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Hydraulic and Flight Control System for Space Shuttle Orbiter

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THE PURPOSE OF THIS PAPER is to present the varied functions performed by the hydraulic system in the Space Shuttle Orbiter during a typical mission; to discuss briefly the concept selection rationale; to review the operational requirements; to summarize in detail the overall system design concept; and to discuss the innovative features incorporated in the design. This system summary also includes discussions of redundancy philosophy, "fly-by-wire" flight controls, maintainability, and "on-board" monitoring.

SYSTEM REQUIREMENTS

The reusable space shuttle utilizes boost engine thrust vector controls (TVC), the Orbit Maneuvering System (OMS), the Attitude Control Propulsion System (ACPS), and aerodynamic surfaces for vehicle attitude control. The TVC and aerodynamic surface control systems were evaluated, and it was determined that a hydraulic system was the optimum power medium for these applications. The vehicle configuration is shown in Fig. 1 and the mission profile in Fig. 2.

CONTROL - The orbiter utilizes three main boost engines for ascent, each being gimballed by two hydraulic actuators. During ascent, reentry, transition, cruise, approach, and landing the vehicle attitude is controlled by elevons, rudder, rudder/flare, and body flaps. The hydraulic system is also used to power various utility functions, that is, brakes, landing gear, steering, Environmental Control System (ECS) compressor drive, and air breathing engine system (ABES) deployment and start. A summation of the design parameters is shown in Table 1.

FUNCTIONAL - The hydraulic system includes the power generation element, distribution, control, and all load actuating devices. The system shall be capable of providing power for normal orbital missions, 7 to 30 d duration; horizontal flight test and ferry missions; and post landing operation for ground maintenance, check-out, and refurbishing operations. The system shall be capable of operating when subjected to normal g, reduced g, zero g, or reversed g environments, with no time limitation imposed for any of these conditions. The system shall also operate satisfactorily in a hard vacuum and incorporate the capability of rejecting excess heat to a cooling medium without adverse effect on vehicle performance.

INTERFACE - The system must interface with other space shuttle elements, as shown in Fig. 3.

RELIABILITY - The hydraulic system shall be "fail operative–fail safe" (FO/FS). In terms of specific hydraulic system requirements, all hydraulically powered equipment or mechanisms must be able to operate in normal fashion after a first critical failure (FO). FS after the second critical failure infers that the performance must not be degraded to a level which would keep the vehicle from returning safely to earth from the point of failure. The loss of a hydraulic system is the most

ABSTRACT

The Space Shuttle Orbiter is a combination spacecraft and aircraft which can remain in orbit from 7 to 30 d and also fly horizontally and land on existing commercial airport runways. The vehicle utilizes gimballing of the main rocket engines for control during ascent and typical aerodynamic surfaces for control during reentry, approach, and landing. A hydraulic system was selected as the power source for operation of these controls and for actuation of the landing gear, brakes, steering, and jet engine deployment.

This paper discusses the system selection rationale, power requirements, flight control characteristics, operational profile, maintenance features, built-in test requirements, and innovative features of the hydraulic system. The system design provides for spacecraft reliability with commercial aircraft serviceability.

critical failure. Minimal back-up systems which require excessive or unusual pilot expertise for safe flight will not be utilized. The system shall be designed to have a combined storage and operational life of 10 years. Reliability and safety shall be provided by conservative design practices and redundancy.

MAINTAINABILITY - Maintainability of the system shall be consistent with a two week turnaround operation and the

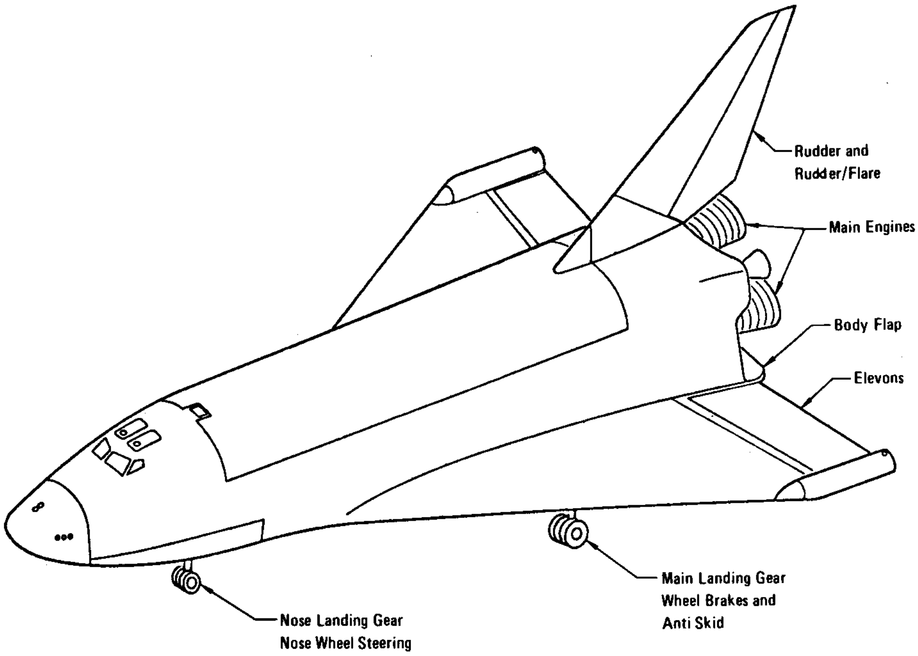


Fig. 1 - Orbiter configuration

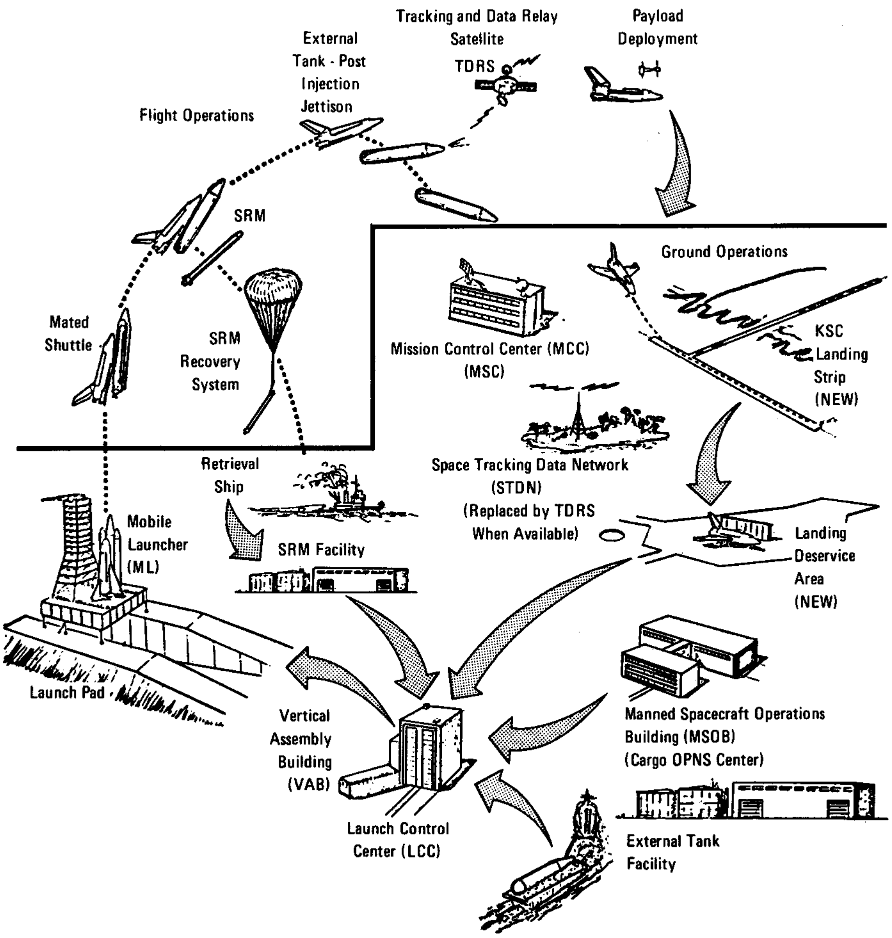


Fig. 2 - Space shuttle system mission profile

"on-condition" maintenance concept. The system shall be capable of being maintained in the horizontal or vertical position. Components shall be of modular construction for ease of replacement. On-board test and check-out equipment shall provide ground status monitoring and fault detection of all critical subsystem assemblies.

