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FINAL REPORT

INVESTIGATION OF CRYOGENIC RUPTURE DISC DESIGN

by

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MARTIN MARIETTA CORPORATION

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16. Abstract

Rupture disc designs of both the active (command actuated) and passive (pressure ruptured) types were evaluated for performance characteristics at cryogenic temperatures and for capability to operate in a variety of cryogens, including gaseous and liquid fluorine. The test results, coupled with information from literature and industry searches, were used to establish a statement of design criteria and recommended practices for application of rupture discs to cryogenic rocket propellant feed and vent systems.

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FOREWORD

The work described herein was conducted by the Martin Marietta Corporation, Denver Division, under NASA Contract NAS3-14345. Work was done under the management of the NASA Project Manager, Mr. Thomas W. Godwin, NASA-Lewis Research Center, Cleveland, Ohio, Chemical Rocket Evaluation Bench.

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ABSTRACT

Rupture disc designs of both the active (command actuated) and passive (pressure ruptured) types were evaluated for performance characteristics at cryogenic temperatures and for capability to operate in gaseous and liquid nitrogen, hydrogen and fluorine. The test results, coupled with information from literature and industry searches, were used to establish a statement of design criteria and recommended practices for application of rupture discs to cryogenic rocket propellant feed and vent systems.

INVESTIGATION OF CRYOGENIC RUPTURE DISC DESIGN

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SUMMARY

This is the final report of a 22-month program that was conducted under Contract NAS3-14345. The objective of the program was to investigate a number of rupture disc designs applicable to propellant flow lines and tank safety vents for cryogenic systems in general, and for hydrogen-fluorine and FLOX-methane rocket systems in particular. Two active disc designs and three passive disc designs were procured and tested to determine their performance at cryogenic conditions. The results of this program have been summarized in the form of design criteria and recommended practices.

The program consisted of five basic tasks, namely:

Task I - Study of Design Concepts

Task II - Cryogenic Static Testing

- Phase I - Screening Tests
- Phase II - Cryogenic Static Tests

Task III - Water Flow Testing

Task IV - Fluorine and FLOX Compatibility

Task V - Reports and Design Criteria

During Task I, a literature search, patent search and industry survey were made to acquire information on all available design concepts. Requests for proposals were then sent out to all known rupture disc manufacturers and to all interested valve manufacturers. Proposals were then evaluated to select two active (command-actuated) disc designs and three passive (pressure-ruptured) disc designs for test evaluation.

In Task II, passive discs having ratings of 50 psi (34.5 N/cm^2) and 100 psi (68.9 N/cm^2) were subjected to rupture tests on gaseous nitrogen at -285°F (97 K) and gaseous hydrogen at -395°F (36 K) respectively. Active discs were subjected to actuation tests in liquid nitrogen and liquid hydrogen. The Phase I rupture tests served to assess the relative merits of the three passive designs from the standpoints of predictability and repeatability of rupture pressure and debris generation. Active disc designs were evaluated for reliability of operation and repeatability of disc open area. Phase II consisted of more extensive cryogenic tests on one preferred passive design and one preferred active design.

In Task III, the active rupture discs were tested for flow capacity, using water as the test medium, in order to assess the repeatability of pressure drop characteristics in the post-actuation condition.

In Task IV, the preferred passive and active disc designs were tested at cryogenic temperatures in gaseous and liquid fluorine respectively, in order to determine whether a catastrophic reaction would occur, when the device opens.

Task V consisted of preparing a statement of design criteria and recommended practices, utilizing available information and the new findings resulting from this program.

The salient results of this program were as follows:

1. One currently-available passive rupture disc design was identified which is suitable for cryogenic service, and has a minimum sensitivity to temperature. Due to a planned testing program at NASA-Lewis Research Center on that design (Design A), it was not tested in this program.

2. Previously unavailable data on the cryogenic performance of passive rupture disc designs having reduced sensitivity to temperature was obtained.

3. Two cryogenic active rupture disc concepts were conceived and developed to the prototype hardware stage, and one of the concepts was tested extensively in liquid nitrogen, liquid hydrogen and liquid fluorine.

4. A current assessment of the state of the art in passive and active rupture discs was made.

5. The feasibility of operating both passive and active rupture discs in a fluorine system has been demonstrated.

6. The feasibility of employing pressure cartridges (squibs) as an actuation energy source at temperatures down to $-423^{o}F$ (20 K) was proved.

7. The information acquired in this program was employed to establish an up-to-date set of design criteria and recommended practices for application of rupture disc devices to propellant feed systems.

INTRODUCTION

Background

The requirements of proposed longer-duration space exploration missions are stimulating the development of larger propulsion systems that use the high energy cryogenic propellants such as fluorine/hydrogen and FLOX/methane. The long coast times associated with the missions place very stringent constraints on propellant loss caused by boiloff or leakage. The requirements for zero leakage propellant retention to the degree of reliability demanded by such missions can only be satisfied by hermetic closures such as those afforded by rupture discs and frangible-section valves.

In addition to the deep space mission propulsion systems, the Space Shuttle system will also employ cryogenic propellants. In such a man-rated system, the safety requirements for tank over-pressure protection may dictate that rupture discs be employed. In this application, the simplicity and reliability of a rupture disc are more relevant than its hermetic sealing characteristics.

Passive, or pressure actuated, discs are generally used for system protection against overpressure. As a system protection device, the passive rupture disc protects the tank from possible catastrophic failure by rupturing at a predetermined pressure level. This type of device is referred to as pressure-ruptured or pressure actuated. Active, or command actuated, discs are more applicable as propellant isolation devices. They can be used alone or in series with a shut-off valve. For 2.5 inch (6.4 cm) and larger diameter feed-lines, an active rupture disc would appear more attractive than an hermetically sealed valve, from the standpoint of weight, reliability and actuation force requirements.

There exists considerable experience and design information on passive rupture discs (bibliography) at ambient and elevated temperatures, but the application of rupture discs to airborne cryogenic propellant systems, particularly fluorine systems, has been handicapped by very limited experience with either passive or active rupture discs in cryogenic service.

A potential problem that becomes particularly severe for low pressure cryogenic service typical of propellant tankage is the substantial increase in the strength of the disc material at low temperature. Both these factors (high strength and low pressure) tend to force the use of thinner disc sections, with the associated more severe requirements in design, material properties control and manufacturing process controls. The most significant aspect of this potential problem, however, is that the severity of the problem is not generally known, as evidenced by the conspicuous absence of literature on this subject.

In light of the anticipated usage of rupture disc devices in cryogenic systems, and in view of the substantial lack of information on these devices, the program described in this report was undertaken with the objective of assessing the state of the art for both passive and active discs, upgrading it on important areas of deficient knowledge and presenting a current and useful compendium of criteria and recommended practices for propulsion system designers.

Approach

The approach to the problem addressed in this program was organized into a logical sequence of tasks consisting of first searching out all existing information on the subject; acquiring industry proposals for design concepts which reflected the requirements peculiar to low pressure cryogenic service in general and fluorine service in particular; procuring and evaluation testing of the more promising designs; and analyzing both the beneficial and adverse performance characteristics for the purpose of identifying the significant design criteria which must be recognized and the recommended practices to be employed to successfully fulfill the criteria.

Task I was a study of design concepts, starting first with a search of the technical literature and U.S. patent files, and then an inquiry survey of all known organizations in the rupture disc and valve industries. Requests for proposals for both active (command-actuated) and passive (pressure-actuated) rupture disc devices, designed to the accompanying design specifications, were then solicited from all rupture disc manufacturers and those valve manufacturers who had indicated an interest in the subject. Proposed designs were then evaluated on the basis of a set of weighted criteria in order to select the most promising designs (2 active disc designs and 3 passive disc designs) for evaluation testing. The purpose of this program was to evaluate the selected design concepts, and was not in any way an evaluation of manufacturer's capabilities.

Task II was devoted to performing cryogenic temperature testing on the designs which were selected in Task I. Phase I of Task II was to identify one of the two active discs and one of the three passive discs as being the most worthy of more extensive cryogenic testing in Phase II and fluorine compatibility testing in Task IV. In Task II, 50 psi (34.5 N/cm^2) rated passive discs of fluorine and hydrogen compatible materials were subjected to rupture tests in gaseous nitrogen at -285°F (97 K) and gaseous hydrogen at -395°F (36 K) respectively. Active rupture discs were subjected to actuation tests in liquid nitrogen and liquid hydrogen, using a limited volume flow system. The Task II Phase I tests served to evaluate the relative merits of the three passive disc designs from the standpoints of predictability and repeatability of rupture pressure and also debris generation. The active disc designs were evaluated for reliability of operation, repeatability of disc open area and debris-generating characteristics. Phase II testing of the preferred active and passive designs consisted of a greater number of tests similar to those of Phase I with the addition of various pre-conditioning exercises such as upstream and downstream pressure cycling and pre-exposure to gaseous and liquid fluorine. In addition, the passive disc testing in Phase II included rupturing discs at pressure onset rates of 1000 psi/second (689 N/cm^2/sec). The general objective of the Phase II testing was to aquire a sufficient number of data points to establish the reliability of the passive and active designs to a reasonable confidence level, and also to determine the effects of pre-cycling, high pressure rise rates and pre-test exposure to fluorine.

Task III involved the active rupture discs only, and was conducted concurrent with both phases of Task II. The objective of Task III was to determine the flow capacity (pressure drop) of the active discs and the repeatability of the flow capacity (disc open area). The flow capacity tests were run at a water flow rate which would produce approximately the same pressure drop that would be produced by the cryogenic propellants at the design flowrate.

Task IV was devoted to testing the Phase II preferred active and passive disc designs in gaseous and liquid fluorine at cryogenic temperatures. Although this Task is entitled "Fluorine and FLOX Compatibility", no FLOX was used in the program, since it is generally conceded that hardware which is proved to be compatible with fluorine will also be suitable for use in a FLOX system. The single objective of the Task IV testing was to establish that rupture discs could be operated in gaseous and liquid fluorine without incurring a catastrophic reaction due to energetic exposure of unpassivated surfaces, especially when thin sections with limited heat-transfer areas are involved.

The concluding effort of this program was to translate the information gained into a statement of design criteria and recommended practices for the designer's use in applying rupture discs to flight propulsion systems in general, and cryogenic and fluorine systems in particular. This information is included as Appendix A.

The main text of this report is separated into two categories, namely, the passive disc program and the active disc program, since it is anticipated that the reader's interest may be oriented more toward one category of disc than the other.

PASSIVE RUPTURE DISC PROGRAM

Study of Design Concepts

The initial task (Task I) of the passive rupture disc program was to acquire all possible information on existing passive disc designs and to assess the relative merit of the various concepts for the purpose of selecting the more promising designs for test evaluation.

Study Methods. - Three avenues were used to search out information on rupture disc devices: A search of the literature, a search of the U.S. Patent Office files and a survey of the industry. The information being sought included not only descriptions of the available concepts, but also information on analytical work and empirical data on the behavior of various types of discs, particularly in cryogenic and corrosive-medium service.

The literature search was conducted through the Defense Documentation Center, Arlington, Virginia, and consisted of a search of the Department of Defense (DOD) and NASA listings under subject titles such as Rupture Discs, Rupture Diaphragms, Burst Discs, Diaphragm-type Valves and Propellant Tank Closures. Concurrent with this effort, a "state-of-the art" search under the same subject titles was initiated through the U.S. Patent office in Washington D.C.

During the period in which the literature and the patent files were being searched, a listing of all rupture disc and valve manufacturers was compiled from the Martin Marietta Corporation Procurement Department microfilm files. Upon completion of the literature and patent searches, the completed list was used to mail out a letter describing the general scope and objectives of the proposed evaluation program, and inviting expressions of interest. A request for proposals (RFP) was then sent out to all interested manufacturers, with an accompanying preliminary design specification. The RFP included a request for rough-order-of-magnitude costs.

The passive disc design proposals were evaluated on the basis of the design criteria and vendor qualification criteria shown in Figure 1. The results of the evaluation were reviewed by the Martin Marietta Corporation Technical Advisory Group assigned to this program. Members of the group represented the disciplines of airborne hardware mechanical design, reliability engineering, ordnance, metallurgy, fluorine technology and cryogenic technology. Based on the evaluations and reviews, three passive disc designs were selected for the NASA Project Manager's review and approval.

Study Results. - The results of the literature search through the DOD listings were completely negative; however, the search of the NASA listings yielded eight pertinent reports and papers which are listed in the bibliography. The patent search resulted in acquisition of the names of nine potential manufacturers who would otherwise not have been identified.

PASSIVE DESIGN

MFGR:

DESIGN EVALUATION		
Item	Range	Grade
Adaptability to Rocket Propulsion Systems	0-3	
Reliability (Repeatability)	0-10	
Debris Generating Potential	0-7	
Suitability for Cryogenic & Fluorine Service	0-7	
Cleanability	0-5	
Relation to State of Art (Advanced Concept?)	0-3	
Weight; Size	0-2	
Tolerance to Pressure Cycling	0-3	
Temperature Sensitivity	0-5	
Materials Selection	0-5	
Development Status (Shelf Item, Modified S/I)	0-2	
Sealing Characteristics (Internal, External)	0-7	
Ease of Disc Replacement	0-2	
Flow Capacity (ΔP)	0-2	
Rupture Technique (Complex, Simple)	0-7	
TOTAL	0-70	

Remarks:

COMPANY EVALUATION		
Item	Range	Grade
Rupture Disc Experience	0-5	
Cryogenic Experience	0-5	
Fluorine Experience	0-5	
Zero-Leak Experience	0-5	
Present Related Work	0-5	
Adequacy of Facilities	0-5	
TOTAL	0-30	

DESIGN EVAL:	
COMPANY EVAL:	
GRAND TOTAL:	

Figure 1. - Passive Disc Design Evaluation Sheet

In the industry survey, 250 valve manufacturers were sent a letter describing the general program objective and inviting expressions of interest in either passive or active rupture discs. The results of the survey were as follows:

No Answer:	184
No Interest:	46
Definitely Interested:	20

Requests for proposals were mailed to 22 known rupture disc manufacturers, the 20 interested valve manufacturers and 2 of the 9 manufacturers identified in the Patent Search. Copies of the exhibits which accompanied the RFP (Exhibit A: Program Scope and Objectives; Exhibit B: Preliminary Design Criteria) are included as Appendix B to this report. The response to the RFP resulted in the acquisition of seven proposals for passive rupture discs. It should be noted here that one of the significant design criteria given the proposers was that a temperature-insensitive design was desired, i.e., one which would experience not more than a 15% shift in rupture pressure throughout the temperature range from room temperature to liquid hydrogen temperature. The 15% value was selected as a feasible target on the basis of limited data provided by one manufacturer for reverse-buckling discs. All of the proposed concepts reflected techniques for circumventing reliance on tensile failure of the disc to effect rupture. No constraints on rupture method were imposed by the design criteria.

The proposed passive disc concepts are shown schematically in Figures 2 through 8. Code designations have been used to identify the various designs. Identification of the manufacturers may be requested of the NASA Project Manager by reference to the code letter.

Design A, consisting of a movable disc, a Belleville spring and a fixed hole-punch, utilizes the previously discussed advantages of the modulus of elasticity to minimize the effects of temperature on set-point. In addition, the negative spring rate characteristic of the Belleville spring provides a snap action which permits satisfactory hole-punching of discs which are thick enough to insure that the disc rupture pressure is significantly higher than the pressure at which the device actuates. A desirable feature of Design A is that it incorporates set-point adjustments which are set with the hole-cutter removed.

Three of the designs submitted (designs B, C and D) were revserse-buckling discs in which the only significant difference was the method of retaining and sealing the disc in the holder or body. The manufacturer of design B had also produced all-welded versions similar to design C; however, he had proposed the screwed-union version as a more economical means of satisfying the multiple-test requirements of the program. The manufacturers of designs B, C and D also manufacture tensile-failure discs such as the pre-bulged and coined-groove flat disc types; however, three constraints of the program criteria compelled them to propose their reverse-buckling designs: First, the program was restricted to the low-pressure range which is characteristic of flight propellant tanks, being in the range of 50 psi (34.5 N/cm^2) to 100 psi (68.9 N/cm^2).

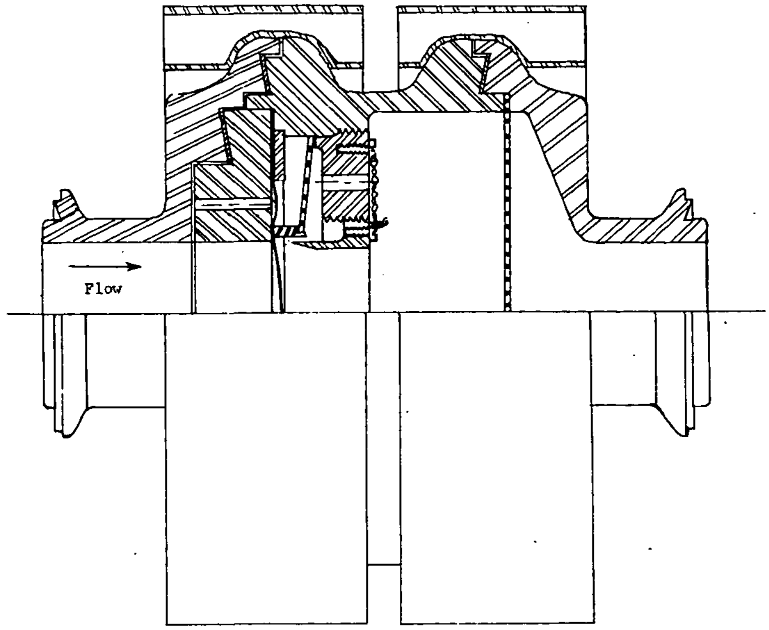


Figure 2.- Design A

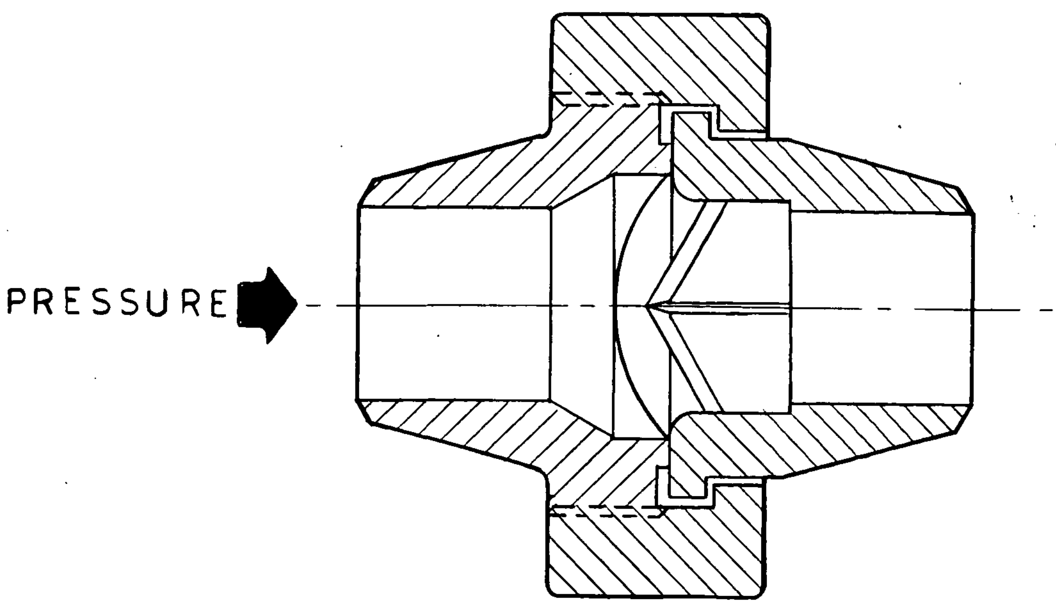


Figure 3.- Design B

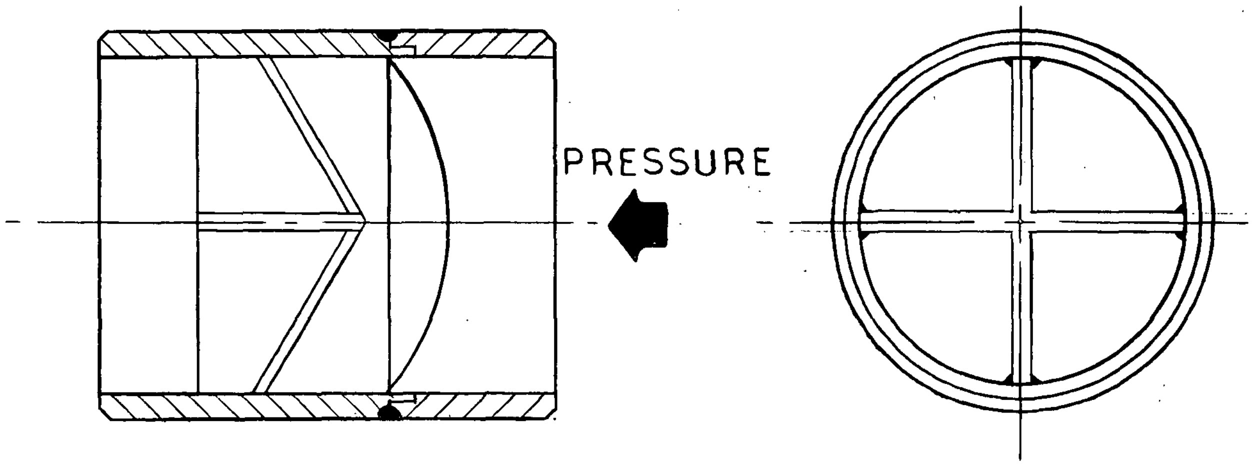


Figure 4.- Design C

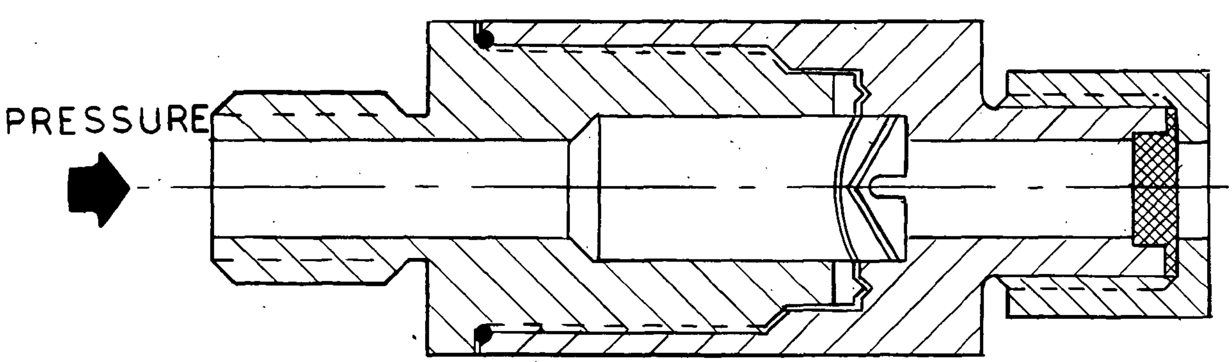


Figure 5.- Design D

Second, the nominal piping size was restricted to the range of 1 inch (2.5 cm) to 1.25 inch (3.2 cm). Both of these constraints force the use of very thin disc sections and the associated severe tolerance controls. For a given disc diameter and pressure rating, the reverse-buckling design requires a thicker disc than pre-bulged or coined discs, thereby improving the repeatability of the disc for a given level of thickness tolerance control. The third constraint imposed was that the disc be designed to minimize the effect of temperature on rupture pressure. Whereas the tensile-failure types of discs can be expected to increase their rupture pressure by an amount proportional to the significant increase in ultimate strength of most materials at cryogenic temperatures, the reverse-buckler can be expected to react to the modulus of elasticity of the material, which does not change as markedly as the ultimate strength.

Two of the seven designs submitted, designs E and F, used a pressure-operated trigger and spring loaded cutter to achieve a design which is largely independent of the disc strength changes. The remaining design, Design G, utilizes the

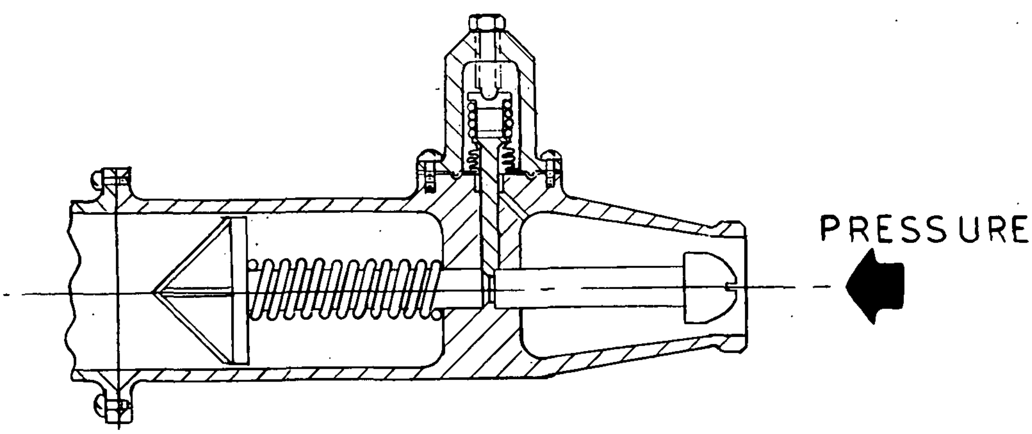


Figure 6. - Design E

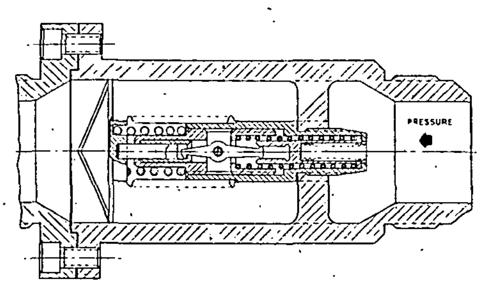


Figure 7. - Design F

temperature-independent strength characteristic of zinc as a shear disc material to restrain the poppet shaft, plus the pressure sensitivity afforded by the force amplification resulting from applying commodity pressure over the large poppet area and reacting the force with the small diameter shear disc. The periphery of the poppet is serrated to enhance the cutting action of the inlet closure disc or diaphragm. The inlet diaphragm is configured with a single bellows-like convolution to permit the poppet to move into and cut the diaphragm.

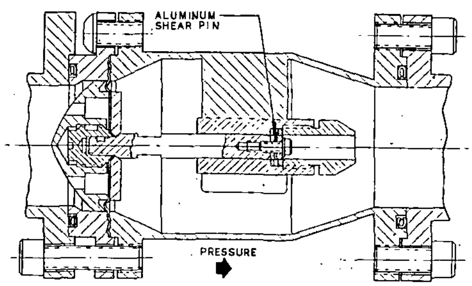


Figure 8.- Design G

In the evaluation of the seven proposed designs, the most heavily weighted criteria were simplicity of design, reliability, repeatability, sealing characteristics and suitability for fluorine service (cleanability of the design and compatiability of materials). Since several of the designs were conceptual, no measure of reliability in even room-temperature operation was available; therefore, the assessment of the probable reliability of the design was necessarily qualitative. The general criterion used was that the more complex designs would be less reliable, although the more complex designs might be superior from a temperature-insensitivity standpoint.

Design A (Figure 2) was rated very highly; however, Lewis Research Center had already acquired several of these units for testing, and data on their performance at cryogenic temperatures and in fluorine service would be made available to this program. Design A was accordingly eliminated from the evaluation.

Of the remaining six designs, the three reverse buckling designs (Figures 3, 4 and 5) and the shear-disc restrained poppet design (Figure 8) were considered to be the remaining contenders, mainly on the basis of their relative simplicity. One of the reverse buckling designs (Design D, Figure 5) was only available in a 3/8 inch(1.0 cm) size with a 5/8-inch (1.6 cm) diameter disc, being considerably smaller than the 1.25 inch (3.2 cm) nominal size desired for the program. In view of the availability of the other reverse-bucklers in the desired size range, Design D was retired from consideration.

As a result of the above elimination process, the three remaining designs were the all-welded reverse buckler (Design C), the union-type reverse buckler (Design B) and the restrained-poppet design (Design G). The initial scope of the program specified that only two passive designs be selected for test evaluation in Task II Phase I; however, it was decided that all three of the selected designs be included. The poppet/shear disc design was definitely wanted for the program, since it held promise of being the least temperature sensitive of the designs under consideration. With regard to the two reverse-buckling designs, the all-welded design was desired because its configuration more closely approached that anticipated for flight systems; however, the projected costs for providing these one-usage units for the very extensive testing in the subsequent Phase II and Task IV argued for including the reusable Design B reverse-buckler as a hedge. In the event that the Phase I test results indicated substantially equal performance of the two reverse-buckling designs, the less costly Design B could be chosen to continue the program into Phase II.

Cryogenic Testing (Task II, Phase I)

Test Scope. - The three passive disc designs approved at the conclusion of Task I were subjected to the tests summarized in Table 1.

Phase I consisted of a relatively small series of LN_2 and LH_2 temperature tests to compare the performance of the three selected designs. The end result of the Phase I testing was the selection of one passive rupture disc design for more extensive testing in Phase II. All three phase I designs were procured in both the 50 psi (34.5 N/cm^2) and 100 psi (68.9 N/cm^2) ratings. The 100 psi (68.9 N/cm^2) units were intended for hydrogen service, while the 50 psi (34.5 N/cm^2) units were intended for fluorine service.

TABLE 1. - CRYOGENIC TESTS, PHASE I

[Typical Number of Tests for Each of Three Designs]

Fluid	Temp.		Design Burst Press		Pressure Rise Rate		No. of Tests Each Design
	^oF	K	psi	N/cm^2	psi/sec	$N/cm^2/sec$	
GH_2	-395	36	100	68.9	<10	<7	5
GN_2	-285	97	50	34.5	<10	<7	5
*GN_2	-285	97	50	34.5	<10	<7	3

*Following 240 hrs. salt fog exposure per KSC-STD-164D

Test Specimen, Design B, Passive Disc. - The design B 1-inch I.D. (2.5 cm) passive disc is shown in Figures 3 and 9. The unit is shown in Figure 9 with the test fixture interface piping and bucking-wrench nut installed. The nut was added to accommodate the 350 foot-pound (475 N-m) torque requirement specified by the manufacturer for tightening the union nut. The holder body was not equipped with wrenching flats.

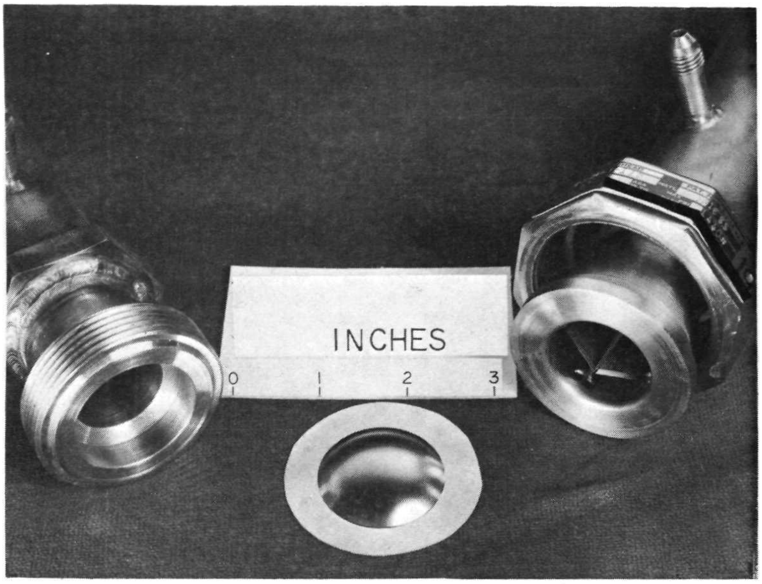


Figure 9.- One Inch (2.5 cm) Diameter Passive Disc - Design B

This disc design, intended for cryogenic propellant tank safety protection, is a reverse-buckler, designed such that it can be disassembled for disc replacement. One of the significant reasons for selecting this design was to permit evaluation of the mechanical disc sealing arrangement.

Test Specimen, Design C, Passive Disc. - The 1.25 inch (3.2 cm) Design C passive rupture disc is shown in Figures 4 and 10.

As with design B, this disc design operates on a reverse-buckling principle, in which the system pressure loads the convex side of the rupture disc until the disc buckles and snaps through onto a cutter.

The reverse-buckling concept (design B and C) tends to minimize the temperature effects on rupture pressure since the buckling phenomenon is more a function of the modulus of elasticity of the disc material rather than its tensile strength. The modulus of most disc materials changes only about 10% between temperature of $70^{\circ}F$ (294 K) and $-423^{\circ}F$ (20 K), whereas the tensile strength generally undergoes a much higher increase. The significant reasons for selecting the welded configuration of Design C were to evaluate the influence of welding on the repeatability or rupture pressure and to assess the cleanliness of this fabrication method for fluorine service. The 100 psi (68.9 N/cm^2) unit was furnished with a 316L annealed stainless steel disc. The 50 psi unit (34.5 N/cm^2) was identical to the 100 psi (68.9 N/cm^2) unit, except that the disc was made of nickel 200.

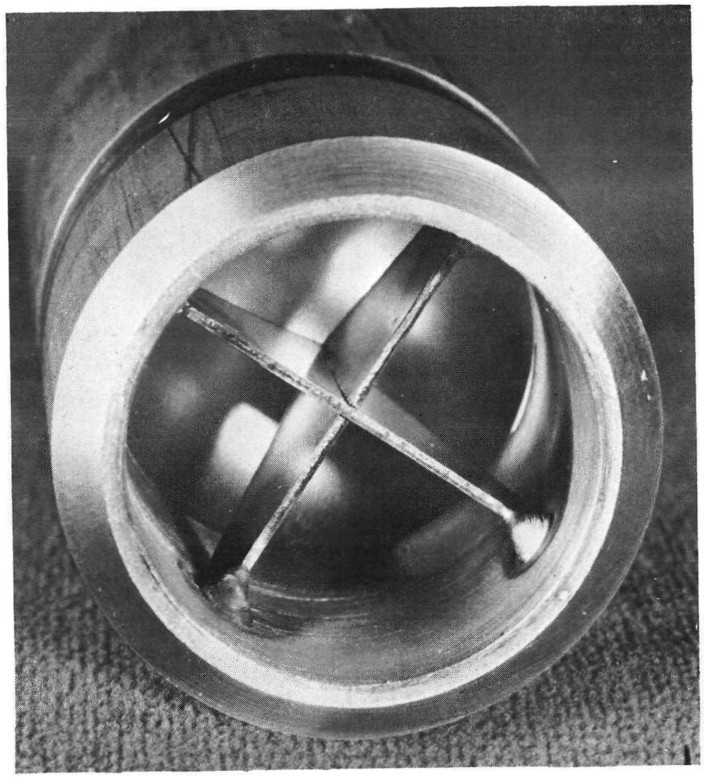


Figure 10.- Design C - Outlet View

Test Specimen, Design G, Passive Disc. - This design, shown in Figures 8 and 11, consists of an inlet diaphragm 0.002 to 0.003 inches (0.006 to 0.008 cm) thick, supported by a poppet and plunger which are in turn supported by aluminum shear pins. A feature of this design is the force-amplification afforded by the large poppet/diaphragm area and the small bearing area at the plunger/shear pin interface. The force amplification so provided was intended to reduce the variation or uncertainty in actuation pressure. This design would be expected to exhibit less temperature-induced shift in set pressure than the reverse-buckling designs, and would also be expected to exhibit less variation in operating pressure from run to run. The design is more complex than the reverse-bucklers. It was furnished with nickel 200 diaphragms (discs) for the 50 psi (34.5 N/cm^2) fluorine service and 1100-0 aluminum diaphragms for the 100 psi (68.9 N/cm^2) hydrogen service.

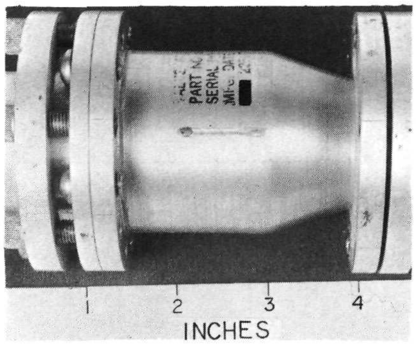


Figure 11.- Design G - Passive Disc

Test Fixture. - The passive disc test fixture, shown schematically in Figure 12 and pictorially in Figures 13 and 14, was equipped to perform all cryogenic testing through Task IV. The design of the fixtures was oriented toward minimizing test time by testing multiple passive units at a time and permitting alternate testing of passive and active units in the same cryostat. As shown in the figures, the entire test fixture is mounted in the lid of the cryostat.

During test, the cryogen level in the cryostat was maintained just above the bottom of the cryostat, so that the test items were conditioned to approximately $40^{\circ}F$ (22 K) above the cryogen boiling temperature. This arrangement permitted pressurization of the passive discs at the lowest temperature possible without encountering liquefaction of the GN_2 or GH_2 pressurant gas. The flow control orifices in the pressurant supply line were sized to provide the 1000 psi/second ($689\ N/cm^2/sec$) pressure rise required for some of the passive disc tests. The receiver vessels mounted on the outlets of the passive disc assemblies were provided to catch fragments. Thermocouples were attached to the bodies of the disc assemblies to confirm attainment of test temperature prior to pressurization.

The test fixture control valves and pressure transducers were mounted on a unitized structure which was disconnected from the cryostat lid with a minimum of effort and with minimum disturbance of the test setup. The commodity controls bench is shown to the left of the cryostat in Figure 14. The controls bench contains all of the remotely-operated valves to control admission of helium, hydrogen, nitrogen and fluorine gas to the fixture. The inlet pressure and outlet pressure transducers for each of the test items are also mounted in the tubing on the bench. The high-accuracy test gage being monitored by the technician was provided to obtain pressure-stimulus calibrations of all recording channels immediately after each disc rupture. This in-place pressure calibration technique was employed to circumvent any effects of temperature induced set point shift of the pressure transducers. All valves and transducers in the commodity control system were suitable for usage in fluorine, so that the fixture remained essentially unchanged throughout the Phase I, Phase II and Task IV test programs.

