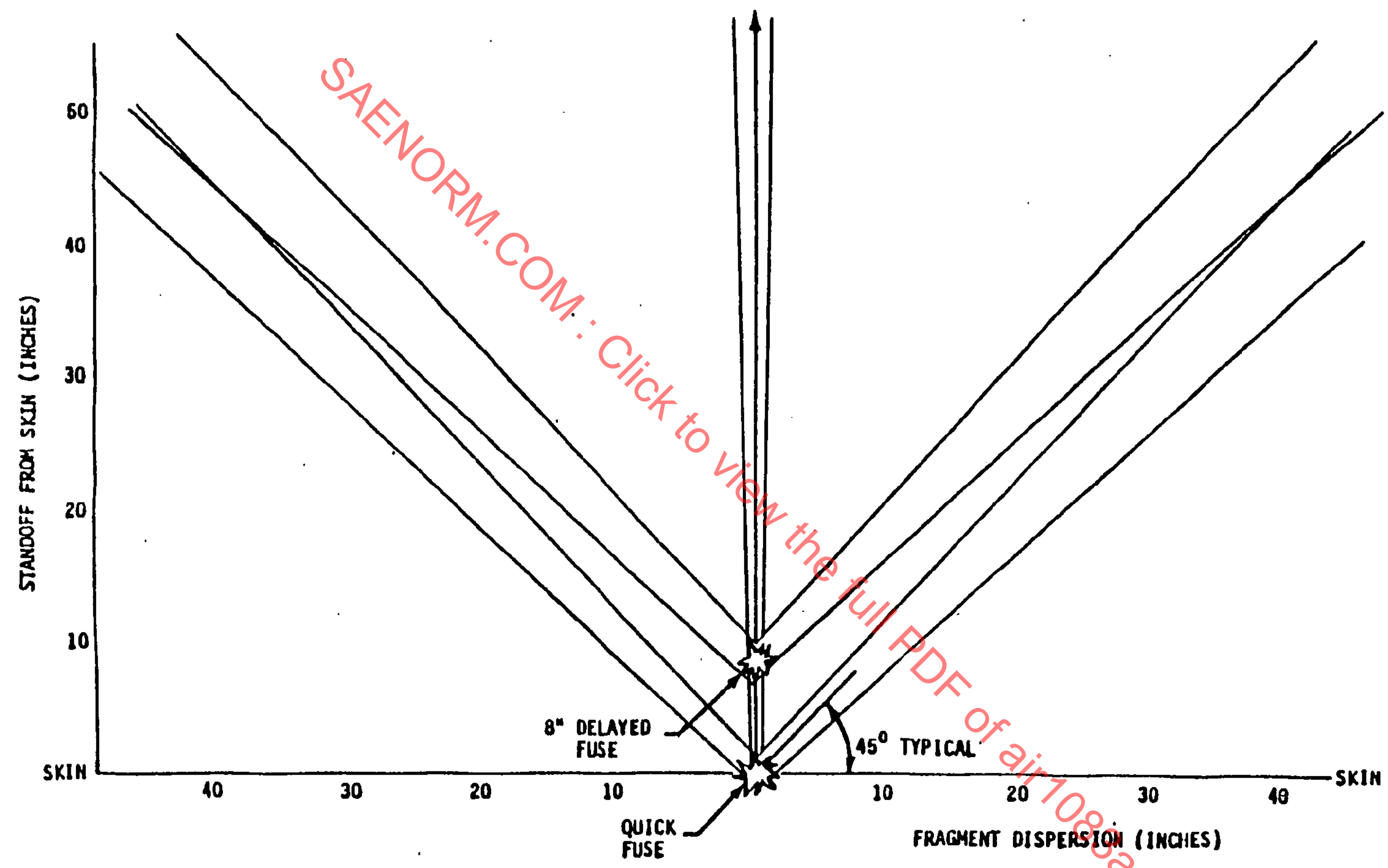

Figure 1. Vulnerable Areas for High Explosive Bursts

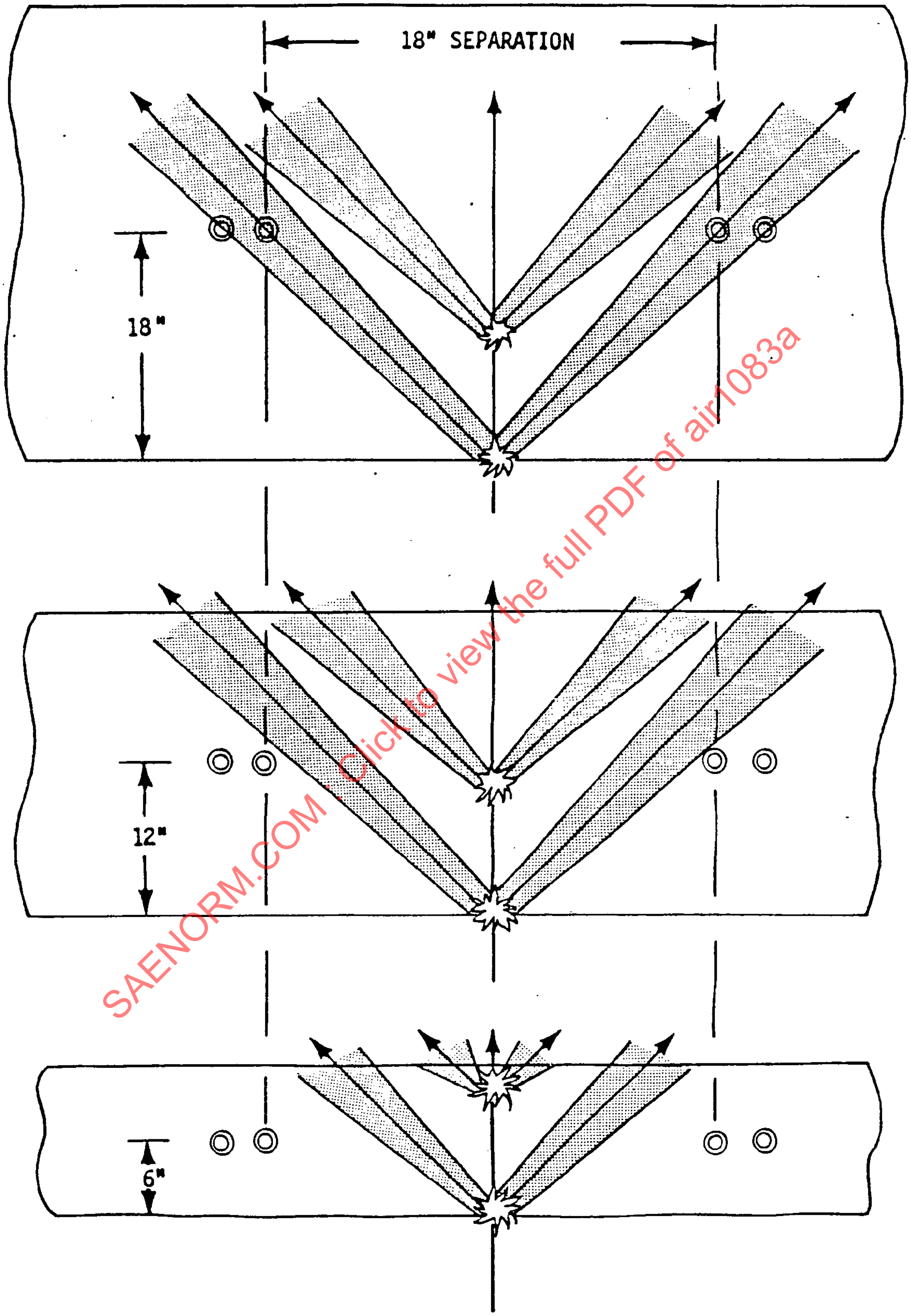

Figure 2. The Hazard of using Constant Separation Distances between Tube Runs

As illustrated in Figure 1, the fragments from a high-explosive shell fan out in two side-spray paths approximately 90 degrees apart, both with a quick fuse and delayed fuse. As shown in Figure 2, the 18-inch separation provides multiple-kill protection from a single hit only for components located within 12 inches of the skin line or further than 30 inches.

Consideration should also be given to separation of subsystems/circuits by routing on opposite sides of fuselage and on the front and rear spare of wings and empennage. (See Figure 3). Maximum separation should be maintained as close to the using function as practical. Where adequate separation is impractical, additional protection can be provided by judicious use of structural shielding and/or armor protection. This is discussed further in the next section.