SELECTED SYSTEM DESIGN CONCEPT

The hydraulic system provides power, control, and actuation of the previously mentioned aerodynamic and utility services. The characteristics of the selected system were established by the system studies shown in Table 2 and by proven experience

Table 1 - Hydraulic System Design Parameters

Function	Stall Hinge Moment (HM), in-lb	Deflection, deg	Rate deg/s	Max Power per System, hp	HM After Two Fail, %
Elevon	1.735×10^6 per surface	+40 −20	25	114	100
Rudder/flare	1.3×10^6 per surface	±15 R +45 F	20	68.5	100
TVC	2.08×10^6 per engine	±10 pitch ±6.5 yaw	8	99	100
Main landing	0.358×10^6 per gear	101	20 Down	40	100
Brakes	N/A	N/A	N/A	29	100
Steering	0.160×10^6	±15	40	8.5	N/A
Body flap	1.8×10^6	+18 -10	1	2.4	100
Boost engine Service	Valve control per engine	N/A	N/A	8.8	N/A

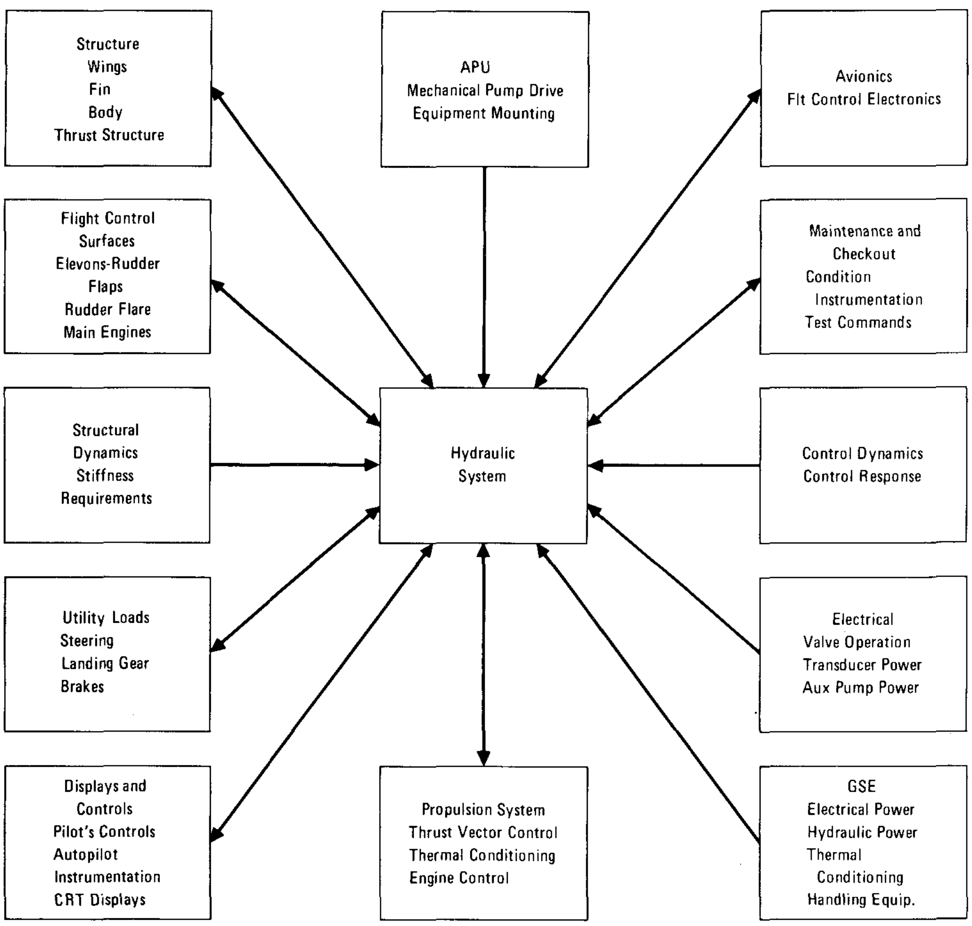


Fig. 3 - Hydraulic system interface diagram

gained on such successful programs as the A-4, F-4, DC-9, DC-10, and SIVB.

FO/FS operation is provided for all subcircuits by using four, 50% capacity, completely independent, 3000 psig systems and providing two tandem actuators per control surface, each capable of 100% hinge moment and rate. The systems are each sized for 145 hp output capacity and are distributed as shown in Fig. 4. MIL-H-83282 synthetic hydrocarbon fluid is used because of its fire resistance, high temperature capabilities, and elastomeric compatibilities.

The system is active during lift-off, ascent, and insertion to provide for concurrent operation of aerodynamic control surfaces and main engine thrust vector control. The system is passive in orbit except for a low pressure, electrically driven pump in each system for fluid circulation to provide thermal conditioning. The system is activated prior to deorbit burn and operates through reentry and landing. The main pumps are driven by hydrazine-fueled auxiliary propulsion units (APUs). The load profile for each system is shown in Fig. 5. The location of the hydraulic power generation, distribution, and actuation components is shown in Fig. 6. ABES-driven pumps are used for horizontal development and operational ferry flights.

The flight control system utilizes the "fly-by-wire" approach developed for the F-4 Survivable Flight Control System. Electronic signals are received from the avionic system by four-channel, electrohydraulic force-summing secondary actuators. These signals are voted within the secondary actuator and

Table 2 - Selection Criteria

Analysis	Baseline Selection	Rationale
3000 versus 4000 psig	3000 psig	State-of-the-art Less costly
3 versus 4 circuits	4 independent circuits	Less weight Less costly
Fluid evaluation	MIL-H-83282 (synthetic hydrocarbon)	Fire resistant Less weight Normal handling
1 versus 2 pumps/ system	1 main pump	Less weight Lower heat rejection
Pump characteristics	Q.A.D. (manifold) Constant pressure High response	Easier maintenance Less weight Eliminates accumulators
Thermal control	Integral	More efficient Minimum interface
Heat exchanger	Flash evaporator, H_2O	Lightest Minimum complexity
Permanent fittings	Swaged	Minimum cost Ease of replacement
FBW controls	Force summing secondary actuator	Developed by McDonnell for F-4 program

