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EVALUATION OF
SELF-SEALING BREAKAWAY VALVES
FOR
CRASHWORTHY AIRCRAFT FUEL SYSTEMS

By

Bruce Anson

November 1971

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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DYNAMIC SCIENCE ENGINEERING OPERATIONS
A DIVISION OF MARSHALL INDUSTRIES
PHOENIX, ARIZONA

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~~The~~ program was aimed at improving the component performance characteristics of breakaway valves used to eliminate fuel spillage and subsequent fire in otherwise survivable aircraft crashes. It consisted of an initial study and literature survey to establish the state of the art followed by two series of static and dynamic tests of various types of valves to define problem areas and to verify that the problems had been corrected. An analysis to correct the indicated deficiencies was accomplished between the two test phases. The results of all the work were then collated into a draft military specification. Implementation of this specification in future procurements should provide a significant increase in operability and reliability compared to designs which are currently being produced.

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This report was prepared by Dynamic Science (The AvSER Facility), a Division of Marshall Industries, under the terms of Contract DAAJ02-70-C-0038. The technical monitor for this program was Mr. H. W. Holland of the Safety and Survivability Division.

The purpose of this effort was to conduct the necessary testing and evaluation of breakaway, self-sealing valves to define the essential physical constraints, functional characteristics, and tests required to qualify a crashworthy, breakaway, self-sealing valve. Several different breakaway, self-sealing valve designs were tested both statically and dynamically under various separation modes (tension, shear, bending) to determine the loads required for separation, nature of separation, general valve functioning, and leakage following valve actuation. In addition, environmental tests were conducted to determine the effects on the self-sealing capability of the valves. Test requirements and performance criteria to improve the self-sealing capability of valves upon separation were established from this program; however, breakaway design loads to establish crashworthy requirements were not established.

The conclusions and recommendations submitted by the contractor are considered to be valid; however, they apply only to the sealing function of the valve and not to breakaway design loads. Research and development will be continued in an effort to optimize and further develop crashworthy, breakaway, self-sealing valves for use in Army aircraft.

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INTRODUCTION

Through its support of the crash-safety program of the Eustis Directorate of the U. S. Army Air Mobility Research and Development Laboratory (USAAMRDL), Dynamic Science has acquired a considerable amount of experience in the postcrash fire prevention field. Full-scale aircraft testing and system performance evaluations commenced in 1961 and have continued for the last 10 years. When helicopter crash statistics showed that a great many survivable crashes resulted in fatalities due to postcrash fires, a concentrated program was undertaken to reduce the incidence of postcrash fires.

As the program progressed, it became apparent that the problem of postcrash fires could be attacked from four different directions:

- Containment of fuel upon impact
- Control of ignition sources
- Modification of fuel properties to reduce the possibility of igniting the spilled fuel
- Provision of increased escape time from the aircraft by such methods as improved fire insulation

A key element in the implementation of the first approach was the development of a self-sealing breakaway valve which would automatically actuate on impact, thus isolating the fuel in the various fuel system components. Initial work on the development of breakaway valves began in 1967 under Contract DAAJ02-67-C-0004. At that time, help was solicited from various manufacturers and engineering concerns in a search for valves which could separate in various modes, including axial and direct shear. The initial objective was to find valves that, when installed as cell-to-cell interconnects, would prevent spillage if the tanks were separated. Several firms contributed candidate valves that were installed in a simulated cell-to-cell mounting and loaded under simulated crash conditions. The tests proved the feasibility of using breakaway valves. Unfortunately, all of these prototype valves were complicated and somewhat costly, a fact that weighed heavily against the use of a cell-to-cell breakaway valve in the UH-1D/H helicopter retrofit program.

Despite the emphasis on cell-to-cell breakaway valves in 1967, a study of the fuel systems represented in the Army aircraft inventory showed the greatest need was not for cell-to-cell breakaways but for cell-to-line and line-to-line fittings.

In 1969, under Contracts DAAJ02-67-C-0004* and DAAJ02-69-C-0030**, a preliminary design effort on the UH-1A helicopter brought about an extensive test and evaluation of breakaway valves for specific use in cell-to-line and line-to-line applications. Several manufacturers participated in this competition, supplying valves that were tested under dynamic conditions. Certain improvements were made in Dynamic Science test techniques to include wet tests with the valves pressurized to 5 psi.

The test results indicated that a more thorough test series would be necessary to assure definite and satisfactory valve function under some environmental conditions not covered in this series. However, the breakaway valves became part of the first fuel containment system to be installed in flying aircraft. The UH-1D/H helicopter was selected, and recent information obtained from postcrash data has shown the system to be functioning better than initial predictions.

Figure 1 shows the modified fuel system which uses such special features as crash-resistant fuel tanks and frangible fuel fitting attachments as well as breakaway self-sealing valves. As shown, the breakaway valves are placed at any point in the system where a large displacement between one component and another might occur. In a crash, these breakaway valves will separate and seal, preventing any damage to adjacent components of the system and thereby preventing any external leakage.

In order to further develop the requirements necessary to assure proper breakaway valve functioning under all conditions, USAAMRDL issued the present contract, DAAJ02-70-C-0038. The major objective of this contract is to specifically define the requirements associated with the design of a crashworthy self-sealing breakaway valve through an extensive test program. The defined requirements are then to be assembled in a draft military specification which can be used to govern the design of all applications of self-sealing breakaway valves used in aircraft.

The program commenced with a literature survey. This literature survey had as its intended purpose the establishment of

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*S. H. Robertson, "Development of a Crash-Resistant Flammable Fluids System for the UH-1A Helicopter", USAAVLABS Technical Report 68-82, January 1969, AD 688 165.

**R. L. Cook and D. E. Goebel, "Evaluation of the UH-1D/H Crashworthy Fuel System in a Crash Environment", USAAMRDL Technical Report 71-47, November 1971.

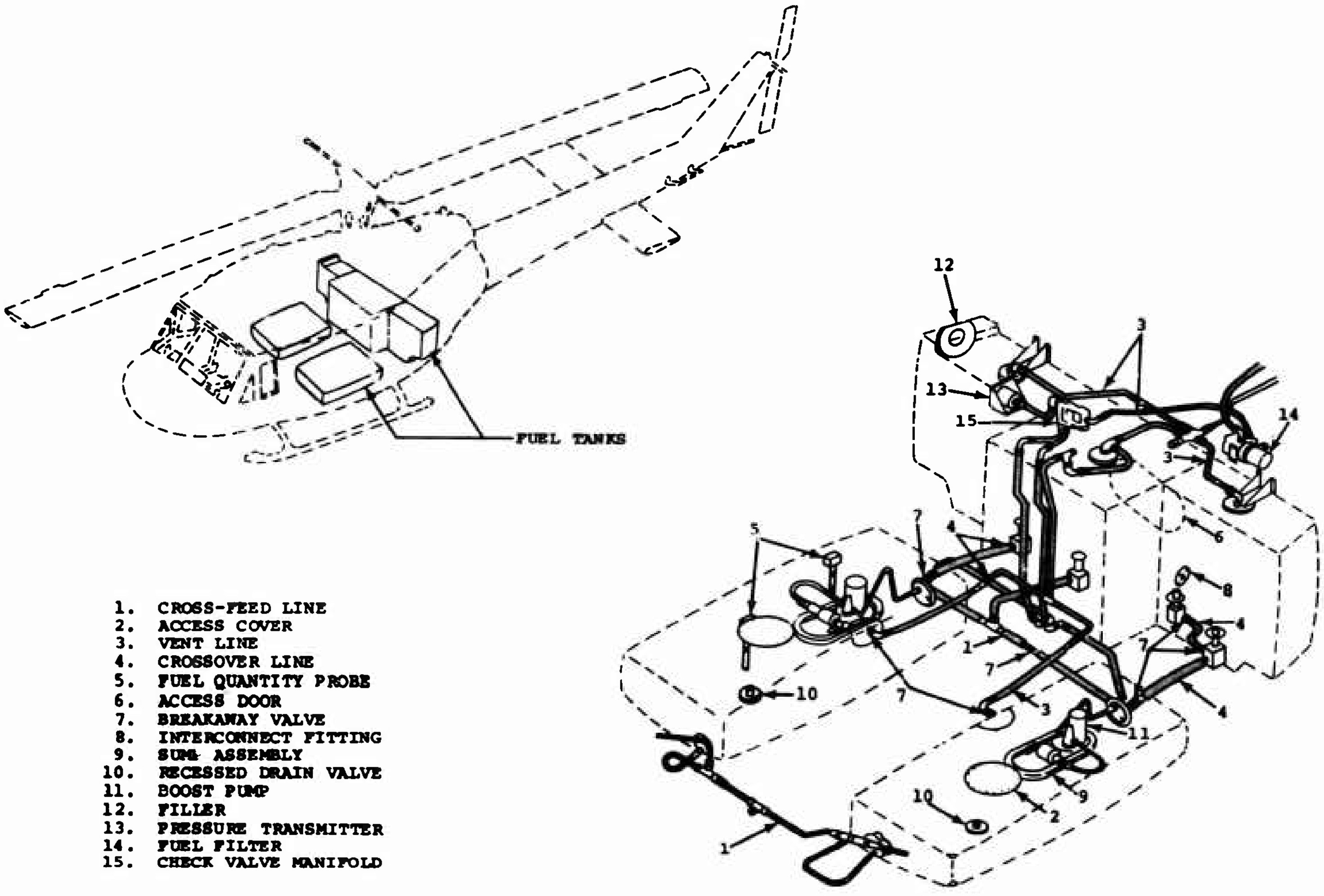

Figure 1. UH-1D/H Crashworthy Fuel Supply System.

the various design approaches which are presently used for breakaway valves. In addition, it was also necessary to determine the availability of these different designs on an expedited basis for immediate testing to be conducted during the program.

The results of the literature survey were less than anticipated. Of the 136 possible valve manufacturers contacted, only one was presently producing breakaway valves. Furthermore, although breakaway valves for several different applications were being produced, the self-sealing mechanism for each of these valves was similar. However, the design of the frangible section was dependent upon the particular application. Two of the three valves initially tested in the program were selected from this manufacturer. A different frangible section design was used on these valves. Of the remaining manufacturers contacted, only one had development hardware available for testing. The self-sealing mechanism of the valve was of a different design concept, and, therefore, while not meeting the initial requirements for "production" status, it was selected.

The first test phase included three major test series: static tests, dynamic tests, and environmental tests. The major objective of the static tests was to determine the load required to separate the valve, the displacement required to actuate the self-sealing mechanism, and the effect of a partial separation condition on the performance of the valves. To accomplish these goals, the valves were installed in specially designed test fixtures and placed in a tensile test machine. The separation loads were recorded through the use of load cells and an oscillograph. The separation distances were also recorded coincidentally. The partial separation condition was created by controlling the application of load through the machine. At appropriate separation distances during each test, the load application was stopped and observations of the partial separation condition of the valve were made. Where conditions of external leakage occurred due to separation of the valve body prior to sealing of the self-sealing mechanisms, photographs were taken for documentation.

The results of the first series of static tests indicated two major problem areas. First, the present designs require relatively long distances between the two separating valve halves before the self-sealing mechanism is actuated. With the designs tested, this separation distance was sufficient to expose great areas of the sealing boot to damage from an outside source. In one case the boot actually broke before the self-sealing mechanism actuated, causing unrestricted external leakage. One of the valve designs tested also showed that, under certain partial separation conditions, it was possible to contain parts of the self-sealing mechanism between the two separating valve halves, which had the overall effect of increasing the separation distance. In this particular case, external leakage also occurred. The second problem area concerned the design of the frangible section and the relationship between the three forces required to cause separation. As an example, one of the three valves exhibited a shear force of approximately five times the tension force required to separate the same valve. Also, only two of the three valves tested were designed to separate under any of the three potential forces being applied: shear, tension, or bending. A study of all of the results showed that the forces required to cause separation in each of these three modes for all the various valves varied considerably. As a result, the valves as presently designed have a very restricted anticipated failure mode.

The dynamic tests were designed so that all valves were subjected to separation at a velocity of 65 ±5 fps. These velocities were attained by use of a 60-foot drop tower and a horizontal sled test track. Each valve selected was tested separately in shear, tension, and bending modes. The velocity of the sled which was used to impart the dynamic load was measured just prior to impact, and high-speed photographs were taken of the valve separations. The results of these tests were most informative. All the valves were subjected to the same loads under both dynamic and static conditions. However, the tests showed that in many cases the valve's operation was different under the two test conditions. The greatest percentage of failure occurred because the time required for the dynamics of the self-sealing mechanism to actuate was greater than the time required for dynamic separation of the two valve halves. When this condition occurred, the result was damage to part of the self-sealing mechanism, which caused improper valve functioning upon complete separation. In all cases this malfunction resulted in at least one-half of the separated valve's remaining in the open position, thereby creating unrestricted external fuel flow.

The environmental tests -- contaminated fuel and cold weather -- conducted on the initial test valves completed the first test series. The purpose of the contaminated fuel tests was to determine the susceptibility of a valve which had been in service for a long period of time to contamination by dirt buildup within the valve, sufficient to impair the valve's correct functioning under crash conditions. The three valve test specimens were subjected independently to circulation of contaminated fuel. Upon completion of the fuel circulation, each valve was tested in the same manner as in the static test series. One of the three valves subjected to the contaminated static tests failed to operate correctly upon complete valve separation. These results indicated that it was possible for contamination to build up in a self-sealing mechanism and prevent actuation of the self-sealing mechanism upon valve separation.

The cold weather tests investigated the possibility that water trapped in the valve over a given period of service might freeze and prevent proper functioning of the self-sealing mechanism. To simulate this condition, the valve was installed in the test system and water was passed through it. Fuel was then circulated through the valve at 0°F long enough to freeze any water that might have been trapped in the valve. Then, keeping the temperature of the valve below 20°F, the valve was subjected to a static test. The results from the two valves subjected to this test showed that ice which formed in the self-sealing mechanism did, in fact, delay the closing of the valve after complete separation, thus indicating that careful consideration must be given in the design of the breakaway valve to eliminating the possibility of any water traps within the valve.

When the first test phase was completed, the test data were carefully analyzed. Major deficiencies discovered in the valves tested were discussed with respective manufacturers. At this time, possible fixes were discussed, and both participating manufacturers agreed to supply new development valves. Also in this period, the valve manufacturers who expressed a desire to contribute development hardware to the second test phase were contacted. Despite the optimism of several manufacturers, only one new manufacturer was willing and/or able to present hardware in the required period of time.

The second test phase consisted of static and dynamic testing of the development valves of the new manufacturer as well as the modified designs of the two original manufacturers. Since the major deficiencies of the valves tested during the first phase occurred mainly in the dynamic test series, the resubmitted development valves of the same basic design used in the first test phase were subjected only to dynamic tests. Both static and dynamic tests were conducted on the new design. Test results on the newly developed design indicated that some of the overall basic deficiencies inherent with the breakaway valve could be overcome by the use of different design techniques.

The information collected throughout the test program was then compiled and used to prepare a draft military specification.

This specification was written in such a manner as to eliminate the design deficiencies of the presently produced valves and incorporate all the requirements discovered to be necessary. As a result of this program and in conjunction with other past experience obtained by Dynamic Science, the specification contained many requirements for breakaway valves which heretofore have not been included. Areas such as load determination, separation distance to actuate the self-sealing mechanism, specific contamination and icing tests, and required proportional limits of the actuation forces are some of the major areas of concern which are covered in the new specification.

PROGRAM RESULTS

LITERATURE SEARCH

The literature survey was conducted in three major directions. The first direction was a brief review of the work previously performed under Contract DAAJ02-67-C-0004 for the UH-1 series helicopters pertaining to self-sealing breakaway valves. The second area of the search centered upon a survey of the Defense Documentation Center for any information pertaining to self-sealing breakaway valves. The only response to this search was two documents involving quick-disconnect fittings. The third major area of the literature search was a survey of the industry. A letter was drafted and sent to 136 possible valve manufacturers requesting complete literature, drawings, prices, and delivery dates on their self-sealing breakaway valves. Only 73 of the 136 firms responded to the letters sent them requesting this information. The majority of the responses were to the effect that they did not produce any valves that presently met the requirements of self-sealing breakaway valves. The results of this literature survey showed that only two companies were capable at that time of supplying hardware for the test phase of the program. Of these two, only one manufacturer had actual production breakaway self-sealing valves available for testing. The second manufacturer had breakaway valves under development and was able to supply development-type valves for the test phase of the program on very short notice. Three of the remaining 73 manufacturers indicated active development programs in this area, but at that time had no workable valves. Each promised continued support throughout the program and pledged the availability of prototype hardware to be used on the second phase of the program.

As a result of this literature search, three valves were selected to be used in the first test phase of the program. Valves 1 and 2, shown respectively in Figures 2 and 3, were supplied by the only production manufacturer, hereinafter referred to as Manufacturer A. Figure 4 is a drawing of Valve 3, a prototype development valve supplied by Manufacturer B. As can be seen in Figures 2 and 3, the self-sealing mechanism of the valves is essentially the same. However, since the design of the frangible section differs, testing of both designs provided a direct comparison of the effects of this variable. Manufacturer B's design, Figure 4, incorporates a different design principle for the self-sealing mechanism as well as the frangible section. The survey of valves under development or in production by both of these manufacturers showed the above selections to be the best variation attainable within the nearly "off-the-shelf" procurement ground rule.

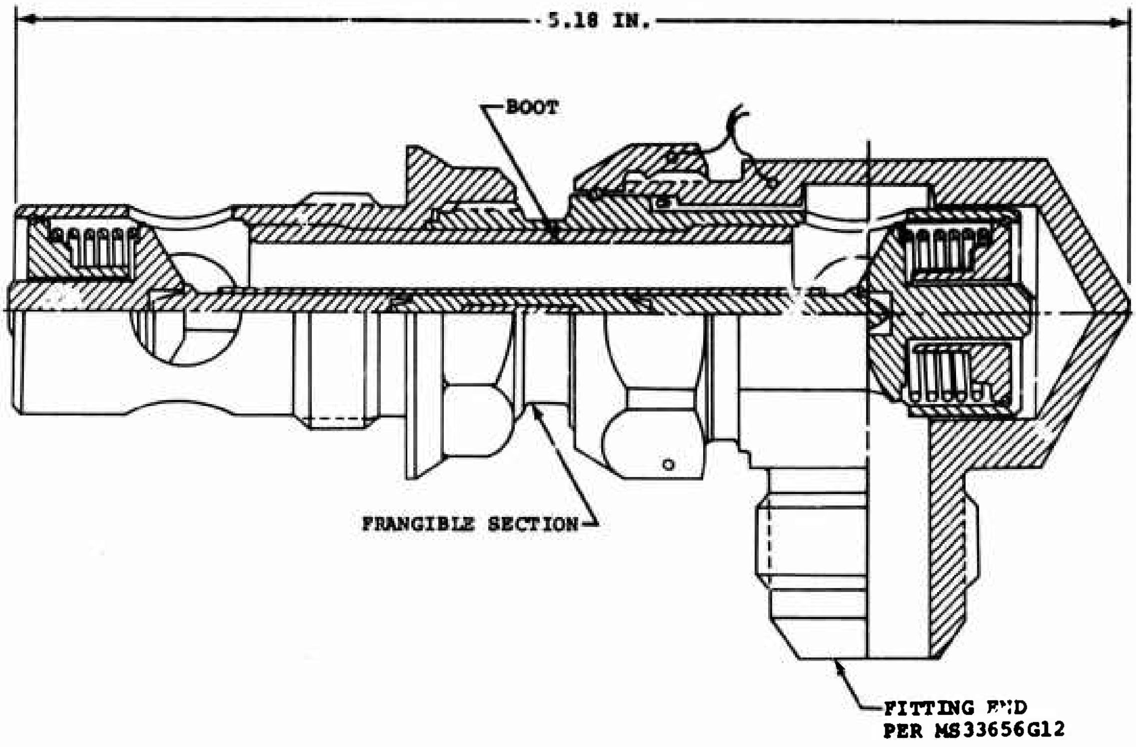

Figure 2. Cell-to-Line Valve Design (Valve 1).

