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FUEL/HYDRAULIC TRANSFER VALVE IMPROVES RELIABILITY OF ATLAS SPACE LAUNCH VEHICLE

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SUMMARY

The Atlas Fuel/Hydraulic transfer valve (FHV) design is enhancing the Atlas space vehicle launch reliability without a major redesign. The concept represents a rational evolutionary design change. General Dynamics Convair Division has designed a fuel/hydraulic transfer valve to permit controlled interfacing with the RP-1 fuel supply. The design satisfies primary goals such as fuel and oil isolation before launch in order to use existing ground support and airborne hardware and procedures. The valve will operate only after the vehicle has been committed to launch. Hydraulic system function will be maintained if the valve fails to function. Valve operation is mechanical and interfaces only with the propulsion system.

BACKGROUND

The Atlas vehicle has two independent hydraulic systems, one for each stage, used to provide power for thrust vector control and to the engine propellant utilization system. As a first generation missile designed primarily as a high priority weapons delivery system, no consideration was given for designing redundancy features into the hydraulic system. As a weapon system vehicle, its development and operational flight record was tarnished by occasional hydraulic system failures attributed to system leakage.

The changeover from a weapons system to a space launch vehicle placed greater emphasis on vehicle reliability. The hydraulic system reliability was improved by critical analysis, design improvements, generous testing, and tender loving care.

The Atlas vehicle carries at liftoff approximately 47.3 cubic meters (12,500 gallons) of RP-1 fuel and the hydraulic systems carry 0.0011 cubic meters (0.3 gallons) of reserve hydraulic fluid. Leakage of the hydraulic fluid in flight in excess of reserve capacity could result in a costly mission failure. The concept of tapping the RP-1 fluid as an "infinite" reservoir for the hydraulic system became attractive. System reliability can be increased to permit the hydraulic system to become leak-tolerant. An estimated 50% of the previous hydraulic system flight failures (and mission losses) would have been prevented if the concept had been utilized.

CONCEPT

The fuel/hydraulic transfer valve design uses a diaphragm to isolate hydraulic and RP-1 fluids. A ram is used to rupture the diaphragm. This event can only occur when the engines are ignited and high-pressure RP-1 fluid is generated. The high-pressure RP-1 fluid is ported to the ram which then ruptures the diaphragm. The subsequent interface attainment between low pressure RP-1 and hydraulic fluid thus makes the "infinite" supply of RP-1 available to the hydraulic system. With zero system inflight leakage, the hydraulic system functions on a low mixture of RP-1 in hydraulic fluid. If a leak is manifested, system function will continue as RP-1 flows into the hydraulic system.

PREVIOUS DEVELOPMENT

Air Force funds were made available in 1967-68 to design and develop a similar interface valve to the subject valve. The major difference between the two designs was that the earlier version had a design feature that would not allow inflight interfacing of RP-1 fuel with hydraulic fluid under any circumstances except when a system leak developed. The valve would function by sensing an inflight pressure loss in the return or low pressure system circuit.

A valve was designed, developed, and tested to demonstrate the concept feasibility. The diaphragm-design configuration was the major hurdle to overcome. After starting with no experience, a satisfactory diaphragm configuration was attained. System tests using surplus flight hardware demonstrated all program objectives, but the program was cancelled without implementation. Fortunately, the data was used to design the current valve now in flight service.

HYDRAULIC SYSTEM DATA

- Number of independent systems: two (one for each stage)
- Operating pressures (nominal)
  High pressure: 205 ATM (3,015 psia)
  Return or low pressure: 5.3 ATM (80 psia)
- Hydraulic pump flow (variable, engine driven):
  Booster: 0-1.45 $\times$ 10^{-3} m^3/sec (0-23 gpm)
  Sustainer: 0-0.50 $\times$ 10^{-3} m^3/sec (0-8 gpm)
- Hydraulic fluid: MIL-H-5606, (hydrocarbon — red color)
- Fuel: RP-1 per MIL-R-25576
- Function:
  Booster system: Provide power to engine nozzle thrust vector servoactuators
  Sustainer system: Provide power to engine nozzle thrust vector servoactuators and engine propellant control system

OBJECTIVES AND CONSTRAINTS

The task objective was to design, test, and integrate a valve into three existing Atlas vehicle configurations requiring three different installation versions. Fortunately, the three vehicle hydraulic systems used common hardware and functioned identically. This allowed the designer to create a common valve design and envelope with port fitting configuration differences to accommodate unique installation requirements.

