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ADVANCED PROPELLANT MANAGEMENT SYSTEM FOR SPACECRAFT PROPULSION SYSTEMS

PHASE I - SURVEY STUDY AND EVALUATION

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PHASE I -- SURVEY STUDY AND EVALUATION

FEBRUARY 1969

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FOREWORD

This document is submitted in accordance with Appendix A of Contract NAS9-8939 dated 21 November 1968. The report contains the results of the Phase I effort and represents the completion of this phase of the two-phase program.

This work was performed by the Martin Marietta Corporation under the technical direction of Mr. Larry Rhodes, NASA Technical Monitor.

ABSTRACT

As Phase I of a two-phase program, a survey study and evaluation of propellant management techniques for the larger Apollo spacecraft propulsion system was conducted. Analysis of systems and interpretation of study results are documented in this report. For evaluation purposes, the propellant management systems are divided into six categories: non-metallic bladders and diaphragms, metallic diaphragms, capillary forces, sliding seal pistons, metallic bellows, and miscellaneous systems. Preliminary designs in the report are presented and their applicability to a given set of propulsion system requirements is discussed.

Based upon the results of the evaluations, capillary propellant management systems are recommended for the Phase II detail design study.

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I. INTRODUCTION

Applications of spacecraft propulsion systems require multiple restart capability under low acceleration environments. During thrusting periods the propellant will be positioned over the tank outlet; however between thrust periods the disturbing accelerations, such as attitude adjustment and docking maneuvers, may cause the propellant to migrate to other areas in the tank and become mixed with the pressurant. Without some provision for maintaining liquid over the outlet, gas-free liquid feed cannot be assured for subsequent engine restarts unless the propellant is resettled by an auxiliary propulsion system prior to the engine restart attempt. While many techniques for propellant control have been proposed, for large propulsion systems with a wide latitude in duty cycle, many of these devices become quite unattractive from both a weight and operational standpoint.

The primary objective of this program is the design of an advanced propellant management system capable of positioning and retaining propellants to assure gas-free liquid feed to the engine in the presence of upsetting body forces caused by vehicle maneuvers. The reference configuration for evaluation is the Apollo primary propulsion system. A sketch of the tank envelope is shown in Fig. 1. The guideline operating characteristics are presented in Table I. The design goals for the advanced propellant management system are presented in Table II.

The program is divided into two basic phases. This report, covering the results of the Phase I work, presents a survey of various propellant management techniques and an evaluation of the techniques applicable to the propulsion system requirements outlined above. Phase II will describe detail design studies of not more than four of the systems evaluated in Phase I.

In the Phase I survey all known methods of propellant control were considered with the exception of propellant settling by auxiliary propulsion. This mode was not included since the first Priority I design goal was to eliminate any requirement for auxiliary propulsion propellant settling. An extensive survey was conducted to uncover new thoughts and ideas for propellant management systems. The survey included both a NASA and DDC machine literature search on related subject matter, personal contact with various government agencies, aerospace companies, and known vendors of expulsion systems. Although there has been a considerable advancement in the state-of-the-art of many systems in recent years, no new techniques were discovered over those reported in previous surveys such as that conducted by Bell Aerosystems Company (Ref. 1, 2, and 3).

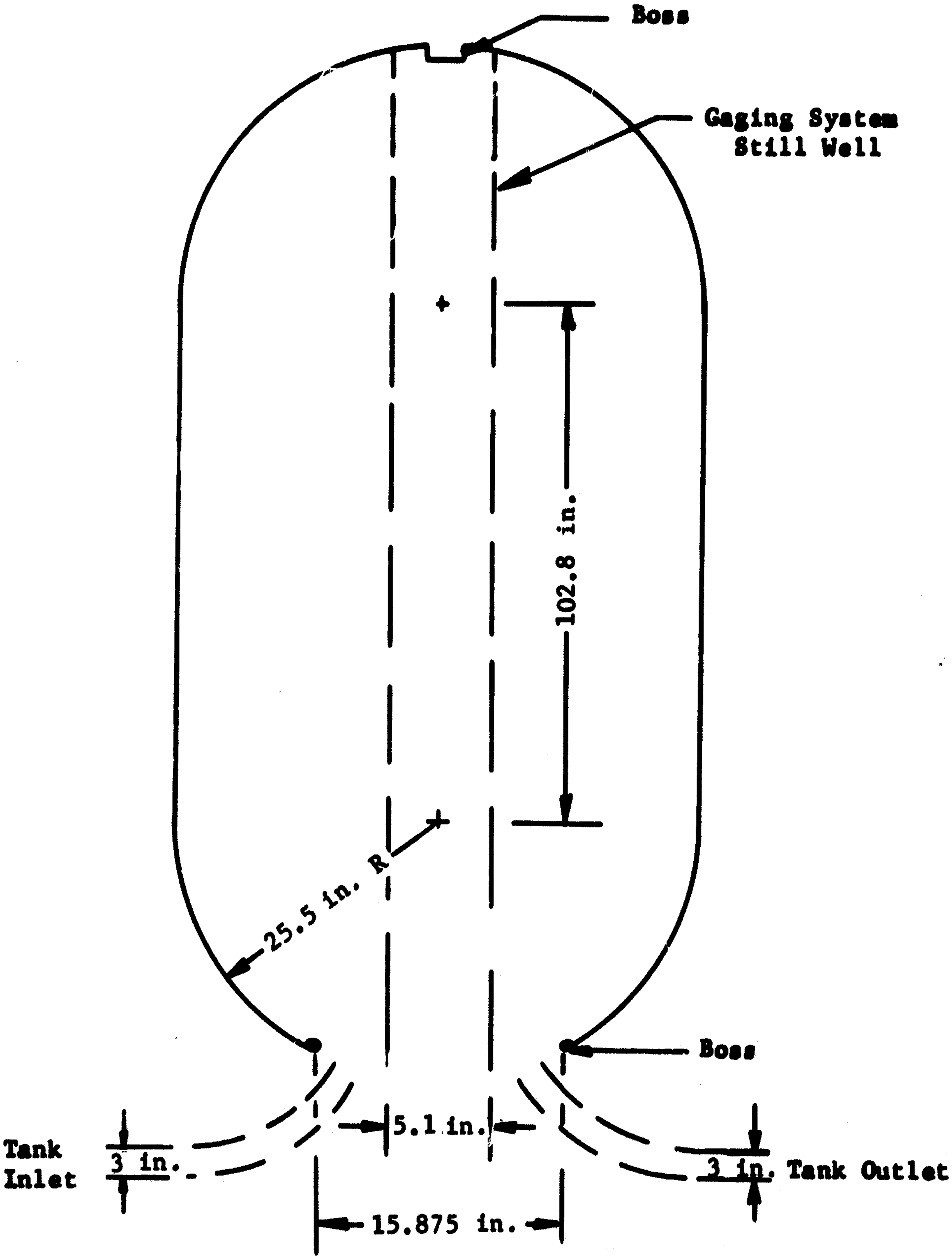


Fig. 1 Oxidizer and Fuel Tanks

Table I Propulsion System Characteristics

Oxidizer	Nitrogen Tetroxide, N_2O_4
Fuel	50% N_2H_4 - 50% $(CH_3)_2$ N_2H_2 (b.w.)
Pressurant Gas:	Helium
Entering Temperature	-50 → +120°F
Tank Volume	161.3 ft^3 (see Fig. 1)
Operating Pressure	175 to 220 psia (nominal)
Oxidizer Flowrate	39.26 lb$_m$/sec
Fuel Flowrate	24.54 lb$_m$/sec
Feed Line Diameter	3.0 in.
Acceleration Levels:	
+g boost	0 → 7.35
operation	0.33 → 0.94 (see Fig. 2)
-g	0 → 0.2
Transverse g	0.009 → +0.009
Roll g	-0.001 → +0.001 (5 deg/sec)
Restart Condition	$\leq 10^{-5}$g 5 sec prior to restart
Pitch Rate	5 deg/sec
Vibration Levels	10 to 1000 cps at 3 db/octave increase 1000 to 1500 cps at 0.3 g^2/cps spectral density Decrease at 6 db/octave Time: 700 sec in each of three axes
Engine Duty Cycle:	
Number of Restarts	0 → 50
Burn Duration	1 sec → propellant depletion

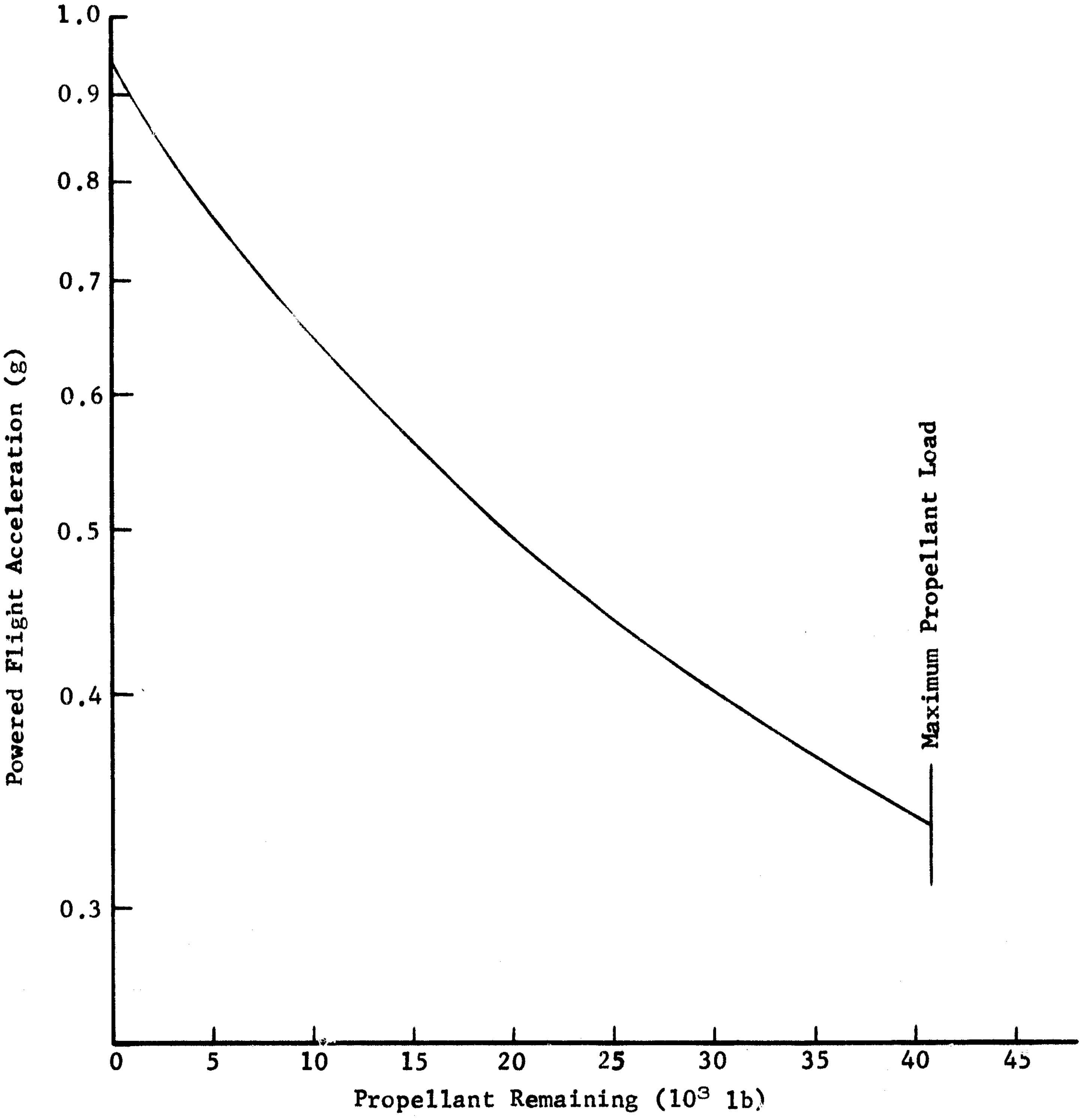


Fig. 2 Powered Flight Acceleration Profile

Table II System Design Goals

Priority I

1. Passive operation (no auxiliary propulsion settling required)
2. 99.5 percent expulsion efficiency (by volume)
3. 10 lb/tank
4. No pressurant gas ingestion at tank outlet

Priority II

1. Not affected by propellant slosh
2. Operation in either negative or positive acceleration field
3. No hardware changes to the propulsion system as outlined in Table I and Fig. 1
4. No engine duty cycle limitations
5. No off-load propellant limitations
6. Multicycle capability
7. Propellant exposure tolerance of system in the range of one year without replacement
8. Series tankage capability

To illustrate the broad nature of these studies, a morphological classification of expulsion methods generated under Contract NAS1-44 (Ref. 1) is presented in Fig. 3.

A significant portion of the background material and arguments supporting conclusions developed in this study represent the reflection of a large number of studies and reports by agencies other than the Martin Marietta Corporation. Where possible specific references are cited, but in many cases a direct reference does not apply and yet there is an indirect influence. In an attempt to recognize this contribution, a bibliography of most of the documents used to support this study is presented in addition to a list of specific references.

A. STUDY APPROACH

To keep the study within reasonable bounds and yet cover the various techniques in sufficient detail to include all reasonable approaches for the reference system, the propellant control techniques were divided into the following categories for evaluation:

1) Non-metallic bladders and diaphragms;
2) Metallic bladders and diaphragms;
3) Capillary forces;
4) Sliding seal pistons;
5) Metallic bellows:
6) Miscellaneous systems.

Selection of the category groupings was based upon the similar operational considerations of possible concepts within the categories rather than the number of potential configurations within the category. For this reason the emphasis is not necessarily equal for each category, but is related to the amount of material that must be considered in each group. The number of different configurations evaluated was restricted to the minimum that was required to adequately cover the general types of systems within the category classification, i.e., configuration changes to a basic technique that would not appreciably affect the evaluation of that technique were not considered individually. In all cases an attempt was made to evaluate a representative preliminary design for each technique.

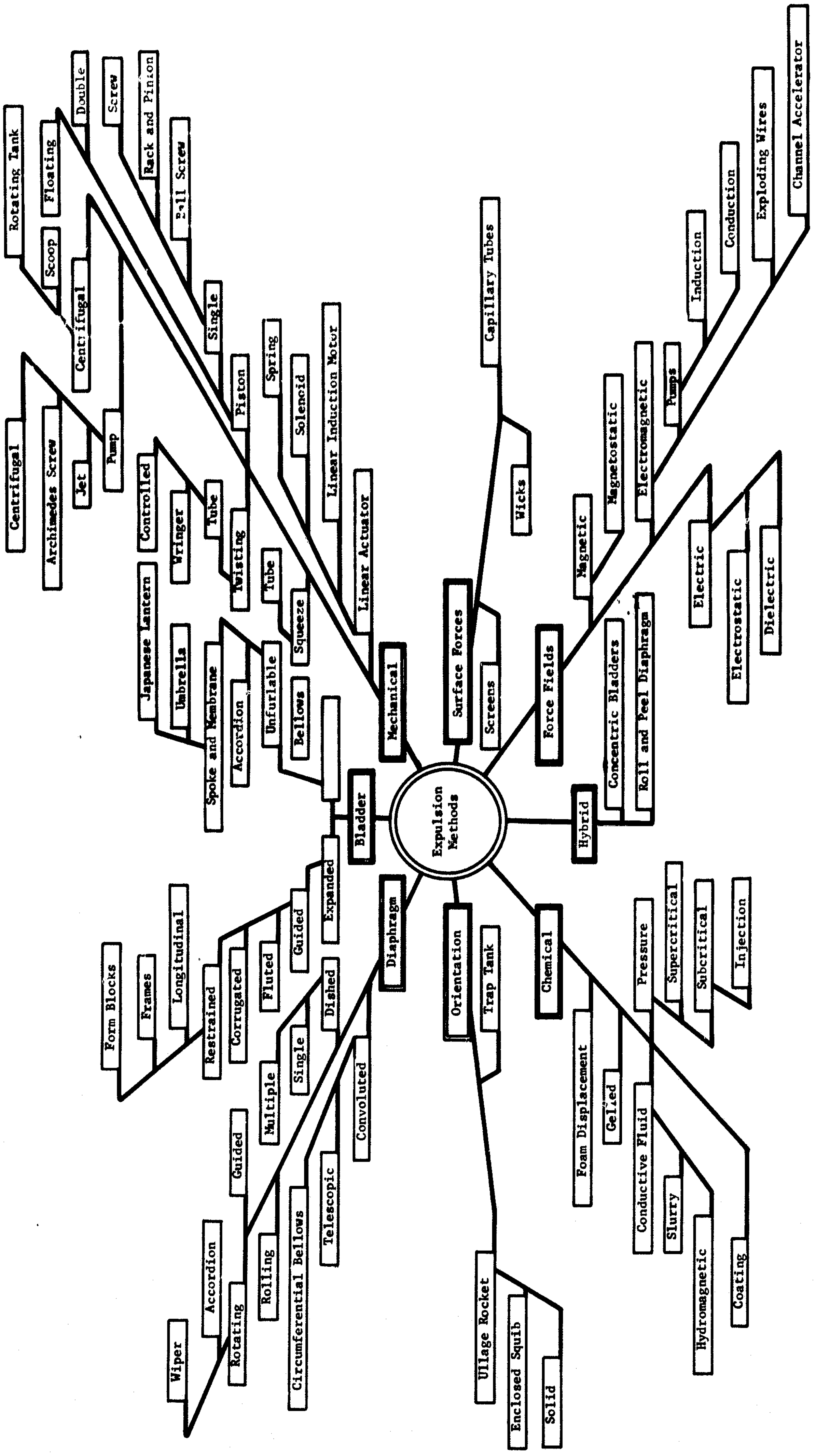


Fig. 3 Positive Expulsion Methods

To avoid the problem of obtaining a biased evaluation between categories, each grouping (with the exception of the miscellaneous systems) was studied independently. The objective was to formulate preliminary designs of reasonable configurations and evaluate them relative to the system criteria as shown in Fig. 1 and Tables I and II without intercategory comparisons that might influence the results. Systems were evaluated subject to the following limitations:

1) No hardware changes to the system as outlined in Fig. 1 and Table I;
2) No hardware limitations.

The constraint for the "no hardware change" evaluation is that the propellant control system must be capable of retrofit to the existing tankage (Fig. 1) without penetrating the tank shell or affecting external plumbing interfaces and the gaging system still well. Thus these systems are constrained to hardware that can be inserted through the 15.875-inch opening in the bottom of the tank.

For the "no hardware limitation" evaluation, any change to the configuration is permissible within the existing tankage envelope. However, the ground rule used was to start with the basic configuration as presented and incorporate only those changes which would be necessary to enhance the desirability of the total expulsion-tankage system.

All analyses performed in Phase I were based upon a bulk propellant temperature of 68°F unless noted otherwise. For purposes of propellant consumption determinations during the propulsion system short duration burns, a square wave steady-state flowrate for the burn duration was used.

B. EVALUATION CRITERIA

The criteria used to evaluate the different expulsion systems are:

Adaptability. The various concepts are evaluated relative to their applicability to a system as outlined in Table I and Fig. 1. Changes required to adapt the system are also identified.

Reliability. Quantitative reliability information is not possible for most of the systems; therefore failure modes are discussed.

State-of-the-Art. The state-of-the-art evaluation is concerned primarily with theoretical, developmental, and manufacturing technologies at the present time.

Weight. Weight estimates are based upon preliminary designs of the techniques. A sincere attempt was made to obtain representative weights in each case; however, where detailed design information was lacking, extrapolation of existing system data was utilized. The design goal was 10 lb/tank for each technique.

Development Time and Cost. Because of the size class of the system under consideration, in most cases extrapolation of current state-of-the-art capability was required; therefore a quantitative appraisal of the development time and cost is of questionable value. A relative rating was used for purposes of evaluation of the systems for the Phase II recommendation.

Expulsion Efficiency. The expulsion efficiency of the various techniques is defined as the amount of propellant that can be loaded minus the trapped residual divided by the total, expressed as a percentage. The expulsion efficiency design goal for all systems was 99.5 percent. In addition to this efficiency, the volumetric packaging efficiency of some techniques is also calculated. This volumetric efficiency is the total tank internal volume minus the unusable tank volume divided by the total.

Passive Operation. Of prime concern within the meaning of passive operation is avoidance of any requirement for propellant settling by an auxiliary propulsion system prior to restart. To meet this requirement, the system must have the capability to expel liquid in an omnidirectional acceleration environment within the constraints presented in Table I.

Propellant Slosh Control. In the application of the various techniques, no attempt was made to incorporate slosh control capability. However, the inherent slosh control characteristics of the propellant orientation techniques are discussed.

Series Tankage Capability. Series tankage refers to a system, such as the existing SPS, having two tanks plumbed in series which are used to store the propellant. The first tank expels into the second which, in turn, supplies the feed to the engine.

The pressurant enters the first tank. When the propellant is completely displaced from the first tank, the pressurant travels through the liquid feed line to the second tank. Since both pressurant and propellant enter the second tank through the same inlet, positive barrier expulsion systems are not generally adaptable to series tankage. The alternative dual tankage arrangement is a parallel system in which each tank has a separate pressurant inlet and propellant outlet line. For single engine feed, the outlets would be manifolded together externally from the tank and the propellant feed accomplished independently from each tank.

Pressurant Gas Ingestion. With many propellant management techniques it is possible to have the pressurant gas (helium) become entrained in the liquid flow to the engine. The possibility of this condition will be discussed for the different techniques.

Adaptability to Varying Acceleration Gaging System. For each technique evaluated, a brief analysis will be made of the problems associated with measuring the amount of propellant remaining under low gravity environments. While the operational nature of some propellant control techniques provides unique gaging concepts, other techniques do not. In addition to these peculiar concepts, the general zero-g gaging techniques considered in this report are:

1) Radio frequency illumination;
2) Gamma ray attenuation;
3) Molimetric system (infrared detection);
4) Acoustic gas compliance.

Radio Frequency Illumination. Based on current state of development, the RF illumination technique is probably the most promising of the four methods. The system is based upon exciting a single radio frequency mode and measuring the frequency shift due to variation in propellant mass within the tank. The system is suitable for tank filling measurements as well as mass measurements during expulsion. The sampling frequency rate can be very high (response), in the range of milliseconds per readout. Accuracy of the system is in the range of ±5% of the amount of propellant in the tank with the best accuracy at the near full and empty conditions. Both the Pioneer-Central Division of the Bendix Corporation and Lockheed Missiles and Space Company have built and tested experimental RF gaging systems.

Gamma Ray Attenuation. In this system radioactive sources are mounted on the outside of the tank wall with a number of detectors placed on the opposite wall. The signal level at the detector decreases proportionately to the mass in the container. The response of this system is on the order of tens of seconds which makes accuracy a problem if the liquid is in motion (slosh) or high or intermittent flowrates are a consideration.

Molimetric System. The molimetric system is based upon mixing infrared absorbing gas with the initial pressurizing gas. As additional pressurant is added, the doped gas concentration is reduced. The infrared detector measures the decreased doped gas concentration (proportional to the liquid volume in the tank) by sensing the decrease in its infrared absorptivity. To convert the sensor output to liquid volume, the ullage and propellant temperature must be known thus making accuracy difficult. While the stated accuracy (Bendix Corporation) is 1% in gaging fuels under laboratory conditions, under space flight the error will probably be many times larger.

Acoustic Gas Compliance. In the acoustic system the gas volume in a reference cavity and the tank is driven by an oscillator at acoustic frequencies and the phase angles compared. The difference in phase angle is proportional to the gas volume and therefore to the volume of propellant in the tank. As in the molimetric system, the ullage and propellant temperatures must be known; in addition, the temperature and pressure of the reference and gaging volumes must be identical. Measurement and control of these items can lead to extensive errors in the mass gaging results.

Design Goals. The selected designs in each category are assessed as to their conformance to the design goals established in Table II.

II. NON-METALLIC BLADDERS AND DIAPHRAGMS

The desire to control propellant orientation within a tank, in a space environment, has resulted in the generation of many bladder/diaphragm concepts for aerospace application. In this chapter those concepts that appear applicable to the basic system, as defined in Chapter I, are discussed. Following a discussion on selection of material, bladder and diaphragm management systems are examined and a recommended concept for each system is presented.

A. MATERIAL SELECTION

When evaluating bladder/diaphragm propellant management systems, a major concern is the material from which the bladder or diaphragm will be constructed. To assure reliable performance, the "ideal" material should have high tensile strength and elongation, low flexural modulus, low density, low pressurant gas and propellant premeability, good propellant compatibility and should lend itself to the fabrication of a variety of shapes in such a manner that all of the above characteristics can be consistently reproduced in the finished product.

Three candidate materials are presented for each propellant commodity; following a discussion of each candidate, reasons are given to justify the recommended bladder/diaphragm material for use in the oxidizer and in the fuel.

1. Oxidizer (N_2O_4) Application

CPBU. Poly (cyclized 1, 2 polybutadiene) tolylurethene (CPBU) elastomeric composites have been under study by TRW Systems (Ref. 4). Basic CPBU polymer, developed as an ablative resin, was found to be highly resistant and impermeable to N_2O_4 but insufficiently flexible for bladder application. CPBU and ethylene-proplylene terpolymer (CPBU/EPT), combined with newly developed processing techniques, have resulted in a material which shows promise as an oxidizer bladder material in all respects except extended propellant exposure. Present exposure in N_2O_4 is limited to three to four days.

CNR. Carboxy nitroso rubber (CNR), as developed by Thiokol RMD, has proved to be a flexible material for bladder application, and highly resistant to N_2O_4. Spherical CNR bladders, 6-inch and 12½-inch diameter, and hemispherical ended cylindrical CNR bladders, 12½-inch diameter by 37-inch long, were fabricated on mandrels (Ref. 5). Two fabrication techniques were used in making the two shapes: solution spraying and hand lay-up. The first method involved spraying a solution of the material onto the mandrel, allowing it to dry, and then repeating the process until the desired thickness was developed. With the second method, preformed hemispheres (for the spheres) or preformed hemispheres and sheet stock cylinders (for the cylinder) were hand positioned on the mandrel prior to steam autoclave cure. In some instances, fabric reinforcement was used to strengthen the bladders in critical areas. With both fabrication techniques, the mandrels were dissolved subsequent to curing of the rubber. Some of the problems encountered during fabrication were seam delamination, pinhole porosity, tearing of reinforced areas and leaks due to the sharp edges of the mandrel piercing the bladder during dissolving of the mandrel.

In addition to some spherical shapes, two of the cylindrical bladders were tested. Of the latter two, one appeared in good condition demonstrating 98% expulsion efficiency after 50 expulsion cycles, the other achieved 97% expulsion efficiency but tore after 22 expulsion cycles. Although the basic CNR material properties are well defined, considerably more fabrication experience must be developed before it can be assured that these properties can be reproduced in bladder form consistently.

Teflon. Teflon is currently available in two chemical forms: TFE, tetrafluoroethylene; and FEP, fluorinated ethylenepropylene. Both materials are inherently compatible with N_2O_4. FEP has been shown to be less permeable to N_2O_4 but it lacks the required strength to be used individually as a bladder material. An extensive development effort over the past few years has resulted in a combination of these materials (TFE/FEB laminates) for bladder construction. The Teflon dispersion spray technique, which is described in Secion II,B,1, is a fully developed manufacturing method that has been used to produce most of the present day flight qualified TFE/FEP laminate bladders.

Oxidizer Material Selection. No ideal material is available presently for oxidizer application. Of the candidate N_2O_4 materials discussed, the elastomeric compounds offer the greatest inherent resistance to flexural failure. A CNR bladder has demonstrated up to 50 expulsions without failure and it is expected that a CPBU bladder or diaphragm would perform similarly. With sufficient development of fabrication techniques the cycle life should at least be doubled. By comparison TFE/FEP laminate bladders used on the Apollo program have demonstrated 20 expulsion cycles during flight qualification. TRW Systems reports comparitive N_2O_4 permeation data on the candidate materials (Ref. 4). This data shows that for material thicknesses that can be considered typical for production (9.8 mil Teflon laminate and 37 to 38-mil elastomers), the Teflon permeation rate is 80 times less than CNR and at least 7,700 times greater than CPBU as expressed in absolute permeability units of mg-mil/hr-cm^2.

Although it is flexible and highly impermeable, the propellant compatibility of CPBU (presently three to four days) must be improved before it can be considered for bladders or diaphragms that are to function in N_2O_4. CNR fabrication techniques must be improved to produce more consistently reliable parts, and the gas and propellant permeation rates reduced to make it more attractive for N_2O_4 bladder application. The primary disadvantage of Teflon is its vulnerability to flexural failure. With proper bladder-tank design, it appears that a cycle life of approximately 20 complete expulsions is reasonable. Considering all of these factors, a TFE/FEP laminate appears to be the compromise between the ideal and the available material characteristics and is, therefore, the recommended material for N_2O_4 application.

2. Fuel 50% N_2H_4 - 50% $(CH_3)_2 N_2H_2$ (b.w.) Application

Butyl and EPR (Ethylene Propylene Rubber). Thiokol RMD has demonstrated that proper compounds of each of these elastomers show very little change in tensile properties after 30-day immersion in this fuel blend. With longer exposure (38 weeks) EPR shows the least change in "as molded" mechanical properties (Ref. 6). Tensile strength of EPR was reduced by 16% and elongation by 12% as compared to butyl which underwent a 20% reduction in tensile strength and a 31% reduction in elongation. Gas generation on the liquid side of a bladder or diaphragm, resulting from decomposition of the fuel, would be considerably less with EPR than with butyl. This was demonstrated by Thiokol in 14-day exposure tests. Test results showed the 14-day, closed container pressure rise with butyl to be 7 times that of EPR and 28 times that of Teflon.

Teflon. In all respects Teflon laminate bladder materials appear to be equally as practical for fuel application as for application in the oxidizer. As with oxidizer the dispersion spray fabrication technique is most commonly used.

Fuel Material Selection. The butyl and EPR candidate materials provide flexibility as well as good compatibility in a 50/50 hydrazine/UDMH fuel blend. Of the two materials, EPR is more compatible as evidenced by Thiokol data showing less reduction in mechanical properties and less propellant decomposition after extended exposure to the fuel. Both of these materials can be fabricated into bladder or diaphragm shapes by techniqes well established within the rubber industry. Teflon laminates have demonstrated good performance in this propellant. Although flexibility is a limitation, 20 expulsion cycles have been demonstrated in the Lunar Orbiter and Apollo Lunar Module applications with this fuel blend. With proper design and development considerations, 20 expulsion cycles seem obtainable with the TFE/FEP laminates.

On the surface all three material candidates appear acceptable for use in a 50/50 hydrazine/UDMH fuel blend. When weight is considered however, the choice narrows. As an example, in a tank of the shape established earlier (51-inch diamter by 102.8-inch long barrel section and 25.5-inch radius hemispherical ends), a 35-mil butyl or EPR bladder would weigh 28 pounds. A TFE/FEP laminate, 10-mils total thickness, for the same tank size would weigh 19 pounds. Assuming a Teflon bladder or diaphragm were developed to meet the functional requirements of the oxidizer tank, the result would be a bladder or diaphragm for use in a fuel tank of equivalent geometry. With this latter consideration and realization of a significant weight savings over an elastomer, a TFE/FEP laminate is recommended for use in 50/50 hydrazine/UDMH fuel.