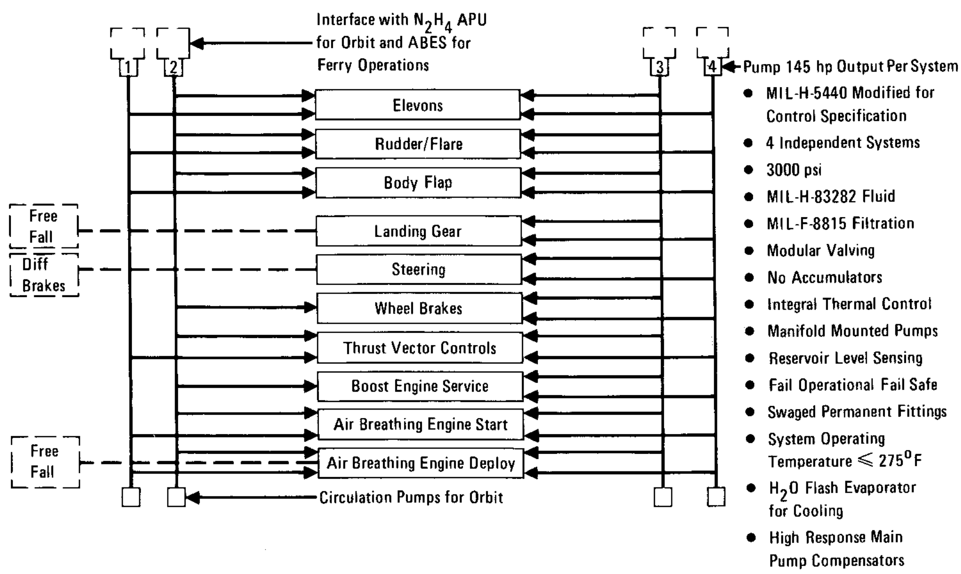


Fig. 4 - Hydraulic system schematic

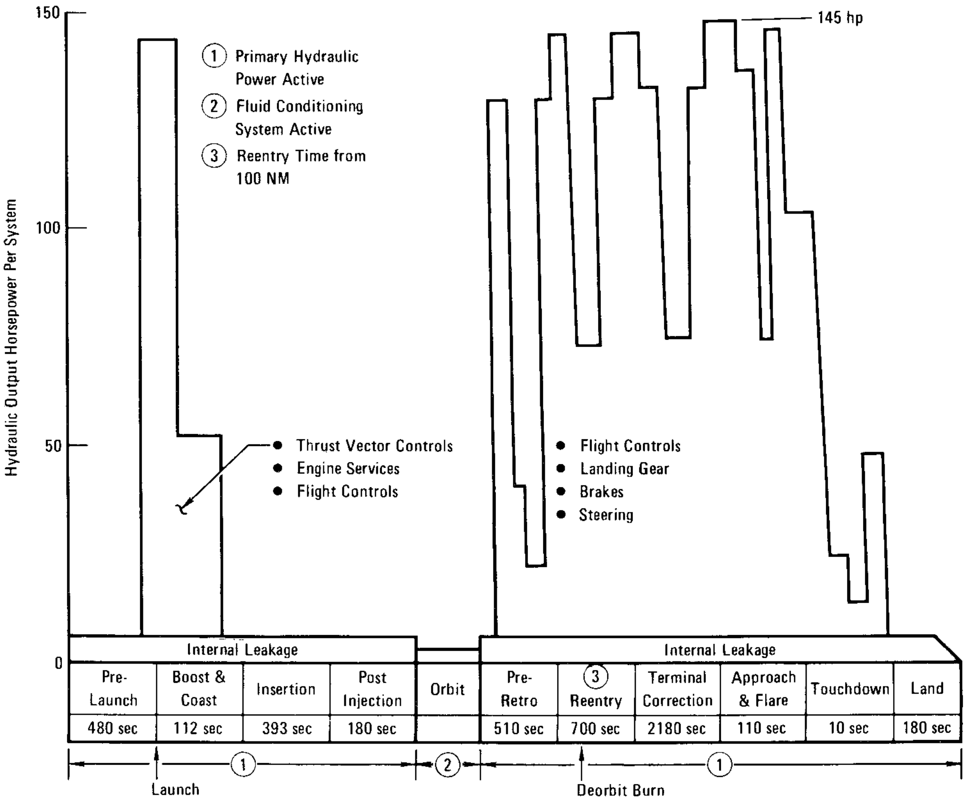
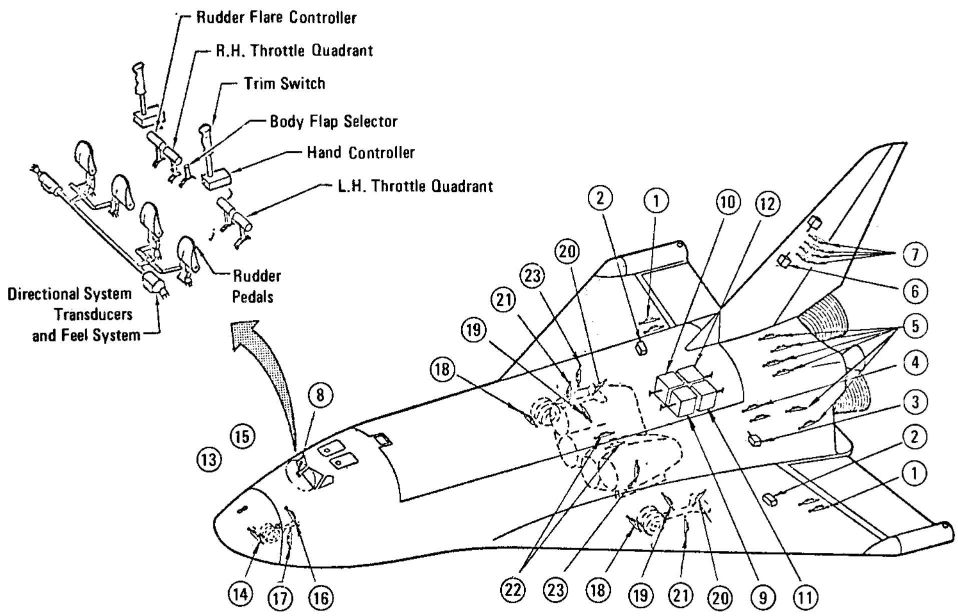


Fig. 5 - Hydraulic system power profile



Item	Component		
1	Elevon Surface Actuators	12	No. 4 Hydraulic Power Generation System
2	Elevon Servo Actuators	13	Nose Wheel Steering Actuators
3	Body Flap Servo Actuator	14	N.G. Door Actuator
4	Body Flap Surface Actuators	15	N.G. Door and Gear Uplatch Actuator
5	Engine TVC Actuators W/Integral Servo	16	N.G. Actuator
6	Rudder/Flare Servo Actuator	17	N.G. Door Latch Actuator
7	Rudder/Flare Surface Actuators	18	M.L.G. Door Actuator
8	Hydraulic Control Panel	19	M.L.G. Door and Uplatch Actuator
9	No. 1 Hydraulic Power Generation System	20	M.L.G. Actuator
10	No. 2 Hydraulic Power Generation System	21	M.L.G. Door Latch Actuator
11	No. 3 Hydraulic Power Generation System	22	ABES Door Actuation
		23	ABES Actuation

Fig. 6 - Orbiter component location

summed as a mechanical output to position the surface actuator.

Hydraulic system design is vehicle dependent; therefore, as the vehicle design matures additional studies must be performed to optimize actuator and power generation configurations, system power capacities, and thermal control approaches.

POWER GENERATION ELEMENT

The power generation element, including the pumps, reservoir, central service module, and thermal control element, is shown schematically in Fig. 7.

PUMPS - Each system is powered by one main hydrazine APU-driven pump and one electrically-driven pump. The APU-driven pump supplies the main power for the system, while the electrically-driven pump is used for thermal conditioning in orbit. The electric pump is also turned on prior to APU start to prevent cavitation. Two innovative features have been incorporated; manifold mounting and high-response compensation.

The manifold connection, shown in Fig. 8, eliminates the need for hose connections to the pump and houses the fluid passages, connections to pump and system, and seal drain cavity. The unit is retained by a "V" band clamp and the drive-shaft penetrates the center of the unit. Integral quick disconnects permit the pump to be removed without tubing disconnection or fluid spillage.