The Atlas SLV-3D model is manufactured for NASA under a Lewis Research Center managed contract. The Atlas SLV-3A and E/F models were manufactured and subsequently modified for the U.S. Air Force Space Division use. The U.S. Air Force Space Division and NASA jointly provided the design and testing funds for the valve basic design. All agencies participated in preliminary and critical design reviews.

The prime technical objectives were:

1. To increase booster and sustainer hydraulic system reliability by utilizing RP-1 fuel as a ready reserve fluid in the event of a hydraulic system leak to maintain system function:
   A. With any size return system leak.
   B. With a limited leak in the pressure system.
2. To maintain hydraulic system function if the FHV valve does not activate.

3. To achieve program economy by utilizing a wholly mechanical system and avoiding a more costly electrical system.

Design Objectives Achieved:

A. System reliability has been increased.

B. No pyrotechnic devices or electrical interfaces were used..

C. The FHV valve uses high-pressure fuel to activate the valve. Valve integration between hydraulic and propulsion systems is not affecting either system performance.

D. Prior to vehicle launch, there is zero leakage of hydraulic or RP-1 fluids into the alien system.

E. Interface of RP-1 fuel and hydraulic fluid occurs only when the vehicle is committed to launch. This occurs for:
   1. Atlas E/F vehicles: at initiation of "Engine Start" sequence.
   2. Atlas SLV vehicles: at vehicle release (Post Engine Start).

F. Valve design makes maximum use of design features of the "emergency fuel valve" design developed in 1967-68.

In Design Objective E.1 above, the E/F vehicle is a nonrestrained launch concept. The vehicle will liftoff when engine thrust exceeds vehicle weight. No launch abort is possible. The SLV vehicle, being of an earlier design, is restrained to the launcher until engine thrust has increased to a steady state level. The vehicle is then automatically released for flight after satisfying all launch control monitor functions. During the interim period between engine start and "launch release" an abort capability exists. The problem presented here is twofold: (1) how to delay valve operation past the engine start transient for E/F and SLV vehicles, and (2) how to allow an abort event for SLV vehicles without activating the valve.

In Design Objective E.2, the use of a pyrotechnic device to trigger the FHV valve with high pressure fuel would have been ideal, but this introduces an electrical interface. This concept was dropped because the E/F vehicle would have required an electrical relay box to fire the pyrotechnic squib. The qualification cost of the relay box and lot control costs of the squibs would have exceeded allocated funds.

HOW THE FHV VALVE FUNCTIONS

See Figure 1. A diaphragm is used to isolate RP-1 fuel from hydraulic fluid. The diaphragm is ruptured by high pressure RP-1 that is only available upon engine ignition. When the diaphragm ruptures, low pressure RP-1 and hydraulic fluid interface. The RP-1 pressure is greater than the hydraulic return pressure by the amount of the RP-1 head pressure in the vehicle tank (about 0.4 atm, 6 psid). With no hydraulic system leakage, the hydraulic return pressure will rise to equalize with RP-1 pressure. The small extra volume of RP-1 is accommodated by the airborne hydraulic reservoir and no further mixing occurs. In case of an external leak in the hydraulic system, RP-1 fuel will flow into the hydraulic system and be directed to hydraulic pump inlet to maintain system pressure and flow. System function will be maintained with any size leak in the return portion of the circuit upstream of the FHV valve and a limited leak in the pressure circuit.

In the event the diaphragm inadvertently does not rupture at lift off, the hydraulic system will function as if the FHV valve does not exist. The airborne reservoir will maintain sufficient pump inlet pressure to feed the pump fluid.