B. BLADDER CONCEPTS

1. Fabrication

First generation Teflon bladders were constructed by assembling pre-cut sheet stock sections into the required bladder shape. The desire to improve reliability by eliminating bonded seams led to the modern day dispersion spray technique for producing seamless Teflon bladders. Basically the process consists of spraying a 0.0003-

to 0.0004-inch layer of aqueous Teflon dispersion on a rotating hollow aluminum mandrel and oven sintering to form a film. This process is repeated until the desired film thickness is achieved and then an etching process is used to remove the mandrel. Maintaining a constant distance from spray tip to mandrel is essential to producing a uniform film thickness. Thus, surfaces of revolution are the shapes that best lend themselves to the spray dispersion technique. Discussions with personnel at Dilectrix Corporation, Farmingdale, Long Island, a company specializing in Teflon bladder fabrication, reveal that the dispersion spray technique used to produce smaller TFE/FEP laminate bladders should be directly applicable to the fabrication of a single cell bladder of the size required for this tankage concept (4¼ feet in diameter by 13 feet long). Although sintering ovens presently in use at Dilectrix are too small to accommodate this size, proper facilities could be constructed.

2. Internal vs External Bladder Pressurization

External pressurization (pressurant gas introduced into the cavity between the bladder and the tank wall) is preferred for the following reasons:

a) Internal pressurization would tend to trap propellant between the bladder and the tank wall, reducing expulsion efficiency;

b) At a full load condition the internally pressurized bladder is folded around the standpipe, resulting in a folded and creased bladder that is then subjected to the booster vibrational environment, and bladder flexural failure is likely to occur;

c) Significantly more analytical and operational knowledge is available on externally pressurized bladders, so that application of this knowledge could minimize development costs.

3. Multiple vs Single Cell Tankage

Multiple cell tankage (more than one bladder in a tank) was examined. With this concept all bladders expel into a common manifold at the tank outlet. A representative 3-bladder configuration is shown in Fig. 4. The primary advantages of multiple cells in a tank of this size, as compared to a single cell, are twofold. First, the individual bladder size being smaller, bladder fabrication is simplified. Smaller bladders would mean less complex mandrel construction, smaller sintering ovens and, in general, a part that

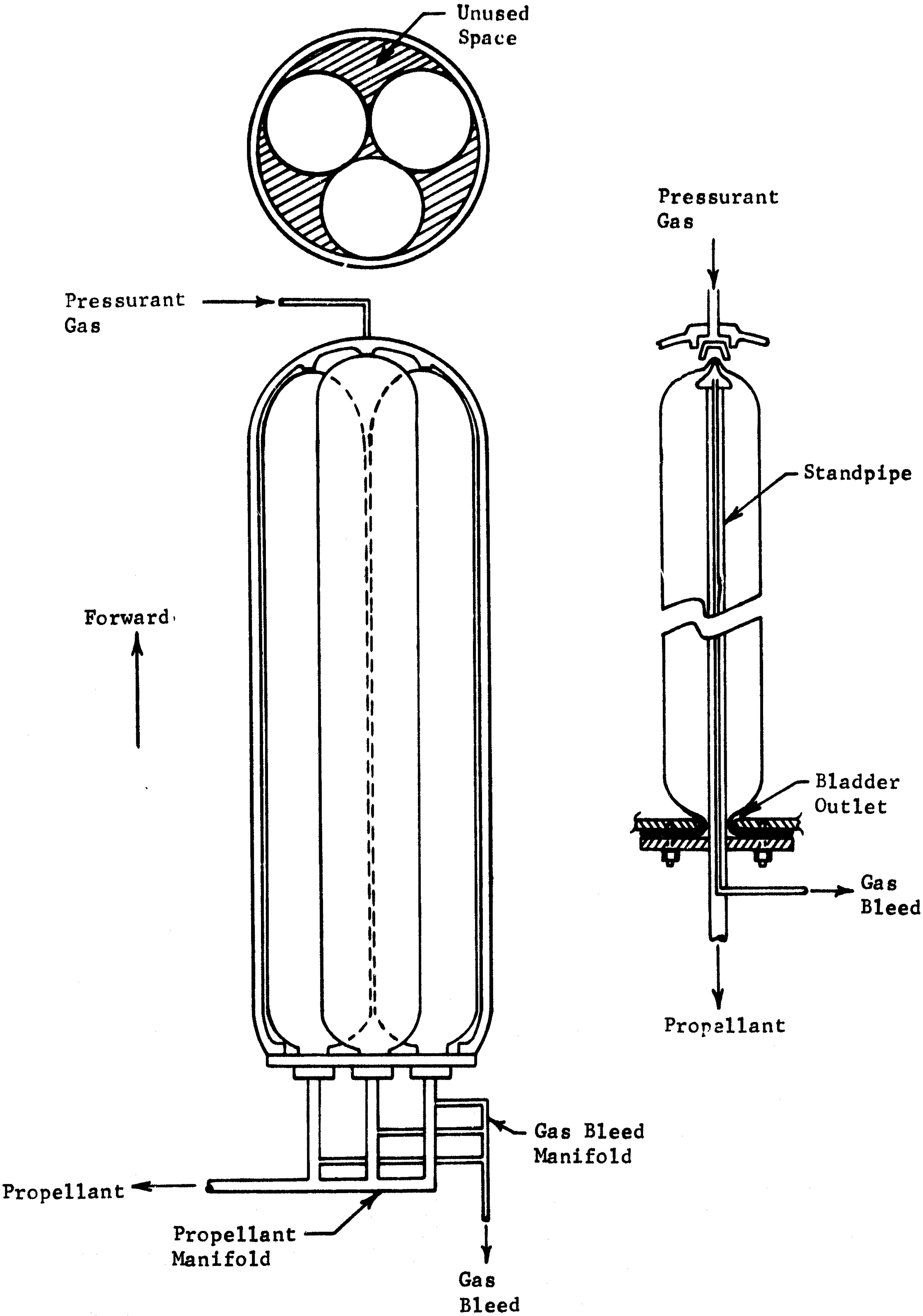


Fig. 4 Three-Cell Bladder Configuration

would permit simpler handling equipment during fabrication. Secondly, with smaller diameter bladders, bladder cycle life is improved because the quantity of material in each bladder and the distance thru which the material must move during expulsion are reduced.

Overshadowing the advantages of multicell tankage are the following disadvantages, once again as compared to single cell tankage:

a) Poor volumetric efficiency (loadable propellant volume as related to overall tankage volume). In all probability the bladders would be long cylinders with surface of revolution ends. Cylindrical bladders in a cylindrical tank would result in considerable unused space;

b) Reduced reliability because of the increased number of mechanical seals (bladder outlets, standpipe propellant and gas bleed outlets, manifold joints);

c) Increased weight due primarily to multiple standpipes and related supporting and manifolding hardware.

4. Expulsion Efficiency

In order to predict expulsion efficiency accurately, the extent to which the propellant can be expelled from the creases and folds in the bladder during the latter stages of expulsion, without rupturing the bladder material, must be clearly understood. In addition to the amount of propellant that can be expelled, the expulsion rate that can be consistently assured at a given pressurization level must be predictable during the final expulsion. For a bladder of this size, expulsion characteristics are highly empirical and any accurate performance predictions would have to be preceded by a fairly extensive full-scale development program. However, some comments and comparisons that might yield an insight to the possible expulsion efficiency are as follows: (1) the propellant trapped within the standpipe would amount to 0.4% of the 161 ft^3 tank volume based upon a 3-inch diameter standpipe extending the full length of the tank; (2) flight qualified Apollo bladders (as presently used in the Lunar Module oxidizer and Saturn IVB fuel and oxidizer tanks) of the same basic shape, the same material, and essentially the same length-to-diameter ratio, have met 98% expulsion efficiency requirements (Ref. 7 and 8).

These bladders are 6 mils thick (3 mils TFE and 3 mils FEP). Bell Aerosystems has made several test runs on each of two 12-mil Teflon laminate bladders of the Lunar Module oxidizer configuration (Ref. 7). One bladder was constructed of 9 mils TFE and 3 mils FEP; the other, 6 mils TFE and 6 mils FEP. The expulsion fluid for these tests was Freon TF at room temperature for some runs and at 35 to 40°F for others. An expulsion efficiency in excess of 98% was obtained for each run. These data are significant in that a substantial increase in material thickness, as might have been required to extend the bladder service life, did not produce a bladder so stiff as to drastically reduce its expulsion efficiency. Considering these results it is reasonable to expect 98% expulsion efficiency with the proposed bladder concept.

5. Material Thickness

To improve expulsion efficiency the amount of propellant trapped in creases and folds should be minimized. Good closure of folds and creases under the influence of the pressure differential across the bladder will reduce the amount of trapped propellant. As the material thickness is reduced the bladder becomes more flexible and good fold closure can be expected. For every bladder design, there is an optimum material thickness that incorporates the advantages of a thicker material for durability and a thinner material for flexibility. TFE/FEP laminates become quite stiff at thicknesses in excess of 12 mils and have poor durability at less than 4 mil thickness. The recommended laminate thickness for this bladder is 10 mils (5 mils of FEP over 5 mils of TFE).

C. NO HARDWARE CHANGE BLADDER CONFIGURATIONS

This portion of the study was approached with two basic ground rules as guidelines: (1) retain the existing sump tank still well gaging system; and (2) make no system plumbing changes. The still well concept relies upon the propellant and ullage being oriented within a fixed geometry container such that a gaged liquid height is an indicator of propellant volume. A flexible container bladder with the ullage exterior to the contained propellant would result in the still well always being full of propellant. As such, a still well gaging system would not present a measurement of propellant volume in a bladdered tank. If the requirement for still well gaging were waived and series tankage were not required, a bladder concept such as that shown schematically in Fig. 5 might be feasible. The upper portion of the standpipe would be supported

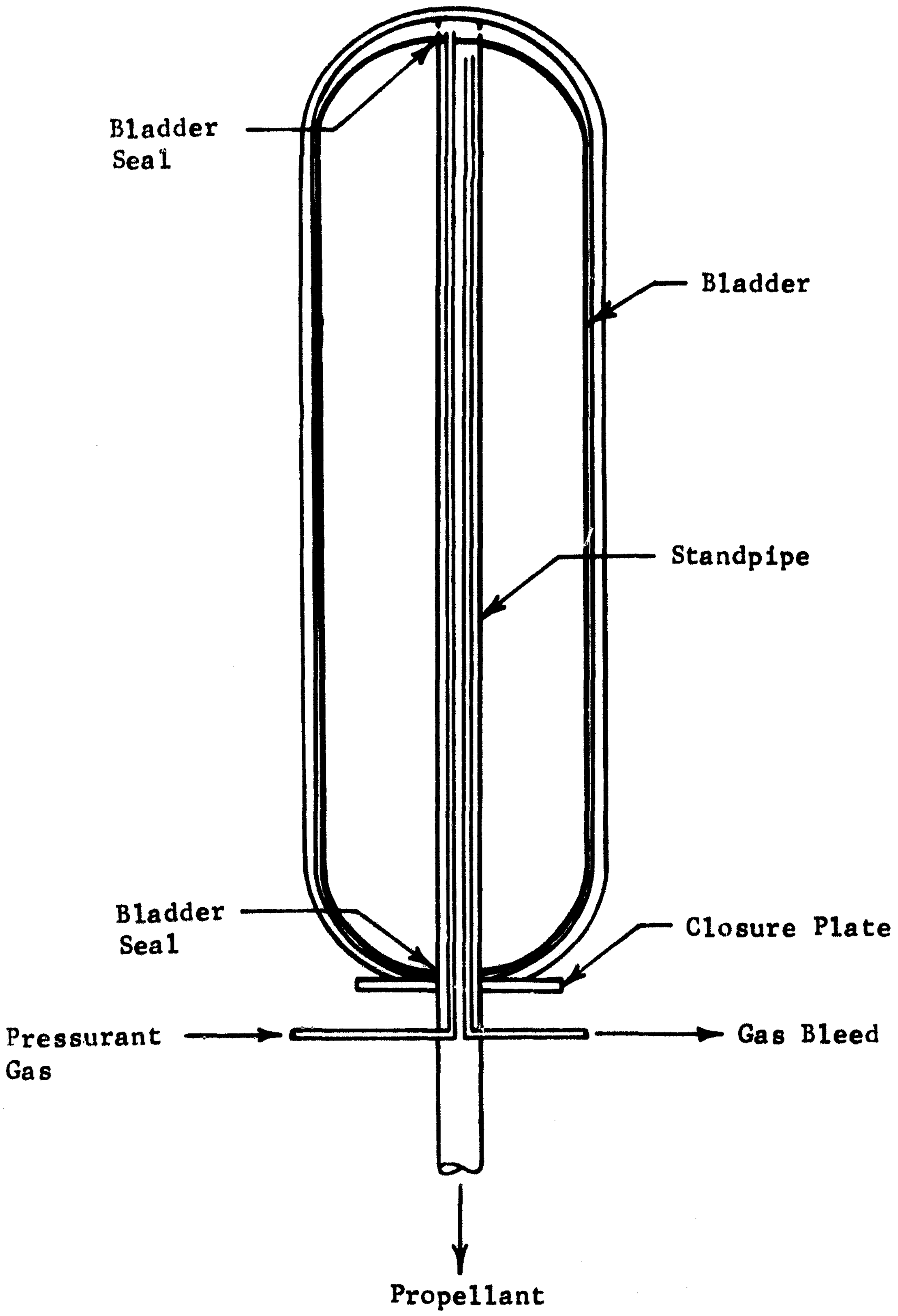


Fig. 5 Bladder Concept for Minimum System Changes

in a manner similar to the existing still well. All plumbing. would interface at the closure plate requiring no modifications to the basic tank shell.

D. NO HARDWARE LIMITATION BLADDER CONFIGURATIONS

A single cell bladder such as the configuration shown in Fig. 6 is the preferred approach. With proper design and development an expulsion efficiency of 98% seems obtainable. The estimated weights for this system are as follows:

	lb
Bladder	19
Standpipe (including inner bleed tube and bladder retention hardware)	13
Total	32

The 15.9-inch outlet diameter on the tank in Fig. 6 is suitable for insertion and removal of the bladder-standpipe assembly so no change would be made to the aft dome. In all probability the forward dome forgings have sufficient material to allow the required machining modifications for standpipe support and inlet pressurization. Aside from the forward dome modifications, no other changes would be required to the tank shell.

E. DIAPHRAGM CONCEPTS

1. Simple Reversing Diaphragm

One concept of a reversing diaphragm that might apply to this study is shown in Fig. 7. The shape of the tank exerts a strong influence on diaphragm folding patterns during expulsion, and because of the 51.4-inch cylindrical section, the diaphragm in Fig. 7 would undergo severe wrinkling during expulsion as it traversed the cylindrical section of the tank. Excessive wrinkling enhances the probability of material flexural failure. To fill this system the diaphragm would be cycled to the bottom of the tank by pressurizing through the gas inlet. The space between the diaphragm

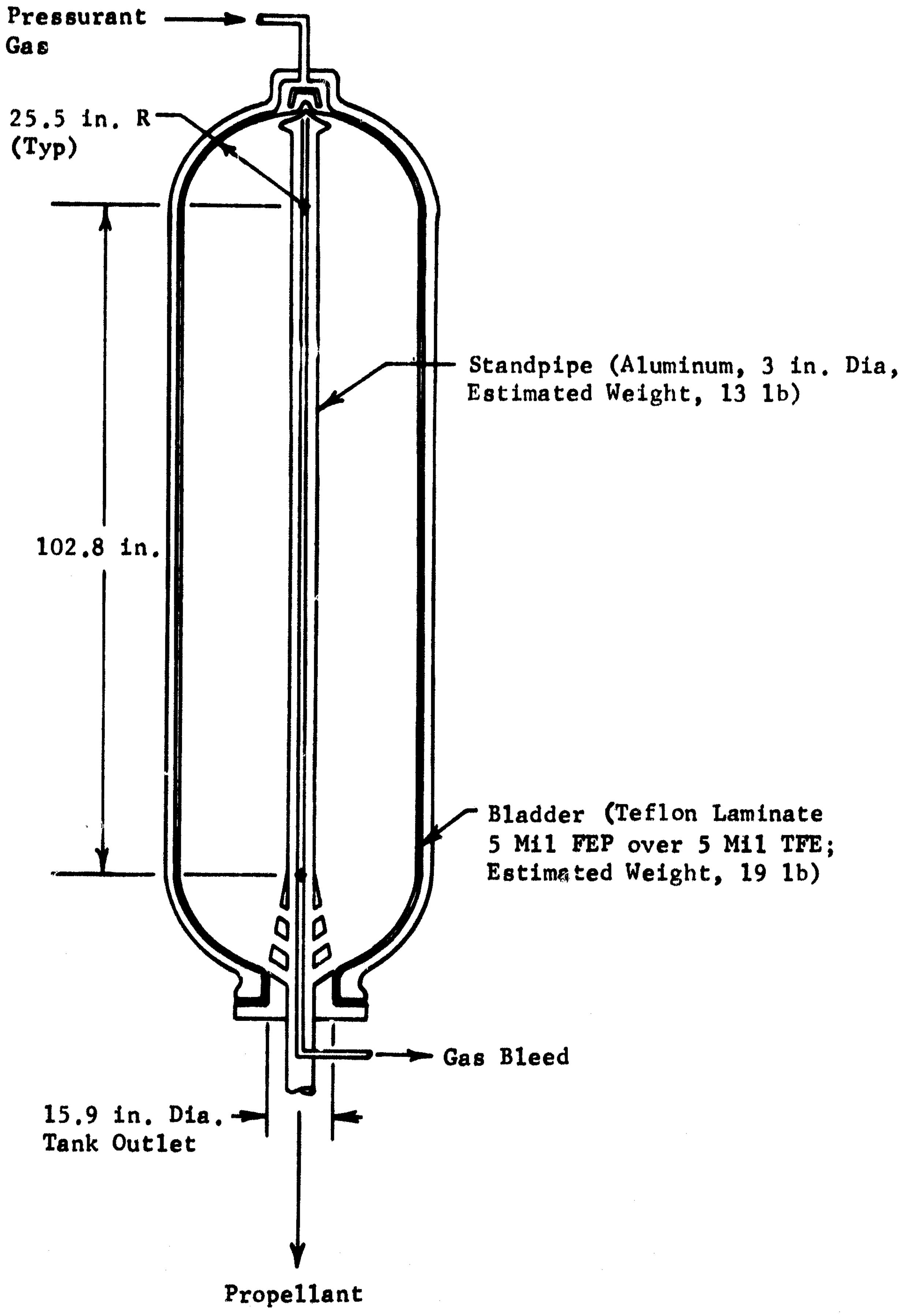


Fig. 6 Single Cell Bladder Configuration

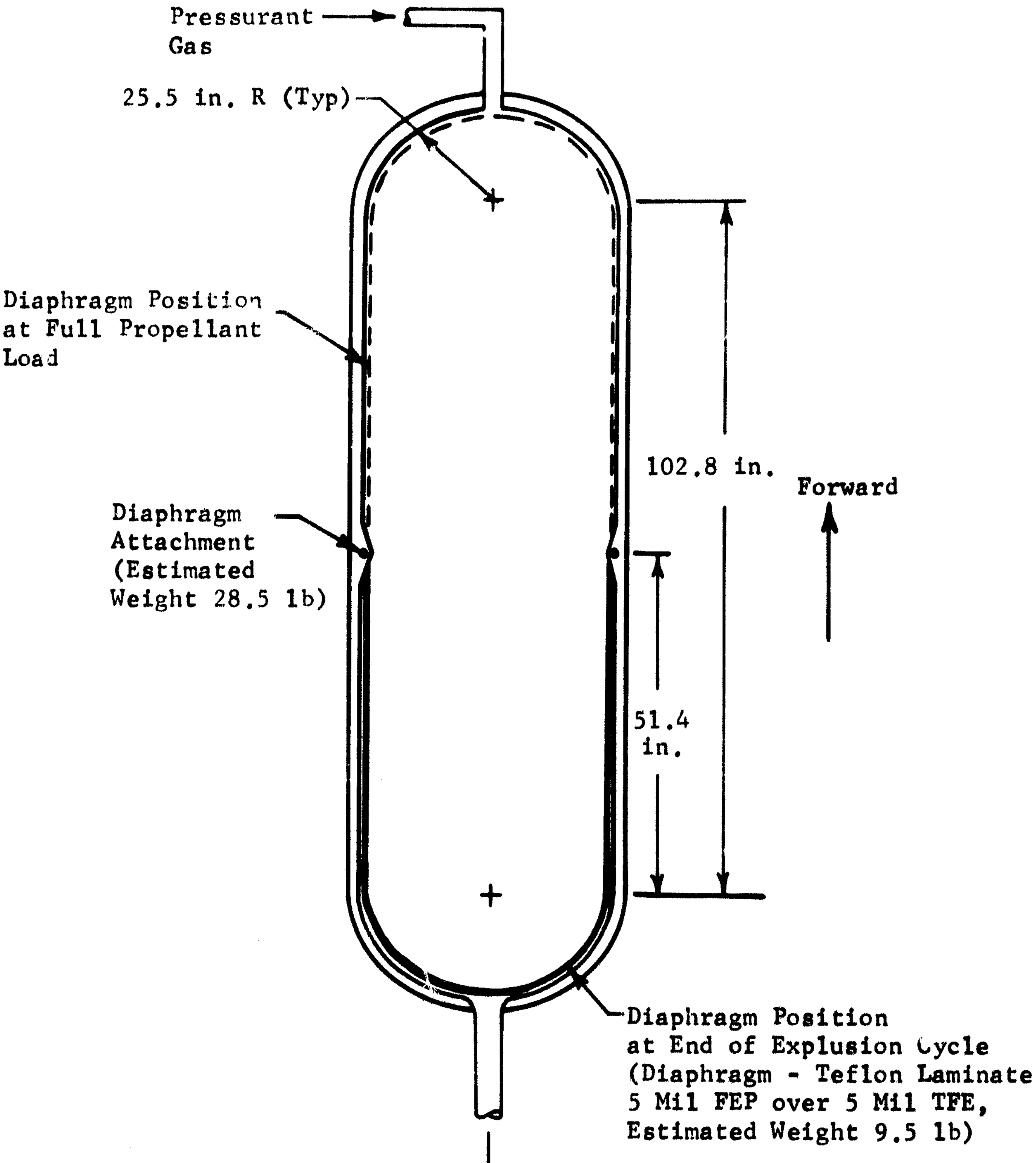


Fig. 7 Simple Reversing Diaphragm

and the engine valve could be evacuated if this gas volume were considered detrimental to engine performance. The desired quantity of propellant would then be loaded with ullage gas venting through the pressurant inlet.

2. Roll and Peel Diaphragm

Different methods have been conceived to minimize diaphragm wrinkling during expulsion. One such method, shown in Fig. 8, is referred to as a "roll and peel" diaphragm. The diaphragm is adhesively bonded to the tank wall prior to propellant loading. During the expulsion cycle, the diaphragm is progressively peeled away from the wall as the propellant is expelled. There are several reasons why the roll and peel concept would not be applicable to this study. First, it is a single cycle expulsion device in that the adhesive must be refurbished after each expulsion. Secondly, because there is no diaphragm vent capability, the liquid side of the tank would have to be evacuated prior to propellant loading. Heavy external support structure would be required to preclude tank collapse. Finally, a functional yet propellant-compatible adhesive is not presently available.

3. Bathtub-Type Diaphragm

A bathtub-type reversing diaphragm is shown schematically in Fig. 9. As compared to the two previously described diaphragm concepts, the bathtub diaphragm attachment plane is parallel rather than perpendicular to the longitudinal tank axis. There are several design considerations related to this concept; among them are the following:

a) As compared to the two previous diaphragm concepts, a significant weight penalty would be incurred because of additional 17 feet (twice the tank barrel length) of diaphragm attachment hardware;

b) The tank parting plane is perpendicular to the direction of principal stress (hoop stress), in contrast to parting planes in the previously described tank/diaphragm concepts. As such, an additional weight penalty would be realized because of the thicker weld land areas required to keep the operational stresses within acceptable limits;

c) The advantage of this concept compared to the previous diaphragm concepts is that in long cylindrical tanks the diaphragm traverses a distance equivalent to the tank diameter rather than the tank length, and it would

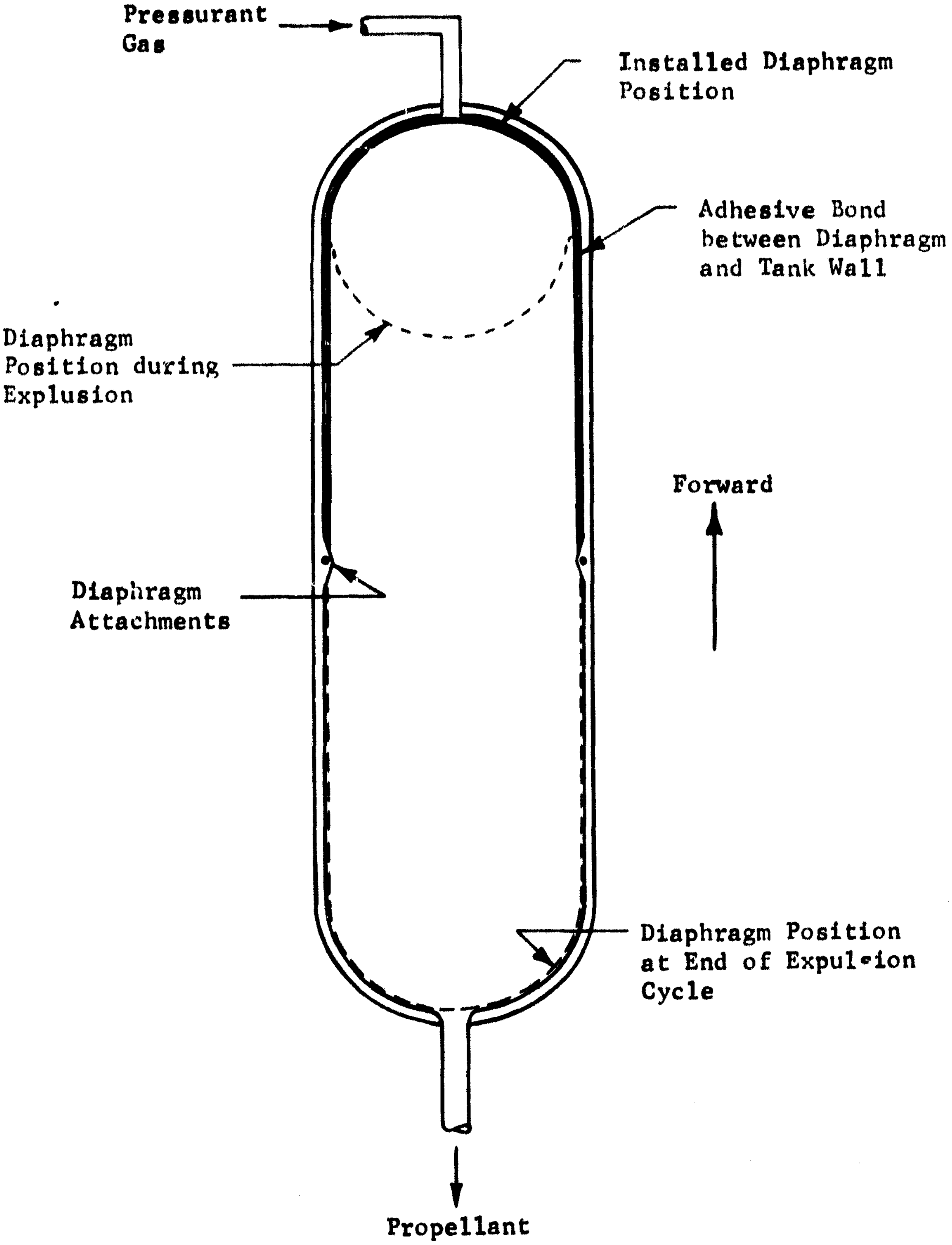


Fig. 8 Roll and Peel Reversing Diaphragm

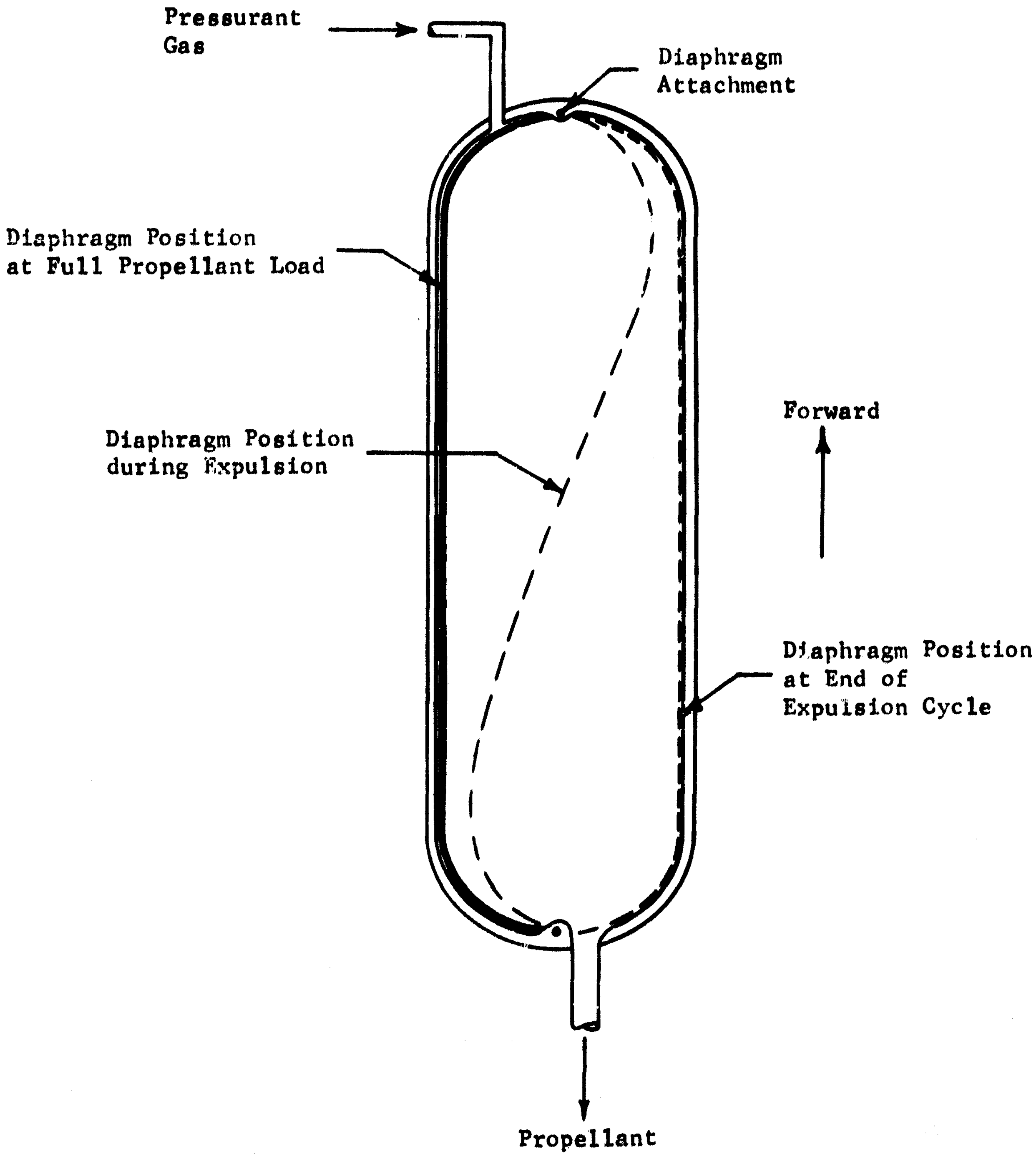


Fig. 9 Bathtub-Type Reversing Diaphragm

be expected that less folding and wrinkling would occur during expulsion and diaphragm cycle life would be improved.