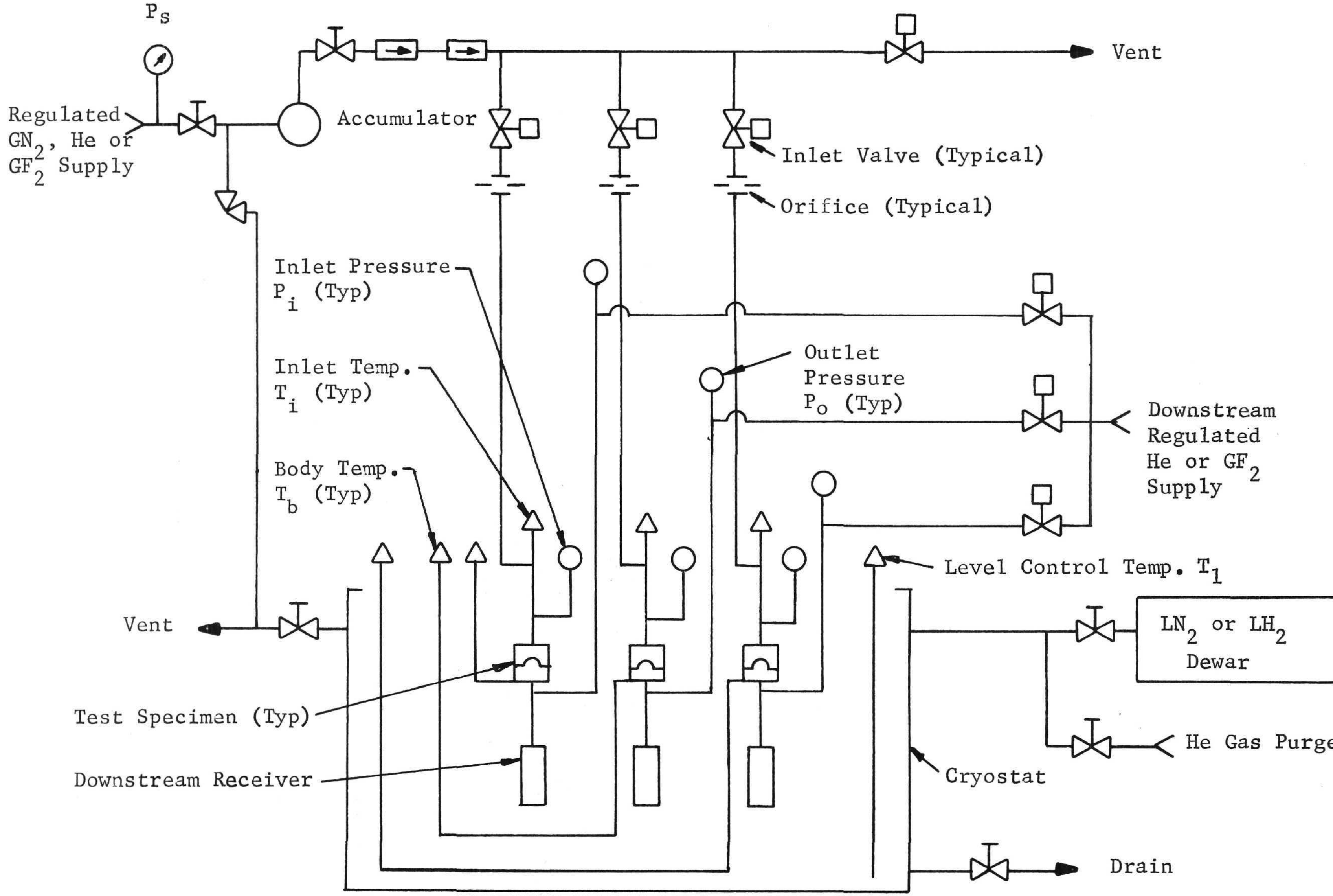


Figure 12.- Test Fixture Schematic

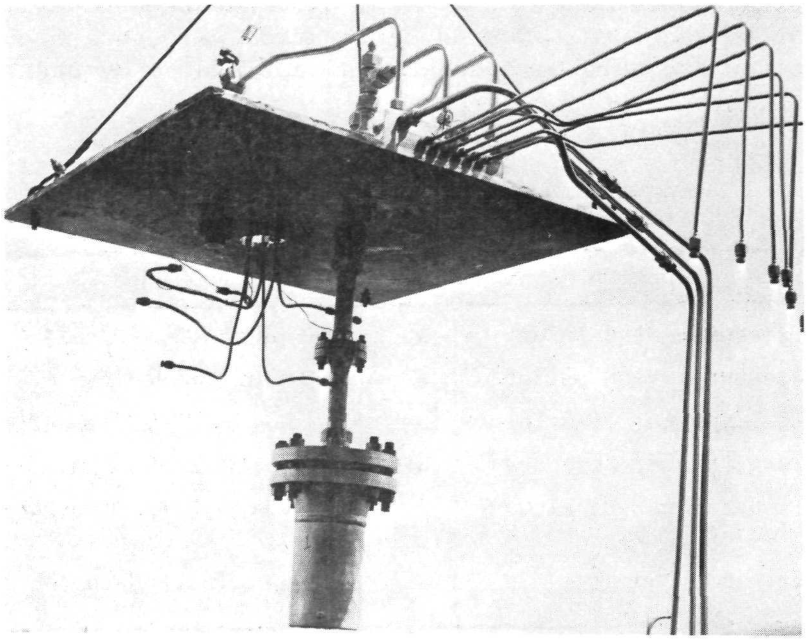


Figure 13.- Passive Disc Test Installation

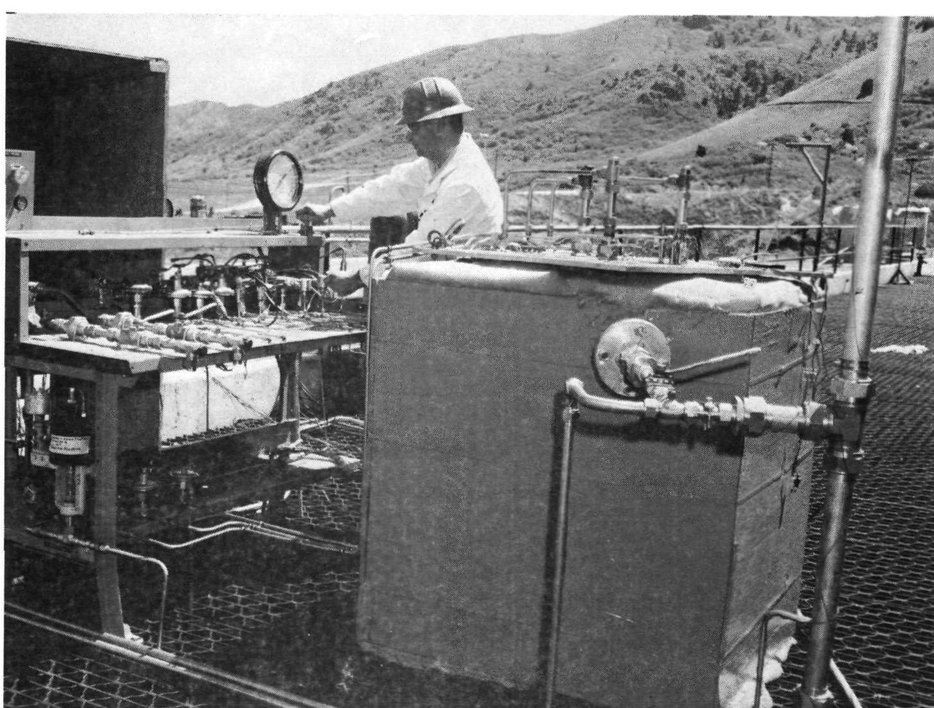


Figure 14.- Cryogenic Static Test Fixture

Instrumentation. - The instrumentation for all passive disc tests is shown in Table 2. During instrumentation set-up, all measurement devices were examined to insure that the equipment was in calibration. In addition, the data acquisition channels for pressure were end-to-end calibrated by pressure stimulus as noted earlier in this section.

TABLE 2.- INSTRUMENTATION - PASSIVE DISC TESTS

Symbol	Function	Type	Range	Accuracy
P_i	Pressure, Disc Inlet	A	150 psi (103.4 N/cm^2)	$\pm$ 1%
P_o	Pressure, Disc Outlet	A	100 psi (68.9 N/cm^2)	$\pm$ 1%
T_i	Temperature, Disc Inlet	B	0 to -423^oF (255 to 20 K)	$\pm$ 10^oF (6K)
T_b	Temperature, Disc Body	B	0 to -423^oF (255 to 20 K)	$\pm$ 10^oF (6K)
T_1	Temperature, Level Control	B	0 to -423^oF (255 to 20 K)	$\pm$ 10^oF (6K)
P_s	Pressure, Supply	C	100 psi (68.9 N/cm^2)	$\pm$ 0.2%

NOTES: A = Strain-Gage Type Pressure Transducer
B = Copper-constantan Thermocouple
C = Bourdon Tube Gage

Test Method. - The passive discs were mounted in the cryostat as shown in Figure 13. The cryogen (LN_2, LH_2) was introduced into the cryostat and maintained at a level sufficient to cool the test items to the required test temperature of -260 to -285^oF (111 to 97 K) for GN_2 tests or -380 to -395^oF (44 to 36 K) for GH_2 tests. During the cool-down, the pressurant supply system and the upstream side of the rupture discs were pressurized slightly, between 1 and 5 psi (0.7 to 3.4 N/cm^2) with GN_2 or GH_2. The downstream side of the rupture discs were maintained at approximately ambient pressure with helium during the cool-down period. After the body temperatures had stabilized at the required test temperature, the supply pressure was increased at the rate shown in Table 1 until the test item diaphragm ruptured. Continuous chart recordings were made of all parameters during the rupture sequence. Where indicated in Table 1, discs were preconditioned by salt fog exposure for 240 hours per KSC-STD-164D prior to installation in the test fixture. After the three test specimens had been tested, the cryostat was purged with warm GN_2, and the lid/fixture assembly removed for inspection and refurbishment of the test specimens and inspections (rinse and particle filtering) of the receivers.

Test Results. - The results of the Phase I passive rupture disc testing are shown in Figures 15 through 18 and Tables 3 through 5.

The design G passive disc failed to actuate during each of the five hydrogen tests and during one of the nitrogen tests. The test results are shown in Figure 15 and Table 3. Inspection of the unit indicated that, although the shear pins were shearing properly and thereby removing the poppet restraint, the poppet had been drawing the ductile 1100-0 aluminum diaphgram into the annular clearance space between the poppet periphery and the housing bore, with resultant jamming of the poppet before it had completely cut the diaphragm.

During the 10-day salt fog exposure pin holes developed in the very thin design G discs. The 50 psi (34.5 N/cm^2) discs are fabricated from nickel 200 sheet 0.0015 inches (0.0038 cm) thick, then chem-milled to the 0.0008 inch (0.002 cm) thickness. The manufacturer had reported earlier that pinholing was encountered after chem-milling; however, the delivered discs had no visible pin holes.

The design C all-welded reverse buckling disc exhibited the best performance; although the mean rupture pressure was approximately 15% above the design pressure, and the variation in rupture pressure was $\pm$ 15%. (See Figure 16 and Table 4). Characteristic performance of passive rupture discs at room temperature indicated that the variation in rupture pressure should not exceed $\pm$ 10%. No adverse effects due to the 10-day salt fog exposure were noted.

The performance of the design B union-type reverse buckling disc was quite erratic, exhibiting rupture pressure veriations from 2% above design pressure to 45% below design pressure (see Figure 17 and Table 5). The erratic behavior was attributed to wrinkling of the disc (shown in Figure 18) caused by rotation of the union halves during tightening of the union nut. The correlation between disc wrinkling and rupture pressure is also shown in Figure 18. The results shown in Figure 18 indicated that a rupture pressure variation of less than $\pm$ 10% could be expected of design B unit if the disc had not been damaged. The basic design of the union-type disc holder was such that no positive means of preventing relative rotation of the union halves was provided. In investigating the disc wrinkling problem with the manufacturer, it was found that their testing had all been done with a bolted-flange version of the disc holder, and further, that their experience with low pressure (thin) discs in the union version was virtually non-existent. Because of these factors, they had never encountered the rotation-induced wrinkling problem. Tests conducted by the manufacturer with the bolted-flange version at $70^{\circ}F$ (294 K), $-60^{\circ}F$ (222 K) and $-300^{\circ}F$ (89 K) showed variations in rupture pressure of not more than $\pm$ 6%, consistent with the performance of non-wrinkled discs shown in Figure 18.

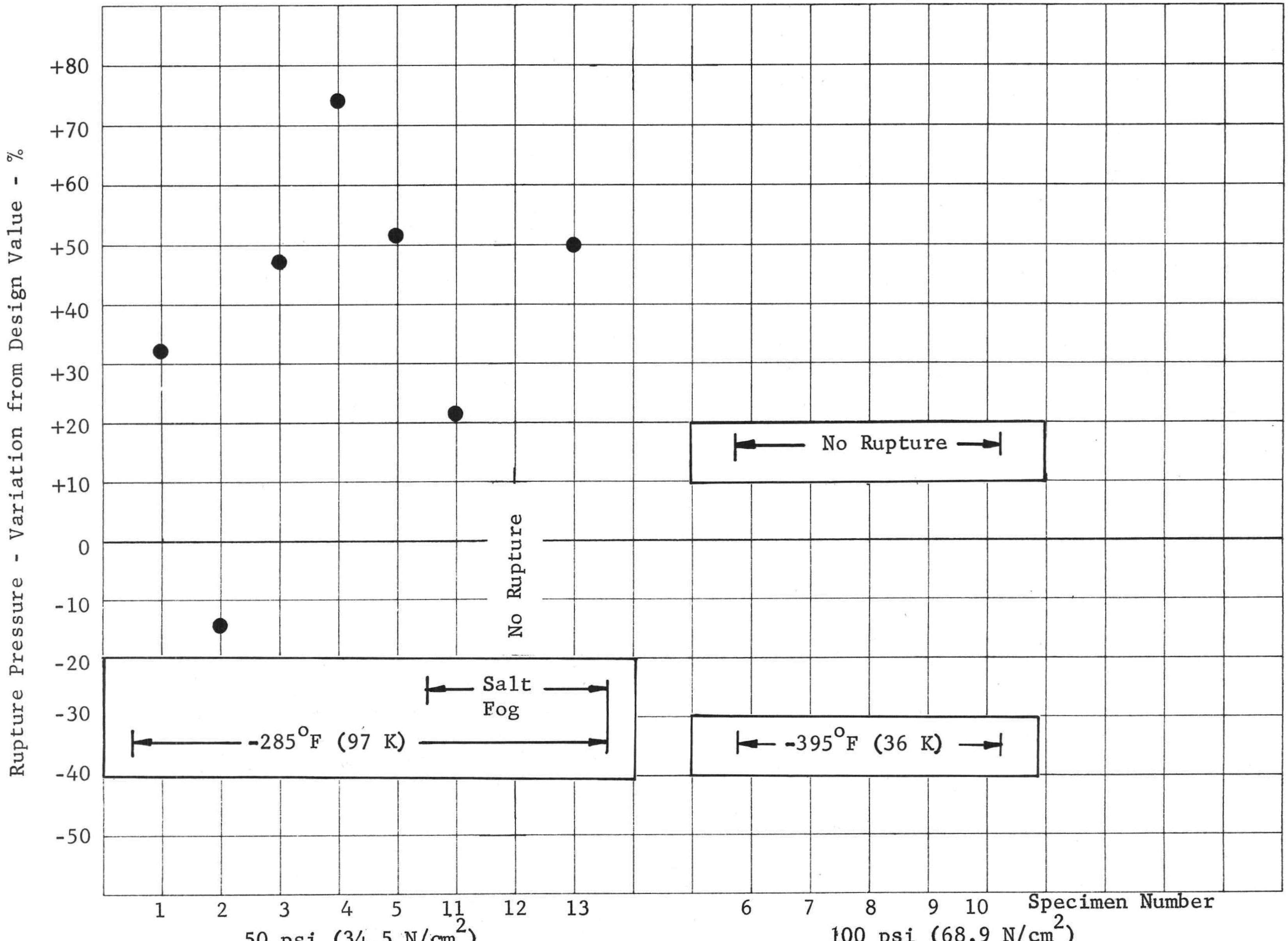


Figure 15. - Phase I Passive Disc Performance - Design G

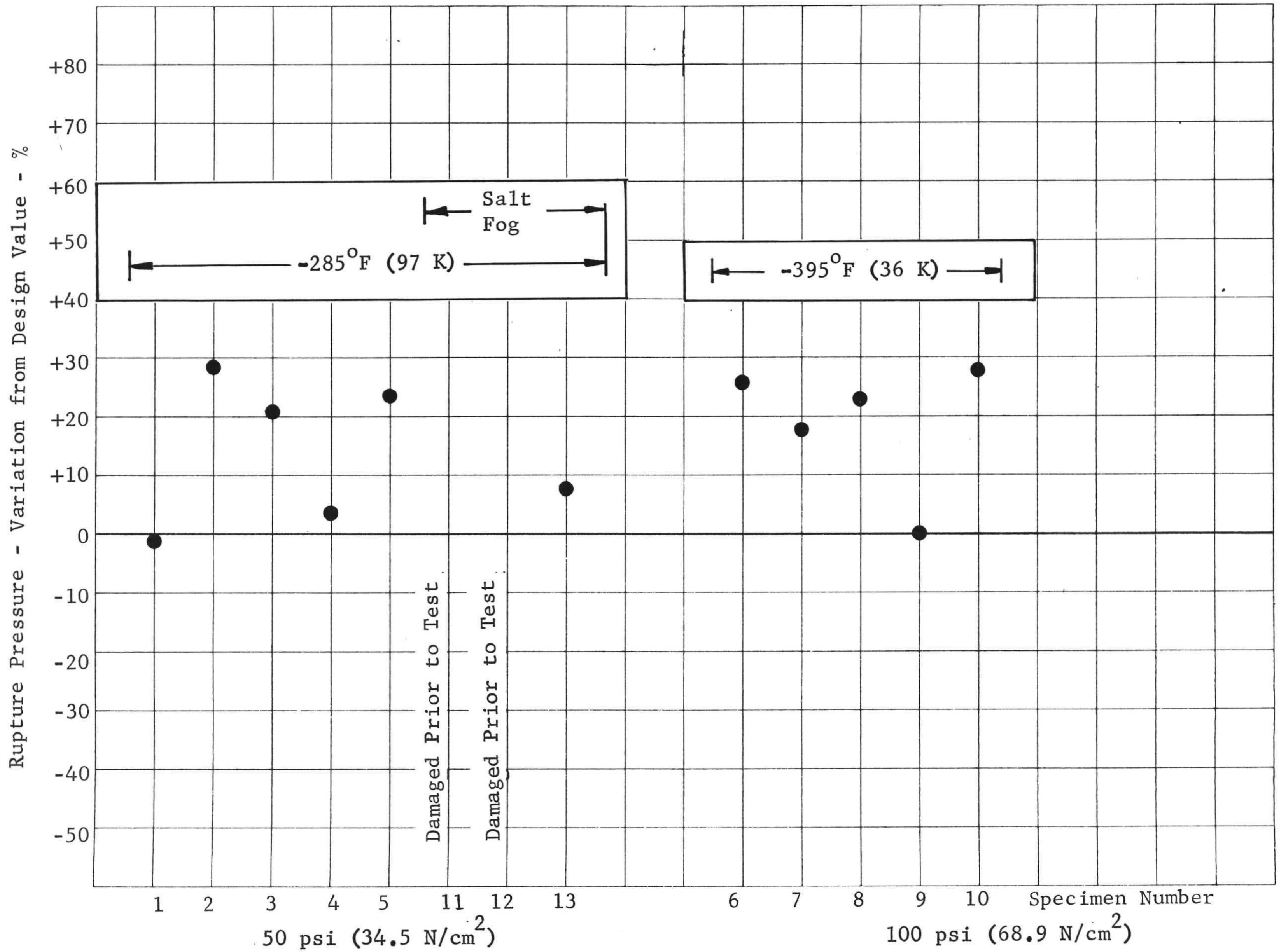


Figure 16.- Phase I Passive Disc Performance - Design C

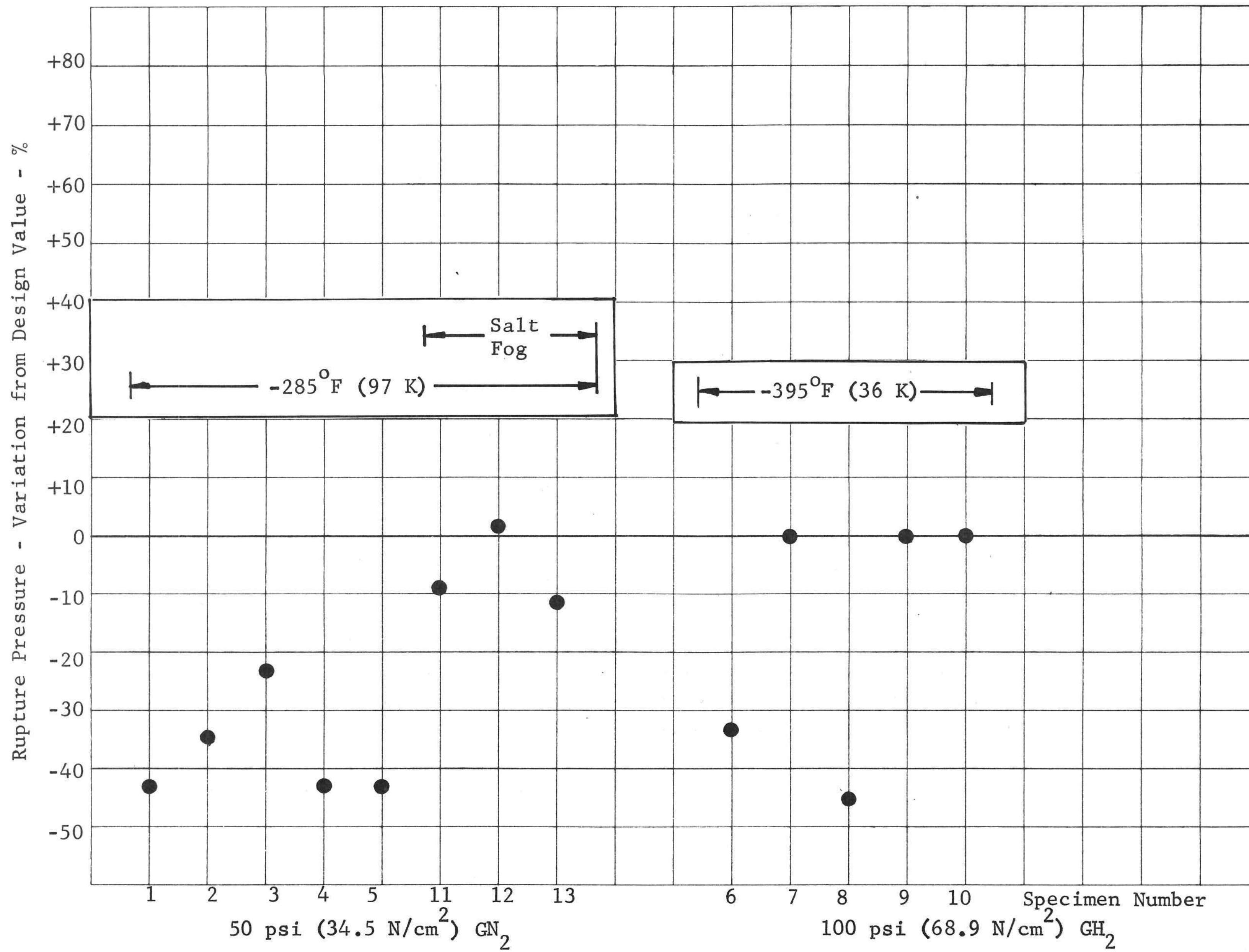


Figure 17. - Phase I Passive Disc Performance - Design B

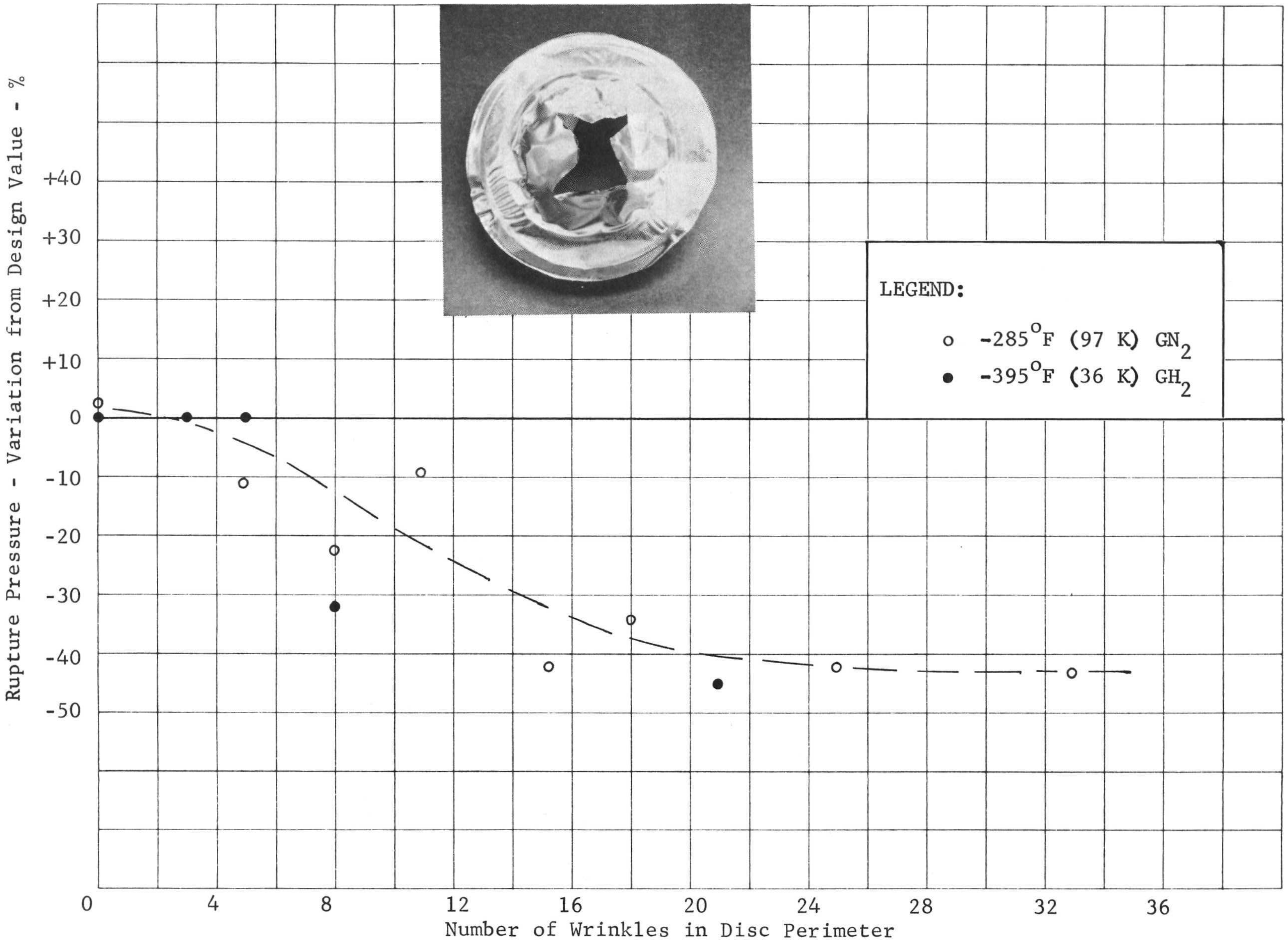


Figure 18.- Effect of Disc Wrinkling on Rupture Pressure - Design B

TABLE 3.- PHASE I DESIGN G PASSIVE DISC DATA SUMMARY

Specimen No.	Test Medium	Body Temp. °F	Body Temp. K	Rupture Pressure Design psi	Rupture Pressure Design N/cm^2	Rupture Pressure Actual psi	Rupture Pressure Actual N/cm^2	% Deviation From P Design	% Deviation From P Mean	Open Area (%)	Rise Rate psi/sec	Rise Rate N/cm^2/sec	Remarks
1	GN_2	-268	106	50	34.5	66	46	+32	- 7	100	0.8	0.6	N.P.G.
2		-275	102			57	39	+14	-20	100	2.0	1.4	N.P.G.
3		-270	105			74	51	+48	+ 4	100	2.5	1.7	N.P.G.
4		-269	105			88	61	+76	+24	100	2.2	1.5	Partial Rupture at 80 psi (55 N/cm^2)
5		-270	105			76	52	+52	+ 7	100	1.5	1.0	N.P.G.
11 (S.F.)		-264	109			61	42	+22	-14	100	4.0	2.8	N.P.G.
12 (S.F.)		-273	104			127*	88*	-	-	0	2.0	1.4	No Rupture
13 (S.F.)	GN_2	-271	105	50	34.5	75	52	+50	+ 6	100	1.5	1.0	N.P.G.
6	GH_2	-423	20	100	68.9	126*	87*	-	-	0	0.8	0.6	**
7		-400	33			192*	132*	-	-	0	1.1	0.8	Pins sheared at 120 psi (83 N/cm^2)
8		-390	39			199*	137*	-	-	0	1.8	1.2	
9		-400	33			202*	139*	-	-	0	3.4	2.3	Pins sheared at 128 psi (88 N/cm^2) Partial Rupture Leak thru
10	GH_2	-383	42	100	68.9	152*	105*	-	-	0	2.3	1.6	

* = Maximum differential pressure imposed - no rupture.
N.P.G. = No particle generation.
(S.F.) = Disc pre-conditioned by exposure to salt fog for 240 hours.
** = Disc had cut and separated during disassembly but failed to open during test.

TABLE 4. - PHASE I DESIGN C PASSIVE DISC DATA SUMMARY

Specimen No.	Test Medium	Body Temp.		Rupture Pressure				% Deviation From		Open Area (%)	Rise Rate		Remarks
				Design		Actual		P Design	P Mean		psi/sec	N/cm²/sec	
		°F	°K	psi	N/cm²	psi	N/cm²						
1	GN_2	-319	78	50	34.5	50	34	0	-13	34	0.5	0.3	N.P.G.
2		-278	101			65	45	+30	+13	55	2.3	1.6	N.P.G
3		-270	105			62	43	+24	+ 7	50	2.5	1.7	N.P.G.
4		-270	105			53	37	+ 6	- 8	54	1.9	1.3	N.P.G.
5		-296	91			62	43	+24	+ 7	32	1.9	1.3	N.P.G.
11 (S.F.)		-278	101			15	10	Not Incl	Not Incl	3	3.0	2.1	Damaged (Dented Pre-Test)
12 (S.F.)		-275	103			27	19	Not Incl	Not Incl	3	2.5	1.7	Damaged (Dented) Pre-Test Leaked thru before rupture
13 (S.F.)	GN_2	-295	91	50	34.5	54	37	+ 8	- 6	7	2.5	1.7	N.P.G.
6	GH_2	-365	52	100	68.9	126	87	+26	+ 6	87	3.8	2.6	50% of Disc detached & went downstream in 2 pieces
7		-364	53			118	81	+18	- 1	81	3.7	2.6	N.P.G.
8		-375	47			123	85	+23	+ 3	91	0.9	0.6	25% of Disc detached & went downstream in 1 piece
9		-387	40			100	69	0	-16	96	2.2	1.5	70% of Disc detached & went downstream in 3 pieces
10	GH_2	-401	32	100	68.9	128	88	+28	+ 8	68	2.3	1.6	N.P.G.

(S.F.) = Disc pre-conditioned by exposure to salt fog for 240 hours.

N.P.G. = No particle generation

TABLE 5. - PHASE I DESIGN B PASSIVE DISC DATA SUMMARY

Specimen No.	Test Medium	Body Temp.		Rupture Pressure				% Deviation From		Open Area (%)	Rise Rate		Degree of Wrinkling (No. of Wrinkles)
				Design		Actual		P Design	P Mean		psi/sec	$N/cm^2/sec$	
		^oF	K	psi	N/cm^2	psi	N/cm^2						
1	GN_2	-270	105	50	34.5	29	20	-42	-23	4	0.4	0.3	Extreme (33)
2		-270	105			33	23	-34	-12	4	0.8	0.6	Heavy (18)
3		-271	105			38	26	-24	+ 1	25	2.5	1.7	Moderate (8)
4		-270	105			29	20	-42	-23	9	0.9	0.6	Extreme (25)
5		-296	91			29	20	-42	-23	6	1.4	1.0	Moderate (15)
11 (S.F.)		-312	82			46	32	- 8	+23	51	3.0	2.1	Moderate (11)
12 (S.F.)		-286	96			51	35	+ 2	+36	64	6.0	4.1	None
13 (S.F.)	GN_2	-264	109	50	34.5	45	31	-10	+20	51	2.7	1.9	Light (5)
6	GH_2	-415	25	100	68.9	67	46	-33	-21	29	3.5	2.4	Moderate (8)
7		-388	40			100	69	0	+18	49	3.5	2.4	Light (5)
8		-398	34			55	38	-45	-35	3	5.0	3.4	Heavy (21)
9		-402	32			100	69	0	+18	37	3.1	2.1	None
10	GH_2	-408	29	100	68.9	100	69	0	+18	40	3.9	2.7	Light (3)

NOTES: 1) Wrinkling noted occurred around the flat sealing surface of the disc, extending inward to periphery of the domed section.

2) No particle generation or petal detachment noted on any run.

(S.F.) Disc pre-conditioned by exposure to salt fog for 240 hours.

Photographs of the design B passive rupture discs were taken and are shown in Figure 19. As may be noted in the photos the design B discs exhibited wide variations in the degree of opening. A major portion of the open area variation was attributed to the variation in rupture pressure. For those discs which ruptured at lower pressures, the kinetic energy of the released gas and the acceleration of the reverse-buckling disc were not sufficient to permit the desired cutting action to occur. The correlation of disc open area with rupture pressure is shown in Figure 20. The results show that if the disc ruptures at design pressure, open areas in the range of 38% to 65% of maximum area may be expected. This rather large variation in open area at design rupture pressure is in large measure attributable to the fact that the cutter only cuts the disc from the center out to approximately 3/4 of the radius. Deployment of the petals from that point is dependent on tearing of the disc, which is a less repeatable phenomenon than cutting. Since approximately 44% of the disc open area exists beyond the 3/4 radius point, the open area attained is quite sensitive to the amount of tearing involved. No adverse effects due to the 10-day salt fog exposure were noted on design B.

During review of the Phase I passive disc tests results the possibilities of modifying the design B cutter to obtain a more complete cutting action were discussed. It was concluded that, although the contemplated redesign was certainly feasible technically, the procurement cost and schedule risks which attend any development program could not be accommodated under the program scope. Accordingly, no change in the standard cutter configuration was requested.

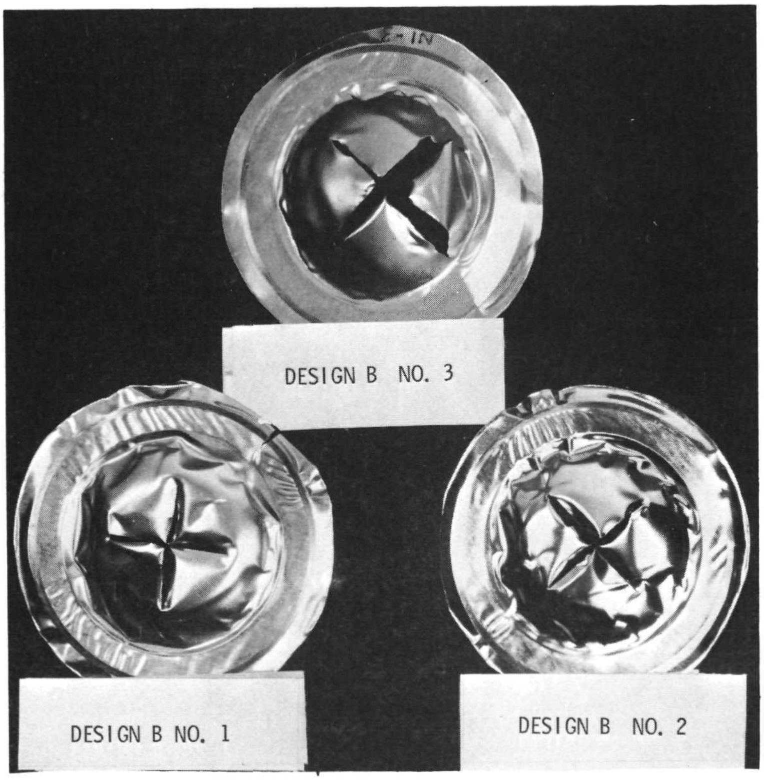


Figure 19.- Design B Discs

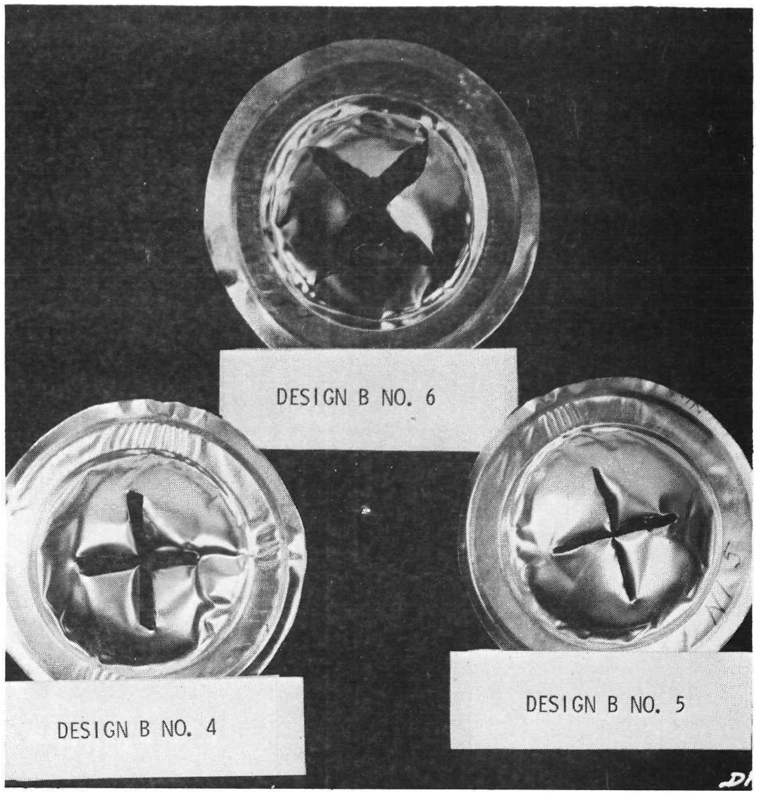


Figure 19.- (Continued)

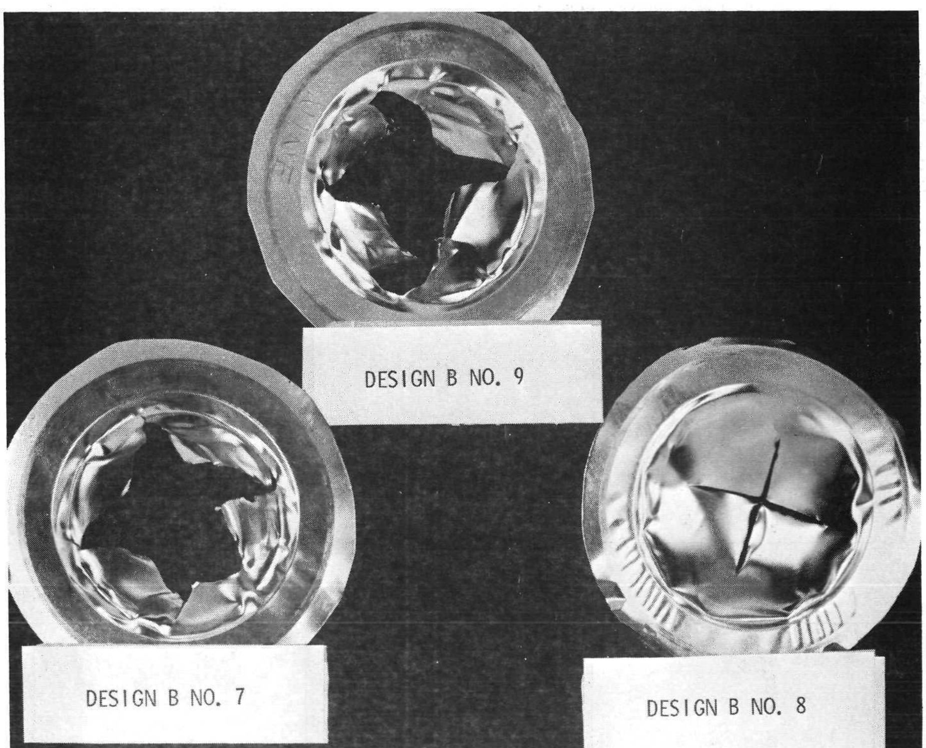


Figure 19.- (Continued)

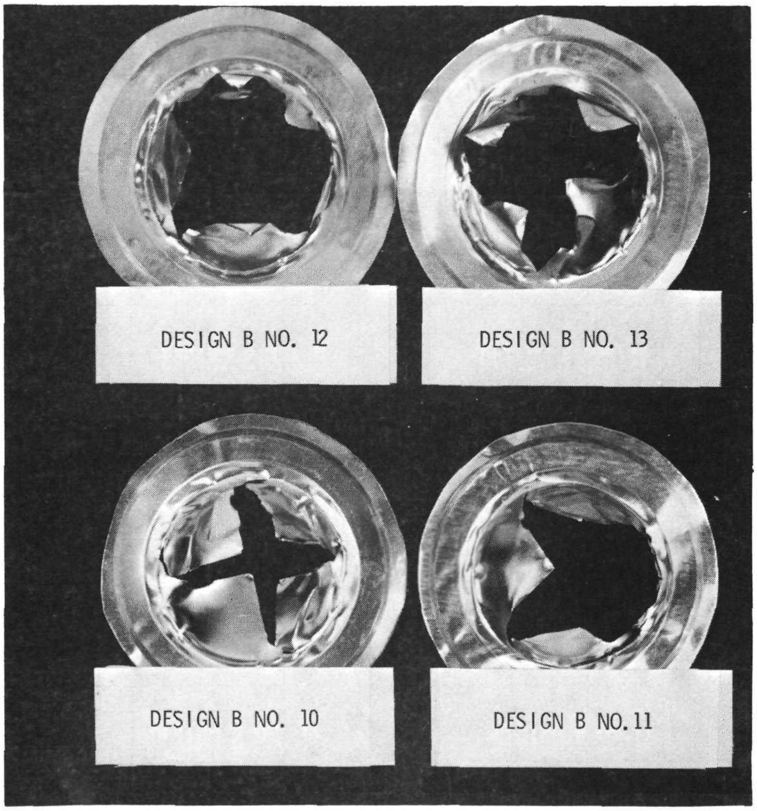


Figure 19. - (Concluded)

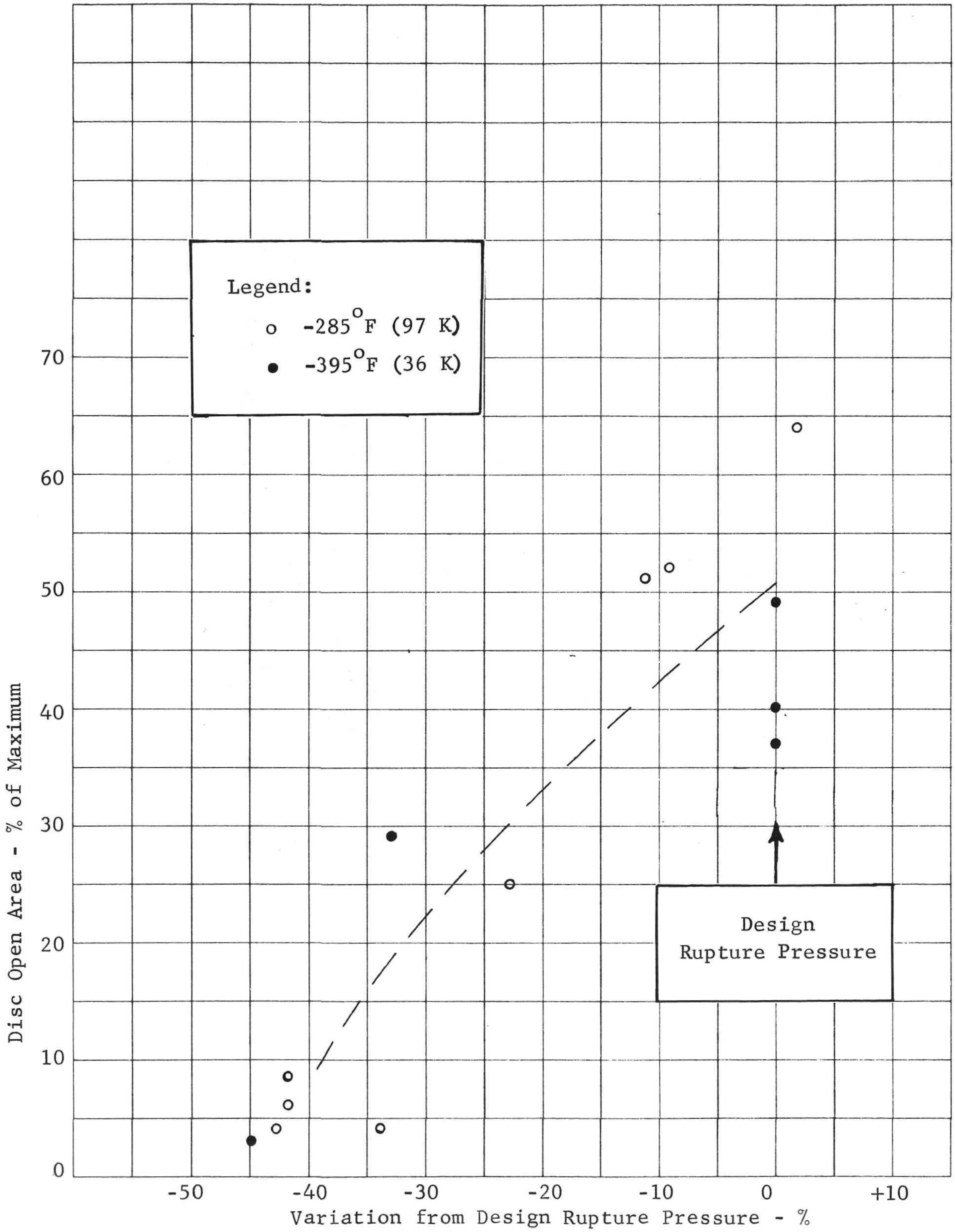


Figure 20. - Design B Disc Rupture Pressure/Open Area Correlation

Photographs of the design C & G discs after testing are shown in Figures 21 and 22.