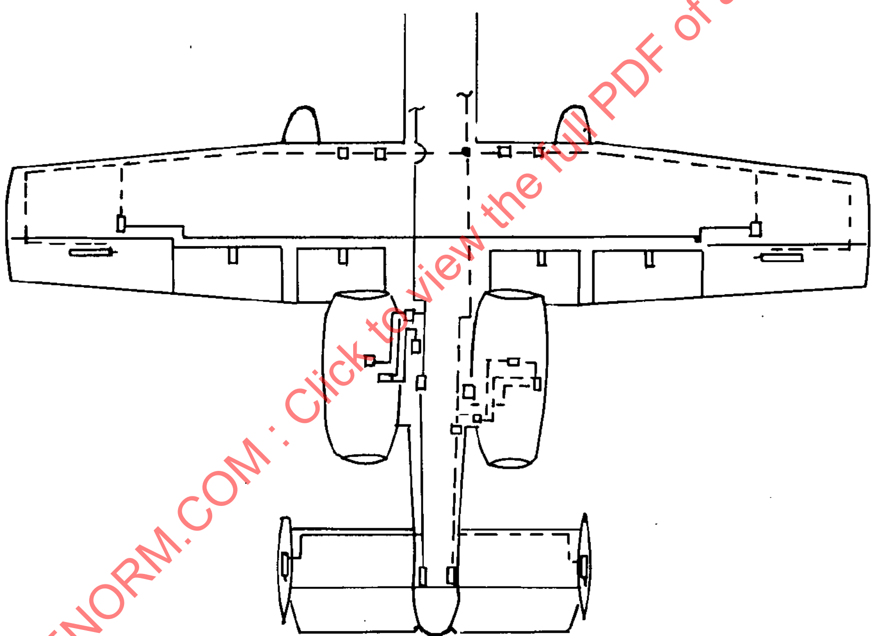

FIGURE 3
A-10 SKETCH (EXAMPLE)

4.2.2 <u>Structural Shielding</u>: Hydraulic lines should be routed as close as possible to the heaviest structure of the air vehicle. Landing gear support, wing, and transmission support frames are but a few examples. On multiengine aircraft, engine-driven pumps should be located such that they are shielded by the engine and airframe. Accessory gearboxes should be designed to provide shielding to flight-critical components. Non-flight-essential hydraulic components may be used to shield essential areas.

4.2.2 (Continued):

Figure 4 illustrates how the judicious location of system tubing can be used to provide shielding, both from the primary (ballistic) threat, and also from spallation fragments from the aircraft skin and structure.

4.2.3 Isolation Valving: Isolation valves should be considered which will effectively isolate non-flight-critical systems from flight-essential systems. The valve should be fail safe to the closed position in case of electrical power or mechanical failure. Manual override may be required at mission end for an emergency operation of non-flight-critical systems such as landing gear.

4.3 Leakage Protection: During aircraft operations, a cause of hydraulic system loss is depletion of fluid due to damage of a line and/or component, the probability of which is greatly increased during operation in a hostile environment. Ignition of the fluid by either the projectile's effect, damage to the electrical system, or a hot surface, can lead to total aircraft loss and accordingly, serious consideration should be given to providing maximum leakage protection to all flight-critical components and systems. When using any of the various leakage protection devices described herein, the designer must consider where and how much of the hydraulic fluid will be released before the protection device actuates to shut-off the flow.

4.3.1 Line Check Valves:

4.3.1.1 Return-Line Check Valves: Check valves, located at or near the return ports of components and/or return branches of the supply system, can delay fluid loss in the event of return-line damage. The degree of delay depends upon which subsystem return line is damaged, where it is damaged, how frequently the related subsystem branch operates, and upon the internal leakage of the damaged subsystem components.

4.3.1.2 Pressure-Line Check Valves:

Pressure-line check valves may be considered in certain case where loss of system power allows the external flight load to back-drive the control actuator leading to aircraft instability. The addition of a restrictor check valve at the actuator inlet can eliminate or minimize these effects.