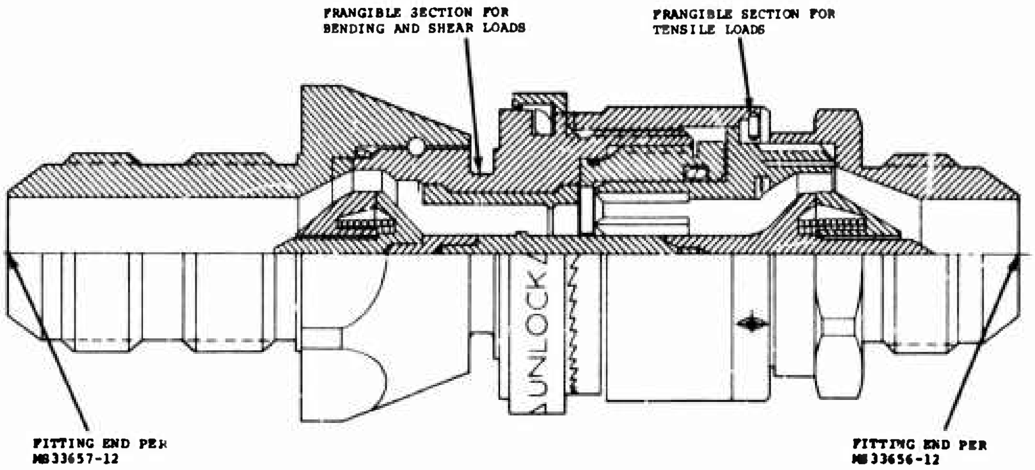

Figure 3. Bulkhead Valve With Quick Disconnect (Valve 2).

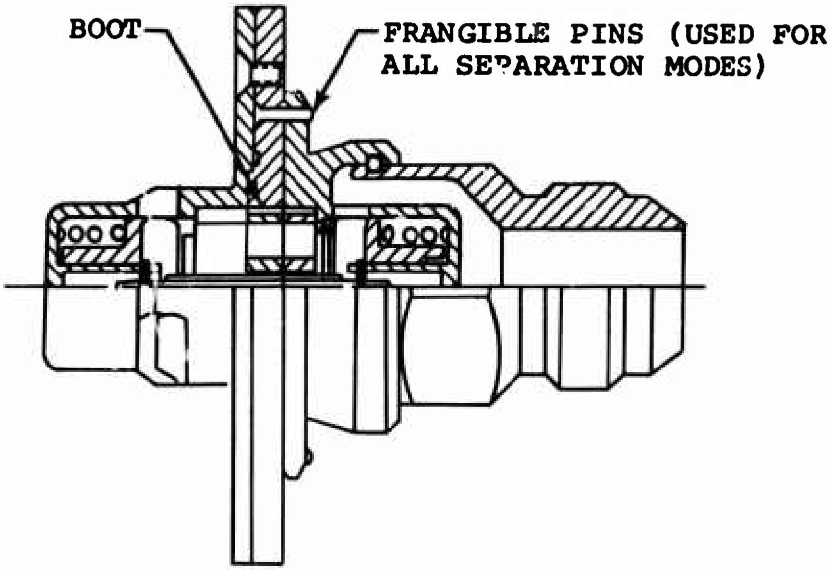

Figure 4. Cell-to-Line Valve Design (Valve 3).

FIRST TEST PHASE

The first test phase was divided into three major test sections: static tests, dynamic tests, and environmental tests. In the static tests, major interest was placed on evaluation of the functional characteristics of the self-sealing breakaway valves. This was accomplished by determining the loads required for separation, the nature of the separation, leakage during valve separation, and general valve functioning and leakage following valve actuation. Any other pertinent behavior shown by the valves during these tests was also noted.

Test Hardware Description

Three 3/4-inch line size valves were selected for the test. By maintaining the same line size for all test valves, the separation load obtained for each design of the frangible sections was more comparable.

Valve 1 (Figure 2), produced by Manufacturer A, was designed as a drain valve to be inserted in the fiberlock fitting in the bottom of the fuel tank. The valve body forms a 90-degree angle with a standard MS fuel line hose fitting on the outlet side. The self-sealing mechanism consists of two spring-loaded poppets which are held in the open position through the use of a multipiece rod which passes through the frangible section of the valve. As the valve is subjected to a crash load and separates, the rod distorts, collapses in column failure, and releases the spring-loaded poppets. The resultant closing of the poppets prevents fuel loss from either half of the separated valve assembly. The frangible section which joins the two major halves of the valve can be represented as a thin tube. By controlling the wall thickness of this tube, loads in tension and bending can be carefully controlled. Also, this section is capable of breaking in shear when impacted by a somewhat larger force.

Valve 2, illustrated in Figure 3, was also produced by Manufacturer A. The design of the self-sealing mechanism for this valve is very similar to that of Valve 1, but the frangible section design varies somewhat. This valve is designed to be attached to a structure such as a firewall. The valve incorporates a quick-disconnect coupling which adds to its length. To obtain the proper tension and bending actuation forces, it was necessary to install two frangible sections in this valve. The section which breaks under the bending load is similar to the valve shown in Figure 2. To reduce the tensile load to the proper value, three shear pins are installed in the quick-disconnect fitting. By using this combination of frangible sections, the desired separation properties for this valve were met.

Valve 3 is shown in Figure 4. While this valve is designed to operate under conditions similar to those of Valve 1, it incorporates a different frangible section as well as a different design of the self-sealing mechanisms. Figure 4 shows that the frangible section is made up of two flanges held together by several rivets. The self-sealing poppets, which are located in each valve half, are spring loaded in the closed direction. However, these poppets are held in the open position by a small pin in each valve half. These pins are connected by a cable device, which, upon valve separation, bends the pins and allows the poppets to close. Upon further relative motion of the valve halves, the cable snaps, allowing complete separation of the valve halves.

Static Test Methodology

The actual static testing of the selected valves required separation due to tension, shear, and bending loads. To acquire the necessary information throughout these tests, instrumentation consisted of strain-gage type load cells for measuring the load, a linear potentiometer for measuring the displacement of the two valve halves relative to each other, a pressure gage for determining the fluid pressure in the valve at the time of separation, and photographic coverage to record information pertinent to the valve's operation. The load cell readings and the linear potentiometer readings were recorded permanently on an oscillograph.

During all static tests, both halves of the valve were pressurized to 50 psi. Prior to the beginning of each static test, the valves were carefully bled of all air to assure that, if a small leak occurred during separation, it would not go undetected. This was accomplished by alternately opening Main Valve A and bleeding through Bleed Valve B (Figure 5), and then reversing the flow by opening Main Valve B and Bleed Valve A until bubble-free liquid was obtained. Also, the fluid pressurization system was used to determine the point at which poppet actuation occurred in the valves. This was accomplished by maintaining a trickle flow through the valve during the separation process (by opening Main Valve A and Bleed Valve B in Figure 5, for example). When the valve actuated, this flow ceased. At this point, Bleed Valve B was closed and Main Valve B was opened. Separation was continued until the valve's integrity was destroyed (i.e., the seal or "boot" was ruptured). If any sustained flow was observed at separation, the two main valves were closed in turn to isolate the leaking/malfunctioned poppet. In the cases where the valve malfunctioned by separating prior to poppet actuation, the gross amount of liquid leakage graphically demonstrated the failure.

All static tests were conducted in a tensile test machine. Due to the design of this machine, the test fixtures used to transmit the bending, tension, and shear loads into the test valves required special design. Careful attention was paid to assuring that the load introduced by the machine was applied on the same axis as the load cell was installed. This assured that no bending moments were introduced which would reduce the accuracy of the load ratings. The fixtures were also designed, as previously mentioned, to carry pressure to both valve halves. A schematic of a typical tensile test setup is shown in Figure 6. The tensile load was applied through the crosshead of the tensile machine, which was moved at a rate of 0.2 inch per minute in the direction directly opposing the load cell. The cross-feed motion of the tensile machine was continued until the valve body had fractured and actuation of the self-sealing mechanisms had occurred. If external leakage occurred at some point prior to valve actuation, the cross-feed motion of the tensile machine was stopped and documentary photographs were taken. Motion was again applied to the crosshead until the valve halves separated completely. Following complete separation, the oscillograph traces of valve displacement and separation load were processed and analyzed.

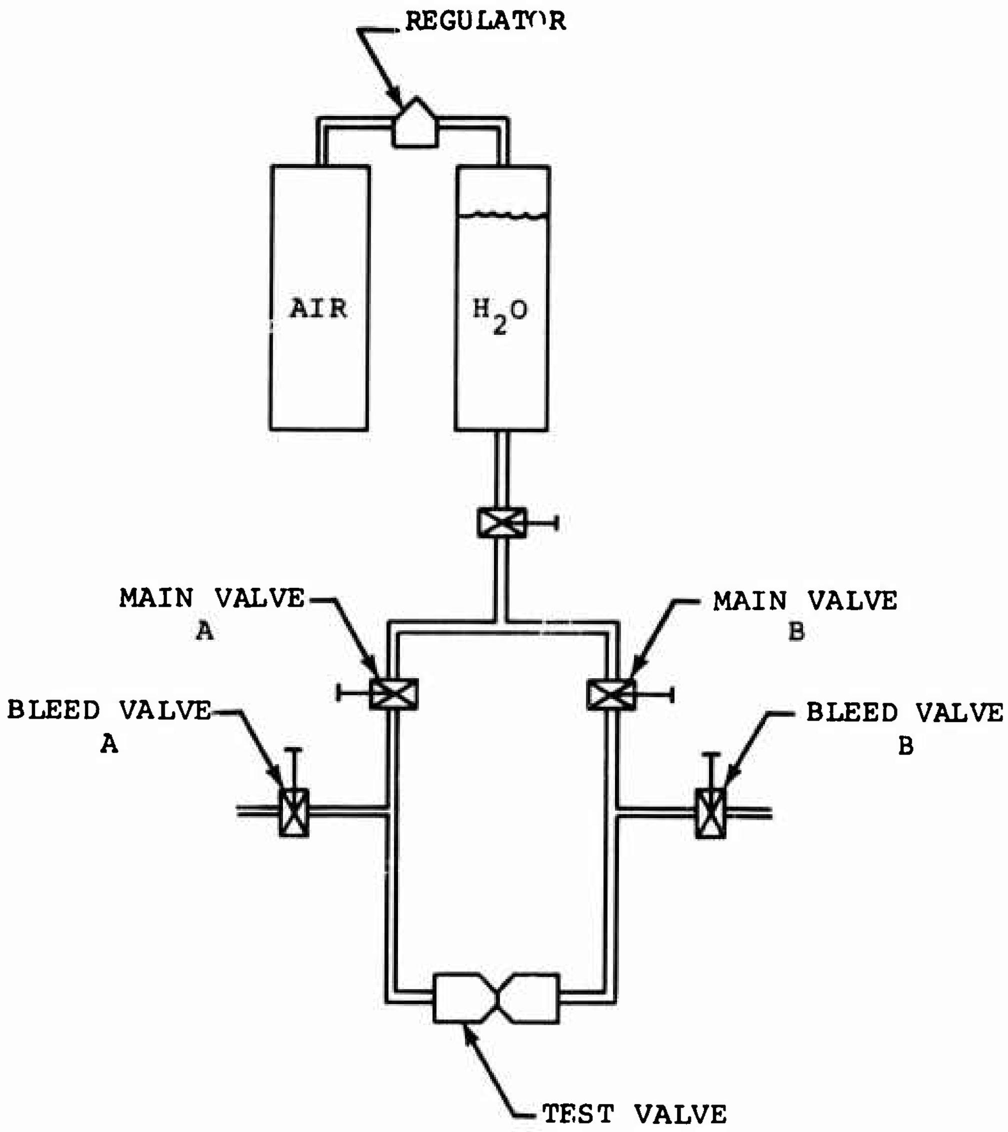

Figure 5. Pressurization/Flow System Used During Static and Dynamic Testing.

Figure 7 shows a sketch of a typical installation of the breakaway valve in the tensile machine for a shear test. As can be seen from the figure, the relationship of the input force to the load cell is the same as that in the tensile test, but the test fixture was designed to transmit a shear load into the frangible section of the breakaway valve. The operation of the tensile machine throughout the test sequence was the same as that established for the tensile test.

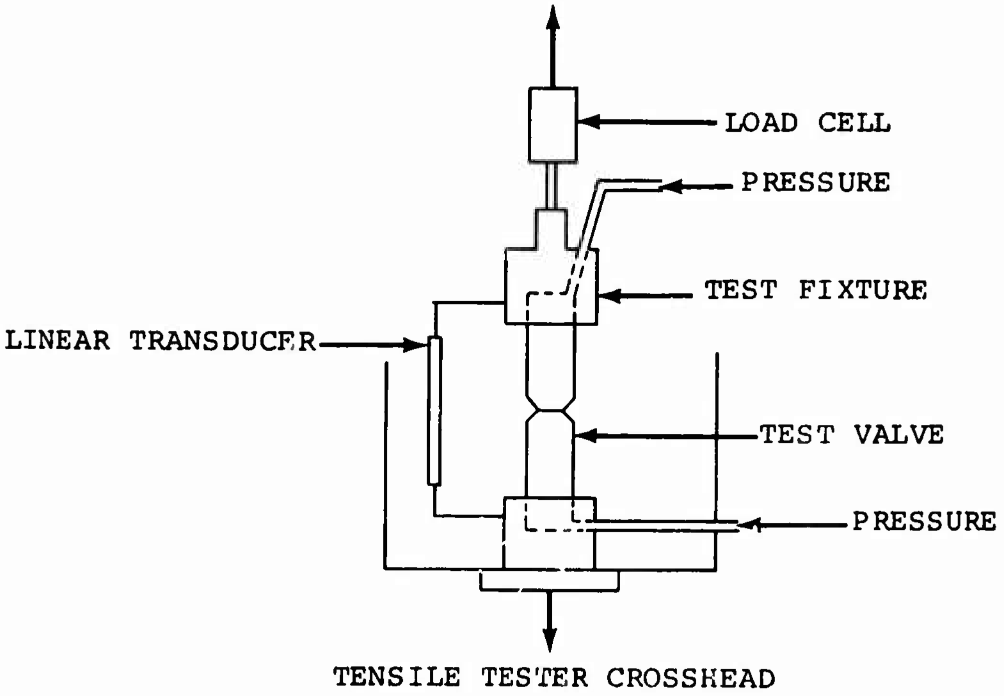

Figure 6. Tensile Tests.

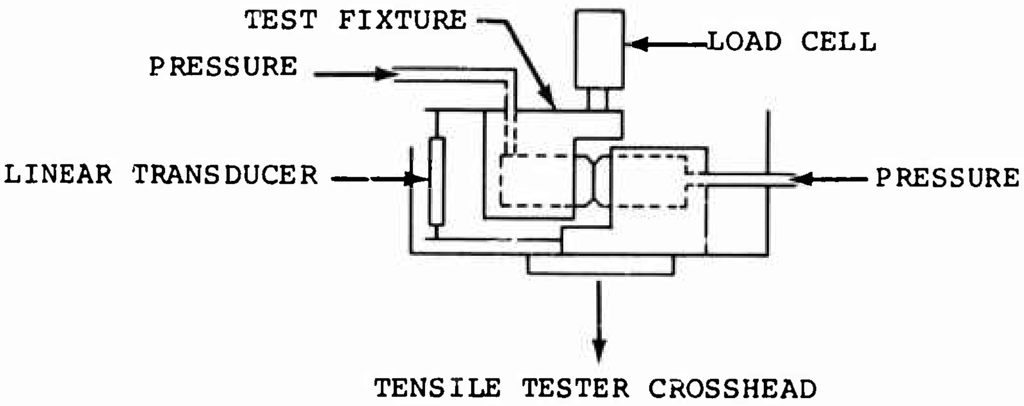

Figure 7. Shear Tests.

Figure 8 is a test schematic of a breakaway valve being subjected to a bending load in the frangible section by use of the tensile machine. As in the two previous test schematics, the load cell and the input force from the tensile crosshead were along the same axis. The test fixture was designed not only to introduce a bending moment into the frangible section of the valve, but to simulate the moment arm that would be present if the valve was being pulled on by a flexible hose at 90 degrees to the valve centerline. A 2.875-inch moment arm, simulating a 3/4-inch flexible hose, was used for all bending tests. This was possible since all the valves selected for this test program were 3/4-inch line size.

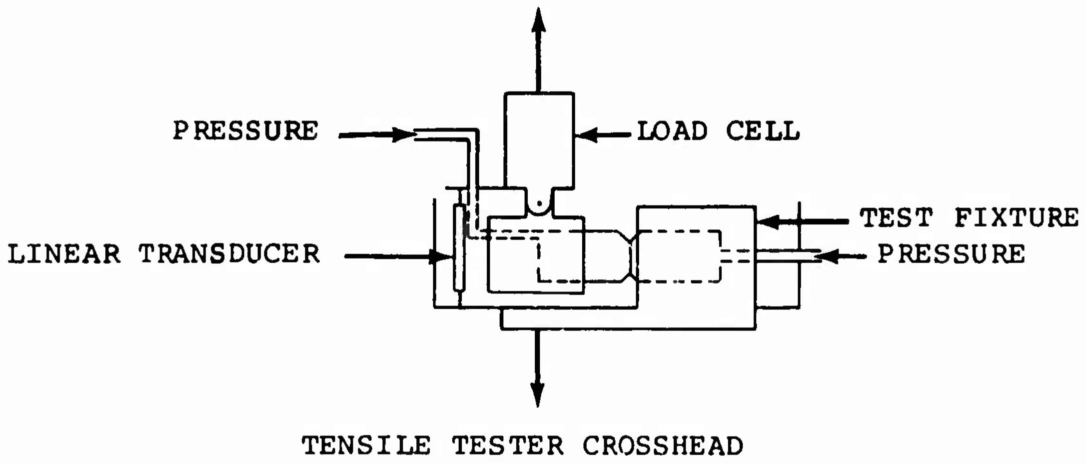

Figure 8. Bending Tests.