The above described results of the passive rupture disc testing are summarized with the following conclusions:

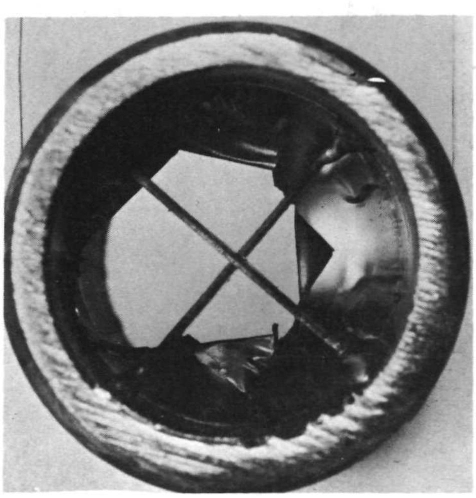
- The design G passive disc was not considered as acceptable for further testing in Phase II because of its inability to actuate at hydrogen service conditions and its extremely erratic behavior at the other cryogenic service temperatures.

- Of the two remaining designs, the design B reverse buckler appeared to have the potential of more reliable performance than the all-welded design C reverse-buckling design, provided that the bolted-flange design B version would be employed to eliminate the disc wrinkling problem. Re-design of the union-type holder to prevent rotation was not considered to be justifiable.

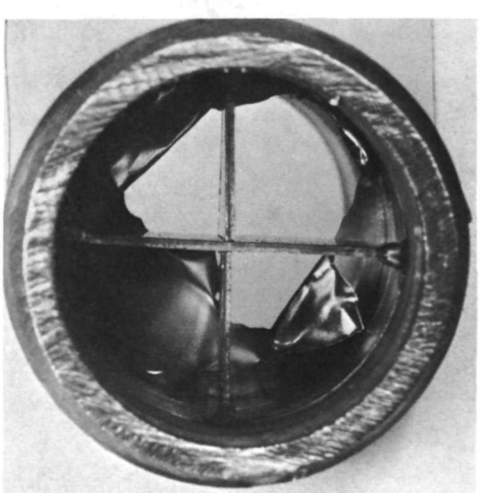
- In view of the above analysis of the relative technical merit of designs C and B, a bolted-flange version of design B was selected for use in Phase II, as opposed to the union type holder used in Phase I. As additional insurance against a recurrence of the disc wrinkling problem, the design B flanged unit was to be fitted with locating pins in the flanges to provide a positive means of preventing any rotation of the flanges during assembly; although the tendency toward rotation was admittedly minimized in the flanged design.

- Chem-milling of thin rupture disc material is not desirable due to the possibility of pin holes developing in the final disc thickness.

- Installation practices are critical to proper performance. Specifically wrinkling or any deformation of the disc must be prevented.

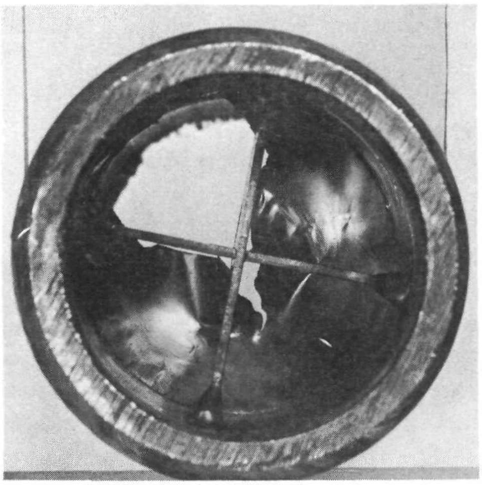


DESIGN C NO. 1

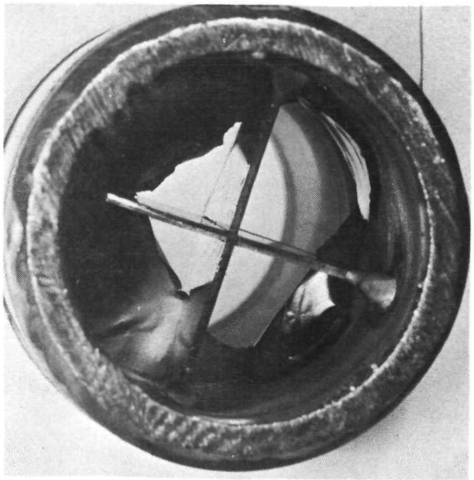


DESIGN C NO. 2

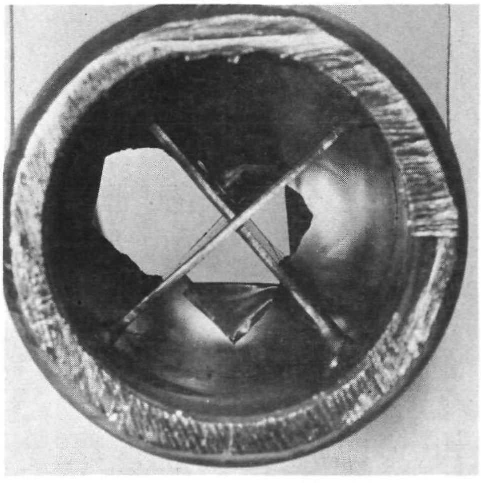
Figure 21.- Design C Discs



DESIGN C NO. 3



DESIGN C NO. 4



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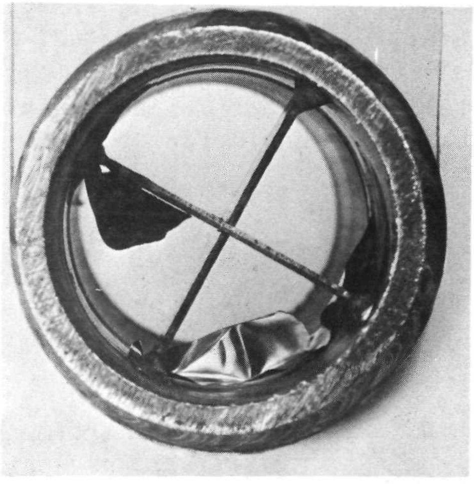
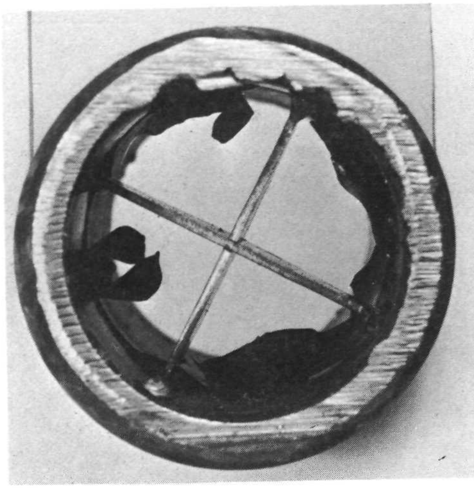


DESIGN C NO. 6

Figure 21.- (Continued)



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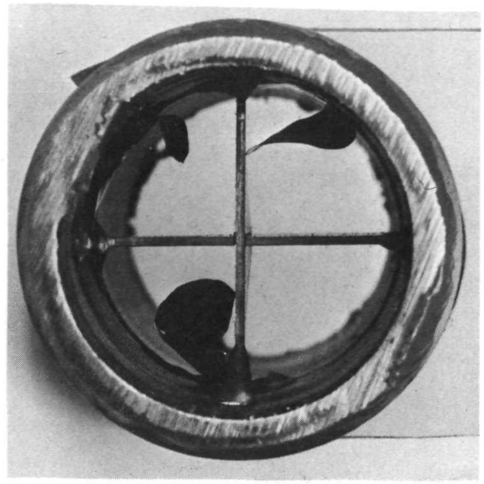
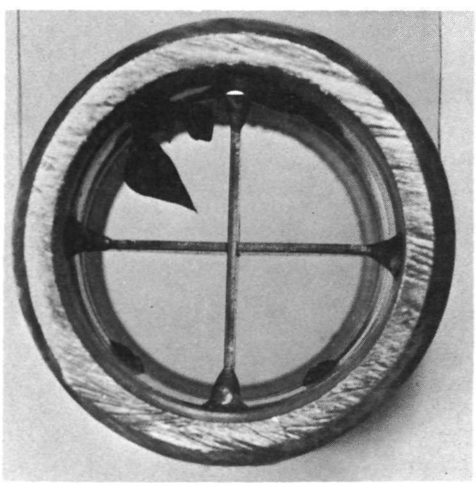
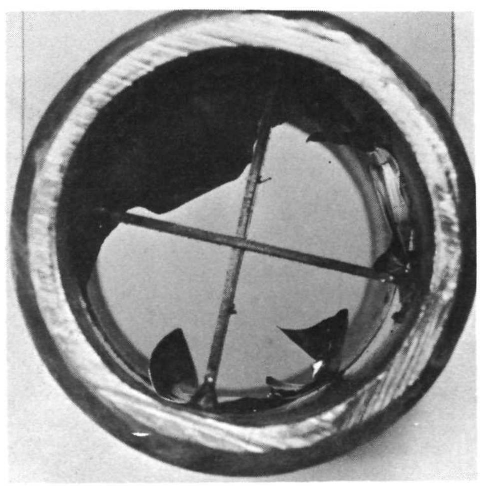


DESIGN C NO. 8

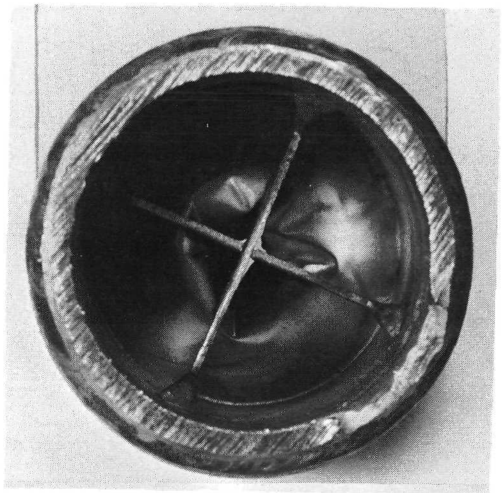


DESIGN C NO. 9

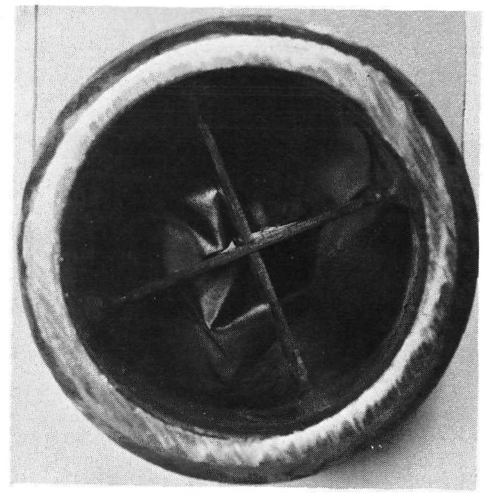


DESIGN C NO. 10

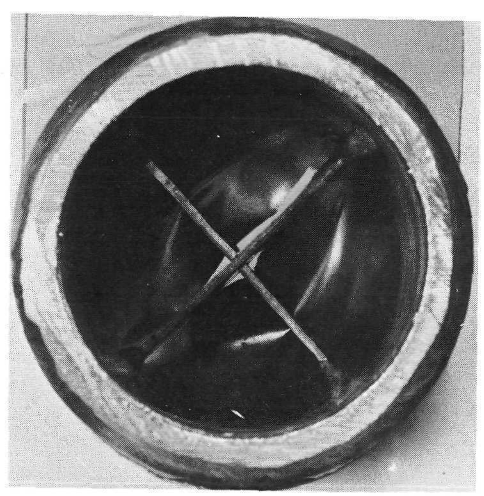
Figure 21.- (Continued)



DESIGN C NO. 11



DESIGN C NO. 12



DESIGN C NO. 13

Figure 21.- (Concluded)

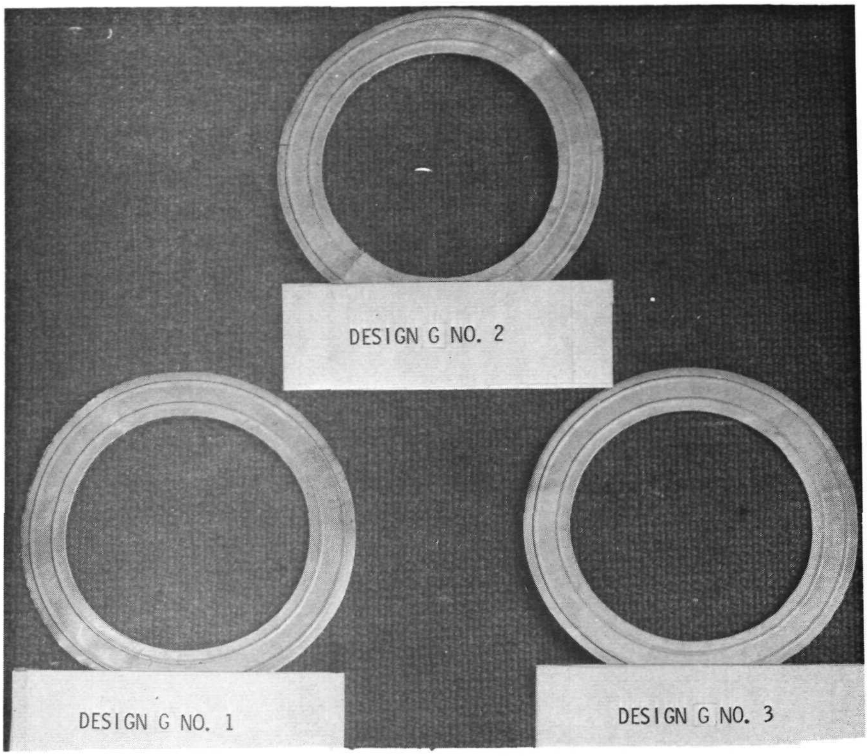


Figure 22. - Design G Discs

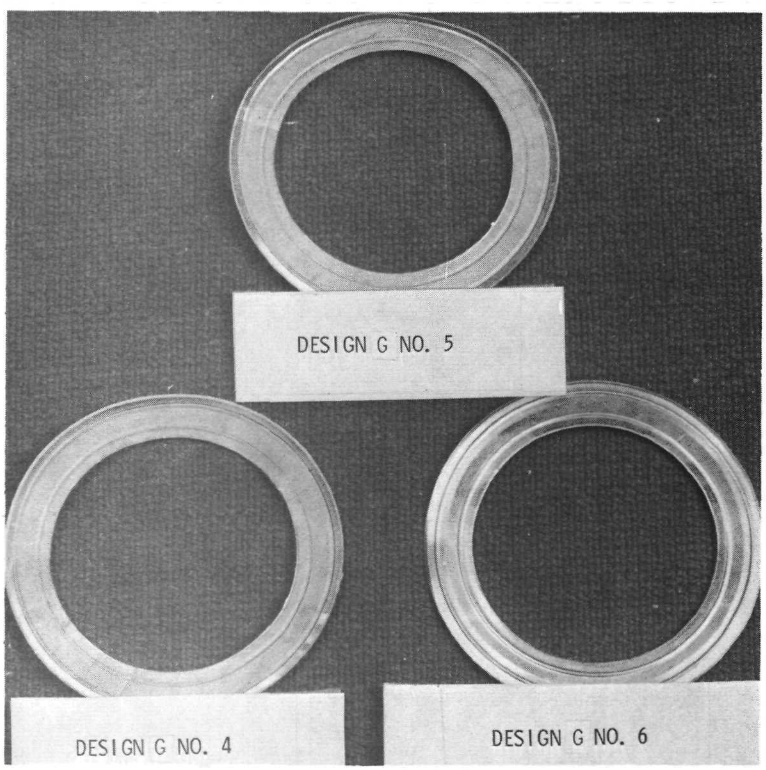


Figure 22. - (Continued)

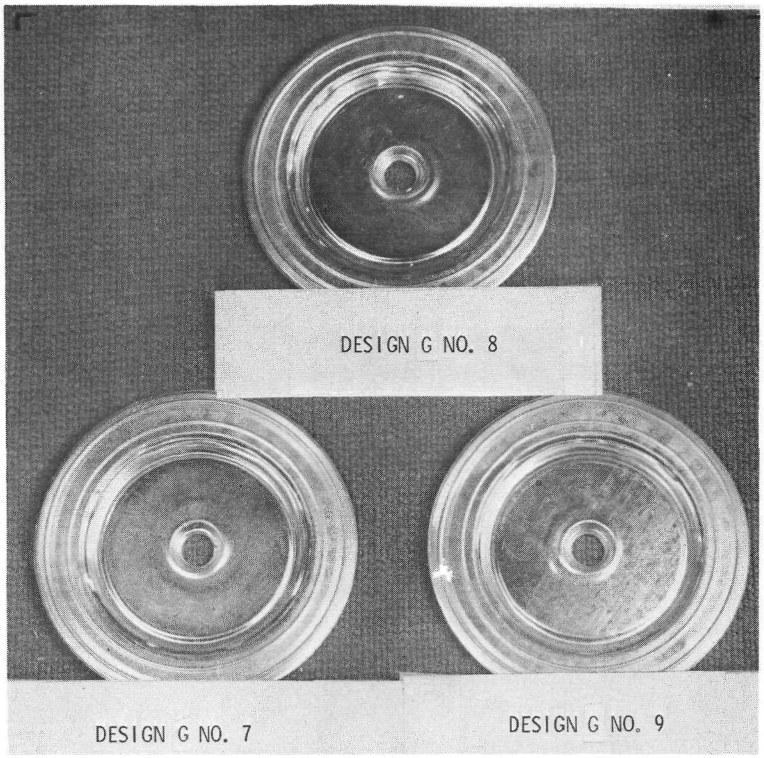


Figure 22.- (Continued)

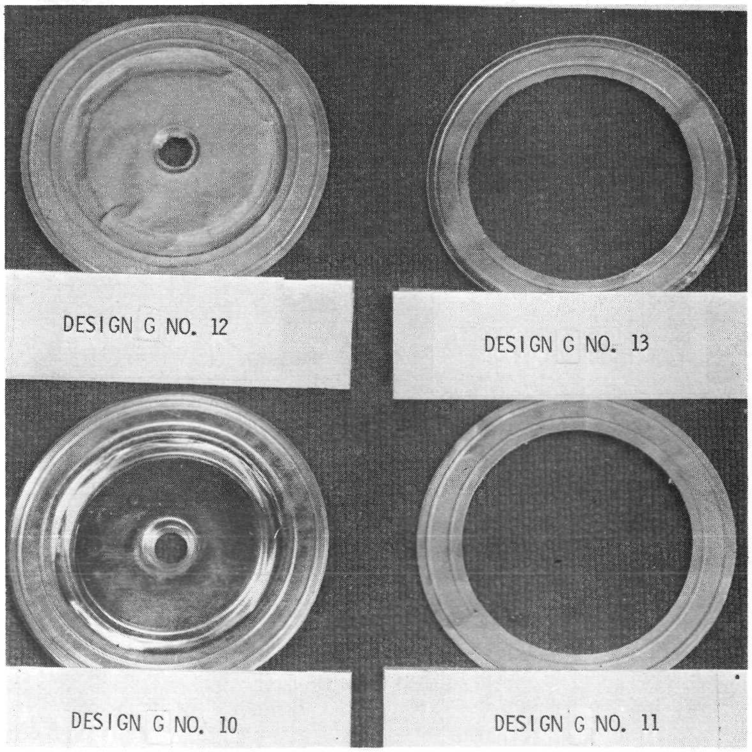


Figure 22.- (Concluded)

Cryogenic Testing (Task II, Phase II)

Test Scope. - Design B, selected as a result of the Phase I testing was subjected to the tests summarized in Table 6.

Phase II testing was essentially the same as that in Phase I, with the addition of pre-actuation conditioning (pressure cycling and pre-exposure to GF_2) and the requirement for an inlet pressure rise rate of 1000 psi/sec (689 N/cm/sec) on 10 each of the 50 psi (34.5 N/cm^2) burst pressure discs.

TABLE 6.- CRYOGENIC TESTS, PHASE II PASSIVE DISC (DESIGN B ONLY)

Test Fluid	Temperature		Design Burst Press.		Press. Rise Rate		Precondi-tioning	No. of Tests
	^oF	K	psi	N/cm^2	psi/sec	$N/cm^2/sec$		
GH_2	-395	36	100	68.9	10	7	None	7
GH_2	-395	36	100	68.9	1000	689	None	10
GH_2	-395	36	100	68.9	10	7	10 cycles to 70 psid (48 N/cm^2) at -395^oF (36 K)	10
GN_2	-285	97	50	34.5	10	7	None	6
GN_2	-285	97	50	34.5	1000	689	None	10
GN_2	-285	97	50	34.5	10	7	10 Cycles to 35 psid (24 N/cm^2) at -285^oF (97 K)	10
GN_2	-285	97	50	34.5	10	7	GF_2 exposure	11

Test Specimen. - The Design B, 1-inch (2.5 cm) disc is shown in Figure 23 with the test fixture interface piping installed. The flanged design shown was selected from the analysis of Phase I test data and the predicted improvement in variation of rupture pressures based on manufacturers test data using the bolted flange design. Discs and cutter configurations were not affected by the removal of the union connection and the addition of the bolted flanges.

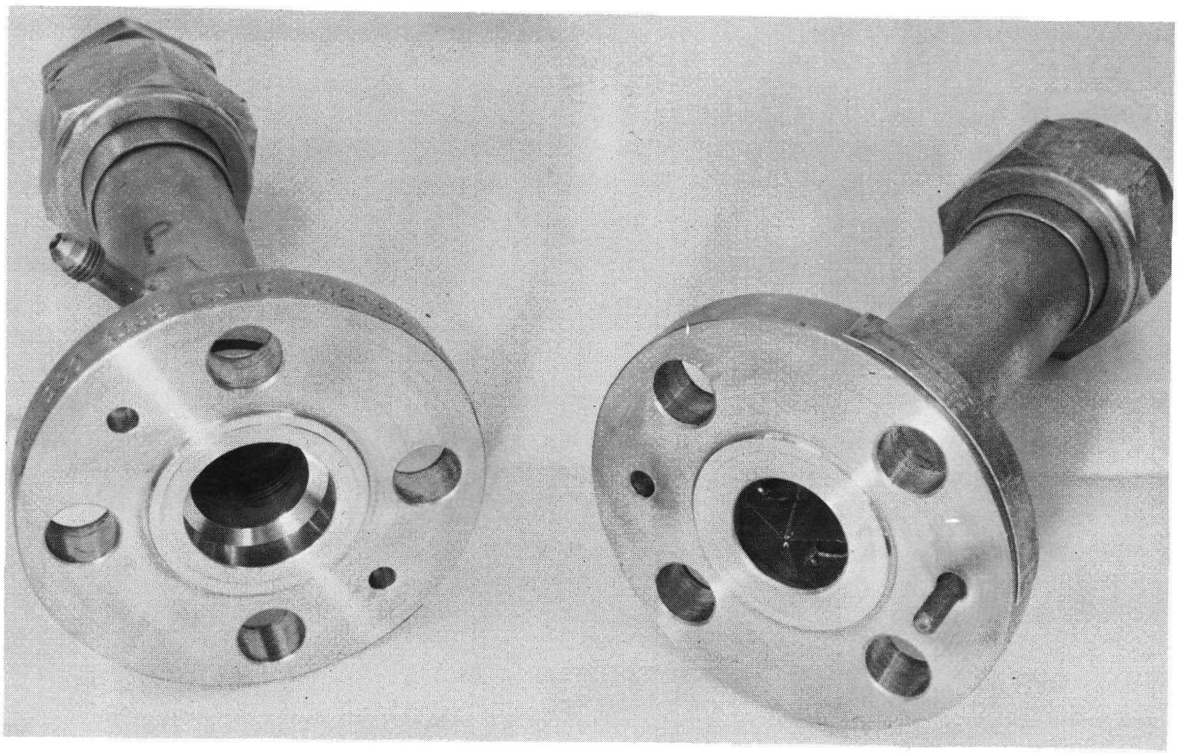


Figure 23.- Design B Flanged Unit

Test Fixture. - The test fixture used for Phase I, Figures 12, 13 and 14, was employed for all tests performed in Phase II.

Instrumentation. - The instrumentation used for Phase I (Table 2) was employed for all tests performed in Phase II with the addition of an oscillograph recorder.

Test Method. - Generally, the test method described in Phase I was used for Phase II testing. The 1000 psi/sec (689 $N/cm^2/sec$) rise rate requirement was obtained through the accumulator and flow control orifices incorporated in the basic test fixture shown in Figure 12.

Pre-conditioning pressure cycling was accomplished with the test items at the stabilized test temperatures, followed by pressurization to disc rupture at the specified rise rates. When applicable the test fixture and discs were preconditioned by GF_2 exposure at 30 psi (20.7 N/cm^2) on the upstream side of the disc, using an approved passivation procedure. The GF_2 pre-conditioning was performed in the test fixture at ambient temperature for a period of 2 hours. Prior to fixture cooldown and test, the GF_2 system was disconnected and the test items were purged with nitrogen gas.

Test Results - 50 psi (34.5 N/cm^2) Nitrogen Discs. - The results of the Phase II Design B passive rupture disc testing are shown in Figure 24, and Table 7. The general conclusions for the 37 discs rated at 50 psi (34.5 N/cm^2) and tested in gaseous nitrogen at -285^{o}F (97 K) are as follows:

- The average rupture pressure was approximately 14% higher than the design value for operation at -285^{o}F (97 K). The manufacturer had predicted a rupture pressure of 46 psi (31.7 N/cm^2) at room temperature and 50 psi (34.5 N/cm^2) at -285^{o}F (97 K). The limited room temperature testing done in this program verified the manufacturers rating at room temperature. From these results, the increase in rupture pressure between room temperature conditions and -285^{o}F (97 K) is approximately 24% for the design B reverse-buckling design.

- The variation in rupture pressure about the mean was on the order of ± 15%.

- Pressure rise rates up to approximately 1500 psi/second (1030 N/cm^2/sec) had no adverse effect on rupture pressure.

- Cycling of upstream pressure to 70% of design rupture pressure had no measurable effect on rupture pressure.

- Passivation of the rupture disc with gaseous fluorine had no measurable effect on rupture pressure.

At the inception of the Phase II passive disc test program, the first three discs were installed in the holders with the manufacturer's metal identification tab still attached. The presence of the large tab made it difficult to maintain the disc centered in the holder, while the two holder flanges were mated. A post-test inspection of the first three discs revealed that they had not been well-centered in the holder and that the bearing pressure of the seal land had caused wrinkling at the perimeter of the disc. The very erratic behavior of these discs was attributed to the mounting eccentricity and the wrinkling. Since the design B flanged holder design had no provisions for positive centering of the disc, it was decided that removal of the large identification tab from all subsequent discs would permit the disc to center itself to the maximum extent possible with the existing holder design. With regard to elimination of the wrinkling problem, the holder flange bolt torque was reduced from the manufacturer's upper limit value of 30 ft-lbs (41 N-m) to the

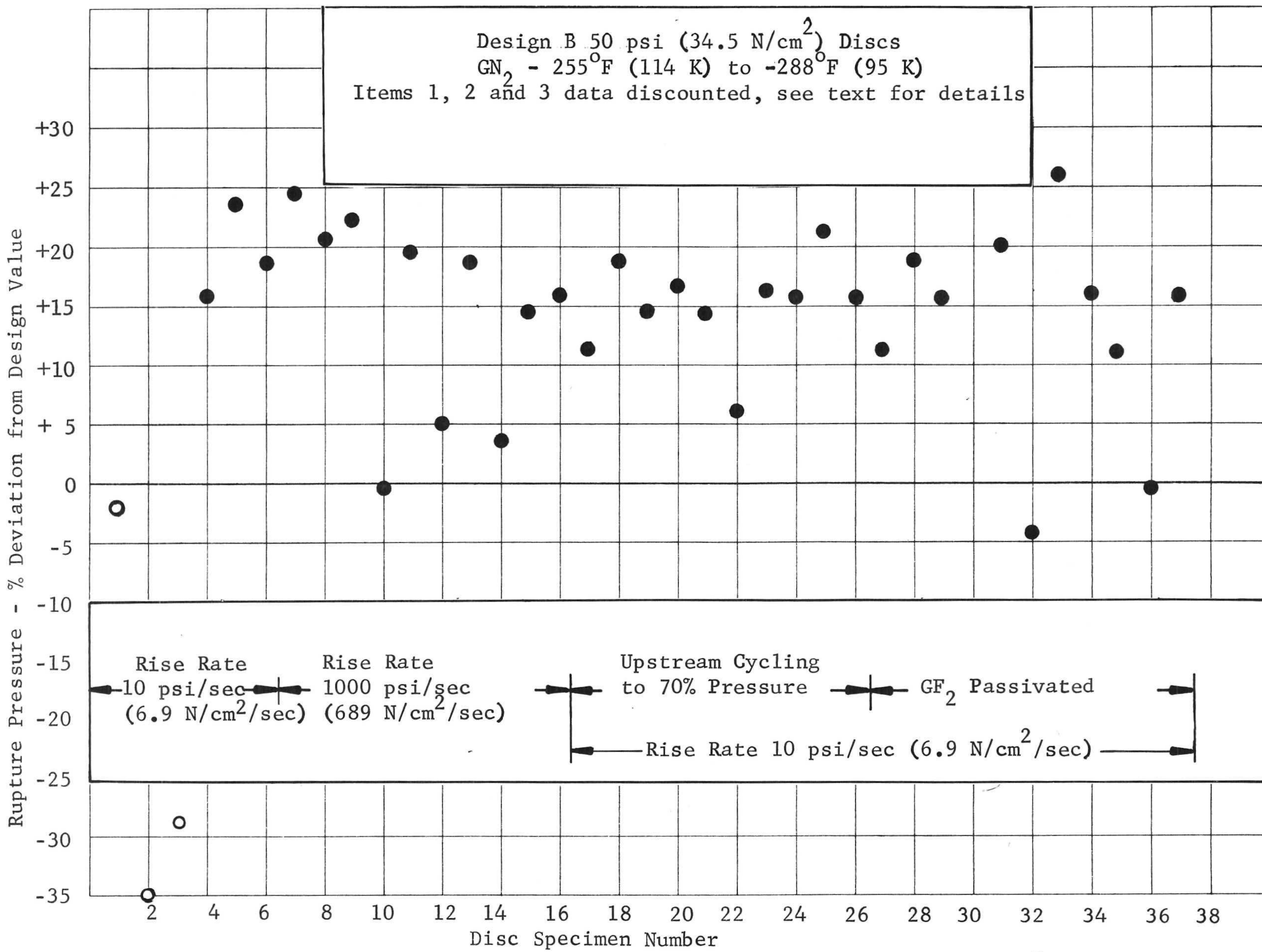


Figure 24.- Phase II Passive Disc Performance - 50 psi (34.5 N/cm^2)

TABLE 7.- PHASE II PASSIVE DISC DATA SUMMARY - GN_2 DISCS

Specimen No.	Rupture Pressure psi	Rupture Pressure N/cm^2	% Deviation From Design	Body Temp. ^oF	Body Temp. K	Rise Rate psi/sec	Rise Rate $N/cm^2/sec$	Open Area (%)	Remarks
1	49.0	33.8	- 2.0*	-274	103	2.3	1.6	54	Low rise rate
2	32.5	22.4	-35.0*	-270	105	3.0	2.1	6	
3	35.5	24.5	-29.0*	-262	110	2.0	1.4	7	
4	57.9	39.9	+15.0	-286	96	1.4	1.0	54	
5	61.7	42.5	+23.5	-282	99	1.5	1.0	68	
6	59.2	40.8	+18.5	-290	94	1.4	1.0	62	
7	62.3	43.0	+24.5	-261	110	858	592	65	High Rise Rate
8	60.2	41.5	+20.5	-268	106	1116	769	59	
9	61.0	42.1	+22.0	-264	109	1093	754	68	
10	49.7	34.3	- 0.5	-275	102	907	625	32	
11	59.8	41.2	+19.5	-274	103	950	655	45	
12	52.6	36.3	+ 5.0	-266	107	1066	735	56	
13	59.2	40.8	+18.5	-265	108	1472	1015	57	
14	51.6	35.6	+ 3.5	-280	100	950	655	44	
15	57.2	39.4	+14.5	-264	109	962	663	58	
16	58.2	40.1	+16.5	-285	97	1190	820	69	
17	55.6	38.3	+11.0	-265	108	1.6	1.1	35	10 upstream cycles to 70% design burst followed by low rise rate
18	59.2	40.8	+18.5	-265	108	0.5	0.3	58	
19	57.2	39.4	+14.5	-255	114	3.8	2.6	57	
20	58.4	40.3	+17.0	-268	107	1.5	1.0	58	
21	57.0	39.3	+14.0	-262	110	8.2	5.7	54	
22	53.1	36.6	+ 6.0	-266	107	4.0	2.8	62	
23	57.9	39.9	+16.0	-280	100	2.8	1.9	61	
24	57.7	39.8	+15.5	-275	102	4.6	3.2	48	
25	60.5	41.7	+21.0	-275	102	1.4	1.0	63	
26	49.2	33.9	- 1.5	-271	105	4.6	3.2	37	
27	55.5	38.3	+11.0	-281	99	1.0	0.7	25	GF_2 Passivated followed by low rise rate
28	59.3	40.9	+18.5	-288	95	1.7	1.2	65	
29	57.8	39.9	+15.5	-277	101	0.5	0.3	60	
30	No Data Inadvertment Rupture								
31	59.9	41.3	+20.0	-273	104	2.2	1.5	72	
32	47.6	32.8	- 4.5	-278	101	2.3	1.6	33	
33	63.0	43.4	+26.0	-269	106	1.8	1.2	62	
34	58.1	40.1	+16.0	-272	104	1.9	1.3	57	
35	55.5	38.3	+11.0	-268	107	1.1	0.8	62	
36	49.6	34.2	- 0.5	-268	107	1.6	1.1	39	
37	57.6	39.7	+15.5	-278	101	2.0	1.4	48	

*Discs damaged during installation in the holder and data should be discounted and eliminated from calculations.

lower limit of 20 ft-lbs (27 N-m) and anti-rotation pins were installed between the flange faces. A small number of spare discs were tested at room temperature to ascertain that the lower torque value appeared to reduce the severity of the wrinkling while still effecting a zero-leakage seal at the disc.

The relationship between rupture pressure and the degree of disc opening is shown in Figure 25. The results show substantial agreement with the data acquired in Phase I. In general, those discs which ruptured at pressures reasonably close to design pressure produced an open area of 35% to 70% of the maximum possible open area, with the majority of such discs producing open areas of between 50% and 70%.

Test Results - 100 psi (68.9 N/cm^2) Hydrogen Discs. - The performance of the 27 discs rated at 100 psi (68.9 N/cm^2) and tested in gaseous hydrogen at approximately -395°F (36 K) is presented in Figure 26 and Table 8. The general conclusions which were drawn as a result of this testing are as follows:

- The mean value of rupture pressure for those discs which were subjected to pressure rise rates of less than 10 psi/sec (6.9 N/cm^2/sec) was approximately 25% above the design rupture pressure.

- The mean value of rupture pressure for those discs which were subjected to high pressure rise rates of from 525 to 1058 psi/sec (360 to 730 N/cm^2/sec) was approximately 37% above design rupture pressure, indicating that the high pressure rise rates cause the rupture pressure to increase by approximately 12%.

- Cycling the inlet pressure to 70% of design operating pressure ten times had no discernible effect on rupture pressure.

- The variation in rupture pressure about the mean value was $\pm$ 12% for the low pressure rise rate discs and $\pm$ 9% for the high pressure rise rate discs.