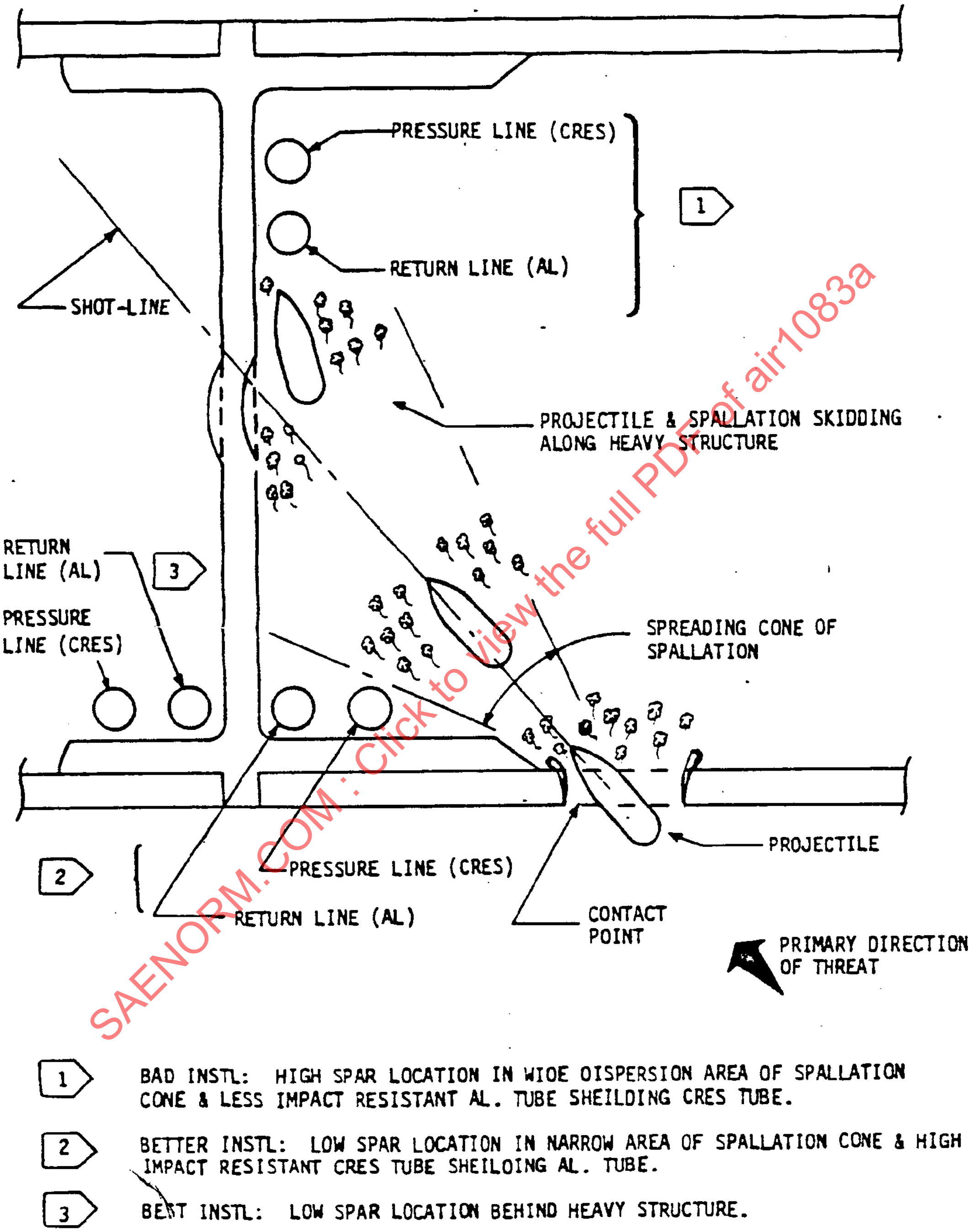

Figure 4. Enhancement Techniques Against Spallation Threat

4.3.2 Reservoir Level Sensing: This is a method of monitoring the reservoir fluid level to determine the existence of system leakage and subsequently shut off the damaged circuit. This isolation technique is used to retain a portion or portions of the system in the event of damage causing loss of fluid. One or more fluid level signal points are used to actuate shut off valves controlling flow to branch circuits. The shut off logic reactivates an isolated branch in the event the fluid level continues to drop to the next signal point. The number of branches employed is dependent upon the flight-critical subsystems arrangement and logic of separation. This principle would generally be limited to two (2) or three (3) branch arrangements by weight and complexity considerations. The basic principle is illustrated in Figure 5, which depicts a two-branch system design. In this illustration, the reservoir piston shaft would contain two cams that mechanically actuate sensing valves for control of pressure-operated shut off valves. In the event the shut off of branch No. 1 does not eliminate the leakage source, the No. 2 branch cam will shutoff the second branch and at the same time reopen the No. 1 branch.