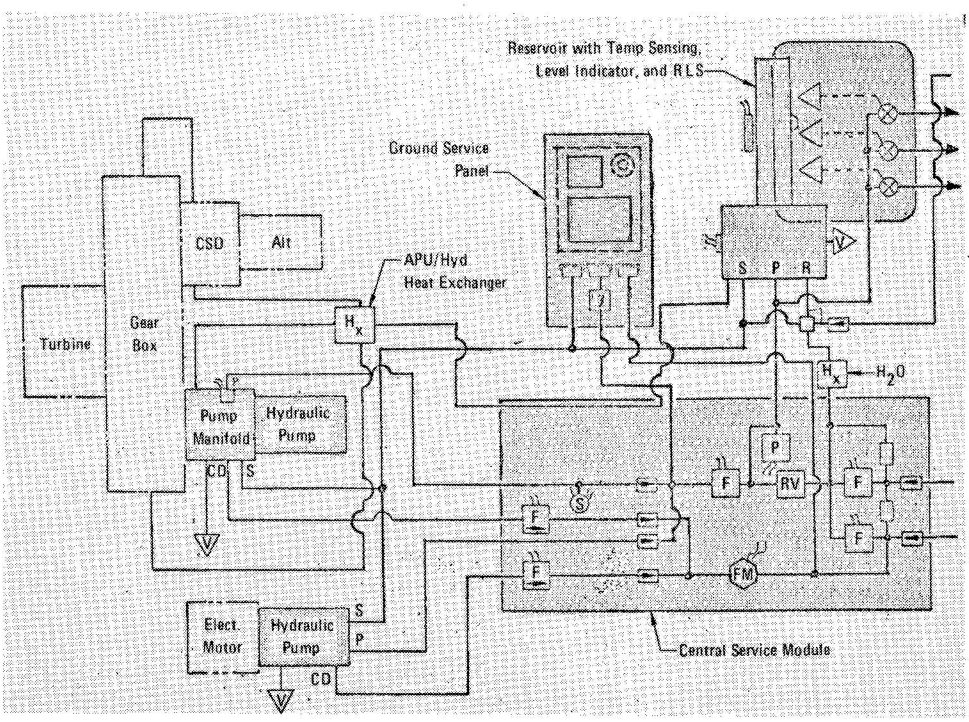


Fig. 7 - Power generation system

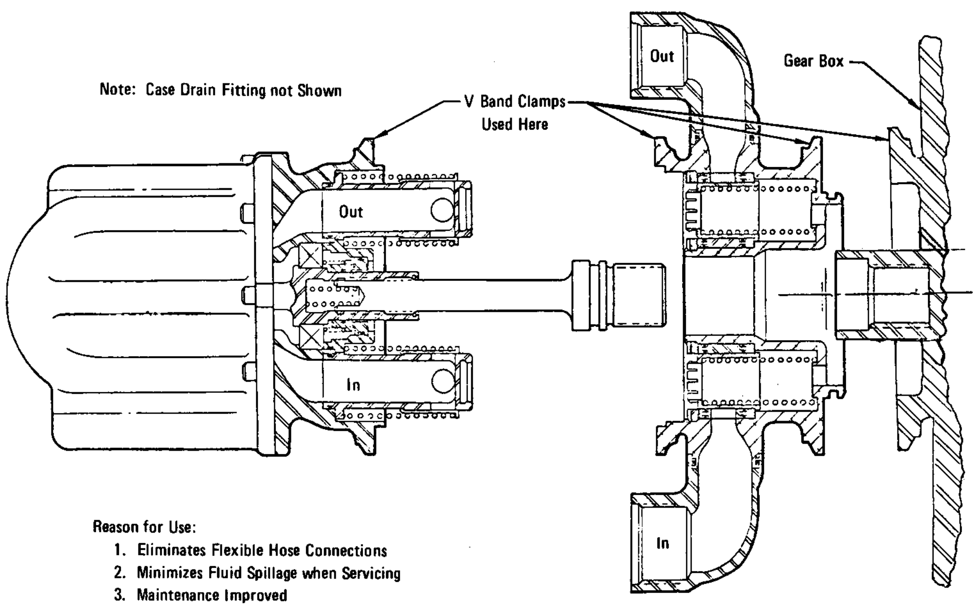


Fig. 8 - Hydraulic pump interface

The pump is a variable displacement, in-line type with a pressure derivative compensator supplying flow at 3000 psig. This type of compensator, in conjunction with a fast-acting main system relief valve, eliminates the need for accumulators in the system, thereby improving reliability and maintainability. The pump delivers 90 gal/min operating at 5000 rpm.

RESERVOIR - The reservoir of each system is an airless reservoir of the "boot-strap" type design and incorporates reservoir level sensing, a temperature sensor, fluid level indicator, pressurization device, and overboard drain. The reservoir level sensing (RLS) concept is incorporated to sense external leakage and isolate the faulty subcircuit. A simplified schematic of the RLS is shown in Fig. 9. The sensing portion may be electrical or mechanical. The RLS unit is normally passive with no wear problems, reliable in operation, and can sense any magnitude of leakage. The RLS unit permits a subcircuit failure without total system loss. The pressurization device previously mentioned is a spring bellows which retains fluid pressure at a level in excess of the vapor pressure for in-orbit passive conditions.

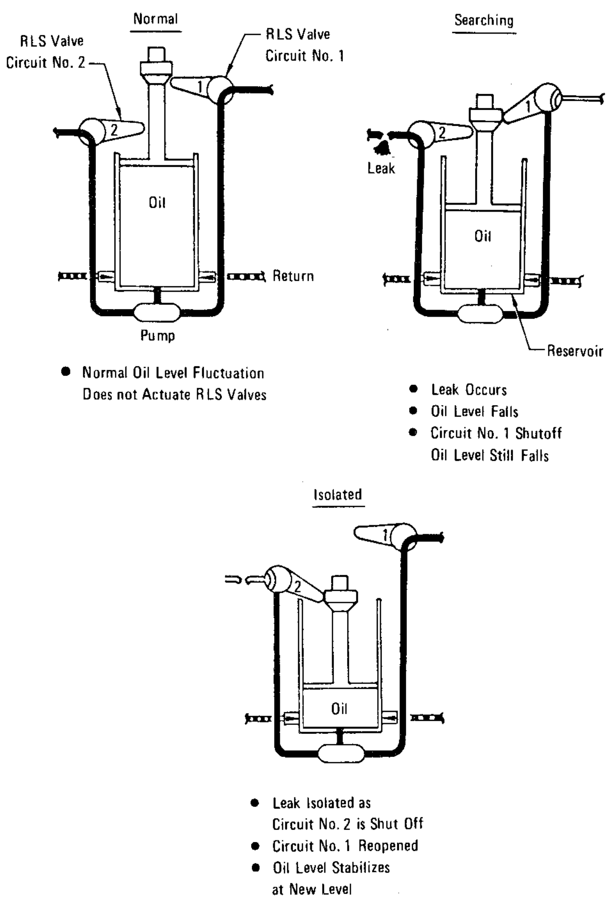


Fig. 9 - Reservoir level sensing (RLS) concept

CENTRAL SERVICE MODULE - The central service module is located in the power generation area and houses the filters, pressure switches, flow meters, check valves, relief valves, pressure transmitter, and bypass valves. All of these elements are of modular construction and can be removed without tubing disconnection. The filter elements selected are MIL-F-8815, depth-type filtration, 15 μm absolute. Nonbypass types are used in the pressure system and bypass types in the return. All filter elements are identical. Differential pressure indicators, both mechanical and electrical, are incorporated to display the need for element replacement. The electrical signal is stored in the onboard maintenance recorder. The tapered plug concept is used for all components, which are indexed to eliminate incorrect component installation.

THERMAL CONTROL - It was determined by analysis that system cooling is required during reentry and landing. An integrated APU/Constant Speed Drive (CSD)/hydraulic system approach was chosen as the most optimum cooling system. The APU/CSD lube system heat is transferred to the hydraulic system and the total heat load is then rejected by a H_2O flash evaporator. It was found during the analysis that the pump case drain leakage was inadequate to transport the heat when in a vacuum environment. Therefore, a circulation pump was added as an integral part of the APU-driven main pump to increase flow around the rotating group. A schematic of the cooling loop is shown in Fig. 10.

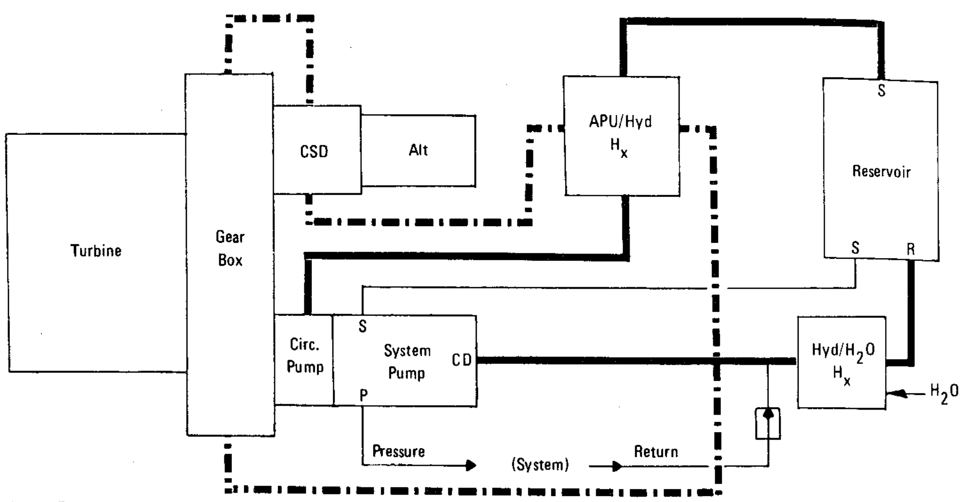


Fig. 10 - Hydraulic/auxiliary power unit (APU) thermal control circuit

UTILITY SERVICES

The primary utility services consist of landing gear operation, wheel brakes, nose gear steering, and ABES deployment.