A comparison of the 100 psi (68.9 N/cm^2) GH_2 disc performance with the 50 psi (34.5 N/cm^2) GN_2 disc performance shows that the repeatability of rupture pressure for the 100 psi (68.9 N/cm^2) discs at approximately -395°F (36 K) is substantially the same as the 50 psi (34.5 N/cm^2) discs at approximately -285°F (97 K), in that the variation in rupture pressure about the mean value was $\pm$ 15% for the 50 psi (34.5 N/cm^2) discs and $\pm$ 12% for the 100 psi (68.9 N/cm^2) discs. The mean value of rupture pressure was 14% above the predicted design value for the 50 psi (34.5 N/cm^2) discs and 25% above the design value for the 100 psi (68.9 N/cm^2) discs. The above departures of average rupture pressure from the design value had not been expected, since the Phase I tests had indicated no such trend. However, although the Phase II discs were fabricated from the same material which had been held in reserve from the Phase I disc

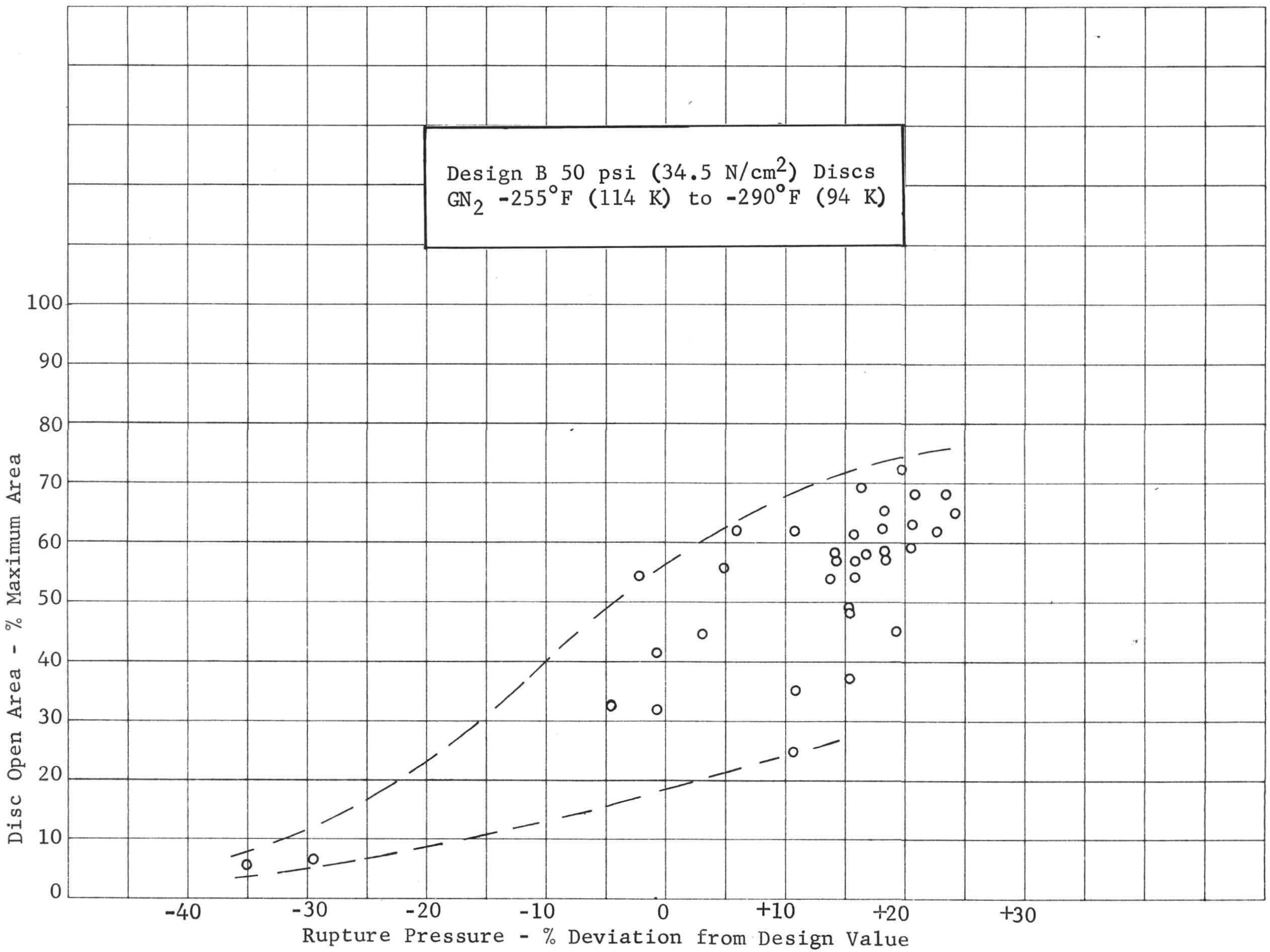


Figure 25.- Phase II Open Area as a Function of Rupture Pressure

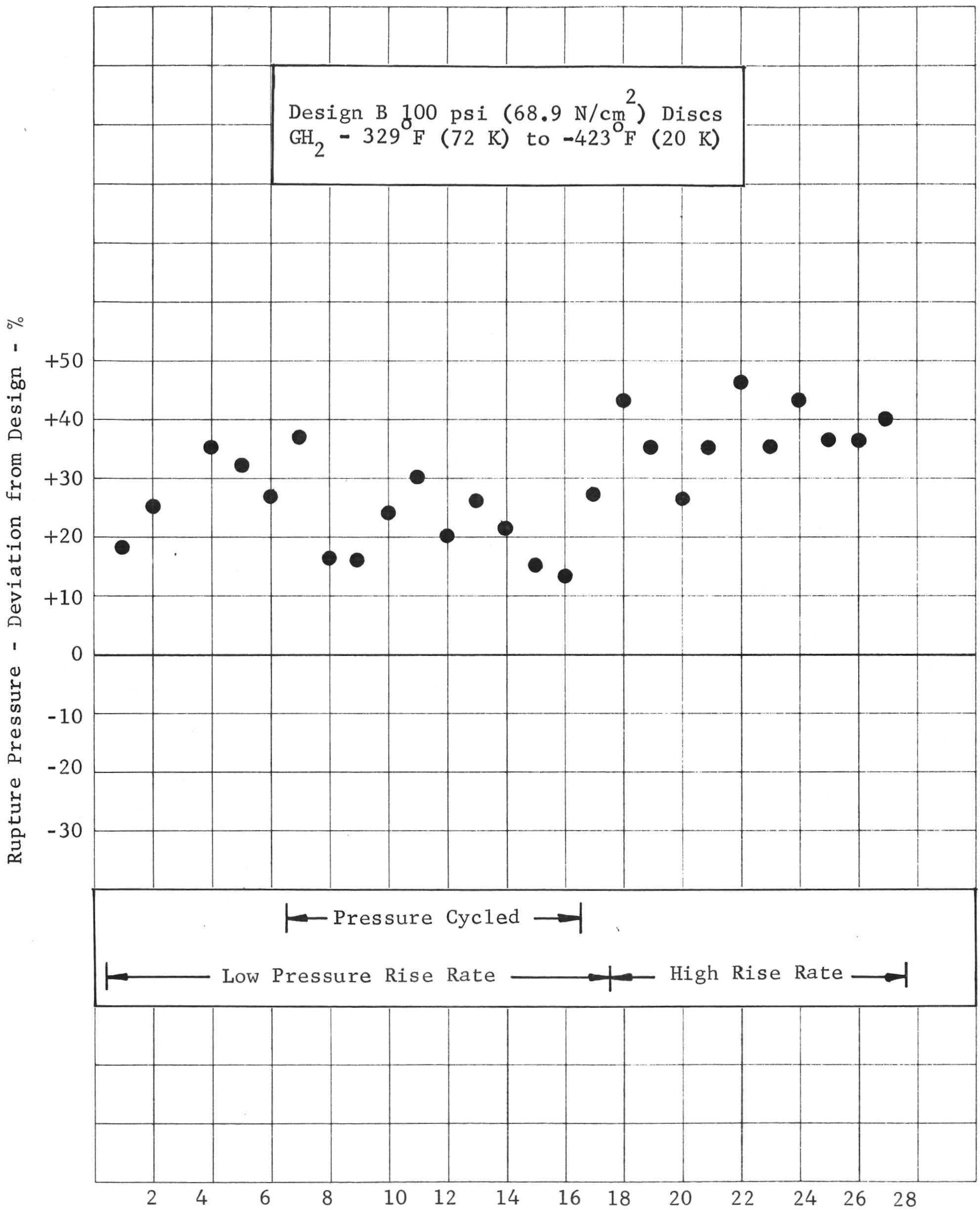


Figure 26.- Phase II Passive Disc Performance - 100 psi (68.9 N/cm^2)

TABLE 8.- PHASE II PASSIVE DISC DATA SUMMARY - GH_2 DISCS

Specimen No.	Rupture Pressure psi	Rupture Pressure N/cm^2	% Deviation from Design	Body Temp °F	Body Temp K	Rise Rate psi/sec	Rise Rate $N/cm^2/sec$	Open Area (%)	Remarks
1	118	81	+18	-388	40	3.7	2.6	39	Low Rise Rate
2	125	86	+25	-329	72	7.9	5.4	46	
3	Invalid Test - incorrect temperature								
4	135	93	+35	-423	20	3.4	2.3	40	
5	132	91	+32	-346	63	3.4	2.3	61	
6	127	88	+27	-379	45	3.3	2.3	48	
7	137	94	+37	-404	31	2.9	2.0	50	10 upstream pressure cycles to 70% of design press. followed by low rise rate
8	116	80	+16	-394	36	4.7	3.2	56	
9	116	80	+16	-383	42	4.1	2.8	51	
10	124	85	+24	-397	35	2.4	1.7	47	
11	130	90	+30	-391	38	5.4	3.7	50	
12	120	83	+20	-381	44	3.6	2.5	59	
13	126	87	+26	-353	59	2.8	1.9	21	
14	121	83	+21	-356	57	3.3	2.3	42	
15	115	79	+15	-373	48	4.6	3.2	53	
16	113	78	+13	-347	62	3.8	2.6	61	
17	127	88	+27	-406	30	141	97	42	Low rise rate
18	143	99	+43	-381	44	1029	709	39	High rise rate
19	135	93	+35	-360	56	720	496	54	
20	128	88	+28	-363	54	922	636	49	
21	135	93	+35	-362	54	790	545	57	
22	146	101	+46	-394	36	684	472	51	
23	135	93	+35	-398	34	525	362	59	
24	143	99	+43	-396	35	777	535	55	
25	136	94	+36	-372	49	841	580	55	
26	136	94	+36	-384	42	1058	729	58	
27	140	97	+40	-389	39	1010	696	62	

fabrication, the holder used in Phase II was of a different configuration than the holder used in Phase I. Also during the Phase II testing, all discs subsequent to the first three 50 psi (34.5 N/cm^2) specimens were assembled using the manufacturer's low-limit flange bolt torque.

The above departures from the predicted design values presented strong indications that the high clamping load used on the Phase I disc--with the associated plastic deformation of the disc perimeter caused by the seal land--had a significant detrimental effect on disc performance. Since the disc design being tested was a reverse buckling type, in which the buckling phenomenon occurs at the perimeter of the disc, deformation of material in that same location might be expected to influence the behavior of the disc. In-depth evaluation of this phenomenon could not be accomplished within the scope of this program.

Fluorine Testing (Task IV)

Test Scope. - The passive rupture disc (Design B) was subjected to gaseous fluorine compatibility tests as shown in Table 9. The objective of the tests was to determine if a catastrophic reaction occured due to actuation of the passive discs in gaseous fluorine. No testing with FLOX was done, since the results of this fluorine test program were considered applicable to FLOX systems.

TABLE 9. - FLUORINE TESTS, TASK IV

Test Media	Temp. at Burst		Design Burst Press.		No. of Discs
	^{o}F	K	psi	N/cm^2	
GF_2	-275	102	50	34.5	5

Test Specimen. - The design B, 1-inch diameter (2.5 cm) disc, described previously and shown in Figure 23 was used for Task IV testing.

Test Fixture. - The test fixture used for Task II, Figures 12, 13 and 14, was employed for all tests performed in Task IV.

Instrumentation. - The instrumentation used for Task II, Table 2, was employed for all tests performed in Task IV.

Test Method. - The general test method, outlined in Phases I and II, was used for Task IV. The test fixture and discs were passivated, upstream and downstream, with GF_2 for a minimum of 30 minutes prior to starting the test sequence. During cooldown, a positive GF_2 pressure of 1 to 5 psig (0.7 to 3.4 N/cm^2) was maintained on the upstream side of the rupture disc. Approximate barometric pressure was maintained with GHe on the downstream side. When the test item body temperature was -250 to -275^{o}F (116 to 102 K) the test item upstream pressure was increased by further addition of gaseous fluorine until disc rupture occurred.

Test Results. - The results of Task IV passive rupture disc testing are shown in Figure 27 and Table 10. No evidence of fluorine reaction was noted during the test, and no evidence of any reaction was noted on the discs during post-test inspection. The discs used for these tests were taken from the same material lot as Phase II discs. Rupture pressures ranged from 13% to 29% above the design pressure of 50 psi (34.5 N/cm^2), compared to the +11% to +23% range in which most of the Phase II discs ruptured during the cold GN_2 testing.

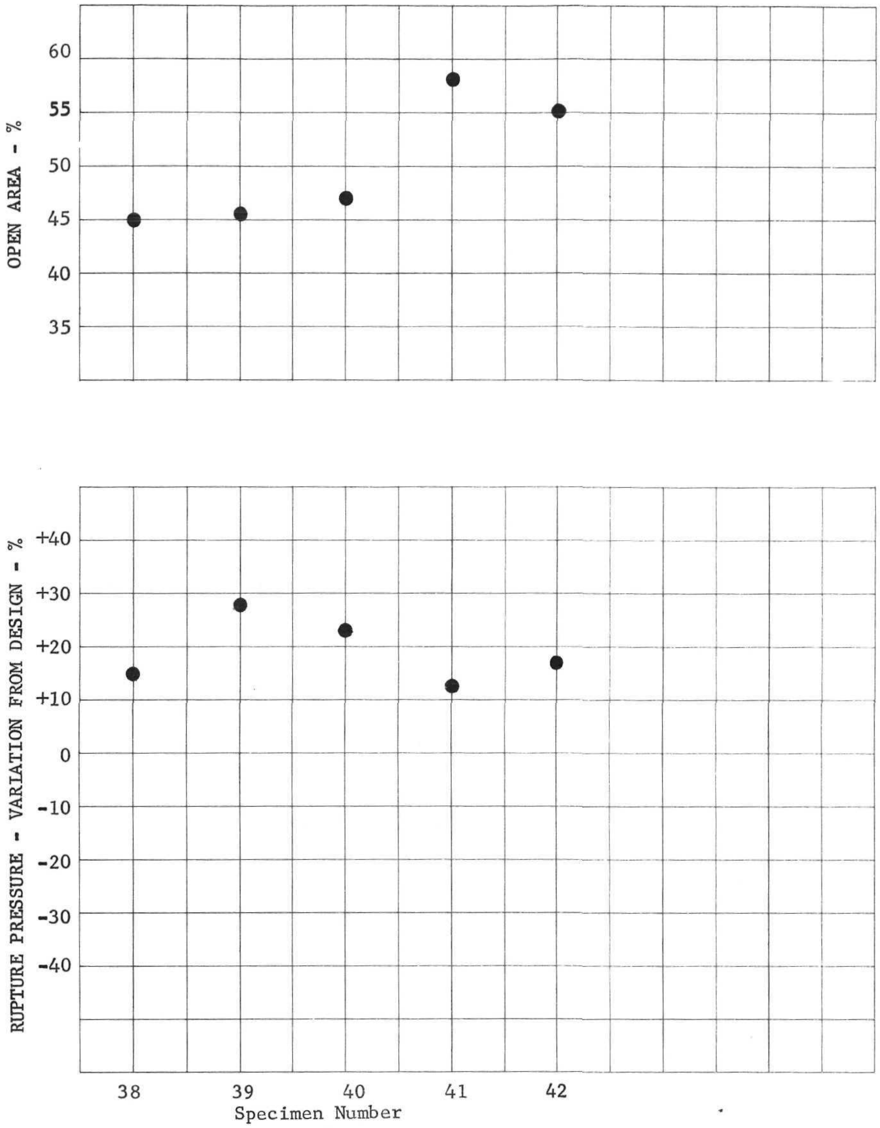


Figure 27. - Task IV Passive Disc Performance

TABLE 10. - TASK IV PASSIVE DISC DATA SUMMARY - GF2 DISCS

Specimen No.	Rupture Pressure		% Deviation from Design	Body Temp		Pressure Rise Rate		% Area
	psi	N/cm^2		^oF	K	psi/sec	$N/cm^2/sec$	
38	57.6	39.7	+15	-255	114	2.9	2.0	45
39	64.3	44.3	+27	-256	113	4.2	2.9	46
40	61.6	42.5	+23	-239	122	1.7	1.2	47
41	56.4	38.9	+13	-253	115	2.5	1.7	59
42	58.4	40.3	+17	-240	122	2.0	1.4	55

Materials Testing

Test Scope. - One of the general requirements of the contract statement of work was to characterize the disc materials used in the program. It was decided to limit the characterization to tensile strength determination of Phase II disc materials only since the material strength is important for the passive discs only. In addition, the testing was not to be undertaken if adequate information already existed in the literature. The three disc materials used in Phase II were 1100-0 aluminum, nickel 200 (full annealed) and 316 stainless steel. Data on tensile strength of these three materials at temperatures down to liquid hydrogen temperature was found in references 2, 3 and 5; however, the data for the nickel and stainless steel did not include results for the very thin sheet which was used in the Phase II passive discs. Accordingly, the tensile test program was set up to test the Phase II passive disc sheet material in one grain direction at $-320^{\circ}F$ (77 K) and $-423^{\circ}F$ (20 K). Three tests were to be made on each material at each temperature.

Test Specimens. - The materials for the test specimens were nickel 200 sheet 0.0025 inches (0.0064 cm) thick, and 316 stainless steel sheet 0.003 inches (0.0076 cm) thick. These materials were from the same lot which had been used to manufacture all of the design B discs in Phase I and II. The material was furnished in strips with the grain transverse to the length of the strip. From this material, cross-grain specimens were prepared per the ASTM specifications for foil tensile testing.

Test Results. - The tensile tests were conducted using a conventional tensile testing machine equipped with a cryostat. The results of the testing are shown in Table 11. Yield strength was not determined during these tests since only the tensile results are applicable to rupture discs. The data may not compare to data from other investigations but is representative of the temper and material thicknesses used in this program.

TABLE 11.- TENSILE TEST RESULTS

Temperature		Specimen No.	Tensile Strength (in thousands)		Percent Elongation
°F	K		psi	N/cm^2	
Nickel 200 (full annealed)					
70	294	1 2 3 4	42.1 44.4 40.9 46.8	29.0 30.6 28.2 32.3	8.5 9.0 7.5 11.5
-320	77	1 2 3 4	52.0 60.0 58.3 61.9	35.8 41.3 40.2 42.7	18.0 17.0 14.0 18.0
-423	20	1 2 3	82.3 84.6 81.7	56.7 58.3 56.3	20.0 22.0 16.0
316 Stainless Steel					
70	294	1 2 3 4 5	86.8 89.4 82.1 80.8 84.8	59.8 61.6 56.6 55.7 58.4	16.5 17.0 13.0 12.0 13.5
-320	77	1 2 3	151.2 156.4 155.6	104.3 107.8 107.3	31.5 28.0 32.0
-423	20	1 2 3	197.4 214.1 202.7	136.1 147.6 139.8	29.0 34.0 28.0

ACTIVE RUPTURE DISC PROGRAM

Study of Design Concepts

The application of active rupture discs to airborne cryogenic propellant systems has been handicapped by very limited experience with such devices in cryogenic service, either as a system protection device or as a propellant isolation device. In these applications, an active (command actuated) rupture disc device, either used alone or in series with a shutoff valve, would appear to be more attractive for the larger systems than a hermetically sealed valve, from the standpoint of weight, reliability and actuation force requirements. Unfortunately, devices of this type in diameters exceeding approximately 1 inch (2.5 cm) do not exist except as prototypes or conceptual drawings.

The purpose of this portion of the program was to identify candidate designs and determine the feasibility of using these designs as zero leakage, positive actuation, cryogenic propellant isolation devices.

The initial task (Task I) of the active rupture disc program was to acquire all possible information on existing active disc designs and to assess the relative merit of the various concepts for the purpose of selecting the more promising designs for test evaluation.

Study Methods. - The methods of acquiring information on active rupture discs were the same as described for the passive disc program earlier in this report, and the effort on both types of discs was carried on concurrently. The literature search, patent search and industry survey yielded the names of interested manufacturers, to whom requests for proposals (see Appendix B) were sent.

Design proposals were submitted by ten manufacturers for a total of 12 designs. The active disc design proposals were evaluated on the basis of the design criteria and vendor qualification criteria shown in Figure 28. As a result, two designs were selected for fabrication and evaluation testing in Task II.

Study Results. - The results of the literature search for information on active rupture disc devices were completely negative; however, the patent search yielded information on one cutter-type active disc and a number of explosively-opened discs. In the case of the latter-mentioned devices, the assignees of the patents were rupture disc manufacturers which had already been identified through available vendor files. As previously mentioned in the passive disc section of this report, an extensive survey of the valve industry was made to elicit expressions of interest in an active rupture disc device. This survey resulted in submittal of 12 active disc designs.

ACTIVE DESIGN

MFGR:

DESIGN EVALUATION			COMPANY EVALUATION		
Item	Range	Grade	Item	Range	Grade
Rupture Technique (Hi/Lo Force, Flow Dependence)	0-7		Rupture Disc Experience	0-5	
Adaptability to Flight Propulsion Systems	0-3		Cryogenic Experience	0-5	
Reliability (Repeatability)	0-10		Fluorine Experience	0-5	
Actuator Design (Complexity, Critical Dimensions)	0-3		Zero-Leak Experience	0-5	
Debris Generating Potential	0-7		Present Related Work	0-5	
Suitability for Cryogenic & Fluorine Service	0-7		Adequacy of Facilities	0-5	
Cleanability	0-5		Total	0-30	
Relation to State of Art (Advanced Concept)	0-3				
Weight, Size	0-2				
Tolerance to Pressure Cycling	0-2				
Materials Selection	0-5				
Development Status (Shelf item, Modified Shelf item)	0-2				
Sealing Characteristics (Int., Ext., Pre & Post Actuation)	0-10				
Ease of Disc Replacement	0-2				
Flow Capacity (ΔP)	0-2				
Total	0-70				
Remarks:			DESIGN EVAL:		
			COMPANY EVAL:		
			GRAND TOTAL:		

Figure 28. - Active Disc Design Evaluation Sheet

The proposed active disc concepts are shown in Figures 29 through 40. Code designations have been used to identify the various designs. Identification of the manufacturers may be requested of the NASA Project Manager by reference to the code letters.

Design H (figure 29) is a sliding sleeve device coupled with a frangible poppet section. Pressure cartridge actuation fractures the frangible poppet section and forces the sleeve/poppet downstream, creating a smooth propellant path around the poppet. The vented body, required to maintain proper ΔP across the omni-seals during actuation, is considered undesirable from the leakage aspect in the open position.

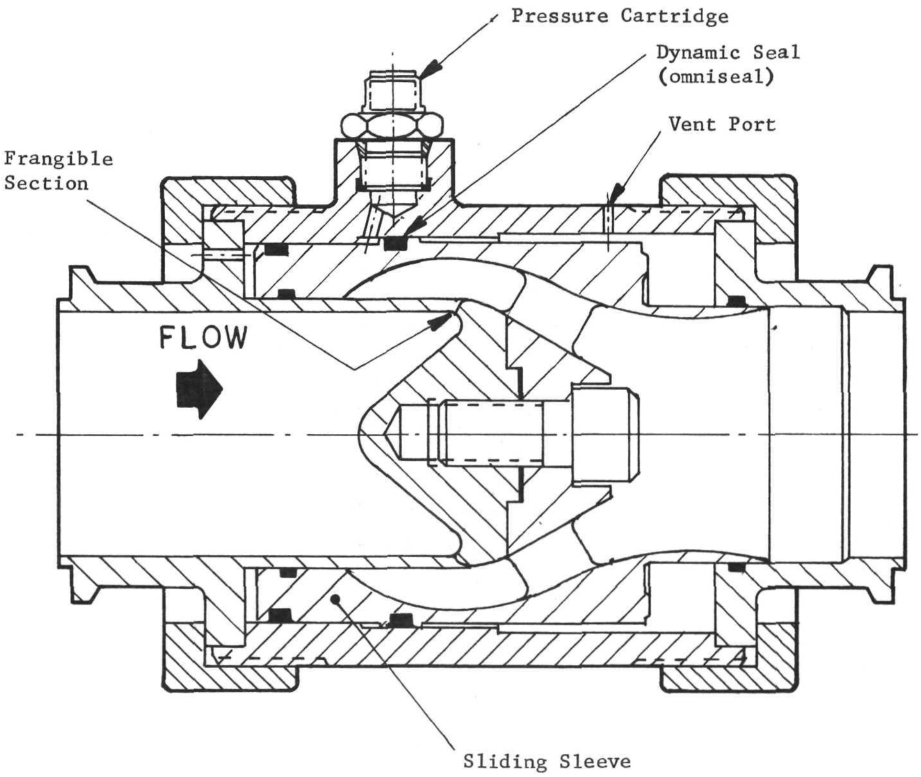


Figure 29.- Design H - Active Disc

Design J (figure 30) employs a frangible poppet section, a stem position locking device and a unique open position metal to metal stem seal. Pressure cartridge actuation unlocks the poppet stem and opens a path for cartridge gas to enter the valve actuating piston area. Poppet position, following actuation, is completely out of the propellant flow path but dynamic sealing abilities appear inadequate.

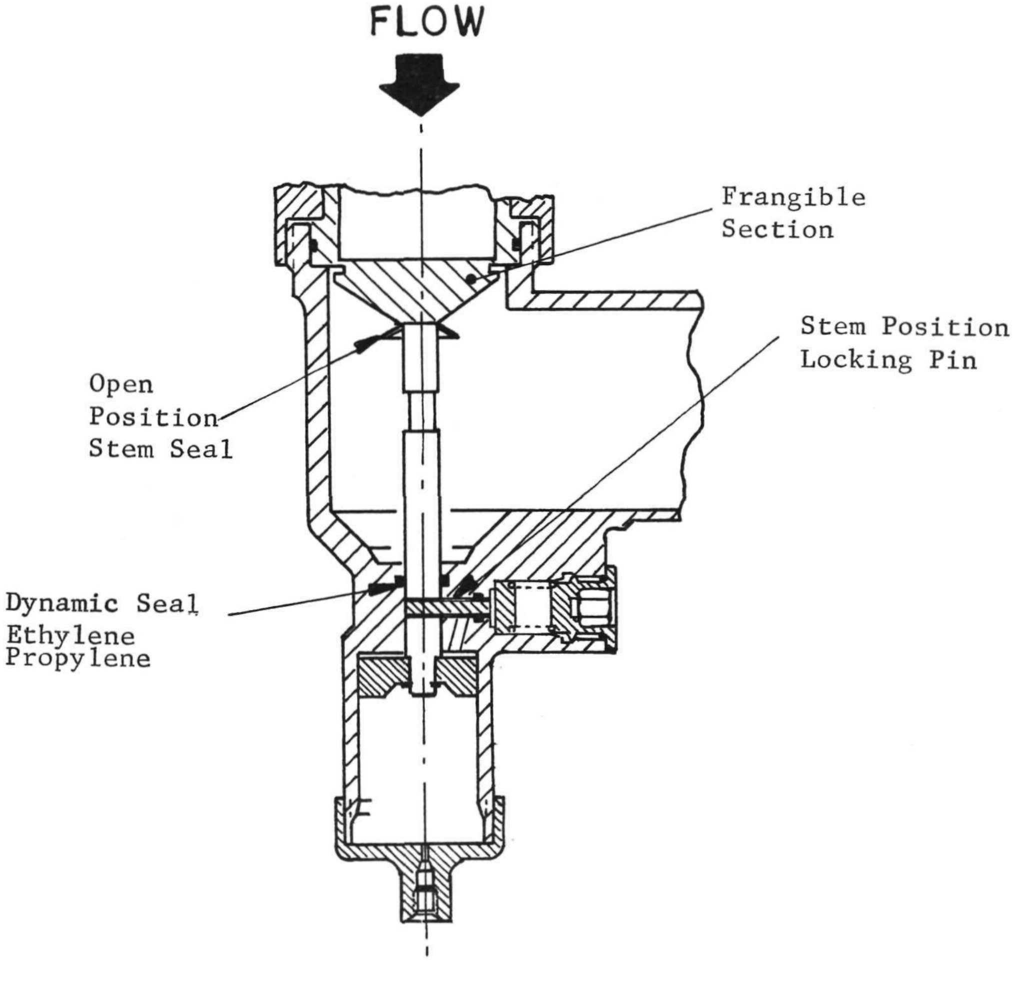


Figure 30.- Design J - Active Disc

Design K (figure 31) is a sliding sleeve/swinging gate design which could be modified to accept a pressure cartridge. Valve actuation moves the sleeve downstream forcing open the gate diaphragm. The sleeve remains in this downstream position to assure full diaphragm deployment. The effectiveness of the sliding sleeve dynamic seals isolating cartridge combustion gases from the propellant path is considered inadequate.

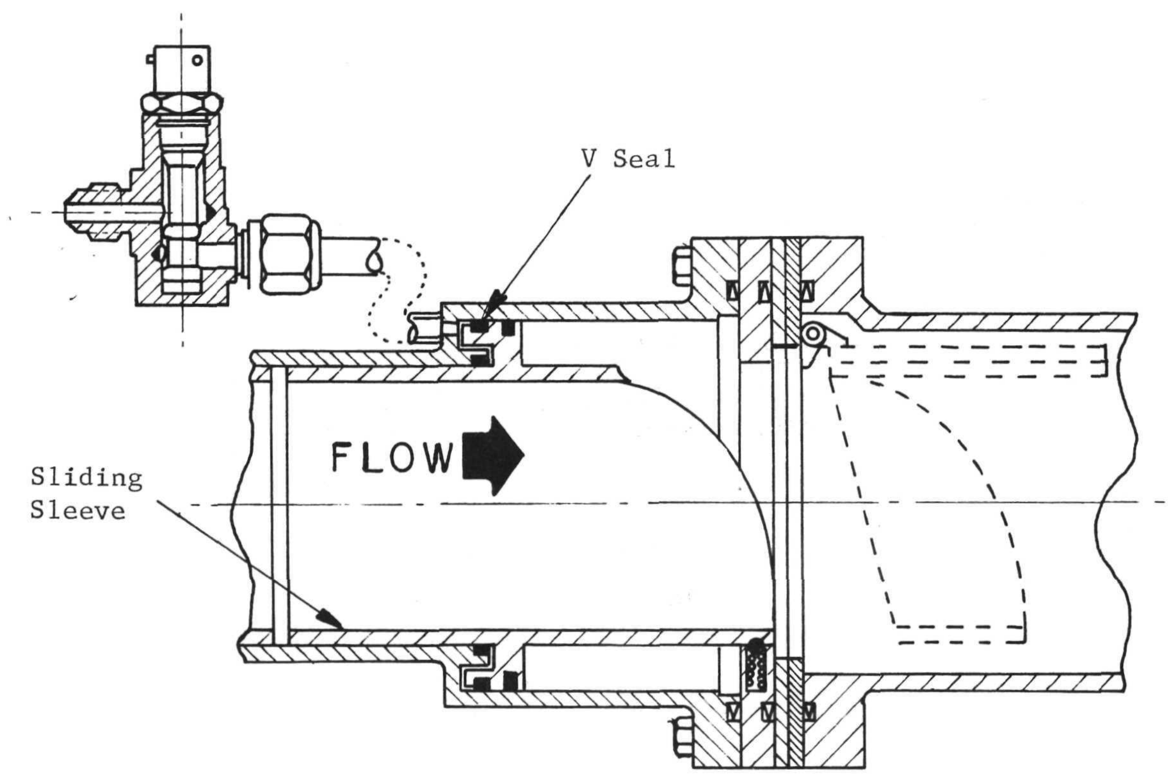


Figure 31.- Design K - Active Disc

Design L (figure 32) is a piercing-cutter concept employing a cutter shaft locking device which maintains compression on a driving spring. Initiation of the pressure cartridge unlocks the cutter shaft. The device then becomes dependent on the spring for the diaphragm piercing and cutting force. The pressure cartridge cavity is not considered to be adequately isolated from the propellant passage.

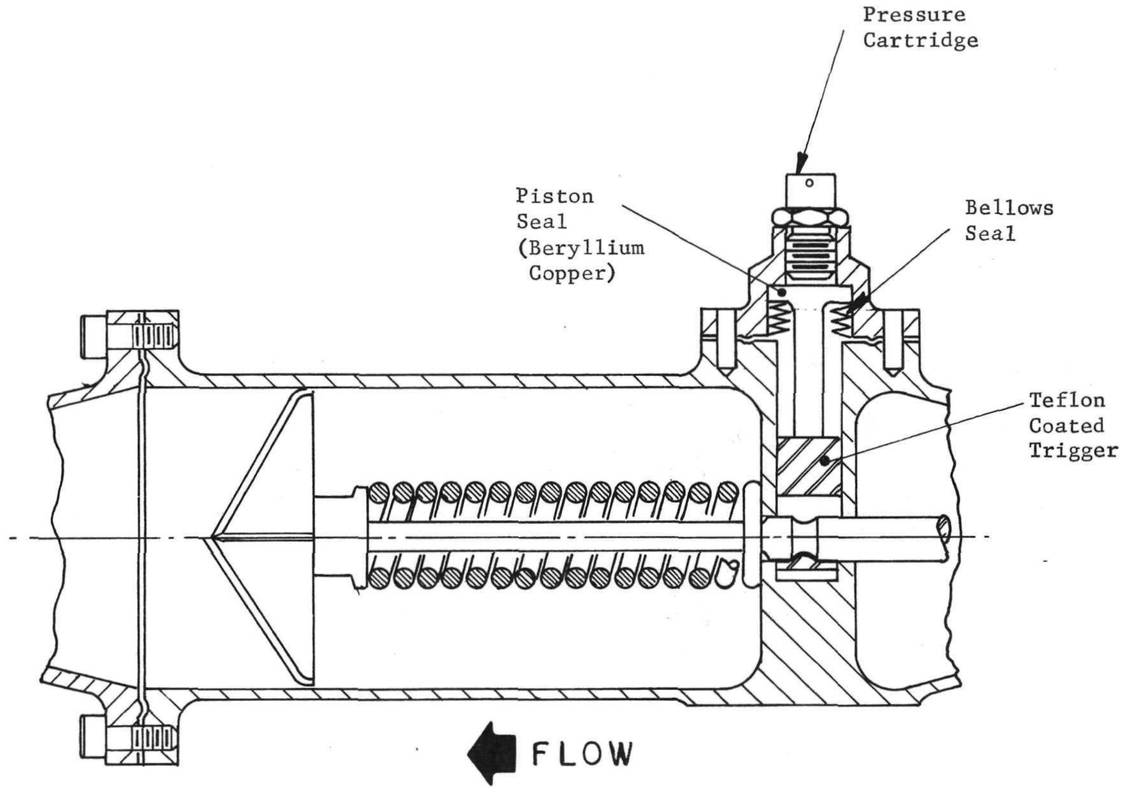


Figure 32.- Design L Active Disc

Designs M and N (figures 33 and 34) are both swinging gate devices with frangible sections. Design M is operated by a pressure cartridge actuated piston and pin acting on the gate diaphragm. Design N is similar, employing a pressure cartridge actuated wedge to fracture the frangible section of the gate.

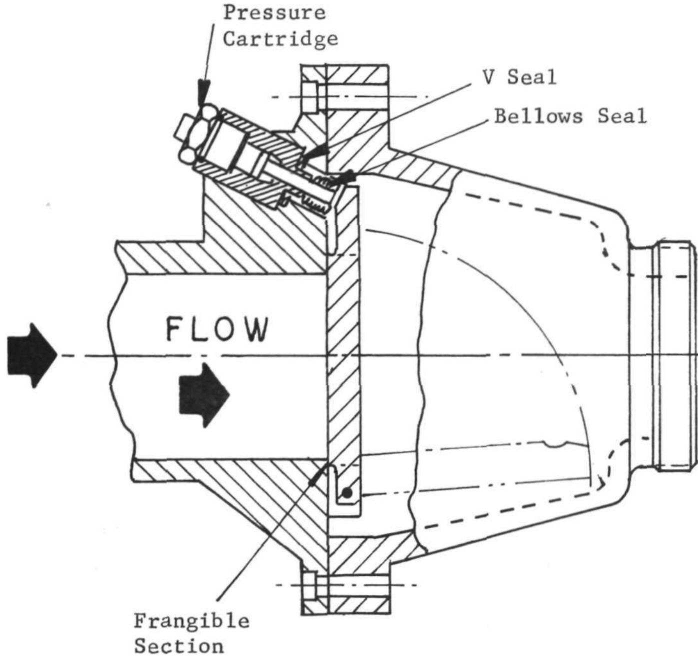


Figure 33.- Design M - Active Disc

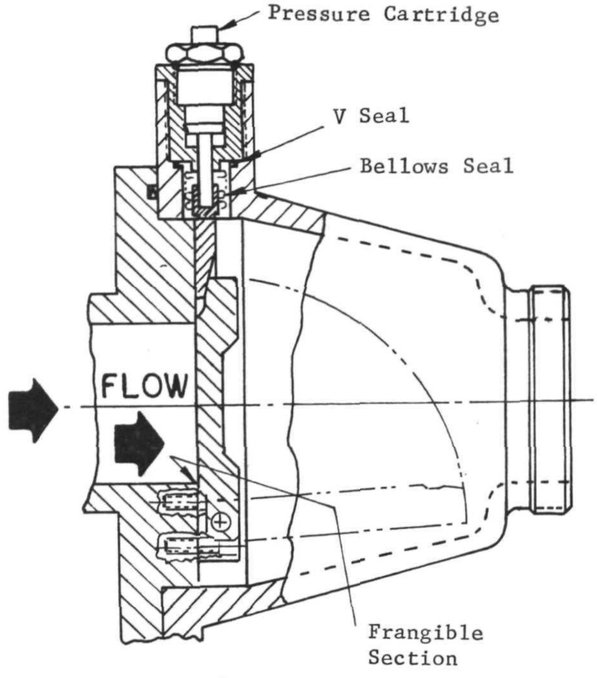


Figure 34.- Design N - Active Disc

Design P (figure 35) is a normally closed flying gate valve rather than a rupture disc. Pressure cartridge actuation against the limited travel piston is sufficient to drive the gate into the receiver where gate/receiver interference maintains the open position.

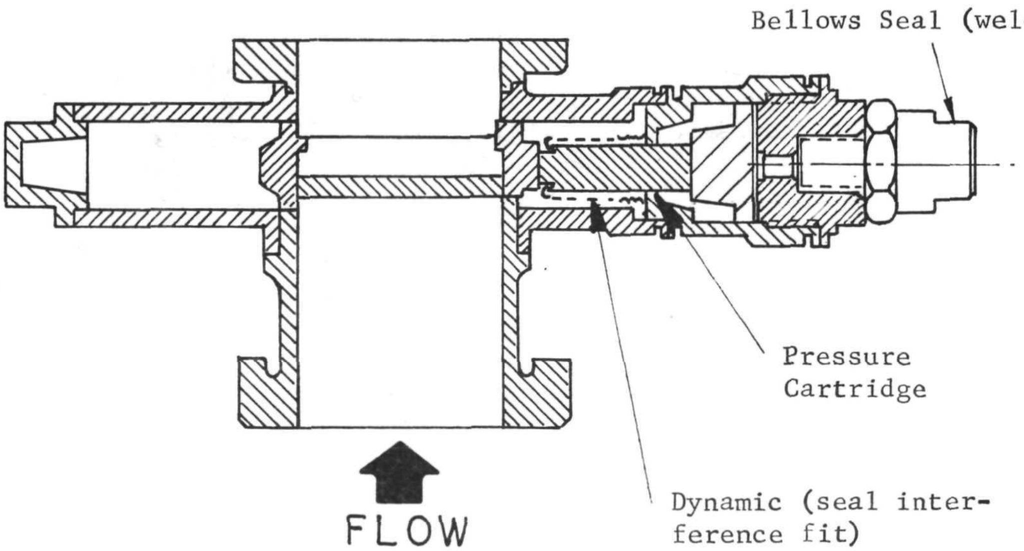


Figure 35.- Design P - Active Disc

Design Q (figure 36) was graded quite highly, being a relatively straight forward piercing cutter design which had been prototype-tested with water at room temperature, using nitrogen gas as the actuation medium. This design was also desirable from the standpoint that it more closely approached the rupture disc concept than some of the other designs, and it was easily refurbishable.

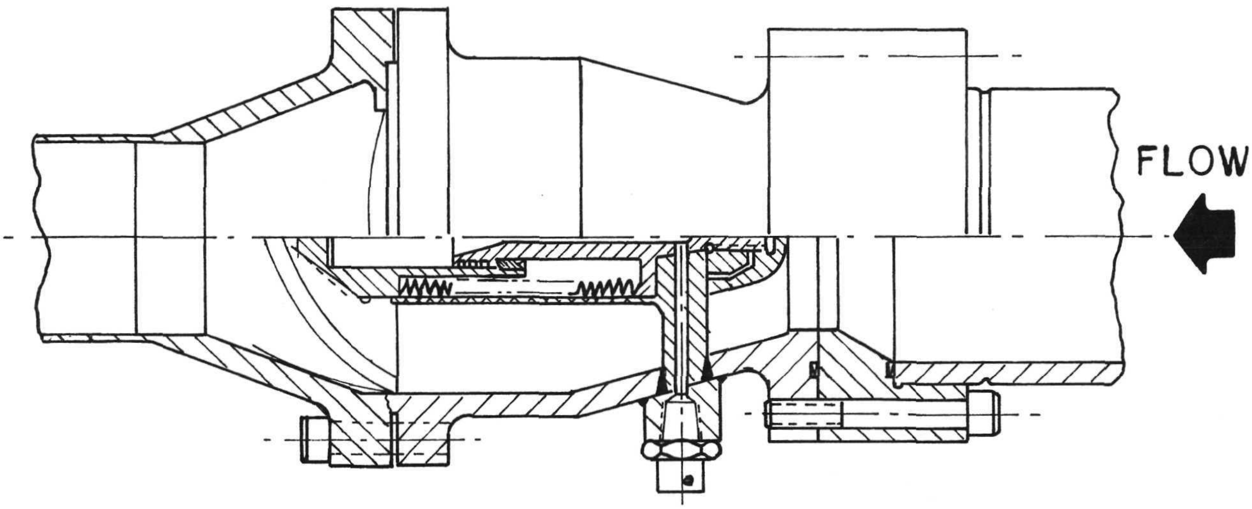


Figure 36.- Design Q - Active Disc

Designs R, S and U (figures 37, 38 and 39) utilize a metal-to-metal, elastically loaded interference fit seal as the dynamic seal between the combustion products zone and the commodity passage. These designs reflect the desire to effect a dynamic seal without the use of non-metallic materials -- none of which are known to be reliable in fluorine service (Refs. 1 and 2) -- and without resorting to bellows designed for the relatively high actuation pressures which are typical of compact actuators.

Design T (figure 40) has a frangible section swinging gate device employing interference fit and teflon seals to the critical dynamic seal areas. Pressure cartridge actuation does not directly fully open the gate diaphragm but rather shears the frangible section. The degree of gate opening then becomes a function of system flow conditions rather than mechanical action.