In Figures 9, 10, and 11, photographs are presented to show some of the actual setups of the tensile, shear, and bending tests, respectively. Part of the fabricated test hardware included a clear Plexiglas cover over the test item and test fixtures. This permitted close test observation and good photographic coverage even during periods of extreme external leakage.

Static Test Results

Since all three valves were tested separately for the required forces to produce separation in bending, shear, and tension, nine static tests were conducted in the first phase of the

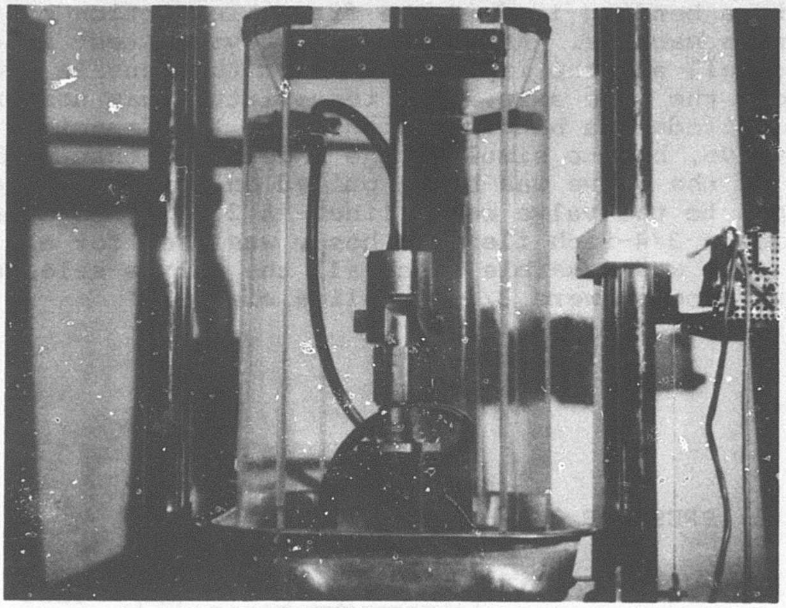

Figure 9. Typical Tensile Static Test Setup (Valve 3).

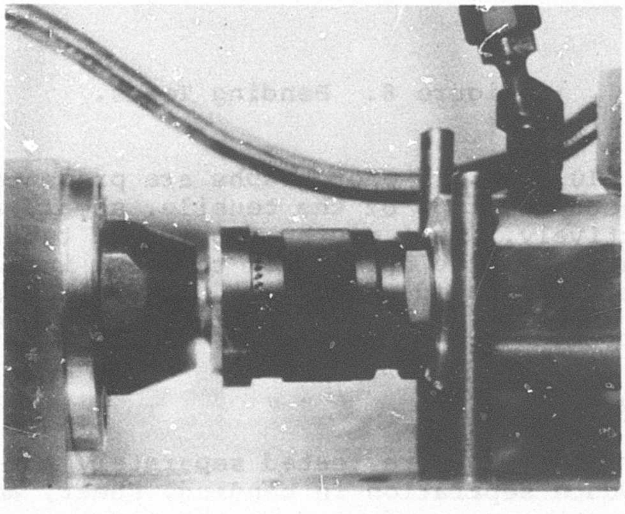

Figure 10. Typical Bending Static Test Setup (Valve 2).

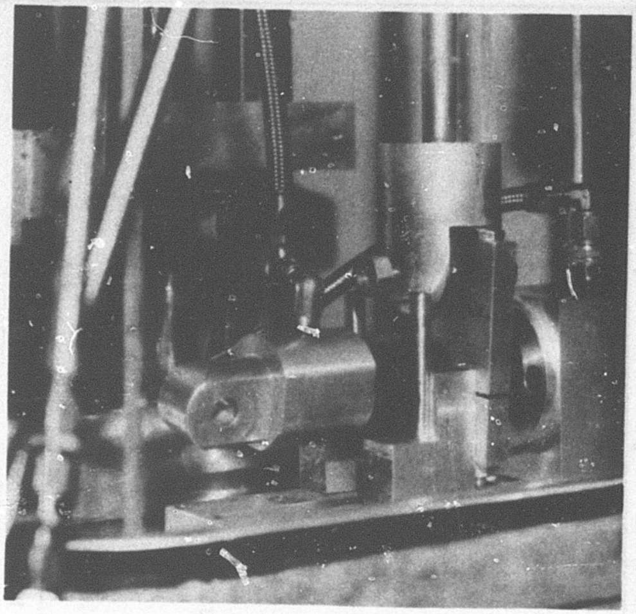

Figure 11. Typical Shear Static Test Setup (Valve 1).

program. The results are summarized in Table I. A discussion of each valve test and its results follows.

Test 1 - Manufacturer A, Valve 1 - Tensile Mode

A tensile load of 4,820 pounds was applied to the valve before fracture occurred. This load is extremely high for a frangible valve of this size. However, with the 90-degree outlet connection, it is unlikely that this type of loading could be obtained in service. The valve was tested in this manner to establish baseline values for comparison with the other tests discussed below as well as to determine the performance potential if an in-line outlet configuration were to be considered for this type of frangible section design.

Following fracture, further displacement of the lower valve half produced a large distortion in the boot with rupture/leakage occurring at .515-inch displacement. The self-sealing poppets required additional displacement of the valve halves to .625 inch before both halves totally sealed. This test illustrates the importance of the relationship between the separation displacement required to actuate the self-sealing

TABLE I. STATIC TEST RESULTS

Test No.	Valve No.	Force Mode	Ultimate Force to Separate (lb)	Axial Displacement of Tensile Machine (in.) For Fracture	For Boot Rupture	For Mechanism Actuation	External Leakage At Valve Body Separation	For Boot Rupture	At Complete Valve Separation
1	1	Tension	4,820	.174	.515	.628	No	Yes*	No
2	1	Shear	800	.218	7.000	.445	No	No	No
3	1	Bending*	600	.100	.381	.420	No	Yes*	No
4	3	Tension	1,030	.064	.668	.252	No	No	No
5	3	Shear	845	.099	1.060	.362	No	No	No
6	3	Bending**	200	.242	2.120	.833	No	No	No
7	2	Tension	750	.100	****	.510	No	No	No
8	2	Shear	3,850	.235	.490	.725	No	Yes*	No
9	2	Bending**	1,325	.595	2.840	3.200	No	Yes*	No
10***	4	Tension	364	.010	****	.015	Yes	NA	No
11***	4	Bending	270	.095	****	.325	Yes	NA	No
12***	4	Shear	1,225	.020	****	.040	Yes	NA	No

*Leakage due to unrestricted flow as a result of the self-sealing mechanism remaining in the open position and the external seal (boot) rupturing.

**See Figure 18 for definition of axial displacement in bending.

***These tests were conducted during the second test phase.

****An O-ring seal accomplished sealing in the tension mode for this valve.

mechanism within the valves and the structural integrity of the boot in valves of this design. No leakage existed in either half after actuation.

Test 2 - Manufacturer A, Valve 1 - Shear Mode

An 800-pound shear load was required before fracture occurred. Throughout the continuing displacement of the valve halves, during which the self-sealing mechanism was actuated and total separation was completed, the valve functioned satisfactorily. The poppets actuated at a small enough displacement of the separated valve halves that no pressure distortion was noted in the boot. Only a small amount of spillage took place when the boot ruptured, and no leakage occurred upon total valve separation.

Test 3 - Manufacturer A, Valve 1 - Bending Mode

A 600-pound load was applied to the valve, producing a bending load in the frangible section of the valve. Figure 12 shows the pressure distortion of the boot just before it ruptured.

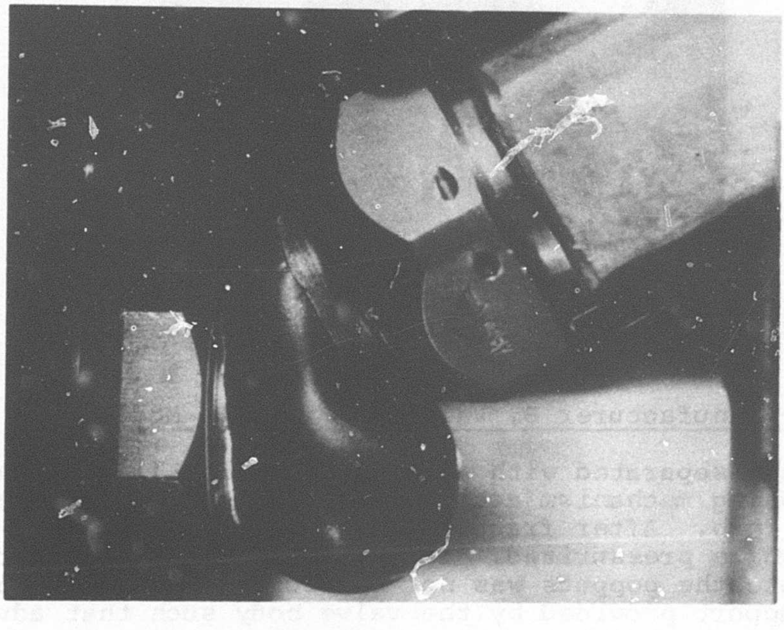

Figure 12. Bending Test, Valve 1, Prior to Boot Rupture.

The boot rupture, which occurred with a vertical displacement of the test machine crosshead of .381 inch, is shown in Figure 13. A further vertical displacement to .421 inch was required to actuate the self-sealing mechanism, after which no leakage was observed. This test illustrates that, under conditions of partial separation similar to those obtained during this test, this design would be inadequate to maintain fuel isolation.

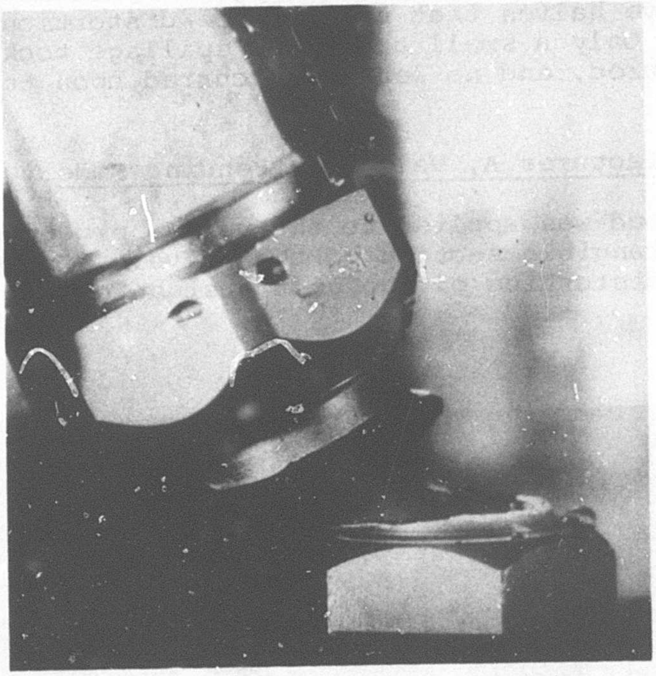

Figure 13. Bending Test, Valve 1, Following Boot Rupture.

Test 4 - Manufacturer B, Valve 3 - Tensile Mode

This valve separated with a tension load of 1,030 pounds. The self-sealing mechanism actuated at a separation displacement of .250 inch. After fracture, the boot was partially unsupported while pressurized. However, the displacement required to actuate the poppets was not sufficient to reduce the structural support provided by the valve body such that adverse effects on the boot were observed. The valve completely parted at a distance of .670 inch, and no leakage was measured from either valve half.

Test 5 - Manufacturer B, Valve 3 - Shear Mode

A shear force of 845 pounds on this valve resulted in separation. Increased displacement of the two valve halves to a distance of .360 inch produced poppet actuation. The relative motion of the two valve halves created by this shear loading did not produce an unsupported condition of the boot following separation and prior to the poppet actuation. The boot itself is susceptible only to being cut by the shearing action of the valve halves, which did not occur. At a distance of 1.06 inches, complete valve separation occurred and no leakage was detectable.

Test 6 - Manufacturer B, Valve 3 - Bending Mode

A 200-pound load was applied to the valve, producing a bending moment in the frangible section of the valve. Figure 14 shows the valve in a partial separation condition just prior to poppet actuation. As can be seen from the photograph, the actual separation displacement, while not large, was sufficient to allow gross distortion of the boot by pressure. The poppets did actuate before the boot ruptured, but it is clearly possible that the boot could be damaged by an outside source under this condition. Posttest examination of the valve halves showed no leakage.

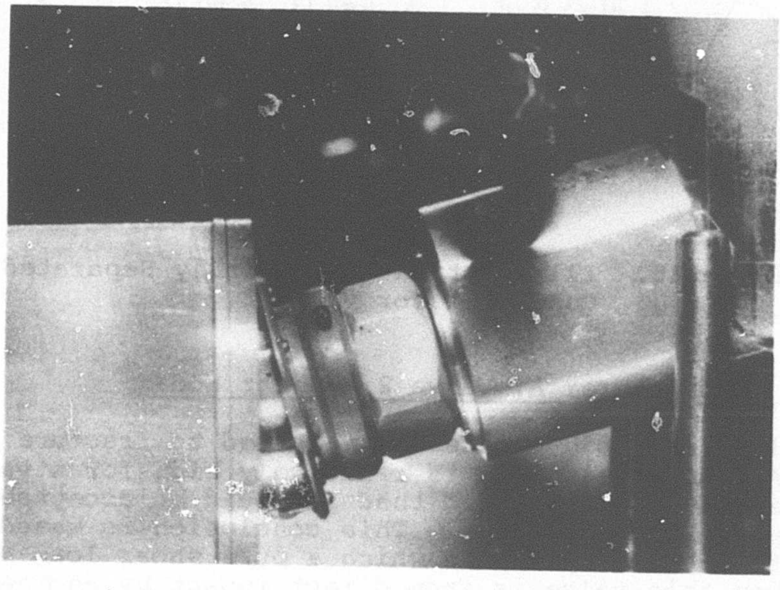

Figure 14. Bending Test, Valve 3.

Test 7 - Manufacturer A, Valve 2 - Tensile Mode

A tensile load of 750 pounds was applied at the frangible section of the valve to effect separation. As can be seen from the valve schematic in Figure 15, sealing is accomplished with an O-ring seal around the cylindrical section of the separating valve half. The valve is designed so that the poppets close before the cylindrical section leaves the O-ring seal. The valve operated as designed, and no leakage was noted. This includes both external leakage during the separation prior to poppet actuation and internal leakage across the poppet seat following actuation.

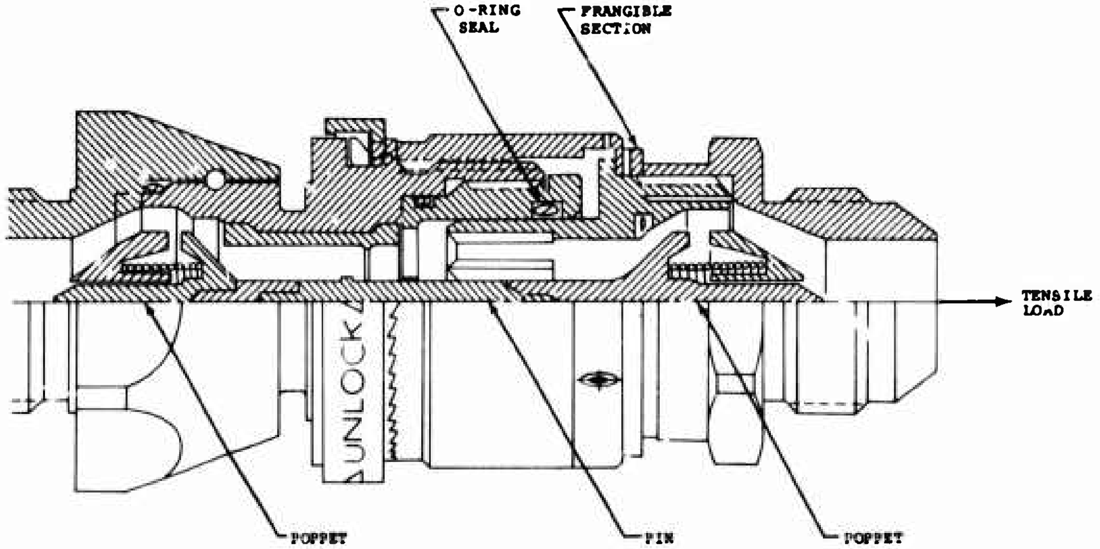

Figure 15. Illustration of Partially Separated Condition for Valve 2.

Test 8 - Manufacturer A, Valve 2 - Shear Mode

A shear load of 3,850 pounds was required to fracture this valve. Although this load is relatively high for a valve of this size, it is anticipated that it would be acceptable under actual operating conditions. This conclusion is based on the premise that the only way in which a pure shear load may be placed upon this valve is from direct impact by another object.

Thus, a shear load of this magnitude would not necessarily be transmitted to the attached fuel system components.

After fracture, the valve halves were separated to a vertical displacement of .490 inch, where the boot ruptured. Because of the boot rupture prior to actuation of the poppets, leakage occurred out of both separated halves (Figure 16) until a displacement of .654 inch was reached, at which point the disconnect half of the valve closed. When a displacement of .725 inch was obtained, the fixed half of the valve closed and no further leakage was observed.

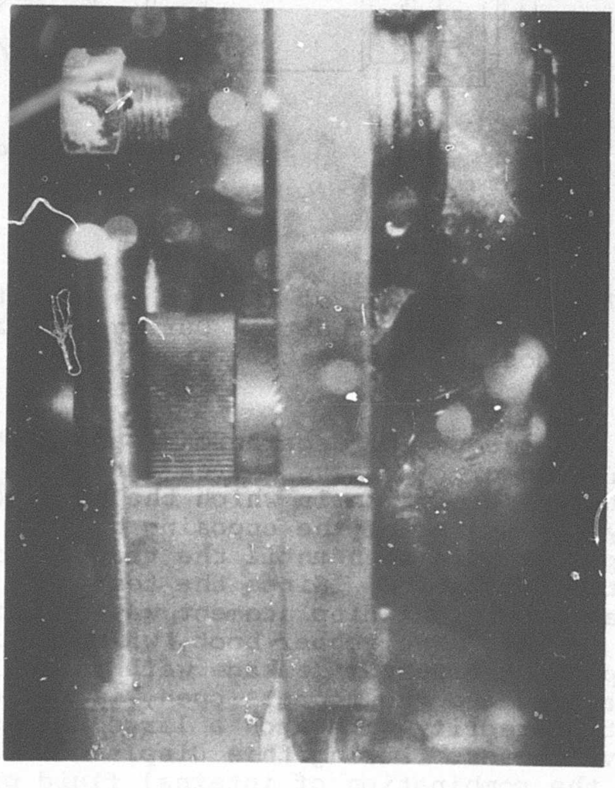

Figure 16. Valve 3 Leaking in Shear Mode Static Test.