4. Fabrication

The dispersion spray method, previously discussed in the section II,B,1 is equally applicable to the fabrication of TFE/FEP laminate diaphragms.

5. Expulsion Efficiency

At the end of the expulsion cycle a diaphragm is essentially free from wrinkles and folds and is in intimate contact with the tank wall; therefore in excess of 99% of the propellant can be expelled from the tank. The Titan III altitude control system diaphragm-type tank developed by the Martin Marietta Corporation (Ref. 9), has consistently demonstrated in excess of 99.5% expulsion efficiency regardless of tank orientation. The Jet Propulsion Laboratory reports test results on a diaphragm-type tank with an expulsion efficiency in excess of 99.7% (Ref. 10).

6. Material Thickness

For reasons of flexibility and durability, as discussed in section II,B,5 on bladder material thickness, a 10-mil (5-mil FEP over 5-mil TFE) laminate thickness is recommended for diaphragms.

F. NO HARDWARE CHANGE DIAPHRAGM CONFIGURATIONS

The requirement for still well gaging negates the use of diaphragms for "no hardware modification" application. Diaphragms in the process of expulsion traverse either the length or width of the propellant container. Any physical restriction within the tank, such as a still well, would prevent the diaphragm from performing its intended expulsion function. Even excluding the still well requirement, extensive modification to the tank interior would be required to provide for diaphragm attachment.

G. NO HARDWARE LIMITATION DIAPHRAGM CONFIGURATIONS

Of the three diaphragm concepts discussed, the simple reversing diaphragm shown in Fig. 7 is the recommended approach. Considering adaptability to the basic tank shape, it would yield a lighter tankage system than could be obtained with the bathtub concept and it has recycle capability which is not a feature of the roll and peel concept. The estimated weight breakdown for the simple reversing diaphragm is as follows:

	lb
Diaphragm	9.5
Diaphragm peripheral attachment hardware (attachment designed into weld joint, i.e., not bolted attachment)	28.5
Total	38.0

It is expected that the expulsion efficiency of the proposed diaphragm concept should be in excess of 99%.

H. GENERAL CONSIDERATION FOR BLADDERS AND DIAPHRAGMS

1. Pressurant Gas Ingestion

A definite need exists for less permeable membrane materials because propellant that has permeated through the membrane into the ullage is unusable and dead weight. Pressurant gas that collects in the propellant can severely affect engine performance and, at worst, cause catastrophic engine failure. Lee, at Rocketdyne, has established relationships for determining the amount of propellant vapor and pressurant gas that will permeate a bladder (Ref. 11). Applying these relationships to a bladdered tank of the size under consideration in this study, the amount of pressurant gas that could be expected to migrate through the bladder to the propellant side can be determined. Assuming a TFE/FEP laminate bladder consisting of 9-mil sprayed TFE Teflon plus 5-mil sprayed FEP Teflon, 70°F oxidizer, 198 psia helium pressurant gas and a 25% ullage volume, Equation 15 of Ref. 11 yields an equilibrium volume of the migrated gas bubble on the liquid side of 3950 in.^3 This is approximately equivalent to a 20-inch diameter sphere.

2. Gaging Systems

In recent years several different methods have been studied for gaging propellants in space environments. Of the different concepts the RF resonant cavity method appears most practical for bladder or diaphragm tanks. This system is under development by the Bendix Corporation, and its operational theory and developmental status is described in detail in Ref. 12. Basically, the system interprets the changing resonant frequency of an enclosed metallic structure (the tank) containing propellant as a measure of the mass of propellant contained within the tank. Although other systems mentioned in Ref. 12 have in-flight gaging capability in bladder or diaphragm tanks, the RF resonant cavity system is unique in that it can be used for gaging during propellant loading.

3. Reliability

Because of the conceptual nature of the bladder/diaphragm systems presented, no accurate failure rates can be determined. The failure modes, however, can be discussed along with the implication of the failure and considerations for minimizing failure probability.

a) Bladder/Diaphragm Rupture. A failure of this nature implies total loss of system operation. Assuming a flight qualification program that has demonstrated adequate operational margin, consideration must be given to close quality control to assure reproducible material properties, and also to assure adherence to installation and checkout procedures to preclude inadvertant bladder/diaphragm degradation.

b) Excess Permation and/or Leakage. Propellant that migrates into the ullage is unusable and could result in premature mission termination. Pressurant gas mixing with the propellant can seriously degrade engine performance. Bladder/diaphragm fabrication processes must be closely controlled to assure that each unit produced has permeation characteristics representative of those units used for flight qualification. Individual unit acceptance tests as well as tank assembly acceptance tests must be capable of detecting leaks that would cause unacceptable system performance.

4. Development Time and Cost

To predict development time and cost is to predict the measure of success anticipated from the original bladder/diaphragm design. Any such prediction would be suspect in that the expulsion characteristics would be highly empirical and no size and shape comparitive performance data exist.

A comparison of the recommended bladder and diaphragm configuration (Fig. 6 and 7) shows that the diaphragm is one-half the size of the bladder. As such, the per unit labor and material costs for diaphragm fabrication should be about one-half the corresponding bladder costs. Assuming that the remaining recurring costs (acceptance testing, packaging, shipping, coordination, etc.) and the nonrecurring costs (basic bladder/diaphragm design, development costs, procurement specifications, tooling design and drawings, etc.), would be essentially the same, the overall cost for a diaphragm system should be less than for a bladder system.

5. Compliance With System Design Goals

a) Priority I Goals.

1) Passive Operation. Bladder and diaphragm systems do not require auxiliary propellant settling;

2) 99.5% Expulsion Efficiency. In all probability, diaphragm systems will meet this goal but it is extremely doubtful that a bladder system could consistently produce in excess of 98% expulsion efficiency;

3) **Ten Lb/Tank.** Neither system satisfies this goal. A bladder system would weigh about 32 pounds and a diaphragm system about 38 pounds;

4) No Pressurant Gas Ingestion at Tank Outlet. In both systems the membranes are subject to gas permeation and it is expected that some pressurant gas will migrate through the membrane and to the tank outlet.

b) Priority II Goals.

Bladder and diaphragm systems restrict the movement of propellant in the tank during low-g operation. As such they limit the slosh amplitude and actually provide some degree of slosh dampening. It is expected that the systems would be capable of twenty expulsion cycles and would function in both positive and negative acceleration fields with no engine duty cycle limitations. Both systems are theoretically capable of carrying any partial propellant load that may be required for a particular mission. However, with both systems, partial propellant loads result in wrinkled membranes that are subjected to the boost phase high acceleration loads (7.35 g) and the preflight launch pad and booster flight vibrational environments. The impact of these conditions on bladder/diaphragm systems would require a development program to investigate the vibration cycle life over a range of propellant loads.

Neither bladders nor diaphragms are adaptable to series tankage systems. In the existing Apollo SPS, each propellant commodity is supplied from series-connected tanks. Bladder/diaphragm applications in multiple tankage systems require a bladder or diaphragm in each tank, with the tanks connected in parallel, to prevent pressurant gas ingestion into the propellant feed systems. Considering the extent of required modification, bladder/diaphragm systems do not lend themselves to retrofit of the existing SPS tankage.

Much of the damage sustained by Teflon bladders and diaphragms occurs during installation, system checkouts, filling and post-abort decontamination. With the implementation of proper procedures for each of these events, the proposed bladder/diaphragm concepts should have an operational life in excess of one year.

III. METALLIC DIAPHRAGMS

Metallic diaphragms are used to ensure liquid phase expulsion by providing a barrier between the propellant and the ullage volume. The diaphragm is attached to the wall of the container to separate ullage and propellant. During expulsion, the diaphragm moves in response to the pressure differential, displacing the consumed propellant with ullage volume.

A. CONFIGURATIONS

Metallic diaphragm expulsion devices considered in this evaluation include convoluted diaphragms, rolling diaphragms, and bladders. The state-of-the-art reflects substantial progress through development efforts in recent years, but additional work is required in this area before satisfactory performance of these devices can be achieved. Some of the significant efforts in metallic diaphragm development are discussed in the following paragraphs.

1. Convoluted Diaphragms

The convoluted diaphragm is a surface of revolution consisting of circular convolutions precisely formed from thin flat stainless steel or aluminum sheet. It is positioned on a diametrical plane of a spherical container with one side exposed to the propellant and the other to the pressurant. The diaphragm deforms in favor of the imposed pressure differential expanding to conform to the container walls during expulsion.

The surface area of the convoluted sheet equals that of the fully expelled form to achieve minimum diaphragm strain. Several basic convolution designs are discussed in Ref. 10. Two diaphragms nestled back-to-back would be required to expel liquid from a spherical tank. The diaphragms are attached to the sphere at a diameter. Pressurant enters the volume between the diaphragms to provide the pressure differential required for expulsion.

The convoluted diaphragm method of positive expulsion was considered for the ALPS program which used earth storable propellants, N_2O_4 and N_2H_4 (Ref. 1). The 18-inch diameter tanks contained the dual diaphragm arrangement permitting fuel and oxidizer storage in the same tank. The biggest problems encountered during this effort were:

1) Controlled expansion of the diaphragm under lateral acceleration;
2) The inability of the devices to recycle.

This technique will not be given further consideration in this evaluation as other types of metallic diaphragms are more adaptable to the cylindrical tankage envelope.

2. Rolling Diaphragms

The second class of metallic diaphragms used for positive expulsion has several variations which all employ the same operating procedure. A spherical, conical, or cylindrical configuration rolls during expulsion turning inside out to result in a mirror image of the initial form at reversal completion.

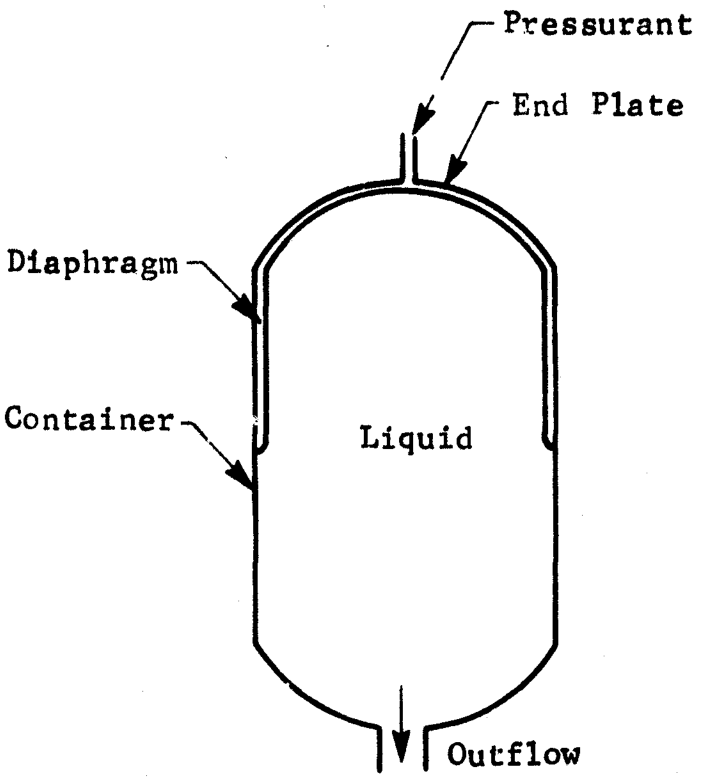


Fig. 10 Rolling Diaphragm

Cylindrical Diaphragms. The cylindrical rolling diaphragm configuration usually consists of a thin cylinder, one-half the length of the container being expelled. One end of the cylinder is attached to the container wall at the midplane; the other to a movable endplate (Fig. 10).

When the ullage space is pressurized, the end plate moves towards the tank outlet rolling the thin cylinder inside itself during expulsion. Successful operation of this device depends on the relationship between the pressure required to roll the diaphragm and the thin cylinder collapsing pressure. The rolling pressure must be less than collapsing pressure for satisfactory operation. Unfortunately, this condition cannot be achieved without additional support to the walls. This problem has been investigated by the Naval Ordnance Test Station at China Lake, California. The initial approach was to bond the cylinder to the wall of the container with a bonding agent having a tenacity that would permit a desirable peel strength during expulsion (Ref. 13). A fair degree of success is reported using this procedure; however, voids in the bond created problems in the rolling process during expulsion. The cylinder tends to collapse when the void is uncovered, resulting in potential tear points and ultimate failure.

In the test models used for the investigation reported in Ref. 13, cocking of the end plate was prevented by a central column guide. A second cylindrical diaphragm was bonded to this column and the upper end welded to the end plate. The inner cylinder rolled over itself while the outer cylinder rolled inside itself during expulsion.

Other approaches to the collapsing problem included methods to either keep the pressurant from entering the space between container and cylinder or to strengthen the cylinder wall. The use of sliding seals which followed the diaphragm roll line proved ineffectual. Circumferential stiffening groves placed in the cylinder increased the collapsing pressure but also increased the rolling pressure requirement. Further development efforts conducted by LTV Aerospace Corporation under U. S. AMC sponsorship have advanced the state-of-the-art in adapting the roll diaphragm expulsion method to small tactical missiles. Encouraging results were obtained from roll diaphragm expulsion of both fuel (UDMH) and oxidizer (IRFNA) tanks arranged in tandum (Ref. 14). Improved bonding techniques were significant in demonstrating expulsion performance. Teflon was used to bond the 1100-0 aluminum diaphragm to a 2014 aluminum sleeve which in turn was welded to the propellant tanks near the forward end. A static hot firing demonstrated successful performance for a single expulsion.

Another method used to prevent cylinder collapse has produced encouraging results. Collapse is prevented by the use of a sliding sleeve fitted inside the cylindrical diaphragm. Bonding of the diaphragm is not required. During expulsion, the sliding sleeve moves aft as the diaphragm is rolled over the forward end of the sleeve. A finite diaphragm roll radius can be maintained by the sliding sleeve rim contour. Single expulsion demonstrations have been successful using this configuration (Ref. 15).

One other approach to metal rolling diaphragm development is of interest. This method combined the diaphragm fabrication and bonding operation by using a chemical vapor deposition (CVD) technique (Ref. 16). The process used deposited aluminum on the container wall from an unstable alkyl (Triisobutyl aluminum) thermally decomposed when contacting the heated container wall.

Obtaining a uniform deposit of high quality metal was a problem with this approach. The surface receiving the deposit must have a fine finish (64 micro-inches) to achieve a desirable bond peel strength. The requirement for fine surface finishes, complicated deposition techniques, and the difficulty in obtaining a uniform deposit makes this approach less attractive than other types of metallic devices.

Ring Reinforced Diaphragms. This type of diaphragm is supported by additional structure to permit controlled deformation of the diaphragm and recycle capability. A thin metal shell is stiffened by rings attached to the shell surface in planes parallel to a reference base, usually the diaphragm-container attach point. During expulsion, the diaphragm inverts to a mirror image of its initial shape at propellant depletion. The reinforcing rings roll with the shell in the process straining the diaphragm as the ring inverts. Work hardening of the shell material results, limiting the number of reversals achievable. The shape of the shell is limited to a conical, elliptical, or spherical surface of revolution to prevent ring interference during expulsion.

Multicycle operation using this type of device has been demonstrated by Arde, Inc., Paramus, New Jersey. Six successful reversals were achieved using a 321 stainless steel hemispherical wire reinforced diaphragm (Ref. 16). Diaphragm material strain increases with increased rolling point diameter, reaching a maximum at the hemispherical diameter. If a conical section is used in the high strain area near the spherical diameter, improved performance is obtained as the material strain is reduced. This type of geometry was used by Arde in demonstrating multicycle performance. Both aluminum and stainless steel modified hemispheres have been fabricated in sizes up to a 30-inch diameter. Fabrication of a spherical diaphragm 60 inches in diameter for cryogenic application is currently in process.

Wire reinforced spherical diaphragms 13 inches in diameter are currently being fabricated by Arde, Inc. from both aluminum and stainless steel for cryogenic application. The goal is to achieve 20 successful reversals.

Aerojet General used the Arde Conospheroid concept for a post-boost propulsion subsystem study involving earth storable propellants, N_2O_4 and N_2H_4. The goal was one successful reversal sweeping a volume 14.5 ft^3. Control of the diaphragm rolling by diaphragm thickness variation and ring stabilization was demonstrated. Diaphragm flexing began at the point of minimum wall thickness. During reversal, diaphragm rolling was stabilized by the reinforcing rings. The rolling action was uneven between wires, but the wires usually caused the diaphragm to center itself before rolling past the wires.

Combination Approach. The bulk of the development work with metallic diaphrgams thus far has used containers with simple surface of revolution. Investigations have used either cylindrically or spherically shaped containers, with the exception or Arde, Inc. who combined the sphere and cone in the **Conospheroid** concept. A combination of the sliding sleeve and the reinforced spherical diaphragms, a configuration adaptible to a cylindrical tank with domed ends, has not been developed as far as can be determined. One big disadvantage of diaphragms adaptible to cylindrical containers is the inability to recycle. Goals in all the development work to date have been for one successful expulsion only.

3. Metallic Bladders

The current evaluation of metallic expulsion devices includes metallic bladders. The present state-of-the-art is probably best represented by development effort conducted by the Bell Aerosystems Company for the Lance missile propulsion system (Ref. 8). This concept features a cylindrical bladder with 2:1 elliptical heads collapsed on a three-lobe center structure. The collapsed bladder domes are folded over rods welded to each lobe at both ends of the center structure to minimize sharp creases. Bladder material was 1100 aluminum 0.032 inch thick, annealed after being collapsed. Both cold and hot gas expulsion tests were conducted to demonstrate expulsion feasibility. The propellant is contained in the volume between the collapsed bladder and tank. The bladder is expanded toward the tank wall during expulsion.

Failure of the bladder resulted during the first expulsion although an expulsion efficiency of 99% is reported. Controlled expansion with this type of expulsion device is difficult to achieve.

The development of a workable system using this approach is probably not warranted for current application.

4. Telescoping Diaphragms

A recent development in the metallic diaphragm field involving a new approach has been reported by Bell Aerosystems Company (Ref. 18). The name "telephragm" has been coined by Bell for this type of diaphragm. This approach applies to cylindrical tankage and consists of telescoping a thin cylinder within itself to form three concentric convolutions. The outer convolution is attached to the container wall at one end of the cylindrical tank. During expulsion, rim rolling at the outer convolution occurs first, followed by rim rolling of the inner sections. In the fully expelled configuration, the diaphragm forms a stepped cylinder where the diameter decreases with each of the three steps. Aluminum 1100 only has been used for the diaphragm material which is fully annealed after telescoping. An expulsion efficiency of 94% using an 8-inch diameter telephragm has been achieved. Better efficiencies are anticipated with continued development efforts. Only one expulsion can be achieved with this device.

5. Gaging Systems

Propellant gaging in rolling diaphragm systems can be achieved by determining the diaphragm position during expulsion. A series of electrical circuits which open progressively as the diaphragm leaves the tank wall is an attractive approach. Changes in accelerating force direction would not appreciably affect the device. Any of the various gaging systems discussed earlier are also adaptable.

B. DESIGNS FOR NO HARDWARE CHANGE APPLICATION

The existing still well and gaging system presents a difficult problem in the retrofit design approach. The gaging system is not adaptable to diaphragm-type expulsion. Two configurations which seemed to present attractive development possibilities in retrofit are impractical with this gaging system. These configurations are: (1) an initially collapsed bladder which expands during expulsion; (2) the chemical vapor deposition rolling diaphragm. Both of these possibilities, previously discussed, require more development than other metallic devices which appear more attractive for the no hardware limit application. With either of the two possibilities, hardware modification of the existing system, in addition to still well removal, would also be required to obtain a functional system. Rerouting of the pressurization line would be required and the existing series tankage and system would require a sequencing valve arrangement to isolate the tanks during expulsion from the diaphragm tank. Retrofit of the SPS tank without at least the above modifications does not appear practical for metallic diaphragm usage. Design configuration for this application will not be given further consideration.

C. DESIGNS FOR NO HARDWARE LIMITATION APPLICATION

Metallic diaphragms have not been used in any flight system to date. The state-of-the-art is progressing and these devices seem attractive for small tactical systems. The Lance propulsion system will probably use this type of device in the near future. Systems like the Apollo SPS, used in this evaluation study, require diaphragm sizes larger than previously fabricated which suggests substantial development effort requirements before reliable positive expulsion can be demonstrated. Two tentative designs using metallic diaphragms have been selected for comparative purposes in the current evaluation study. Neither design meets all the design goals in the study; however, the nonpermeable positive containment feature of metal diaphragms warrants their consideration. The long term storage potential, excellent permeation characteristics, and desirable material compatibility are significant features in the evaluation study.

1. Design A: Sliding Sleeve and Reinforced Hemisphere Combination

Adaptability. This design utilizes the same tank envelope used in the existing service propulsion subsystem. The diaphragm conforms to the tank wall in the upper half of the tank (Fig. 11) and is attached to the tank at the midplane. A combination of the sliding sleeve and the reinforced hemisphere is used in the diaphragm design. The diaphragm material is 321 stainless steel with a nominal wall thickness of 0.010 inch. A slight reduction in wall thickness in the dome area will promote apex rolling of the diaphragm. A tapered sheet thickness from the hemisphere base to the apex is desirable to control the rolling mode.

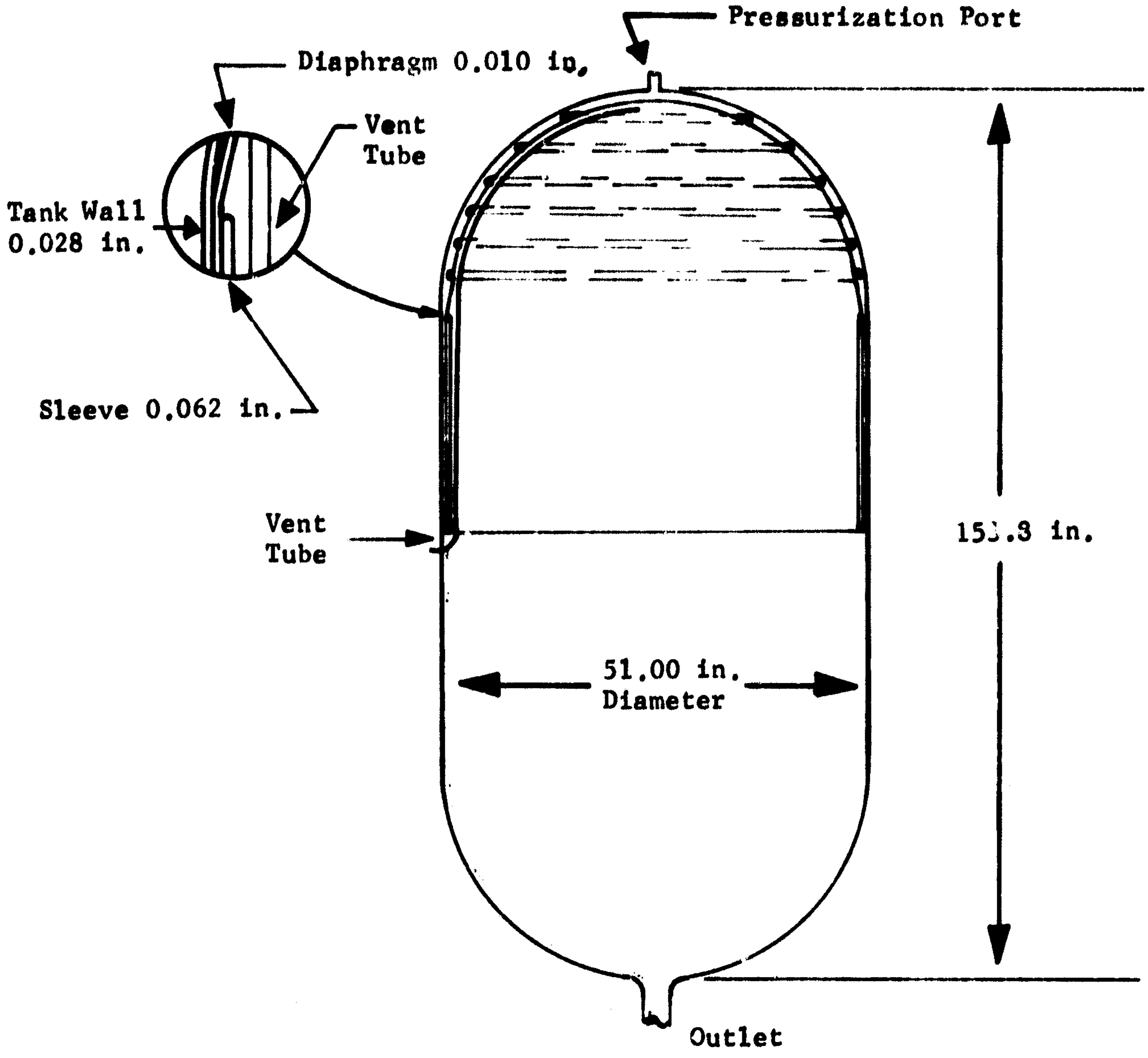


Fig. 11 Sliding Sleeve-Reinforced Diaphragm

A conical transition section is used between the cylinder and spherical section to reduce the high strain in this area and to prevent reinforcing ring interference. The cone forms an 80 degree angle with the base. Reinforcing rings, 3/16 O.D. tubing with a 0.035 wall, are attached to the cone in planes parallel to the base at 1.5-inch spacing and 1.0-inch spacing on the spherical section. Twenty-eight tube rings are used to support the cone and domed section of the diaphragm. Support in the cylindrical section is provided by the titanium sliding sleeve that is held in position prior to cylinder rolling action by clips at the tank midplane. A port is required in the forward tank dome for pressurizing gas flow.

Propellant filling of these devices presents a problem. A first thought might be to turn the tank so the outlet is forward to permit gravity fill and venting from the outlet port, but this approach has the disadvantages of outflow line plumbing complications and the undesirable diaphragm pressure differential during boost (hydrostatic lead pressure of liquid in the thin shell). The possibility of turning the tank for filling through the outlet and reorienting to the "outlet aft" attitude after filling is impractical in this application. Filling in the outlet aft attitude is obviously the most desirable approach. Three possibilities are available; vacuum filling, venting the diaphragm, or filling with the diaphragm initially in the expelled position.

The latter method cannot be used in this design as the diaphragm does not have a recycle capability. The structural integrity of the tank will not permit the high vacuum approach without severe weight penalty. Diaphragm venting in the outlet aft attitude appears to be the most attractive filling method. Filling and venting through the outlet using a removable vent probe which extends to the top of the diaphragm is impractical as it imposes severe design complications in the outflow line to facilitate removal of the vent probe. Two other methods to vent the tank at the diaphragm apex are conceivable. Venting through both the diaphragm and tank dome can be achieved by a disconnect mechanism or by a light supple metallic tube attached to the propellant side of the diaphragm. The tube, open at the diaphragm apex, would terminate at a vent port located in the tank wall below the midplane. The vent port would be capped after loading has been completed. The tube, attached to the diaphragm dome, follows the dome curvature as it inverts during expulsion. As the sliding sleeve moves aft, the vent tube is either sheered off or flattened against the tank wall by the sleeve leading edge. This approach is attractive, as a vent port is not required in the diaphragm. Collapsing pressure of the tube must be great enough to withstand only the hydrostatic pressure encountered during filling thereby offering minimum resistance to diaphragm deformation during expulsion. This venting method also provides the capability for propellant gravity draining without flexing the diaphragm.

Reliability. The potential failure of the metallic diaphragm expulsion system can be estimated by anticipating individual failure modes. A failure mode for the purpose of this evaluation is defined as any function which prevents gas-free liquid from entering the engine feed line. Anticipated failure modes for the sliding sleeve-Conospheroid diaphragm are summarized as follows:

a) Reinforcing ring to shell attachment failure;

b) Diaphragm material work hardening from flexing during slosh modes;

c) Diaphragm to tank seal;

d) Binding of sliding sleeve during travel;

e) Vent tube interference.

Weight. The calculated weight of the Design A diaphragm using a 321 stainless steel shell and reinforcing rings with a titanium sliding sleeve is 118 pounds. Replacing the stainless steel with titanium would reduce the weight of the tentative design to 104 pounds. This weight is based on the same material geometry used for stainless steel. No change in metal thickness was considered.

Development. Metallic diaphragms have some features which make them attractive for positive expulsion devices. The present state-of-the-art has not advanced to the point where reliable devices with multicycle capability can be fabricated. Design and fabrication areas requiring additional analysis and development are:

a) Diaphragm forming and wall thickness control in large diaphragms;

b) Reinforcing tube ring attachment techniques which minimize diaphragm strain during rolling to increase cycle life;

c) The effect of propellant slosh on diaphragm material (work hardening effects);

d) Diaphragm-sliding-sleeve fit tolerances and surface finishes to minimize sleeve cocking potentials and friction drag;

e) Diaphragm to tank attaching technique (dissimilar metal joining);

f) Joining diaphragm transition sections with no adverse effect on rolling performance.

Expulsion Efficiency. The expulsion efficiency of these systems, defined as the ratio of maximum propellant expelled to propellant loaded, is at least 99.5%. The diaphragm is designed to sweep the entire volume occupied by the propellant.

The volumetric efficiency, defined as the ratio of maximum propellant loaded to total interior tank volume, is 99% for the Design A configurations.

Slosh Control. The effect of propellant slosh on the metallic diaphragm requires further investigation. The diaphragm in a partially expelled tank will tend to oscillate with the propellant motion. Slosh damping will be provided by the diaphragm, but if the slosh force is great enough to flex the diaphragm, work hardening of the material and ultimate failure will result. The limitation of the diaphragm under a sloshing mode is unknown at this time.

Design Goals. The sliding sleeve-reinforced hemisphere combination design does not meet all of the design goals indicated in the statement of work. All goals under Priority I can be met with the exception of the weight goal. The stainless steel design discussed above weighs about 118 pounds which is considerably in excess of the 10 pound goal. A reduction in this weight of about 20 pounds could be realized by using titanium for the diaphragm material. The largest weight contribution is the sliding sleeve which is titanium in the stainless steel design discussed. The use of titanium would simplify diaphragm-to-tank attachment but titanium diaphragm techniques for expulsion devices have not been developed.

Some of the goals under Priority II can be met with qualification; others cannot.