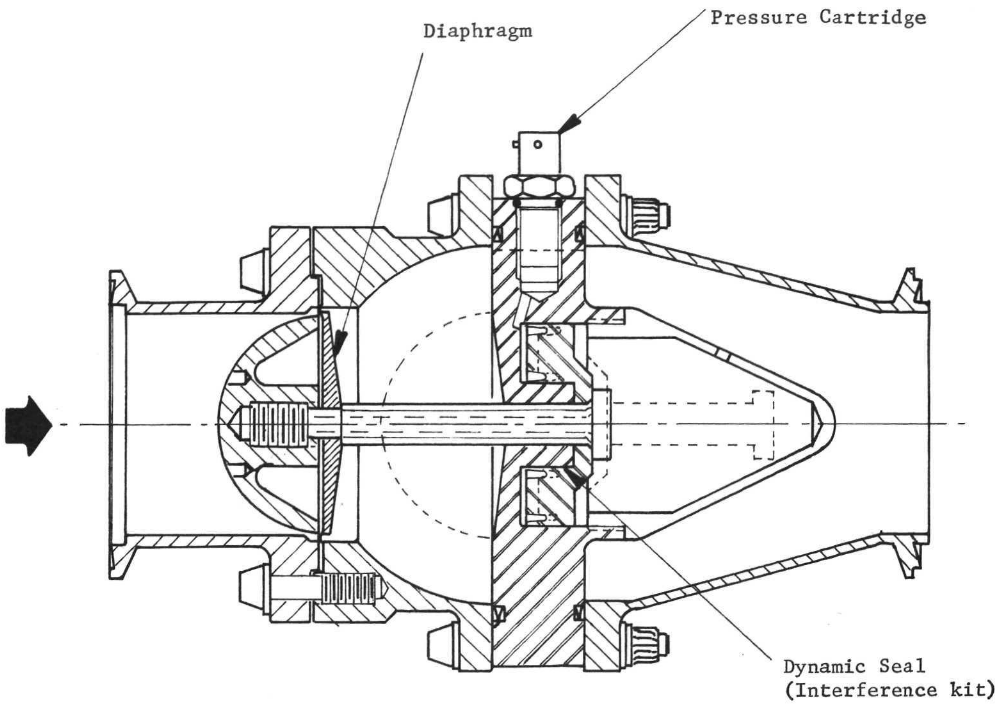


Figure 37. - Design R - Active Disc

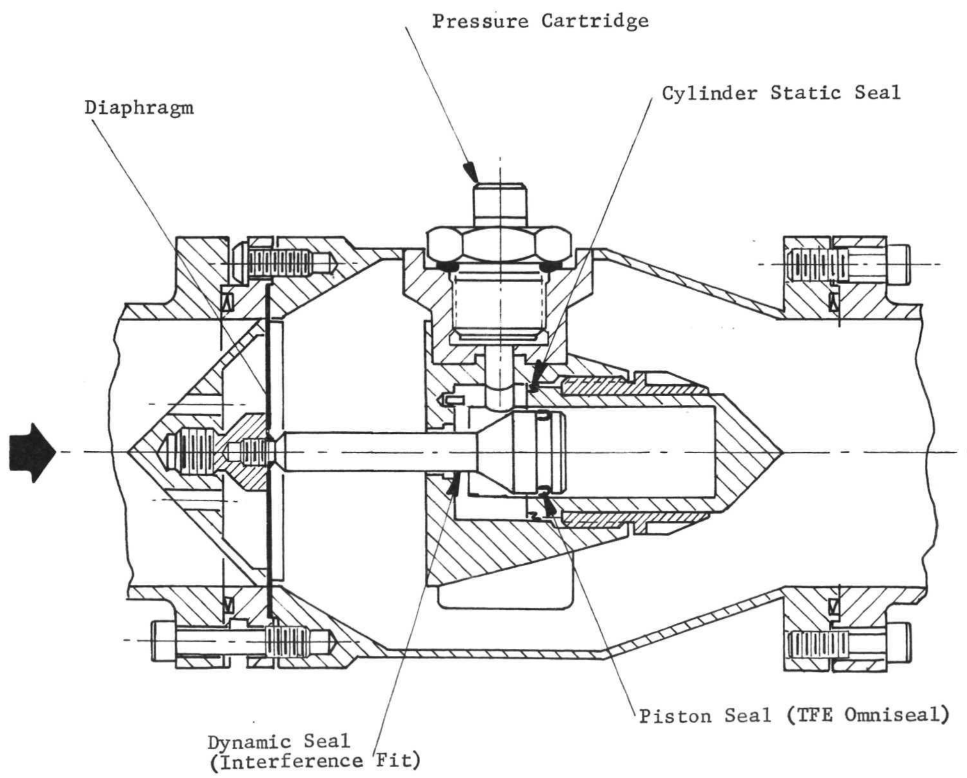


Figure 38.- Design S - Active Disc

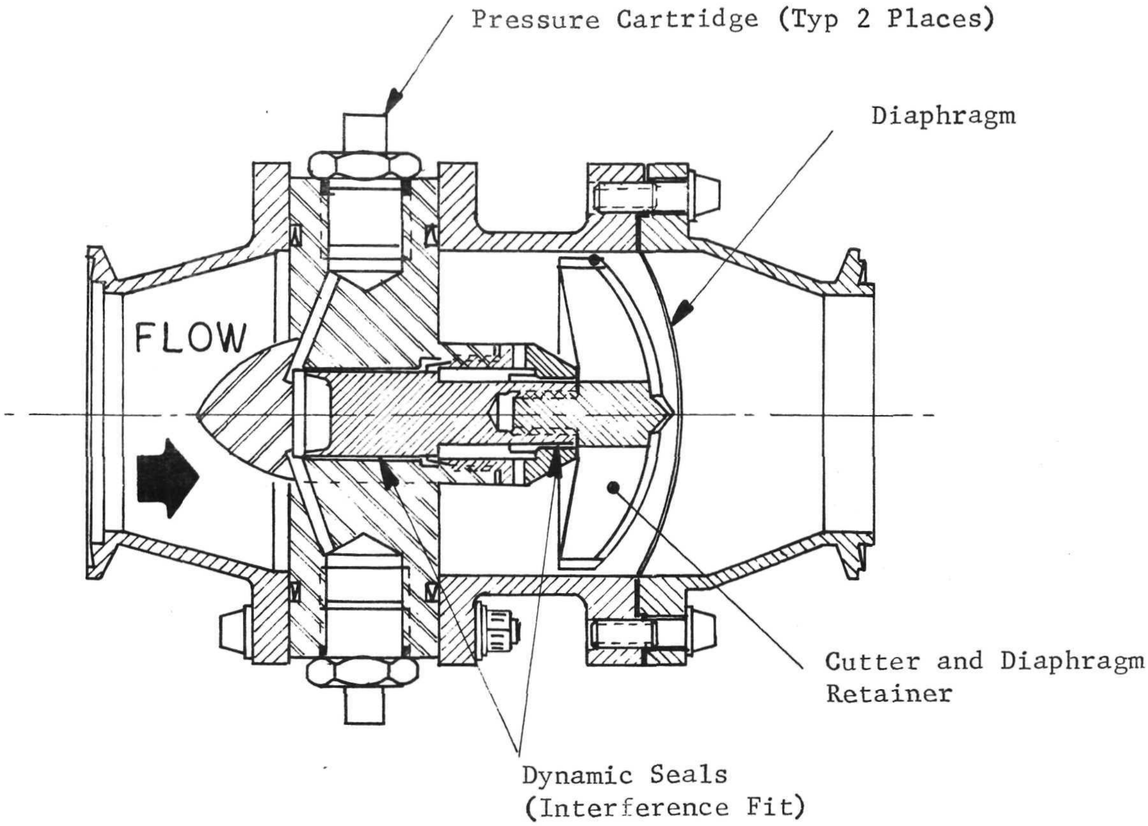


Figure 39. - Design U - Active Disc

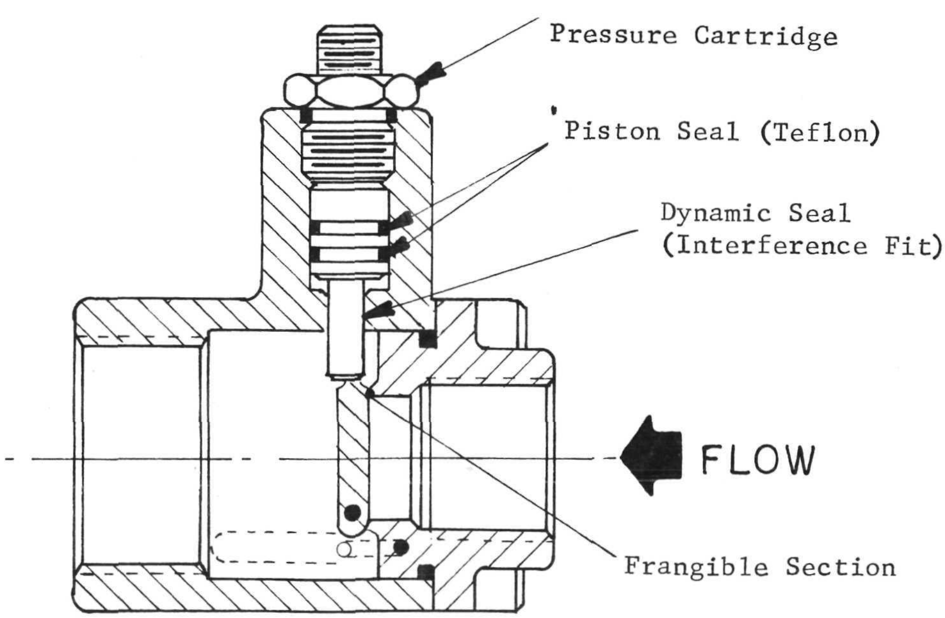


Figure 40. - Design T - Active Disc

The first phase of the evaluation process consisted of a screening operation in which the proposed designs were evaluated on the basis of relative simplicity of operation and effectiveness of dynamic surface sealing techniques, particularly in areas where cartridge combustion gases can intrude into the propellant passage. On this basis, designs H, J, K and L were eliminated. The remaining designs were graded according to the weighted criteria. At this point, procurement cost impact was, of necessity, added into the evaluation, since it became apparent that the program budget could not possibly accommodate the cost of some of the designs. Designs M, N and P all proposed by the same manufacturer, had the common characteristic of requiring replacement of a substantial portion of the device after each actuation. The associated costs, on the basis of the total program requirement of 23 actuations, were prohibitive. Therefore, although these designs were rated highly on a technical basis, they were eliminated from further consideration. Two incidental factors entered into this decision: 1) Designs M and N are not true rupture discs and 2) A NASA-Lewis Research Center program was already in process to evaluate a normally open version of this design. It was expected that the data obtained would be relevant to the normally closed versions. Design Q was dropped from consideration since its cost was beyond the cost limitations of this program and its essential (basic) features were very similar to design U. Design T was eliminated on the basis of inadequate provisions for deployment of the sheared disc after actuation. In view of the similarity of Design R, S and U, the program objectives would be effectively served by retaining only one poppet diaphram design and one piercing-cutter design, while retaining the same dynamic sealing concept. Design U as shown schematically in Figure 39, incorporated a cutter having a peripheral shroud ring to provide positive deployment and capture of the disc petals after cutting. In addition, the design included two series-redundant dynamic seals between the cartridge gas zone and the commodity passage.

The Task I study of active rupture disc design concepts was completed with the selection of designs S and U. These two designs are more fully described in the following sections of this report.

Cryogenic Tests (Task II, Phase I)

Test Scope. - The two active rupture disc designs selected at the conclusion of Task I were subjected to the tests summarized in Table 12. The objective of the Phase I testing was to select one active disc design for more extensive testing in Phase II.

TABLE 12.- TASK II - PHASE I TEST PROFILE

ACTIVE DISCS - 2 DESIGNS					
Fluid	Temp		Pressure at Actuation		Number of Tests (Each Design)
	$^{\circ}F$	K	psi	N/cm^2	
LH_2	-423	20	65	45	4
LN_2	-320	77	30	21	4

Test Specimen - Design U, Active Rupture Disc. - This 2.5 inch (6.4 cm) diameter design is shown in Figures 39 and 41. The device consists of a closure diaphragm located in the aft section of the housing, a six-bladed cutter, an actuating piston, and an electrically-initiated pressure cartridge. Due to the diaphragm cutting action employed in this design, the actuating forces required were expected to be relatively low. The strength of the diaphragm was such that it was able to withstand inlet pressures of approximately twice normal operating pressure and a reverse pressure differential of approximately 50% of normal inlet pressure. Two dynamic seals were provided to seal the cartridge gas/propellant interface. Both seals were of the elastically-loaded interference fit type. The primary seal was a lip on the gas end of the actuating piston, as shown in Figure 39. The secondary seal is formed by the same type of lip on the seal bushing which also helps guide the piston rod. The secondary seal also performs the function of preventing propellant contact with the critical metal-to-metal running surfaces of the piston chamber. This requirement was oriented toward the fluorine service application. The cutter in this design was configured to not only cut the diaphragm into six pie-shaped segments, but also to deploy the segments and lock them against the housing wall. Forced deployment, as opposed to fluid-dynamic deployment was used to obtain reliable flow characteristics and to prevent any partial re-closure due to propellant rebound or geysering in the feed line.

Figure 41.- 2.5-Inch (6.4 cm) Diameter Active Disc-Design U

Test Specimen - Design S, Active Rupture Disc. - This 2.5 inch (6.4 cm) diameter design is shown in Figure 38 and 42. The unit consisted of an inlet sealing diaphragm, an actuator piston, and a gas generator type electrically initiated pressure cartridge (squib). Sealing between the propellant flow passage and the actuating gases is effected in two ways. The dynamic seal at the piston rod is an interference fit, the static friction of which serves to support loads imposed on the inlet diaphragm from either side. The static combustion gas/propellant seals were Teflon TFE omniseals. These sealing methods reflect the requirement for fluorine compatibility. The inlet diaphragm was a 0.006 to 0.008-inch (0.015 to 0.020 cm) thick disc of nickel 200 for fluorine service or 1100-0 aluminum for hydrogen and nitrogen service. The diaphragm is sealed at the body of the housing by being clamped over a stepped surface.

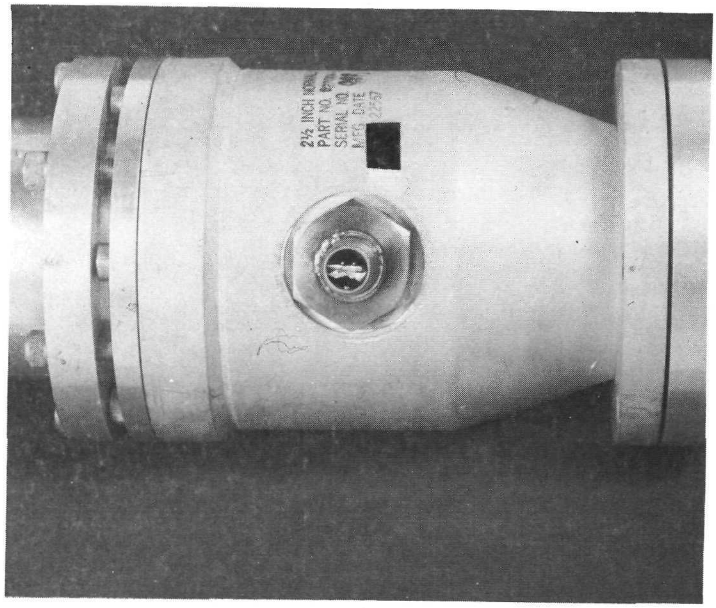


Figure 42.- 2.5-Inch (6.4 cm) Diameter Active Disc-Design S

This sealing method was used to permit repeated replacement of the diaphragm in the test program. For a flight unit, the body flange split line would be seal welded. A significant feature of this design was that the actuating mechanism was not subjected to propellant prior to actuation. This device was designed for operation at all temperatures between $+140^{\circ}$F and -423°F (333 and 20 K).

Test Fixture. - The basic test fixture is described in the Task II, Phase I passive disc section of this report. Fixture items peculiar to the active disc testing are shown in Figures 43 and 44.

The active disc test fixture (Figure 44) consisted of two assemblies, each having a 1-gallon (3.8 liter) capacity supply reservoir and a 1.5 gallon (5.7 liter) capacity receiver. A regulated helium supply was connected to the receivers to permit cycling of downstream pressure (pre-conditioning) and to establish a 1-atmosphere pressure prior to actuating the test item. The supply reservoirs, which were 90% immersed in cryogen, were equipped with cryogen fill and vent lines. Helium pressurant gas was supplied to the reservoirs from a facility supply.

The pressurant supply system was designed for the rigorous Phase II requirement of pressurizing the supply reservoirs to 100 psi (68.9 N/cm^2) or 50 psi (34.5 N/cm^2) at a rate of 1000 psi/second (689 N/cm^2/sec). To provide this capability, the supply system contained an accumulator, flow control orifices, and fast-acting, timer controlled, inlet pressurization valves.

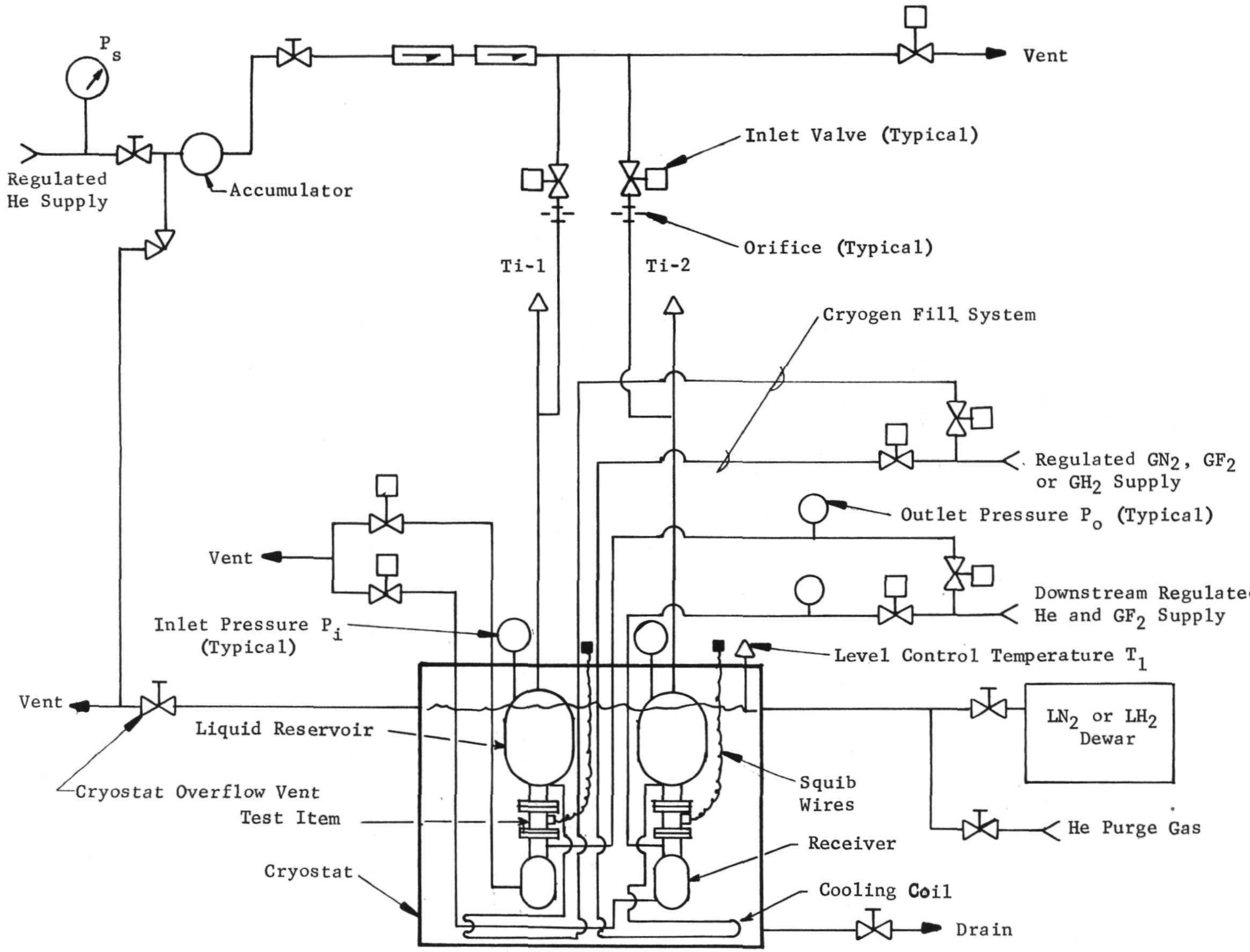


Figure 43. - Test Fixture Schematic

Since the pressure rise rate was also governed by the ullage volume of the reservoirs, the internal cryogen level was maintained at a known value by keeping the cryostat liquid level at the fixed value (see Figure 43 for level control thermocouple and overflow type cryostat vent).

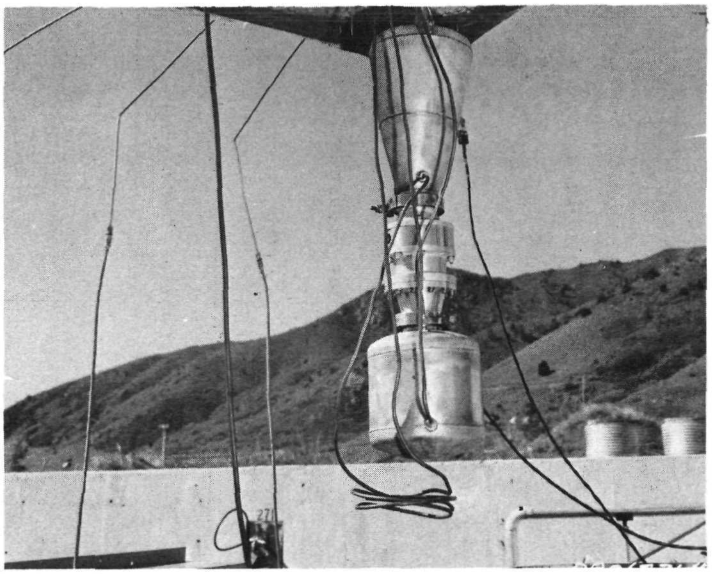


Figure 44. - Active Disc Installation

<u>Instrumentation</u>. - The instrumentation for all active disc tests is shown in Table 13. The inlet pressure transducer for the active disc tests was a 200 psi unit in order to prevent over-range damage during the 1000 psi/second (689 $N/cm^2/sec$) pre-conditioning cycles.

TABLE 13 - INSTRUMENTATION - ACTIVE DISC TESTS

Symbol	Function	Type	Range	Accuracy
P_i	Pressure, Disc Inlet	A	200 psi (138 N/cm^2)	$\pm$ 1% F.S.
P_o	Pressure, Disc Outlet	A	100 psi (68.9 N/cm^2)	$\pm$ 1% F.S.
T_i	Temperature, Disc Inlet	B	0 to -423°F (255 to 20 K)	$\pm$10°F (6 K)
T_1	Temperature, Level Control	B	0 to -423°F (255 to 20 K)	$\pm$10°F (6 K)
P_s	Pressure, Supply	C	1000 psi (689 N/cm^2)	$\pm$0.2% F.S.
I_a	Current, Actuator Squib	--	20 amps	$\pm$ 1%

NOTES: A = Strain-gage Type Pressure Transducer
B = Copper-constantan Thermocouple
C = Bourdon Tube Gauge

Test Method. - The active discs were tested two at a time while immersed in LN_2 or LH_2. Prior to cool-down the upstream reservoirs were pressurized to between 5 and 10 psi (3.4 to 6.9 N/cm^2) with GN_2 or GH_2. This pressure was maintained on the pressurant supply system throughout the cool-down period. The test items were cooled slowly with the introduction of the applicable cryogen in the cryostat. The cryostat was filled until approximately 90% of the upstream reservoirs were covered. The continuous supply of gaseous commodity to the upstream reservoirs liquefied as the reservoir became submerged providing approximately one gallon (3.8 liters) of liquid commodity. The downstream side of the rupture discs were maintained at approximately ambient pressure with helium during the cool-down period. After the test item inlet and cryostat temperatures had stabilized at the required test temperature, the supply pressure was increased to the value shown in Table 12, and the rupture discs actuated open. Continuous chart recordings were made of all parameters during the rupture sequence. After the two test specimens had been actuated, the cryostat was purged and the assembly removed for inspection and refurbishment of the test specimens.

Post-test inspection, cleaning and re-build of the rupture discs were performed in an area that includes a cleaning facility and a Federal Spec. 209 Class 100 clean room. Assembly and inspection of test units was done in a clean environment to avoid contamination of critical sealing surfaces and provide fluorine compatible assembly.

Test Results. - The results of the Phase I active rupture disc testing are shown in Table 14. During the first of four liquid nitrogen tests performed on design S and U, only design U actuated satisfactorily. Design S did not actuate, although the pressure cartridge had fired. Upon removal of both units from the cryostat immediately after the test, a strong odor of combustion products was noted, emanating from the outlet of the design S unit, indicating gas leakage past the static seals in the actuator section.

Both units were disassembled according to the manufacturers' written procedures. Inspection of the design S unit revealed evidence of gas blow-by past the piston dynamic seal. The piston had not moved from its pre-test position. Immediately following the inspection, this unit was shipped back to the manufacturer with all parts in the "as-is" condition for failure analysis and remedial action. The failure analysis of design S, performed by the manufacturer, resulted in re-machining of a surface discontinuity in the cylinder static seal area.

Inspection of the design U unit revealed no unusual wear or evidence of gas leakage. Deployment of the disc petals (Figure 45) was complete. The open area of the disc, after removal from the unit, was determined by photographing the disc against a grid background and counting squares on the photograph (Figure 46). The projected open area was found to be 6.5 in^2 (41.9 cm^2), which is 33% greater than the area of a 2.5 inch (6.4 cm) inlet and outlet ports. During removal of the disc from the U unit, it was noted that the petals relaxed inward slightly when the cutter was withdrawn; therefore, the open area of the disc, while still in place, was somewhat larger than the measured area after

TABLE 14. - TASK II - PHASE I DATA SUMMARY

Design	Run No.	Body Temp		Pressure psia		Absolute Pressure N/cm^2		ΔP		Response Time (ms)	Disc Open Area	
		^oF	K	Inlet	Outlet	Inlet	Outlet	psi	N/cm^2		in^2	cm^2
U	1	-320	77	42.8	11.9	29.5	8.2	30.9	21.3	12.0	6.5	41.9
U	2	-320	77	43.8	13.6	30.2	9.4	30.2	20.8	11.0	6.8	43.8
U	3	-320	77	44.4	12.7	30.6	8.8	31.7	21.8	9.0	6.8	43.8
U	4	-320	77	42.9	14.9	29.6	10.3	28.0	19.3	15.5	6.7	43.2
U	5	-423	20	77.3	14.5	53.3	10.0	62.8	43.3	13.6	6.8	43.8
U	6	-423	20	87.7	17.1	60.5	11.8	70.6	48.7	6.3	6.6	42.6
U	7	-423	20	77.3	7.8	53.3	5.4	69.5	47.9	9.7	6.9	44.5
U	8	-423	20	82.2	14.5	56.7	10.0	67.7	46.7	5.8	6.8	43.8
S	1	-320	77	42.8	11.9	29.5	8.2	30.9	21.3	*	*	*
S	2	-320	77	43.8	13.6	30.2	9.4	30.2	20.8	*	*	*
S	3	-320	77	44.4	12.7	30.6	8.8	31.7	21.8	*	*	*
S	4	-320	77	42.9	14.9	29.6	10.3	28.0	19.3	*	*	*
S	5	-423	20	76.6	30.4	52.8	21.0	46.2	31.8	2.4	4.9	31.6

Response Time = Current onset to first indication of downstream pressure increase, in milliseconds.

* Test item failed to actuate.

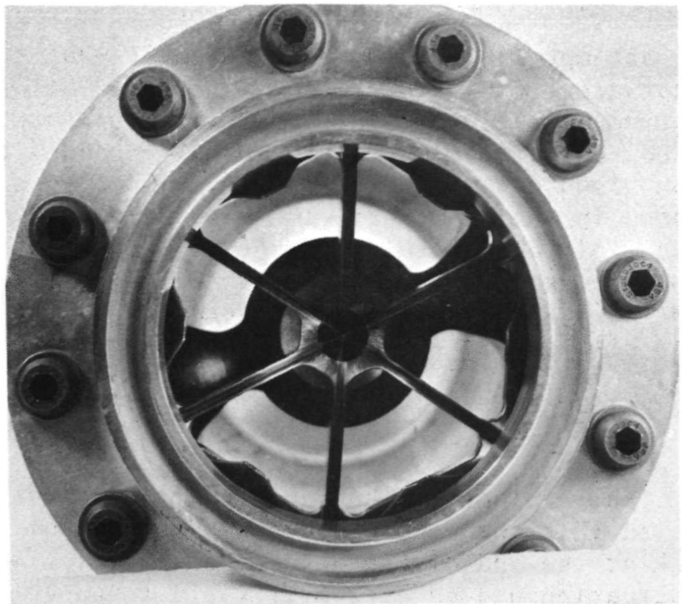


Figure 45.- Design U Active Rupture Disc - Petal Deployment

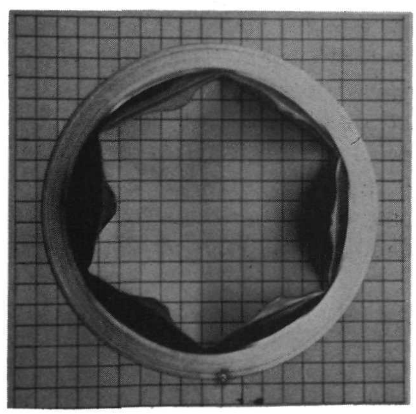


Figure 46.- Open Area Determination - Design U

removal. Particle generation during the U unit actuations consisted of 20 to 30 aluminum disc particles (slivers) approximately 10 microns thick, the major portion of the population being on the order of 40 to 80 microns in length. This characteristic was noted throughout all testing.

Design S was returned following rebuild, and liquid nitrogen tests were resumed on both units. Design S again failed to actuate during test numbers 2 and 3. Inspection of the unit after each attempt revealed evidence of incomplete combustion of the cartridge charge, gas blow-by past the piston dynamic seal and gas leakage past the static cylinder seal. The fourth run was made using the Government Furnished Equipment cartridge which was used in the design U active disc, after having conferred with the design S engineering department. During this fourth and final attempt in LN_2, the design S unit was extensively damaged and failed again to actuate. Analysis of the structural failure of the unit indicated that the extremely rapid pressure rise rate characteristic of the GFE cartridge -- as opposed to its final pressure level -- caused the center-body/ actuator housing to be blown off of the cartridge chamber before actuating pressure was established in the cylinder. The gross misalignment of the poppet which resulted from the initial lateral movement of the actuator housing prevented the poppet from moving. The objective of the above - described test - that of attempting to isolate the cartridge performance contribution from the mechanical performance of the unit -- was therefore not attained.

In the first LH_2 test, the replacement design S unit actuated; however, post-test inspection revealed that the poppet had been broken from the piston rod by the arresting shock at the end of the actuation stroke. The pressure cartridge used for this actuation had an extremely rapid response time of 2 milliseconds which may have contributed to the failure. The design S unit was eliminated from the test program after this test. The design U unit actuated satisfactorily during all four LH_2 tests.

On the basis of the significant disparity in performance between the design U and design S active discs during the LN_2 tests, and in light of the schedule constraints, design U was selected for the remaining program activities. The primary reason for rejection of design S was the cartridge gas leakage which was evident during the three runs preceding structural failure of the unit in LN_2. Since a fundamental sealing concept change could not be made in the remaining time available, the design was not suitable for fluorine service and therefore unacceptable as the selected design for further testing in Phase II and Task IV.

Cryogenic Testing (Task II, Phase II)

Test Scope. - Design U, selected as a result of the Phase I testing, was subjected to the tests summarized in Table 15. The test specimen used in Phase II testing consisted of the refurbished Phase I unit, designated unit 1, and a newly manufactured unit designated as unit 2. Phase II testing was essentially the same as that in Phase I, with the addition of pre-actuation conditioning. The test fixture and instrumentation used for Phase I was employed for all tests performed in Phase II.

TABLE 15. - TASK II - PHASE II TEST PROFILE

Test Fluid	Temperature		Pressure at Rupture		Pre-Conditioning (at Test Temp)	No. of Tests
	^{o}F	K	psig	N/cm^2		
LH_2	-423	20	65	45	5 cycles to 50 psia ($34\ N/cm^2$) downstream 5 cycles to 100 psia ($69\ N/cm^2$) upstream at 1000 psi/second ($689\ N/cm^2/sec$)	4
LN_2	-320	77	30	21	5 cycles to 50 psia ($34\ N/cm^2$) downstream 5 cycles to 50 psia ($34\ N/cm^2$) upstream at 1000 psi/second ($689\ N/cm^2/sec$)	4
LN_2	-320	77	30	21	LF_2 exposure	4

Test Method. - The general test method outlined in Phase I was used for the tests in Phase II. The high rise rate upstream pressure cycling was accomplished, using helium as the pressurant gas, after the upstream reservoirs were filled with the applicable cryogen. The downstream pressure cycling was also accomplished with helium under the loaded conditions. For the LF_2 exposure tests the units were preconditioned by exposure to LF_2 in the actuation test fixture. This was accomplished by first passivating the assembled test specimen and test fixture with GF_2 at ambient temperature and operating pressure, then filling the cryostat with LN_2 and permitting enough GF_2 (approximately 45 cc) to liquify, covering the inlet side of the test specimen disc with LF_2. The LF_2 was then removed by draining the cryostat to the extent required to permit the LF_2 to boil off. The upstream reservoir was then filled with LN_2 as previously described in preparation for the actuation test.

Test Results. - The results of Phase II active rupture disc testing are shown in Table 16.

The refurbished design U unit 1 and the new unit 2 were each actuated twice at LN_2 conditions. Prior to testing, the actuator sections of the units were leak checked using a helium mass spectrometer leak detector and exhibited no measurable leakage on the most sensitive leak detector scale (instrument sensitivity = 3×10^{-10} scc/sec/division). After the first actuation test, the actuator section of unit 2 was leak tested in the same manner and again exhibited no measurable helium leakage. Unit 1 was not leak-checked after the first actuation, since the cutter hub bolt threads sheared off and permitted the cutter to strike the aft housing. The leak-check was waived in order to expedite repair of the unit. After cleaning and reassembly of unit 2 and repair of unit 1 by installing a new actuator, piston and cutter, both units again exhibited no measurable leakage. The results of these leakage tests indicated no cartridge gas leakage past the series-redundant metal seals during actuation.

The two LN_2 actuation tests completed on unit 2 were accomplished without incident, although the amount of deformation of the copper impact-absorbing sleeve was much more severe than that observed in the Phase I testing. The rebuilt unit 1 sustained damage during both of the actuation tests. Although the unit opened satisfactorily during both tests, the cutter hub threads failed on the first test and the piston cap/seal assembly threads failed during the second test. Both of these failures were ascribed to the prior history of eight actuations made on the unit during Phase I, and to some extent the apparent higher actuation energy (impact loads) experienced during the Phase II tests. This theory was subsequently supplanted and is discussed in detail in the discussion of results sections of this report.

The four LH_2 tests consisted of two tests of each unit. The LH_2 actuations were completed satisfactorily; however, a helium leak check made after the tests showed that the actuator seals were leaking. An inspection of both units revealed the seal surfaces had been scored and that the cylinder bore and seal lips were pitted. This phenomenon had been observed earlier during the Phase I liquid nitrogen tests, and is ascribed to the combined erosive/corrosive action of the explosive cartridge exhaust products and the nitric-hydrofluoric acid used to clean the actuators after each test for re-cycling.

Actuation of the test items exposed to liquid fluorine was normal except during test numbers 9, 10 and 12 (Ref. Table 16). During test 12 the unit did not open fully due to lodging of the squib closure disc over the gas passage hole, with attendant throttling of the cartridge gas (Figures 47 and 48). The incomplete 5 in^2 (32 cm^2) disc opening of the test item was still compatible with the open area of the 2.5-inch (6.4 cm) diameter test item ports.

TABLE 16. - TASK II - PHASE II DATA SUMMARY

Test Number	Design U Unit No.	Test Fluid	Test Temperature		Differential Pressure at Actuation		Response Time (milli-seconds)	Open Area		See Notes
			^oF	K	psi	N/cm^2		in^2	cm^2	
1	1	LN_2	-320	77	28.3	19.5	4.3	6.8	43.9	1
2	2				31.7	21.8	6.6	-	-	1 and 2
3	1				30.9	21.3	3.2	6.8	43.9	1
4	2	LN_2	-320	77	38.0	26.2	6.5	6.7	43.2	1
5	1	LH_2	-423	20	72.4	49.9	1.7	6.7	43.2	3
6	2				67.4	46.5	4.0	6.7	43.2	3
7	1				67.4	46.5	4.9	6.7	43.2	3
8	2	LH_2	-423	20	68.0	46.9	3.7	7.0	45.2	3
9	1	LN_2	-320	77	29.4	20.3	-	0	0	4 and 5
10	2				32.2	22.2	-	0	0	4 and 5
11	1				29.9	20.6	5.0	6.9	44.5	4
12	2				26.6	18.3	5.6	5.0	32.3	4 and 6
13	1				31.2	21.5	10.6	6.7	43.2	4
14	2	LN_2	-320	77	32.7	22.5	9.7	6.8	43.9	4

NOTES:

1. Precondition cycles; 5 cycles to 50 psi (34.5 N/cm^2) downstream and 5 cycles to 50 psi (34.5 N/cm^2) upstream at 1000 psi/second (689 N/cm^2 sec)
2. Disc mutilated during disassembly - no area measurement made
3. Precondition cycled: 5 cycles to 50 psi (34.5 N/cm^2) downstream and 5 cycles to 100 psi (68.9 N/cm^2) upstream at 1000 psi/second (689 N/cm^2 sec)
4. LF_2 exposure
5. Did not open
6. Incomplete opening. Squib closure over gas passage port

RESPONSE TIME = Current onset to first indication of downstream pressure increase

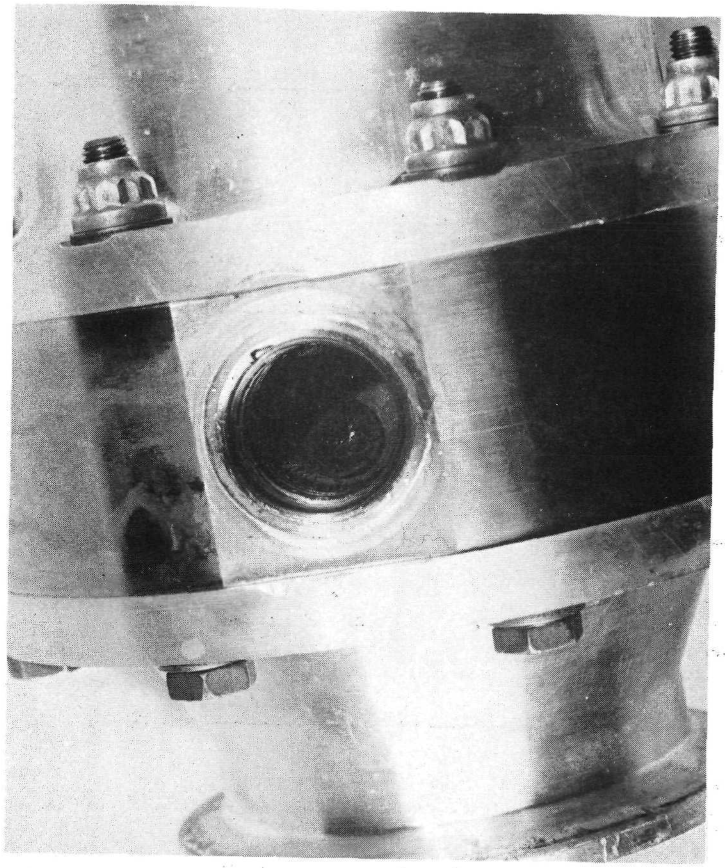


Figure 47.- Squib Closure Restriction - Test Number 12

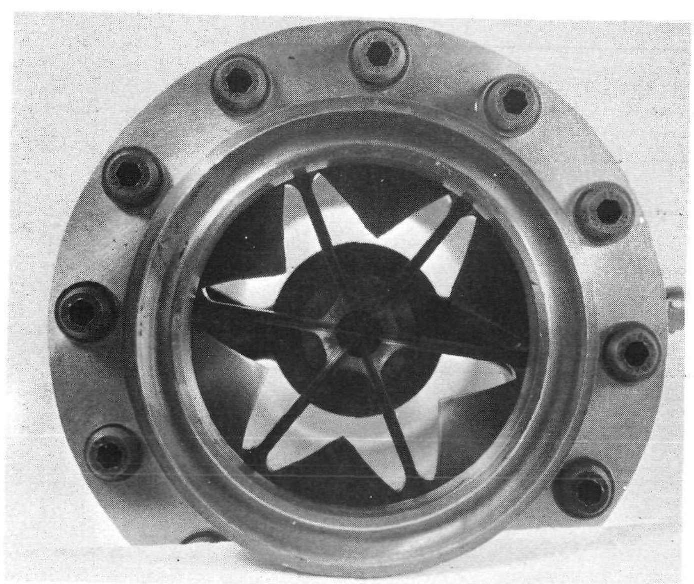


Figure 48. - Incomplete Disc Opening - Test Number 12

Test specimens 9 and 10 were subjected to liquid fluorine exposure prior to actuation with LN_2. In an attempt to make operation of the test fixture with cryopumped GF_2 as simple as possible, the coolant coils which had been used in Phase I, were removed from the fixture. It was recognized that removal of the coolant coils would increase the possibility of incurring damage to the test specimens during cool-down; however, it was thought that this problem could be circumvented by using a very slow cool-down. Inspection after these tests showed that the pistons and cylinders of both units had been permanently deformed, and that both units had actuated only about 20% of the required stroke. The cutters of both units came to rest against the rupture disc, making an imprint but not cutting the disc as shown in Figure 49. Although the failure was not completely explained, the immediate corrective actions were to re-install the cooling coil and to cool down more carefully. No evidences of piston seizure were noted on the four subsequent runs.