Figure 17 illustrates this process schematically. The valve is shown in a partially separated condition produced by the pure shear load. The pin that is used to hold the poppets

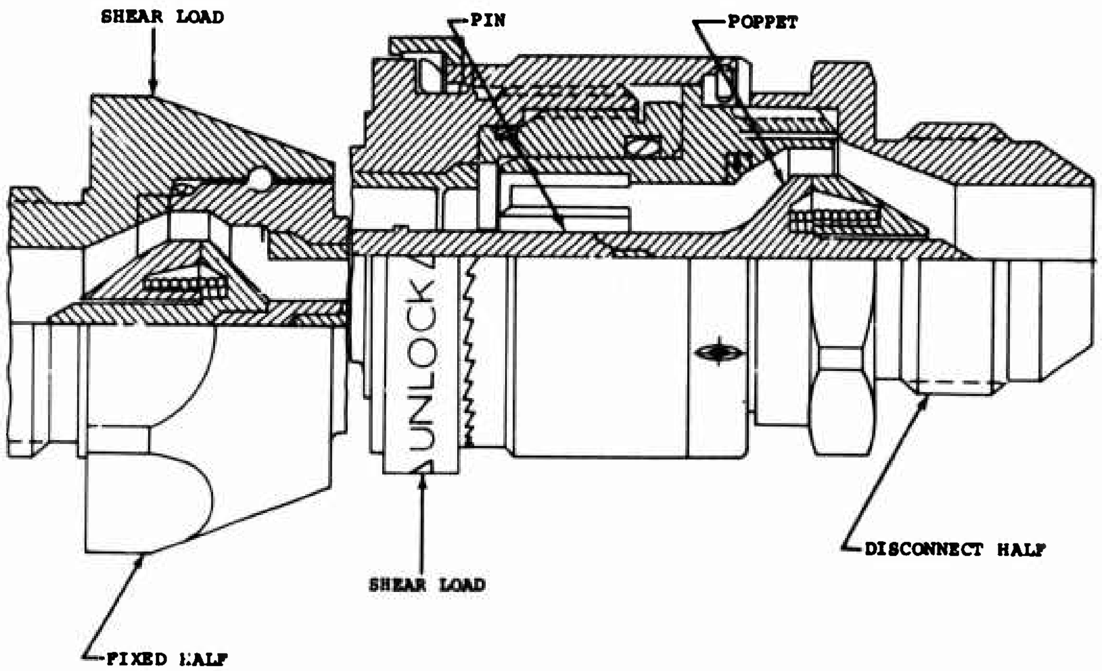

Figure 17. Illustration of Valve 2 in a Partially Separated Condition During a Shear Mode Static Test.

open has been sheared by the separation loads. It can be seen that the separation of the valve halves caused by the shear load has produced a condition in which the sheared pin halves are trapped by the bodies of the opposing halves. As a result, the valve poppets remain open until the trapped pin halves are released due to translation. Since the test used shear loading only, a large vertical displacement was required to release the pin halves. The rubber boot, which is installed in the valve to prevent external leakage with the valve halves partially separated and the poppets open, is not capable of maintaining its integrity with such a large displacement between the valve halves. During this displacement, the boot ruptures from the combination of internal fluid pressure and physical elongation.

Test 9 - Manufacturer A, Valve 2 - Bending Mode

A load of 1,325 pounds was applied to the valve, producing a bending load in the frangible section of the valve. As shown in Figure 18, the vertical displacement was measured at the

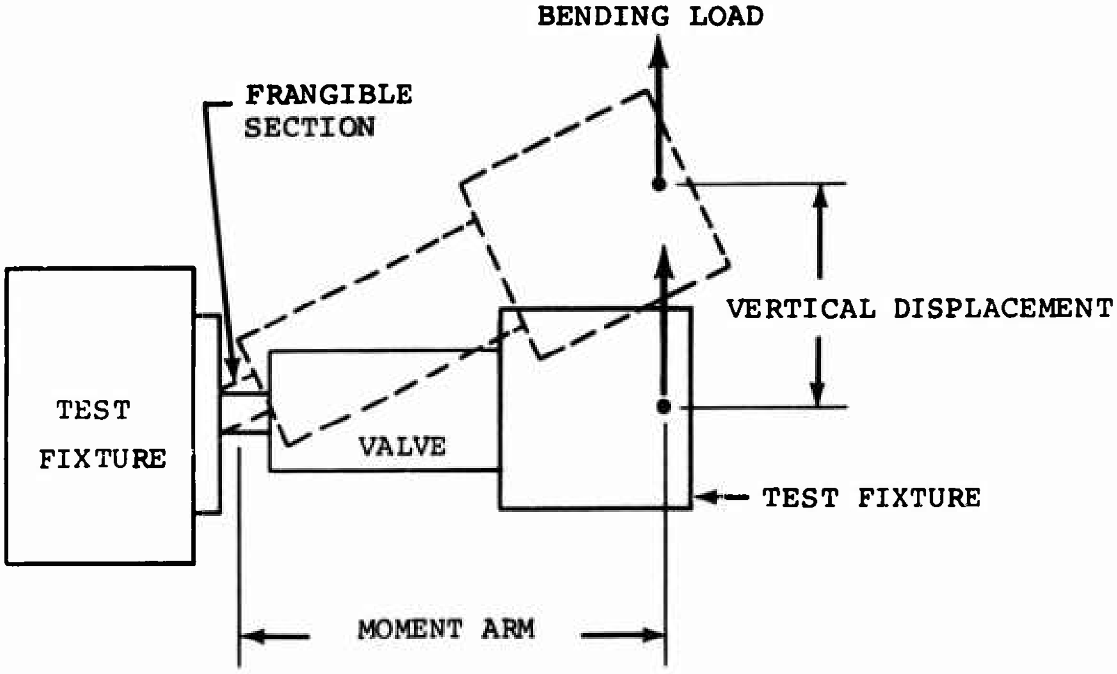

Figure 18. Vertical Displacement Measurement for Bending Tests.

end of the moment arm. This is the same technique used in all bending tests. At a displacement of .590 inch, the fracture commenced in the frangible area. The boot ruptured at 2.840 inches of displacement, allowing fuel to flow from both valve halves, as shown in Figure 19. At a displacement of 3.200 inches, the valve halves completely separated, allowing the pin to fall out and the poppets to close. After the poppets actuated there was no further leakage from either valve half.

Figure 20 illustrates schematically the condition that existed with the valve partially separated and leaking as described above. It can be seen from Figure 19 that the valve did not separate completely in the frangible section. This produced a condition of large displacement at the bottom of the frangible section while maintaining enough structural strength between the valve halves at the top to keep the pin entrapped. When complete fracture occurred, the pin fell out, releasing the poppets.

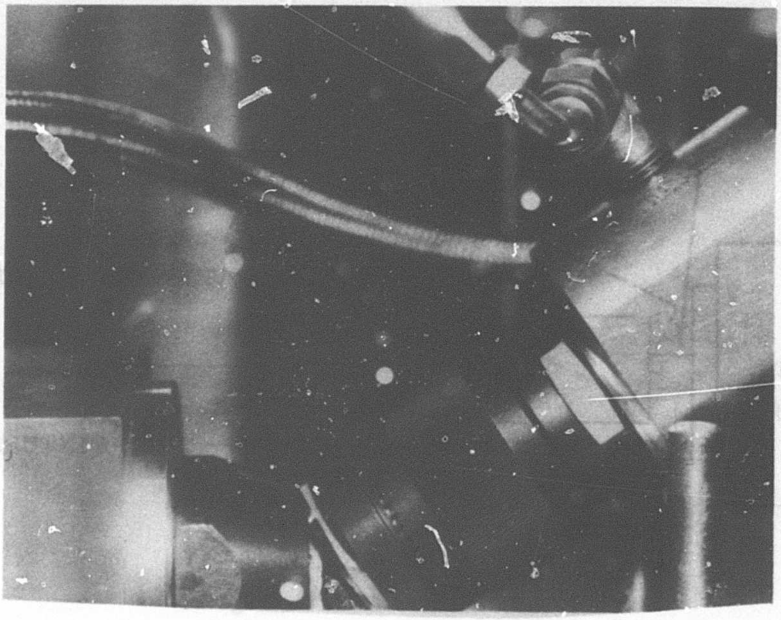

Figure 19. Valve 2 Partially Separated and Leaking in Bending Mode Static Test.

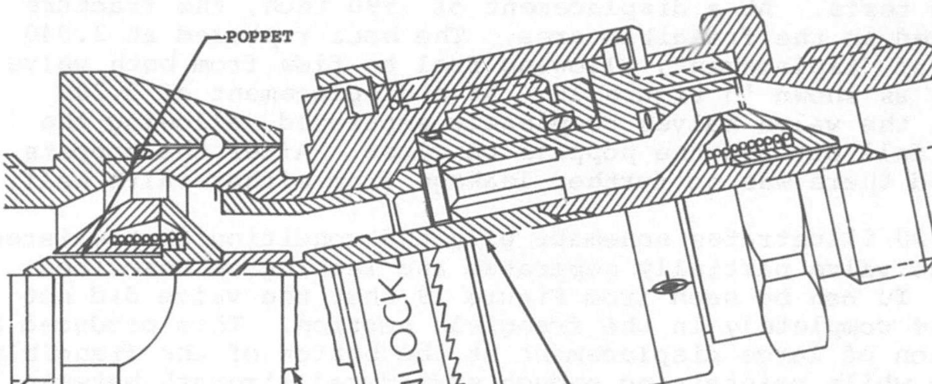

Figure 20. Illustration of Valve 2 in a Partially Separated Condition During a Bending Mode Static Test.

Dynamic Test Methodology

The dynamic tests conducted in the first test series subjected the three test valves to the same separation forces as those applied during the static test series, but under dynamic conditions. The objective of these tests was to evaluate the functional characteristics of the self-sealing breakaway valves with separation rates equivalent to the survivable impact velocity of an aircraft. Based on past programs,* this velocity has been established at 65 fps.

The data obtained from these tests were of two basic types. The first, the actual phenomenon of valve separation, was recorded by the use of two high-speed cameras. The primary camera used was capable of film speeds up to 11,000 frames per second. The secondary, or backup, camera was operated at 1,000 frames per second. This photographic coverage not only gave detailed documentation of the actual valve separation at these high velocities but made possible the determination of the relative separation velocity between the two valve halves. The second major data source during this test series was the measurement of the velocity of the sled just before valve separation. This sled was used to impart the necessary forces to achieve the separation velocity of 65 ±5 fps. Upon valve separation leakage, measurements were made of the separated valve halves where practical and still photographs recorded any abnormalities in the valve test.

These dynamic tests were accomplished by the use of a 60-foot drop tower and a horizontal test track. The valves were installed in specially designed fixtures that transmitted the dynamic loads to the valves in the same manner as the loads were applied during the static tests. Since the intention of these tests was to duplicate the static test under dynamic conditions, each of the three valves selected was tested dynamically in shear, tension, and bending.

The test schematic shown in Figure 21 defines the test setup used in conducting the dynamic tensile tests. A study of the schematic will show that the load was applied by impacting the valve through a tension link which engaged the sled arm traveling at a velocity of 65 ±5 fps. The valve assembly was pressurized from both ends with fluid at 50 psi. By using this technique, the valve halves remained at the 50-psi pressurization level upon separation. High-speed cameras were activated by a programmer just prior to the release of the sled. Careful sequencing of the camera actuation and sled release made

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*"Crash Survival Design Guide", USAAMRDL Technical Report 71-22, October 1971, Chapter 1.

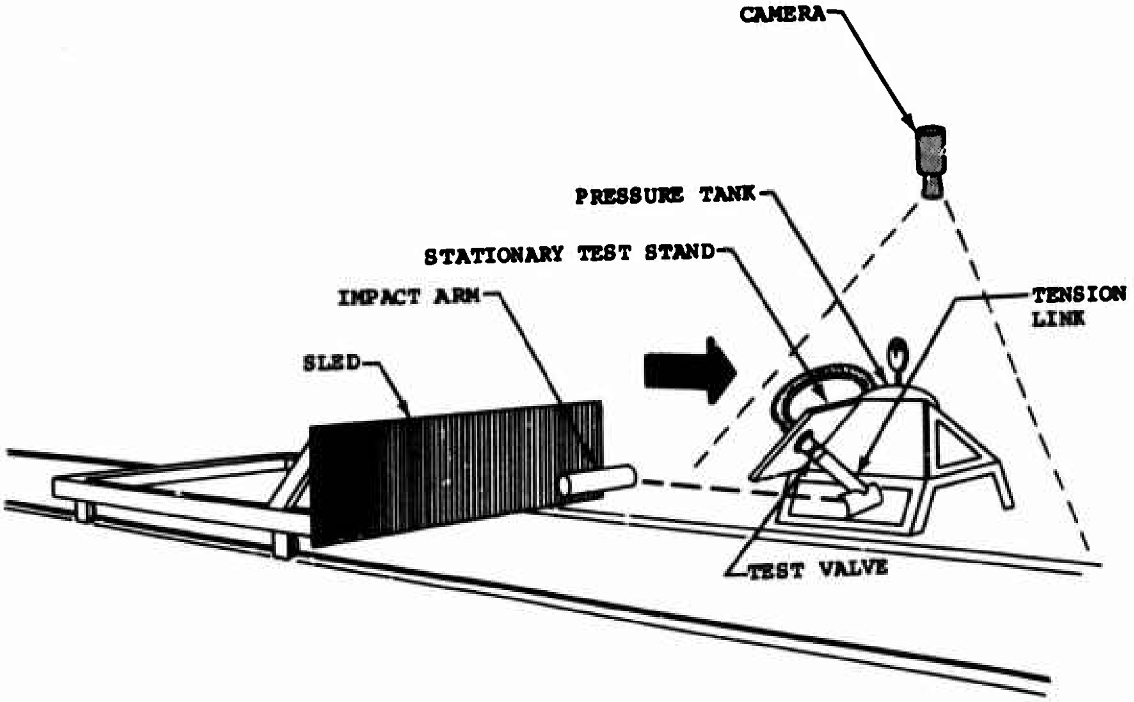

Figure 21. Dynamic Tensile Test Schematic.

photographic coverage possible throughout the entire separation sequence. After separation, both valve halves were examined for leakage at the 50-psi level.

The dynamic bending and shear tests were performed using the same procedures. However, test fixtures were constructed for each specific case, which assured the proper load application to the valves. Figures 22 and 23 schematically illustrate the general technique used for applying bending and shear forces to the valve through the use of the sled. Figure 24 is a photograph of the actual test setup for one of the dynamic tests conducted. This photograph shows the relationship of the cameras and the lighting to the valve. Also visible are the fluid pressurization system and the test fixtures designed for this specific test to impart the load to the valve body. The honeycomb, which is seen affixed to the end of the barrier, is only to decelerate the sled in a controlled manner after valve separation has occurred.

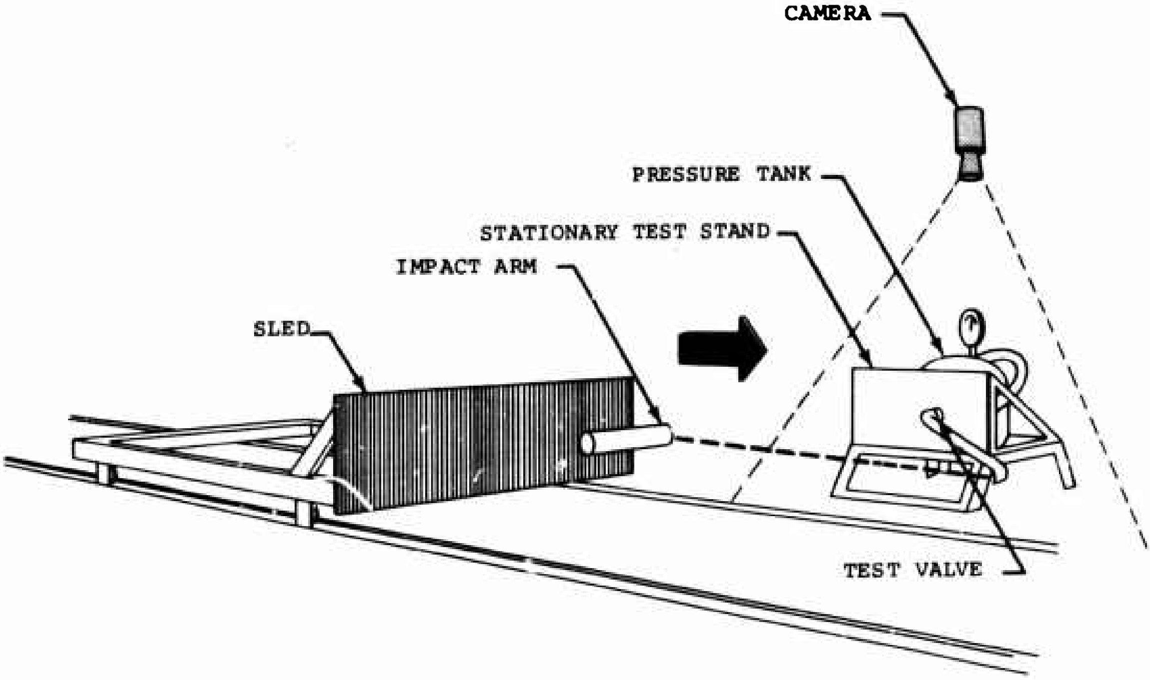

Figure 22. Dynamic Bending Test Schematic.

Dynamic Test Results

The results of all dynamic tests conducted during this program are summarized in Table II.

The results of the dynamic tests conducted during the first test series are discussed in the following text.

Dynamic Test 1 - Manufacturer B, Valve 3 - Tensile Mode

After being installed in the test fixture, the valve was separated at a velocity of 69.7 fps in the tension mode. Examination of the valve halves after separation showed that both halves actuated and closed but leaked severely. The leakage was due to separation of the rubber O-ring seat from the valve body. This is shown in Figure 25. Since the design of the valve does not incorporate a mechanical trap for the O-ring, it is likely that the failure was caused by either of the following:

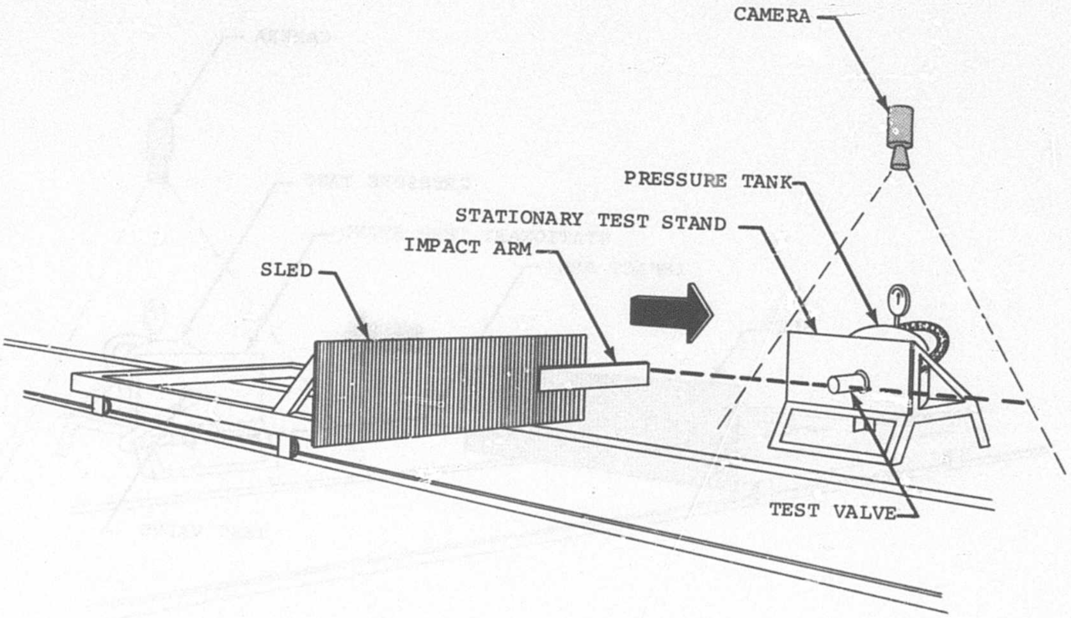

Figure 23. Dynamic Shear Test Schematic.