Operation of the diaphragm under positive or negative g will not be a problem providing the hydrostatic head resulting from negative g forces does not produce rupture stresses in the diaphragm.

Hardware changes to the propulsion system will be required in this design. Changes to the tank consist of: (1) pressurization port, (2) vent port installation, and (3) tank modification at the midplane to facilitate diaphragm attachment. In addition, pressurization lines from the storage will have to be routed to the tank dome. The existing pressure regulation system is probably adequate.

The expulsion life of this system is limited to one cycle where the design goal specifies multiple cycles. The reinforced cone and sphere of the diaphragm can be reversed, but the cylindrical section does not have this capability.

The series tankage capability goal can be obtained only by sequence valving or a parallel system.

Off loading can be achieved in this design by first completely filling the tank and then expelling propellant to the desired off-load point.

2. Design B Conospheroid Diaphragm

Adapability. The metallic diaphragm in Design B may be recycled. As previously mentioned, performance on the Conospheroid concept has been demonstrated in achieving at least six complete successful reversals using water as the expelled fluid. Diaphragms of the size required for this design have never been fabricated or evaluated. The diaphragm consists of a conical and spherical section fabricated from 321 stainless steel 0.010-inch thick, reinforced with 3/16 O.D. stainless steel tube rings attached in planes parallel to the cone base (Fig. 12). The tube ring spacing is 1.5 inches on the conical section and 1.0 inch on the spherical section. The cone length is 60 inches and has a taper of 10 degrees to reduce strain and to prevent ring interference during expulsion. The diaphragm is attached to the tank at the mid-plane, as in Design A. The dimensions of the diaphragm result from using the existing tank envelope, i.e., 51-inch diameter by 152 inches long. Within this envelope, the tank geometry should conform to that of the diaphragm for the best efficiency. The tank would then be symmetrical about the mid-plane and taper by 10 degrees, fairing into a spherical section at each end. The resulting tank volume is 100 ft^3 which is greater than a 36% reduction. If this tank configuration were expanded to create a volume of 160 ft^3, the required envelope would be 62-inches in diameter by about 160 inches in length. This configuration, designated as Design B-2 is included for consideration in the evaluation. Design B-1, also a modification of Design B, is included for comparison purposes. In this configuration, the same diaphragm used in Design B is used in a tank having the same dimensions as the existing SPS tank.

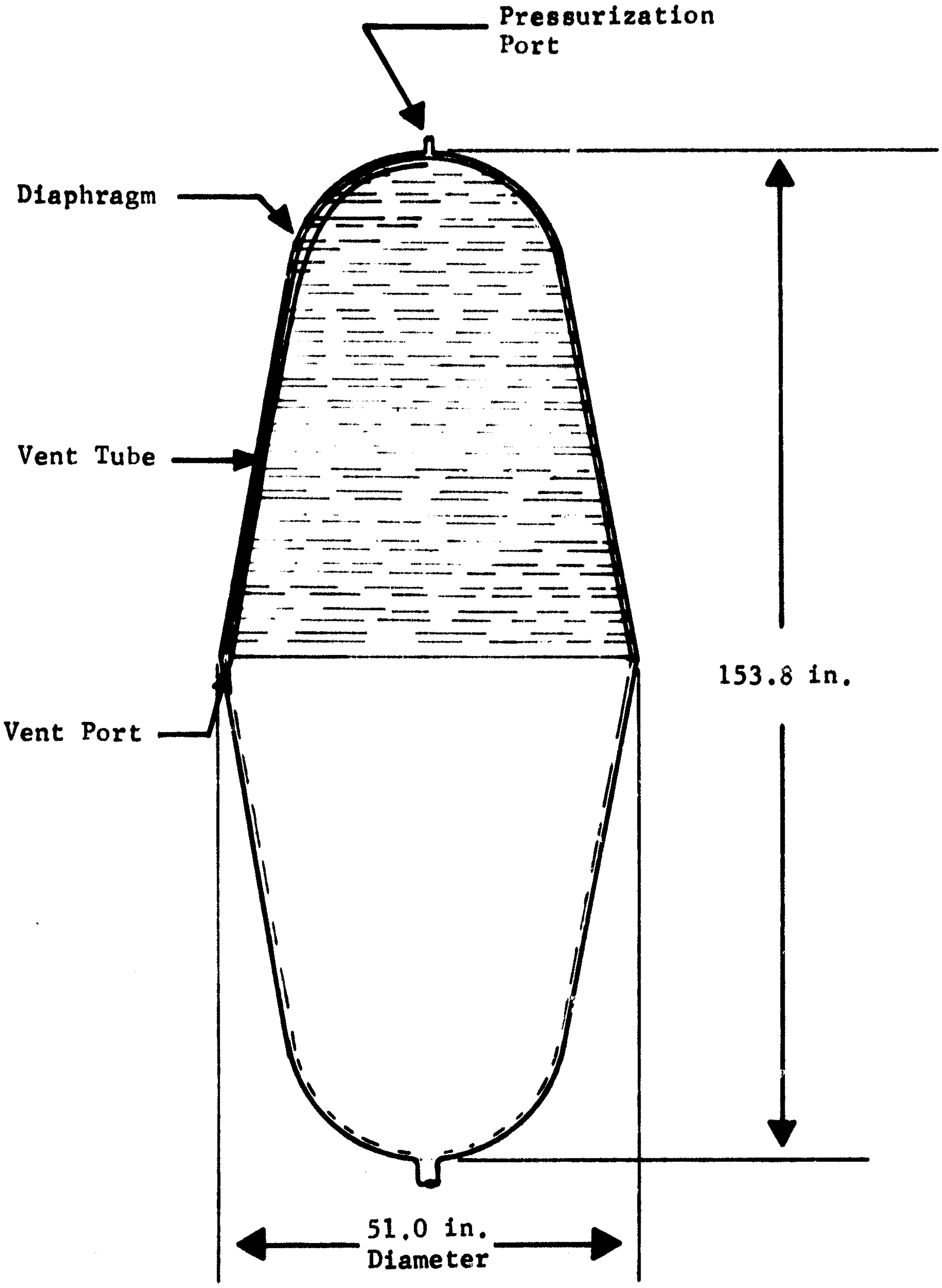


Fig. 12 Conospheroid Concept

The propellant loading problems in Design B are the same as in Design A, although filling could be accomplished by expanding the diaphragm from the expelled position to the fully extended position, venting the ullage through the pressurization port. It is probably more desirable to use the vent tube approach to vent the propellant side of the diaphragm as previously discussed, rather than flex the diaphragm during loading because work hardening of the diaphragm increases with each reversal.

Reliability. Failure modes in Design B and the two modifications are similar to those for Design A, with the exception of the sliding sleeve failure mode.

Weight. Diaphragm weights for Design B and modifications B-1 and B-2 are presented in Table III. The diaphragm for Design B-2 is heavier than those for B and B-1 as the diaphragm surface area has been increased. Weights are based on the same material thickness for both stainless steel and titanium. An additional weight penalty results from the larger tank requirement in the B-2 configuration. A 12% weight increase based on diameter increase appears conservative as the domes of the tapered tank are smaller than the existing tank.

Table III: Expulsion Device Evaluation Variables for Design B

Design	Titanium Weight (lb)	SS	Volumetric Efficiency	Expulsion Efficiency	Tank Volume (ft^3)
B	25	46	97.5	>99.5	100
B-1	25	46	66	80	161
B-2	32	60	97.5	>99.5	161

Development. Development time and costs for this design would not be as large as for Design A if stainless steel is used for the diaphragm assembly. Development of a titanium device, however, would probably require an expenditure equivalent to that required for Design A. Other development problems are similar to those summarized for the Design A configurations.

Expulsion Efficiency. Expulsion efficiency for Design B configurations are presented in Table III. The relatively low efficiency for the B-1 modification reflects the outage resulting from the mismatch between diaphragm and tank contour in the expelled condition. Volumetric efficiency, also presented in Table III, is 97.5% for configurations B and B-2. The diaphragm-tank contour mismatch is again reflected in the low efficiency value for modification B-1.

Slosh Control. The effect of sloshing propellant on the diaphragm performance requires additional analysis in these designs as well as in Design A.

Design Goals. Deviation from the design goals for Design A also applies to the design B configurations with the following exceptions:

a) This design does have recycle capability, probably limited to less than six complete expulsions;

b) The design does not meet the propellant load volume requirement of 161 ft^3 if the tank envelope is maintained.

IV. CAPILLARY EXPULSION SYSTEMS

In the last few years a considerable effort has been expended on the application of surface tension forces to provide propellant control (management) for spacecraft propulsion systems. The underlying theory is quite simple, and experimental test results have been obtained to verify and establish criteria for capillary system design. Many aerospace companies and government agencies such as LeRC, MSFC, and MSC have sponsored studies in this area.

While the feasibility of surface tension propellant management is well established, application on existing propulsion systems is quite limited. The sump tanks in both propellant tanks of the Apollo SPS are probably the most significant example of the application of surface tension control. A sketch of the Apollo SPS is given in Fig. 13 with a comprehensive discussion of its operation presented in Ref. 19. Other systems using more basic forms of surface tension control are the Agena and Transtage primary propulsion systems. Capillary expulsion systems have also been fabricated and tested on R&D programs such as the Packaged Liquid Missile Program [Contract AF04(611)-11398], the Sterilizable Liquid Propulsion System (Contract JPL 951709), and the In-Space Propellant Orientation and Venting Experiments [Contract AF04(611)-11403].

Hardware is also being developed and fabricated for future applications as discussed in Ref. 20 and 21.

These programs and the various technology programs leave little doubt about the merit of surface tension propellant control for a wide variety of space applications. For devices employing perforated plates or square weave mesh screens, the supporting fabrication technology is existing and does not differ significantly from existing technology involved in tank design and support structures. However, for systems employing micronic porous materials as Dutch twill woven cloth, sintered powder metals, sintered fibers, etc., the supporting technologies are not well defined. Quality control procedures, inspection techniques, cleaning procedures, manufacturing procedures and processes such as welding, bonding, and forming have not been extensively developed. If systems are designed that require the use of these materials, additional development will have to be conducted.

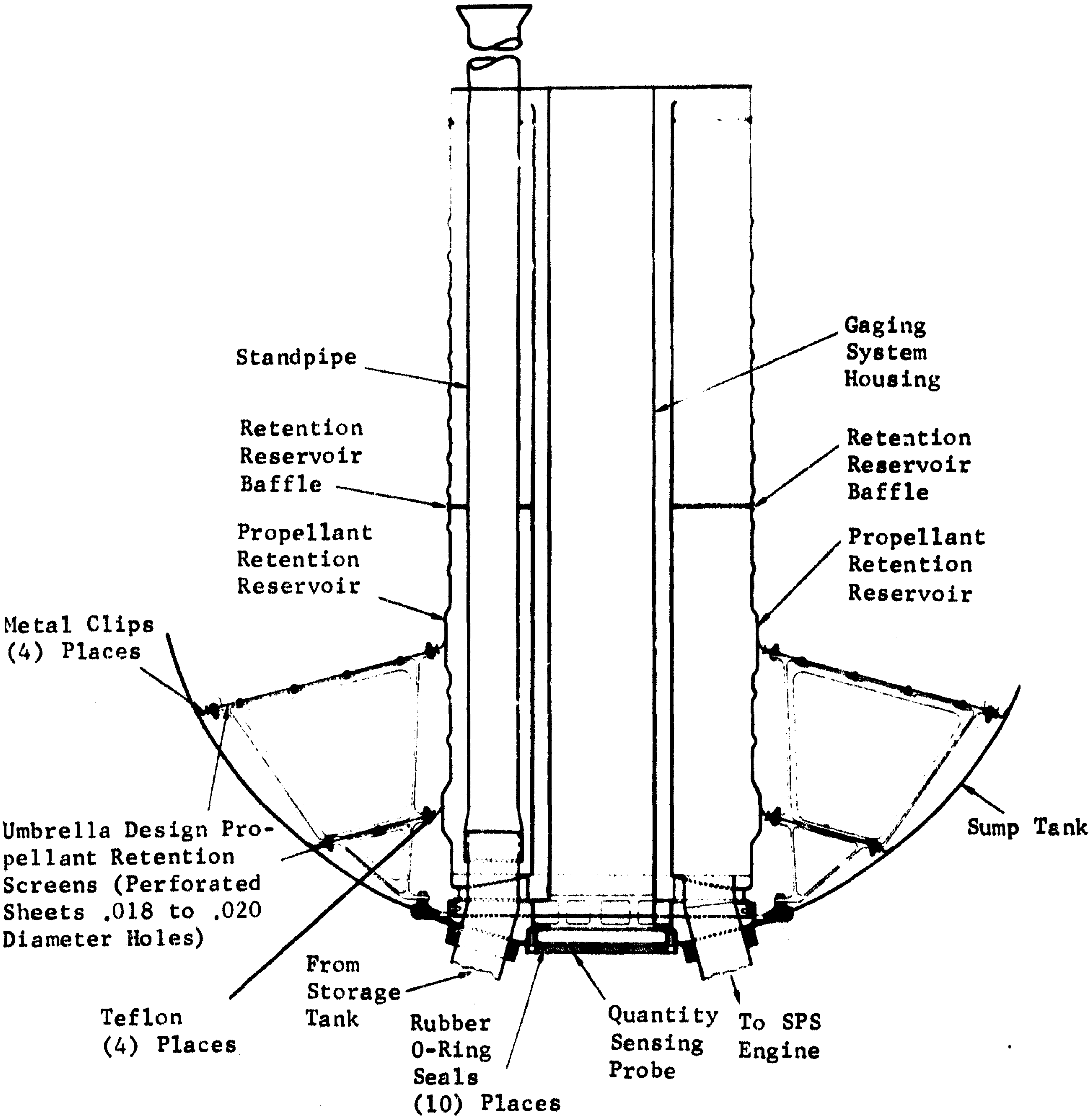


Fig. 13 SPS Apollo Propellant Retention Reservoir

A. DESIGN CONSIDERATIONS

In the application of capillary systems for propellant control, there are two distinct operational considerations: the case of liquid retention by surface tension forces directly; and the case of pressure forces providing the retention with surface tension forces acting to stabilize the gas (pressurant)-liquid interface. The former will be referred to as capillary retention and the latter pressure-supported capillary stability.

Figure 14 illustrates the configuration of pressure supported capillary stability in a partially filled tank with and without a porous barrier. The acceleration vector is parallel to the tank axis and acts in the direction to cause the propellant to tend to migrate to the opposite end of the tank. However, if the proper relationships of fluid properties and system geometry exist, the gas liquid interface will be stabilized by the surface tension forces and the liquid will remain at the top of the tank supported by the ullage pressure (in excess of the vapor pressure of the liquid) beneath the interface. Thus, the interface acts as a barrier in a manner similar to that of a movable piston to prevent gas penetration into the liquid and hence, liquid displacement to the other end.

The classical criteria for determining this hydrostatic stability regime is the bond number (Bo), which is a dimensionless ratio of body forces to capillary forces.

$$Bo = \frac{\rho a L^2}{\sigma} \qquad (1)$$

where

ρ = liquid density

a = acceleration normal to liquid-gas interface

L = system characteristic dimension (usually radius of the opening in which interface is located)

σ = liquid surface tension

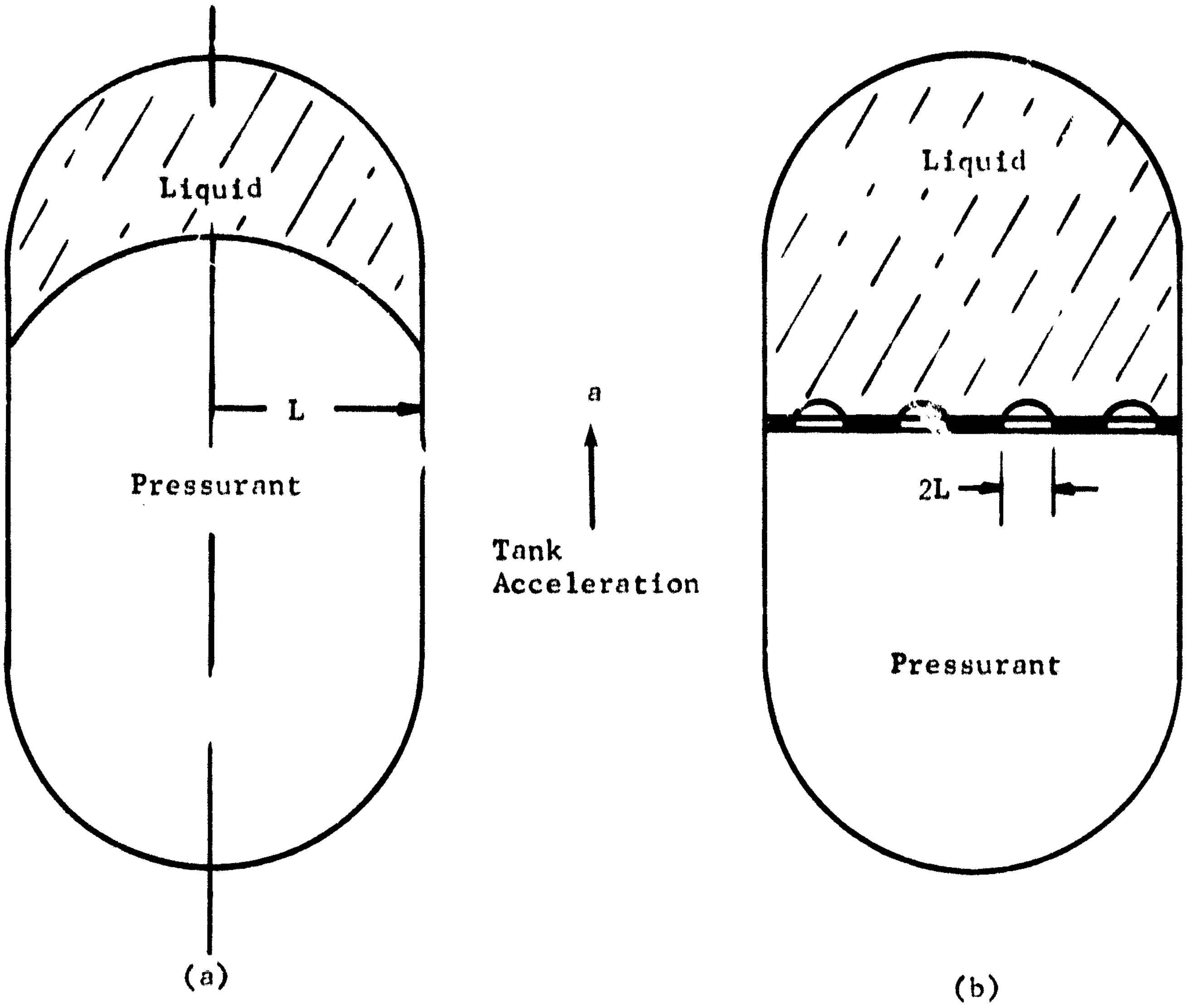


Fig. 14 Pressure Support Capillary Stability

This equation can be arranged to define the critical system dimension to maintain stability

$$L_{crit} = \left(\frac{Bo_{crit}\, \sigma}{\rho\, g} \right)^{\frac{1}{2}} \qquad (2)$$

It has been shown experimentally that for bond numbers below a critical value, the system is stable. The critical value is a function of the liquid to solid surface contact angle and the geometry of the pore. Several investigations have studied this interfacial stabilizing effect for tubes (Ref. 22), plates (Ref. 23) and screens (Ref. 24) in a one-g environment. More recently Martin Marietta, under Contract NAS8-20837, has investigated the hydrostatic stability characteristics of large pore sizes ($d > 0.02$ in.) under accelerations of 0.001 to 0.05g (Ref. 25).

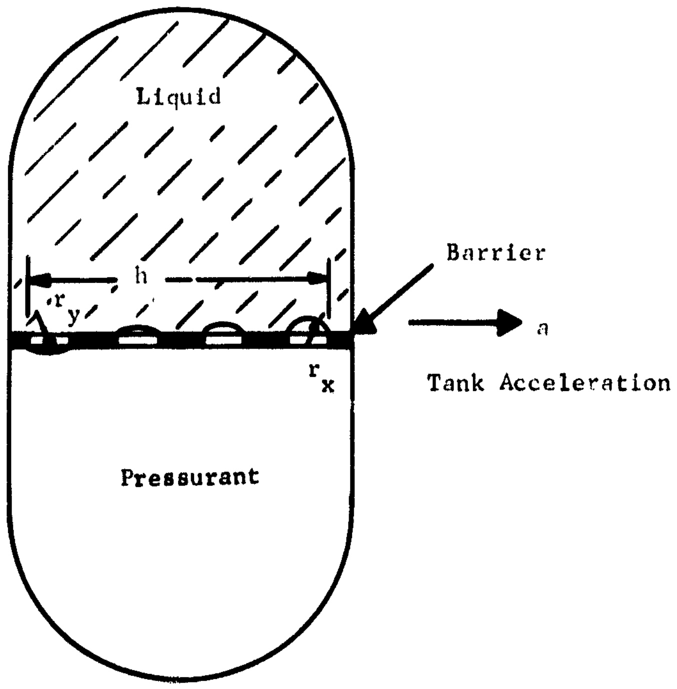


Fig. 15 Capillary Retention

Figure 15 illustrates the case of capillary retention. The acceleration vector is normal to the axis of symmetry of the interface. For the single interface partially filled tank, Masica et al. (Ref. 22) has shown that the interface stability limit as defined by the Bond number, where a is now the acceleration normal to the tank axis, is slightly greater than that for the earlier case. That is, the stability margin of an interface in a tank with a given acceleration vector is slightly greater when the tank is oriented with the acceleration vector normal rather than parallel to the tank axis. In general, the capillary support condition of interest is that associated with a porous surface as shown in Fig. 15. Here the hydrostatic head across the individual pore is small enough in relation to the total system so that it can be ignored.

The condition of interest is the maximum pressure difference across the interfaces at the holes. This can be expressed by the Young-Laplace equation -

$$\Delta P = \sigma \left(\frac{1}{r_1} + \frac{1}{r_2} \right) \qquad (3)$$

where r_1 and r_2 are the principal radii of curvature. The failure of the instability mode is characterized by the ullage entering the holes in the liquid low pressure region and liquid draining into the ullage from the high pressure location. Isolating and examining only the two extreme holes, Fig. 15 (the critical condition for a homogeneous system), the pressure difference for the upper hole (subscript x on Fig. 15) is equal to the ullage pressure minus the liquid pressure and for the lower hole (subscript y) is equal to the liquid pressure minus the ullage pressure. The total retention capability is then

$$\Delta P = \sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right)_x + \sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right)_y \qquad (4)$$

For totally wetting fluids, experimentation at Martin Marietta has shown that contribution of the lower hole to the total retention capability is small and should be assumed to be zero for capillary system design purposes, i.e., r_{1_y} and $r_{2_y} \rightarrow \infty$. Therefore, the capillary retention capability of the system reduces to

$$P = \sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right)_x = \rho a h \qquad (5)$$

where: ρ = liquid density

a = system acceleration

h = distance between holes

For a circular opening, the maximum retention (ΔP max) occurs when the interface is hemispherical ($r_1 = r_2 = r$). For all other interface positions, the radius of curvature is greater; therefore the pressure retention capability is less.

To utilize Equation (5) for design purposes requires consideration of other factors such as barrier surface geometry and condition, and contact angle. One approach is to modify the equation in the form

$$\Delta P_{max} = K'\sigma \qquad (6)$$

where the value of K' for different surface geometries, such as square weave or Dutch twill screen, is determined empirically by a technique known as a bubble point test. A plot of K' versus the absolute micron rating of Dutch twill cloth, as determined by a bubble point test, is presented in Fig. 10 of Ref. 26.

Another consideration in addition to hydrostatic stability is induced capillary flow, or what is often referred to as capillary wicking. Normally these forces are fairly small and do not provide a means for retention of fluid in the presence of upsetting body forces caused by attitude control maneuvers of spacecraft.

However, they may be useful for repositioning part of the propellant to a desired location during near zero acceleration periods following disturbing forces. Such a device could conceivably be used in conjunction with a capillary barrier where the capillary duct or wick would supply liquid to the barrier sump where it would be retained during adverse accelerations and made available for outflow at demand.

The capillary pressure capability of the duct should be less than that of the sump so that a pressure difference will exist to cause flow from the duct to the sump. The duct can be a closed tube or an open channel. The open channel is preferable since large bubbles are much more likely to block the action of a closed tube. If the open duct is made in the form of a V-shaped channel, entrained bubbles will be moved outward by capillary action to a point where the channel width is as large as the bubble diameter. Coalescence of bubbles will result in increased diameter bubbles which will be moved further out in the channel. By a continuation of this process, the duct may be largely cleared of entrained gas.

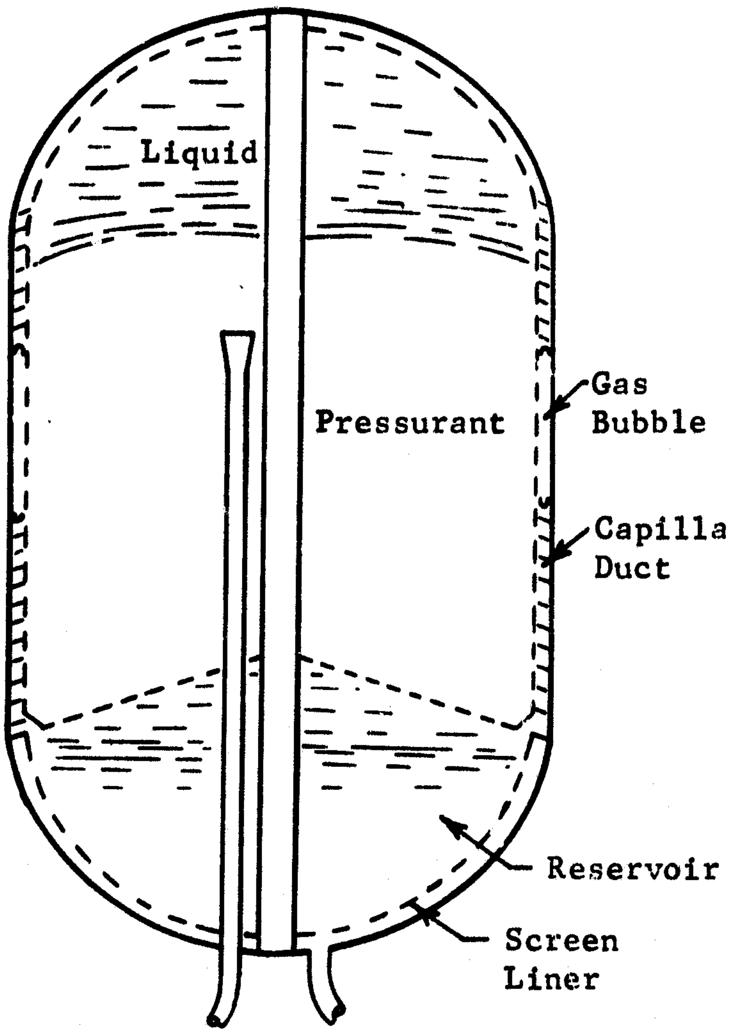


Fig. 16 Capillary Duct Pressurant Blockage

Of primary concern with closed channel capillary ducts is the fact that the porous surfact will be sealed off by liquid before the duct is filled, trapping a gas pocket in the duct and thereby destroying its liquid transfer capability or supplying gas to the outlet, as illustrated in Fig. 16. This sealing off of the porous surface could be caused by more rapid capillary wicking of the external surface than the channel fill rate, by propellant slosh or in some cases by propellant condensation on the channel surfaces. This particular problem would have to be considered in detail for each application.

B. EXPULSION DESIGN CONCEPTS

In developing capillary concepts for the propulsion system characteristics defined in Table I, the study started with what appeared to be the simplest configuration and progressed to increasingly complex concepts to gain performance advantages.

The system characteristics (Table I) of 50 restarts with durations as short as one second each, impose specific design requirements on the propellant management system. Because one second is not sufficient time to settle propellants that may have migrated away from the outlet and provide a reasonable refill time for a trap design, the restart system must have a propellant feed capacity to accomplish the starts without relying on bulk propellant resettle or refill. For purposes of this study, a square wave steady-state flowrate of fifty seconds (50 one-second pulses) was chosen as a minimum design requirement for the duty cycle, resulting in an adverse environment propellant feed requirement of approximately 22 ft^3 of both oxidizer and fuel, or slightly greater than 12% of the tank volume. Two approaches are possible to provide this capacity. One is to provide a flow path from the bulk propellant to the outlet, as by a capillary duct, regardless of the bulk propellant location; the other is to trap at the outlet the required propellant for the total mission. The capillary duct approach is quite constrained by the duty cycle and acceleration environment of the system. The negative acceleration value of 0.2 g with only five seconds of low-g (10^{-5}g) prior to restart, is such that an open capillary duct would not be practical. Even a closed channel of micronic porosity would not remain full of liquid over the entire tank length. With a barrier of 325 by 2300 woven wire cloth (the finest weave commercially available), the maximum supportable hydrostatic pressure at 0.2 g acceleration would be about 75 inches of nitrogen tetroxide. Since the total tank length is over 150 inches, this would represent approximately 50% of the tank volume that could be connected by a duct under the negative acceleration and static conditions, before gas would enter the duct and liquid would be drained away from the outlet.

Therefore, before a capillary duct could be considered for the oxidizer tank under present technology, the negative acceleration environment would have to be less than 0.1 g. This would represent an optimistic limit without any operational margin or allowances for dynamic flow losses.

For the fuel tank, the propellant properties (density and surface tension) are more favorable and a hydrostatic head of 136.5 inches of Aerozine-50 could be supported with a 325 by 2300 Dutch twill screen material. The maximum negative acceleration for further consideration of this type of design would therefore be about 0.17 g.

If we limit the negative acceleration environment to a value less than 0.1 g (0.05, for example), complete draining of propellant away from the outlet will not occur. The lateral acceleration of 0.009 g and the roll and pitch maneuvers would not present limitations. The limiting design criteria is the positive acceleration during thrusting. Although the propellant will tend to locate over the outlet to prevent gas ingestion by the engine, it is possible to drain the liquid out of the capillary channels that are exposed in the ullage area. Unless the channels can be designed to remain full of liquid or refill between thrust periods, this ingested gas could be transferred to the engine during subsequent thrust periods.

Based on the desired system characteristics, the duty cycle does not provide for any duct refill time between engine burns. Typical refill rates for closed capillary ducts are presented in Figs. 17 and 18 for a concentric liner and single tube with 10 in.^{2} of the flow area. The positive acceleration levels (see Fig. 2) are too high to permit a channel design that will remain full. Therefore, the design must allow for gas ingestion in the channels without gas feed to the engine. This can be accomplished by connecting the capillary duct to a reservoir (located over the outlet) that contains a capillary liner to prevent the gas from passing into the engine feed line. A concentric screen capillary duct and reservoir system is shown in Fig. 16.

Assuming no total loss of communication in the capillary duct (i.e., wetted walls), the sump must be large enough to trap the intermittent gas ingestion. However, the sump size is also constrained by the acceleration environment because the sump liner must provide gas-free expulsion capability to the engine.