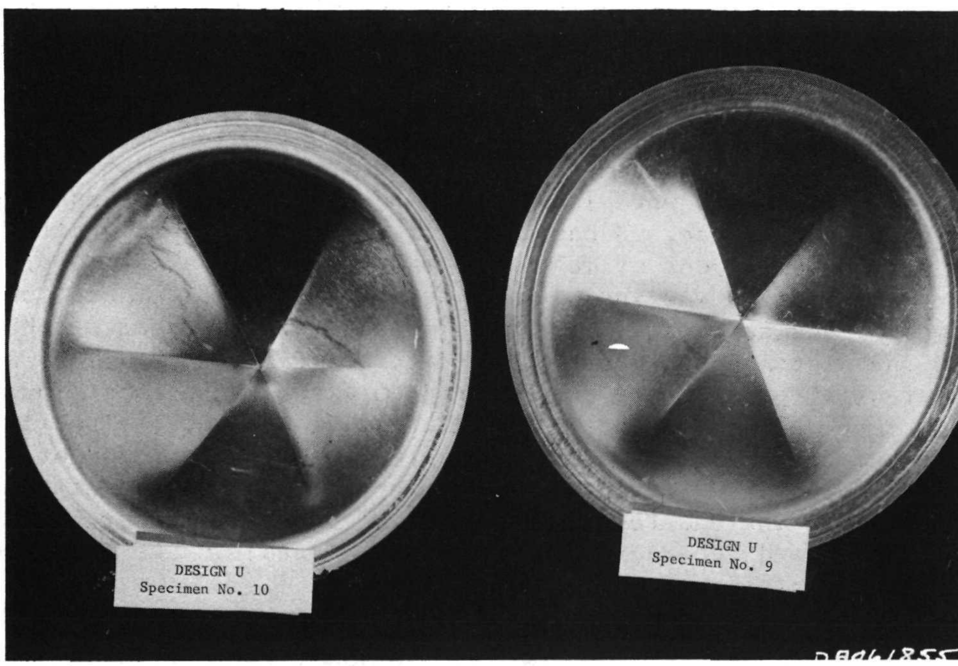


Figure 49. - Unopened Discs - Tests 9 and 10

Water Flow Testing (Task III)

Test Scope. - The objective of the water flow test was to determine the pressure drop characteristics of the active rupture discs at design flow rate, and to determine the variations in flow capacity as a function of the degree of opening of the discs from one actuation to another (repeatability to open flow area). Six of the active rupture discs that were subjected to Task II, Phase I and four of the active discs that were subjected to Task II, Phase II, were water flow tested. Since design S failed to open properly on any run, only design U units were subjected to this testing.

Test Fixture. - The test fixture is shown in figures 50 and 51. The setup consisted of a water supply and an outflow line that included differential pressure measurements and a flow control valve. Flow control was provided by a hand-operated valve which was pre-set during trial runs using a spool piece in place of the active rupture disc. Flow initiation and shut-off was accomplished with a hand-operated gate valve in the water supply line. A turbine flowmeter was used for flow measurement.

The differential pressure measurement system conformed to ASTM standards. Pressure taps were flush and were located 10 diameters from the test articles or any other flow disturbance. Because the tare (fixture piping) differential pressure was of the same order of magnitude as the net differential pressure, a tare measurement section was included in series with the test section. The distance between pressure taps for the tare section was the same as the test section minus the distance between the test article interfaces. This allowed the tare differential pressure to be measured to exactly the same flow conditions and flow rate as the test article differential pressure. The flowpath tubing had the same internal diameter as the test specimen throughout the measurement section. The differential pressure transducers were of the smallest range practical. The end-to-end differential pressure measurement accuracy, including transducer and recorder, was $\pm$ 1% of full scale. The instrumentation for the water flow tests is shown in Table 17.

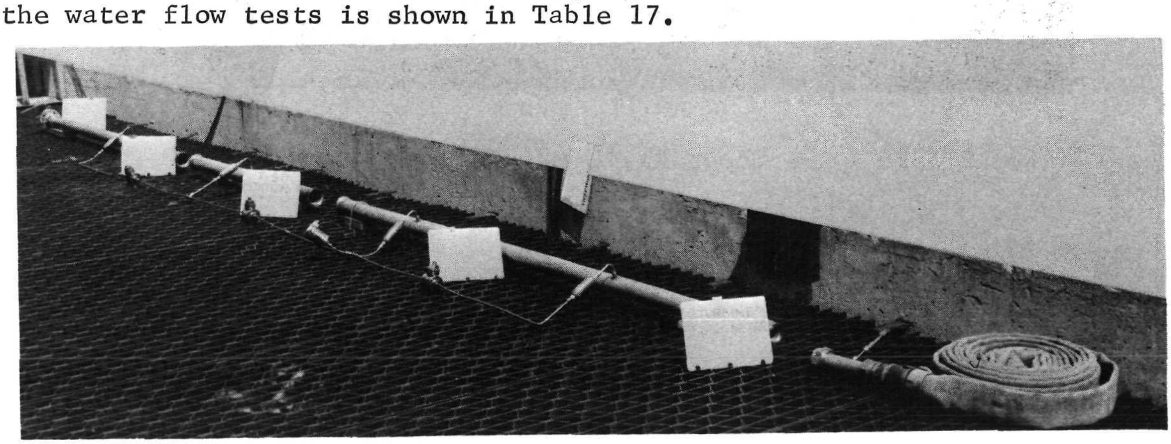


Figure 50. - Water Flow Test Fixture

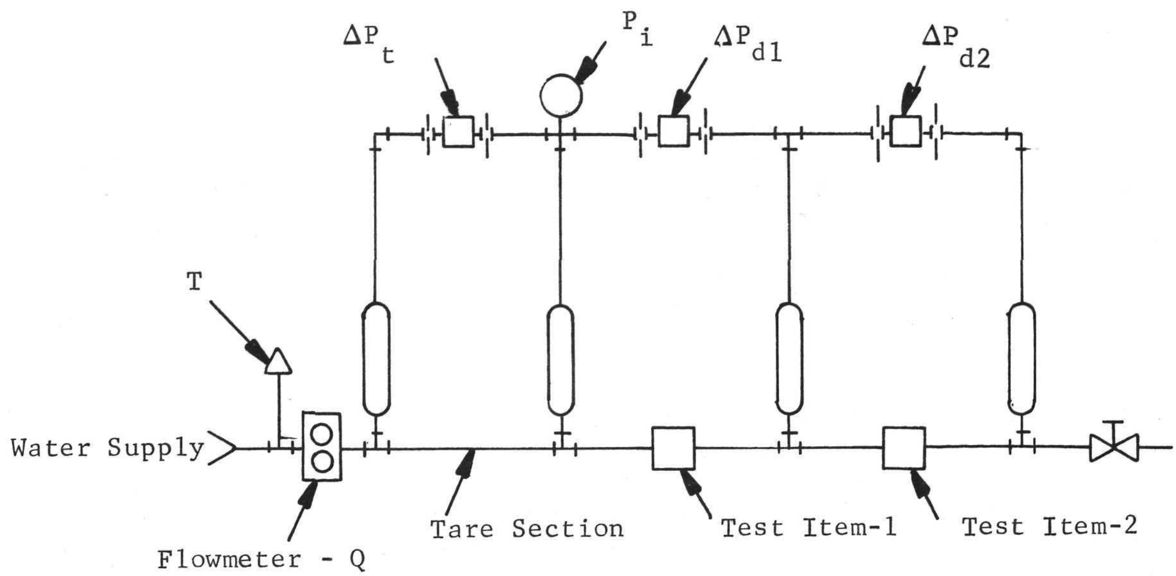


Figure 51. - Water Flow Fixture Schematic

TABLE 17. - INSTRUMENTATION - WATER FLOW TESTS

Symbol	Function	Type	Range or Maximum Scale	Accuracy
P_i	Pressure, Disc Inlet	A	100 psi (68.9 N/cm^2)	$\pm$ 1%
Q	Flowrate	D	300 gpm (18.9 l/sec)	$\pm$ 2%
ΔP_t	Diff. Press., Tare Spool	B	10 psi (6.9 N/cm^2)	$\pm$ 1%
ΔP_{d1}	Diff. Press., Disc 1	B	10 psi (6.9 N/cm^2)	$\pm$ 1%
ΔP_{d2}	Diff. Press., Disc 2	B	10 psi (6.9 N/cm^2)	$\pm$ 1%
T	Temperature, Water	C	0-100°F (255-311 K)	$\pm$ 2°F($\pm$ 1.1 K)

NOTES:
A = Strain Gauge Type Pressure Transducer.
B = Strain Gauge Differential Pressure Transducer.
C = Copper-constantan Thermocouple.
D = Turbine Type Flow Meter.

Test Method. - The Reynolds numbers for the flight propulsion system liquid hydrogen and liquid fluorine flowrates are in the range of 1 x 10^6, which places the flow well into the turbulent regime. In order to flow water at the same Reynolds number, an excessively high flowrate would have been required (approximately 2000 gpm (126 liters/sec). An alternative method of employing a water flowrate which produced the same pressure drop as the design conditions was therefore used. The water flowrate for this condition was approximately 260 gpm (16 liters/sec). The Reynolds number for this flowrate is in the range of 10^5, which is still in the turbulent flow regime. In keeping with the multiple-unit testing philosophy, when possible, two active rupture discs were installed for each test run.

The test was conducted by opening the supply valve slowly with the outlet valve at a pre-set open position. The supply valve was then adjusted to obtain a flow rate of 260 gpm (16 liters/sec), at which time the test section pressure was 30 to 65 psi (21 to 45 N/cm^2) as dictated by the pre-set outlet valve position. Continuous recordings of flow rate and differential pressures were made during each run.

Test Results. - The test results for the Task III water flow testing are shown in Table 18.

TABLE 18. - TASK III - DATA SUMMARY

Phase	Test No.	Design	Water Flowrate		Pressure Drop		Open Area	
			gpm	liters/sec	psi	N/cm^2	in^2	cm^2
I	1	U	260	16.4	0.9	0.62	6.5	42
	2	U	251	15.8	0.9	0.62	6.8	44
	3	U	266	16.8	0.9	0.62	6.8	44
	4	U	260	16.4	0.9	0.62	6.7	43
	5	U	254	16.0	0.6	0.41	6.8	44
	8	U	259	16.3	0.5	0.34	6.8	44
II	5	U unit 1	258	16.3	0.8	0.55	6.7	43
	6	U unit 2	258	16.3	0.6	0.41	6.7	43
	13	U unit 1	259	16.3	0.7	0.48	6.7	43
	14	U unit 2	259	16.3	0.5	0.34	6.8	44

Test numbers 5 and 6 (both Phase II) were tested simultaneously, in tandem as were test numbers 13 and 14.

Fluorine Compatibility Testing (Task IV)

Test Scope. - The design U active rupture disc was subjected to liquid fluorine compatibility tests as shown in Table 19. The objective of the tests was to determine if a catastrophic reaction would occur due to actuation of the active discs in liquid fluorine. No testing with FLOX was done, since the results of this fluorine test program are considered applicable to FLOX systems also.

TABLE 19. - TASK IV - FLUORINE COMPATIBILITY TEST PROGRAM

Test Media	Temperature at Actuation		Design Actuation Press.		No. of Discs
	^{o}F	K	psi	N/cm^2	
LF_2	-320	77	30	21	3

Test Fixture. - The test fixtures used for the Task II testing was also used for this task (Ref. Figures 43 and 44). Liquid and gaseous pressurization media were provided above the rupture disc and a liquid receiver was located below the disc. The reservoir, rupture disc, and receiver were immersed in a liquid nitrogen bath when liquid fluorine was required to be in contact with the rupture disc. The liquid flow duration of this fixture was on the order of 0.2 second, which is the approximate time required to transport the 1 gallon (3.78 liters) of stored liquid through the test item. Because of the extreme rapidity of the initial passivation reaction of freshly exposed surfaces at disc rupture, the flow time was considered adequate for the objectives of this task. The instrumentation was the same as given in Table 13 for the Task II testing.

Test Method. - The general test method outlined in Task II was used for this task. The active rupture discs were placed in the test fixture and the system was passivated in accordance with the applicable portions of References 1 and 7 using an approved procedure. A positive GF_2 pressure was maintained upstream of the rupture disc and a helium pressure of approximately 1 atmosphere was maintained in the downstream receiver as the cryostat was filled with LN_2. Gaseous fluorine cryo-pumped to fill the supply reservoir. When liquefaction was complete, as indicated by the inlet temperature, the upstream reservoir was pressurized with helium to 30 psi (21 N/cm^2). The rupture disc was then actuated with all data being continuously recorded.

Test Results. - The three planned liquid fluorine tests on the design U active rupture disc were completed; however, the unit did not open on any of the attempted actuations. After the first attempt, inspection revealed that the cutter had actuated to the extent of deforming the disc until the entire length of the six blades was in contact with the disc, (Figure 52); however the apex point of the cutter had not penetrated the disc sufficiently to initiate the cutting action. An analysis of this failure resulted in the conclusion that retardation of the cutter velocity may have resulted from the dashpot effect of expelling a very dense fluid (LF_2) from the piston rod/seal cap annulus (see Figure 39 section view of the active disc).

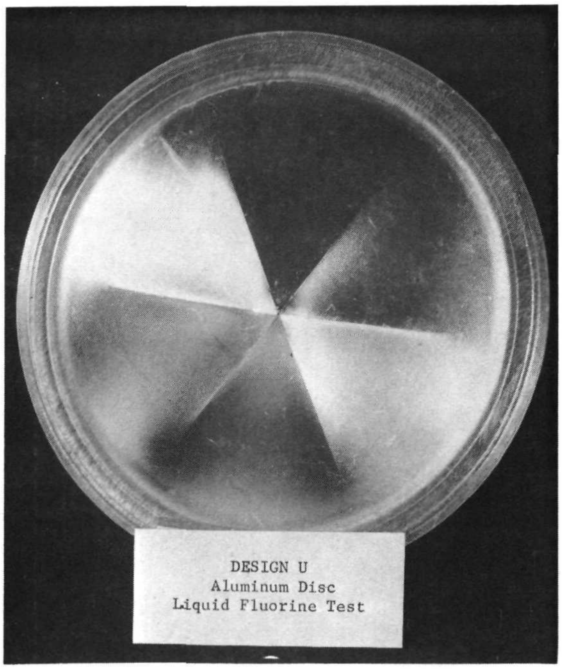


Figure 52.- Unopened Aluminum Disc - Fluorine Test

Based on the failure analysis, eight 0.25-inch (0.6 cm) diameter vent holes were drilled in the nose of the piston seal cap to augment the existing four 0.19-inch (0.5 cm) vent/spanner holes, thus increasing the available expulsion flow exit orifice area by a factor of five. The second and third actuation attempts were made with two of the modified test items mounted in the test cryostat at the same time. Both test items failed to actuate and produced the same deformation pattern experienced during the first LF_2 test on the unmodified unit. Significantly, the identical pattern had been produced in Phase II during tests 9 and 10, which had been pre-exposed to LF_2 and then actuated with LN_2 as the fluid medium. These failures had been attributed to permanent deformation of the piston primary seal and cylinder bore due to having cooled down the unit too rapidly, although the units should have actuated since the secondary seal was still functional. Since the subsequent LN_2 actuations of LF_2 exposed specimens during tests 11, 12, 13 and 14 were uniformly successful, the conclusion that the failures were caused by crippling of the actuator was substantiated.

In view of the repeated failures in the attempts to open an active rupture disc in liquid fluorine, a significant program objective remained unattained; therefore, an intensive analysis and a series of tests were made to isolate the cause of failure. Results of these analysis and testing are presented in the Discussion of Results section.

DISCUSSION OF RESULTS

Passive Disc Results

The general results of the passive disc program may be briefly summarized as follows:

- Two types of passive rupture discs were tested which exhibited significantly less sensitivity to temperature changes than the prebulged and coined types of discs.
- The capability of passive rupture discs to operate in cryogenic-temperature gaseous fluorine with no adverse effects were established.
- The reliability of repeatability characteristics of the reverse buckling type of rupture disc were established for both room temperature and cryogenic temperature operation.
- The sensitivity of reverse-buckling discs to pressure cycling and changes in pressure onset rate was evaluated to a limited extent.
- Certain recommended practices for the design of reverse-buckling rupture discs were established as a result of analysis of the disc behavior in this program.
- A new concept rupture disc design was evaluated to the extent of identifying the sensitive criteria applicable to the design.
- None of the discs tested were reliable enough to recommend their use for precision installations involving cryogenic service, nor did they perform as well as the Belleville disc design (Design A) (See Appendix D).
- Although any of these designs could be used in a non-critical application, in general additional development is needed to adapt them to a specific use.

The results of the passive disc test program are discussed in this section by means of a progression starting with a review of the test data, discussions of both the beneficial and adverse behavior apparent in that data, discussions of the known and probable causes of adverse behavior, and concluding with recommended ways of eliminating the adverse characteristics.

Data Review - Task II Phase I. - In the passive disc test program, the salient characteristics being evaluated were the predictability of the nominal or average rupture pressure at cryogenic conditions, the amount of variation about the mean rupture pressure, the tendency to generate debris, the leakage characteristics and the compatibility of the design with fluorine. The average rupture pressure of the three designs is shown in Table 20.

TABLE 20. - AVERAGE RUPTURE PRESSURE OF PHASE I DISCS

Design	Disc Material	Disc Rating	Average Rupture Pressure		Variation From Average Pressure %
			psi(N/cm^2)	% Deviation from Rating	
B	Nickel 200	50 psi @ -285^oF (34.5 N/cm^2 @ 97 K)	38 (26)	-24	+36, -23
	316 Stainless Steel	100 psi @ 395^oF (68.9 N/cm^2 @ 36 K)	84 (58)	-16	+18, -35
C	Nickel 200	50 psi @ -285^oF (34.5 N/cm^2 @ 97 K)	58 (39)	+16	+13, -13
	316 Stainless Steel	100 psi @ -395^oF(68.9 N/cm^2 @ 36 K)	119(81)	+19	+ 8, -16
G	Nickel 200	50 psi @ -285^oF (34.5 N/cm^2 @ 97 K)	71 (48)	+42	+24, -20
	1100 Alumi- Aluminum	100 psi @ -395^oF(68.9 N/cm^2 @ 36 K)	Did Not Rupture		Did Not Rupture

These results showed that, from the standpoint of predictability of rupture pressure, the design C all-welded reverse buckling disc was the best design; however, the average rupture pressure over-shot the predicted value by 15% to 19%.

On the basis of repeatability of rupture pressure, the Design C disc was again the best performer, with rupture pressure variations of $\pm$ 13% for the 50 psi (34.5 N/cm^2) discs at -285^oF (97 K) and +8%, -16% for the 100 psi (68.9 N/cm^2) at -395^oF (36 K).

From the standpoint of debris generation, both the Design G poppet-type disc and the Design B union type reverse buckler were superior, in that no pieces of the disc detached during actuation, and no discernable particles were found in the downstream receivers. Design C, however, lost substantial sections (25% to 70%) of its disc during three of the five tests with the 100 psi (68.9 N/cm^2) rated disc.

The projected open area of the discs, which is a measure of flow capacity, is shown in Table 21.

From the standpoint of the maximum flow capacity and the predictability of that flow capacity, poppet-type Design G was superior. The Design B union type reverse buckler had the lowest average flow capacity and the widest variation in flow capacity from run to run. Design C, the all-welded reverse buckler, exhibited approximately the same performance as Design B in the 50 psi (34.5 N/cm^2) version, but exhibited larger open area in the 100 psi (68.9 N/cm^2) version; however, the increased open area was attained largely at the expense of losing petals. Design characteristics that affect the open area and petal loss in the reverse buckling designs are discussed in the following section.

TABLE 21.- OPEN AREA OF PHASE I DISCS

Design	Nominal Rating		Open Area - % of Disc Projected Area		
	psi	N/cm^2	Minimum	Maximum	Average
B	50	34.5	3.5	64.5	26.7
	100	68.9	2.7	48.6	21.5
C	50	34.5	7.0	55.0	38.7
	100	68.9	81.0	96.0	84.6
G	50	34.5	100	100	100
	100	68.9	Did Not Rupture		

Analysis - Task II Phase I. - The data presented in the preceding section were analyzed, and examinations were made of the test hardware in order to isolate the factors which were influencing the behavior of the discs.

The failure of the Design G poppet-type unit (Figure 53) to actuate at hydrogen temperatures with the 100 psi (68.9 N/cm^2) kit installed was traced to an eccentricity of the poppet mounting on the shaft and eccentricity of the shaft guide centerline with respect to the housing inlet bore. This was the result of an inaccurate line-boring set-up for the inlet bore/shaft guide concentricity and the result of designing the poppet centering on the shaft to be partially dictated by the screw threads instead of machined surfaces. The eccentricity was found to be so severe that the poppet would pass freely through the inlet bore through only one quadrant of poppet rotational position. The manufacturer's assembly instructions furnished with the unit referenced match marks which were to be used to index the poppet shaft with respect to the housing. These instructions were followed rigorously throughout the program. The index marks on the poppet shaft were made with the 0.0008 inch (0.002 cm) thick nickel disc installed for the 50 psi (34.5 N/cm^2) service. With the 0.005 inch (0.013 cm) thick aluminum disc installed for 100 psi (68.9 N/cm^2) hydrogen service, the increased disc (shim) thickness causes the poppet position to index approximately 1/4 turn on the shaft when screwed down to the tightened condition, thereby indexing the poppet out of the operable quadrant. It is significant to note that in all cases where the unit failed to open, the shear pins had sheared to release the poppet.

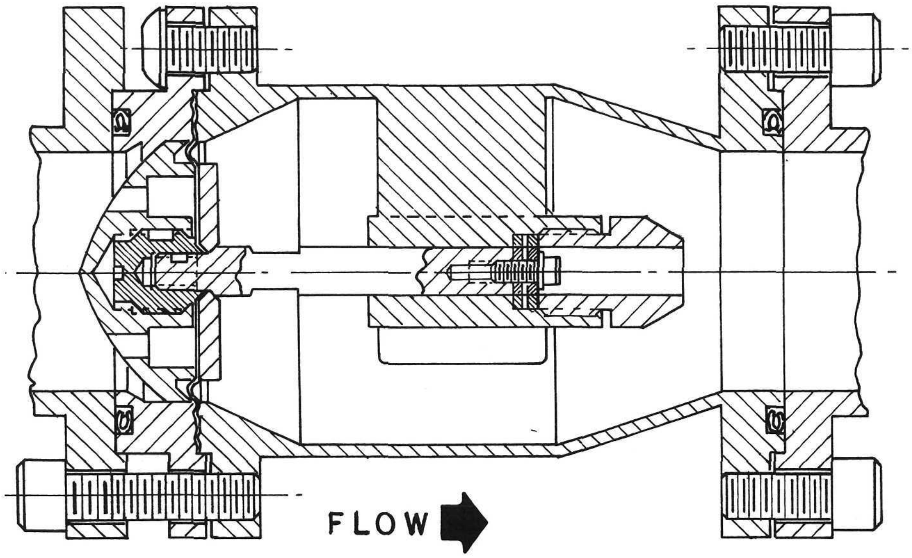


Figure 53.- Design G Passive Disc (Sectioned)

In analyzing the characteristics of the design C all-welded reverse-buckling disc, both the predictability and the repeatability of rupture pressure were better than the other two designs; however, the design is susceptible to petal detachment. In order to investigate the cause of this problem, one of the spare units was sectioned, as shown in Figure 54. As can be noted in the figure, the downstream section of the disc holder abuts the periphery of the disc with a sharp shoulder. By contract, the union-type design B reverse buckler (Figure 55) employs a very generous radius in this same area, and design B did not show a tendency to detach petals. Therefore, it was concluded that the petal-detachment problem of design C could be solved by providing a radius at the shoulder.

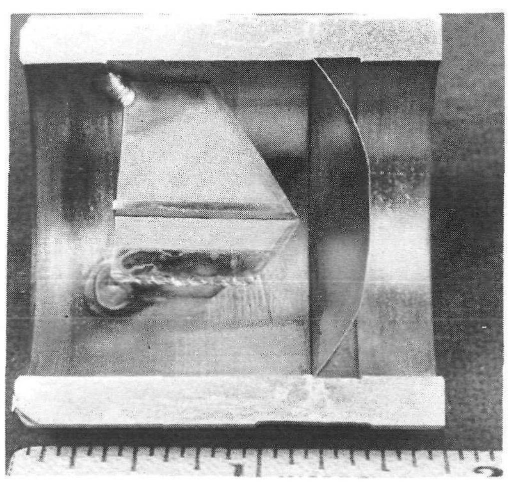


Figure 54.- Design C Passive Disc (Sectioned)

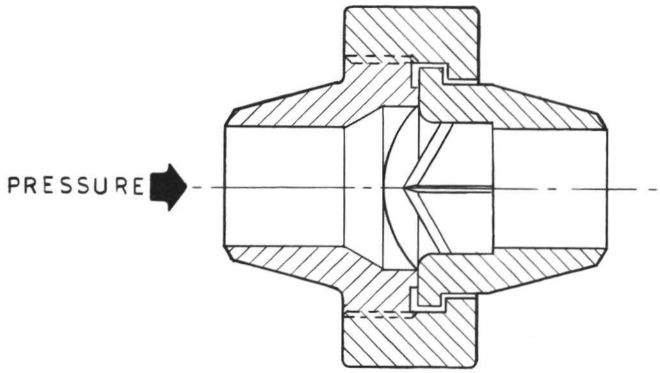


Figure 55.- Design B Passive Disc (Sectioned)

With regard to the amount of variation in rupture pressure of design C, which is somewhat higher than the value of ± 10% that is generally quoted by rupture disc manufacturers it must be recognized that this program stipulated not only the pressure rating of the disc, but also the size and selection of disc materials. The pressure at which buckling occurs (Ref. 4) is a function of the modulus of elasticity (type of material), disc thickness and disc geometry (diameter and radius of curvature). Since the buckling pressure is a function of the cube of the disc thickness, very small variations in disc thickness have a significant effect on buckling (rupture) pressure. When constraints on diameter, disc material and buckling pressure force the use of a thin disc,such as the 0.002 inch (0.005 cm) thick 316L stainless steel material shown in the photo of the sectioned design C disc, even the most stringent manufacturing tolerances may produce variations in rupture pressure of the magnitude demonstrated by the design C units.

The results of testing the design B union-type reverse-buckling disc, which exhibited very erratic performance, pointed up another aspect of the use of thin disc materials. The design B disc holder was designed with a raised land on the upstream flange face to effect gripping and sealing of the disc. The plastic deformation of the disc material, which was required to effect an adequate seal, caused extensive wrinkling (buckling) of the disc perimeter material. This condition was aggravated by a wringing action caused by relative rotation of the union halves during tightening of the nut to the 350 foot-pound (475 newton-meter) torque value specified by the manufacturer. Regardless of the mechanism which caused the wrinkling, the existance of perimeter wrinkles was shown to have a profound effect on the rupture pressure of the discs. The pertinance of this phenomenon to the present discussion is that its severity is undoubtedly a function of the disc thickness, being more severe in thin discs. The subject is discussed further in the analysis of the Phase II test results.

With regard to temperature sensitivity, the two reverse buckling disc designs showed the expected characteristics of being less sensitive to extreme changes in operating temperature than tensile-failure type discs. Testing of 1 inch (2.5 cm) aluminum pre-bulged discs prior to the inception of this program showed that the room temperature rupture pressure doubled (100% increase) at $-320^{\circ}F$ (77 K). This change is commensurate with the 100% increase in the tensile strength of 1100-0 aluminum at that temperature (Ref. 3). The reverse-buckling designs exhibited the performance summarized in Table 22.

TABLE 22 - REVERSE BUCKLING DISC-SET POINT SHIFT

Design	Average Rupture Pressure							
	$70^{\circ}F$ (294 K)		$-285^{\circ}F$ (97 K)			$-395^{\circ}F$ (36 K)		
	Nameplate Rating		psi	N/cm^2	Percent from $70^{\circ}F$ Value	psi	N/cm^2	Percent from $70^{\circ}F$ Value
	psi	N/cm^2						
B	46	32	50*	34	+ 9*			
	85	59				100	69	+18
C	45	31	58	40	+29			
	85	59				119	82	+40

* = Based on only those few design B discs which had little or no wrinkling.

From the ratings given the discs by the manufacturers for operation at cryogenic temperature, it is apparent that the anticipated or predicted pressure shift would be + 10% for the 50 psi (34.5 N/cm^2) nickel discs at $-285^{\circ}F$ (97 K) and + 15% for the 100 psi (68.9 N/cm^2) 316 stainless steel discs. The actual shifts of the design B discs very closely approached the predicted values, but only based on small number of discs. The design C discs exhibited shifts of approximately 29% and 40% at $-285^{\circ}F$ (97 K) and $-395^{\circ}F$ (36 K) respectively.

The buckling pheonomenon is thought to be a function mainly of the modulus of elasticity; however, the modulus of nickel increases only 9% from ambient temperature to $-285^{\circ}F$ (97 K) and that of 316 stainless increases approximately the same amount from ambient to $-395^{\circ}F$ (36 K). If the design B set-point shift is discounted on the basis of insufficient data, these results indicate that some factor other than the modulus change is influencing the disc behavior such that the set-point changes by 29% to 40%, as in the case of design C, as opposed to the expected 10% to 15%. In any event, the temperature sensitivity of the reverse-buckling concept was shown to be substantially less than that which can be expected of tensile-failure types of discs.

Data Review - Task II Phase II. - A summary of the rupture pressure performance of the design B bolted-flange reverse buckling disc is given in Table 23 for the various test conditions which were imposed.

TABLE 23 - PHASE II PASSIVE DISC RUPTURE PRESSURE DATA SUMMARY

Test Condition	Average Rupture Pressure			Variation
	psi	N/cm^2	Deviation% from Predicted	from Average-%
Predicted Value of Nickel 200 Discs: 50 psi @ -285^oF (34 N/cm^2 @ 97 K)				
Low Rise Rate, <10 psi/sec. (<6.9 $N/cm^2/sec$)	60	41	+20	+4, -3
High Rise Rate, 1000 psi/sec (689 $N/cm^2/sec$)	57	39	+14	+9, -13
10 Cycles to 70% of Rating	57	39	+14	+7, -13
Passivated with GF_2	56	39	+12	+12, -15
Predicted Value of 316 Stainless Discs: 100 psi @ -395^oF (69 N/cm^2 @ 36 K)				
Low Rise Rate, <10 psi/sec (<6.9 $N/cm^2/sec$)	127	88	+27	+6, -7
High Rise Rate, 1000 psi/sec (689 $N/cm^2/sec$)	138	84	+38	+6, -7
10 Cycles to 70% of Rating	122	95	+22	+6, -7

From the data listed in the earlier tabulations for Phase II, the 50 psi (34.5 N/cm^2) discs had open areas ranging from 25% of the maximum possible area to 72% of maximum area, with an average open area of 54%. For the 100 psi (68.9 N/cm^2) discs, the range was 21% to 62%, with an average of 52%.

Analysis - Task II, Phase II. - Examinations were made of the discs in order to isolate some of the factors which influenced the behavior of the discs. The disc perimeter wrinkling problem which was noted in the Phase I testing of the union-type design B holder was again evident on the first three Phase II tests. Since the wrinkling could no longer be attributed to rotation of the flange halves, the problem was ascribed solely to excessive plastic deformation of the disc perimeter by the sealing land. The manufacturer's assembly instructions specified a flange bolt torque of from 20 to 30 foot-pounds (27 to 41 Newton-meter). The decision after the initial tests was to reduce the bolt torque value from the originally-used maximum value to the low-limit value. Although this relaxation of the clamping load decreased the wrinkling appreciably, it did not in all cases eliminate it.

Another factor believed to be influencing the behavior of the discs was the eccentric positioning in the holder. On this basis, and on the basis of the adverse effects of wrinkling exhibited in the Phase I results, the correlation plots shown in Figures 56 and 57 were prepared. Although these correlations fail to explain the behavior of all of the discs, it is apparent that both excessive wrinkling and eccentricity lowered the rupture pressure of the disc.

With regard to the feasibility of designing the disc and holder to limit the eccentricity to reasonable values, it will be noted in the correlation plot that the majority of the discs were installed with an eccentricity of less than 0.035 inch (0.089 cm) with no more centering control available than was provided by gently vibrating the inlet flange with the disc lying loosely on the flange and the convex side of the disc protruding downward into the bore provided in the inlet flange. In view of this, it would seem that the holder and disc could feasibly be designed to limit eccentricity to the range of 0.010 to 0.015 inch (0.025 to 0.039 cm) with no great difficulty.

Analysis - Task IV. - Although the principal objective in the Task IV fluorine testing was to establish whether or not discs could be ruptured without a catastrophic reaction, the performance of discs in gaseous fluorine was also of interest. The performance of the five 50 psi (34.5 N/cm^2) rated discs is presented in Table 24 along with the performance of the same rating discs from the Phase II gaseous nitrogen tests for comparison.

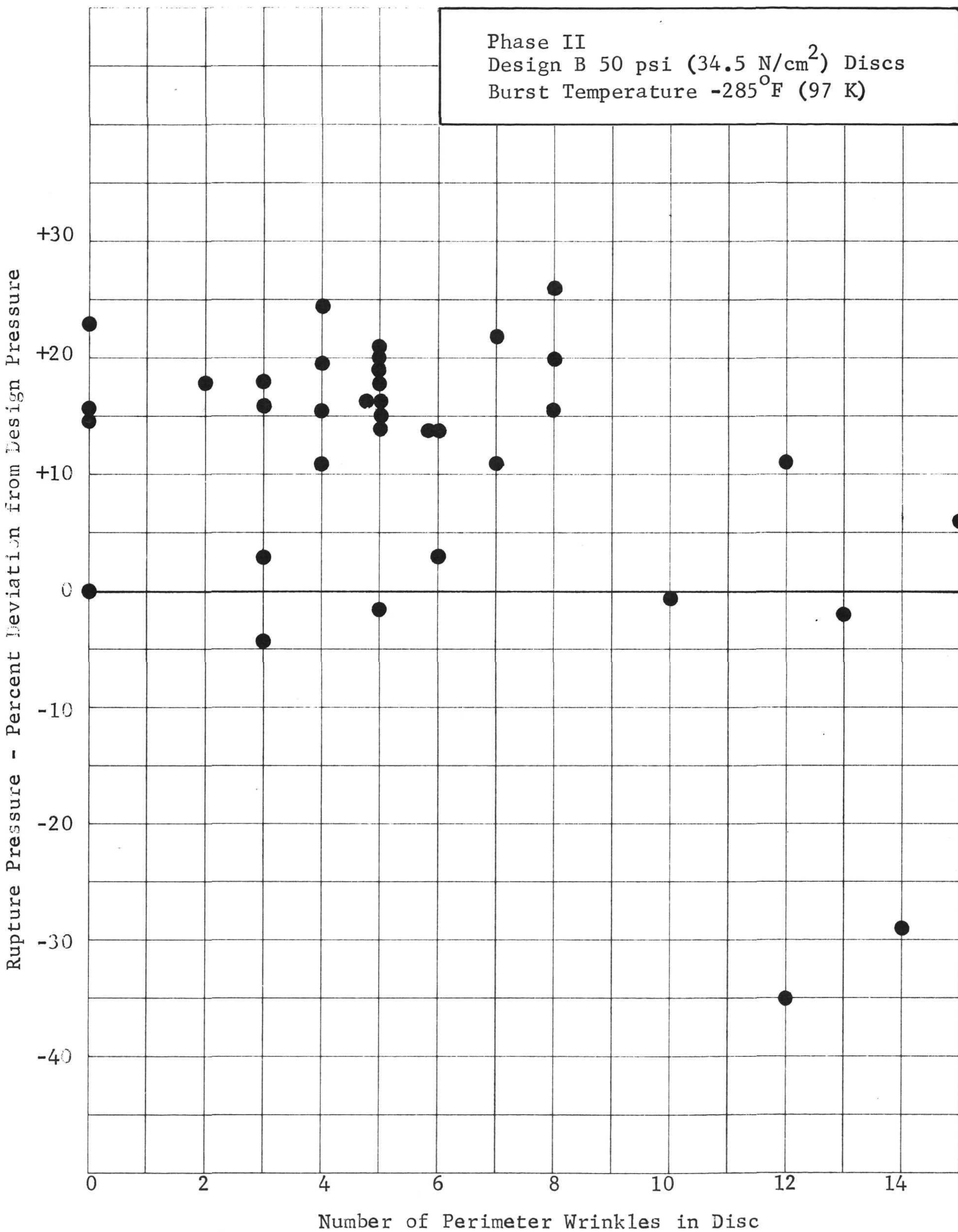


Figure 56.- Effect of Disc Perimeter Wrinkling on Rupture Pressure

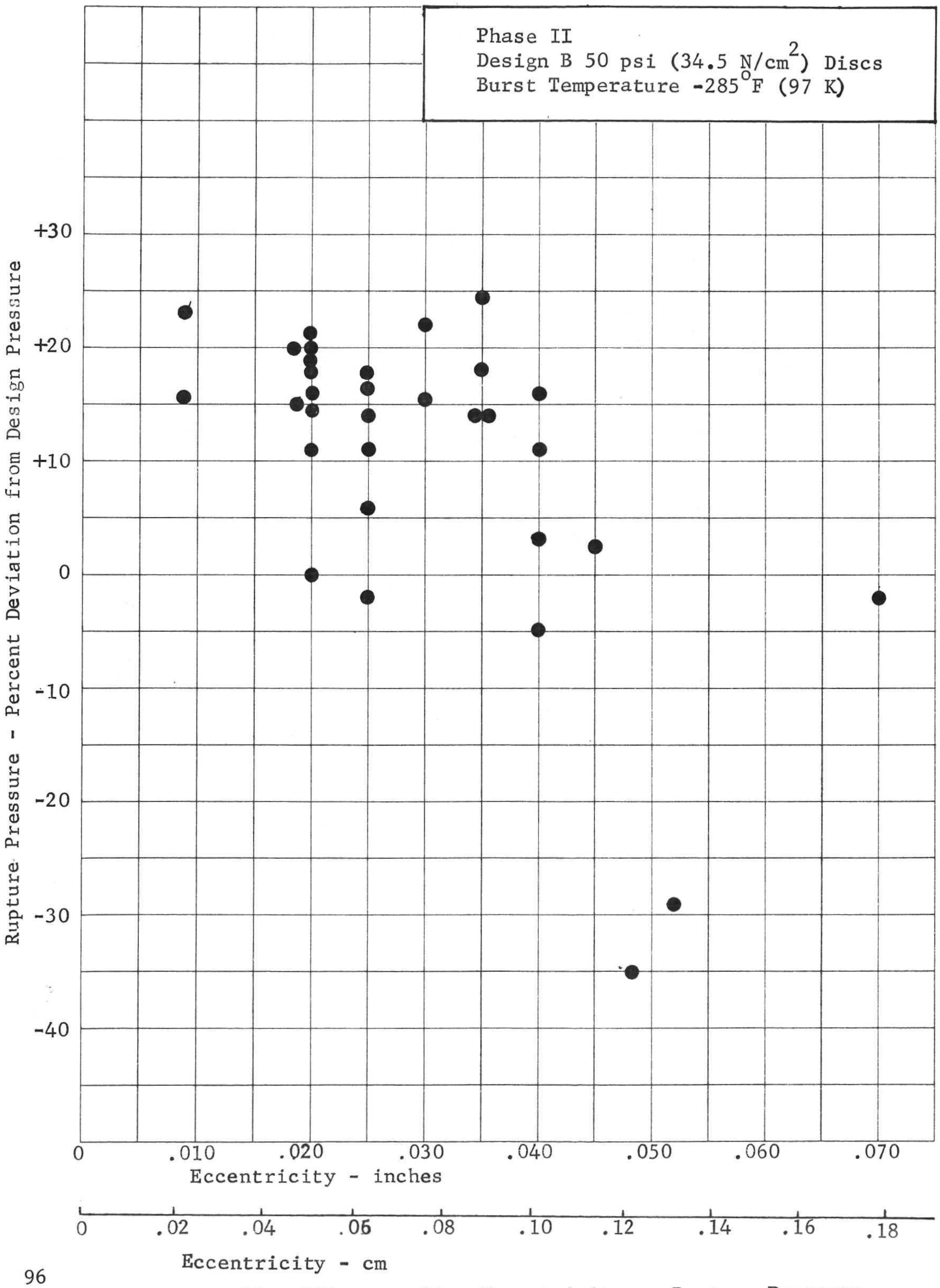


Figure 57. - Effect on Disc Eccentricity on Rupture Pressure

TABLE 24 - DISC PERFORMANCE IN GASEOUS FLUORINE

[Nickel 200 Discs Rated 50 psi (34.5 N/cm^2) at $-285^{o}F$ (97 K)]

Test Medium	Rupture Pressure						Open Area - % Maximum		
	Max.		Min.		Average		Max.	Min.	Average
	psi	N/cm^2	psi	N/cm^2	psi	N/cm^2			
GN_2	63	44	48	32	58	40	72	32	54
GF_2	64	44	56	38	60	41	66	45	52

From these results, it is apparent that the performance of the discs in gaseous fluorine was not significantly different than the performance in gaseous nitrogen.