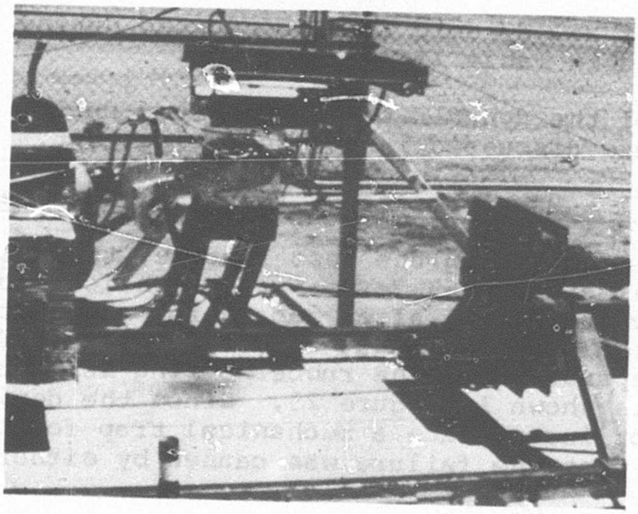

Figure 24. Overall View of Dynamic Sled Test Setup.

1. Deformation of the O-ring when the piston impacted the O-ring surface, thereby forcing the O-ring to grow in length and leave the bore of the valve body. This expansion is illustrated in Figure 26.

2. The sudden flow induced by the valve's separating and/or the piston's closing could have produced a blow-by under the O-ring and forced it away from the valve prior to closure.

TABLE II. DYNAMIC TEST RESULTS

Test No.	Valve Manu-facturer	Valve No.	Type of Separation	Sealed Upon Separation
1	B	3	Tensile	No, both halves
2	B	3	Bending	Yes
3	B	3	Shear	No, stationary half
4	A	2	Tensile	Yes
5	A	2	Bending	Yes
6	A	2	Shear	No, impacted half
7	A	1	Tensile	Yes
8	A	1	Bending	No, impacted half
9	A	1	Shear	No, impacted half
10	A	1	Shear	Yes
11	A	1	Bending	Yes
12	A	2	Shear	Yes
13	B	3	Tensile	Yes
14	B	3	Shear	Yes
15	C	4	Shear	No, impacted half*
16	C	4	Bending	No, impacted half*
17	C	4	Tensile	No, impacted half*

*Liquid seepage.

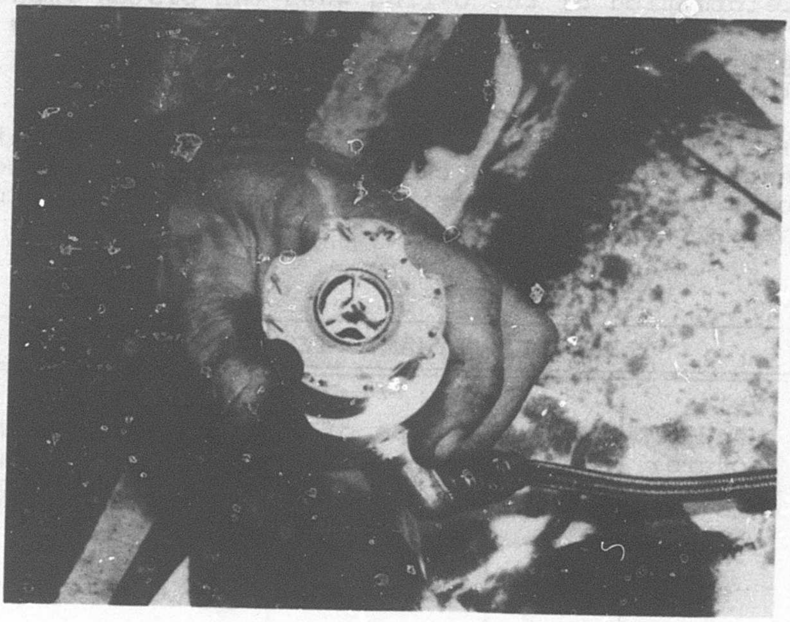

Figure 25. Valve 3 After Tensile Test. (Note Extruded O-Ring).

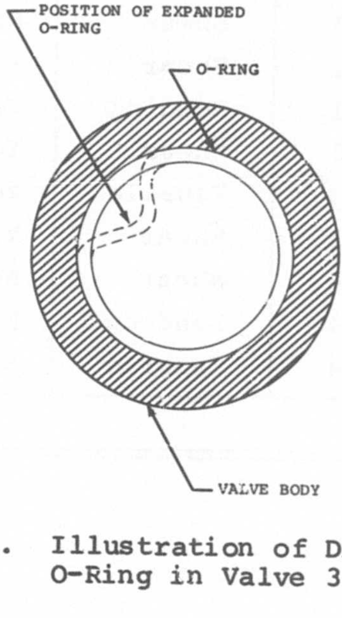

Figure 26. Illustration of Displaced O-Ring in Valve 3.

Dynamic Test 2 - Manufacturer B, Valve 3 - Bending Mode

This valve was separated in the bending mode at a velocity of 68.9 fps. The valve was inspected after complete separation and found to have actuated correctly with no leakage from either valve half. Inspection of the high-speed films also showed normal operation of the valve.

Dynamic Test 3 - Manufacturer B, Valve 3 - Shear Mode

The valve was impacted by the sled at a velocity of 68.9 fps, which produced a separation of the valve in the shear mode. Examination of the valve after separation showed that one-half of the valve failed to actuate, thereby allowing unrestricted fuel flow, as shown in Figure 27. Further investigation showed that the failure was caused by fracture of the actuation wire before the piston was released in one of the valve halves. Figure 28 illustrates the probable mode of failure. As shown, the shearing action created by the wire guides plus the high rate of separation, which did not allow the wire to yield as it had under the same separation conditions in the static test, caused the premature fracture of the wire.

Dynamic Test 4 - Manufacturer A, Valve 2 - Tensile Mode

A tensile load was applied to the valve by impacting the test fixture with the sled at a velocity of 69.9 fps. Examination of the detached valve halves following separation indicated a normal actuation of the self-sealing mechanism in both valve halves with no subsequent leakage.

Dynamic Test 5 - Manufacturer A, Valve 2 - Bending Mode

The valve was separated at a velocity of 69.4 fps with a force applied that produced a bending moment in the frangible section. However, this valve has two frangible sections, one for a tension failure and one for a bending and shear failure, as shown in Figure 3. Posttest examination showed that both frangible sections had separated and that the poppets had actuated and closed. No leakage was evident from either valve half.

The fact that both frangible sections separated does not affect the operation of the valve. It is of importance, however, because it does indicate the difference between applying the same force under static or dynamic conditions. This valve had separated only as predicted in the static test.

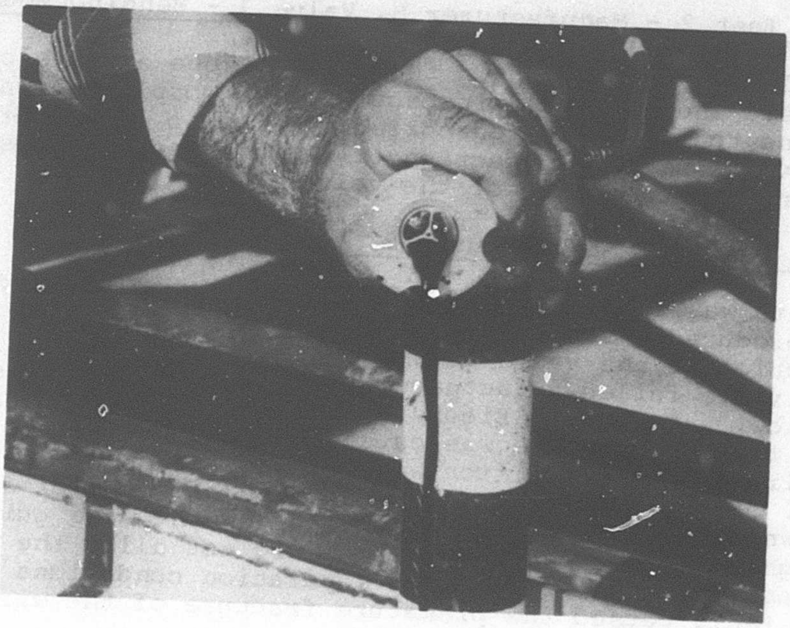

Figure 27. Valve 3 After Shear Test.

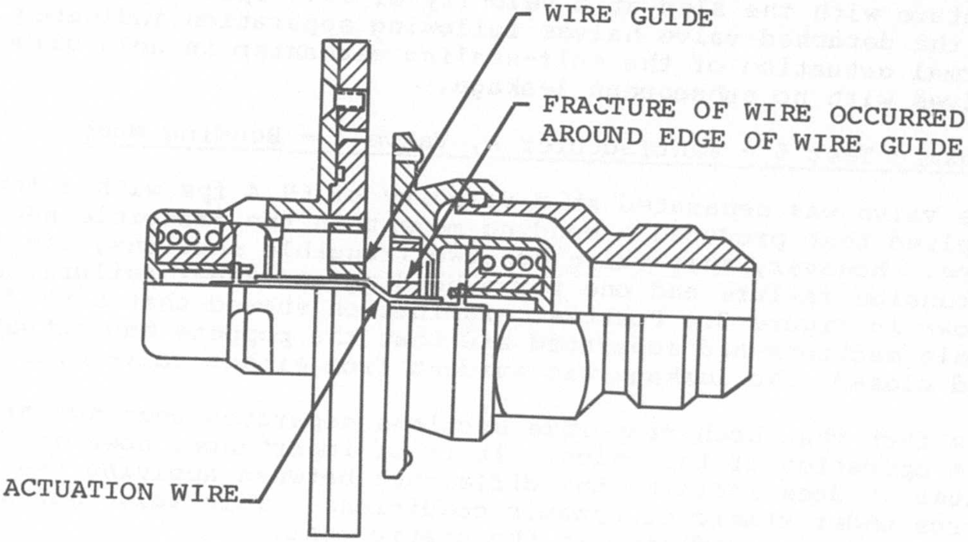

Figure 28. Schematic of Valve 3, Showing Wire Fracture After Dynamic Load.

Dynamic Test 6 - Manufacturer A, Valve 2 - Shear Mode

The valve was impacted at a velocity of 68.9 fps to produce a separation induced by a shear load. Inspection of the valve following separation showed that the poppet in the impacted valve half had not actuated. This produced the unrestricted flow shown in Figure 29. The other valve half operated correctly and exhibited no leakage.

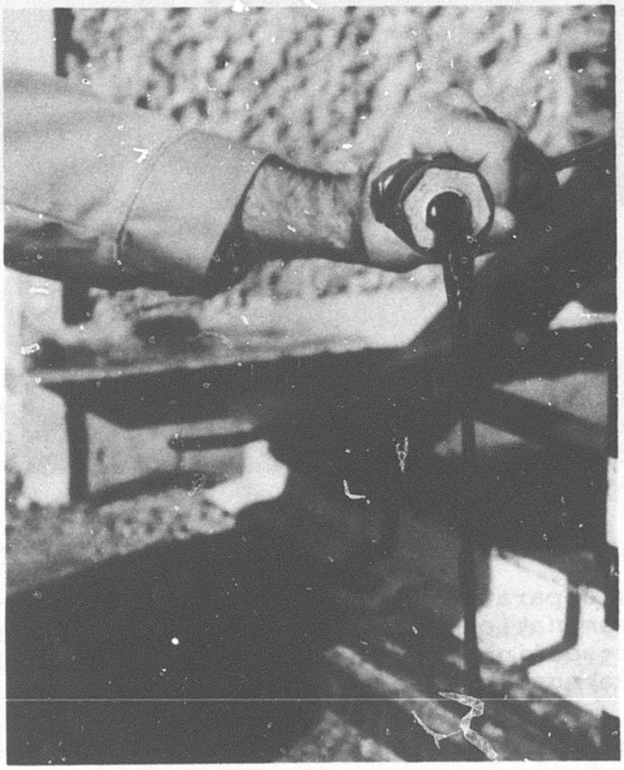

Figure 29. Valve 2 After Dynamic Shear Test With Fluid Pressure.

Further study of the faulty valve half showed that the pin used to hold the poppets apart until the valve separated had become bent and lodged in the pin guide. This is shown in Figure 30.

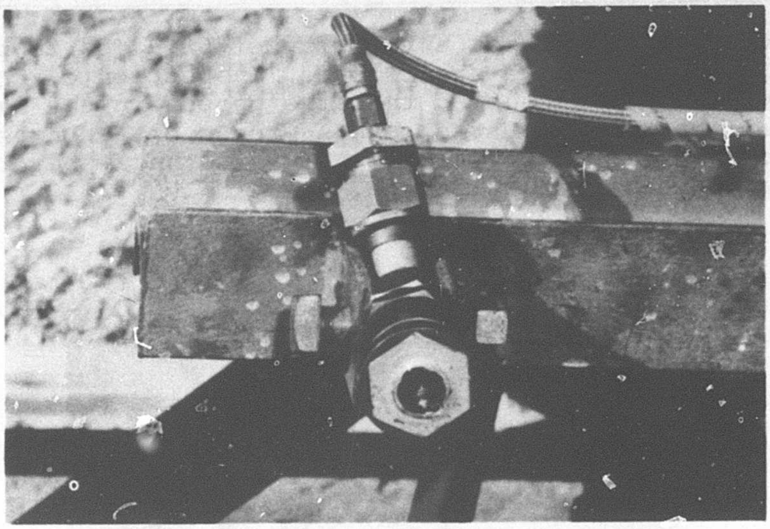

Figure 30. Valve 2 After Dynamic Shear Test. (Note Pin Still Lodged in Valve.)

The pin fractured in the same area as a result of both the dynamic and static shear tests of this valve. However, the pin only bent in the dynamic test. This is apparently due to a high transient load seen by the pin during dynamic separation of the valve.

Dynamic Test 7 - Manufacturer A, Valve 1 - Tensile Mode

The valve was separated in the tensile mode at a velocity of 66.6 fps. Examination of the separated valve halves revealed that the self-sealing mechanisms had operated correctly with no ensuing leakage.

Dynamic Test 8 - Manufacturer A, Valve 1 - Bending Mode

The valve was subjected to a dynamic bending load which separated the valve at a velocity of 68.9 fps. Posttest examination of the separated valve halves indicated that both poppets had closed but one half was leaking. Figure 31 shows the fluid leaking from the valve half at reduced flow.

Inspection of the faulty valve half showed that the rubber bond between the boot and the valve body had partially separated. This part of the boot acts as the poppet seal when the

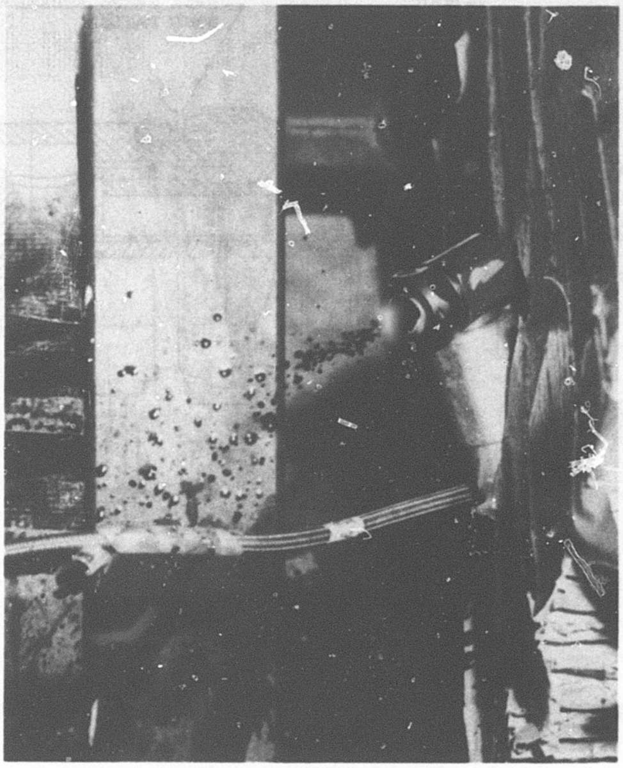

Figure 31. Valve 1 After Dynamic Bending Test.

valve is in the separated condition. Figure 32 illustrates where the failure occurred. The failure was probably due to a faulty bond between the rubber boot and the valve body. However, the high-speed films did show an extremely large deformation of the boot before rupture during the valve separation, which indicates a high transient load into the bond area.

Dynamic Test 9 - Manufacturer A, Valve 1 - Shear Mode

The valve was impacted in a manner that placed a shear load on the frangible area of the valve. The valve then separated at a velocity of 68.9 fps. After the test, the poppets were found to have actuated in both valve halves, but the impacted valve half had gross leakage. Examination of the valve showed that the impact on the valve body had seriously distorted it, thereby distorting the seat.