LANDING GEAR - The landing gear extension-retraction system, consisting of three systems for extension (FO/FS) and one for retraction (not a mission function), is shown schematically in Fig. 11. Gear extension is electrically controlled by the pilot or the autoland system signal to the two solenoid-operated hydraulic selector valves. The primary selector valve ports pressure to unlock the door and gear latches and to operate the gear actuators. The secondary selector valve ports pressure to the latches only through dual tandem actuators. The nose landing gear (NLG) forward door is closed after the nose gear extends to enhance aerodynamic stability of the vehicle. Opening and closing of the NLG forward door is controlled by the two NLG sequence valves which are mechanically attached to gear position. If the primary system does not operate, the secondary system automatically operates the dump valve to allow the actuators to port to return, and the gear free-falls to the down and locked position. If the secondary system malfunctions, the emergency cable system is operated manually by the pilot or by an electromechanical actuator for autoland. The cable opens the dump valves, mechanically opens the latches, and allows the gears to free-fall. The NLG forward door will remain down when the gear is

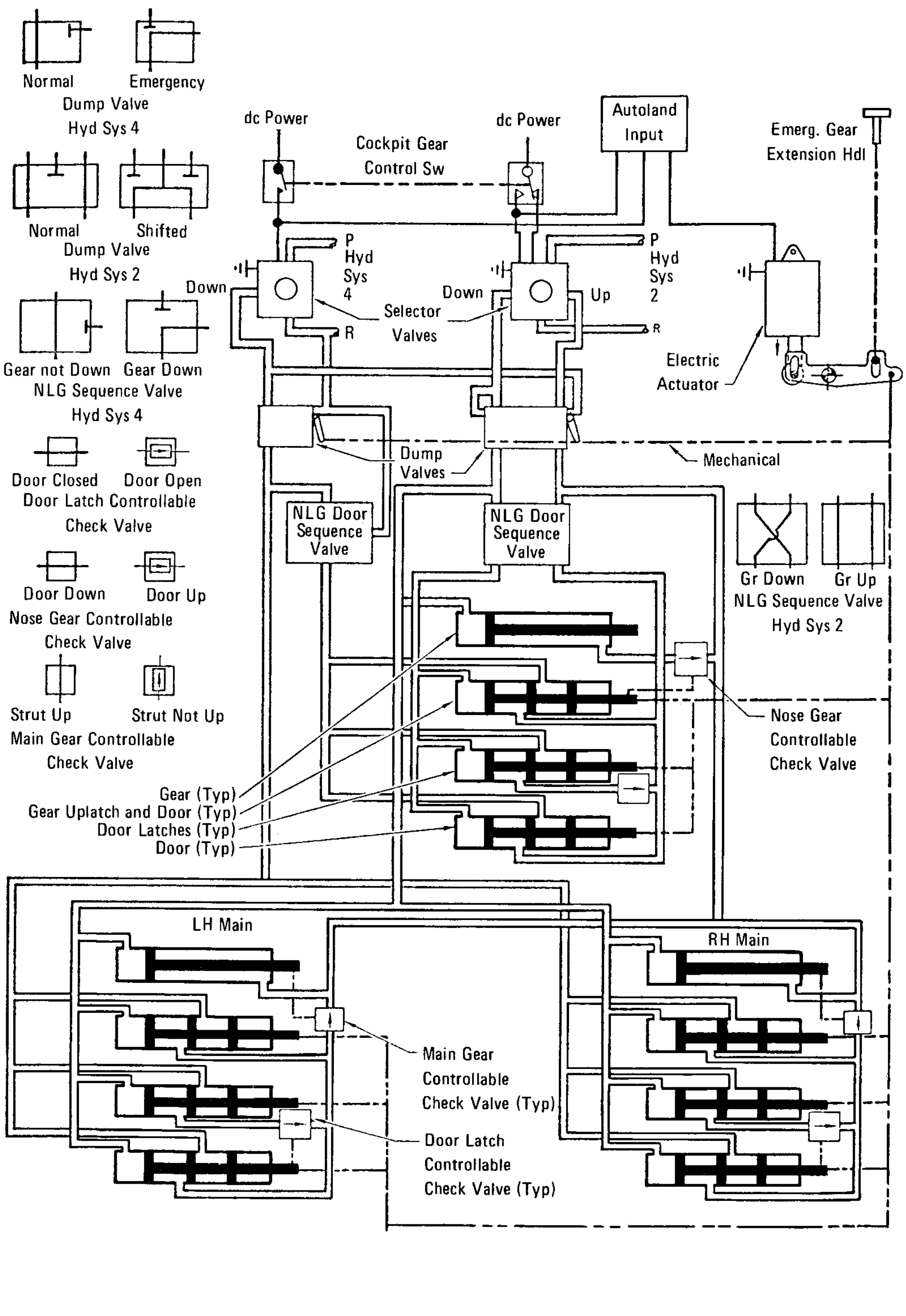


Fig. 11 - Orbiter landing gear extension schematic

extended by the secondary or emergency systems. The gear-up cycle is available through the primary system only, and is the reverse of the gear-down cycle. The main gear controllable check valves ensure that the door and uplatch do not close before the gear is up. The door latch controllable check valve keeps the door latch open until the door closes. For the nose gear-up cycle, the NLG sequence valve ports pressure to open the forward door. The nose gear controllable check valve prevents the strut from retracting until the door is open. As the strut comes to the up position it reverses the position of the NLG sequence valve, providing hydraulic pressure to close the door and uplatch. The nose gear door latch controllable check valve locks the door only when the door is up.

WHEEL BRAKES - The braking system, shown in Fig. 12, employs two separate hydraulic systems including lines and brake pistons. This system is essentially the same as the DC-10 system. A third hydraulic system operating through switching valves provides a backup power source for each system (FO/FS). The pilot mechanical inputs operate the metering valves and allow differential brake operation. The antiskid valves modulate the pilot-metered pressure to provide a brake pressure consistent with the runway friction level. The antiskid controller measures each individual wheel speed, detects incipient skids, and supplies the antiskid valve signal required to develop maximum braking force to the pair of valves on the skidding wheel. In addition, the antiskid controller provides touchdown and crossover locked wheel protection. Automatic braking during autoland is achieved by energizing the autorollout solenoid which bypasses the metering valves and ports full system pressure to the antiskid valves for maximum braking effort at all brakes. Pressure modulation to the brakes is provided by the antiskid system. The autorollout braking concept and the analog antiskid controller are used on the latest generation of commercial aircraft and are cost effective.

NOSE GEAR STEERING - The steering system, Fig. 13, is quadrupally redundant, electrically controlled, hydraulically actuated, and on at all times when the vehicle is on the ground (nose gear squat switch). The steering has ± 15 deg authority, with a quick disconnect provided at the torque arms for towing at greater angles. The electrical control was selected because it provides the lightest, most efficient, most direct method of integrating the autorollout requirement into the steering system. It also provides failure monitoring of the actuator level and more flexibility for steering design changes (such as two-mode steering) is provided. The pilot steers by inputs to the linear variable differential transformers (LVDTs) through four separate electrical channels to four balanced actuators. Each electrical channel consists of input and output LVDTs; a discriminator, which permits the pilot to override the autorollout steering input; a summer, which compares the input and feedback signals and produces the corrected error signal; a fader, which operates only at turn on and provides a