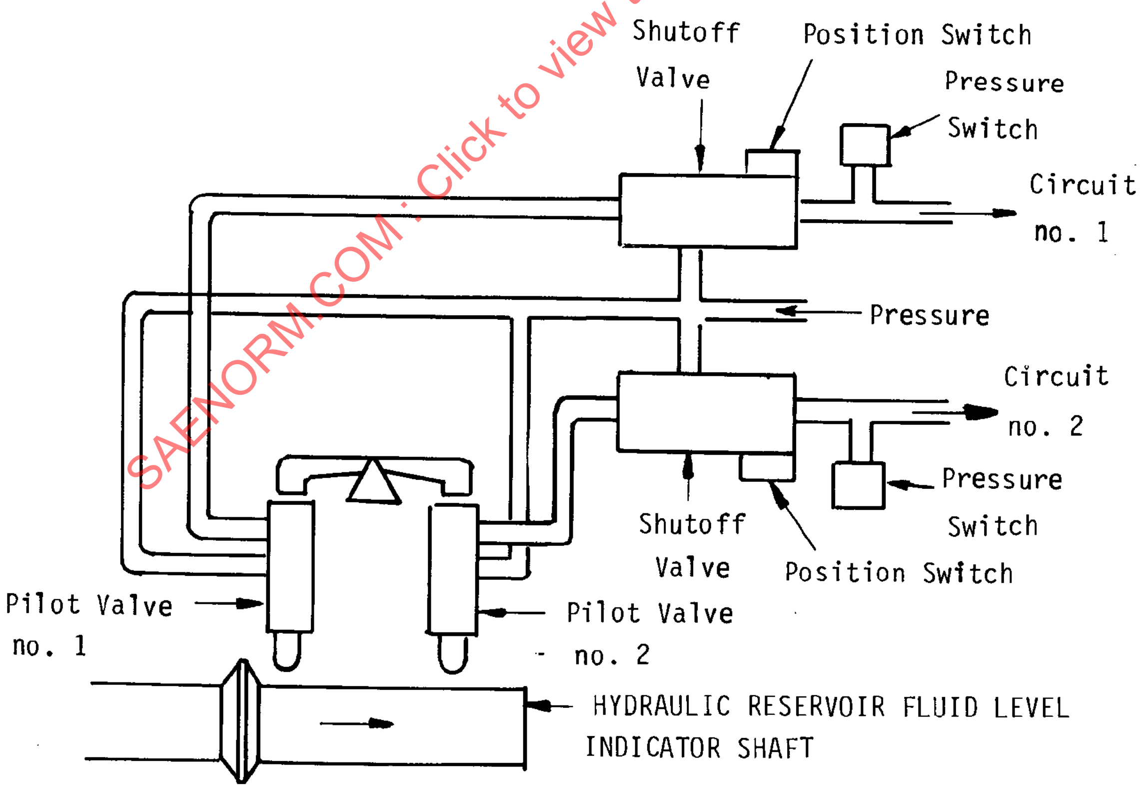

FIGURE 5. RESERVOIR FLUID LEVEL SENSING

4.3.2 (Continued)

Like redundant subsystems, the survivability improvement provided by this technique is dependent upon the amount of branch separation and the subsystem arrangements employed. Consideration must be given to the additional circuitry required and its impact on the overall system vulnerability. Also, it is important to consider shielding or armor protection for the more critical common fluid supply items. Reservoir level indication or branch circuit pressure loss should be annunciated to the flight crew to allow the crew to take possible corrective actions.

4.3.3 Fuses: Fuses of the types described below should never be used in flight essential systems.

4.3.3.1 Volumetric Fuses: Volume measuring fuses may be applied to certain unidirectional circuits to provide leakage (fluid loss) protection. This type fuse senses volume rather than flow rate. Once the predetermined volume is exceeded the circuit is shut off. For example, circuits to utility actuators, landing gear or door actuators might be protected by a fuse of this type. The potential internal leakage of the circuit must be considered in the use of such a device since the rated volume of the fuse is determined with a minimum flow rate limit. Internal flow rates above this minimum can result in inadvertent shutoff. Careful consideration must be given to the possible effects of inadvertent fuse shutoff on the overall aircraft safety.

4.3.3.2 Velocity Fuses: Unlike the Volumetric Fuse, the velocity fuse is flow-rate sensitive. It is a simple device and is best suited to protect system branches which carry a known quantity of fluid flow. The velocity fuse is insensitive to system operating temperatures except at the extreme low limits. Threshold levels should be carefully set to avoid nuisance shut off due to flow surges or air. Once triggered, this device remains shut off until supply pressure is dumped. The major limitation of the velocity fuse is that it detects only major leaks. Leakage flows below the fuse threshold cannot be detected by this simple device.