In order to satisfy the requirement to actuate the FHV valve after the engine transient phase, a timing restrictor is installed in the high-pressure RP-1 line at the engine thrust chamber. This line normally contains no fluid and is at atmospheric pressure. At engine start, RP-1 is metered into the line and pressure builds up thermodynamically until the ram overcomes diaphragm-rupture resistance. The metering creates sufficient time delay for the engine start transient to be completed before the diaphragm will rupture. Imposing a time delay prior to diaphragm rupture is more critical for SLV vehicles which have abort capabilities. The diaphragm must not break prior to run out of time allotted for an abort period while at the same time minimizing the time wherein the FHV valve is not activated while airborne. See Figure 2. Because of the many variables involved in calculation of the thermodynamic pressure rise in the timing circuit coupled with no meaningful data associated with some of those variables, the size of the timing restrictor was determined by making reasonable assumptions for calculation purposes.

Flight data revealed that the valve was activated early, but still within acceptable limits. What had transpired, was a race between the run out of the abort timer and the diaphragm rupture event. By design, the abort timer was to run out a fraction of a second prior to the diaphragm rupture. Any abort during the abort period would maintain the diaphragm structurally intact and thereby maintain isolation between propulsion and hydraulic systems. In reality, a photo finish occurred.

FHV VALVE DESIGN FEATURES

The valve detail elements are shown in Figure 3. The simplicity of the valve design contributed to its successful performance. A short stroke ram is the only moving part. Dual seals with an in-between vent in the body assure no intermixing of fuel or hydraulic fluid because of seal leakage. The same dual seal is also employed on the diaphragm.

A filter is located in the hydraulic section which allows hydraulic fluid to pass through its core without filtration. RP-1 fuel allowable contamination content is greater than that allowed for the hydraulic system. Consequently all RP-1 entering the hydraulic system is filtered.

Between the low-pressure fuel port and the diaphragm is installed a fine mesh screen. Its function is to prevent particles, generated when the diaphragm ruptures, from entering the fuel system.

The diaphragm design is basically a V-groove cut 360 degrees in the interior wall end of cup design. The "shear" thickness of the V-groove is controlled dimensionally. This control consists of physical dimensions, surface finish condition and anodize thickness. The choice of 5059H116 aluminum material was primarily based on its excellent corrosion characteristics. All diaphragms are leak checked with helium. Lot test consists of 2 out of 10 units being subjected to rupture tests. The allowable rupture force is 5,782 N (1,300 lb) to 7,606 N (1,710 lb).

The original diaphragm rupture force tolerance requirements were not met. This was anticipated and our design concept allowed us to open the tolerance in either direction. One lot of diaphragms failed rupture tolerance limits. This was baffling since all machining tolerances were satisfied. A metallurgical analysis of the V-groove revealed differences between thin coat anodize thicknesses of the failed and acceptable lots. This was a surprise as it was assumed that the anodized strength capability was insignificant. As a consequence, anodized thickness was subsequently controlled.

Diaphragm seal and structural integrity loss by accidental or unrecognized means was addressed during the design review phase. The problem was not so much a gross diaphragm rupture, but rather detection of a small leak. A gross rupture by pressure was remote as it would require approximately 115.6 atm (1,700 psid) to rupture the unit. Neither the low-pressure fuel or hydraulic return systems during factory or site checkout or in launch status are capable of such pressure magnitudes.

In order to detect a potential small leak, a port was designed into the low pressure fuel section to allow for leak inspection. With no fuel tanked, it was simple to open the port cap and inspect for hydraulic fluid. With fuel tanked, it was difficult to detect hydraulic fluid in fuel, since both fluids are hydrocarbons and red in color. This was resolved by using infrared spectrophotometer analysis to detect hydraulic oil in RP-1 fluid. Hydraulic oil has a viscosity improver compound and hydraulic fluid is detectable as low as a half-percent in fuel. Fluid samples were taken on about 20 installed valves until sufficient confidence was gained to eliminate sample tests.

The ever-present potential of human error did occur at the component level. A technician failed to follow prescribed testing procedures and managed to burst a diaphragm. This has been the only adverse incident to date.

The restrictor check valve function is to minimize the back flow of RP-1 fluid in the event an external leak occurs in the return system upstream of the valve.