A worst case for consideration is a duty cycle where most of the propellant is consumed in the first burn, with only enough left to complete 49 one-second pulses. With the liner duct concept shown in Fig. 16, the maximum gas volume that could be ingested during 49 burns is about 30 ft^3. This volume of gas would require a sump design larger than the propellant volume required for the 50 restarts (22 ft^3) and therefore would not be a reasonable approach.

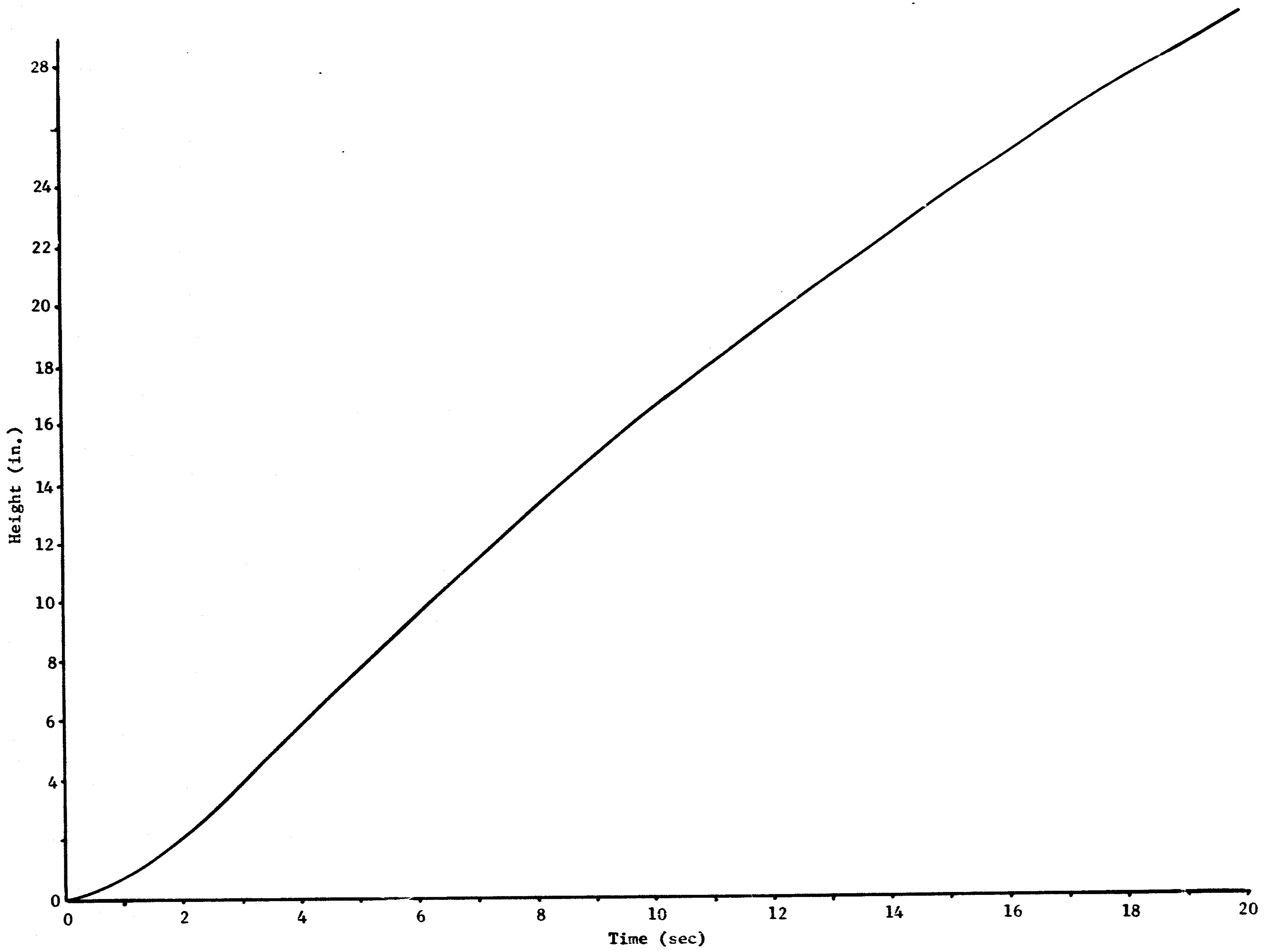


Fig. 17 Capillary Annulus Refill History

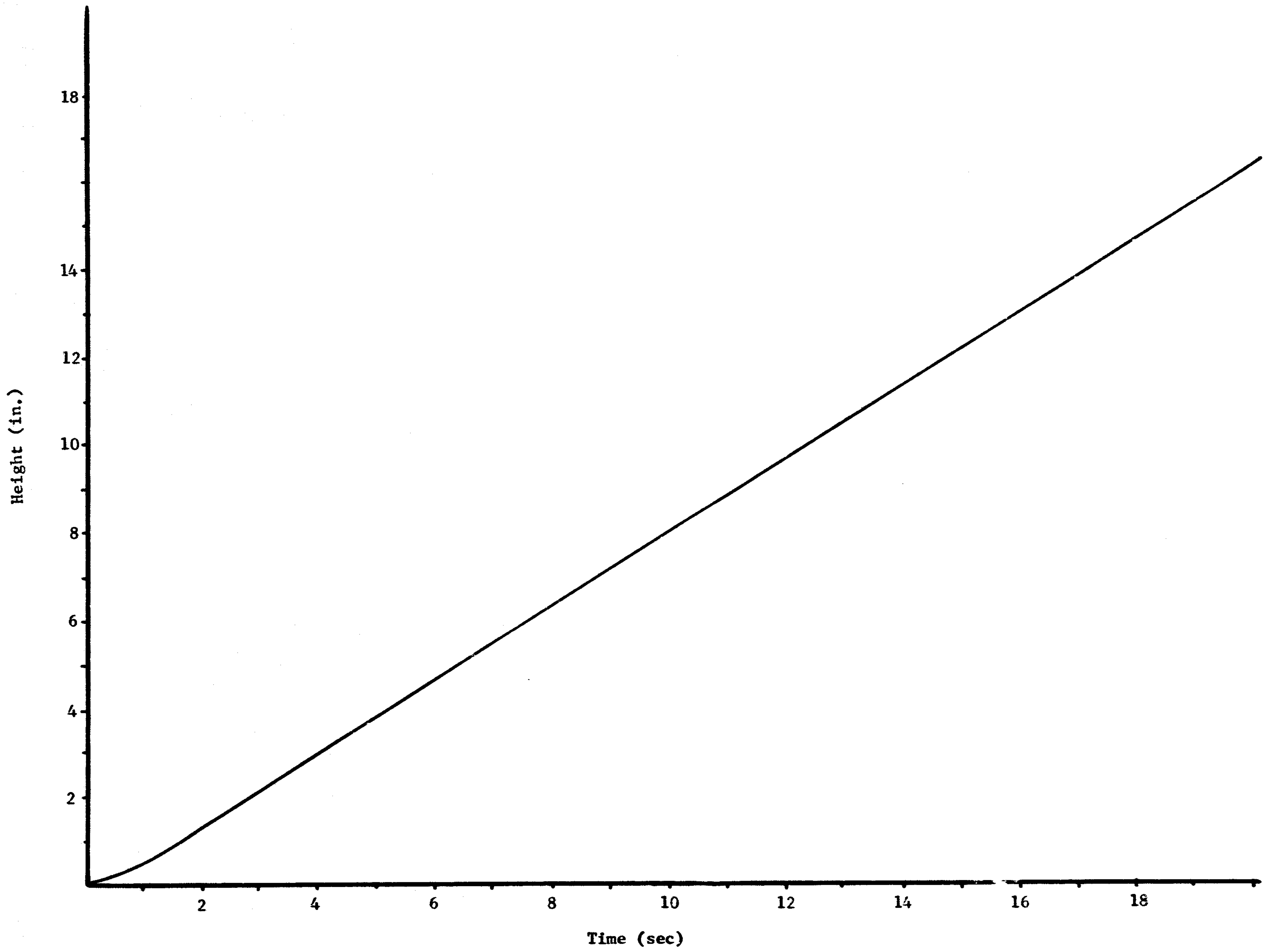


Fig. 18 Capillary Duct Refill History

An alternative technique is to trap a sufficient quantity of propellant at the outlet (about 22 ft^3) to provide the required restart capability. This design is shown in Fig. 19. The size of the lower compartment (1) is determined by the acceleration environment and porous material limitations of the compartment liner, with the upper compartment (2) sized to provide the remaining required propellant volume. For the axial acceleration in the nagative direction of 0.2 g, the finest Dutch twill cloth would provide a retention capability of approximately 78 inches of nitrogen tetroxide and 136.5 inches of 50% N_2O_4 - 50% UDMH (50-50). For the lateral acceleration of 0.009 g the retention capability is even greater, so these would not limit the liner geometry. In the propulsive period, the screen liner must prevent gas entry into the annulus during thrusting as shown in Fig. 19. The pressure drop across the screen during thrusting is equal to the hydrostatic head of the exposed liquid column (h) plus the viscous losses due to propellant flow through the screen liner and flow in the annulus to the outlet.

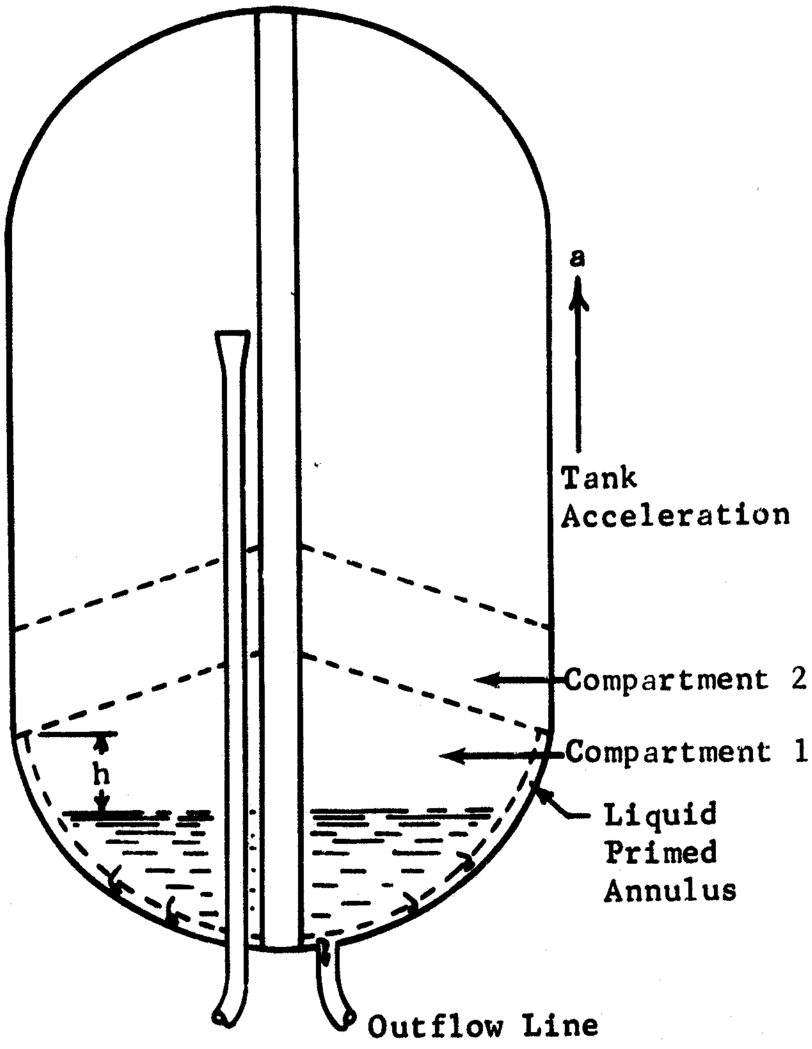


Fig. 19 Capillary Liner Propellant Trap

$$\Delta P_1 = \Delta P_H + \Delta P_{V_1} + \Delta P_{V_2} \qquad (7)$$

ΔP_H = hydrostatic head

ΔP_{V_1} = viscous losses for fluid transfer across screen

ΔP_{V_2} = viscous losses for fluid transfer in annulus

Preliminary sump sizing, based upon the use of 250 by 1375 mesh Dutch twill cloth, indicates an exposed screen liner height of 8.5 inches is reasonable to prevent gas ingestion during the terminal acceleration level of 0.9 g. This value was used to generate the capillary retention designs shown in Figs. 22 and 26. The cover screen is designed to be stable in acceleration environments up to 0.2 g, negative axial and 0.009 g lateral, unstable under 1.0 g (earth gravity) so gas will be purged out during ground fill; and provide a lateral wicking capability to prevent screen "dry out" during non-propulsive periods. Cover plate design considerations were investigated extensively under Contract NAS8-21259 (Ref. 25). The proposed design would involve a double layer for the cover plate consisting of a perforated plate and screen. Wicking would take place between the two layers and the perforated plate would act as a deflector of rebounding fluid to aid in establishing a liquid film over the cover plate at engine cutoff. Further test effort is required to establish the effectiveness of this type of barrier design relative to the acceleration environment.

Two approaches to the upper compartment design are considered. The simpler method provides a single conical barrier across the tank diameter. The pore size considerations are the same as discussed above for the lower compartment cover plate. During thrusting, liquid in this compartment in contact with the lower compartment would be preferentially expelled into the lower compartment. Any pressurant ingested by the lower compartment during the transient periods would be retained in the lower compartment until propellant depletion. For high expulsion efficienty, this design requires that all of the propellant be expelled to the lower compartment prior to propellant depletion in the lower compartment. The volume of the lower compartment will provide approximately 10 one-second pulses. Furthermore, the propellant shown in the shaded section of the upper compartment (Fig. 20) is considered a conservative estimate of the propellant drainage into the lower compartment without any resettling consideration. This represents an additional 10 one-second pulses. A plot of propellant free-fall distance versus time for the minimum acceleration during propulsion (0.34 g) is shown in Fig. 21.

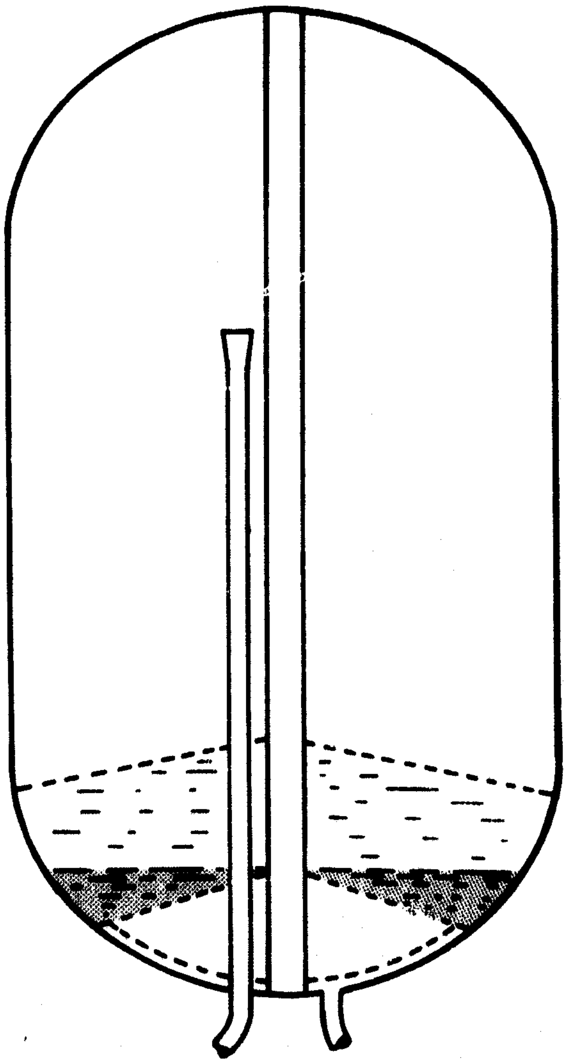


Fig. 20 Dual Compartment Propellant Reservoir

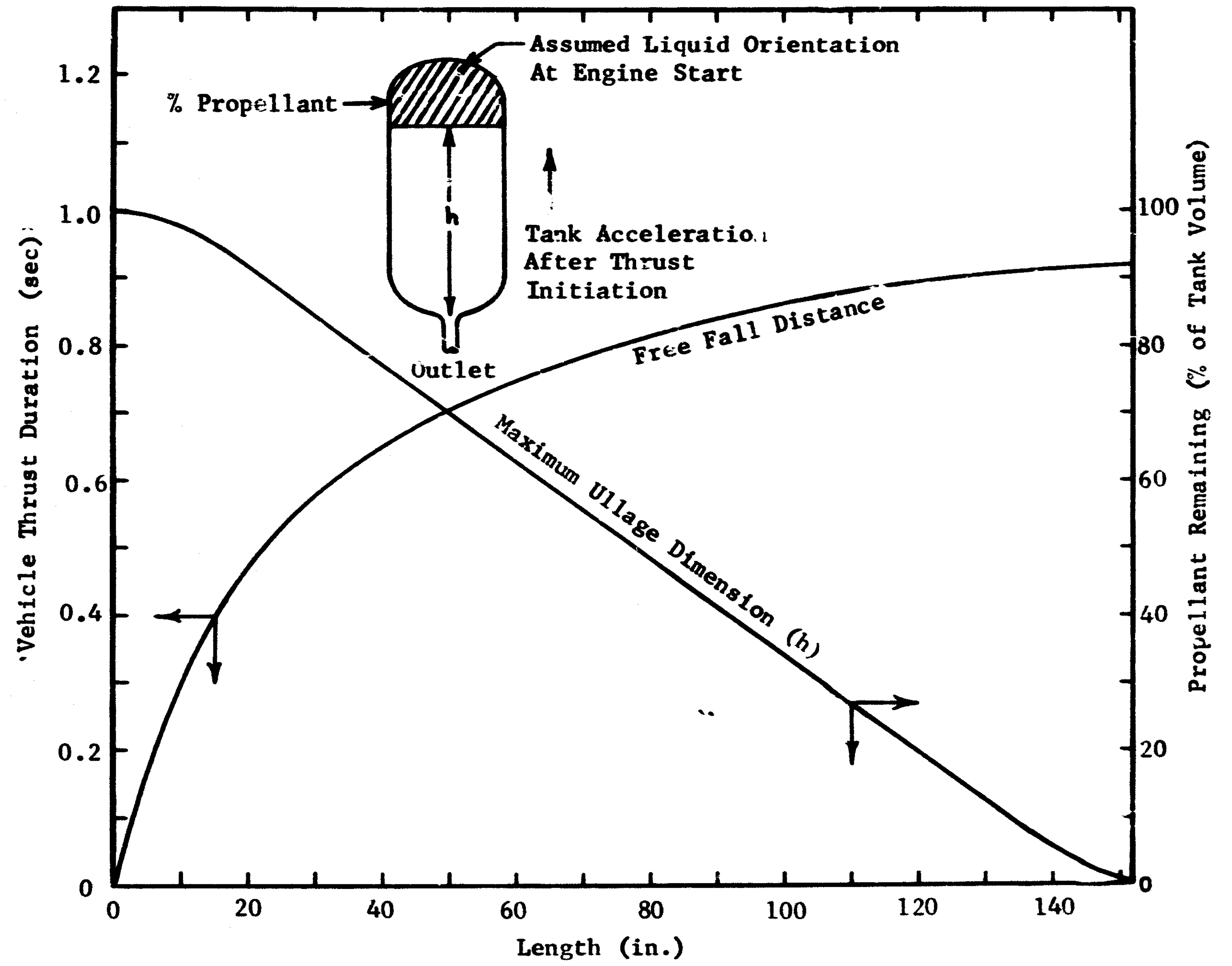


Fig. 21 Propellant Free-Fall Bottoming Time

The maximum distance that liquid would travel from the upper to the lower screen is only on the order of 13 inches. This indicates some liquid contact from the upper compartment with the lower screen during each pulse. Therefore, complete drainage of the upper compartment prior to depletion of the lower should not present a problem.

If an additional margin of safety is desired for complete drainage of the upper compartment, a liner similar to that employed in the lower compartment can be incorporated. This liner would expell propellant into the lower compartment. The design considerations for this liner are not as critical as for the lower compartment since some gas penetration through the liner **would be permissible. The primary consideration would be** to ensure wicking of the liner surface to maintain the flow path. Use of a Dutch twill weave material should ensure a barrier rewetting capability.

C. NO HARDWARE CHANGE CONFIGURATIONS

To comply with the no hardware change criteria as outlined earlier, the capillary system must be designed to be inserted through the manhole cover in the bottom of the tank. This appears to be feasible with the basic concept discussed above.

A resulting design is presented in Fig. 22 and 23. Slight modifications to this basic structure are possible to increase the design performance margin, or to simplify the installation procedure. The modifications are shown in Figs. 24 and 25. The first sketch indicates a modification to increase the exposed surface area of the screen liner which provides a greater propellant scavenging capability under omnidirectional acceleration environments. Figure 24 shows a design where the liner is limited to the diameter of the manhole cover. The advantage of this system is elimination of the requirement of maintaining a micronic sealing capability at the tank wall to trap cover plate joint. In addition, it reduces the assembly requirements within the tank during installation. The disadvantage of this system is that the liner-to-propellant contact area within the compartment is decreased considerably. The final configuration will depend on detailed analysis of the expected propellant interface locations as a function of residual propellant and acceleration environment at the time of engine restart.

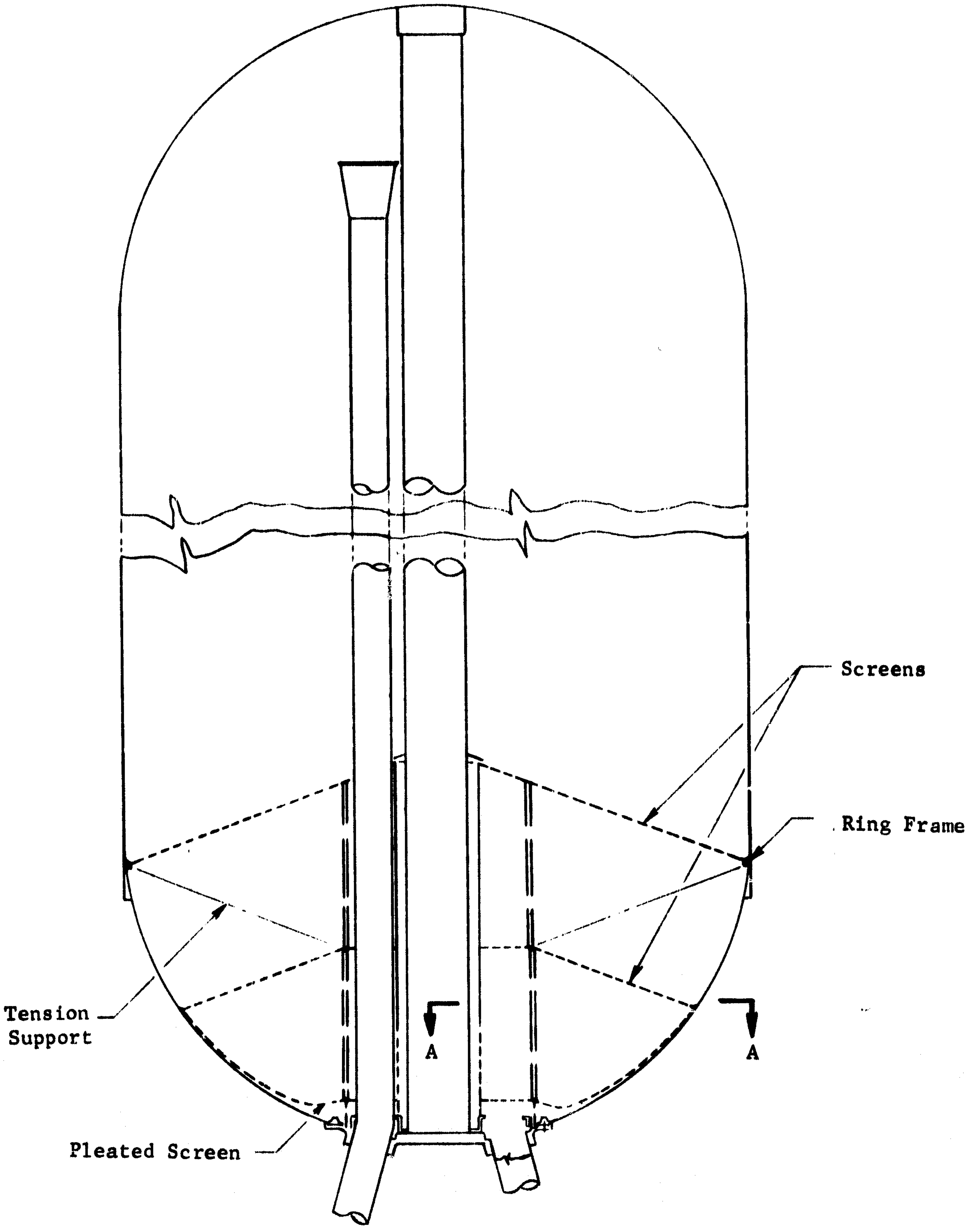
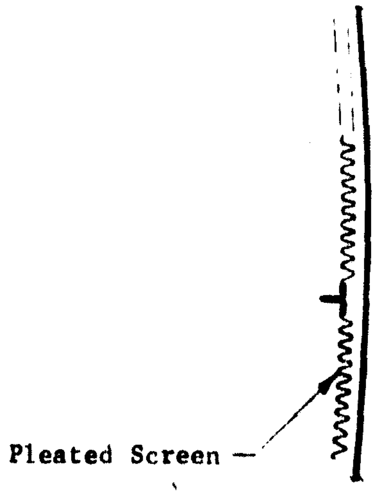
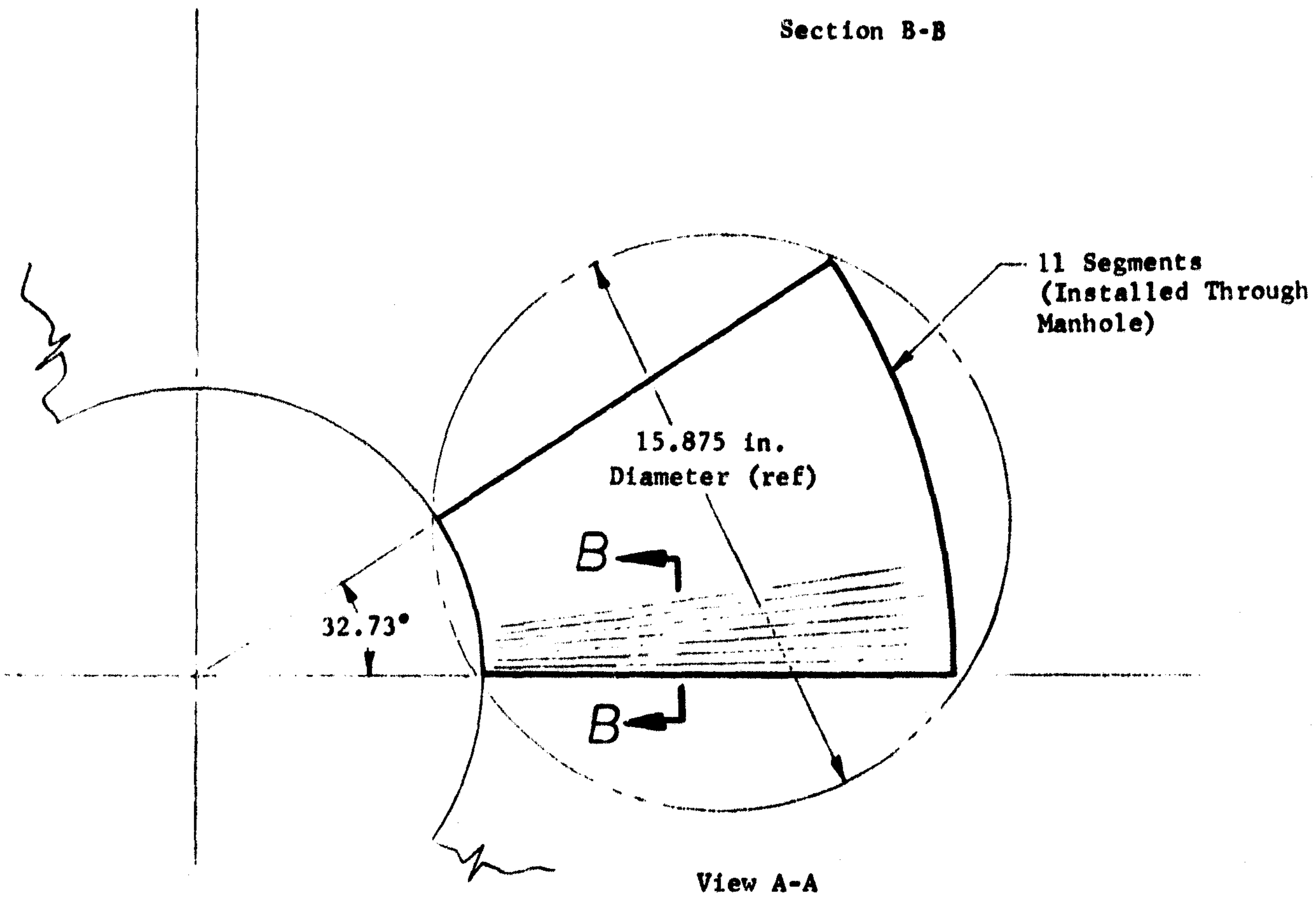


Fig. 22 Retrofit Capillary Design



Section B-B



View A-A

Fig. 23 Retrofit Capillary Design Details

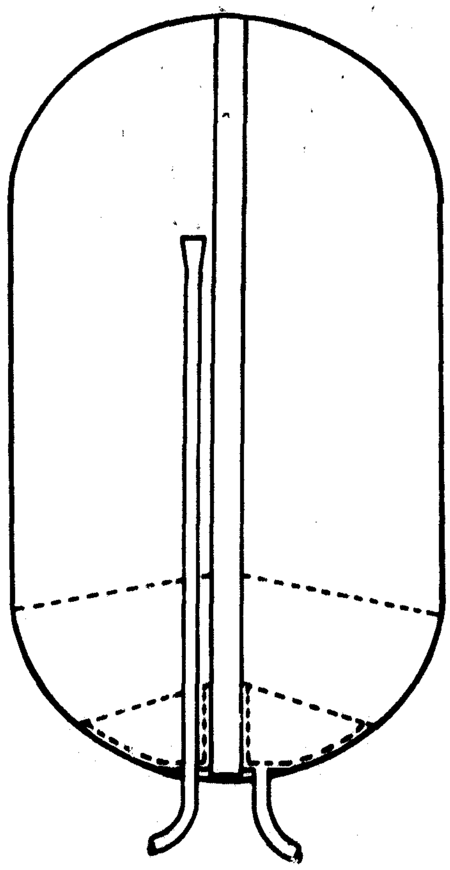


Fig. 24 Large Liner Area Reservoir

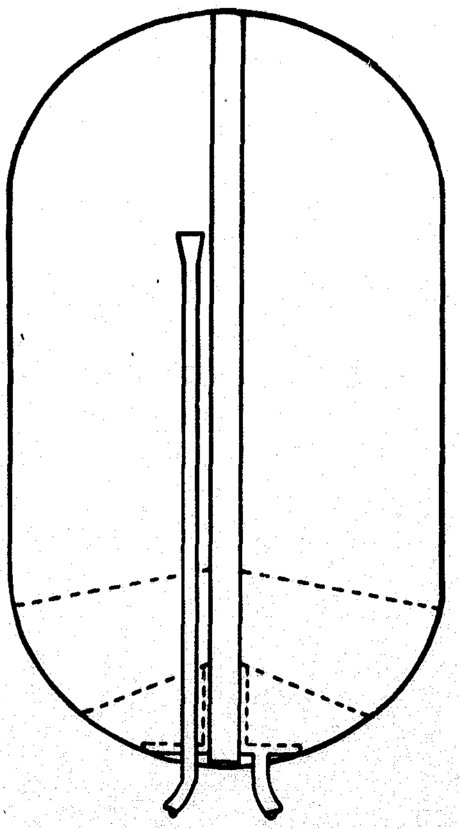


Fig. 25 Small Liner Area Reservoir

The design shown in Fig. 22 was selected for evaluation as a representative midpoint between the two modification possibilities incorporating all the technology required for fabrication of this type of expulsion system.