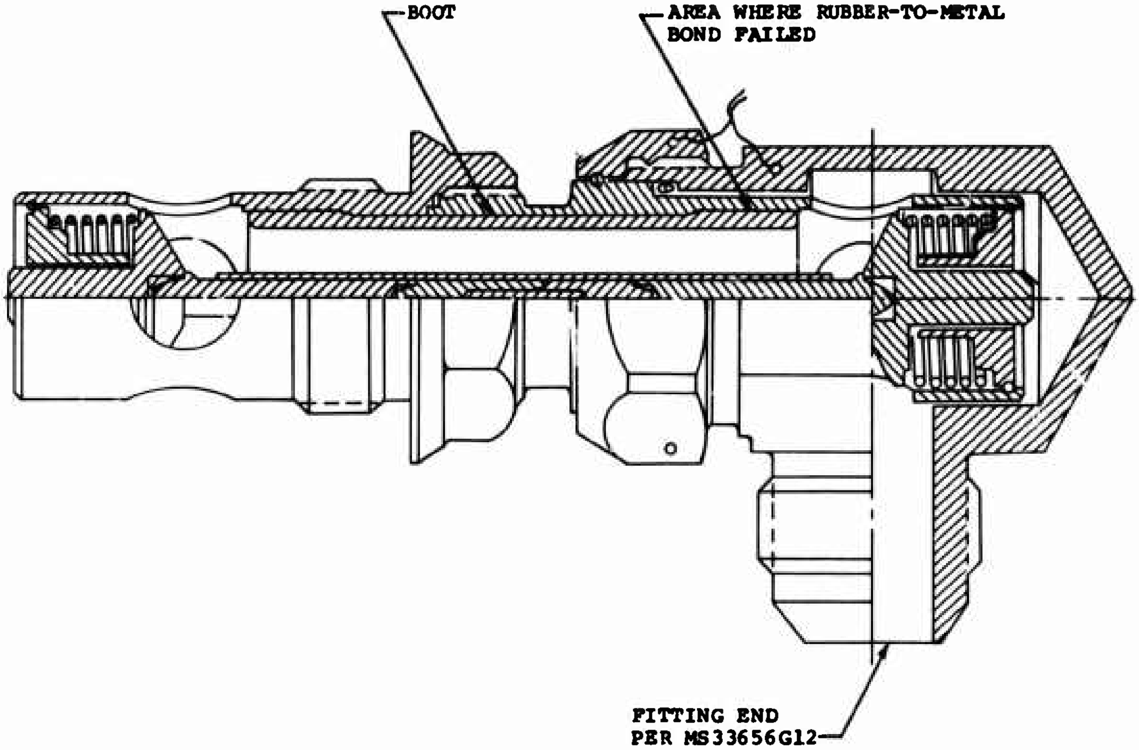

Figure 32. Illustration of Bond Failure in Dynamic Test 8.

Environmental Tests

The contaminated fuel and cold weather environmental tests were the final tests to be performed in the first test phase. In the preparation of the program plan it was felt that these two environmental tests represented the most severe environmental conditions that might be imposed upon a valve of this type.

Contaminated Fuel Tests

The contaminated fuel tests were based on the assumption that a valve of this type might be in service in the aircraft for a long period of time before it might be required to function. During this time, great quantities of fuel would have passed through the valve, exposing it very probably to a great deal of fuel-borne contamination. If flow stagnation areas existed in the valve, any resultant deposition of the contamination would possibly build up in the self-sealing mechanism of the valve. This contamination could prevent actuation of the self-sealing mechanism upon separation.

The contaminated fuel tests conducted in this program were an effort to simulate contamination deposition conditions. The tested valves were installed in the tested flow system, as shown schematically in Figure 33. The fuel to be circulated through this system was contaminated as prescribed in MIL-F-8615. For the purpose of these tests, a maximum flow rate of 10 gpm was assumed for the test valve. The contaminated fuel was allowed to flow for 2-1/2 hours at 10 gpm through the valve. Flow was then reduced to 1 gpm or 10 percent of the rated flow and allowed to circulate for an additional 2-1/2 hours. Upon completion of the flow period, the valve was statically tested in the same manner as it was in the previous static tests. All data recorded during these tests were identical, with the major emphasis being placed on the actual functioning of the valve. Of the three valves tested, Valve 1 (Manufacturer A) and Valve 3 (Manufacturer B) operated in a normal manner. Valve 2 (produced by Manufacturer A) failed to operate correctly. When subjected to the static tensile test, the bulkhead half of the valve failed to close, as shown in Figure 34. This was due to buildup of contamination between the poppet shaft of the self-sealing mechanism and the valve body, as illustrated in Figure 35. The results of this test illustrated the need for design consideration to be given to eliminating possible areas for buildup of contamination in the self-sealing mechanism of the valves.

Cold Weather Tests

The cold weather tests dealt with another problem very common to fuel systems. The purpose of the tests was to simulate a condition where a valve installed in a fuel system might act as a water trap and collect moisture from the fuel over a period of time. The combination of the trapped water and an in-service exposure to a subzero environment would obviously freeze this water. Given these conditions, the question arose as to the valve's ability to function should a crash occur. The following test procedure simulated this condition.

The test valves were installed in a test system as shown schematically in Figure 36. The valve was positioned in this system so that it would act as the most efficient water trap. A sufficient quantity of water to assure

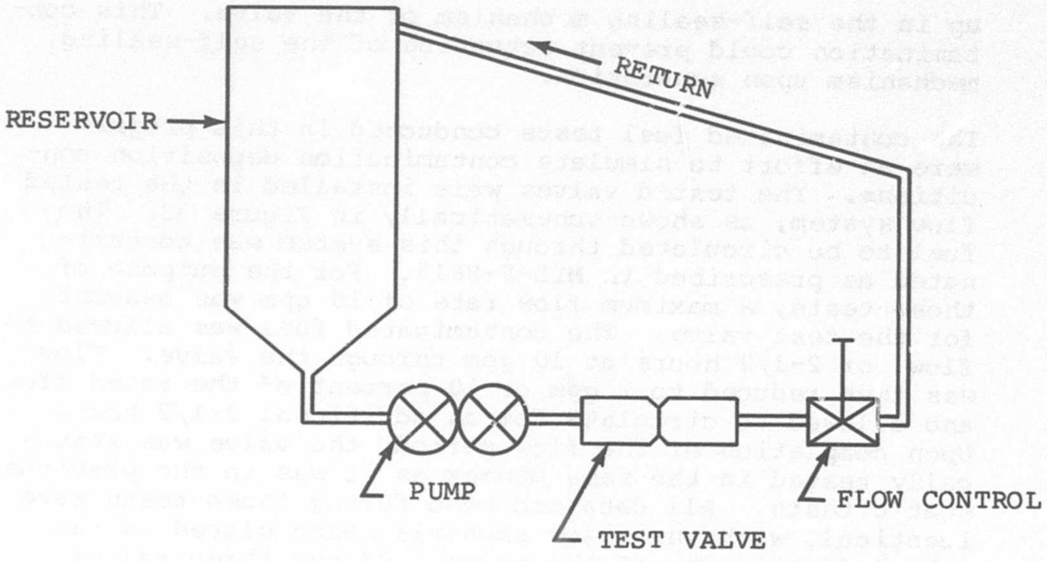

Figure 33. Contaminated Fuel Test Flow Schematic.

Figure 34. Static Tensile Test of Valve 1 After Contaminated Fuel Exposure.

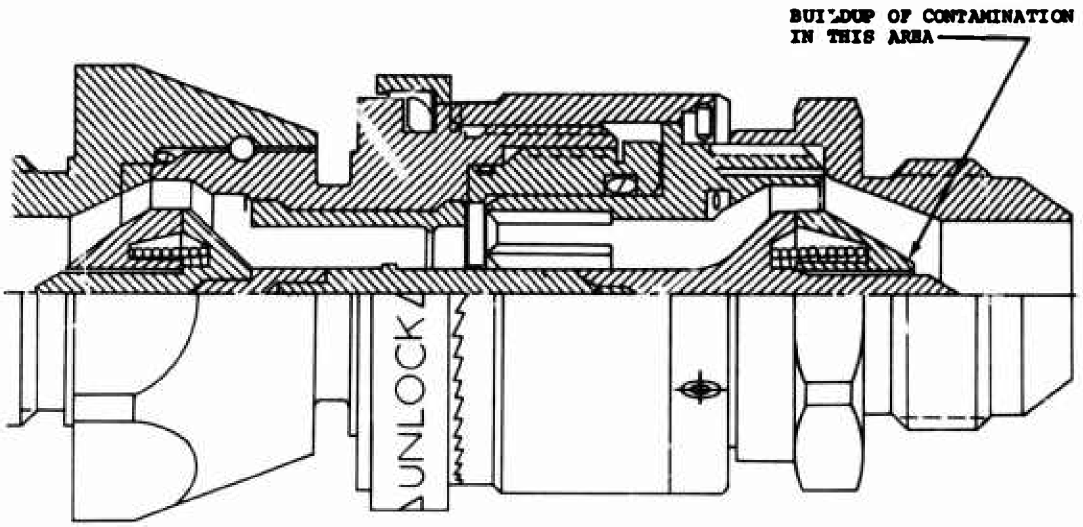

Figure 35. Contaminant Failure of Valve 1.

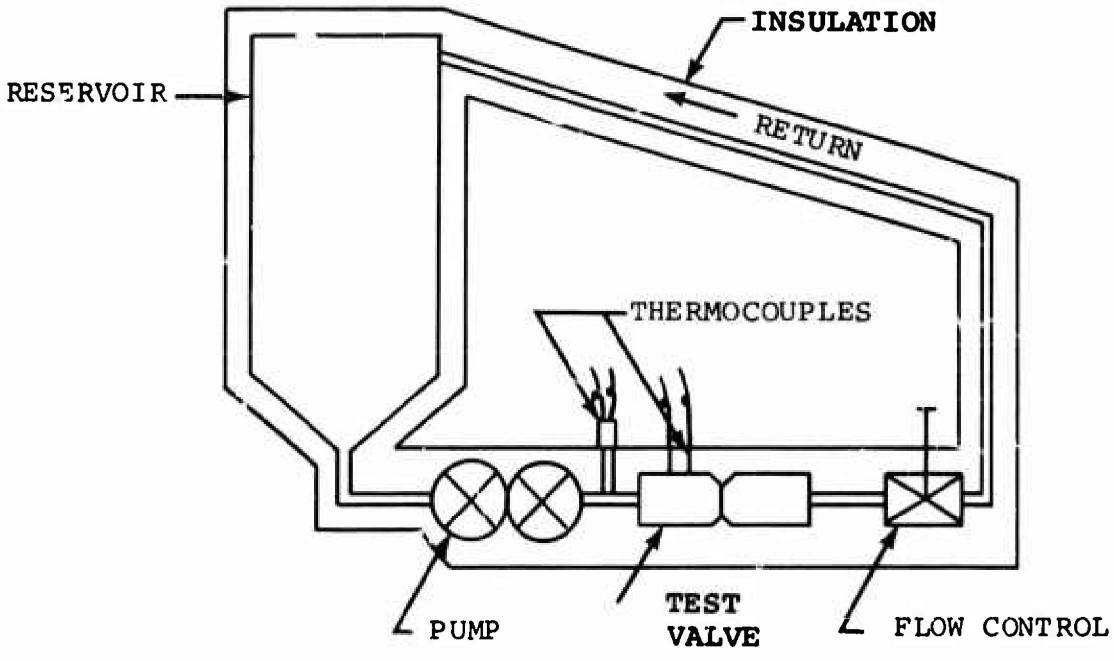

Figure 36. Cold Temperature Test Flow Schematic.

that all internal areas of the valve were filled was then passed through the system. Any water trapped in the valve remained. The system was then filled with fuel which was cooled to 0°F. The pump was then turned on and fuel was allowed to circulate through the valve at 1 gpm. The outside ambient temperature of the valve during this flow period was also kept at 0°F. The internal temperatures of the valve were continuously monitored throughout the circulation period. The circulation was allowed to continue for 1/2 hour after a steady-state temperature condition within the valve had been reached. Upon completion of this chill period, the valve was removed and subjected to a static test identical to the one performed on the contaminated fuel valves. Throughout this test, the valve temperature was not allowed to rise above 20°F. The valve was also pressurized to 50 psig during this test with fluid cooled to 0°F.

Valve 1 (Manufacturer A) and Valve 3 (Manufacturer B) were subjected to the cold weather tests. The results of the tests indicated that cold weather water contamination is indeed a real problem. Upon static separation of the two valves, both exhibited momentary failures of the self-sealing mechanism. The result of this failure was a period of time (approximately 1 minute) during which unrestricted flow emitted from one half of the separated valve. Figure 37 is a photograph of the resulting condition. In both tests, the separated half in which the self-sealing mechanism failed to close immediately was the half in which the water was trapped and subsequently frozen. Figure 38 shows some of the ice remaining upon disassembly of the valve after separation.

ANALYSIS AND REDESIGN

With the completion of the first testing phase, the results were analyzed in terms of two objectives. The most important of these was the evaluation of the deficiencies discovered in the tested designs. The goal of this evaluation was to enable the manufacturers to modify their designs to correct indicated deficiencies. Analysis showed that the failures that occurred during the dynamic tests were amenable to correction by relatively minor design changes. However, the deficiencies discovered during the static and environmental tests proved to be too difficult to fix without a complete redesign of the valve. Implementation of the implied design modifications was relegated to the draft specification. The results of these analyses, including recommended design changes, were discussed with both manufacturers. As an outcome of these discussions,

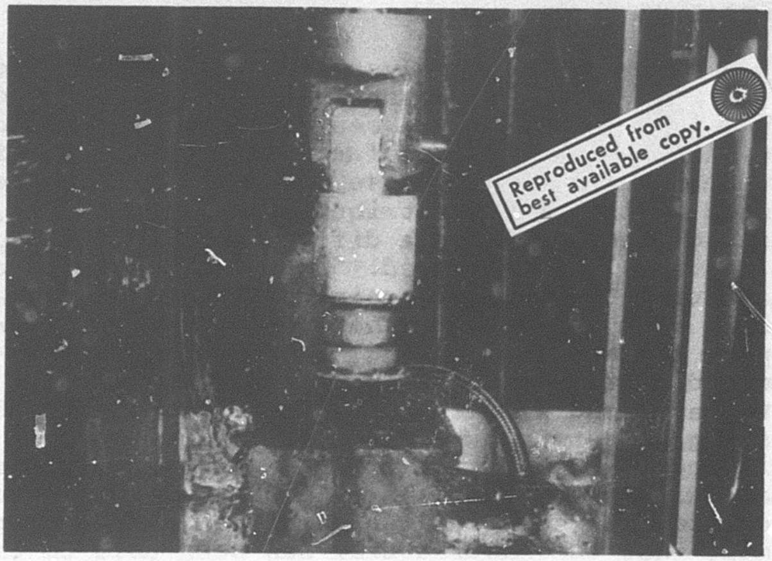

Figure 37. Transient Leakage Following Separation of Cold-Weather Conditioned Valve.

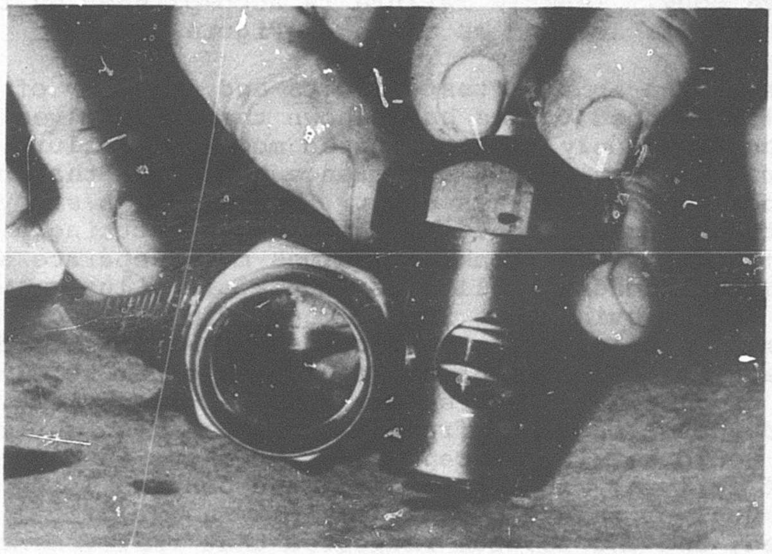

Figure 38. Illustration of Ice Buildup in Valve Following Cold Weather Test.

both manufacturers agreed to furnish modified designs for the subsequent test phase.

In conjunction with this analysis effort, contact had been maintained with the three companies that had promised their support during the literature search phase of the program. As a result of this contact, Manufacturer C submitted six valves for test during the second phase of the program. These valves represented an important contribution to the program, as the self-sealing mechanism used a different design concept from the two previous valves tested. Figure 39 presents a layout of Manufacturer C's valve, herein designated as Valve 4. It can be seen from the drawing that, as in the other two designs, the poppets of the self-sealing mechanism are spring-loaded in the closed direction with fluid pressure assisting. However, unlike Valves 1 and 2, which have segmented pins to hold the self-sealing poppets apart, this design incorporates two small triggering paws. The design of this mechanism is such that very small displacement of one valve half relative to the other actuates the self-sealing mechanism. This displacement is so small that the manufacturer has been able to omit a boot for external sealing during the separation process. The frangible section of this valve is similar to that of Valve 2. As in that design, two separate frangible areas were used to accomplish separation in all three of the modes -- bending, shear, and tension. For the bending and shear modes, separation occurs at a narrowed-down wall section in the center of the valve body. Tensile failure is accomplished by the shearing of two pins located as shown in Figure 39.

Analysis of the initial test results and a review of all other presently designed valves have shown that the valves are designed to break only in anticipated modes of failure. However, crash investigation experience has shown that the anticipated mode does not always occur. Therefore, a study was initiated to determine the feasibility of instituting a general requirement that all breakaway valves must separate at reasonably constant loads in all three modes of failure. Valves capable of achieving this requirement at present do so by the use of mechanical pins, rings, or some similar method, all of which require active external seals. In order to eliminate the use of these external seals, boots, O-rings, etc., it appeared that a machined frangible section was required. This section would have to be capable of breaking in all three modes of failure, with the tension and bending loads being either equal or in any desired ratio. An analytical study was performed, and the results indicated that improvements could be made. The resulting experimental test section was designed and built and is shown in Figure 40. A brief analysis of the

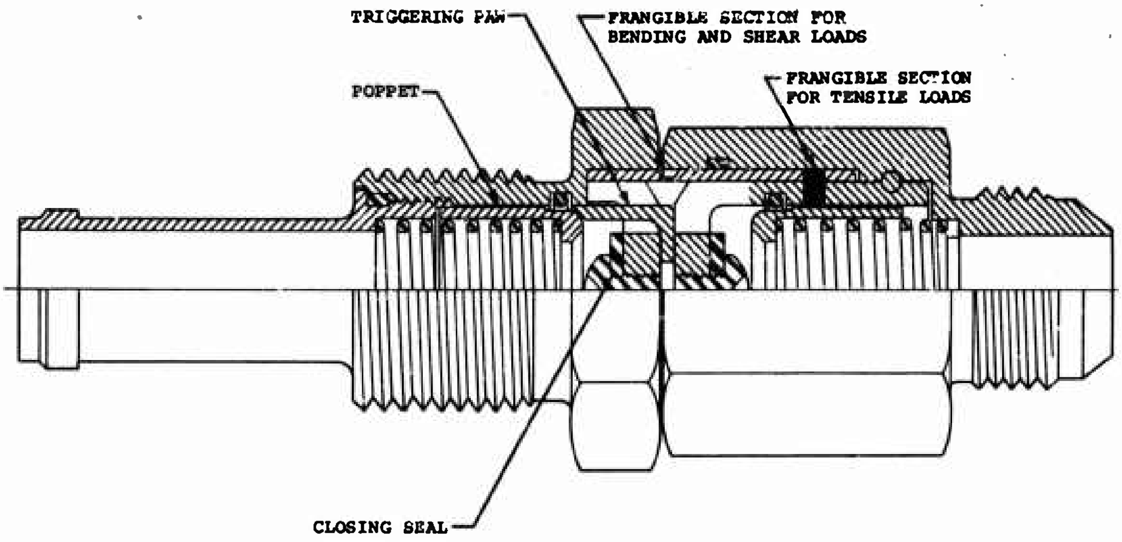

Figure 39. Cell-to-Line Design (Valve 4).