4.3.4 Flow-Differential-Sensing Shutoff Valves: The flow-differential-sensing device detects leakage in a circuit or component and automatically isolates that circuit or component. This device monitors the pressure and return flow to a circuit or component, and isolates the circuit or component when the flow is unbalanced beyond a preset level. The pressure drop across two sets of orifices provides forces that are applied to a summing assembly such that the correct flows balance at the summing lever. An unbalance of the flows and resulting forces causes the summing assembly to move off neutral, cutting off pressure to the circuit or component. A check valve in the assembly prevents backflow into the return side of the circuit. Damping built into the unit prevents inadvertent actuation at system start up or due to surges. This device would primarily be used on each supply circuit to tandem flight control actuators and/or the most vulnerable branches. In circuits that have large differential flow rates due to large exchange volumes, such as landing gears, special considerations are required. See Figure 6 for a typical circuit.

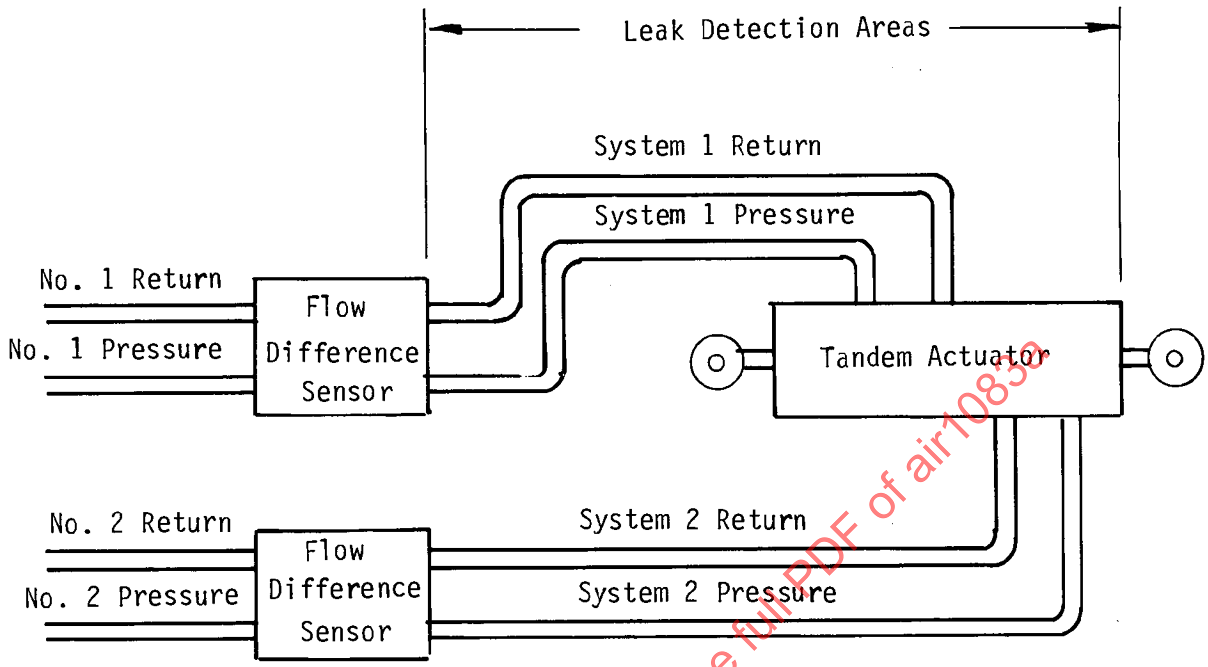

FIGURE 6. FLOW-DIFFERENCE-SENSING VALVE CIRCUIT

4.3.5 Transfer Valves: A transfer valve, also refered to as "SWITCHING VALVE," is basically a dual shuttle valve which accepts inputs from either of two power systems and ports this fluid to a branch or actuator. The valve is usually biased to give priority to one of the two systems. The transfer valve can be combined with a system integrity-check unit. This type of device connects the pressure and return lines of the downstream branch upon loss of primary pressure, while inhibiting transfer to the back-up system. A small integral accumulator pressurizes the downstream branch. If no leak exists, the sensing pressure will not decay, and transfer to the back-up system will take place. A built-in timing device determines the duration of the system integrity check prior to transfer. Careful attention must be given during the design phase to minimize interstage fluid transfer. Rip-stop design is mandatory. The design must avoid the loss of both the primary and back-up power systems due to a single failure in the valve or the downstream subsystem. The valve design must insure stable operation under all conditions including supply and return system pressure variations, system start-up and run-down. Systems employing large differential area actuators are not well suited to use transfer valves unless precautions are taken to minimize fluid transfer.