1. Adaptability

The capillary design shown in Fig. 22 is adaptable to the system characteristics outlined in Table I and Fig. 1. The system is designed to provide sufficient propellant at the tank outlet to accomplish up to 50 one-second engine burns under the most restrictive acceleration environment and propellant usage schedule. If engine restarts occur with bulk propellant in contact with the capillary traps, the restart capability will be increased because consumption will not deplete the trapped propellant volume. As the duration of the pulses is increased, the consumed propellant can reduce the restart capability of the trap arrangement. However, this is true only if the duration does not provide bulk propellant contact with the reservoir cover plate. As soon as liquid contacts the trap surface, the liquid rather than pressurant will preferentially pass through and provide the engine feed requirements.

A plot of the free-fall distance, as a function of thrusting time, is shown on Fig. 21 with the corresponding propellant remaining as a cross plot. Previous studies (Ref. 19) indicate the propellant will contact the surface after 1 to 2 free-fall periods with enough settling to provide substantial liquid feed capability after 3 to 4 free-fall periods. One free-fall period is defined as $t/(2\ell/a)^{1/2}$ with t defined as the free-fall time, ℓ as the free-fall distance, and a as the vehicle acceleration. Figure 26 is a plot of the restart capability of the containment system as a function of the duration of each pulse, assuming no propellant feed from the free propellant bulk. As indicated by the resettle plot, the free-fall time for the tank length above the trap of approximately 125 inches is less than 1.0 seconds, indicating that under worst case conditions some propellant feed will be supplied from the bulk propellant for all pulse duration greater than one second. Therefore, the limitations indicated by the plot are not meaningful but indicate a theoretical minimum. The system could also be designed to hold a larger volume to avoid this theoretical constraint.

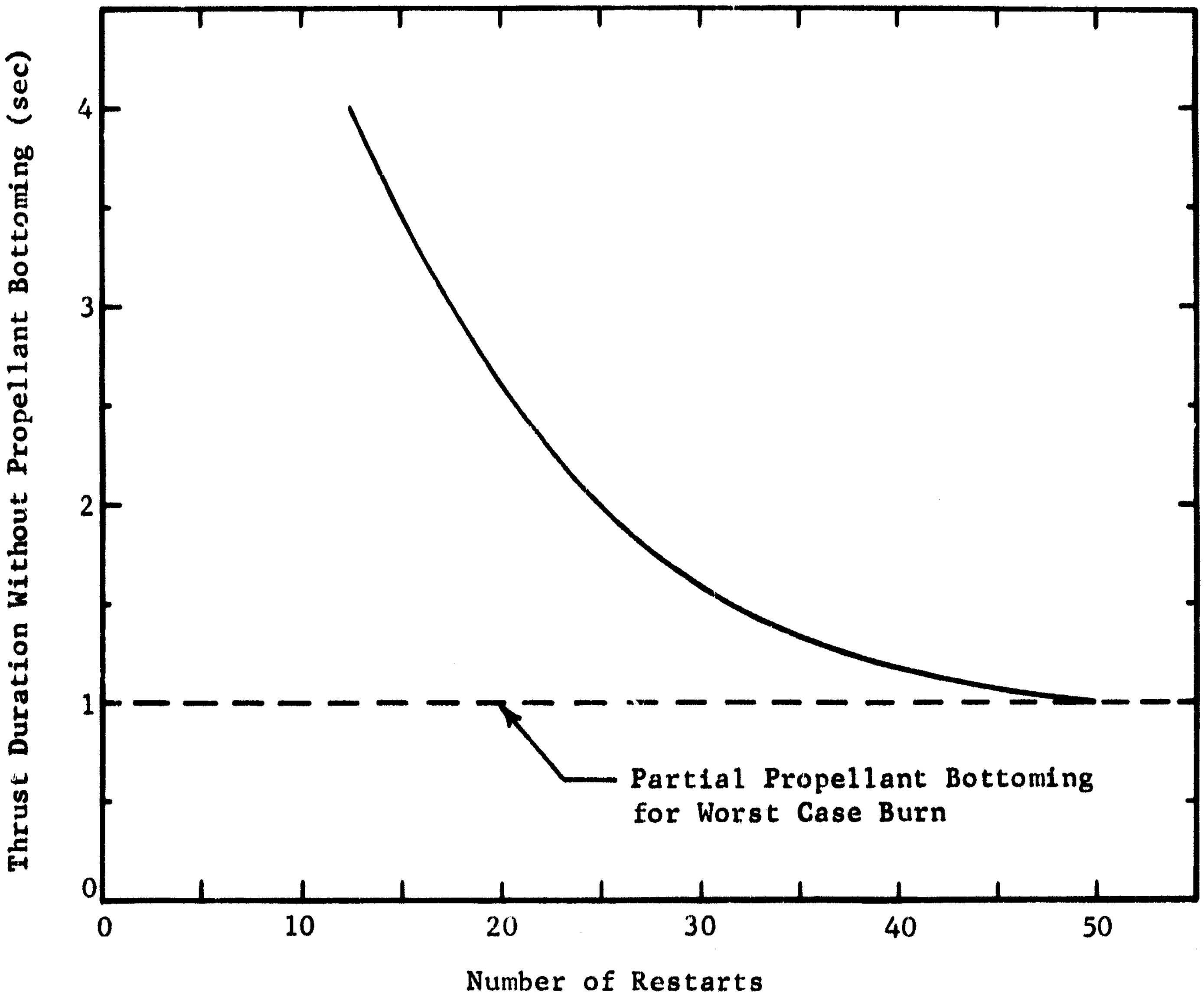


Fig. 26 Capillary System Restart Limitations

The screen system shown, with or without the modifications discussed, is capable of installation into the existing system under the ground rules defined for retrofit of existing tankage. The outer portion of the assembly would be inserted through the manhole and installed in place. The inner section is preassembled on the manhole cover plate and inserted into the tank to complete the installation. With the more simplified configuration, Fig. 25, the installation procedure is the same but less assembly work within the tank is required because the liner is entirely contained on the tank manhole cover plate.

To avoid interaction with the gaging system still well, the propellant reservoir is isolated by a concentric metal shroud. The shroud contains screen material in the lower portion to permit draining of propellant from the still well into the lower propellant compartment during terminal draining. A deflector has been included over the gaging still well shroud to prevent the liquid impact at resettle from forcing gas into the lower compartment. The use of fine mesh screen in the system dictates a material selection of stainless steel based on current weaving technology. The fine micronic cloth recommended for the lower compartment liner, effective pore diameter of 18 microns, is currently available only in 304, 321 and 316 stainless steel. Long term storability of stainless steel in N_2O_4 and amine fuels has been demonstrated for micronic filters (Ref. 27).

Selection of other woven materials such as aluminum or titanium would require extensive development in the weaving industry. At present these materials are not woven in meshes finer than a 75- to 100-micron effective pore diameter. This opening would not permit the design of a gas free scavenging liner as proposed. Other foramenous materials are available, as discussed in Ref. 28 in the 10- to 20-micron opening size. However, test data and experience with these materials for a capillary expulsion system are limited. One of the critical properties is the inherently high flow resistance (pressure drop) across the materials. Extensive development work would be required to appraise the value of these materials for capillary liner expulsion applications. The capillary concept shown is suitable for series tankage application. The inlet to the tank passes through the screen cover plates and discharges into the bulk propellant-ullage area. Therefore, either propellant or pressurant can be pumped into the tank without affecting the operation of the capillary orientation reservoir.

2. Reliability

The reliability of this design is extremely high. No moving parts are involved and the only failure modes would be structural deficiencies or degradation in the fine mesh screen pore size (i.e., retention capability). Multiple cycle capability ($\gg$10 complete expulsion and fill cycles) has been demonstrated without performance degradation (Ref. 29). A more quantitative evaluation of long term propellant storability of the Dutch twill screen is required, especially for the stainless steel in N_2O_4. Existing qualitative data for storage periods in excess of 7 years (Ref. 27) indicate that Dutch twill stainless steel screen does not visibly degrade in N_2O_4 or amine fuels.

3. State-of-the-Art

The technology involved in the design and application of capillary expulsion systems is currently within the state-of-the-art. Critical design parameters and scaling laws have been defined and verified through extensive testing in one-g, high-g (>1) and low-g (near zero) acceleration environments. As discussed earlier, systems have been qualified and flight tested.

The fabrication technology involved in the design presented is not greatly different from that currently employed on the Apollo SPS propellant management design with the exception of the Dutch twill woven wire liner. Considerable fabrication technology for fine mesh Dutch twill cloth has been developed in the filter industry. Martin Marietta has investigated various welding and bonding techniques under IR&D programs and has not encountered any difficulty.

Capillary screen systems of comparable complexity and of the same material as the concept pictured have been fabricated and tested (Refs. 20 and 29). While some development would be required to adapt the procedures to flight hardware, the risk involved would be low. Perhaps the area of most concern is quality control and inspection. Procedures must be developed to ensure against and detect degradation of the screen effective micron size during manufacturing and installation. While development of detailed cleaning procedures and techniques would be required, Martin Marietta and other companies have demonstrated the capability to clean the woven wire materials for storable propellant application with conventional cleaning procedures.

4. Weight

The weight of the capillary system shown in Fig. 22 is approximately 18.7 pounds. The system is constructed entirely of stainless steel with Teflon seals at the joining surfaces. Altering the screen liner as shown in Fig. 24 and 25 would result in less than 10% weight increase and about 15% weight decrease, respectively.

5. Development Time and Cost

Development time for a capillary system design of the type shown on Fig. 22 would be quite short for the fabrication technology does not exceed that which has been demonstrated. It is estimated that an operational system could be qualified in less than one year with a modest funding level. The area of highest risk in the design is the capability to obtain a seal around the periphery of the lower cover plate, where it contacts the tank dome, with an effective opening equivalent to or less than the micron rating of the screen (~15 microns). With the design modification indicated in Fig. 25, the sealing requirement at the cover plate periphery would be less severe. The development cost involved in qualifying a capillary system would be low. As discussed, the technology is within the state-of-the-art and the size of the system does not present any scaling problems.

6. Expulsion Efficiency

The system is designed to have an expulsion capability in excess of 99.5%. Under a terminal positive thrust period of greater than two seconds, the efficiency will approach 100%. These values do not include propellant lost due to vaporization in the ullage space. For the design shown, the screen liner flow area has been sized to remain primed under positive thrusting and steady-state flow with as little as 0.8 ft^3 of propellant remaining in the reservoir (99.5% expulsion efficiency). The volumetric efficiency of the tank with the propellant control device installed is in excess of 99.9%. The displacement of the capillary system is approximately 0.03 ft^3.

7. Passive Operation

The operation of the capillary system is completely passive. No propellant settling is required to initiate propulsion system restart. The system relies entirely on the physical properties of the propellants in contact with the metallic surfaces and gas pressurant to effect control. No rotating, sliding, or flexing parts are involved in its operation.

8. Propellant Slosh Control

No provisions have been incorporated for propellant slosh control or propellant free interface movement control other than the propellant that is trapped below the perforated barriers. The propellant within the compartments will be limited to movement within the confines of the compartments. Additional slosh control or bulk propellant movement control could be added by including more lateral barriers at various points in the tank. The technique for installation would be similar to that employed for the two lower perforated barriers. As demonstrated by Martin Marietta under Contract NAS8-21259 (Ref. 25) perforated barriers can be very effective for dumping propellant motion in low gravity applications.

9. Pressurant Gas Ingestion

The primary goal in the evolution of the design shown in Fig. 22 was to avoid pressurant gas ingestion at the tank outlet prior to propellant depletion. The screen liner is designed to prevent gas from penetrating into the outflow line during conditions of steady-state flow during thrusting and the non-propulsive acceleration environment. An analysis of gas bubble ingestion at the tank outlet during terminal draining was not performed. However, with the large manifolded outlet area (six 3-inch diameter holes around the existing still well) gas ingestion during draining should not present a major problem. The screen liner can be blocked off over the outlet region and additional baffles added to prevent premature vapor pull through. Detailed study and testing is required to determine a satisfactory design configuration.

Some gas ingestion could occur from dissolved helium in the propellants coming out of solution in the feed lines due to a shift in the solubility (e.g. from rapid thermal cycling or a pressure drop in the lines during outflow).

10. Adaptability to Varying Acceleration Gaging System

The capillary design presented has been configured to include use of the existing still well and gaging system. The gaging system has been isolated from the propellant reservoir by a shroud to prevent gas ingestion through the still well and liquid draining from the reservoir by the siphoning action of the still well. However, liquid communication is maintained by the screens around the base of the shroud.

The capillary trap concept is adaptable to various types of zero-g environment mass gaging systems. The more promising techniques that may have application are:

Radio frequency illumination;

Gamma ray attenuation;

Molimetric system;

Acoustic gas compliance.

All of these techniques would require further development and test to assess the implication of the capillary propellant control system on performance.

For the radio frequency system a mode-counting technique can be employed. If the propellant traps interfere with the total tank illumination capability, each compartment can be illuminated and measured separately. This does not impose a serious penalty since the same signal conditioning equipment can be used. However, a separate excitation probe and pickup would be required in each compartment.

In concept, the acoustic gas compliance technique should be adaptable to the capillary propellant management system. However, significant errors could develop in attempting to measure the geometry of restart propellant because of the difficulty of maintaining equivalent gas characteristics in the reference volume and propellant compartments.

The molimetric system should be adaptable to the capillary propellant control scheme with the same limitations as the acoustic system.

The gamma ray attenuation system could also be adaptable to a tank with capillary retention reservoirs. For the propellant above the compartments, the system would function reasonably well; however, the internal structure associated with the capillary propellant retention system would make it difficult to achieve a uniform intensity in the tank. This would probably result in considerable error in measurement of the trapped propellant.

D. NO HARDWARE LIMITATION CONFIGURATIONS

1. Adaptability

Removing the hardware constraints for the capillary system design does not alter the basic concept. The primary difference will be a one-piece design of the liner and cover plates rather than the segmented configuration required for retrofit of the existing tankage. A sketch of the resulting design without the gaging still well is shown in Fig. 27. The configuration shown would be installed during tank assembly. The tank domes would be designed with mounting rings to facilitate installation and sealing of the compartment cover plates.

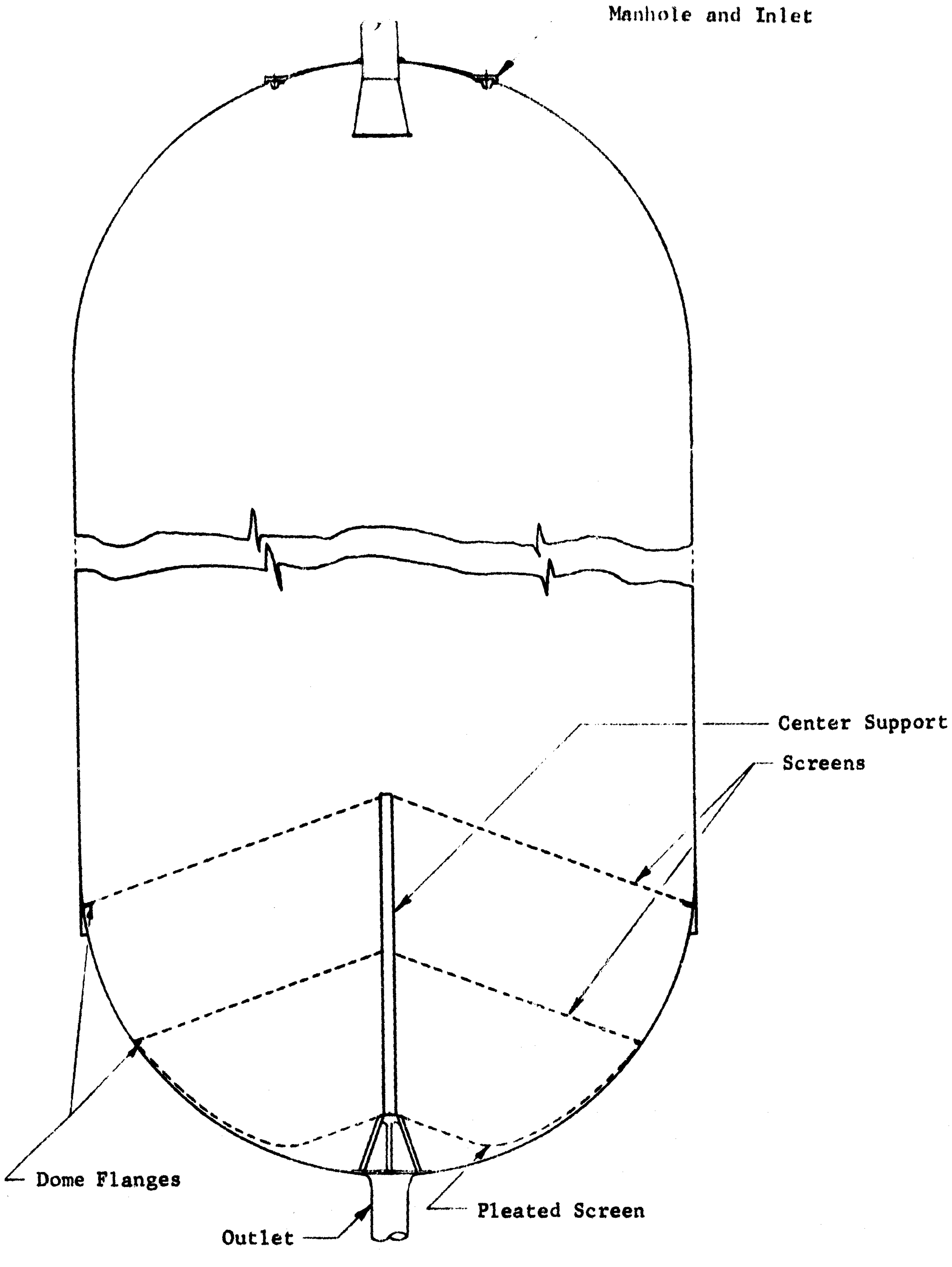


Fig. 27 No Hardware Limitation Capillary Design

The pressurization port would be located at the top of the tank for the configuration shown. A tank entry point, if required for internal tooling for the final tank closure weld, would be in the upper dome. If use of the existing still well were desired, a cavity would be included in the center of the device similar to the earlier design (Fig. 22). In a similar manner, the pressurization and propellant feed line entry could be retained by merely passing the pipe through the barriers and sealing around the penetrations.

The design considerations and functional performance are the same as in the no hardware modification design.

2. Weight

The weight of the capillary system (Fig. 27) is approximately 10.7 pounds.

3. Development Time and Cost

The development time and cost would be minimal, as discussed previously. This system would probably require slightly less development than the retrofit configuration because of the less difficult sealing problem around the periphery of the lower compartment cover plate.

4. Expulsion Efficiency

The expulsion efficiency of the capillary control device is in excess of 99.5% excluding vaporized propellant, with a volumetric efficiency >99.9%.

E. SYSTEM DESIGN GOAL COMPLIANCE

The capillary propellant management system meets all of the Priority I design goals (Table I). The Priority II design goals not achieved are the tank modifications to the system on Fig. 1 as described above and the engine restart-duration constraints presented in Fig. 26.

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V. PISTONS

Piston expulsion has been demonstrated on the X1B airplane, the Corporal missile (6.25-inch diameter), the Sergeant missile development program (6.75-inch diameter), and on a tactical missile system in the 18-inch diameter class. There is no record of a piston tank program approaching the 51-inch diameter of the subject tanks.

Development of a piston expulsion system for such large diameter tanks is not considered to be within the state-of-the-art for the following reasons:

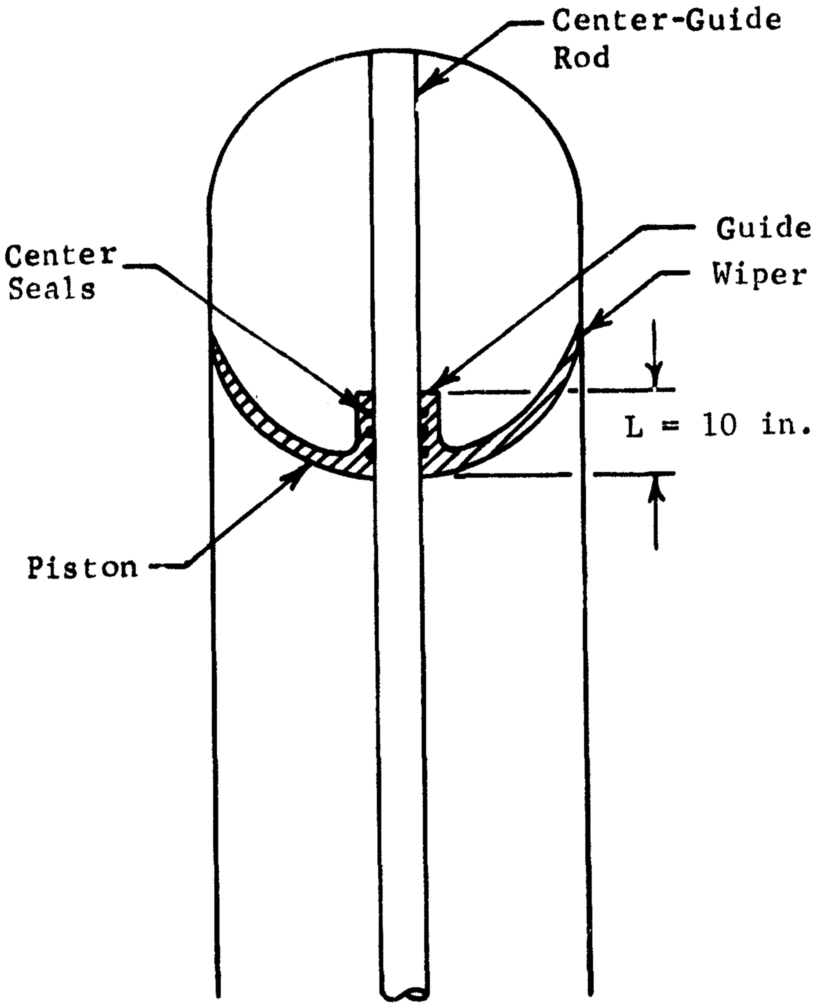
1) Uniformity of tank diameter within close tolerance to ensure proper fit and smooth travel of the piston is difficult to attain;
2) Piston seal materials, particularly in the oxidizer tank, require extensive development work;
3) Adequate stiffness of existing tank walls to maintain required dimensional tolerances under hydrostatic pressure loads is doubtful. Beefing up the tank walls is costly in terms of considerable weight increase.

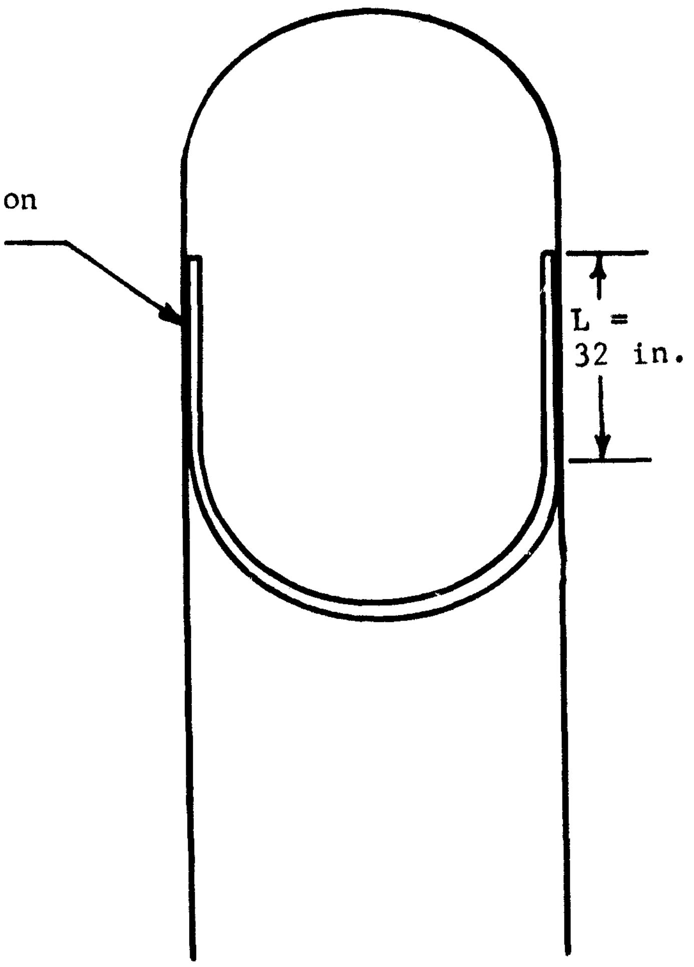
A. PISTON CONFIGURATIONS

Two basic approaches to piston design are possible: center-guided (Fig. 28) and peripheral-guided (Fig. 29).

The advantage of the center-guided piston is that it allows a minimum weight piston. The guidance to control piston movement is provided close to the tank center line where jamming and cocking moments are minimum. This results in a shorter guide section. Disadvantages of the center-guide piston are requirement for (1) sealing both at the tank wall and at the center guide, and (2) installation and weight penalty of a center-guide rod.

The advantage of the peripheral-guided piston is that it requires sealing only at the tank wall. The disadvantages of this piston are requirement for (1) a relatively long guide section at the tank wall where jamming and cocking moments are maximum; and (2) the long guide section length detracts from the volume of usable propellant which may be contained in a given size tank.





L = Length of Guide Section

Fig. 28 Center-Guided Piston

Fig. 29 Peripheral-Guided Piston

Reference 30 recommends a length in contact with the cylinder wall of at least 5/8 of the diameter. For the size of tank under consideration, this amounts to a guide section length of at least 32 inches and a loss of usable propellant volume of at least 38 ft^3 because of the void volume behind the piston. For this reason, the center-guided piston is preferred.

B. PISTON SEALS

A successful piston design necessitates a good static and dynamic sealing capability between the pressurant and propellant. For the diameter under consideration (51-inches) dynamic sealing capability and seal wear are unknown quantities. The problem is particularily acute because multiple piston reversals are a design goal. Considerable development and testing would probably be required to establish a high confidence in seal performance.

1. Wiper Seal Configurations

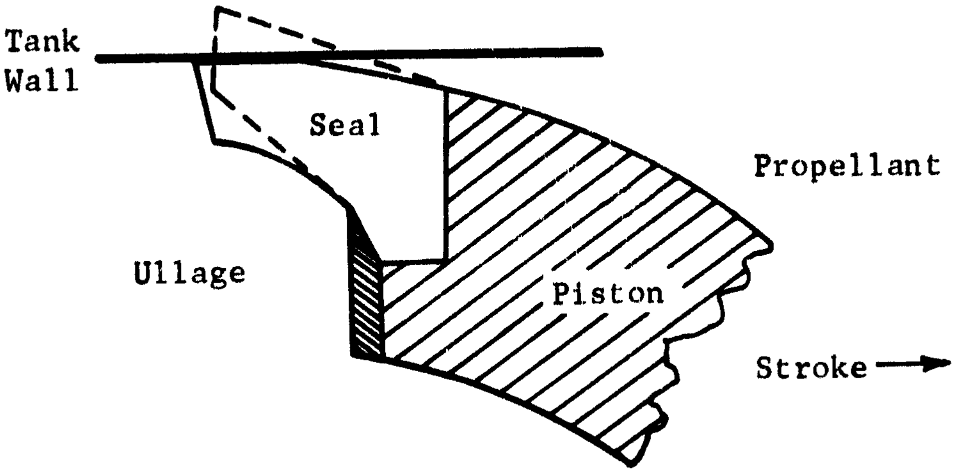
A wiper used as the dynamic seal has the tendency to be pushed against the tank wall by the pressure differential across the seal and by built-in spring force. Seal movement to a greater tank diameter is at the expense of contact pressure while movement to a smaller diameter increases the contact pressure. If diametric tolerances on the tank wall are not too great, a wiper seal will respond to diameter changes at the expense of variable friction.

Possible configurations of the wiper seal are shown in Fig. 30. Both seals depend upon force fit and pressure differential to maintain wall contact. The contact angle of the first seal may interfere with reverse motion of the piston during tank refill or cause excessive seal wear during this operation. The V-seal in b of Fig. 30 provides a double seal and should allow piston motion in either direction.

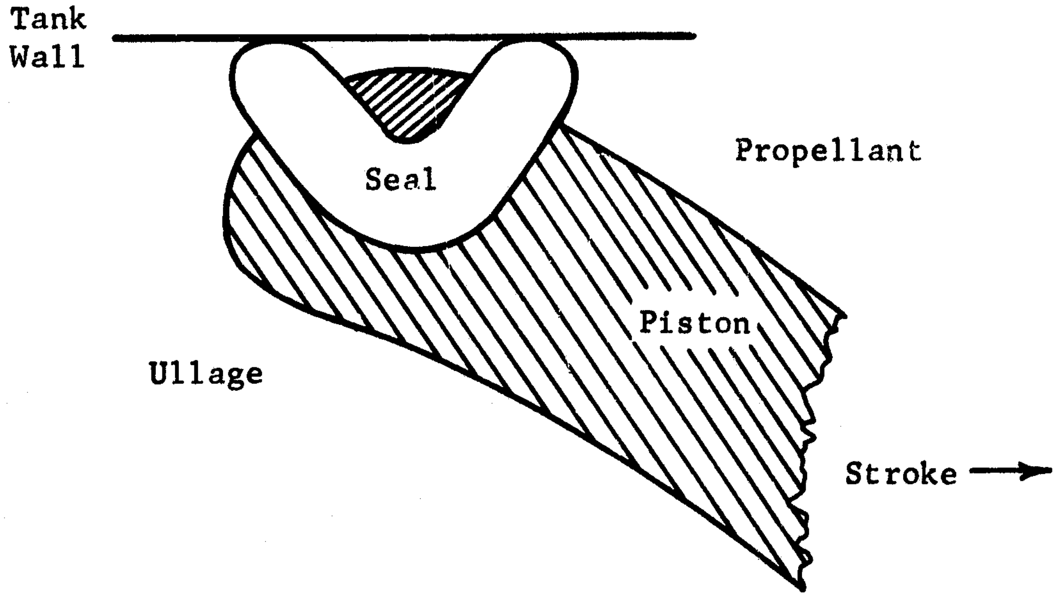
2. O-Ring Seals

O-ring seals can perform the function of both static and dynamic seals. If O-rings are used to seal between the piston periphery and the tank wall, the center-guided piston of Fig. 28 should be modified to incorporate a short skirt to provide grooves for O-ring installation. This results in additional piston weight and about 2 to 3 ft^3 additional loss of usable propellant. O-rings inserted in grooves in the center section are also required to seal against the center-guide rod.