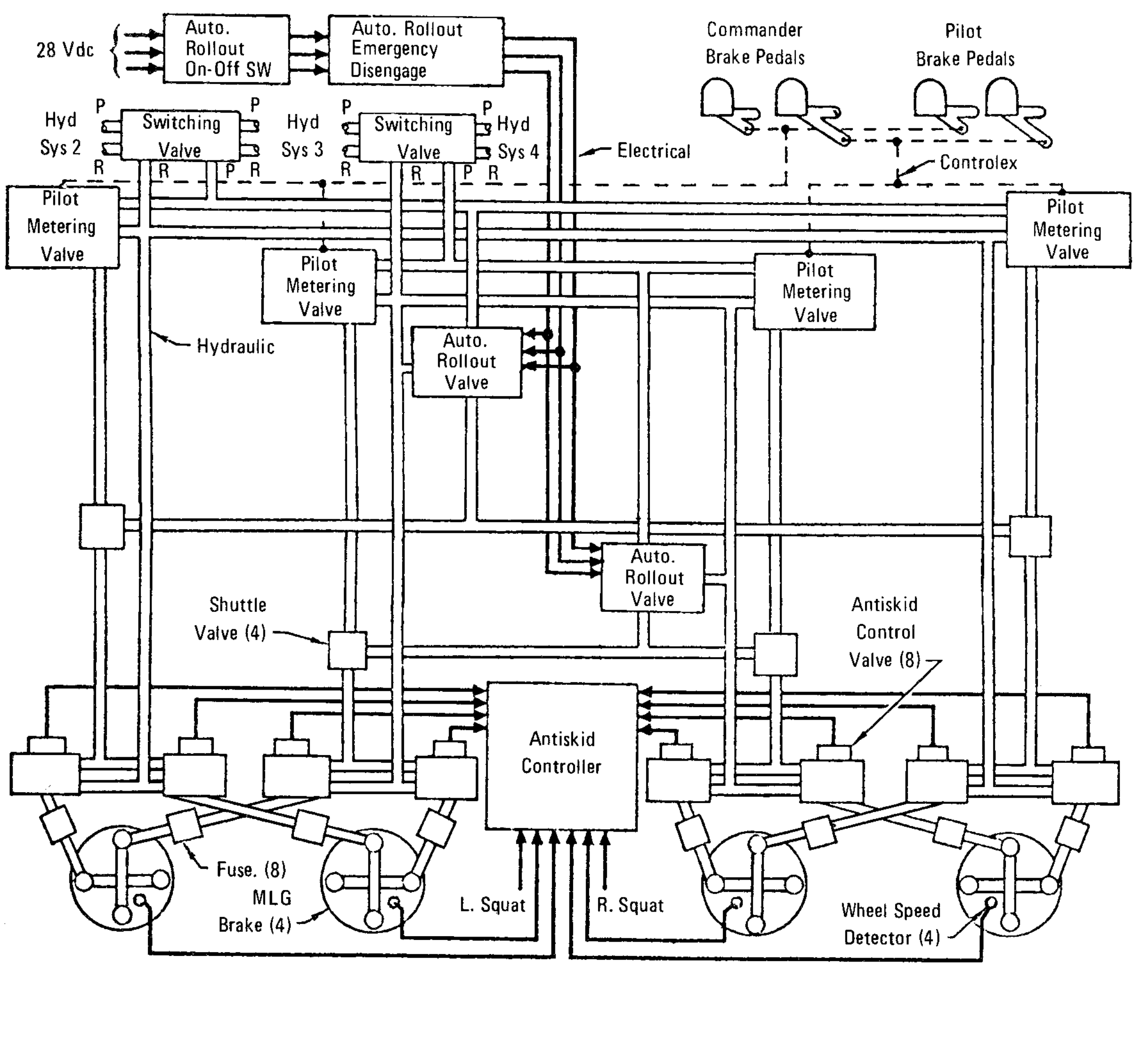


Fig. 12 - Orbiter landing gear braking schematic

gradual (approximately 2 s) fade in of steering signal; and a valve amplifier, which provides a current output to the control valve proportional to the error signal. The control valve ports pressure to the proper side of the actuator to diminish the error signal. The on-off valve functions to energize the steering system or to bypass a failed actuator. The autorollout steering command is generated in the three-channel flight stabilization digital computer and through a voter supplies the four-channel steering input. Pilot override of autorollout is provided either by disengaging autorollout or by rudder pedal displacement. The pressure across each actuator is compared with the others to detect hydraulic or electronic system malfunctions, and the faulty channel or channels are deactivated by fail-safe monitor control of the on-off valve. The steering system is FO/FS in all modes except for the autorollout mode with the pilot incapacitated, which is FO. The fail-safe mode for a failure of both hydraulic systems is differential braking.

ABES DEPLOYMENT - The ABES deploy is basically a free-fall system with some initiating force being exerted through the down lock linkage. No in-flight retract capability is provided. Operation of the extend cycle is initiated by a selector switch in the cockpit. The multiple contact switch positions the three door-open drive circuits, two of which are inhibited from operation by a shutoff valve in the pressure line. After the door opens, a mechanical sequence valve unlocks the engine uplocks and energizes the down lock cylinders allowing the engines to free-fall to the down and locked position. Electrical sequencing then closes the doors for a complete cycle. A ΔP sensor is incorporated to sense a failure of the primary circuit and energize the secondary circuit for identical operation. A failure of the secondary circuit is sensed the same as the primary and switched to the tertiary circuit. Dump valves in the primary and secondary circuits prevent a fluid lock when a control valve malfunction occurs. Since the

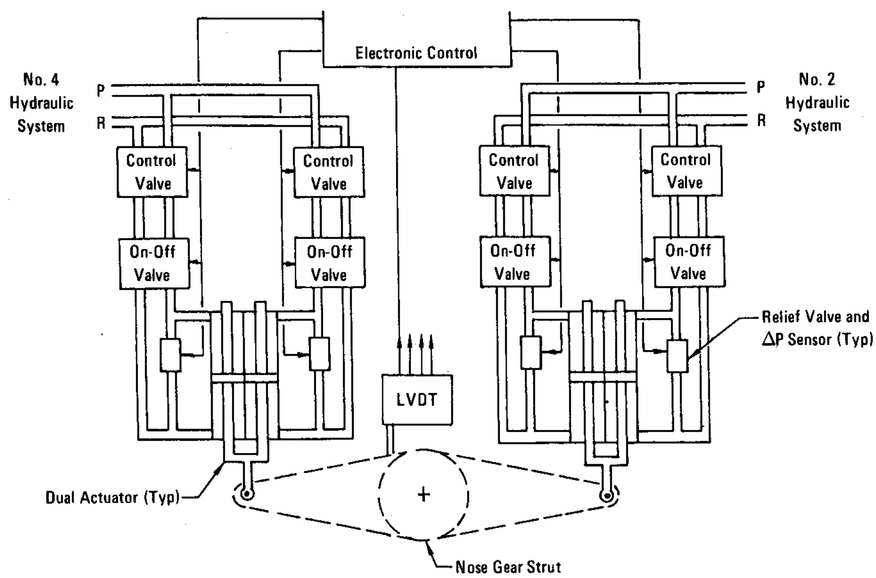


Fig. 13 - Orbiter nose gear steering schematic

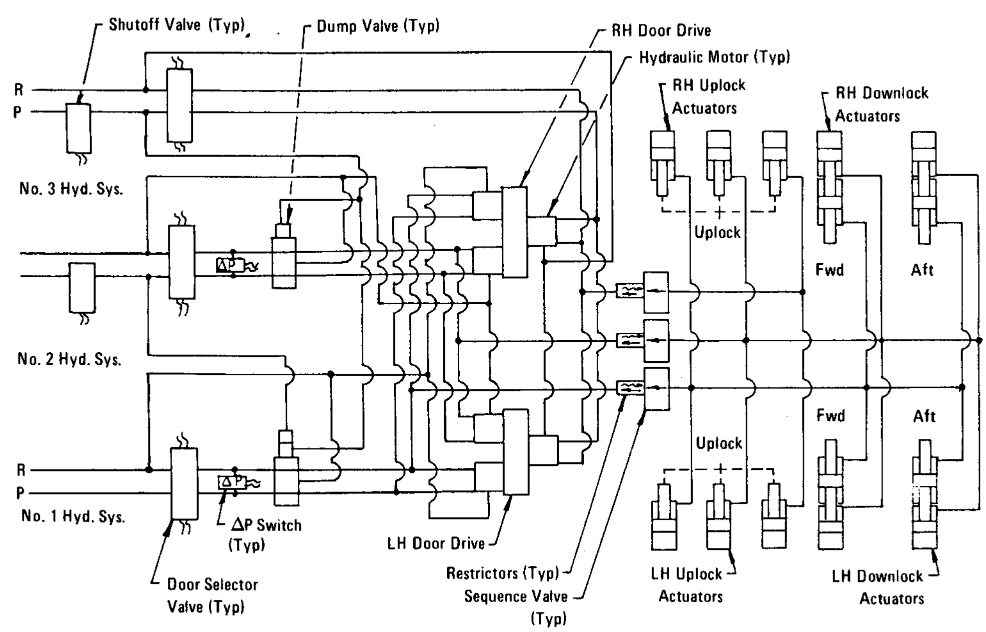


Fig. 14 - Air breathing engine (ABES) deployment system

tertiary circuit does not incorporate a powered down lock, some lateral maneuvering may be required for complete down locking. This scheme, which is shown in Fig. 14, provides a FO/FS system.

FLIGHT CONTROL SYSTEM

The aerodynamic flight control system, diagrammed in Fig. 15, consists of conventional control surfaces for the elevons, body flap, rudder, and rudder flare. Each control surface is powered by four independent hydraulic systems. The actuator control is by quadruplex electronic controls to provide a FO/FS redundant control system.

OPERATION - Operation of the orbiter aerodynamic control surfaces is required for vehicle control during ascent, reentry, cruise-back, and landing. Precise control is required for all flight conditions to assure safe return and landing. In addition, the system shall have the necessary redundancy to be capable of operation after two failures. Other major constraints considered in the system formulation were the effects of friction, inertia, temperature, weight, performance, and the capability of the system to accept automatic programmed flight.

To fulfill the above requirements, a fly-by-wire system was chosen as the leading system candidate because it is capable of automatic programming, control system inertia is minimized, thermal effects on the control cable, linkage, and structure are eliminated, control deflections induced by structural deflections are eliminated, control system friction problems are eliminated, system free play is minimized, and interconnect mechanisms are eliminated.

To accomplish the required redundancy, four independent electronic-control and four independent hydraulic-power generation systems are utilized. A quadruplex electrohydraulic servocontrol actuator will be used to control the multiple surface actuators. The servoactuator accepts quad electrical inputs and sums them to a common output. The output of the servocontrol actuator controls the valve input of the multiple surface actuators. The surface actuators, which are mechanically controlled and hydraulically powered, are body mounted with mechanical feedback.