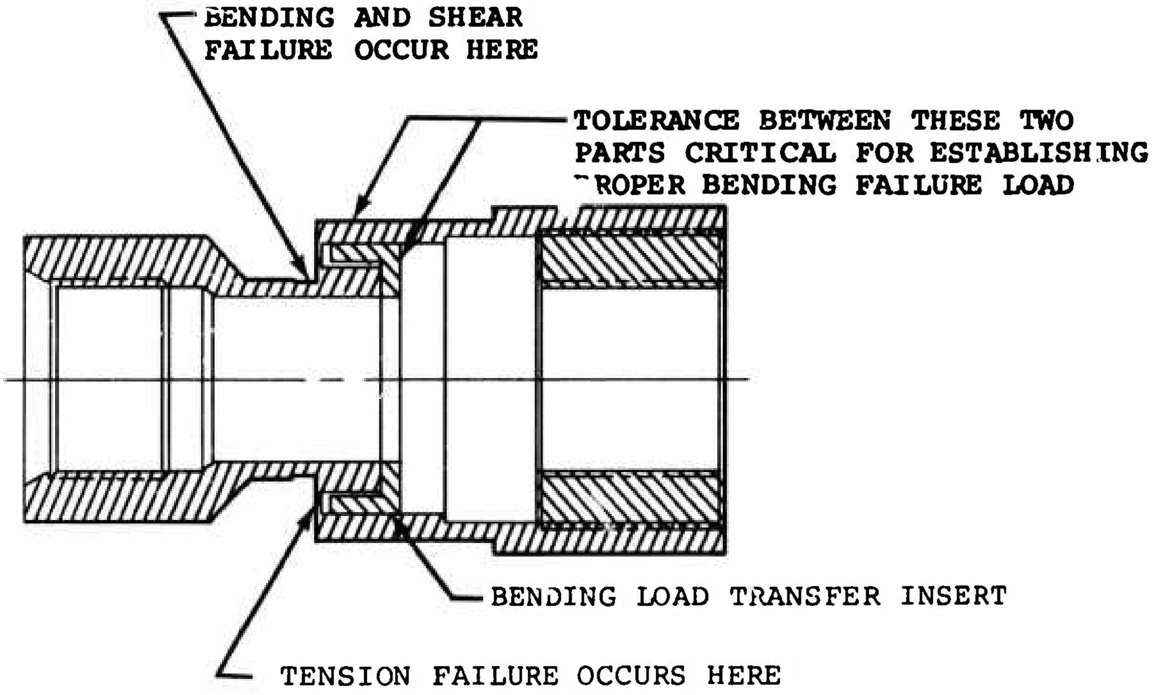

Figure 40. Frangible Section Test Specimen.

anticipated forces required for separation is presented in Appendix I. As shown, the predicted bending and tension forces were approximately equal and approximately one-third of the shear failure load. The primary advantage of this design is that it eliminates the use of separate pieces such as pins for the various failure modes.

SECOND TEST PHASE

The second test phase of the program commenced with the testing of the frangible test section shown in Figure 40. Two sections were tested statically in the same manner used for the valve static tests of the first test phase, except that no fluid pressure was applied to the test section. The sections were tested in tension and bending. Figure 41 shows the test section being separated in the tensile mode. The experimental separation force for this test was 1,575 pounds, which was considerably higher than the 800 pounds predicted. The design load for bending was also 800 pounds, but the test section failed at only 85 pounds. Examination of the specimens after failure showed that design tolerances were not held on these test parts. This was due to the difficulty of machining the parts for the present design using available machine shop methods. As a result, the bending load was not transmitted through the bending load transfer insert as designed. However, these tests do indicate that the basic design idea for establishing a more nearly omnidirectional frangible section is possible and that a relatively straightforward fix could substantially improve the performance of the frangible test sections.

Static Tests

The only static tests conducted during the second test phase were shear, tensile, and bending tests on Valve 4, produced by Manufacturer C. Since these valves were 5/8-inch line size and designed to meet a specific application, the loads cannot be compared directly with the loads obtained on the 3/4-inch line size valves during the first test phase. The procedure used was identical to that used during the previous static tests.

Static Test 10 - Manufacturer C, Valve 4 - Tensile Mode

A tensile load of 364 pounds was required to cause separation of the valve. The self-sealing mechanism functioned correctly and no potential problem areas were indicated. The only fluid lost during the separation process was the small amount trapped between the valve halves; a leak check performed on the separated valve halves indicated that no external leakage existed.

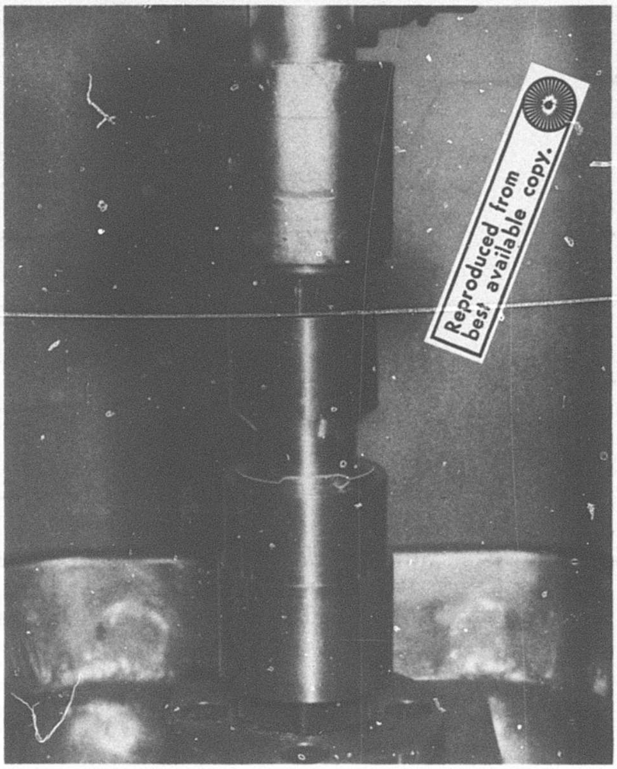

Figure 41. Tensile Test of Frangible Test Section.

Static Test 11 - Manufacturer C, Valve 4 - Bending Mode

A load of 279 pounds applied through a moment arm of 4.5 inches produced a bending load in the frangible section sufficient to cause fracture. The self-sealing mechanism of the valve did not actuate at the first initiation of fracture. This produced a condition which allowed large amounts of liquid leakage from the fractured section of the valve body. As the displacement between the two valve halves was increased, the self-sealing mechanism actuated and closed. Figures 42 and 43 illustrate the relative displacement of the valve halves between fracture and actuation of the self-sealing mechanism. In posttest discussions, the manufacturer expressed the belief that, because the relative displacement before actuation is so small, use of aluminum in a more ductile condition would alleviate this problem. This change would

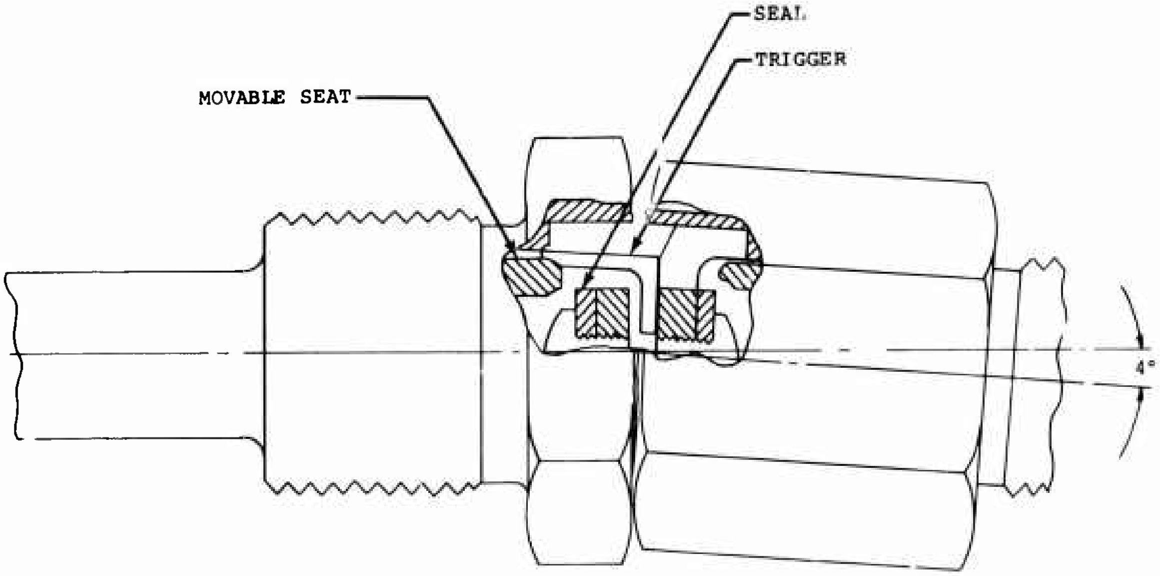

Figure 42. Valve 4 Separation. (Valve Body Fractured But Seat Remains in Open Position With Trigger End Still Trapped by Valve Body.)

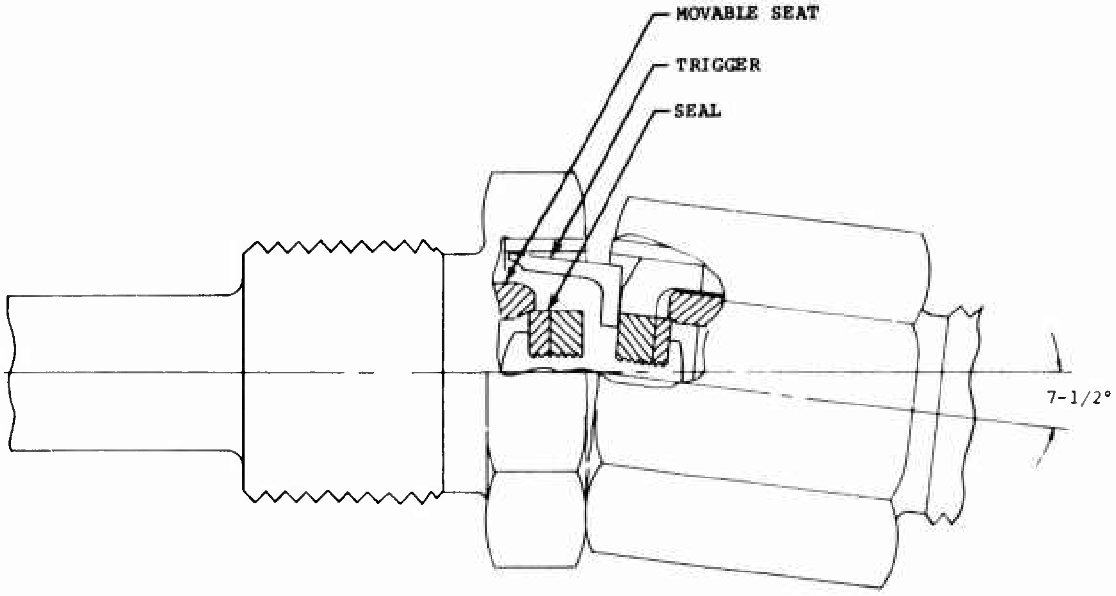

Figure 43. Valve 4 Separation Sequence. (Valve Body Rotated Sufficient Distance to Allow Trigger to Release Seat and Seal.)

increase the valve bending capability to the necessary 7-1/2 to 8 degrees, and would ensure that the self-sealing mechanism would trigger prior to fracture. After the mechanism actuated during the test, all external leakage from both halves ceased.

Static Test 12 - Manufacturer C, Valve 4 - Shear Mode

The valve separated in the shear mode when the load reached 122.5 pounds. The fracture in the frangible section of the valve body occurred at a vertical distance of .020 inch between the valve halves. Poppet closure occurred at .040 inch. As in the bending test, this condition produced large amounts of external leakage during the period between valve fracture and closure of the poppets. However, the manufacturer indicated that, because of these small displacements, this problem may also be correctable by the use of the more ductile aluminum for the valve body. No external leakage was observed after actuation of the poppets.

Dynamic Tests

The performance of the following eight dynamic tests completed the second test phase of the program. All eight of the tests were run in the manner established for the dynamic tests during the first phase. The separation velocity in each case was in the 65 ±5 feet per second range, and all valves were pressurized to 50 psi prior to valve separation and subsequently after valve separation. A brief discussion of these test results follows.

Dynamic Test 10 - Manufacturer A, Valve 1 - Shear Mode

This valve was retested because during the previous shear test one half of the valve body had suffered severe damage due to impact with the sled, causing leakage. To correct this condition, the manufacturer redesigned the valve body by increasing the wall thickness considerably. The results of this retest showed that the body was sufficiently strengthened to prevent this damage from occurring. After valve separation, no external leakage was recorded.

Dynamic Test 11 - Manufacturer A, Valve 1 - Bending Mode

No design changes of the valve as tested in the first test series were necessary for this retest. As discussed previously, the reason for a large amount of external leakage after the first dynamic bending test was due to curing problems of the boot installed in the valve. To confirm this conclusion, however, the valve was retested with a properly cured boot. Retest results, as expected, showed the valve to function normally with no external leakage from either valve half after separation.

Dynamic Test 12 - Manufacturer A, Valve 2 - Shear Mode

The dynamic shear test of this valve in its original design state indicated that the pin used to hold the self-sealing mechanism in the open position had become trapped and damaged upon separation. To correct this problem, the manufacturer redesigned this pin to prevent it from becoming bent or lodged within the valve as had occurred previously. The dynamic test of this valve validated the design fix taken, as the valve was observed to operate normally with no posttest leakage.

Dynamic Test 13 - Manufacturer B, Valve 3 - Tensile Mode

Upon dynamic separation of this valve during the first test phase, external leakage was recorded from both sides. This was traced to the fact that the O-ring seats had been dislodged from their correct position. The redesigned valve presented for retest by Manufacturer B incorporated a mechanical trap in the valve body to prevent this from reoccurring. The valve was checked for external leakage, and there was no evidence of the O-ring seat's becoming dislodged.

Dynamic Test 14 - Manufacturer B, Valve 3 - Shear Mode

As discussed in Dynamic Test 3, premature failure of the actuation wire resulted in the self-sealing mechanism in one half of this valve not actuating. The redesign approach taken by Manufacturer B for this problem was to replace the solid wire cable with a braided wire cable. The successful operation of this valve during this retest indicates that this problem has been alleviated in this design.

Dynamic Test 15 - Manufacturer C, Valve 4 - Shear Mode

The valve was impacted by the sled to produce the necessary shear separation force. The valve separated as expected and functioned normally. However, examination after separation indicated a small amount of liquid seepage, less than 1 cc per minute. This condition was traced to leakage around a pressed pin, illustrated in Figure 44. Though the leakage was so small that it would be a negligible hazard, a design fix to prevent it from occurring could easily be accomplished.

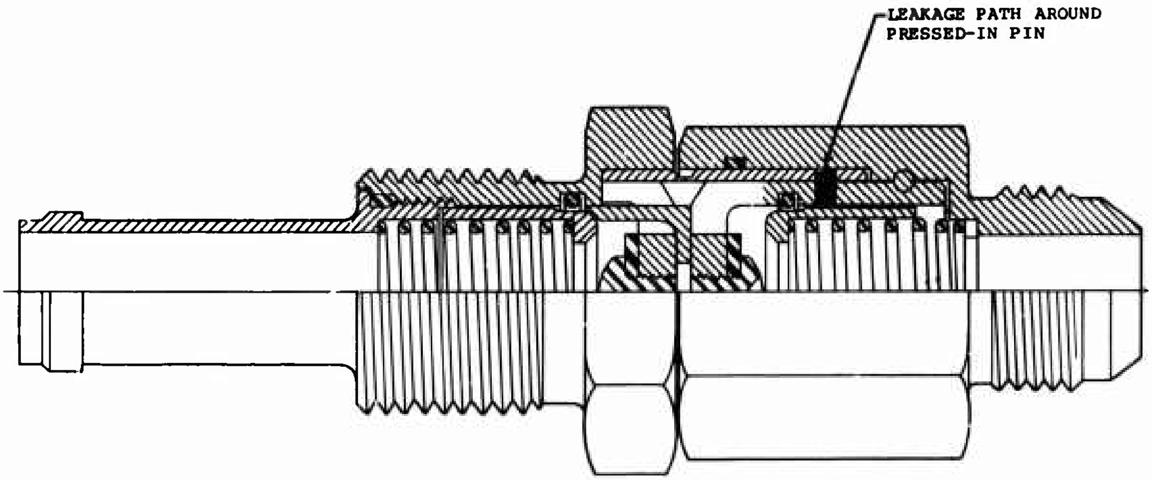

Figure 44. Leakage Mode Observed in Dynamic Tests of Valve 4.

Dynamic Test 16 - Manufacturer C, Valve 4 - Bending Mode

The valve was subjected to a dynamic bending load and, as anticipated, separated in the frangible section. An overall view of the setup excerpted from one of the high-speed cameras is shown in Figure 45. A sequence of close-up frames from the separation sequence for the bending test is shown in Figure 46. As in the shear test, the valve functioned normally with only minor liquid seepage as discussed above.

Dynamic Test 17 - Manufacturer C, Valve 4 - Tensile Mode

A tensile load was applied to the valve by impacting the test fixture with the sled at a velocity of 62.6 fps. The valve functioned normally with a small amount of external leakage following separation. The amount of leakage and the cause were the same as noted on the two previous dynamic tests for this model valve.

SPECIFICATION PREPARATION

Accomplishment of the dynamic tests in the second phase of the program completed the total test program. The results from these tests as well as the literature survey were then carefully analyzed, compiled, and evaluated. From this information, a draft military specification was prepared governing the design of self-sealing breakaway valves.

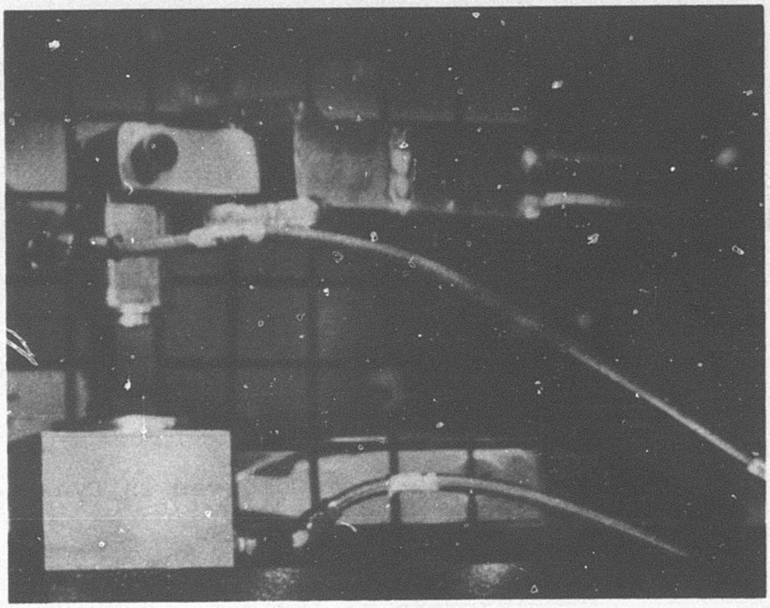

Figure 45. Overall View of Bending Mode Dynamic Test Setup for Valve 4.