With regard to results concerning reaction with gaseous fluorine, visual inspections of the overall disc surfaces and microscopic inspections of the petal edges revealed no evidence of fusion or other indications of reaction. These results, when added to experiences with rupturing fluorine facility safety relief discs at the Martin Marietta Corporation, indicate that passive rupture discs made of compatible material (in this case nickel 200) may be safely used in gaseous fluorine at cryogenic temperatures.

Room Temperature Testing. - In addition to the contracted testing in this program, a relatively small number of spare Phase II passive discs of both pressure ratings were tested at room temperature to acquire information on the shift in rupture pressure due to temperature. In the analyses of this characteristic under Phase I, the baseline was the name plate room temperature rating of the discs, e.g., 46 psi (31.7 N/cm^2) and 85 psi (58.5 N/cm^2).

To obtain a meaningful evaluation of the effect of temperature on the design B reverse-buckling disc, it was considered necessary to use the same installation techniques and flange bolt torque values as were used in the Phase II testing.

The results of the room temperature testing are summarized in Table 25, to establish the average pressure baseline, and to establish the baseline on variation in rupture pressure about the average. These results show the average rupture pressure is very close to the design rating at room temperature, and the variation in rupture pressure is within the design tolerance of $\pm$ 10%.

TABLE 25. - ROOM TEMPERATURE PERFORMANCE - TASK II, PHASE II DISCS

Type Disc	No. of Tests	Design Rupture Pressure		% Variation From Average	
		psi	N/cm^2		
Nickel 200	8	46	32	+8	-9
316 Stainless steel	9	85	58	+8	-4

In comparing the performance at cryogenic temperatures with the performance at room temperature, all the cryogenic test data were used except the high pressure rise rate data. The average values of rupture pressure and percent change from ambient rupture pressure during the cryogenic tests is shown in Table 26.

TABLE 26. - EFFECT OF TEMPERATURE ON RUPTURE PRESSURE

Type Disc	Average Rupture Pressure			% Change from Ambient Average
	$70^{\circ}F$ (294 K)	$-285^{\circ}F$ (97 K)	$-395^{\circ}F$ (36 K)	
Nickel 200	46 psi ($32\ N/cm^2$)	57 psi ($40\ N/cm^2$)		25
Stainless Steel	84 psi ($58\ N/cm^2$)		124 psi ($85\ N/cm^2$)	48

The 50 psi ($34.5\ N/cm^2$) discs exhibited a set-point increase of 25% at $-285^{\circ}F$ (97 K), and the 100 psi ($68.9\ N/cm^2$) discs exhibited a set-point increase of 48% at $-395^{\circ}F$ (36 K). The repeatability of both discs did not change significantly from room temperature to cryogenic temperatures.

Reliability Analysis.- Passive Discs.-A statistical analysis was made of the test data on the Task II, Phase II and Task IV passive discs. The purpose of the analysis was to determine the probability within a confidence interval of the mean rupture pressure. Test type-dependent and test type-independent classifications were considered where "test type" refers to one or more of the variables including pre-conditioning, test temperature, design pressure rating, and pre-burst cycling. The parameters evaluated in each classification were:

The test mean ($\bar{X}$), the standard deviation about the test mean (sigma), the pressure interval for 90% confidence level (X_c) and the probability of no rupture within a $\pm$ 5% interval of the test mean $[P\ (R_n)]$.

The $\pm$ 5% interval was chosen as representing the best performance (rupture pressure repeatability) which can be expected of currently available passive rupture discs. Repeatabilities on the order of $\pm$ 4% were stipulated in a NASA-Lewis Research Center specification for procurement of passive disc design A (Figure 2).

The details of the reliability analysis are contained in Appendix C. The significant results were as follows:

1. The probability of rupture of the discs independant of test-type, within 5 percent of the average are:

   50 psi (34.5 N/cm^2) discs: $P\ (\bar{X} \pm 5\%) = 0.54$

   100 psi (68.9 N/cm^2) discs: $P\ (\bar{X} \pm 5\%) = 0.51$

2. Temperature was not a significant factor in the rupture probability of the discs.

Active Disc Results

Data Review - Task II, Phase I. - During the Phase I testing, design S failed to actuate in liquid nitrogen and actuated once in liquid hydrogen, suffering a structural failure in the process. Performance data on the design S unit is, therefore, limited to one point. The design U unit actuated during all four tests in liquid nitrogen and the four tests in liquid hydrogen. In conjunction with the Phase I cryogenic actuation tests, six water flow tests were run on the design U unit. The design S unit could not be flow tested after its single actuation, since the poppet had been broken off of the shaft. Summaries of the Task II, Phase I cryogenic test data and the associated water flow test data are shown in Tables 27 and 28.

TABLE 27. - TASK II PHASE I ACTIVE DISC CRYOGENIC PERFORMANCE

Design	Test Medium	Response Time - ms			Disc Open Area - % Maximum		
		Min.	Max.	Average	Min.	Max.	Average
U	LN_2 LH_2	9 6	16 14	12 9	93 95	98 99	96 98
S	LH_2	-	-	2	-	-	100

TABLE 28. - TASK II PHASE I DESIGN U WATER FLOW PERFORMANCE

Flowrate		Pressure Drop					
		psi			N/cm^2		
gpm	liters/sec	min.	max.	avg	min.	max.	avg
260	16	0.5	0.9	0.8	0.3	0.6	0.5

Analysis - Task II, Phase I. - The design S active rupture disc tested in Phase I was a prototype model which had been developed to the prototype hardware stage from a concept in the relatively short period of 6 months. The Phase I testing exposed a number of design deficiencies which could be resolved by means of a development program. The significant deficiencies were the performance of the pressure cartridge (squib) and the seals. The cartridge performance problem was resolved during the Phase I program when the manufacturer changed to a completely different type of powder charge. The cartridges which were initially furnished would ignite reliably at liquid nitrogen temperature, but the combustion of the charge was incomplete. The manufacturer ran the development program on the rupture disc by filling the unit with LN_2 on a test bench, rather than immersing the entire unit as was done in the Phase I program. Apparently the difference in the cartridge temperature under the two test conditions was sufficient to actuate the unit in bench test, but not in the cryostat.

The most serious sealing problem in the design S unit involved the use of an Omniseal at the base of the actuating cylinder. Cartridge gas leakage past the seal was experienced during every test. For the fluorine service which was contemplated for the unit, gas leakage into the commodity passage was considered an intolerable condition. The use of an all-metal edge-type seal, of which there are at least two commercial designs, or the use of a soft aluminum seal with serrations would probably have resolved this problem.

A second sealing problem in the design S unit was cartridge gas leakage past the piston dynamic seal; however, it was subsequently demonstrated that the unit could actuate under such seal leakage conditions. Since the pressure onset rate produced by a cartridge is extremely rapid, and since the actuation time is very short (2 milliseconds), the leakage of gas past the piston during actuation probably has an insignificant effect.

In reviewing the data on the performance of design U, the results indicated that the unit would actuate reliably in both liquid nitrogen and liquid hydrogen service, and that the repeatability of the unit with respect to its open area was very good. The pressure drop of the unit was quite low at design flowrate, being less than 1 psi (0.7 N/cm^2). As a comparison, the target values cited in the contract statement of work were on the order of 4 to 6 psi (2.8 to 4.1 N/cm^2) for the flight propulsion systems being contemplated.

Data Review - Task II, Phase II. - The performance of design U during the Phase II cryogenic actuation tests and the associated water flow tests is shown in Tables 29 and 30.

TABLE 29. - TASK II PHASE II ACTIVE DISC CRYOGENIC PERFORMANCE

Test Medium	No. Tests	Response Time - ms			Disc Open Area - % Maximum		
		Min.	Max.	Average	Min.	Max.	Average
LN_2	4	3.2	6.6	5.2	96	97	97
LH_2	4	1.7	4.9	3.6	96	100	97
LN_2 *	4	5.0	10.6	7.7	96	99	97

* Passivated with liquid fluorine prior to test.

TABLE 30.- TASK II PHASE II DESIGN U WATER FLOW PERFORMANCE
[260 gpm (16 liters/sec) Flowrate]

Unit Designation	Pressure Drop					
	psi			N/cm^2		
	min.	max.	average	min.	max.	average
Unit 1	0.7	0.8	0.8	0.5	0.6	0.6
Unit 2	0.5	0.6	0.6	0.3	0.4	0.4

The above data does not include one LN_2 actuation in which the squib hermetic closure disc lodged over the gas passage to the actuator. The cutter did not attain full stroke and opened the disc only to 72% of maximum area. In addition, 6 tests were made in LN_2 with LF_2 pre-passivated units; however, the unit was damaged during cool-down in two tests, with the result that the unit failed to open the disc. The data in the table shows the results of the four tests in which the unit was undamaged prior to actuation.

Water flow performance of the design U active rupture disc is summarized in Table 30. Two units were used, one being the Phase I unit which had been refurbished for use in Phase II (Unit 1), the other being a new-manufactured unit procured for Phase II (Unit 2). The two units were identical except on the new unit the corners of the centerbody support struts had been faired to a greater extent, and the tailcone or aft housing was slightly longer to accommodate the full length of deployed petals. The average pressure drop values shown in the table are commensurate with the 0.8 psi (0.6 N/cm^2) value obtained in Phase I.

Analysis - Task II, Phase II. - The design U units performed satisfactorily during the Phase II test program with three exceptions. In one test, the pressure cartridge hermetic seal lodged over the gas passage and prevented pressurization of the actuation cylinder. This anomoly can be prevented by installing a positive guard over the gas passage to prevent the hermetic seal from reaching or blocking the port. The remaining two unsatisfactory performances were a result of the test method being used, which did not provide proper cool-down of the test units. Since this was a result of test method, no design modification is required to prevent these anomolies during actual service.

Results - Task IV. - The three contracted tests in liquid fluorine resulted in failure of the unit to open the disc in all three attempts. The disc material used in these tests was the same as that used throughout the Phase I and Phase II tests in liquid nitrogen, liquid hydrogen and in liquid nitrogen after having passivated the unit with liquid fluorine. As previously discussed in this report, the units actuated in all instances; however, the cutter point would not penetrate the disc to initiate the cutting action, notwithstanding the fact that the small apex section of the cutter had loaded the disc with a force sufficient to yield the disc apex approximately 0.3 inches (0.8 cm), until the entire length of the six cutter blades was in bearing on the disc. In general, the possible causes of the failure may be divided into two categories: failure of the actuator to provide sufficient energy to the cutter and an increase in the resistance of the disc to penetration by the cutter.

After the first of the three tests, the conclusion of the failure analysis was that the cutter energy was being degraded significantly by the dashpot effect of expelling a very dense fluid from the piston rod/seal cap annulus.

Calculations showed that, for a chamber pressure of 6000 psi (4130 N/cm^2) and a piston stroke speed of 1-inch (2.5 cm) in 0.75 milliseconds as determined during development tests, the expulsion reaction force acting in opposition to the 3600 pound (1.6×10^4 newtons) actuation force was 30 pounds (133 newtons) for liquid hydrogen, 330 pounds (1.5×10^3 newtons) for liquid nitrogen and 610 pounds (2.7×10^3 newtons) for liquid fluorine. The order-of-magnitude change in retardation force between LH_2 and LN_2 operation is now believed to explain the very noticeable increase in deformation of the copper impact-absorbing sleeve during the hydrogen runs, notwithstanding the fact that the retardation force contribution was only 10% of the actuation force at most. The variation in actuation energy had previously been ascribed to variations in squib performance (actuator chamber pressure).

The subsequent two actuations on modified units having a five-fold increase in vent port area failed to produce any change in behavior. These results tended to support the alternative theory that an increase in the disc's resistance to cutting was the problem.

A series of exploratory tests were initiated to confirm the conclusions of the failure analysis performed as a result of the failure of the unit to open during the liquid fluorine tests.

The first test run in the exploratory series included an annealed nickel 200 disc which was installed instead of the aluminum disc in one of the units having the new 12 vent hole piston seal cap configuration. The rationale for this test was to determine if a higher-modulus, higher strength, fluorine-compatible material would resist plastic deformation and permit the full actuator force to be delivered at the cutter point. The test was made with LN_2 to establish the capability of the unit to actuate normally with the new disc material. The test was successful, in that the disc was completely cut; however, the petals deployed only to the extent of providing a projected open area of 5.7 sq. in. (36.7 cm^2) as compared to the typical 6.8 sq. in. (43.9 cm^2) of area (84% opening). The characteristic is considered to be non-critical to the attainment of the Task IV objective, which is to demonstrate that an active rupture disc can be actuated open in liquid fluorine without incurring a catastrophic reaction. This established that the unit could open a nickel disc under the same operating conditions in which aluminum discs have been reliably opened (LN_2 service).

The next test was performed using liquid fluorine with the same nickel disc configuration. Two distinct reactions were noted in the test item during the GF_2 liquefaction portion of the cool-down period. The test was continued and the specimen filled with LF_2. Just prior to upstream pressurization of the test item, a third reaction was noted. The pressures on either side of the rupture disc immediately equalized. Helium pressure was introduced into the upstream side of the test item to verify rupture disc opening and pressure increased simultaneously on both sides of the test item. Post test inspection of the test item verified the three reactions. One was associated with the teflon coated "V" seal. Although teflon has been used with some success in static fluorine service, the teflon coating may contain contaminants at the substrate interface which may become exposed in service. A second reaction was in the thread area under the secondary seal (Figure 39), probably caused by the lubricant on the threads of the nose of the piston seal cap. A silicone base lubricant had been used on the seal cap and piston bore to minimize galling during disassembly and rebuild for future testing if required. The third reaction was in the piston pressure chamber. This reaction was of sufficient magnitude to partially actuate the test item and move the piston/cutter assembly approximately 3/8-inch (0.95 cm). This movement was sufficient to cut the disc (Figure 58) to an approximate open area of 0.1 in^2 (0.25 cm^2). The intent of this test was to fulfill a significant program objective by opening a disc in fluorine without a catastrophic reaction, by using a disc material which would more strongly resist plastic deformation and thus keep the cutter force concentrated at the apex. This objective was fulfilled, despite the fact that the actuation was initiated by a series of fluorine reactions with contaminants in the actuator section. No evidence of reaction was noted on the disc or the cutter.

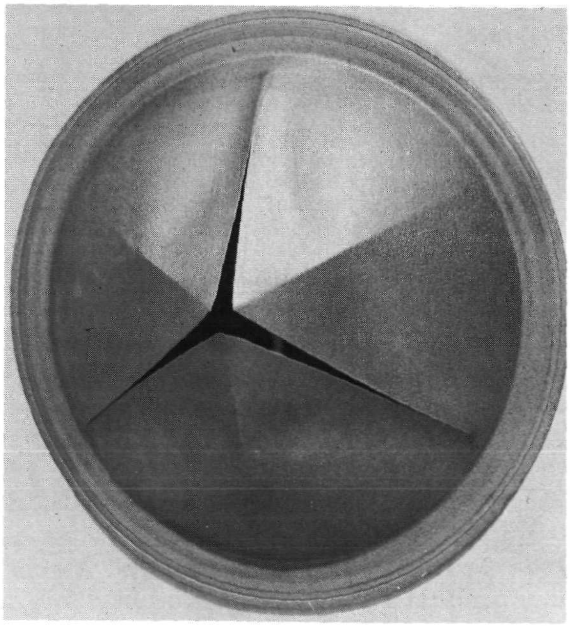


Figure 58.- Nickel Disc Opening in Liquid Fluorine

CONCLUSIONS

In addition to the specific conclusions listed in the applicable sections of this report, some generalized conclusions can be stated.

Among the various concepts of passive (pressure-actuated) rupture discs, two concepts have been identified as most closely approaching the ideal characteristics of a safety pressure relief device for flight cryogenic propellant storage systems. These concepts are the Belleville spring/hole-punch concept identified as design A in this report, and the reverse-buckling concept as represented by design B and design C.

The reverse-buckling concept was evaluation-tested in this program to confirm that the sensitivity to temperature changes from room temperature to cryogenic temperatures was significantly less than the sensitivity of designs which operate on the principle of disc tensile failure. The amount of increase in rupture pressure setting was shown to be on the order of 25% for nickel discs at 285°F (97 K) and 48% for the 316 stainless steel discs at -395°F (36 K). Increases in the set-point of tensile-failure discs for the same materials and temperatures would be on the order of 55% and 130% respectively, based on the tensile strength increase.

The repeatability of rupture pressure of the reverse-buckling design was proved to be substantially unchanged at cryogenic temperatures, being equal to the room temperature repeatability of $\pm$ 10%.

The feasibility of using the reverse-buckling type of rupture disc in gaseous fluorine at cryogenic temperatures was demonstrated. In addition to demonstrating that very thin discs can be ruptured without incurring a catastrophic reaction, it was demonstrated that the disc rupture pressure is unaffected by fluorine.

Two cryogenic active (command-actuated) rupture disc concepts were conceived and developed to the prototype hardware stage under the stimulus of this program. One of the concepts incorporating a pressure cartridge actuation device was tested to the extent that the feasibility of satisfactory operation in liquid nitrogen, liquid hydrogen and liquid fluorine was established. In connection with the active rupture disc portion of this program, the feasibility of employing a pyrotechnic pressure cartridge as an actuation energy source was established at temperatures down to that of liquid hydrogen.

The information gained in this program on the behavior and performance of cryogenic rupture discs has been incorporated into a compendium of design criteria and recommended practices for the application of these devices to flight vehicle propellant systems. The compendium is included in this report as Appendix A.

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APPENDIX

A

DESIGN CRITERIA AND RECOMMENDED PRACTICES

DESIGN CRITERIA

AND

RECOMMENDED PRACTICES

ACTIVE AND PASSIVE RUPTURE DISCS

FOR

CRYOGENIC SERVICE INCLUDING FLUORINE

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1.0 INTRODUCTION

This document is a direct result of NASA CR-121118, "INVESTIGATION OF CRYOGENIC RUPTURE DISC DESIGN." It is not intended to be comprehensive in scope, but rather an attempt to formulate the results of the above effort into the form of design criteria, inasmuch as NASA experience has indicated a need for uniform criteria for the design to space vehicles. It is to be regarded as a guide to the design of rupture discs for cryogenic systems and not as a NASA requirement.

In the course of the reference investigation, it was found that the rather slow development of rupture disc devices for cryogenic systems, and particularly, fluorine systems, was caused by lack of experience and absence of reliable design data. Thus the organization of all pertinant data into this format could help to alleviate the problem and provide a base for further development. It is anticipated that this material will eventually be incorporated into a comprehensive compendium of design criteria and recommended practices being prepared by NASA, Lewis Research Center.

The purpose of this document is to set down in an organized and systematic manner, the body of experience and knowledge that has been accumulated in the development and operational programs to date, particularly in the course of the above investigation; to assess the adequacy of current design practices and to establish norms in areas that presently are deficient; and to achieve consistency in design, in order to reduce costs, increase reliability, or produce greater efficiency in the design effort.

1.1 Guide to the Use of This Document

This document contains information condensed and organized into two major sections, complemented by a set of references supplementing and documenting the material presented. Its use will be most effective if the purpose and function of each major section are understood.

The STATE OF THE ART, Section 2, reviews and discusses the total design problem as well as specific design concepts in use. It identifies the elements of a successful design and describes the current technology pertaining to these elements. This section serves the reader as a survey of the subject that provides background material and prepares a proper technological base for the Design Criteria and Recommended Practices.

The DESIGN CRITERIA, shown in capital letters in Section 3, state clearly and briefly what rule, guide, limitation, or standard must be imposed on each essential design element to assure successful design. The DESIGN CRITERIA can serve effectively as a checklist of rules for the chief designer or project manager to use in guiding a design or assessing its adequacy.

The Recommended Practices, also in Section 3 and shown in lower case letters, state how to satisfy each of the design criteria. Wherever possible, the best procedure is described; when this cannot be done in the space available, appropriate references are provided. The Recommended Practices, in conjunction with the criteria, provide firm guidance to the practicing designer on how to achieve successful design.

This document is not intended to be a design handbook, a set of specifications, or a design manual. It is rather a summary and systematic ordering of the large body of design experience and knowledge that has been accumulated in the field to date. Its value and its merit should be judged on how effectively it makes that material available to the designer.

2.0 STATE OF THE ART

Rupture discs, also known as burst, frangible, and safety discs, can be divided into two basic categories: passive, or pressure actuated discs, and active, or command actuated discs. Within each category there are several different designs or concepts presently in use. Examples of passive discs are the prebulged disc, the flat coined disc, the reverse buckling disc and several types of shear discs. Active rupture discs are generally of either the moving cutter type or some form of shear disc.

Passive discs, until recently, have been used primarily by the processing industries for pressure release applications. The most prevalent design has been the prebulged type, which fails in tension. Considerable theoretical and experimental work has been done on prebulged rupture discs, but actual behavior can only be approximated and final designs are arrived at by statistical testing methods. A variation of the prebulged disc is the reverse buckling disc, which buckles backwards onto a knife edge and is broken into several petals. Reverse buckling discs are more reliable at lower burst pressures.

Shear discs are generally less accurate than the prebulged type, since the imposed stress is a combination of shear and bending due to the clearance between the central hub and the holder. This problem can be alleviated by employing some type of trigger mechanism, but in general this type of disc presents more difficulties than the prebulged type.

The application of rupture discs in the aerospace field has resulted in a refinement of passive disc concepts, such as the development of the flat coined disc, and the emergence of various types of active disc designs, used primarily as zero-leakage valves.

Passive rupture disc devices have been used extensively in liquid propellant chemical rocket systems. They are used for system isolation, as in an autogenous pressurization system, but chiefly they are employed as safety protection devices to prevent catastrophic failure of tanks. Examples of passive disc applications are the propellant isolation valves in the Agena, Aerobee 350, and Nike propulsion systems.

Active rupture disc devices have been used to a limited extent, such as on the Saturn V liquid hydrogen tanks for in-flight venting. However, their main utility is contemplated as being zero-leakage, high flow capacity devices for isolating propellants for extended periods. The status of designs for this use, especially in the larger feedline sizes, is mainly at the prototype level at the present time.

2.1 Passive Rupture Discs

Passive rupture discs, also known as burst discs and safety discs, may be grouped into two general categories: Those that operate on the principle of tensile failure of the disc material, and those that operate on principles other than tensile failure. The significance of this grouping to the design of cryogenic systems is that the tensile failure types of discs are subject to set-point shifts which are commensurate with the significant tensile strength change of most materials when cooled to cryogenic temperatures. Discs which operate on principles other than tensile failure may have significantly less sensitivity to low temperatures.

2.1.1 Tensile Failure Discs

Tensile failure discs include the pre-bulged disc which has been in common commercial use for many years, and the flat coined-groove disc which is of somewhat more recent origin. Both of these types of discs are available from a number of manufacturers. The main feature of the coined-groove type of disc is that the coined pattern dictates the open area of the disc, so that the open area is much more predictible than the pre-bulged disc open area. In addition, the coined-groove pattern employs a hinge section for each petal, in order to retain the petal while permitting full deployment.

The tensile failure discs undergo pressure set-point changes in proportion to the change in tensile strength of the material. Since most materials which can be employed in cryogenic oxidizer and fuel systems exhibit substantial increases in tensile strength at cryogenic temperatures, these types of discs are not of significant interest or value to the cryogenic propulsion system designer.

2.1.2 Other Concepts in Passive Discs

In a recent study of cryogenic rupture disc designs (Ref A1), an extensive survey was made to identify all concepts of passive discs and hardware designs which tended to be less temperature-sensitive than the tensile failure types of discs. Schematics of all candidate designs are included in Reference A1 and representative design schematics are reproduced herein. A bried description of the principle of operation, known and suggested performance characteristics and status of development of the several concepts is given in the following paragraphs.

2.1.2.1 Belleville Spring-Washer Concept

This concept, Figure A-1, employs a flexible disc supported and pre-loaded by a conical Belleville spring washer, and a stationary downstream hole-punch. The pressure at which the unit will operate is dictated by the restraining force of the Belleville spring. The change in this pre-load with temperature is largely a function of the modulus of elasticity of the spring material, rather than its tensile strength. For the particular spring material used in this design, the change in modulus of elasticity between room temperature and liquid hydrogen temperature is only 8% (decrease). This design is in the flight hardware stage and has been verification tested at liquid nitrogen temperature.

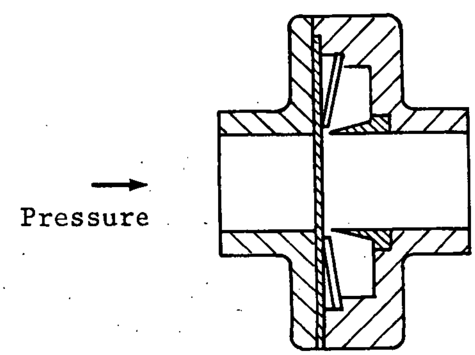

Figure A-1. - Belleville Spring Style Passive Disc

2.1.2.2 Reverse Buckling Concept

The reverse-buckling concept, as shown in Figure A-2, utilizes a spherical dome of given geometry and thickness, the pressure at which the convex side can be loaded before failing in elastic instability (buckling) is substantially less than the pressure which the dome will withstand on the concave side before failing by tensile rupture. Two methods are used to rupture the disc as it buckles and snaps through center. The method in common use is the provision of cruciform cutter blades immediately downstream of the disc. A second method very recently developed is to provide radial score lines on the disc to rupture the disc into six petals when it buckles through center. The buckling pressure is primarily a function of the modulus of elasticity for a disc of given geometry (diameter and radius of curvature), rather than the strength of the material.

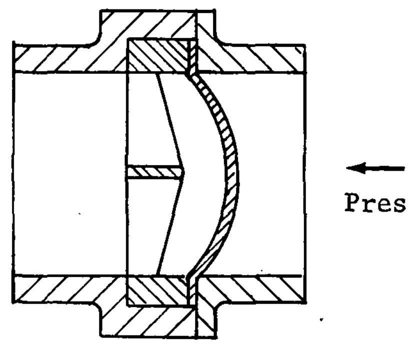

Figure A-2. - Reverse Buckling Style Passive Disc

Versions of the cutter-type reverse buckling concept have been tested at cryogenic temperatures down to -395°F (37 K), and one design has been tested in gaseous fluorine (Ref. A1). The general results showed that the disc room temperature pressure set-point shifted upward 24% for nickel 200 discs at -285°F (97 K) and 49% for 316 stainless steel discs at -395°F (37 K). By comparison, tensile failure discs can be expected to undergo increases in rupture pressure of 55% and 130% for the same materials and temperatures.

Flight hardware versions of the reverse buckling concept exist, although none have been applied to cryogenic systems.

2.1.2.3 Poppet/Shear Pin Concept

This concept, as shown in Figure A-3, utilizes aluminum as a shear pin material to restrain a poppet shaft, plus the pressure sensitivity afforded by the force amplification resulting from applying commodity pressure over a large poppet area and reacting the force with the small diameter shear pins. The periphery of the poppet is serrated to enhance the cutting action of the inlet closure disc or diaphragm. The inlet diaphragm is configured with a single bellows-like convolution to permit the poppet to move into and cut the diaphragm.

This concept has been developed to the prototype hardware stage and tested at cryogenic temperatures (Ref A1); however, testing was limited, and the design requires some additional development to achieve its full potential.

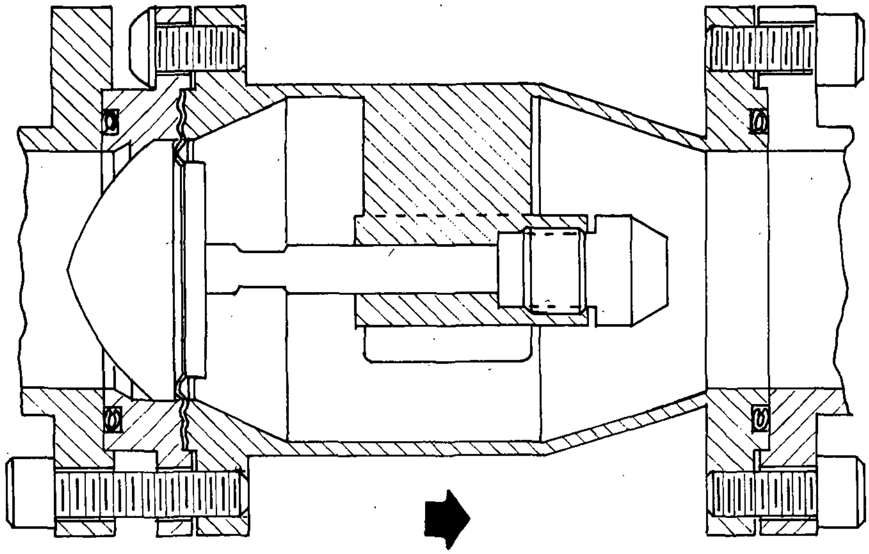

Figure A-3. - Poppet/Shear Pin Style Passive Disc

2.1.2.4 Mechanical Trigger Concepts

Several designs, all in the conceptual stage, were conceived in connection with Reference A1. These concepts employed, in one form or another, a spring-loaded cutter and a pressure-actuated release trigger as shown in figure A-4. Although such devices may very well have the minimum sensitivity to temperature of all the foregoing concepts, the relative complexity of the concept biased the program selection for test hardware toward the simpler concepts which were considered by a qualitative judgement to be potentially more reliable. No performance data, is known to exist on these concepts.

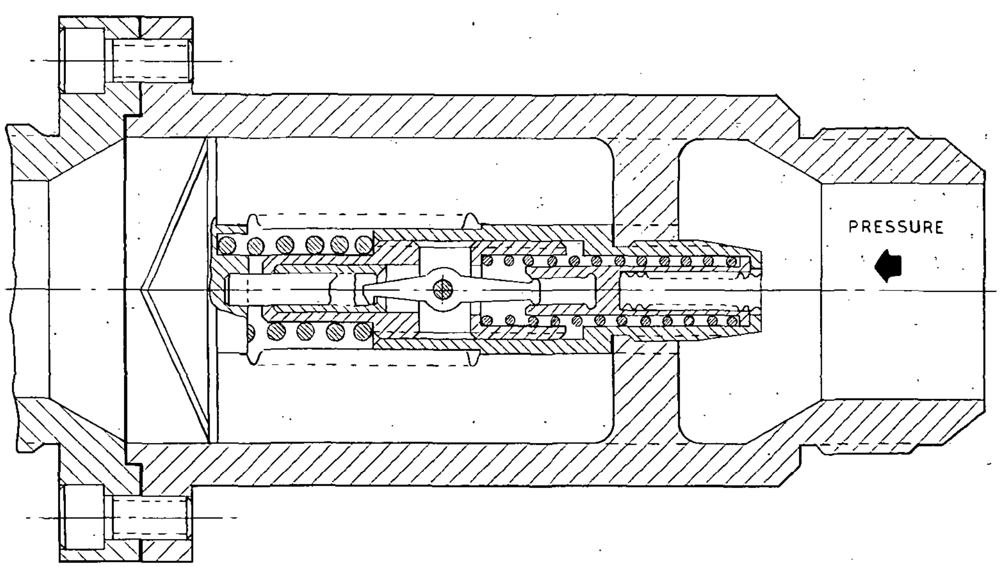

Figure A-4. - Mechanical Trigger Style Passive Disc

2.2 Active Rupture Discs

A number of active rupture disc concepts exist, some of which are called valves. The characteristics that identify these devices are those that are associated with the more familiar passive rupture disc, e.g., they contain an all-metal hermatic closure which is failed structurally in opening the unit, they have no reclosure capability, and they present very little impediment to flow in the open position. These characteristics make the active rupture disc ideally suited for isolating propellants for long periods of time with zero leakage, and for minimizing feedline pressure loss when in the open condition. A reasonably large number of active rupture disc designs and concepts exist; however, an evaluation of the field has led to the conclusion that only a few of the concepts are worthy of consideration for general cryogenic service and in particular for fluorine service. The most promising designs are described briefly in the following paragraphs, along with information on their development status.

2.2.1 Swinging Gate Concept

The swinging gate type of active rupture disc is exemplified by Figure A-5. This concept employs a flapper or gate that is machined integral with the inlet housing and has a frangible section of reduced thickness. Actuation is effected by means of a very short-stroke plunger which is pressurized by a pyrotechnic cartridge (squib). The plunger provides the force required to fracture the frangible section, and also imparts enough momentum to the gate to allow the gate to swing open to the limit provided by the outlet housing. This concept is not known to exist in the hardware stage; however, normally-open versions having the same actuation concept have been tested at cryogenic temperatures.

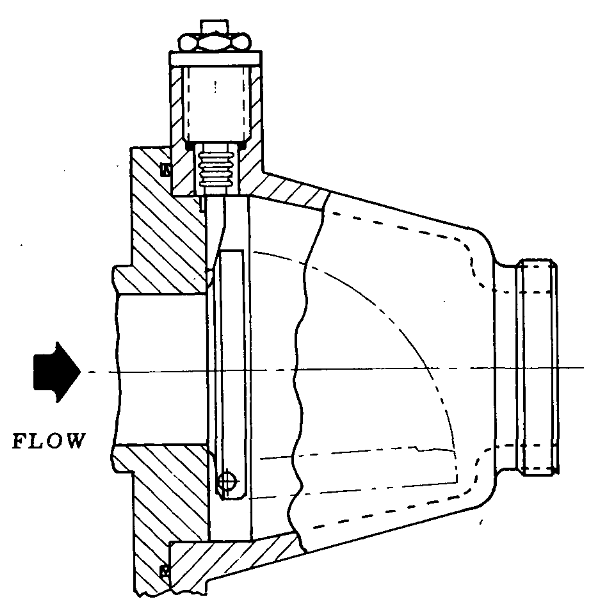

Figure A-5. - Swinging Gate Style Active Disc

2.2.2 Flying Gate Concept

This concept, shown in Figure A-6, uses the short-stroke impulse technique described above to transversely shear an integrally-machined circular gate and allow inertial forces to carry the gate and its carrier into a side receptacle slot, where the carrier is arrested by the swaging action of a section of the receptacle housing. This design has been used in flight on the Saturn V liquid hydrogen tanks to vent the tanks at burnout.

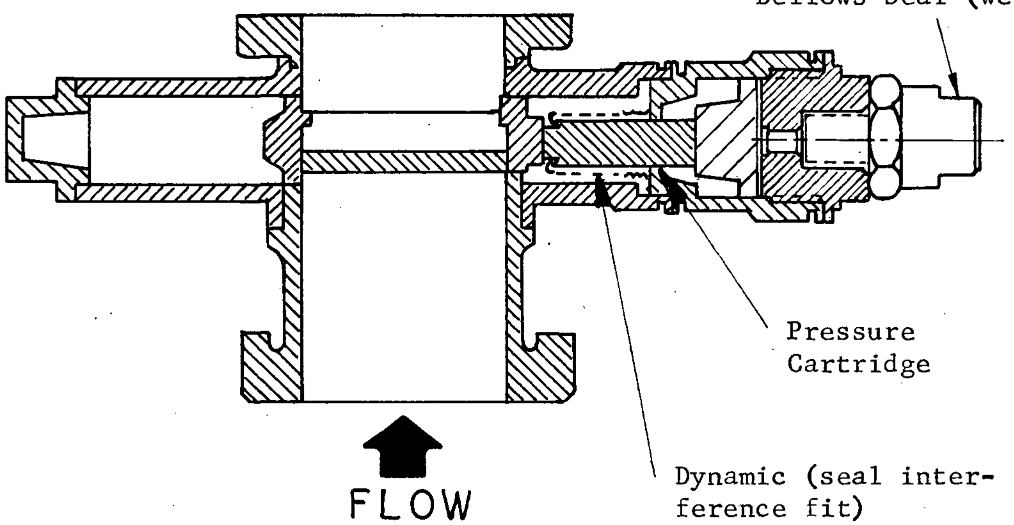

Figure A-6. - Flying Gate Style Active Disc

2.2.3 Poppet Concept

This concept, shown in Figure A-7, employs a piston-driven poppet to plug-shear an inlet closure disc. The piston is actuated by a pyrotechnic pressure cartridge. This concept has been given very limited evaluation testing at cryogenic temperatures (Ref A1). The projected testing was terminated due to structural failure of the poppet shaft. Problems in the dynamic and static actuator seals exist which probably would require a change in sealing philosophy.

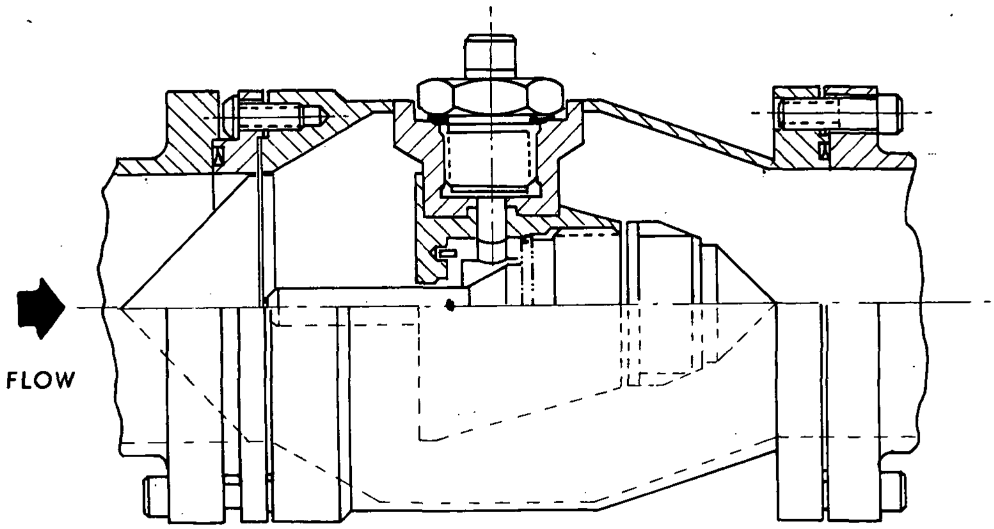

Figure A-7. - Poppet Style Active Disc

2.2.4 Cutter Concept

This concept, shown in Figure A-8, employs a dome shaped closure disc in the outlet housing which is pierced and segmented by a cutter having a number of radial blades. The cutter, which is mounted upstream of the disc, is driven by a cartridge-actuated piston. This particular design employs series-redundant, elastic interference fit metal seals to isolate the actuator section from the propellant passage. Disc petal deployment is effected by a peripheral shroud on the cutter to force the petals to the fully deployed position.

A prototype version of the design shown in Figure A-8 was tested extensively in liquid nitrogen, liquid hydrogen and liquid fluorine (Ref. A1). Reliable and satisfactory operation was demonstrated in liquid nitrogen and liquid hydrogen, and the capability of the concept to actuate in liquid fluorine without initiating a catastrophic reaction was demonstrated.

A similar design using a bellows as the dynamic seal for the actuator, has been prototype tested at room temperature, using water as the fluid medium and nitrogen gas as the actuation energy source. Petal deployment in this design is dependent upon fluid-dynamic sources.