As installed in the system, the FHV valve is located as close to the hydraulic pumps as existing vehicle hardware would permit in order to reduce the amount and length of tubes connecting between the FHV valve and the pump. The low pressure RP-1 connection to the FHV valve is self bleeding with the vehicle erected in the vertical position.

FLIGHT EXPERIENCE

The inflight performance of the hydraulic systems is monitored by low pressure (return) and high pressure transducers via telemetry. Any gross leak manifestation would be revealed by a pressure loss.

To date, 14 vehicles or 28 valves have been flown. All valves have activated properly and all hydraulic system functions were satisfactory. We have experienced no gross hydraulic system leaks during inflight operation.

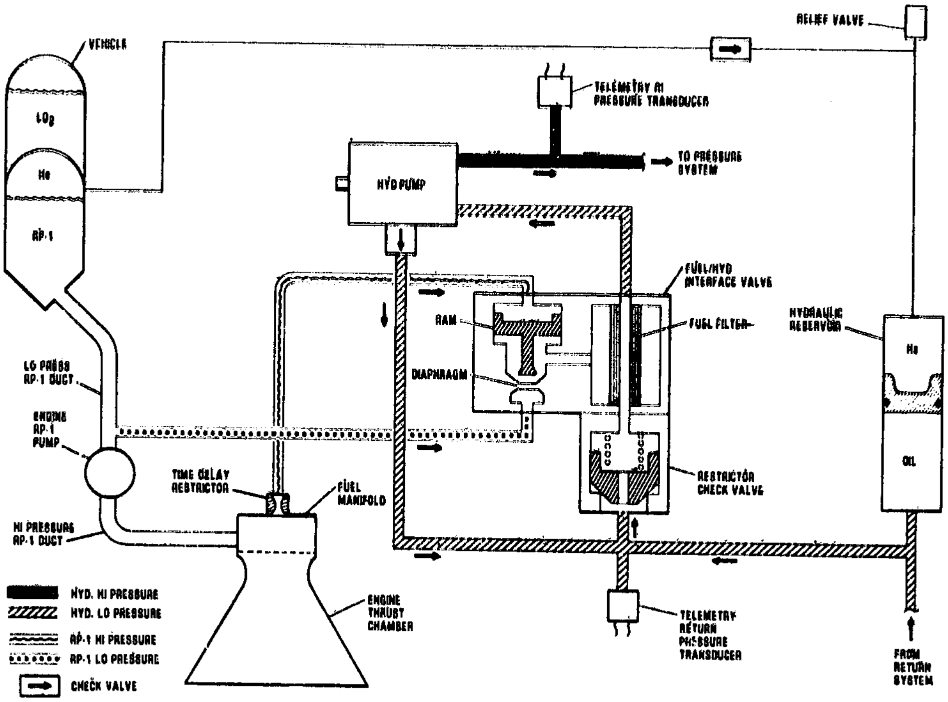

Figure 1.- System schematic with FHV valve.