Dimensionally, O-rings will not be as great a problem in the center-guide section as around the piston skirt because the center guide is of smaller diameter and much closer diameter tolerances can be specified. The O-ring width around the piston skirt must be great enough so that the greatest tank diameter variation over



A.



B.

Fig. 30 Dynamic Wiper Seal Designs

the piston stroke keeps the O-ring compressed against the wall. The possible diametric variations, even after tank rework or redesign, may require an extremely wide O-ring with excessive compression on the minimum diameter tolerance. Resiliency of the seal material to respond to small changes in tank wall diameter is necessary to avoid seal leakage when the tank diameter is increasing with piston travel.

3. Fuel Tank Seal Materials

Possible seal materials compatible with Aerozine-50 fuel are Teflons, butyl rubbers and ethylene propylene rubbers (EPR). For dynamic seal application, the seal must comply with small variations in tank diameter. Teflon is slow to adapt to dimensional change; therefore, for this application, the butyl and ethylene propylene rubbers are considered superior to the Teflons.

Reference 31 reports test results showing no change in physical properties of a butyl rubber and an EPR formulation after complete and continuous immersion in Aerozine-50 for 30 days at 160°F. Either of these materials is considered satisfactory for fuel tank seal application.

4. Oxidizer Tank Seal Materials

Reference 31 lists the dynamic test results of promising materials for N_2O_4 compatability. Candidates selected from this list showing only slight wear over 5000 to 10,000 cycles on a dynamic O-ring tester with N_2O_4 propellant are:

a) Polyethylene-based polymer;

b) Butyl-based polymer;

c) EPR-based polymer.

The latter two candidates exhibited about one-half the volume change of the polyethylene-based polymer, but the polyethylene base showed no signs of wear and no gas or liquid leakage over 10,000 cycles. The butyl and EPR-based polymers showed some wear and some gas leakage.

A more recent material development showing excellent N_2O_4 resistance is carboxy-nitroso rubber (CNR) (Reference 32). Further evaluation of this material is required to assess its applicability. At this point in time, the polyethylene-based polymer would be the recommended seal material.

C. NO HARDWARE CHANGE CONFIGURATIONS

It is impossible to adapt the present tankage to a piston propellant control system without complete rework of the tanks.

First, the piston must be installed through a tank opening as large as the tank diameter, necessitating the removal of at least one dome. Secondly, it is possible that the skin gage on the existing tanks is not stiff enough to provide the necessary close tolerance fit with a piston. Thirdly, the inside diameter of the tank barrel must be reworked to a very close tolerance in alignment with the tank centerline. The interior walls require a machine surface finish. These operations preclude adaptation to piston expulsion without complete tank redesign or overhaul.

D. NO HARDWARE LIMITATION CONFIGURATIONS

1. Adaptability

An extensive amount of tank rework or redesign is necessary to adapt the tanks to the piston system. Most of this work requires detailed analysis not presently available to determine the practicality of such a scheme.

Some of the major items affecting adaptability of piston propellant control to the existing tankage envelope are discussed in the following paragraphs.

Rework of Existing Tanks. To adapt the existing tanks for piston installation, data on diametric tolerances versus cylindrical tank length, as well as the expected deviation of these tolerances under loaded tank and flight load conditions must be known. These data are necessary to determine whether piston seals with sufficient flexibility may be designed to contact the wall during full piston travel. Tank-to-tank variations in these dimensions are important to determine whether each piston design is a custom fitting for one particular tank.

When these dimensions are known, and if they indicate a "sloppy" fit during piston travel, a decision must be made whether reworking the tank interior cylindrical surface will improve the diametric tolerances to provide a satisfactory fit without destroying the integrity of the tank wall (if it has any integrity for piston application).

A seamless cylindrical section is preferred; if the cylinder is seam welded, the seam in the interior of the tank must be ground smooth and maintain the circular arc. Interior surface finish of the tank wall is critical for proper sealing against helium ullage gas. With a Teflon seal and helium, an interior wall finish in the range of 8 to 12 **rms** micro-inches of surface roughness is necessary (Ref. 33). Such a highly polished finish requires a lapping operation on the interior cylindrical wall. Wall finish requirements with other seal materials is not known. Compilation of the diameter measurements and the possibility of refinishing the tank wall requires the removal of both end domes.

If a center-guided piston design is selected, each dome must have a boss accurately positioned in the center of the dome to hold the end of the center-guide rod.

Tank Redesign. Even if dimensional tolerances on the existing tanks are such that cylinder rework is not required, the cylindrical wall skin thickness (0.054 inches) for a 51-inch diameter tank may not be stiff enough to maintain a predictable diameter under loaded conditions. In this case, a thicker walled cylindrical section must be fabricated. Without detailed analysis of the design, a proper wall thickness assessment cannot be made. The fabricating process must specify uniformity of diameter with cylindrical length, exact linearity of the tank center line, and the acceptable deviation from these quantities to reflect small changes in tank shape under flight load.

If tank redesign is a serious consideration, variation of the dome shape (and consequently the piston shape) can materially influence the usable propellant volume within the envelope.

To provide the maximum propellant volume within the envelope restrictions and to provide the maximum piston stroke, the first inclination is to invert the tank upper dome as illustrated in Configuration B of Fig. 31. The inverted dome, however, is subjected to a buckling stress which requires an upper dome thickness approximately five times the comparable lower dome thickness, or a complex dome support structure design. Therefore, a weight savings is realized by the Configuration A (Fig. 31), a tank shape that is a modification of the existing tank domes from hemispheres to oblate spheroids with a lengthened cylindrical section.

To obtain the same usable propellant volume as in the existing tanks (161.5 ft^3), modification of the present hemispherical end domes (total height of 51 inches) to 3:1 oblate spheroids (eccentricity = 1/3) represents a savings of 34 inches in height which may be transferred to the cylindrical section.

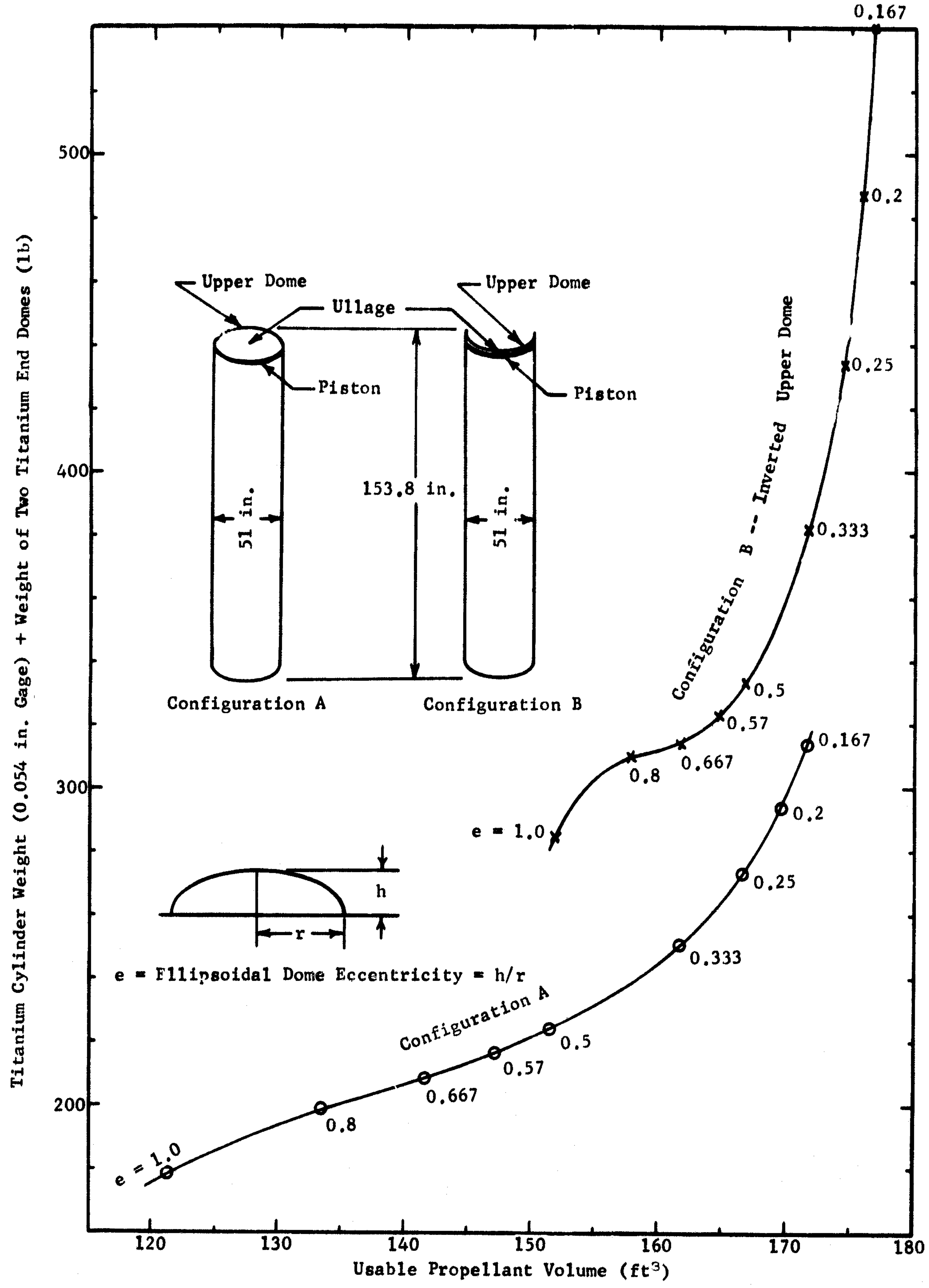


Fig. 31 Upper Dome Configuration Weight and Volume Tradeoff

Gage of the 3:1 oblate spheroid domes must be increased to 0.084 inch with combined weight of both titanium domes reflecting an increase of 25 pounds over the existing dome weights. Weight increase of the lengthened cylindrical section (if 0.054-inch gage is retained) is 47 pounds.

2. Weight

Assuming all-titanium construction, a weight estimate was made for the piston design shown in Fig. 28. Rough sizing of the piston center-guide collar for the subject tanks was accomplished by ratioing to existing systems (Ref 14). Combined weight of the reinforced titanium piston head and collar section was calculated to be 44 pounds. For the titanium center-guide rod, the required moment of inertia of the rod cross-section allows a tradeoff between guide rod O.D. and wall thickness which favors a large diameter thin-walled cylinder for minimum weight. A 6.6-inch O.D. titanium cylinder with wall thickness of 0.1 inch and length equal to tank length at the centerline (153.8 in.) was chosen. Weight of this center-guide rod is 50 pounds; it displaces 2 ft^3 from the usable propellant volume. A weight summary for this system is tabulated including the increased tank weight for an elliptically domed tank to obtain 161 ft^3 of usable volume in the same diameter and length of the Apollo tank (Fig. 1).

	lb
Reinforced piston and guide section	44
Center-guide rod	50
Total piston weight	94
Tank dome and cylinder weight increase	72
Total weight increase	166

3. Reliability

Piston reliability is dependent upon ability to seal a large diameter with variable tolerances tight enough to prevent leakage but not so tight to cause seal failure. Although not enough is known to attach a number to this probability, the reliability of an article of this size is considered quite low.

4. Development Time and Cost

The requirement for fine diametric tolerances and interior finishes, the possibility of customizing each piston to the tank, and the seal development effort all point to long development time and high cost.

5. Expulsion Efficiency

If the piston seals do not leak or fail, the expulsion efficiency of the piston system should be >99.5%.

6. Passive Operation

Inasmuch as the piston separates the ullage from the propellant, the propellant is always settled against the tank outlet under positive or negative g. No auxiliary propulsion settling is required with the piston system.

7. Propellant Slosh Control

Because the piston forms a rigid barrier between the liquid propellant and the gaseous ullage, the propellant is confined and will not slosh.

8. Pressurant Gas Ingestion

Gas ingestion into the propellant is a function of the seal gas leakage rate. The design goal is a zero leakage seal. Whether this may be realized in practice is questionable.

9. Gaging System

Inasmuch as all the propellant is trapped below the piston, the simplest gaging technique, independent of acceleration level, is a piston displacement measuring device. The molimetric and acoustic gas compliance techniques should also be adaptable for this application.

VI. BELLOWS

A propellant control technique that provides a nonpermeable membrane between the pressurant and propellant and yet has a multiple recycle capability is a metallic bellows. Bellows first received wide use in the aerospace industry for items such as dynamic seals, flexible joints and accumulators (Ref. 34). Application to propellant control has been limited to small diameters (less than 1 ft). Systems that have used bellows for expulsion include the Model 8250 Agena-Gemini Target Vehicle, and Model 8247 Agena Multiple Restart Engine. Bellows were also designed and tested for an ultra-low pressure rocket restart system (Ref. 35). Advances in material forming and welding techniques in recent years and increased interest in a metallic multiple cycle expulsion system for the cryogenic application have resulted in renewed interest in bellows systems. Two recent test programs to demonstrate the feasibility of bellows expulsion and provide experimentally verified design criteria are presented in Ref. 36 and 37. Although detailed design of a bellows of the size required for this application (51-inch diameter) has not been attempted to date, extensive development of bellows technology in the area of fabrication and analytical description of functional characteristics indicates that this diameter does not preclude the use of bellows; but further development work would be required. Designs as large as 30 inches in diameter have been considered and do not appear to present major technical problems (Ref. 38).

Although bellows are particularily suited for cylindrical tankage, the design must include both the tank and bellows in combination to obtain reasonable volumetric packaging efficiency. Reversing the upper tank dome or using elliptical domes, as shown in Fig. 32 and 33, improves the volumetric utilization capability but results in increased tank weight.

The bellows can be designed to operate with the propellant on the inside and pressurant on the outside with expulsion achieved by collapsing the bellows, or by reversing the two and expelling the propellant by expansion of the bellows. The former method is recommended for this application because it permits complete expulsion capability without the danger of deforming the bellows convolutions, and thus, at propellant depletion, degrading the recycle capability.

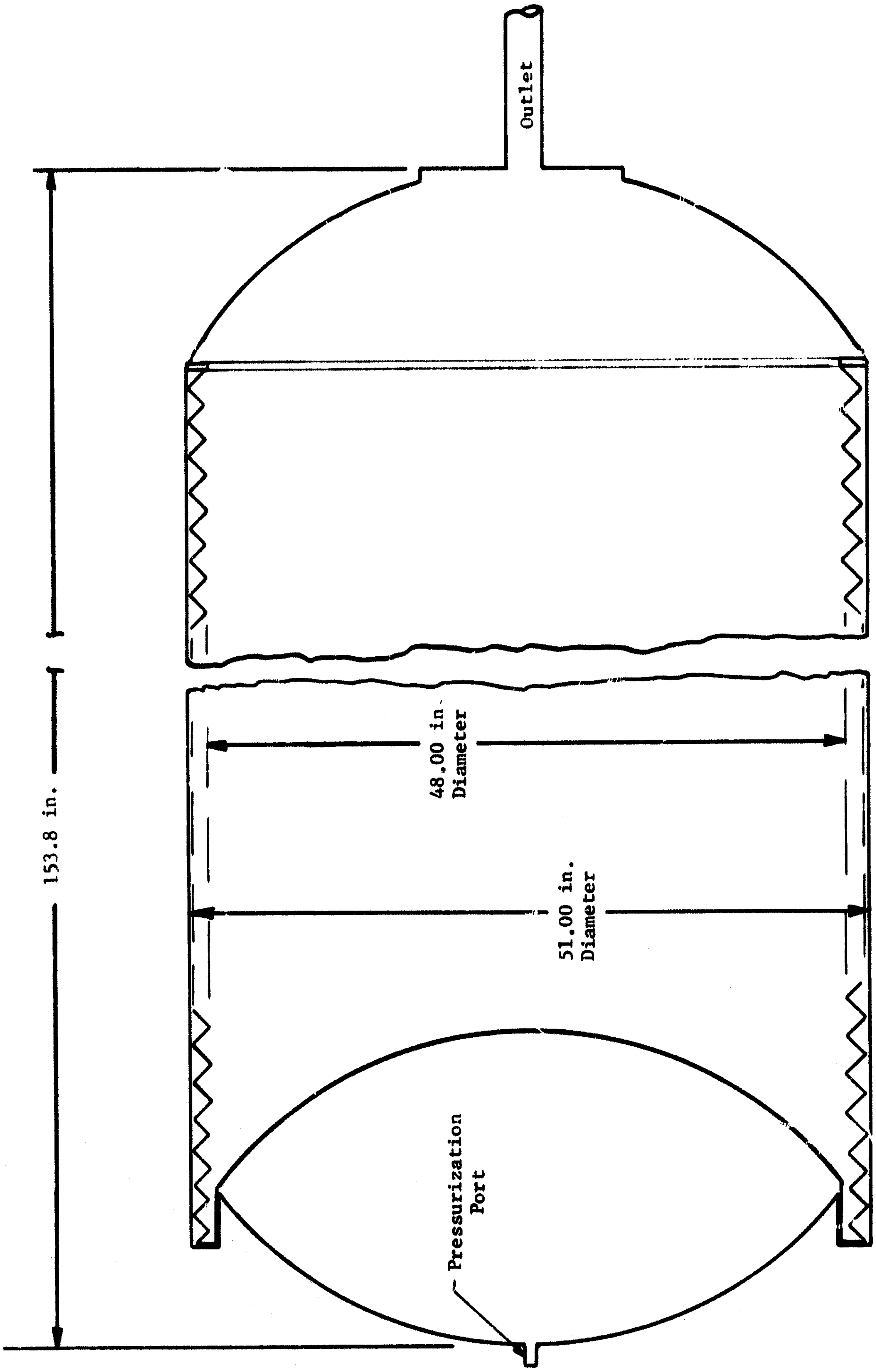


Fig. 32 Bellows Assembly

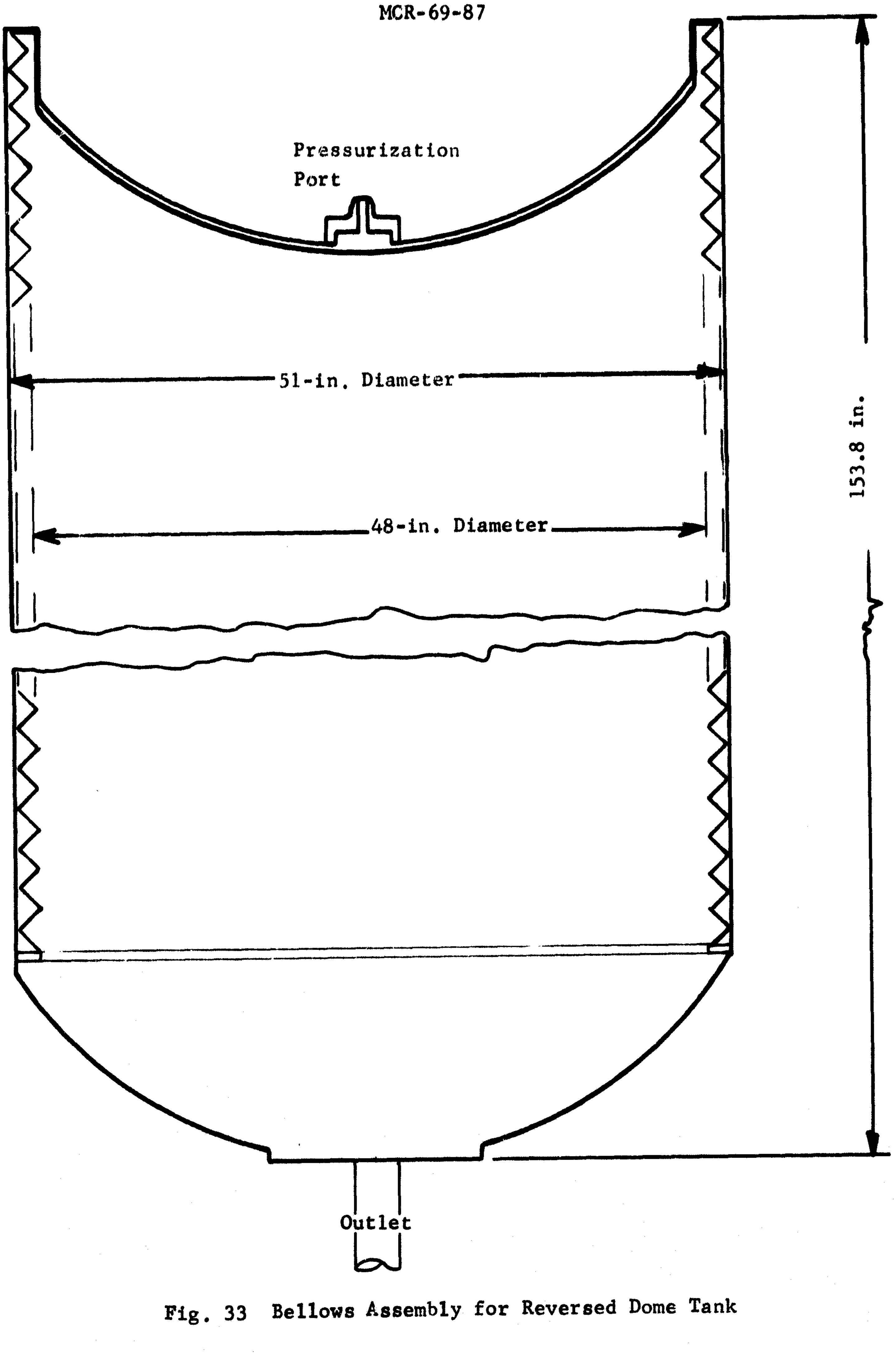


Fig. 33 Bellows Assembly for Reversed Dome Tank

Current bellows fabrication technology is limited to stainless steel designs; fabrication from other materials as aluminum or titanium would require additional development and testing to establish design criteria.

A. NO HARDWARE CHANGE CONFIGURATIONS

A total containment bellows configuration is not possible within the "no hardware modification" ground rules. The bellows is not adaptable to a series tankage application nor is it feasible for a complete bellows system to be installed and welded together through the existing tank manhole. The still well gaging system and pressurant inlet interfere with the bellows expulsion and cycling modes, and the geometric shape of the tank domes does not permit an efficient volumetric design.

B. NO HARDWARE LIMITATION CONFIGURATIONS

A complete redesign of both propellant tanks would be required to adapt a bellows expulsion system to this application. Figure 32 shows a representative layout of a tank and bellows design. The domes have been modified as discussed under the tank modification design considerations in Chapter V (Fig. 31). The design shown would fit into the same cylindrical envelope as the existing system and have the same usable volume (161 feet^3). However, the tank weight would be increased approximately 72 pounds because of the thicker 3:1 elliptic dome sections required. The bellows and tankage would be constructed of titanium.

The design was discussed with three leading bellows manufacturers -- Sealol, Inc., Solar Division of International Harvester Company, and Metal Bellows Corporation -- and all indicated a high confidence in their ability to fabricate a bellows of this size and design with a minimum amount of development effort.

1. Weight

The weight of the titanium bellows system shown in Fig. 32 was calculated based on material thickness of 0.010 inches, span of 1.5 inches (which yields a bellows outside diameter of 51 inches and an inside diameter of 48 inches), and 160 bellows spans or leaves. While these values are considered realistic, final material thickness and span determination would require a detailed analysis of the design. The total weight for the bellows leaves, head support rings, and welds would be approximately 91 pounds. This does not include the 72 pound weight penalty of the tankage modification.

2. Reliability

Bellows have demonstrated high reliability under repeated cycling. The primary failure mode would be leakage in the convoluted section caused by weld joint failure or pinholes in the convoluted area from over-extension or fatigue..

3. Development Time and Cost

Based upon a successful program, design and development of a bellows of this size should be possible within one year. Because of the large size, the cost of tooling and manufacturing could be quite large depending on the technique employed to form the bellows.

4. Pressurant Gas Ingestion

The bellows provides a nonpermeable membrane between the pressurant and propellant. If vapor is not trapped on the propellant side of the bellows during the fill operation, or leaks do not develop in the bellows assembly, gas ingestion will not occur.

5. Expulsion Efficiency

The bellows expulsion efficiency would approach 97% to 99% and the tank volumetric efficiency would probably be about 85%, depending on final design of leafs or spans and bellows heads and tank domes. Most systems in use today have achieved efficiencies within these ranges.

6. Passive Operation

Bellows require no settling acceleration, additional valves or other moving parts to ensure gas free liquid expulsion. Operation is characterized by flexing of the bellows leaves during the expulsion cycle.

7. Gaging System

Bellows provide an inherently positive method of gaging propellant independent of the acceleration environment. By monitoring the displacement of the head and comparing this to a calibration of the displacement versus volume, an accurate liquid volume measurement can be obtained. The molimetric and acoustic gas compliance gaging techniques can also be adapted to this configuration.

VII. MISCELLANEOUS TECHNIQUES

There are several techniques for expulsion that conceivably could be used for the proposed configuration, but they do not appear to be sufficiently serious contenders to warrant extensive evaluation. This group includes electrical systems, chemical foam systems, acoustic forces, and mechanical traps or a separate restart tank.

A. ELECTRICAL SYSTEMS

The most promising electrical technique is a dielectrophoretic system. By applying an electric field in a propellant tank it is possible to preferentially orient liquid by making use of the polarization forces. The electric field intensity, E, induces a surface force density, Te, given by

$$Te = \frac{1}{2}\left(\epsilon - \epsilon_o\right)E^2, \text{ Ref. } 40$$

where ϵ is the permittivity through the bulk of the liquid and ϵ_o is the permittivity of the vapor.

This electrical surface force can be used to provide liquid orientation and slosh control. A considerable amount of experimental and theoretical work has been accomplished in this area, and the feasibility of the techniques has been proven for expulsion and orientation of cryogens; but they are generally not considered suitable for storable propellants. The applicability of dielectrophoretic systems depends to a great extent on the fluid properties of the propellant, specifically the ratio of the dielectric constant to the electrical conductivity. In general, the larger the dielectric constant to conductivity ratio, the more suited the fluid is to this control technique (Ref. 39).

For the propellants under consideration, 50% N_2H_4 - 50% UDMH and N_2O_4, only the N_2O_4 is in the range of applicability. The conductivity of the 50-50 appears too high for a practical design. Based on the information presented in Ref. 40, a weight calculation was performed for a dielectrophoretic system to orient N_2O_4 over the tank outlet against a distributing axial acceleration of 0.2 g. The weight and power are plotted as a function of the retained propellant on Fig. 34. In addition to the fairly heavy weight and power consumption required, there is a certain development risk involved concerning whether the system will operate satisfactorily. Development and test effort would have to be conducted to establish the operational characteristics of the technique for N_2O_4.

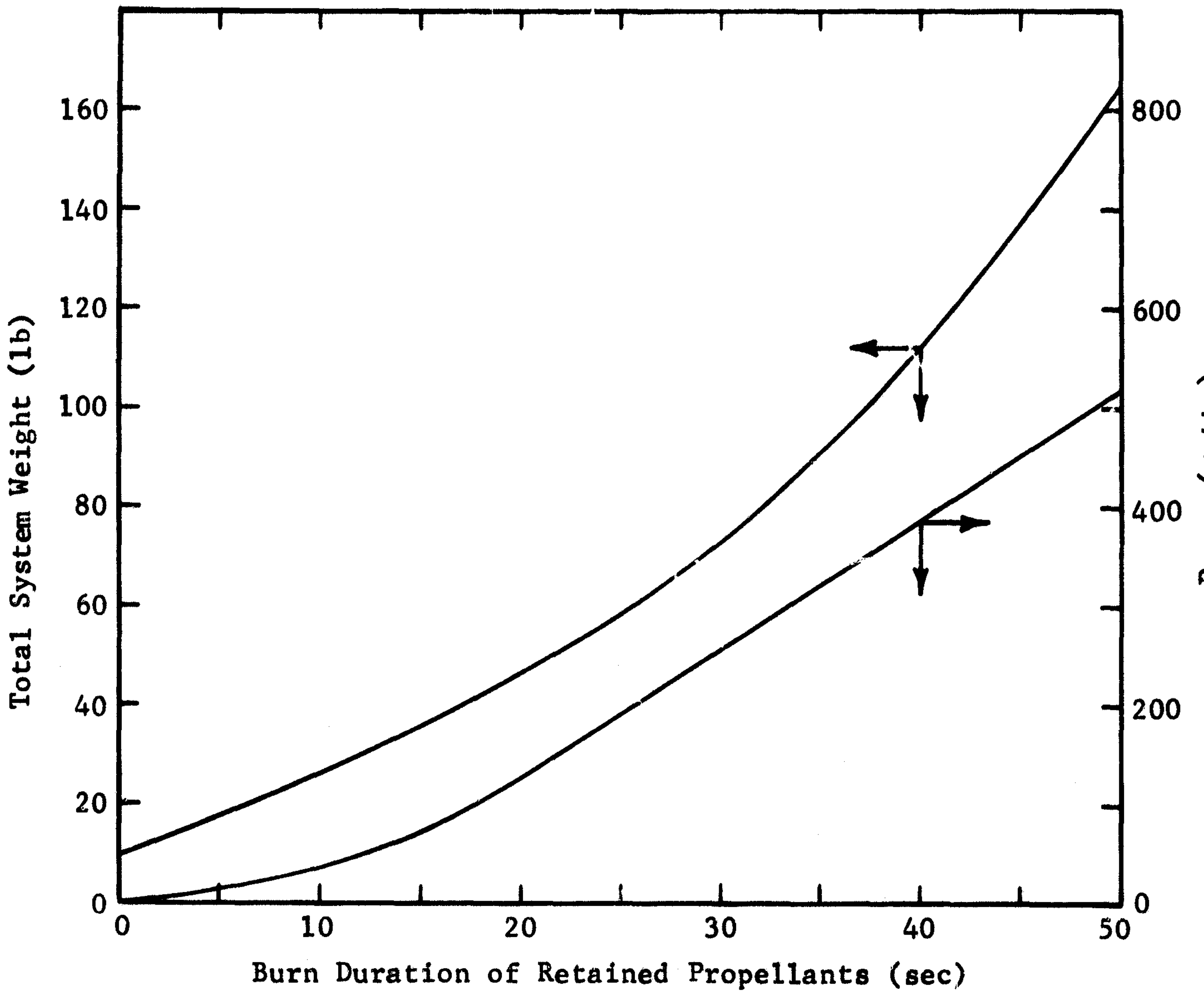


Fig. 34 Dielectrophoretic Propellant Retention System Weight and Power Requirements

B. CHEMICAL FOAM SYSTEMS

A possible technique for expulsion is use of an expandable solid material to fill the tank ullage space as the propellant is withdrawn. The general technique is to react a high density solid such as polyethylene with a catalyst in the tank to form a low density foam (1.5 to 15 lb/ft^3). The obvious advantages are the simplicity and positive propellant control. The disadvantages are that foams must be compatible with the propellant and not absorb the propellant. This may require use of a liner in addition to the foam. The pressure buildup transient is slow because of delay in the initiation of foam formation after injection of the ingredients, and similarly an overshoot will result at shutoff until equilibrium is established. An elaborate pressure control and injection system is required to control tank pressure. Only one expulsion cycle is possible without recleaning the tankage. In addition, for this size tank the weight of such a system would probably exceed 200 pounds.