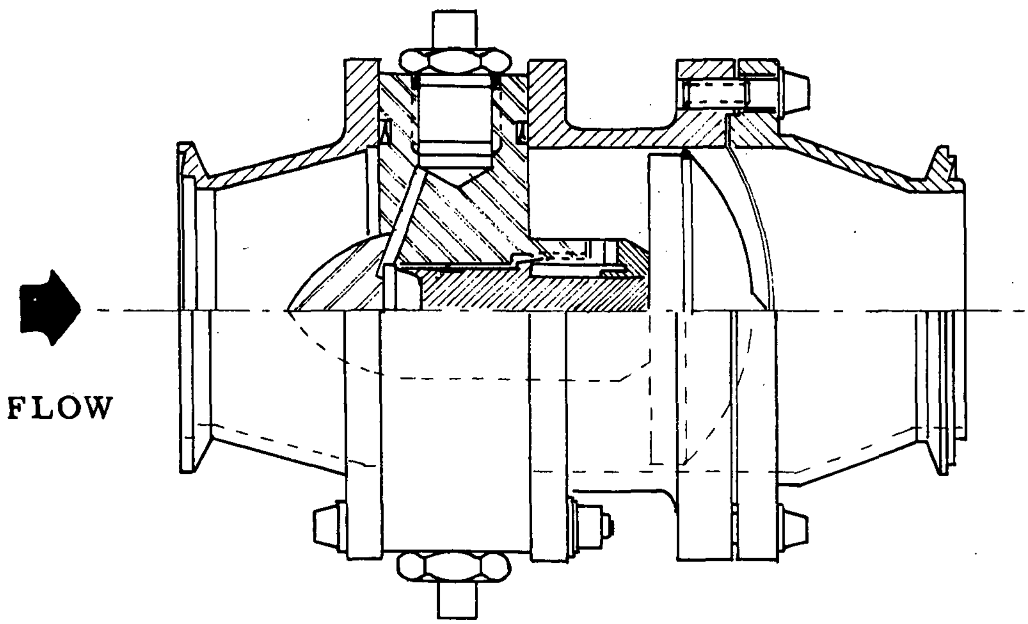

Figure A-8. - Cutter Style Active Disc

3.0 DESIGN CRITERIA AND RECOMMENDED PRACTICES

In this section, the design criteria to be used in the design, evaluation or selection of rupture discs for application in cryogenic propellant systems have been separated into categories of passive discs and active discs. Each of the two sections begins with a summary listing of the criteria, followed by paragraphs giving the recommended practices for effective fulfillment of each of the criteria.

3.1 Passive Disc Criteria

The design criteria for passive rupture discs include the following:

- Rupture Pressure
- Reverse Pressure
- Diameter
- Petal Retention
- Material Selection
- Temperature Sensitivity
- Fatigue Strength
- Installation
- Cleanability
- Leakage

3.2 Passive Disc Recommended Practices

3.2.1 Rupture Pressure

THE DISC SHALL RUPTURE RELIABLY AT THE REQUIRED PRESSURE.

When rupture pressure tolerances of $\pm$ 10% are permissible, use a reverse buckling concept disc. Where tolerances must be restricted to less than $\pm$ 5%, use the Belleville-washer concept disc. Do not predicate systems design on rupture disc tolerances of less than $\pm$ 3%.

3.2.2 Reverse Pressure

THE REVERSE PRESSURE SHALL NOT RUPTURE THE DISC.

Where reverse pressure is expected, do not employ pre-bulged or coined-groove discs without providing a support on the upstream side of the disc since typically these discs can take very little reverse pressure. The use of the reverse buckling or Belleville washer type disc is recommended, since either of those concepts can withstand a reverse pressure differential of at least twice the normal operating pressure.

3.2.3 Diameter

THE DIAMETER OF THE DISC SHALL BE LARGE ENOUGH TO EASE THE CRITICALITY OF DISC THICKNESS.

Use the largest diameter disc permissible within the weight and envelope constraints of the system, where minimum variation in rupture pressure is required. This will permit the use of a thicker disc for a given rupture pressure, thereby decreasing the impact of manufacturing tolerances, surface defects and handling damage.

3.2.4 Petal Retention

THE PETALS SHALL BE RETAINED AFTER RUPTURE UNLESS THEIR PASSAGE DOWNSTREAM CAN BE TOLERATED.

When reverse buckling discs are to be used, a generous radius should be used on the downstream shoulder of the holder to prevent petal tearing along the disc perimeter. Use a cutter blade with a profile which will engage the disc through at least half of the disc radius to reduce random tearing of the petals. Where petal detachment is absolutely prohibited, provide a catch screen.

3.2.5 Material Selection

THE BURST DISC MATERIAL SHALL BE SUITABLE FOR THE APPLICATION.

For reverse-buckling discs, use low modulus materials where small diameters and low pressures are involved. Where possible within propellant compatibility constraints, use a material having a modulus of elasticity which does not change too greatly with temperature.

For fluorine service, and in particular for long-term exposure to fluorine, use discs of pure nickel. For hydrogen service, where metal embrittlement can occur, aluminum is recommended. References A2 and A6 are recommended sources for information on compatibility of materials with fluorine. Reference A3 is an excellent source for material compatibility with a large number of propellants.

The use of non-metallic coatings on discs for fluorine service is not recommended due to the possibility of contaminant entrapment at the substrate interface.

3.2.6 Temperature Sensitivity

THE PERFORMANCE OF THE RUPTURE DISC SHALL MEET THE RUPTURE PRESSURE REQUIREMENTS OVER THE OPERATING TEMPERATURE RANGE.

Where minimum rupture pressure change with temperature is required, avoid the use of tensile failure discs such as the pre-bulged and coined-groove types. For minimum temperature effect, use the Belleville spring-washer type of disc or a design employing some type of temperature insensitive trigger mechanism. Where rupture pressure increases of 50% between room temperature and liquid hydrogen temperature can be tolerated, the use of the reverse buckling type of disc may result in a more compact, lighter unit.

3.2.7 Fatigue Strength

THE RUPTURE DISC SHALL WITHSTAND THE OPERATING PRESSURE AND PRESSURE CYCLING OF THE APPLICATION WITHOUT FAILURE BY FATIGUE.

When the cyclic pressure of the system may reach within 10% of the disc rupture pressure, the Belleville spring washer design should be employed, since its working parts are always in the elastic stress range. The reverse buckling designs are also resistant to fatigue for the same reason; however, reverse buckling discs should not be cycled at pressures above 70% of the rupture pressure without verification testing, since the available data on cycling effects does not go beyond that value.

3.2.8 Installation

THE RUPTURE DISC INSTALLATION SHALL NOT DEGRADE THE PERFORMANCE.

In assemblies where the rupture disc is to be welded into the system, adequate inlet and outlet tube lengths must be provided to prevent heat soak-back to the disc. Great care must be exercised when inert gas purging of the inlet and outlet stubs is employed, to prevent entrainment and impingement of particles on the disc surface. Protection of the disc during all pre-installation handling, and provision of outlet port protection in the installation cannot be over-emphasized. The disc design should preclude relative motion between the disc and the holder assembly. If relative motion can not be avoided in the design, extreme caution must be used during disc installation to eliminate the relative motion.

3.2.9 Cleanability

THE RUPTURE DISC CONFIGURATION SHALL BE SUCH THAT CONTAMINANT ENTRAPMENT AREAS ARE MINIMIZED.

Where rupture discs are to be used in fluorine systems, or in systems in which propellant decomposition due to catalytic reactions are of concern, the design of the rupture disc and holder must reflect minimization or elimination of entrapment areas. Cleanability must remain a major area of design concern for fluorine systems.

3.2.10 Leakage

INTERNAL AND EXTERNAL LEAKAGE SHALL NOT EXCEED THE REQUIREMENTS OF THE APPLICATION.

For control of external leakage to the levels of any fluorine system (i.e., zero leakage) and for most long term storage systems, use seal-welding of split lines where possible. The use of elastomeric or fluorocarbon materials is not recommended for sealing applications in cryogenic systems. Where seal welding is not possible, as in the case where dissimilar metals are employed, use metal-to-metal sealing techniques such as serrated flanges with soft aluminum gaskets, or uncoated V-seals.

3.3 Active Disc Criteria

The criteria for active rupture discs are as follows:

- Operating Pressure
- Reverse Pressure
- Pressure Cycling
- Leakage
- Pressure Drop
- Materials of Construction
- Actuation Techniques
- Lubricant Usage
- Petal Retention

3.4 Active Disc Recommended Practices

3.4.1 Operating Pressure

OPERATING PRESSURE SHALL NOT CAUSE THE DISC TO OPEN. OPERATING PRESSURE SHALL NOT BE A REQUISITE FOR PROPER ACTUATION OF THE DISC.

Use a closure disc of sufficient strength at the highest anticipated service temperature to maintain disc stresses in the elastic range at the inlet pressure dictated by the system over-pressure protection device. In poppet type designs, do not rely on support from calculated friction forces in the actuator. If other design constraints dictate a poppet-type disc having inadequate strength in itself, use shear-pin type restraints in the actuator section.

3.4.2 Reverse Pressure

REVERSE PRESSURE SHALL NOT DAMAGE THE CLOSURE DISC.

Requirements for downstream system pressurization for inerting and leak checks must be considered in the design of the active disc unit. In cutter-type designs, laminated closure discs should not be used to enhance the deployment capability of the petals, since the reverse buckling strength of a domed, laminated disc is a function of the buckling resistance of a single lamination.

In poppet-type designs, the closure disc must have sufficient strength in the reverse pressure direction to stay well within the elastic limit of the material, or additional shearable supports must be provided in the actuator section.

3.4.3 Pressure Cycling

THE RUPTURE DISC SHALL WITHSTAND THE APPLICATION OF OPERATING PRESSURE AND PRESSURE CYCLING WITHOUT FAILURE BY FATIGUE.

Use a closure disc of sufficient strength as identified in paragraph 3.4.1 of this document. Adequate strength margin should be used for adequate cycle life when cycling at the relief pressure setting of the system and the maximum service temperature.

3.4.4 Leakage

INTERNAL AND EXTERNAL LEAKAGE SHALL NOT EXCEED THE REQUIREMENTS OF THE APPLICATION.

For control of external leakage to the levels required of any fluorine system (i.e., zero leakage) and for most long term storage systems, use seal-welding of split lines where possible. The use of elastomeric or fluorocarbon materials is not recommended for sealing applications in cryogenic systems. Where seal welding is not possible, as in the case where dissimilar metals are employed, use metal-to-metal sealing techniques such as serrated flanges with soft aluminum gaskets, or uncoated V-seals.

3.4.5 Pressure Drop

PRESSURE DROP OF THE DISC SHALL NOT EXCEED THE ALLOWABLE VALUE AT DESIGN FLOWRATE.

Where pressure drop is critical, incorporate adequate diameter and passage sizes and employ fairing of the surface in the commodity passage if necessary. Since pump-fed propulsion systems have a suction head requirement that cannot be jeopardized, pressure losses in the feed system result in having to increase the tankage design pressure and incurring the associated weight penalties.

3.4.6 Materials of Construction

MATERIALS OF CONSTRUCTION SHALL BE SUITABLE FOR THE APPLICATION.

Use closure disc materials consistent with the propellant exposure period, the published corrosion rates and the disc thickness employed. In hydrogen service use aluminum or, choose materials which are not subject to excessive embrittlement.

For fluorine service, and in particular for long term exposure to fluorine, discs of pure nickel are recommended.

When using a cutter-type device, thinner discs of higher strength are recommended, within the constraints imposed by the above-mentioned corrosion resistance requirement. References A2, A3 and A6 are recommended sources for material compatibility and fluorine corrosion information. References A4 and A5 are recommended as sources of information on the physical properties of materials at cryogenic temperatures.

When close tolerances are required in metal-to-metal sealing areas or between moving metal parts, materials having very similar or identical thermal expansion characteristics over the entire operating temperature range must be used.

3.4.7 Actuation Techniques

THE DISC ACTUATION TECHNIQUE EMPLOYED SHALL PROVIDE RELIABLE OPERATING OF THE UNIT.

For the most reliable operation, the use of pressure cartridge is recommended as the actuation power source. However, some pressure cartridges are not reliable at LH_2 temperatures. Information on a cartridge which has demonstrated reliable operation at liquid hydrogen temperatures (References A1 and A7) is available from the Chemical Rockets Evaluation Division of NASA-Lewis Research Center. For design purposes, this cartridge has a nominal rating of 6000 psi (4130 N/cm^2) in a 10 cc chamber.

When employing pressure cartridges, incorporate provisions in the cartridge firing chamber to prevent the cartridge closure disc from lodging in the gas passage to the actuating cylinder.

A recommended design would provide for installation of two cartridges for redundancy. The actuation system must be designed to operate reliably with one cartridge, and must be able to operate without structural damage with two cartridges fired simultaneously. The shock or impact loads of the actuated mechanism must be considered and energy absorbing devices incorporated where these loads would be detrimental.

Use an actuator dynamic sealing technique which will reliably prevent leakage of cartridge gas into the propellant passage. Bellows of the cusped-convolution type should be avoided, due to cleanability problems. Open convolution bellows or redundant metal-to-metal interference fit sealing surfaces are recommended.

The damping effects of propellant characteristics on actuators which are required to move in the propellant stream must be accounted for.

3.4.8 Lubricant Usage

> LUBRICANTS SHALL BE USED WHICH ARE COMPATIBLE WITH THE SERVICE TEMPERATURE AND COMMODITY REQUIREMENTS.

Do not use lubricants for fluorine service. The provision of a hermetic seal, such as a bellows, to seal the actuator section is not considered adequate protection to permit lubricant usage in the actuator. Leakage of the bellows in a fluorine system may cause explosive reactions with lubricant in the actuator which can either damage the actuator or operate the actuator prematurely. For usage in propellants other than the most active oxidizers (fluorine, liquid oxygen, FLOX and fluorine-derivatives), the use of a compatible dry-film lubricant is recommended.

3.4.9 Petal or Disc Retention

> THE PETALS SHALL BE POSITIVELY OPENED AND RETAINED AFTER ACTUATION UNLESS THEIR PASSAGE DOWNSTREAM CAN BE TOLERATED.

Use an actuation concept that forces the disc to deploy to the wide open position where possible, rather than depend on fluid dynamic forces under operating conditions to assist in the deployment. In cutter-type designs, unrestrained petals can be re-closed by reverse pressure spikes in the downstream feedline of cryogenic systems.

Where petal detachment is undesirable, provide a positive petal locking mechanism, or provide a catch screen.

REFERENCES

A1 Keough, J. B.; and Oldland, A. H.: Investigation of Cryogenic Rupture Disc Design. Rept. NASA CR-121118 (Contract NAS3-14345), Martin Marietta Corp., Denver Division, March, 1973.

A2 Schmidt, H. W.: Handling and Use of Fluorine and Fluorine-Oxygen Mixtures In Rocket Systems. NASA SP-3037, Lewis Research Center, 1967.

A3 Anon.: Compatability of Materials with Rocket Propellants and Oxidizers. Memorandum 201, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio 43201, January, 1965.

A4 Anon.: Cryogenic Materials Data Handbook. ML-TDR-64-280, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio, August, 1964.

A5 Anon.: Mechanical Properties of Materials at Low Temperatures. Monograph 13, National Bureau of Standards, Boulder, Colorado.

A6 Douglas A/C Co: Fluorine Systems Handbook. CR72064, Santa Monica, Calif., July, 1967.

A7 Dulaigh, D. E.: Testing of Space Storable Explosively Actuated Valves. MCR71-32, Martin Marietta Corp., Denver Division, February, 1971.

APPENDIX B

REQUEST FOR RUPTURE DISC PROPOSALS

MARTIN MARIETTA CORPORATION DENVER DIVISION

POST OFFICE BOX 179, DENVER, COLORADO 80201 TELEPHONE (303) 794-5211

August 25, 1970

Gentlemen:

Martin Marietta Corporation, Denver Division is working a program for NASA Lewis Research Center entitled "Investigation of Cryogenic Rupture Disc Design (Contract NAS3-14345)." The initial task under that contract is to a) acquire design information on rupture disc devices of both the active and passive types, and b) to select two preferred designs of both active and passive devices for subsequent procurement and evaluation testing at our facility.

The purpose of this letter is to invite you to submit a description of your design(s) for active and/or passive rupture disc devices which comply with the criteria established for this program. You are requested to submit the following information to permit us to evaluate the relative merit of your design (active, passive or both):

a. Drawings (conceptual sketches, cutaways, schematics).

b. Description of operating principle or method, pointing out features which are noteworthy.

c. Estimated procurement time from receipt of order (for our planning; procurement time is not a significant evaluation factor).

d. Estimated cost on the basis of an initial procurement of two (2) units plus replacement parts for four (4) actuations each.

I am attaching two exhibits to this request: Exhibit A is a summary of the program scope and objectives to give you an understanding of what we are trying to do. Exhibit B is a statement of design criteria which describes the general characteristics that are desired and the operating conditions under which the units will be expected to perform.

Although your experience and inclinations may direct your interest solely toward the "Active" rupture disc, I would appreciate your investigating the possibilities of applying your concept - - or a new concept - - to a temperature-insensitive "Passive" disc. The need for this type of device is explained in Exhibit B. If your interest is solely in the passive type disc, but you consider a temperature-insensitive passive disc to be beyond the state-of-the-art, you are encouraged to submit the required information on a design which fulfills all other requirements.

In connection with the technical information which we are requesting you to submit, the following comments may be of assistance:

Proprietary Information - Information of a proprietary nature will be fully protected against exposure. If you feel that certain information is too critical to transmit to us, we will send a representative to your plant to acquire the information, if that method is agreeable.

Drawings - Drawings can be in the format of your choosing. The only significant requirement is that the drawings be detailed enough to permit us to evaluate the sealing characteristics, cleanability, mode of operation, particle generating potential, etc.

With regard to the cost and procurement time information we are requesting, the following comments may be helpful:

Drawings - Drawings furnished with procured hardware may be in your format.

Source Inspection - There will be no source inspection.

Development Testing - Our program is not funded for development testing during our evaluation tests; therefore, your anticipated development testing should be reflected in your cost and procurement time estimates.

Qualification - No qualification testing is required.

MIL-/NASA Specifications - Compliance with MIL- and/or NASA specifications is not required.

Cleanliness - Commercial cleaning will be acceptable.

Any questions of an administrative nature should be directed to:

Leo R. Fondacaro
P. O. Box 179
Mail Stop 0840
Denver, Colorado 80201
Phone: 303-794-5211, Ext. 2305

Please submit your technical and cost information to the undersigned in separable form, since we intend to perform the initial technical evaluation free of cost bias. Submittal must be prior to September 30th.

It must be understood that Martin Marietta Corporation will accept no charges for the information requested herein, and reserves the right to reject any and all proposals.

Thank you for your participation in our program.

Sincerely,

MARTIN MARIETTA CORPORATION

Leo R. Fondacaro
Advance Programs - Materiel

LF/bg
Internal Mail 0840

Encl: Exhibit A: Program Scope and Objectives
Exhibit B: Preliminary Design Criteria

EXHIBIT A

PROGRAM SCOPE AND OBJECTIVES

I. INTRODUCTION

A substitute for valves is required for use in the larger size (2½" or 6.4 cm diameter feedline) space probe hydrogen-fluorine and FLOX-methane rocket systems, both for propellant retention and starting and for tank safety venting. Present valve requirements, such as tolerances, reliability and performance at cryogenic temperatures, are stringent, thereby imposing high cost, weight and bulk. In addition, proposed missions include coast times up to 1200 days, which requires that propellant valves have very low or zero leak rates. A simpler concept, such as a rupture disc, could be substituted for a valve or used in series with a valve. Rupture discs would provide zero leakage, and if used alone, would reduce cost, weight, and bulk, as well as eliminate much of the controls required by valves.

Ultimately, a systems demonstration is necessary to prove the value of rupture discs for cryogenic rocket systems. But first, a study must be undertaken to determine which disc designs are best suited for propellant control and for tank safety vents. Next, experiments must be conducted to obtain information on the behavior of rupture discs at cryogenic temperatures, predictability and repeatability of burst pressure, effect of pressure cycling, how to prevent formation of debris, and fluorine and FLOX compatibility. Therefore it is necessary to investigate the design and performance of rupture discs for propellant flow initiation and tank safety venting in cryogenic systems, especially those to contain fluorine.

II. OBJECTIVES

It is the intent of this effort to investigate a number of rupture disc designs applicable to propellant flow lines and tank safety vents in hydrogen-fluorine and FLOX-methane rocket systems. Two active disc designs for flow initiation and two passive disc designs for tank venting shall be fabricated and tested to determine their performance characteristics under the desired conditions. Results shall be summarized in the form of design criteria and recommended practices.

III. SCOPE

The program will be concerned with examination of rupture disc devices to rocket propellant flow and vent systems using the following cryogenics: liquid hydrogen, liquid fluorine, FLOX and liquid methane. The investigation will encompass:

1. A study of design concepts to determine those designs which are best suited to the intended usage.

2. Testing of the selected active (power-actuated) and passive (pressure-actuated) disc designs to obtain data on cryogenic performance, fluorine compatibility, predictability and repeatability of rupture, flow characteristics, effect of pre-actuation conditions and prevention of debris.

3. Establishment of design criteria and recommended practices, based on test results.

EXHIBIT B

PRELIMINARY DESIGN CRITERIA

I. GENERAL DESCRIPTION

Active Rupture Disc. - A device, which when installed in a liquid flow line, will maintain a closed-off condition with a zero leakage until an electrical command signal is given to open. The zero leakage condition may (typically) be attained by use of a shearable, fusible or rupturable closure (disc, diaphragm or membrane) which separates the inlet and outlet flow passages. Upon having been given the command signal, an actuator (pyrotechnic, pneumatic, hydraulic, electro-mechanical or other) causes the closure to open, either partially or fully. Fluid-dynamic forces of the fluid medium may be employed to effect full opening. The device need not necessarily have re-closure capability. Typically, the device opens in such a manner as to afford the minimum impediment to fluid medium flow in the fully-opened position. The intended application of this device is for isolation of cryogenic propellants (tank outlet shut-off) during long-term space storage (interplanetary coasting flight).

Passive Rupture Disc. - A device which, when installed in a pressurized gas system, will maintain a closed-off condition with zero leakage until the pressure differential across the disc (diaphragm, membrane) causes it to open in such a manner as to afford minimum impediment to fluid medium flow in the wide-open position. Known versions of this device employ either structural failure of the membrane due to pressure-loading or using the pressure force to drive the membrane onto a hole-cutter with a snap-through action. The intended use of this device is for safety-relief protection of cryogenic propellant tanks during long term space storage.

II. SIZE

Internal or flow passage diameters are desired to be approximately 2½ inches (6.4 cm) for the active discs and in the range of 1 inch to 1¼ inches (2.5 to 2.9 cm) for passive discs. The size of the active disc has been based on the following considerations:

A. The 2½" (6.4 cm) size is believed to be in the regime where the guillotine-type or gate-type pyrovalve [currently the favored type of zero-leakage isolation device for feed systems 1" (2.5 cm) or less in diameter] may become non-competitive from the standpoint of weight, envelope size and actuation forces.

B. A planned space propulsion system (hydrogen-fluorine or FLOX-methane) is configured for 2½-inch (6.4 cm) feed lines, therefore, the investigation of rupture-disc type feed line isolation devices should center on this size.

Although the 2½ (6.4 cm) I.D. size is desired for the active disc, existing designs in the size range from 2 inches (5.1 cm) to a maximum of 4 inches (10.2 cm) will be acceptable for this program.

III. SERVICE REQUIREMENTS

A. Passive Discs

Medium: Gaseous Hydrogen at $-423^{\circ}F$ (20 K)

Gaseous Fluorine at $-307^{\circ}F$ (85 K)

Gaseous Methane at $-264^{\circ}F$ (109 K)

Burst Pressure: 50 psi to 100 psi (34 to 69 N/cm^2)

Internal Leakage: Less than 1×10^{-8} scc/sec of helium.

External Leakage: Less than 1×10^{-8} scc/sec of helium.

Temperature Sensitivity: The shift in burst pressure between room temperature and operating temperature is desired to be less than 15%. This requirement arises from the need to pressure (leak) test the propulsion system at room temperature prior to propellant loading.

B. Active Discs

Medium: Liquid Hydrogen at $-423^{\circ}F$ (20 K)

Liquid Fluorine at $-307^{\circ}F$ (85 K)

Liquid Methane at $-264^{\circ}F$ (109 K)

Operating Pressure: 100 psia (69 N/cm^2) maximum (propellant inlet pressure)

Flow Capacity:

Medium	Flowrate lb/sec	kg/sec	Pressure Drop (Max.) psi	N/cm^2
LH_2	3	1.36	4	2.8
LF_2	30	13.6	6	4.1
CH_4	2	0.91	4	2.8
FLOX	10.5	4.75	6	4.1

IV. OTHER REQUIREMENTS

Actuator: The actuator shall respond to a D.C. command signal of 14 to 30 volts. Actuation technique is unrestricted (pyrotechnic, pyropneumatic, electromagnetic, electromechanical, etc.)

Debris Generation: Operation of the unit should be such that no debris is generated in the flow passage. In particular, pyrotechnic device exhaust products must be effectively prevented from intruding into the propellant flow passage.

Re-Cycle Capability: For the experimental test usage contemplated in this program, it is required that the units be designed so that they can be refurbished at our test site and actuated a minimum of 4 times. Refurbishment is defined as the replacement of single-actuation-limited parts, using conventional hand tools and/or vendor-furnished special tools.

Inlet/Outlet Ports: Configuration of the inlet and outlet port flanges or fittings is unrestricted; however, mating flanges which terminate in standard schedule piping weld stubs must be provided.

Response Time: Response time is unrestricted (no specification).

Position Switches: Not required.

Multi-Service Usage: For the passive type discs, it is desired that the same holder or body accept discs which are designed to operate (burst) at 100 psi and -423°F (69 N/cm^2 and 20 K), discs which are designed to burst at 50 psi and -320°F (34 N/cm^2 and 78 K), and discs which are designed to burst at 50 psi and -290°F (34 N/cm^2 and 95 K). For the active type discs, it is desired that the same unit operate properly when supplied with either liquid hydrogen at -423^{o}F (20 K) and pressures of 65 to 100 psig (45 to 69 N/cm^2); liquid nitrogen at -320^{o}F (78 K) and pressures of 30 to 50 psig (21 to 34 N/cm^2); or liquid fluorine at -307^{o}F (85 K) and a pressure of 30 psig (21 N/cm^2).

APPENDIX C

PASSIVE RUPTURE DISC RELIABILITY ANALYSIS

Passive Rupture Disc Reliability Analysis

A statistical analysis was made of the Task II, Phase II and Task IV passive disc test data. The results of each analysis are shown on the right hand side of Tables C-1 through C-4. Table C-1 is the distribution of data points for the 50 psi (34.5 N/cm^2) discs according to test type. This distribution is divided into five different test types. The respective mean ($\bar{X}$) of each test type is shown to the right of the type distribution. Table C-2 represents the ranked distribution of data points of the 50 psi (34.5 N/cm^2) discs beginning with the lowest burst pressure and ending with the highest. This distribution is independent of test type. The mean, $\bar{X}$ = 57.3 psi (39.5 N/cm^2) in this case is more meaningful than any of the means shown in Table C-1 since it represents a larger sample size and represents a variety of possible operating conditions. Table C-3 shows the basis for analysis for the 100 psi (68.9 N/cm^2) rupture discs. Table C-4 is the overall analysis for the 100 psi (68.9 N/cm^2) discs. All analysis was based upon the normal curve.

Definitions of terms and symbols used in this analysis are as follows:

$\bar{X}$ = Mean of the group = $\dfrac{\Sigma X}{n}$

Sigma = Standard Deviation = $\sqrt{\dfrac{\sum_{i=1}^{n}(X-\bar{X})^2}{n-1}}$

X_c = 90% Confidence limit around the test mean; that is the prediction of the population mean at a 90% confidence level where:

$$X_c = \bar{X} \pm L$$

$$L = \frac{1.645\ \text{Sigma}}{\sqrt{n}}$$

$P(R_n)$ = Probability of no rupture around $\bar{X} \pm 5\%$ or $\bar{X} \pm 10\%$

X = Observed Rupture Pressure

i' = Member of the Test Type Group

TABLE C-1

RELIABILITY ANALYSIS SUMMARY SHEET - TEST TYPE DEPENDANT

[50 psi (34.5 N/cm^2) Discs]

Specimen No	Test Type	Medium	Rupture Pressure (X) psi	Rupture Pressure (X) N/cm^2	$(X_i-\bar{X})^2$ psi^2	$(X_i-\bar{X})^2$ $(N/cm^2)^2$	Remarks
4	Low Rise Rate	GN_2	57.9	39.9	2.9	1.4	$\bar{X}$ = 59.6 psi (41.1 N/cm^2)
6			59.2	40.8	0.2	0.1	Sigma = 1.93 psi (1.32 N/cm^2)
5			61.7	42.5	4.4	2.0	57.8 psi $\leq X_c \leq$ 61.4 psi (39.8 N/cm^2) (42.4 N/cm^2)
							$P_{\pm 5}$ (R_n) = 0.12
10	High Rise Rate		49.7	34.3	56.2	26.0	
14			51.6	35.6	31.4	14.4	$\bar{X}$ = 57.2 psi (39.4 N/cm^2)
12			52.6	36.3	21.2	9.6	Sigma = 4.35 psi (2.99 N/cm^2)
15			57.2	39.4	0.0	0.0	
16			58.2	40.1	1.0	0.5	54.9 psi $\leq X_c \leq$ 59.5 psi
13			59.2	40.8	4.0	2.0	(37.9 N/cm^2) (41.0 N/cm^2)
11			59.8	41.2	6.8	3.2	$P_{\pm 5}$ (R_n) = 0.51
8			60.2	41.5	9.0	4.4	
9			61.0	42.1	14.4	7.3	
7			62.3	43.0	26.0	13.0	
26	Up-Stream Press.		49.2	33.9	54.8	26.0	
22			53.1	36.6	12.3	5.8	
17			55.6	38.3	1.0	0.5	$\bar{X}$ = 56.6 psi (39.0 N/cm^2)
21			57.0	39.3	0.2	0.1	Sigma = 3.28 psi (2.26 N/cm^2)
19			57.2	39.4	0.4	0.2	
24			57.7	39.8	1.2	0.6	54.9 psi $\leq X_c \leq$ 58.3 psi
23			57.9	39.9	1.7	0.8	(37.9 N/cm^2) (40.2 N/cm^2)
20			58.4	40.3	3.2	1.7	$P_{\pm 5}$ (R_n) = 0.39
18			59.2	40.8	6.8	3.2	
25			60.5	41.7	15.2	7.3	

TABLE C-1
(concluded)

RELIABILITY ANALYSIS SUMMARY SHEET - TEST TYPE DEPENDANT

[50 psi (34.5 N/cm^2) Discs]

Specimen No	Test Type	Medium	Rupture Pressure (X) psi	Rupture Pressure (X) N/cm^2	$(X_i-\bar{X})^2$ psi^2	$(X_i-\bar{X})^2$ $(N/cm^2)^2$	Remarks
32	GF_2 exposure	GN_2	47.6	32.8	77.4	37.2	
36			49.6	34.2	46.2	22.1	$\bar{X}$ = 56.4 psi (38.9 N/cm^2)
35			55.5	38.3	0.8	0.4	Sigma = 4.66 psi
27			55.5	38.3	0.8	0.4	(3.22 N/cm^2)
37			57.6	39.7	1.4	0.6	54.0 psi $\leq X_c \leq$ 58.8 psi
29			57.8	39.9	2.0	1.0	(37.2 N/cm^2) (40.5 N/cm^2)
34			58.1	40.1	2.9	1.4	
28			59.3	40.9	8.4	4.0	$P_{\pm 5}$ (R_n) = 0.54
31			59.9	41.3	12.3	5.8	
33			63.0	43.4	43.6	20.3	
41	GF_2	GF_2	56.4	38.9	10.9	4.8	$\bar{X}$ = 59.7 psi (41.1 N/cm^2)
38			57.6	39.7	4.4	2.0	Sigma = 3.23 psi
42			58.4	40.3	1.7	0.6	(2.23 N/cm^2)
40			61.6	42.5	3.6	2.0	57.3 psi $\leq X_c \leq$ 62.1 psi
39			64.3	44.3	21.2	10.2	(39.5 N/cm^2) (42.8 N/cm^2)
							$P_{\pm 5}$ (R_n) = 0.36

TABLE C-2

RELIABILITY ANALYSIS SUMMARY SHEET - TEST TYPE INDEPENDANT

[50 psi (34.5 N/cm^2) Discs]

Specimen No	Test Type	Medium	Rupture Pressure (X)		$(X_i - \bar{X})^2$		Remarks
			psi	N/cm^2	psi^2	$(N/cm^2)^2$	
32	N/A	GN_2	47.6	32.8	94.1	44.9	$\bar{X}$ = 57.3 psi (39.5 N/cm^2) ($1 \leq n \leq 38$)
26			49.2	33.9	65.6	31.4	
36			49.6	34.2	59.2	28.1	Sigma = 3.91 psi (2.70 N/cm^2)
10			49.7	34.3	54.8	27.0	56.3 psi $\leq X_c \leq$ 58.3 psi
14			51.6	35.6	32.5	15.2	(38.8 N/cm^2) (40.2 N/cm^2)
12			52.6	36.3	22.1	10.2	$P_{\pm 5}$ (R_n) = 0.46
22			53.1	36.6	17.6	8.4	$P_{\pm 10}$ (R_n) = 0.14
27			55.5	38.3	3.2	1.4	
35			55.5	38.3	3.2	1.4	
17			55.6	38.3	2.9	1.4	
41		GF_2	56.4	38.9	0.2	0.4	
21		GN_2	57.0	39.3	0.1	0.0	
15			57.2	39.4	0.0	0.0	
19			57.2	39.4	0.0	0.0	
37			57.6	39.7	0.1	0.0	
38		GF_2	57.6	39.7	0.1	0.0	
24		GN_2	57.7	39.8	0.2	0.1	
29			57.8	39.9	0.3	0.2	
4			57.9	39.9	0.4	0.2	
23			57.9	39.9	0.4	0.2	
34			58.1	40.1	0.6	0.4	

TABLE C-2
(concluded)

RELIABILITY ANALYSIS SUMMARY SHEET - TEST TYPE INDEPENDANT

[50 psi (34.5 N/cm^2) Discs]

Specimen Number	Test Type	Medium	Rupture Pressure (X)		$(X_i-\bar{X})^2$		Remarks
			psi	N/cm^2	psi^2	$(N/cm^2)^2$	
16	N/A	GN_2	58.2	40.1	0.8	0.4	
20	↓	↓	58.4	40.3	1.2	0.6	
42		GF_2	58.4	40.3	1.2	0.6	
6		GN_2	59.2	40.8	3.6	1.7	
13		↓	59.2	40.8	3.6	1.7	
18			59.2	40.8	3.6	1.7	
28			59.3	40.9	4.0	2.0	
11			59.8	41.2	6.3	2.9	
31			59.9	41.3	6.8	3.2	
8			60.2	41.5	8.4	4.0	
25			60.5	41.7	10.2	4.8	
9		↓	61.0	42.1	13.7	6.8	
40		GF_2	61.6	42.5	18.5	9.0	
5		GN_2	61.7	42.5	19.4	9.0	
7		↓	62.3	43.0	25.0	12.3	
33		↓	63.0	43.4	32.5	15.2	
39	↓	GF_2	64.3	44.3	49.0	23.0	
30	No Data Available						

TABLE C-3

RELIABILITY ANALYSIS SUMMARY SHEET - TEST TYPE DEPENDANT

[100 psi (68.9 N/cm^2) Discs]

Specimen No	Test Type	Medium	Rupture Pressure (X) psi	Rupture Pressure (X) N/cm^2	$(X_i-\bar{X})^2$ psi^2	$(X_i-\bar{X})^2$ $(N/cm^2)^2$	Remarks
1		GH_2.	118	81	86.5	46.2	$\bar{X}$ = 127.3 psi (87.8 N/cm^2)
2	Low Rise Rate		125	86	5.3	3.2	Sigma = 5.89 psi (4.06 N/cm^2)
6			127	88	0.1	0.0	123.3 psi $\leq X_c \leq$ 131.3 psi
17			127	88	0.1	0.0	(85.0 N/cm^2) (90.5 N/cm^2)
5			132	91	22.1	10.2	$P_{\pm 5}$ (R_n) = 0.28
4			135	93	59.3	17.6	
16			113	78	77.4	36.7	
15			115	79	46.2	21.9	$\bar{X}$ = 121.8 psi (83.9 N/cm^2)
9			116	80	33.6	16.0	Sigma = 7.57 psi (5.22 N/cm^2)
8	Up-Stream press. cycles		116	80	33.6	16.0	117.9 psi $\leq X_c \leq$ 125.7 psi
12			120	83	3.2	1.5	(81.3 N/cm^2) (86.7 N/cm^2)
14			121	83	0.6	0.3	
10			124	85	4.8	2.3	$P_{\pm 5}$ (R_n) = 0.42
13			126	87	17.6	8.4	
11			130	90	67.2	31.9	
7			137	94	231.0	109.5	
20			128	88	94.1	47.6	
21			135	93	7.3	3.6	$\bar{X}$ = 137.7 psi (94.9 N/cm^2)
23			135	93	7.3	3.5	Sigma = 5.29 psi (3.65 N/cm^2)
19	High Rise Rate		135	93	7.3	3.5	
25			136	94	2.9	0.8	135.0 psi $\leq X_c \leq$ 140.5 psi (93.1 N/cm^2) (96.9 N/cm^2)
26			136	94	2.9	0.8	$P_{\pm 5}$ (R_n) = 0.19
27			140	97	5.3	4.4	
24			143	99	28.1	16.8	
18			143	99	28.1	16.8	
22			146	101	68.9	37.2	

TABLE C-4

RELIABILITY ANALYSIS SUMMARY SHEET - TEST TYPE INDEPENDANT

[100 psi (68.9 N/cm^2) Discs]

Specimen No	Test Type	Medium	Rupture Pressure (X)		$(X_i-\bar{X})^2$		Remarks
			psi	N/cm^2	psi^2	(N/cm^2)^2	
16	N/A	GH_2	113	78	262.4	123.2	$\bar{X}$ = 129.2 psi (89.1 N/cm^2)
15	↓	↓	115	79	201.6	102.0	Sigma = 9.44 psi (6.51 N/cm^2)
9			116	80	174.2	82.8	126.2 psi $\leq X_c \leq$ 132.2 psi
8			116	80	174.2	82.8	(87.0 N/cm^2) (91.1 N/cm^2)
1			118	81	125.4	65.6	$P_{\pm 5}(R_n) = 0.49$
12			120	83	84.6	37.2	$P_{\pm 10}(R_n) = 0.17$
14			121	83	67.2	37.2	
10			124	85	27.0	16.8	
2			125	86	17.6	9.6	
13			126	87	10.2	4.4	
6			127	88	4.8	1.2	
17			127	88	4.8	1.2	
20			128	88	1.4	1.2	
11			130	90	0.6	0.8	
5			132	91	7.8	3.6	
4			135	93	33.6	15.2	
19			135	93	33.6	15.2	
21			135	93	33.6	15.2	
23			135	93	33.6	15.2	
25			136	94	46.2	24.0	
26			136	94	46.2	24.0	
7			137	94	60.8	24.0	
27			140	97	116.6	62.4	
24			143	99	190.4	98.0	
18			143	99	190.4	98.0	
22	↓	↓	146	101	282.2	141.6	

APPENDIX D

DESIGN A TEST DATA

Design A Test Data

The results of the Design A passive disc testing performed at the NASA-Lewis Research Center verify the predicted temperature insensitivity of the Belleville spring-washer burst disc design. The pressure required to snap-over the Belleville spring to the rupture (disc cutting) position, averaged well within the $\pm$ 5% design tolerance during the 48 ambient and 45 cryogenic temperature tests performed. The 41 psia (28.2 N/cm^2) rated, fluorine compatible discs were tested at ambient temperature and at 140^oR (78 K). The 72 psia (49.6 N/cm^2) rated, hydrogen compatible pressure discs were tested at 52^oR (29 K) and at room temperatures. The data obtained for these tests is presented in Table D-1.

TABLE D-1. - DESIGN A TEST DATA

Item No.	No. of Tests	Temperature		Pre-Conditioning	Average Rupture Pressure		Design Rupture Pressure	
		°R	K		psia	N/cm^2	psia	N/cm^2
1	7	530	295	None	41.2	28.4	41.0	28.2
1	3	140	78	None	41.1	28.3	41.0	28.2
2	9	530	295	None	41.3	28.5	41.0	28.2
2	5	140	78	None	41.5	28.6	41.0	28.2
2	12	530	295	None	41.0	28.2	41.0	28.2
2	4	140	78	None	40.5	27.9	41.0	28.2
3	8	530	295	None	41.1	28.3	41.0	28.2
3	4	140	78	None	40.9	28.2	41.0	28.2
4	3	530	295	None	71.0	48.9	71.0	48.9
4	12	52	29	None	71.7	49.4	71.0	48.9
5	4	530	295	None	70.7	48.7	71.0	48.9
5	1	530	295	90 Cycles 0-34 psig (0-23 N/cm^2) at 1 psi/sec (0.7 N/cm^2); 10 cycles 0-48 psig (0-33 N/cm^2) at 1 psi/sec (0.7 N/cm^2)	70.2	48.4	71.0	48.9
5	3	52	29	None	71.2	49.1	71.0	48.9
5	5	52	29	14 Cycles 0-34 psig (0-23 N/cm^2) at 1 psi/sec (0. N/cm^2); 6 cycles 0-48 psig (0-33 N/cm^2) at 1 psi/sec (0.7 N/cm^2)				
6	4	530	295	None	71.7	49.4	71.0	48.9
6	9	52	29	None	70.3	48.4	71.0	48.9

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