ELEVONS - Lateral and longitudinal control of the vehicle is provided by an elevon control system. There is a single elevon surface powered by two servocontrolled dual tandem actuators in each wing. A single servocontrol actuator at each elevon controls the surface actuators. Lateral control is obtained by differential movement of the elevon surfaces, while longitudinal control is obtained by simultaneous operation of the two elevon surfaces. Control is initiated by movement of the side arm controller; fore and aft movement results in longitudinal command while lateral movement results in lateral command signals. The command signals are obtained from the force transducers located in the respective system feel cartridge. Controller deflection causes a force transducer output signal

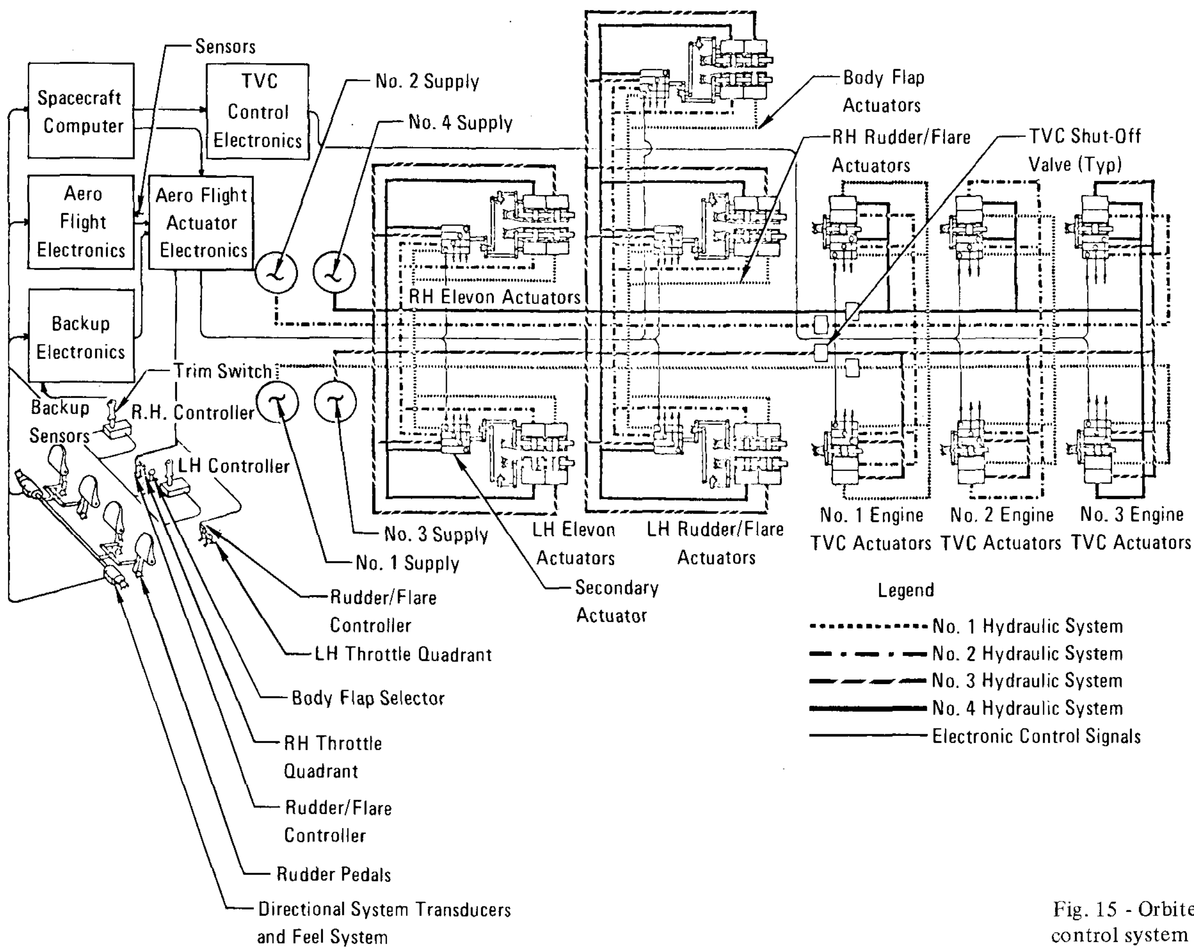


Fig. 15 - Orbiter hydraulic flight control system diagram

which is transmitted to the computers where it is summed with aerodynamic, vehicle motion, and control law signals. The resulting command signal is then transmitted to the servo-control actuator and to monitor electronics which position the surface actuators. The servocontrol actuator position and monitor signals are sent back to the monitor electronics which completes the servoloop. Both elevon surface positions will be displayed in the cockpit.

RUDDER/FLARE - The directional control of the vehicle is accomplished by a full span, flared rudder. Two surface actuators and one secondary actuator are used on each of the two panels. These panel surfaces are moved together for rudder and separately for speed brakes. Signal transmission is accomplished the same as for the elevons. All trim is accomplished electronically.

BODY FLAP - The body flap is used to provide vehicle trim with a forward c.g. and is also used for flight path modulation during unpowered landing. Again, the typical approach for powering and controlling the surface (Fig. 16) is utilized.

COCKPIT CONTROLS - The cockpit controls incorporate a side-arm controller for longitudinal and lateral control and convenient rudder pedals for directional control. These controls are duplicated in a side-by-side arrangement for actuation from either the pilot or copilot station.

SURFACE ACTUATORS - The actuators are dual tandem and constructed to prevent cylinder crack propagation. Dual rod seals with leak detection are also incorporated so operation may be sustained after a primary pressure seal failure. The leak detector senses return leakage flow as an indication of primary seal condition. Excessive leakage is an indication of a worn and/or ruptured seal. An in-orbit hydraulic thermal conditioning system is also incorporated. An auxiliary electrically-driven hydraulic pump unit circulates hydraulic fluid at 500 psi. The fluid bypasses the actuator master control valve and flows through the actuator chamber and back to return, a process which may be accomplished either manually, automatically, or on a time sequence basis. A thermal analysis of the installed system is required to determine the optimum method used. Inlet check valves are provided at each actuator pressure port to prevent surface backdown.

Anticavitation valves are also incorporated in the surface actuator. The anticavitation system is basically a series of check valves arranged to permit free flow from the return to the cylinder port. This arrangement maintains fluid in the piston cavity after a failure of the power generation circuit or during ground operations when all systems are not pressurized. The anticavitation valves prevent pumping of fluid overboard and possible reservoir damage during ground and flight operation. They also maintain fluid in the cylinder for actuator stiffness during flight.

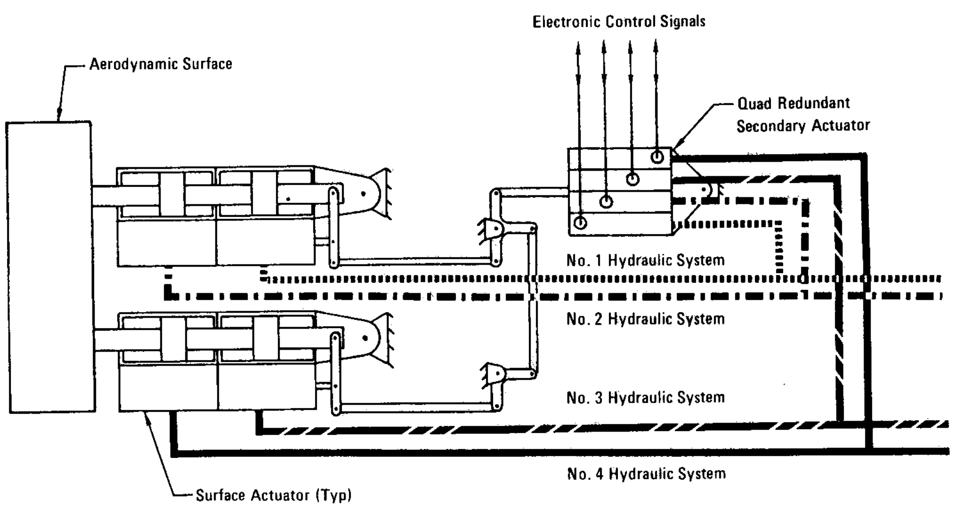
The recommended master control valve is the dual tandem type with a single piece spool and sleeve. This type of control valve has proved to be trouble free in present applications. This method also eliminates adjustments and synchronization difficulties caused by possible tampering and/or readjustments. Consideration was also given to using antijam type control valves.