4.3.6 Power Transfer Units (PTU): The power transfer unit consists of a hydraulic motor coupled via suitable shafting to a pump. Uni or bi-directional units are available. Their purpose is identical to the transfer valve, i.e., using the power of one system to provide power to another, except that the transfer is purely mechanical. Sufficient intelligence must be designed into system using these devices to prevent power loss due to damage in the system branch to be powered. Figure 7 illustrates a typical PTU.

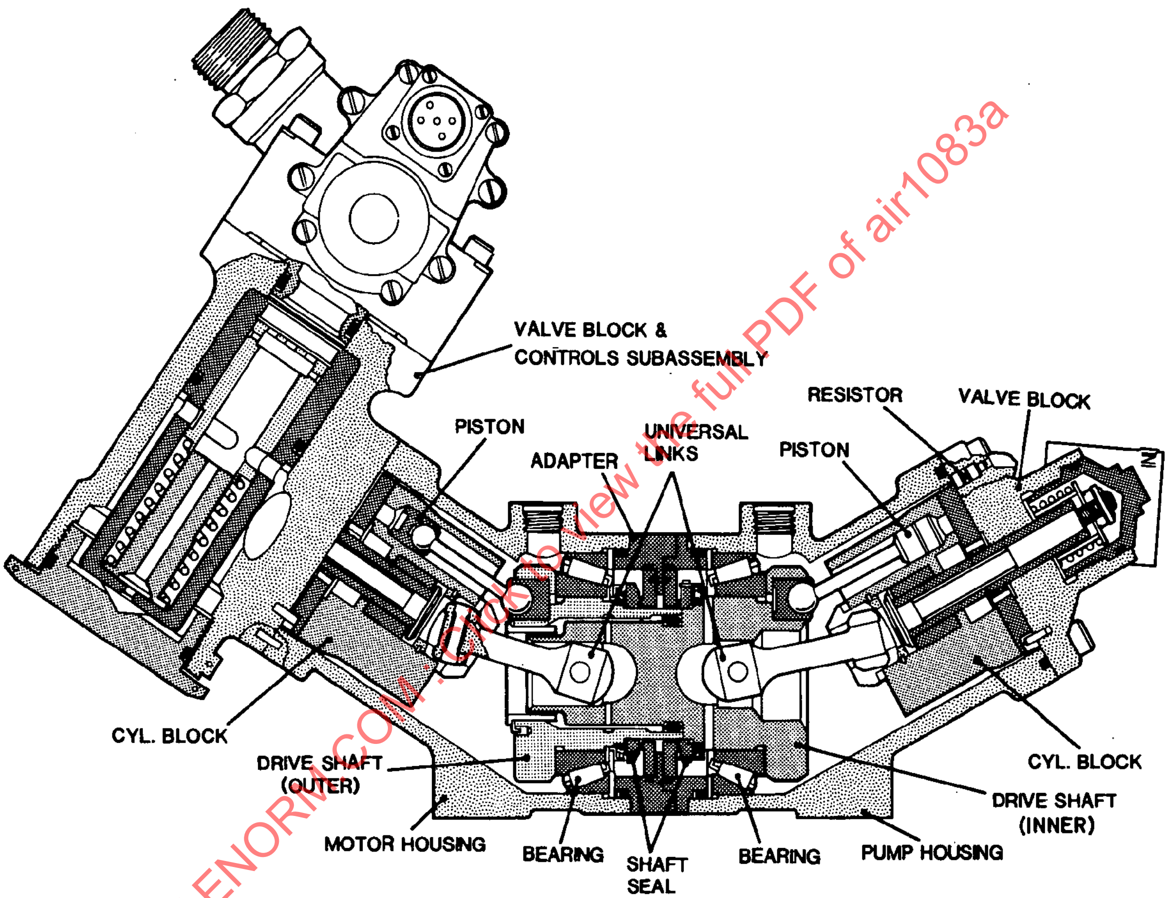

Figure 7. Power-Transfer Unit

4.4 Control Jam Protection: For the more hostile environments, it may be desirable or necessary to provide for aircraft flight control capability following a jammed surface or surface control element.

4.4.1 Mechanical Jam: Compensation for this problem will vary considerably depending on whether the control input is totally fly-by-wire or via a mechanical linkage. In the case of the fly-by-wire control, the compensation can be included in the electronic circuitry, with the level of electronic redundancy primarily dependent on system architecture and management. The jam areas would be limited to power actuators or surface pivots and linkages.