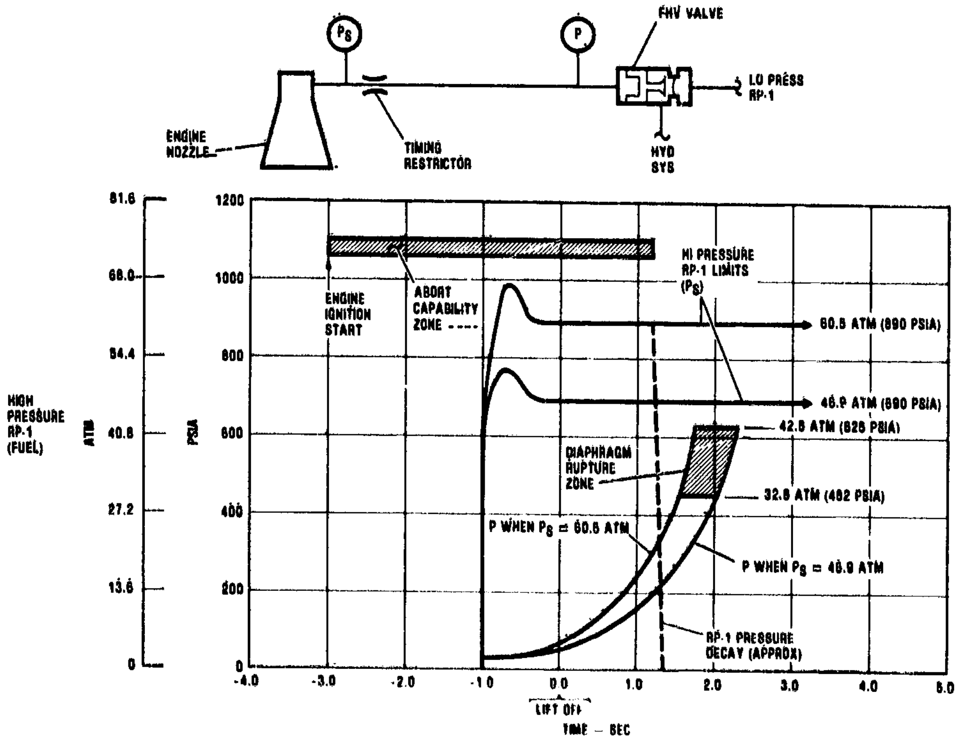

Figure 2.- FHV valve timing curve.

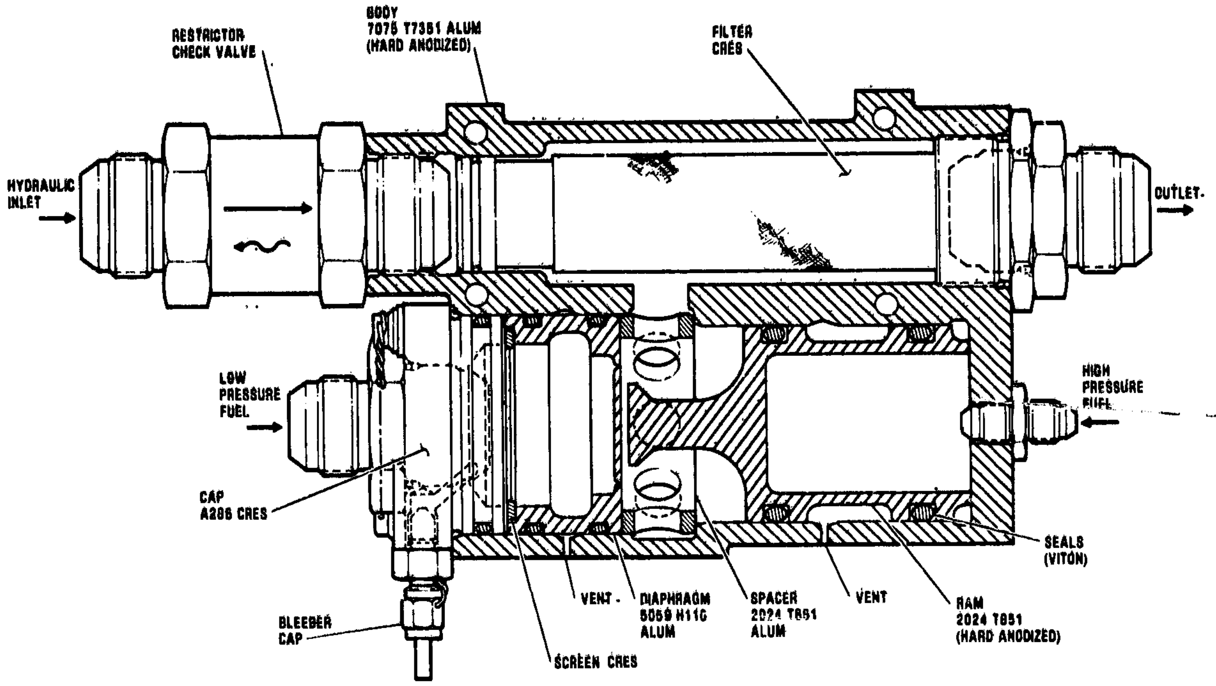

Figure 3.- FHV design details.