A typical surface actuator diagram is shown in Fig. 17.

DISTRIBUTION SYSTEM

The power distribution section of the system includes fluid, flexible lines, hoses, lines, fittings, line supports, packings, and seals.

FLUID - The hydraulic fluid for the vehicle was chosen from a number of candidates: oronites, mineral oils, and synthetic hydrocarbons. The cooling requirement for the system is to control the maximum temperature below +275 F. MIL-H-83282 fluid was selected for the following reasons: compatibility with most materials that are used in the vehicle and hydraulic system, lower density than the oronites, fire resistant qualities determined by hot manifold, high-pressure spray, low-pressure spray, wick flammability, Navy six-wick, and can cover tests, and adequate high-temperature characteristics



Operation: Each Actuator Chamber Capable of 50% H.M.
Total Actuator Force Available is 200% H.M./Surface
Total Actuator Force After 2 System Failures is 100% H.M.
Each Hydraulic System Size for 50% Vehicle Requirements

Fig. 16 - Typical orbiter aerodynamic surface control system

established by Navy laboratory testing at temperatures up to 500 F. The fluid has a low temperature limit of -40 F; however, this is well above anticipated low temperatures of the orbiter.

FLEXIBLE CONNECTIONS - Maximum use is made of the coiled tubing concept in applications where relative motion exists. The coiled tubing is fabricated per applicable requirements of SAE-ARP584. The use of coiled tubing on aircraft applications has become standard practice on A-4, F-4, DC-8, DC-9, and DC-10 aircraft. This usage has resulted in high reliability, long life, and minimum maintenance. The DC-10 utilizes coiled tubing made of commercially pure titanium. The use of Teflon hose has been thoroughly explored on the F-4 aircraft versions where many varied configurations were successfully used. Where hoses are used they are Teflon-lined, fire resistant, stainless steel, fabricated per MIL-H-38360.

PACKING AND SEALS - No elastomers are used in the tubing runs or with fittings because of the types of joints selected. Seals used within actuators, manifolds, and components will be compatible with the fluid and environmental parameters. The elastomer candidate selected was Viton E60C which is funcitonal to temperatures in excess of 400 F. Backup rings are made of a Teflon compound. Metallic seals may be selected for areas where their properties will be advantageous; however, none of these areas have been identified at this time.

TUBING AND FITTINGS - The tubing selected for the system was titanium 3A1/2.5V for all pressure lines and those return lines subject to adverse environmental conditions. The commonly used 6061-T6 aluminum alloy was selected for other return line applications. This titanium alloy was selected for the F-14 and B-1 aircraft. Each program has conducted extensive testing on this material. The permanent fitting selected was the Permaswage, which was designed and developed by McDonnell Aircraft Co. and is used on the DC-10. The use of this type of fitting, rather than welded or brazed fittings, results in a simpler fabrication process in that rigid cleanliness requirements, inert gas purging heat cycles, and x-ray inspection are not required. Maximum use is made of the permanent joint to minimize leak points.

The connectable in-line fitting selected was the Dynatube type, using the deflected beam principle for sealing. The boss fittings selected were the metal lipseal type developed for the DC-10 application.

MAINTAINABILITY

Maintenance is one of the most important criteria in design when cost effectiveness is a primary goal. The latest state-of-the-art design particles are included in this system to improve the overall maintainability characteristics. Those items specifically associated with maintenance are: four identical systems, no gas-oil accumulators in the orbiter, identical control actuator design concepts, modularized components, maximum use of swaged fittings, elimination of elastomers in tubing and fittings, case drain flow indicators for pumps, differential pressure indicators for filters, minimum line disconnection for component removal, automated malfunction detection system, common filter elements, sealed system concept, internal leak check devices, end-to-end system checkout capability, and control servos common in all applications.

ONBOARD CHECK-OUT

The onboard check-out function will subject the shuttle hydraulic system and components to a sequence of known operating conditions to determine the current status of the system. The check-out will: determine system condition before launch, monitor system status during flight, detect faulty line replaceable units (LRUs) to permit in-flight reconfigura-

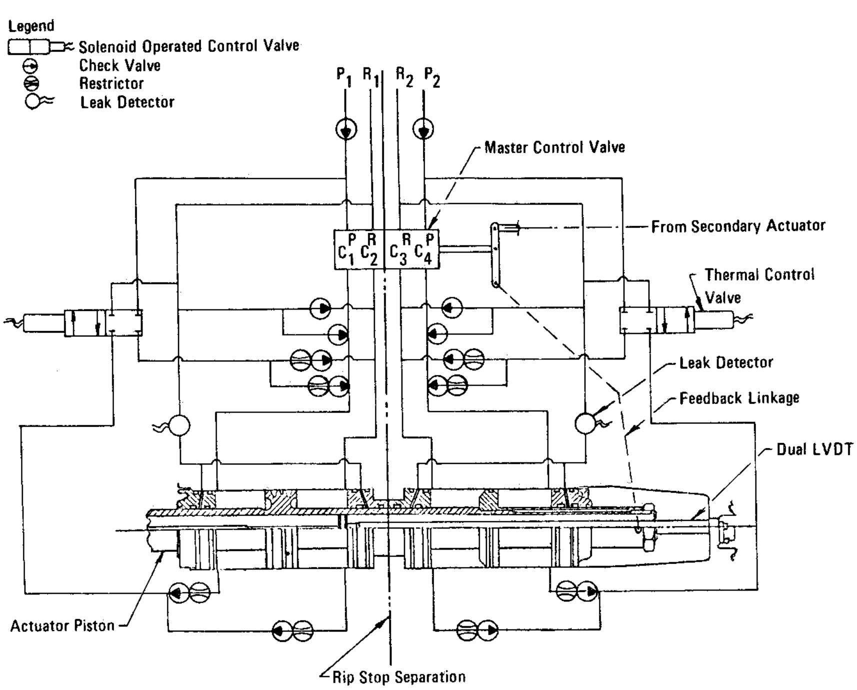


Fig. 17 - Typical aerodynamic control surface actuator schematic

tion as required, and identify faulty LRUs to expedite ground repair.

Since the space shuttle is to be a reusable vehicle, the check-out function philosophy departs from that utilized in previous single-mission space vehicles. The check-out function has been considered since the initial design phases, ensuring an integrated design approach.

The system check-out philosophy is based on maintaining a sealed system concept, end-to-end testing, and on-condition monitoring of performance. Crew display parameters will include pressure, fluid quantity, and indication of loop failures for each system.

The data management subsystem data processing will be the same for both in-flight and ground test. Check-out will be initiated from the crew station with system status verified by cockpit displays and readouts. The verification of system function will be implemented by check-out software which compares the system status with prestored limit values. A maintenance recorder will be used to establish trend data to detect potential component failures.

The hydraulic system design will incorporate subcircuit fault detection such as excessive internal leakage, external leakage, filter status, pump case drain flow, switching valve status, and individual control actuator status. Reservoir level sensing (RLS) will detect external leakage and will isolate the failed subcircuit.

The power actuator monitors will include differential pressure for control surface hinge moment measurements as well as force sharing evaluation. Internal leak check sensors will be provided to monitor the conditions of valves and seals. LVDTs will be incorporated for surface position monitoring, as well as for the control loop feedback. System pressure and return monitors will be provided at one actuator on each surface for flight test instrumentation. Actuator fluid temperature sensors will be included to monitor system conditions and to control the thermal conditioning circuit.

Hydraulic utility functions such as landing gear operation, steering, and braking will also be monitored. Internal system leakage detection will be provided for each gear assembly. In addition, valve position, gear position, lock indications, nose wheel steering position, and antiskid operation will be monitored and can be displayed to the crew through the Data Management System.

SUMMARY AND CONCLUSIONS

The final system concepts selected are a blend of proven design principles associated with commercial and military aircraft which have been adapted to the stringent environmental and operational conditions expected for the space shuttle. The resulting systems exhibit a high confidence level. The use of the latest state-of-the art design approaches, including fly-by-wire control and automated onboard check-out, has resulted in a hydraulic system of maximum reliability with a minimum of maintenance requirements, which is necessary for the rapid turnaround established for the space shuttle.

As the vehicle design matures and wind tunnel test data are available, it is anticipated that changes will occur in loads, rates, services, and configurations. The baseline system presented is expected to adapt easily to these variances rather than resulting in major system concept changes. The first proof of the design will occur at first horizontal flight in 1976, and the reliability and maintainability attributes will be proven in the subsequent 10 years of operation.