In the case of the mechanical input, the protection is complicated by the requirement to disconnect the stick or pedals from the input linkage system. This approach further requires that a detection system be incorporated to provide the pilot with the necessary intelligence to determine what surface or linkage run is jammed. The signal actuation loads should be above those that might be generated by rapid control motion, but not so high as to require extreme pilot effort. The signal light should incorporate a minimum holding cycle to ensure ease of pilot evaluation without retaining the high input loads. To provide maximum protection, the disconnect devices should be located as close to the stick or pedals as practical. The disconnect can be designed as a single cycle unit (once disconnected can only be reset after flight) or with a disconnect/connect capability. The latter provides for in-flight familiarization and training and compensation for actuation errors. Consideration should be given to the routing of the mechanical control system to prevent jamming or restriction due to deformation of adjacent structure resulting from ballistic impacts.

4.4.2 Fluid Jam: Damage to the return circuit of a control actuator may result in a partial or complete fluid blockage. A partial blockage will restrict the actuator rate to the extent of the amount of return flow restriction until all the fluid is expelled from the low-pressure side of the actuator. A complete blockage may result in a complete surface jam. This condition can be eliminated by the installation of bypass (run-around) check valves at or within the primary control actuators. The check valve is installed between the supply pressure and return ports and will permit runaround flow from return into pressure in the event of a blocked return line. Another method to prevent an actuator fluid blockage is to install a bypass valve into the actuator. This valve interconnects the two cylinder chambers whenever system pressure is below a predetermined value. For unequal-area actuators, the interconnections of the cylinder ports can be connected to return. If the valve is balanced, a blocked return line will automatically interconnect the cylinder chambers. With either approach, check or bypass valves, means must be incorporated to dispose of the extra volume in unequal-area actuators. The use of equal-area actuators does not require the return connection, but the designer should be aware of the increased length, increased weight, and the additional seals required for equal area actuators.

4.5 Fire Protection: Consideration should be given to minimizing the impact of fire and/or heat on the hydraulic system.

4.5.1 Location of Hydraulic Equipment: Location of the hydraulic equipment should consider the effect of fire and the associated heat of other aircraft systems. Fuel and electrical short circuits are the major sources.

Components should not be located in fire zones whenever possible. When this cannot be avoided, suitable shutoff valves should be installed at the fire-zone barrier. Only components made from heat resistant materials should be in a fire zone or any other areas suspected to generate high temperatures.

4.5.2 Tubing Material Selection: Although aluminum alloy tubing is the lightest aircraft tubing commonly used, it is also the weakest and prone to failure. Excellent high-strength stainless steel tubing and titanium tubing are available which are far superior to aluminum alloy tubing with respect to strength, ability to withstand abuse, and battle damage survivability with a minimal weight penalty.

Aluminum tubing should never be used in areas exposed to foreign objects damage or subject to fire or high heat, whether due to normal operation or ballistically generated.

Fitting material selection should parallel the tubing material selection. In addition, the effects of thermal cycling of components during battle damage should be considered. Fittings made from materials having different coefficients of expansion than the components material to which they are attached may experience leakage even after the heat source is eliminated. Metal-to-metal seals should be considered on fittings which could be subjected to high temperature. The use of hoses should be minimized. In areas of relative motion between components, or components and structure, coiled tubing designed to ARP 584 should be considered.

4.5.3 Fluid Selection: Careful consideration should be given to the hydraulic fluid media selection. The most widely used fluid, MIL-H-5606 is highly flammable. Its synthetic counterpart, MIL-H-83282 has improved fire resistance but will also burn. Phosphate-ester type fluids offer a higher degree of fire resistance, but are not compatible with elastomers and paints designed to operate with MIL-H-5606 or MIL-H-83282 fluid. A new fluid, chlorotrifluoroethylene (CTFE), offers nonflammability. Drawbacks are high fluid density, low bulk modulus, incompatibility with current elastomers, and cost. AIR 1362 should be used to obtain specific fluid properties.

4.5.4 Electrical Wiring Isolation: Hydraulic plumbing and electrical wiring should be separated as much as possible. Where this cannot be accomplished, wiring must be routed to prevent broken wires from contacting and shorting out on the tubing. Chafing between tubing and wire bundles, which causes insulation wear-through, permits arcing to occur between the wire and tubing. Eventually, the arc will cause a pin hole in the tubing resulting in an oil spray which is easily ignited. Routing wiring through metal conduits should be considered whenever adequate separation is impossible to achieve in dense-pack locations.

4.6 Detailed Component Considerations: Hydraulic systems are composed of many different types of components and the following techniques should be considered in their design and/or selection.