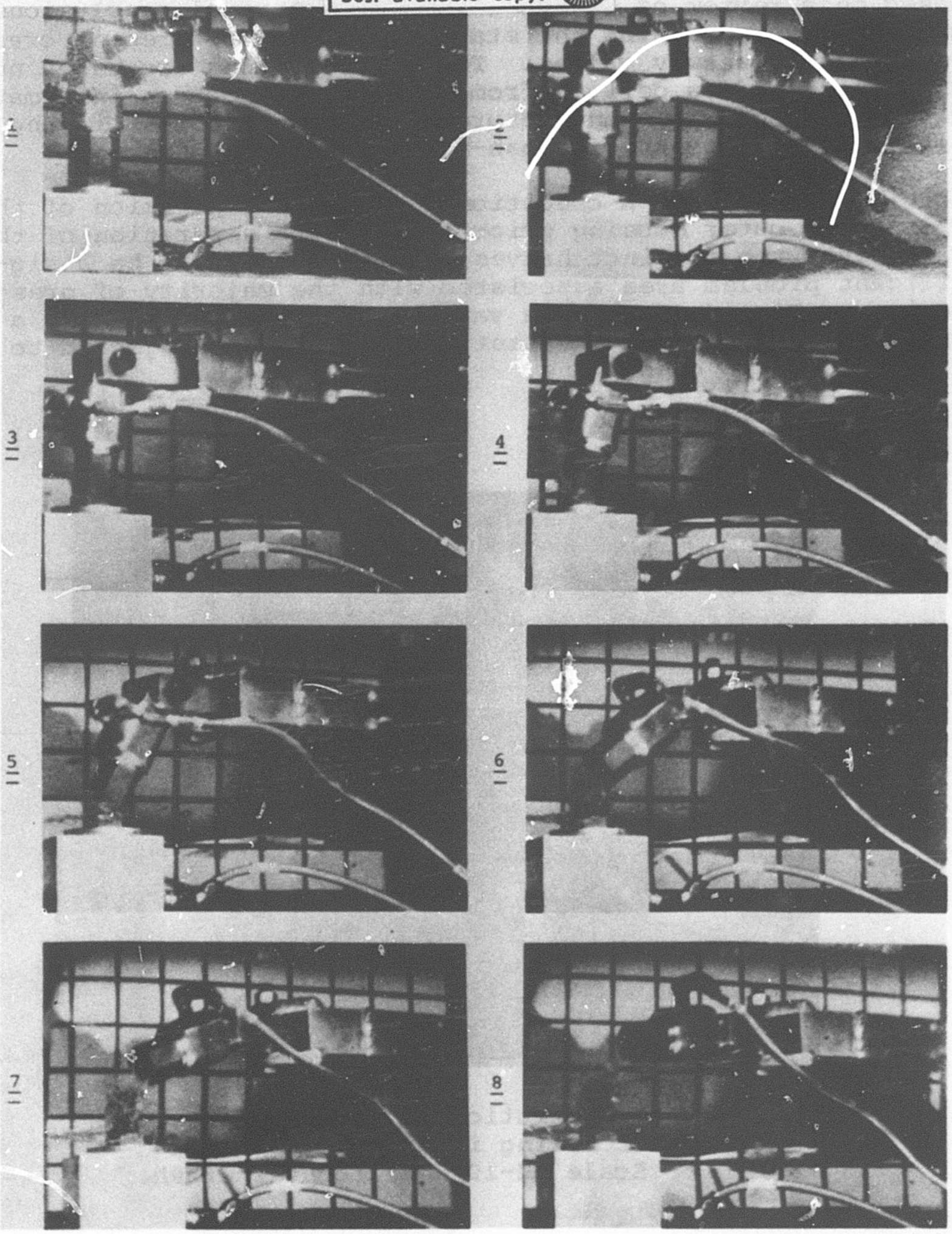

Figure 46. Separation Sequence for Bending Mode Dynamic Test of Valve 4.

CONCLUSIONS

Based on a review of the total program, several conclusions can be drawn regarding the state of the art of present crash-resistant breakaway valves. These conclusions are based not only on test data derived from this program but on information gathered from valve manufacturers and previous work in the design and development of crash-resistant fuel systems.

Partial separation, a condition defined as separation of the valve body outer housing prior to complete separation of the valve into two distinct halves, has been shown to be a significant problem area associated with the majority of present designs. Figure 47 shows a valve partially separated in a full-scale test after the test helicopter was subjected to simulated crash conditions.

Figure 47. Illustration of Partial Separation Occurring in a Simulated Full-Scale UH-1D/H Helicopter Crash.

Two conditions can exist when the valve is partially separated as shown. The first partial separation condition occurs when the valve's self-sealing mechanism has actuated but the valve has not completely separated. Under these conditions there is no problem. The second condition is partial separation with the self-sealing mechanism still in the open position. In this condition, the only means of preventing external leakage is through the use of a boot or some other type of seal. As shown in the test program, if the separation distance becomes sufficiently large prior to actuation of the self-sealing mechanism, the boot can rupture from internal pressure alone. Another possibility which exists under crash conditions is that the boot might possibly be punctured from some outside source such as a sharp piece of structure (see Figure 47), thereby allowing unrestricted external leakage. It is quite apparent that the separation distance required to operate the valve's self-sealing mechanism must be kept at a minimum. Consideration must also be given to the design of the mechanism to assure that under a partial separation condition, various pieces of the mechanism will not become trapped in the valve halves, thereby preventing valve closure.

Another significant area which must be given a great deal of consideration in the design of a crashworthy valve is the type of separation forces which are considered to act on the frangible section of the valve. The design practice in this area is currently based upon transmission of load to the valve through associated fuel system components. However, data obtained from this program and others have shown that all possible failure modes cannot always be anticipated. To increase the probability of the valve's working under all crash conditions, it is important that design considerations be given to the frangible sections of the valve bodies so that they are capable of separating at reasonable loads in shear, tension, and bending.

Various dynamic-fluid and dynamic-mechanical conditions influence the design of a self-sealing breakaway valve. Fluid surges experienced during dynamic tests may tend to displace parts of the valve not normally disturbed during static operation (i.e., Dynamic Test 1). Secondary impacts may produce structural distortions that affect the sealing (Dynamic Test 9). Though the valve may be designed to separate only when subjected to forces by the attaching fuel system components it is entirely possible that in a crash environment a valve could be impacted quite heavily by some outside object.

As in partial separation conditions, dynamic separation conditions also present special design requirements on the self-sealing mechanism of the valve. Dynamic Test 6 is an example. Under high rates of separation, parts of the self-sealing mechanism became trapped, bent, and subsequently lodged in the valve, preventing actuation of the self-sealing mechanism.

The boot separation of Dynamic Test 8 illustrates a problem which occurs in every valve design. The leakage requirements for the valve, the production cost of the valve, and the reliability requirements established for the valve must be weighed together. To this point in time, zero leakage has been required upon separation of the valves. This requirement has forced the valve industry into using rubber seats within the valve body. As a result a certain amount of sacrifice has necessarily been made in the overall reliability of the valve. This overall reduction in reliability comes from curing and bonding problems of rubber seats and boots and inspection problems of the completed valves. Based on the results of the program, it appears that reduction of leakage gained by the use of a soft seat in a valve as opposed to a hard seat does not, in most cases, warrant the attendant reduction of reliability. The state of the art presently is capable of producing hard seat valves which, while not attaining zero leakage on all occasions, will more than adequately provide the fluid control needed in a crash environment.

RECOMMENDATIONS

Based on the results of this program, when considered in the context of other experience gained in the field of aircraft crash safety, it is recommended that:

1. The self-sealing mechanism of the breakaway valves actuate before a maximum separation distance of 0.125 inch is achieved between the separating valve halves. This recommendation allows for the use of boots and seals to prevent external leakage before this actuation occurs as in current practice. However, the design goals should be for the self-sealing mechanism to actuate before the valve body fractures.

2. All valves designed for use as self-sealing breakaway valves be capable of separation by the application of shear, tension, or bending forces. The limit or maximum value of these forces will, of course, depend on the specific application of the valve. However, in no case should any one of the forces be more than three times the magnitude of the other two. Design of the frangible section to meet this criterion will assure that the proper separation of the valve will occur during unanticipated load applications which may occur in the crash environment.

3. The valve body be designed to withstand high impact forces without damaging the self-sealing mechanism. This may be accomplished by the use of extremely strong valve body walls or a crushable valve body which does not affect the self-sealing mechanism or the seat.

4. No "time-life" synthetic materials be used in the valve assembly. Where possible, all external seals should be eliminated. Where practical and leakage requirements allow, the use of hard seat valves should be incorporated. Experience has shown that adherence to this will increase the reliability of the valve and reduce production problems.

5. Breakaway valve self-sealing mechanisms contain as few parts as possible and eliminate sliding fits. Careful consideration must be given to the actuation mechanism with respect to the dynamic separation of the valve. As demonstrated in the test series, the relative speeds achieved during separation under high-speed impact conditions can damage the self-sealing mechanism. Therefore, adherence to simple

designs with no sliding fits will help to prevent this situation.

6. The valve be designed such that no contamination traps exist in the self-sealing mechanism. The elimination of these traps, as well as sliding fits, will prevent jamming of the self-sealing mechanism upon separation.

7. The internal valve configuration be as free of voids as possible. In all cases, the self-sealing mechanism should be designed such that it is not encased in any of these voids which may collect water and cause problems during separation in a sub-zero environment.

APPENDIX I

FAILURE LOAD ANALYSIS FOR EXPERIMENTAL FRANGIBLE TEST SECTION

Assume material used is 2014-T6

BENDING FORCE

$M = SI/C\ K$

where

$S = 57{,}000$ psi

$I = .021$ in.^{4}

$C = .50$ in.

$K = 1.3$, dimensionless (plastic bending factor)

$M = 3{,}120$ in.-lb

$$F = \frac{3{,}120}{4} = 780 \text{ lb}$$

TENSION FORCE

$$S = \frac{3F}{2\pi t^2}\left[1 - \frac{2b^2}{a^2 - b^2}\left(\log \frac{a}{b}\right)\right]$$

where

$F = 800$ lb

$t = .020$ in.

$a = .71$ in.

$b = .59$ in.

$S = 180{,}800$ psi

However, when yielding occurs in the above section, part of the load is carried in tension. This condition has the effect of making the above condition extremely conservative. Test data on a valve section of this size indicates that the actual stress value is one-third.

Therefore, the corrected stress is 60,000 psi, which confirms the assumed force.

SHEAR

$S = F/A$

where

$S = 30{,}000$ psi

$A = .191$ in.^{2}

$F = 5{,}730$ lb

Because of buckling and local bending, only about one-half the area is effective in direct shear:

$$P = \frac{5{,}730}{2} = 2{,}800 \text{ lb}$$

APPENDIX II

SUMMARY OF DRAFT MILITARY SPECIFICATION (SELF-SEALING BREAKAWAY VALVES FOR CRASH-RESISTANT AIRCRAFT FUEL SYSTEMS)

Requirements from the draft specification that are applicable to design and testing of self-sealing breakaway valves are summarized in this appendix.

Design and construction criteria were stipulated as follows:

Design and Construction - The valves shall be designed with a frangible section constructed to fail at a predetermined point and load. Upon separation, internal self-sealing mechanisms in each valve section shall automatically close and seal, preventing leakage of flammable fluids. Means shall be provided to prevent external leakage after separation prior to closing of both valve halves. Construction of the valves shall be the simplest possible design consistent with the requirements of this specification and shall facilitate quantity production.

Because each aircraft fuel system is unique, no attempt was made to control valve configuration (see below).

Valve Configuration - The outside configuration of the valve, such as the method of mounting, the type of fluid connections, and the permissible envelope, shall be determined by the contractor to meet the specific needs of each fuel system.

The following design criteria were presented to insure that the proper functional requirements are given design consideration:

Separation Modes - The valve assembly shall be designed to separate and seal upon application of a predetermined load caused by a force producing tension, bending, or shear, or combinations thereof, in the frangible section of the valve. The self-sealing mechanisms of the valve assembly must close before a maximum relative displacement of 0.125 inch occurs between the separating valve sections at the point of fracture. These loads shall be applied statically and dynamically. Upon separation of the valve assembly, each valve section shall meet all the functional requirements.

Static Load Determination - The valve assembly shall be designed to meet all operational and service forces of the aircraft while being designed to fail at a force between 25 and 50 percent of the load required to fail the weakest component of the fuel system adjacent to the valve assembly. Such force or forces shall be designated as the primary forces. The force or forces produced on the valve assembly by other than direct transmittal through the fuel system shall be designated as secondary forces. The valve assembly must be capable of separation caused by such secondary forces which are to be no larger than three times the primary forces and no less than the force required to meet the operational and service force.

Figure 48 presents an example of the determination of the type of force acting on the valve assembly. All valve assemblies must be designed to separate with the application of primary or secondary forces in any of three basic modes: tension, bending, or shear.

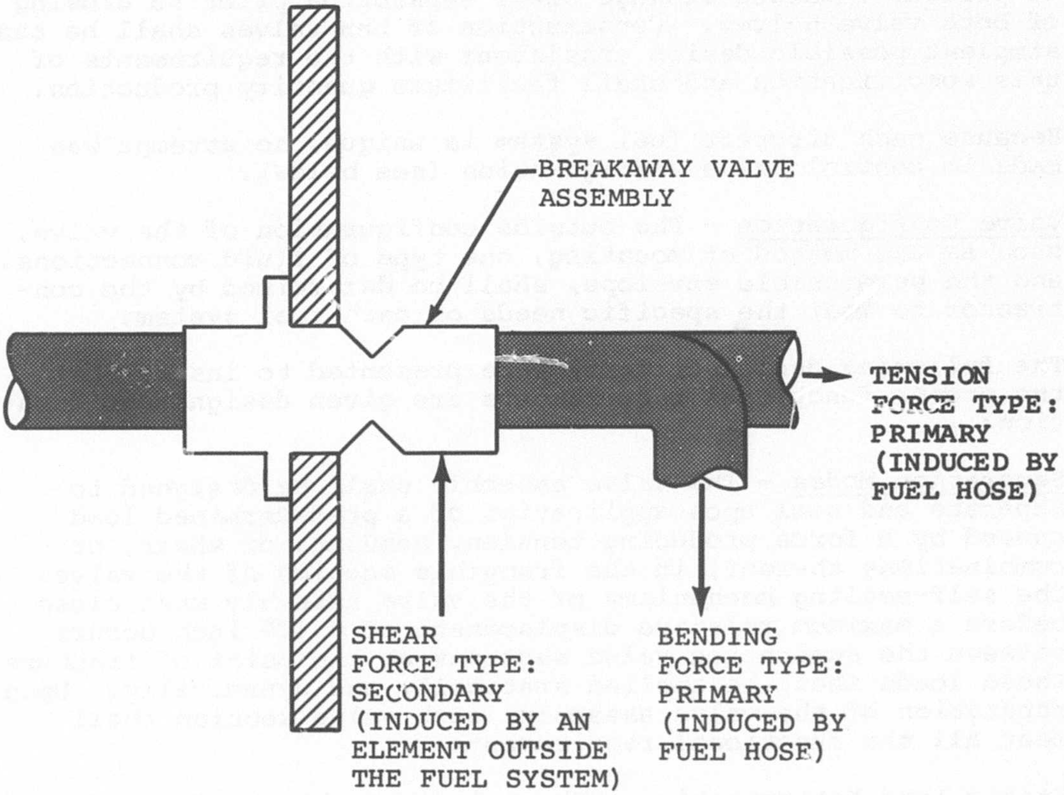

Figure 48. Example of Primary and Secondary Force Determinations.

Spillage - The amount of spillage of fuel upon valve assembly separation shall not exceed four times the volume trapped between the self-sealing mechanisms of the valve assembly.

To validate the valve's performance, several special tests were devised or modified to meet specific operational or crashworthiness needs:

Contaminated Fuel Endurance Test - Test fluids containing specified types and concentrations of contaminants shall be circulated through the valve assembly. This test fluid will be circulated through the valve assembly at rated flow for 2-1/2 hours, followed by an additional circulation period of 2-1/2 hours with the test fluid flow rate reduced to 10 percent of rated flow. Following this 5-hour circulation period, the valve shall be subjected to the static separation load tests covered below. If a recirculating fluid system is used, the minimum fluid quantity in the system shall equal the total fluid flow for 2 minutes at the rated flow of the component plus 10 gallons.

The major modification of this contaminated fuel test was the elimination of the valve flushing after removal from the system and prior to valve actuation. This procedure now more closely duplicates the actual service exposure of the valve.

Icing Test - The valve assembly shall be installed in a test system in the attitude that represents the valve's installation in the aircraft. One gallon of water will then be passed through the system at a flow rate not to exceed 1/2 gpm. The test fluid at 0°F will then be circulated through the system at 10 percent of rated flow until the valve temperature has stabilized at 0°F for a period of 1/2 hour. The test system shall also incorporate a method for maintaining a 0°F environment on the external parts of the valve. With the chill cycle complete, the valve will be subjected to the static test. At no time throughout the static separation load test shall the temperature of any part of the valve rise above 20°F. Following the test, the valve must comply with all of the leakage requirements.

This test was included to simulate the condition in which water may become trapped within the valve and freeze. This condition has been shown to seriously affect the operation of the valve mechanism as it is separated.

Static Separation Load Test - The valve assemblies shall be subjected to static forces that produce tension, bending, and shear loads in the frangible section sufficient to cause valve separation. The forces required to effect this valve separation must be within specified limits and must not be applied at a rate to exceed 1 inch per minute if conducted in a standard tensile machine. The bending force shall be applied through the moment arm anticipated in the actual installation (determined by the manufacturer's analysis). The valve assembly shall be pressurized to rated pressure during the static tests, and the total amount of spillage occurring upon separation of the valve must be within the specified amount. Upon complete separation of the valve assembly, each valve section shall be subjected to the functional tests.

Dynamic Load Separation Test - Three valve assemblies shall be dynamically separated in tension, bending, and shear. The dynamic forces shall be applied to the valve assembly in the same manner as the forces would be applied in the aircraft and within a time period not to exceed .005 second. The relative velocity occurring between the separating valve sections in this period of time must reach 65 ±5 fps. Throughout the test sequence, the valve assembly as well as the resulting valve sections shall be pressurized with the test fluid to the maximum rated pressure. Upon separation, each valve section shall be subjected to the leakage tests.

The above static and dynamic tests were included to verify that the separation requirements are met.