C. ACOUSTIC FORCES

Acoustical forces can be utilized to exert directed force on gas bubbles in liquid systems. Ultrasonic transducers can be designed to repel gas bubbles away from an outlet covered with liquid. This technique has been demonstrated for relatively small bubbles; however, to accomplish orientation in a large tank, this amounts to creating sufficient force to hold the resulting large ullage volume at one end thereby retaining liquid over the outlet. For the size system under consideration, the power consumption requirements would probably be orders of magnitude above the design goal (10 pounds), if indeed an acoustical system could be designed to accomplish the separation. This system would require extensive experimental effort before a quantitative evaluation of its feasibility could be made.

D. MECHANICAL TRAPS

Mechanical traps, such as the false bottom check valve design employed in the Transtage primary propulsion system, offer the advantage of light weight and simplicity. The operation is characterized by the trap being filled with propellant during thrusting or initial tank filling and then preventing the liquid from draining out during adverse acceleration or low-g coast periods. This design provides liquid over the outlet for the next restart. During the restart, pressurant will be ingested into the trap if the bulk propellant is adversely located or it may be ingested during the resettle. If the propulsive period is not of sufficient duration to purge all the pressurant from the trap, gas free liquid cannot be assured for subsequent restarts. Multiple series traps could be employed where each trap would increase the restart capability. For 50 restarts with variable burn durations, where many short pulses may occur during terminal draining, this approach is not considered practical.

1. Separate Restart Tanks

A separate reservoir isolated form the bulk propellant would be another approach to the required restart propellant feed capability. Expulsion from the reservoir could be accomplished by one of the techniques discussed previously. Schematics of a system of this type are shown in Fig. 35 and 36. At engine start, the propellant is supplied from the propellant reservoir. After sufficient thrust duration to establish a settled propellant condition in the main tank, the outflow from the reservoir is terminated by closing the reservoir valve and feed is established from the main tank by simultaneously opening the main flow valve. The system would probably require two additional valves in each propellant feed system, one at each tank outlet to control the propellant source. For durations shorter than that required to settle the bulk propellant, only the reservoir system would be used. A timing circuit could be used for proper valve sequence control.

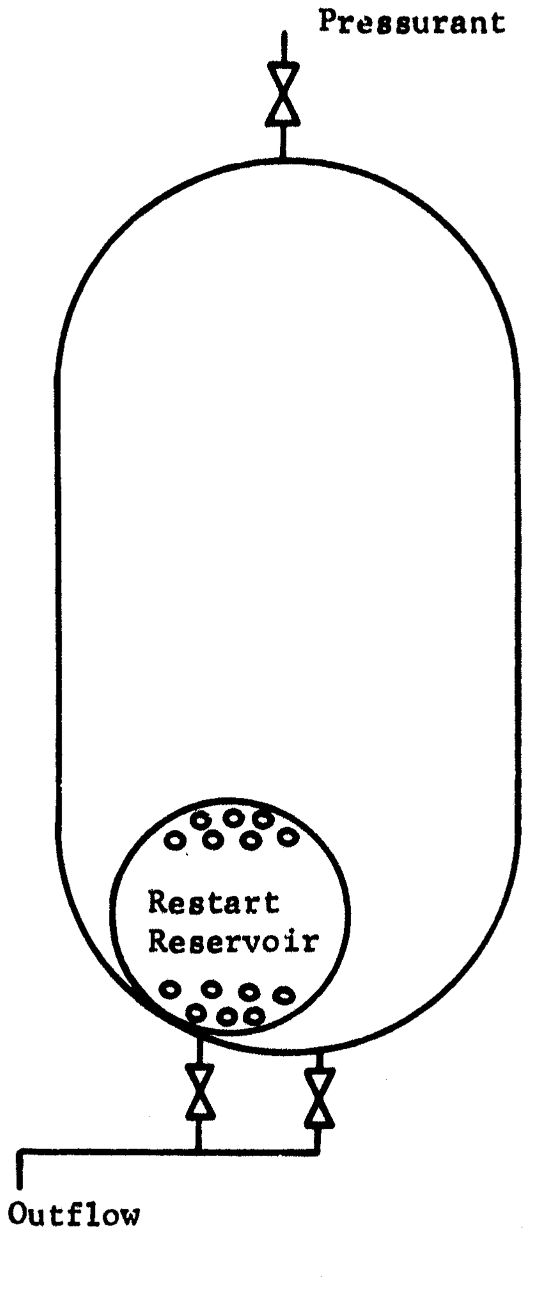


Fig. 35 Start Tank System - Submerged

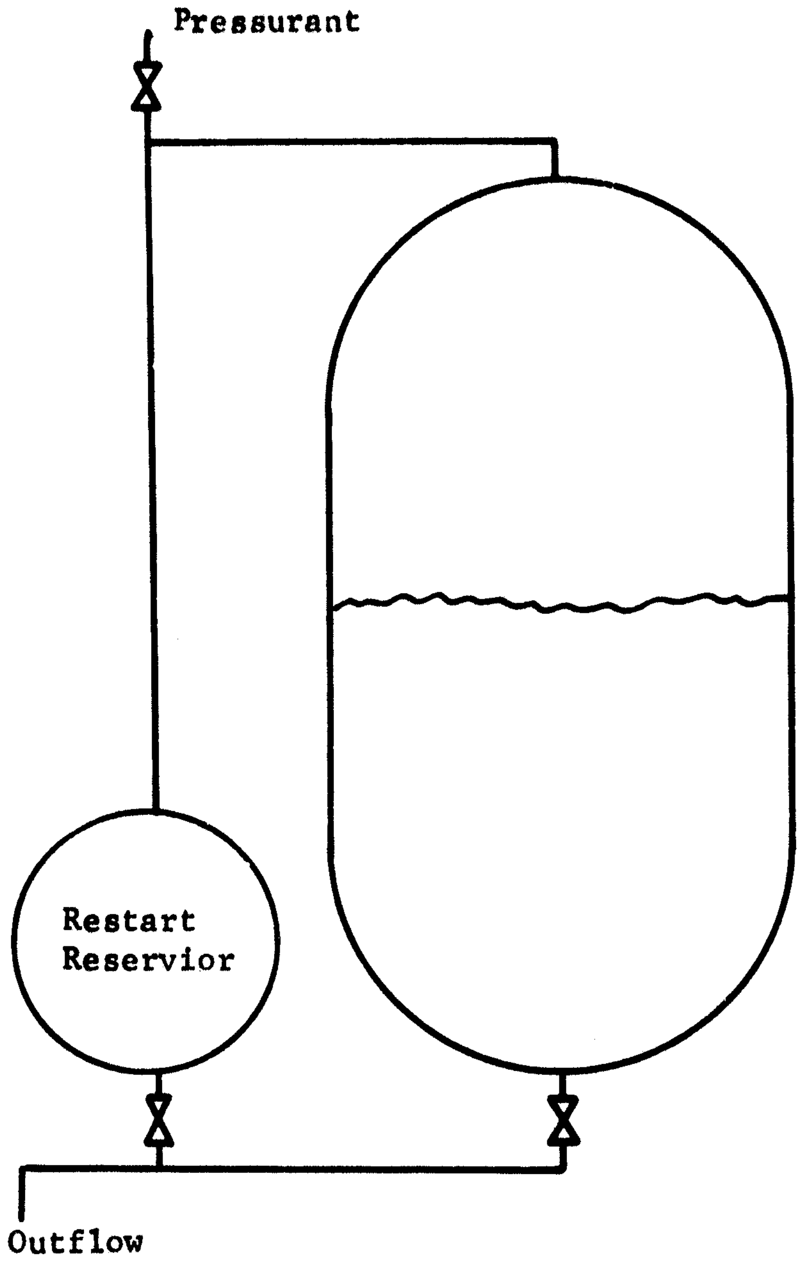


Fig. 36 Start Tank System - Exterior

The critical sizing parameter for the reservoir is the required propellant resettle time after initiation of engine start. From the plot presented on Fig. 21, the maximum free-fall time is 0.9 seconds under the most severe propellant usage schedule. The results of the propellant settling tests presented in Ref. 19 indicate that after four free-fall periods, substantial liquid will be located over the outlet; however, it will probably still contain entrained gas bubbles. Assuming a capillary screen can be used to prevent gas ingestion at the outlet, four free-fall periods (a thrust of 3.6 sec) would be adequate to achieve settling. To meet the goal of 50 restarts, the reservoir would have to have the capacity to supply 180 (50 x 3.6) seconds of propellant flow, or over 40% of the total volume. This large capacity would destroy the advantage of the restart technique. A plot of the propellant requirement as a function of the number of restarts is presented in Fig. 37. In addition to the size requirements, the complex control system and components required make the system extremely unattractive.

One other approach to the restart propellant feed requirement that would eliminate the additional valving is to use a bellows-capillary combination system. This concept (Fig. 38) uses a bellows over the outlet with a capillary screen end closure. The attractive feature of this concept is that it offers a method of preventing gas ingestion into the trap during bulk propellant settling. The pressure retention characteristic of the screen provides the pressure differential desired to collapse the bellows during restart. As the propellant is withdrawn, trap volume decreases maintaining single phase liquid within the trap. After the bulk propellant has been settled, the trap refills under the force provided by the bellows spring action. The addition of screen in the bellows close to the tank outlet permits an outflow path for the propellant outside the bellows in the bottom of the tank.

Unfortunately, the size and restart criteria for the current evaluation does not permit the use of this type of device. A series of burns one second in duration does not permit sufficient bulk propellant settling for the trap to refill. Partial refilling can be anticipated, but satisfactory performance cannot be assured with the imposed restrictions. As previously discussed, a trap capable of holding enough propellant for 50 restarts without refill is impractical. This concept does merit further consideration in smaller, low flowrate systems where the burn profile provides more bulk propellant settling time so the trap can refill.

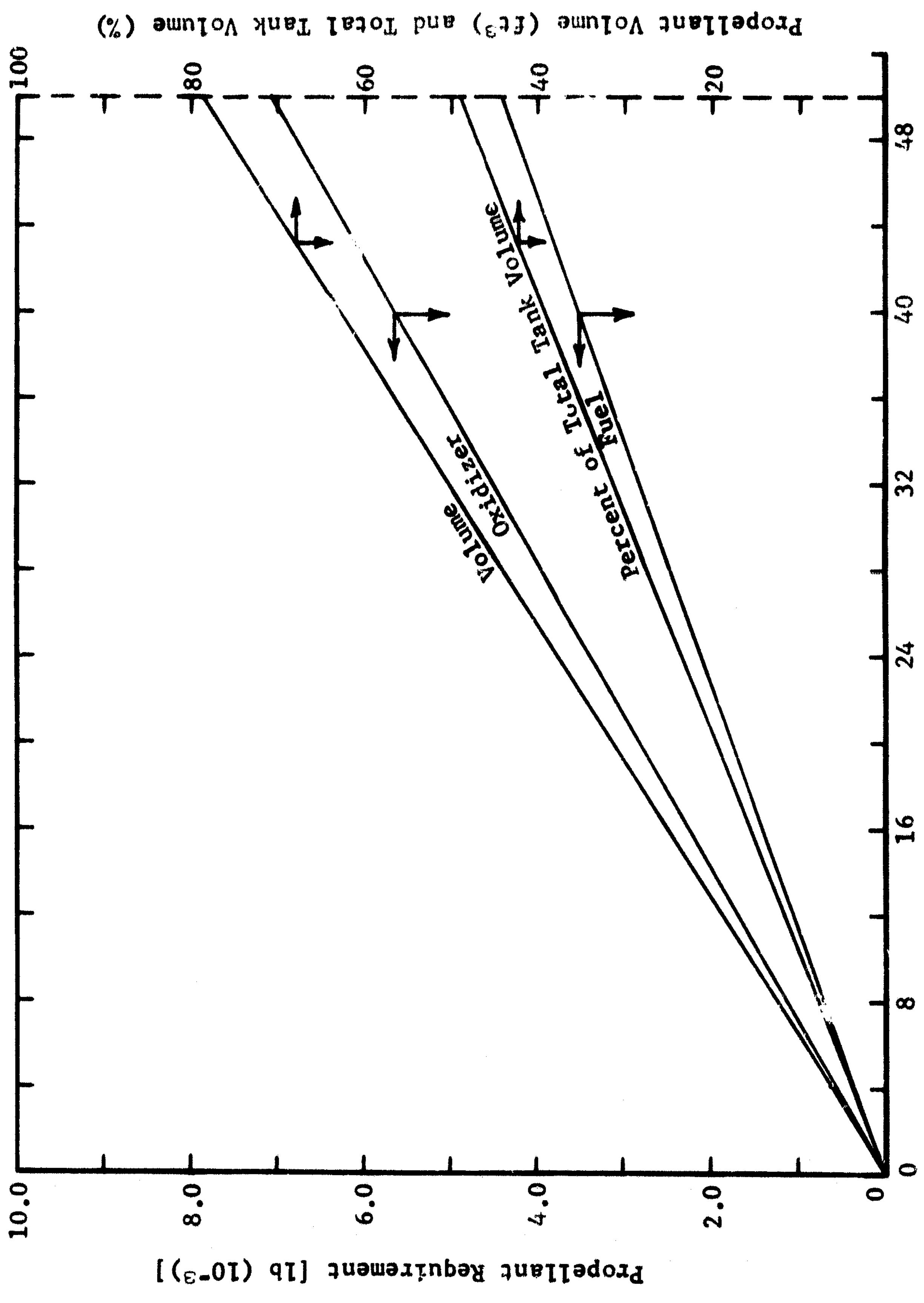


Fig. 37 Propellant Required versus Number of Restarts

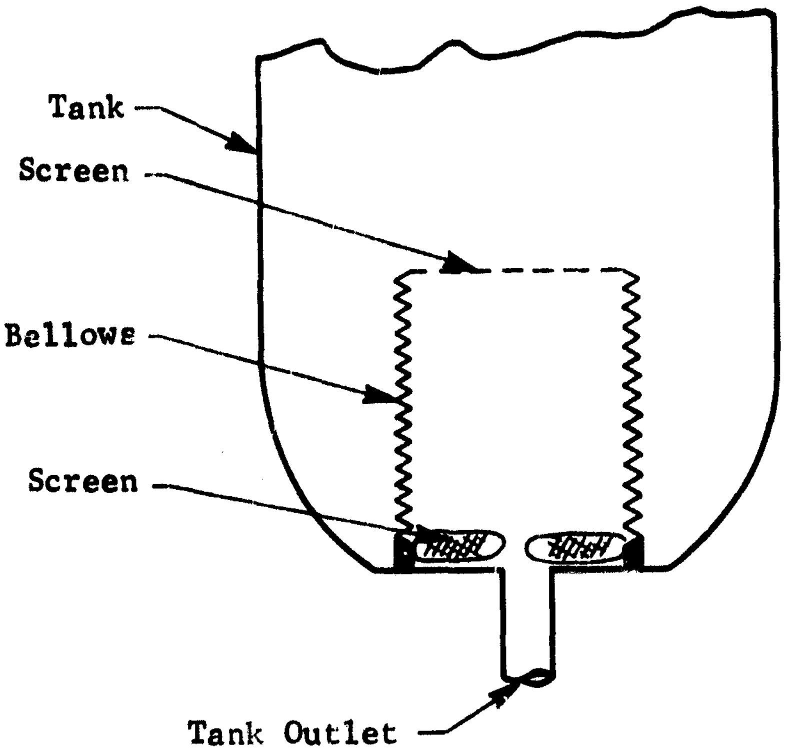


Fig. 38 Bellows-Screen Combination Trap

VIII. SYSTEM RECOMMENDATIONS

Table IV presents a summary of the evaluations of the various techniques that appear to have sufficient merit to rate consideration for the Phase II detail design study. As indicated, none of the systems satisfies all of the design criteria.

For the case of no hardware changes, only the capillary system can be considered. All of the other systems require configuration modifications that violate the definition of no hardware change. The recommended design would be of the type shown in Fig. 22.

For the no hardware limitations design, several candidates appear to offer advantages depending on the relative importance of the different design objectives to the total program. However, in consideration of general applicability, the capillary system with a design such as that illustrated in Fig. 27 is the recommended technique. The second choice recommendation would be a non-metallic bladder concept. The bladder and diaphragm techniques have similar merit, but the serviceability and inspection aspect of the removable bladder gives it a slight edge.

The metallic systems offer the advantage of a nonpermeable membrane between the propellant and pressurant. While none of these systems appears well suited for this application, the Conospheroid reversing diaphragm does offer the potential for a reasonably light weight multiple cycle system.

Table IV Propellant Control Systems Evaluation Summary

Technique / Criteria	Non-metallic		Metallic ①		Capillary Retention	Sliding Seal Pistons	Metallic Bellows
	Bladders	Diaphragms	Design A Cylindrical Rolling Diaphragm	Design B-2 Conospheroid Reversing Diaphragm			
Expulsion Efficiency, % (99.5% Goal)	98	99.5	99.5	99.5	99.5	99.5	97 - 99
Volumetric Efficiency within Tank Envelope, % (Fig. 1)	99.8	99.9	99	66	99.9	75	75
Weight lb (10-lb Goal)	32	38	104	32 ②	10.7 - 18.7	94 ②	91 ②
Pressurant Ingestion	Permeation of Pressurant	Permeation of Pressurant	None	None	Dissolved Pressurant	None with Good Seal Performance	None
Hardware Changes	Minimal Tank Redesign	Modest Tank Redesign	Modest Tank Redesign	Extensive Tank Redesign	Retrofit Possible	Extensive Tank Redesign	Extensive Tank Redesign
Duty Cycle Limitations	None	None	None	None	No. Restarts Constrained See Fig. 25	None	None
Off-Load Propellant Limitations	Off-Load Not Desirable	Off-Load Not Desirable	Off-Load Not Desirable	Off-Load Not Desirable	None	None	None
Cycle Life	≈20	≈20	1 Reversal	≈6	>1000	1 Cycle	>1000
Propellant Exposure Tollerance, Yr (1-Year Goal)	1	1	>1	>1	1	1	>1
Series Tankage Capability	No	No	No	No	Yes	No	No
State-of-the Art ③	1	1	5	4	1	3	2
Development Time and Cost ③	2	2	4	3	1	4	3

① All metallic systems are rated based upon titanium construction.

② Tank weight additions due to configuration change not included.

③ Relative Ratings - 1 through 5 where 1 represents best rating and 5 poorest. No absolute value significance is intended.

IX. REFERENCES

1. A. Krivetsky: Research on Zero-Gravity Expulsion Techniques. Report No. 7129-933003, Bell Aerosystems Company, March 1962.

2. Study of Zero-Gravity Positive Expulsion Technique. Report No. 8230-933004, Bell Aerosystems Company, June 1963.

3. Development of Expulsion and Orientation Systems for Advanced Liquid-Rocket Propulsion Systems. Report No. SSD-TDR-62-172, Rocket Research Laboratories, Edwards Air Force Base, November 1963.

4. H. R. Lubowitz, J. F. Jones, R. A. Meyers and E. A. Burns: The Development and Characterization of New Storable Propellant Bladder Materials. Final Report No. 6104-6013-R000, TRW Systems, 15 February 1968.

5. N. B. Levine: CNR Expulsion Bladders. Joint AIAA/Aerospace Corporation Symposium, Low Gravity Propellant Orientation and Expulsion, 21-23 May 1968.

6. N. B. Levine, H. Krainman and J. Green: Positive Expulsion Bladders for Storable Propellants, Technical Report AFML-TR-65-379, Thiokol RMD, Denville, New Jersey, January 1966.

7. J. N. Krusos, R. G. Higgins and W. H. Dukes: Design Criteria and Quality Control Studies for Teflon Expulsion Bladders. Report No. 8460-933012, Bell Aerosystems, Buffalo, New York, March 1967.

8. Reaction Control System Design Data for Space Vehicle Applications. Technical Note 8500-950008, Bell Aerosystems Co., Buffalo, New York, October 1965.

9. R. G. Peterson and J. R. Taylor: Positive Expulsion Tank for Titan III Transtage Hydrazine Attitude Control System, Joint AIAA/Aerospace Corporation Symposium, Low Gravity Propellant Orientation and Expulsion, 21-23 May 1968.

10. R. N. Porter and H. B. Standford: Propellant Expulsion in Unmanned Spacecraft, Technical Report No. 32-899, Jet Propulsion Laboratory, Pasadena, California, 1 July 1966.

11. J. C. Lee: Counter-Permeation Phenomenon in Bladdered Expulsion Tank. Joint AIAA/Aerospace Corporation Symposium, Low Gravity Propellant Orientation and Expulsion, 21-23 May 1968.

12. Technical Discussion of Measurement of Fluid Mass Under Zero Gravity Conditions. Publication No. 3554-66, Bendix Corporation, Davenport, Iowa, 18 May 1966.

13. Robert A. Gould and Leroy J. Krzyeki: Hot Gas Positive Expulsion Using Rolling Metal Bladders (U), Bulletin of the 7th Liquid Propulsion Symposium, Vol II, Chemical Propulsion Information Agency, October 1965.

14. George H. Hopmier, Bobby D. Richardson and Billy L. Crasswhite: Application of Positive-Expulsion Bladder Concepts to the Lance Feed System (U), 10th Liquid Propulsion Symposium. Vol 1, Chemical Propulsion Information Agency. Las Vegas, Nevada, November 1968.

15. S. Levat Lehman, L. Jablansky and J. Canavan: Progress in Techniques of Propellant Expulsion for Army Weapons (U). 10 LPIA Vol I.

16. David Gleich: Multicycle Metallic Bladders for Cryogenic Fluid Storage and Expulsion. Technical Report AFAPL-TR-66-146, Air Force Aero-Propulsion Laboratory (APIP-1), Wright Patterson AFB, Ohio, September 1967.

17. Robert A Gould and LeRoy M. Stayton: The Use of Chemical Vapor Deposited Aluminum for Propellant Tank Liners and Expulsion Bladders. 10th Liquid Propulsion Symposium (U), Vol I, Chemical Propulsion Information Agency, Las Vegas, Nevada, November 1968.

18. Telephragm-Positive Expulsion Tankage. Report No. 8500-953038, Bell Aerosystems, October 1968.

19. Apollo SPS Propellant Position Control in Low- and Zero-G Environments, SD 67-655, Contract NAS9-150, North American Aviation, Inc, 21 July 1967.

20. L. J. DiPeri: A Resumé of the Management of Liquid Gas Interface Using Surface Tension Technology. Joint AIAA/Aerospace Corporation Symposium, Low Gravity Propellant Orientation and Expulsion, 21-23 May 1968.

21. S. C. DeBrock: Progress Report Development of a Capillary Propellant Management System. Joint AIAA/Aerospace Corporation Symposium, Low Gravity Propellant Orientation and Expulsion, 21-23 May 1968.

22. W. J. Masica, D. A. Petrash and E. W. Otto: Hydrostatic Stability of the Liquid-Vapor Interface in a Gravitational Field, NASA TN D-2267, Lewis Research Center, May 1964.

23. M. P. Hollister: Propellant Containment Utilizing Screen Mesh and Perforated Plate Surfaces, LMSC-A665481, Code 9999, Lockheed Missiles and Space Company, 29 December 1964.

24. V. C. Oltrogge: Test Report, Bubble Retention Test-624A. Martin Marietta, Denver Division, Denver, Colorado, 31 October 1963.

25. H. L. Paynter, et al: Experimental Investigation of Capillary Propellant Control Devices for Low Gravity Environments, MCR-68-199, contract NAS8-21259, Martin Marietta Corporation December 1968.

26. H. L. Paynter, et al: Final Design Report: Development of a Capillary System for Liquid Propellant Orientation during Low-g, TM0444-66-3, Martin Marietta Corporation, December 1965.

27. Study of Long Term Effects of High Energy Propellants on Fine Micronic Stainless Steel Wire Cloth Used in Surface Tension Devices, AFRPL-TR-68-141, Western Filter Company July 1968.

28. D. L. Balzer: Information Concerning Porous Materials, RA631-1, Martin Marietta Corporation, 19 April 1968.

29. T. R. Barksdale and D. L. Balzer: Liquid Outflow Tests of Surface Tension Systems under Minus One-J. TM 1661-66-12, Martin Marietta Corporation, December 1966.

30. R. N. Porter and H. B. Stanford: Propellant Expulsion in Unmanned Spacecraft - Paper 868B presented April 1964 at the SAE Air Transport and Space Meeting.

31. J. Green, Review of Materials Research, Rocket Fuel and Oxidizer Application, Thiokol Chemical Corporation, 23 May 1962.

32. N. B. Levine, W. R. Sheehan and J. Green: Elastomeric and Compliant Materials for Liquid Rocket Fuel and Oxidizer Application, Thiokol Chemical Corporation Technical Report ML-TDR-64-107 Part III, December 1965.

33. Tec-Ring Seals Design Handbook - Tec Seal Corporation, 22624 Avalon Boulevard, Wilmington, California, 3 August 1965.

34. Dr. L. E. Halbert, Dr. R. E. Keithand and T. M. Trainer: State-of-the-Art Survey of Metallic Bellows and Diaphragms for Aerospace Applications, AFRPL-TR-65-125, November 1965.

35. Classified title, RTD-TDR 63-1082, AF 04 (611) 7934 Martin Marietta Corporation 1963.

36. William D. Allingham: Zero-Gravity Expulsion of Cryogens with Metal Bellows. Joint AIAA/Aerospace Corporation Symposium, Low Gravity Propellant Orientation and Expulsion, The Boeing Company, May 1968.

37. D. A. Wendt: High Expansion Metal Bellows with Non-Welded Convolutions Edges for Propellant Expulsion Systems. Joint AIAA/Aerospace Corporation Symposium, Low Gravity Propellant Orientation and Expulsion, Solar Corporation, a Division of International Harvester Company, May 1968.

38. Telecon: Jack Stevens, Metal Bellows Corporation, December 1968.

39. Personal conversation between Mr. M. Hurwitz of the Dynatech Corporation and Mr. D. Balzer of Martin Marietta Corporation, 2 Jan 1969.

40. M. Hurwitz: Research and Development of a Practical and Economical Dielectrophoretic System for the Control of Liquid Fuels under Low Gravity Environmental Conditions. PAS-271, Dynatech Corporation, 22 September 1965.

X. SELECTED BIBLIOGRAPHY

Bauman, A. J.: Some Design Considerations, Large Expulsion Bladders for Nitrogen Tetroxide and Hydrazine. Technical Report No. 32-862, Jet Propulsion Laboratory, Pasadena, California, 15 January 1966.

Bazzare, F. D. and J. V. Petriello: Chemical Vapor Deposited Permeation Barriers in Teflon Expulsion Bladders. Joint AIAA/Aerospace Corporation Symposium, Low Gravity Propellant Orientation and Expulsion, 21-23 May 1968.

Carhart, J., D. W. Moorman, G. W. Hettrick, T. T. Yamauchi and G. H. Hage: The Evaluation of a Composite Teflon Aluminum Expulsion Bladder for Use in Nitrogen Tetroxide. Document No. D2-100645-1, The Boeing Company, Seattle, Washington, May 1966.

Chilenski, John J., Donald E. Limke, and Owen D. Goodman: Demonstration of Advanced Post Boost Propulsion Subsystems. Quarterly Technical Report 1075-Q-5, Aerojet General Corporation, Sacramento, California, September 1967.

Chu, H. N., W. Unterberg and J. C. Lee: Final Report, Improvement of Efficiency and Life of Expulsion Bladders. Report R-7391, Rocketdyne, Canoga Park, California, 29 February 1968.

Depuy, I., V. Daniel and A. Lytle: Study of Zero-Gravity Positive Expulsion Techniques. Contract NAS7-149. Interim Report 8230-933010, Prepared by Bell Aerosystems Company, March 1965.

Development of Expulsion and Orientation Systems for Advanced Liquid Rocket Propulsion Systems. Technical Documentary Report No. SSD-TDR-62-172, Bell Aerosystems, Buffalo, N. Y., December 1962.

Fearn, R. and D. Covington: Cryogenic Metallic Positive Expulsion Bellows Evaluation. Contract No. NAS3-12017. Final Report MCR-69-67, Martin Marietta Corporation, February 1969.

Green, J.: Review of Materials Research Rocket Fuel and Oxidizer Application. Thiokol RMD, Denville, New Jersey, 23 May 1962.

Green, J. and N. B. Levine: Elastomeric and Compliant Materials for Liquid Rocket Fuel and Oxidizer Application. Report RMD 5029-02, Thiokol RMD, Denville, New Jersey, 1 June 1963 to 31 August 1963.

Green, J. and N. B. Levine: Elastomeric and Compliant Materials for Liquid Rocket Fuel and Oxidizer Application. Report RMD 5029-Q3, 1 September 1963 to 30 December 1963.

In-Space Propellant Orientation and Venting Experiment. AFRPL-TR-66-270, Lockheed Missiles and Space Company, 31 October 1966.

Keller, O. F. and L. R. Toth: ALPS Generant Tank and Cell Assembly. Technical Report No. 32-865, Jet Propulsion Laboratory, Pasadena, California, 28 February 1966.

Krivetsky, A., W. H. Bauer, H. L. Loucks, J. Padlog, J. V. Robinson, and W. H. Walters: Final Report, Research On Zero-Gravity Expulsion Techniques. Report No. 7129-933003, Bell Aerosystems, Buffalo, New York, March 1962.

Krusos, J.: A Study of Teflon Bladder Design Criteria for Use in the Expulsion Propellant Tanks of the Apollo-Saturn and Lunar Orbiter Vehicles. Monthly Progress Report No. 7, Bell Aerosystems, Buffalo, New York, May 1966.

Levine, N. B. and H. Krainman: Nitroso Rubber Expulsion Bladders for Nitrogen Tetroxide Application. Report RMD 5094-Q2, Thiokol RMD, Denville, New Jersey, December 1966.

Levine, N. B. and H. Krainman: Nitroso Rubber Expulsion Bladders for Nitrogen Tetroxide Application. Thiokol RMD, Report 5094-Q3, April 1967.

Levine, N. B., H. Krainman and R. C. Keller: Nitroso Rubber Expulsion Bladders for Nitrogen Tetroxide Application. Report RMD 5094-Q1, Thiokol RMD, Denville, New Jersey, October 1966.

Levine, N. B., W. R. Sheehan, and J. Green: Nitroso Rubber Expulsion Bladders for Nitrogen Tetroxide Application. Technical Report ML-TDR-64-107, Part III, Thiokol RMD, Denville, New Jersey, December 1965.

Liquid Propellant Behavior during Periods of Varying Accelerations. LMSC-A874728, Lockheed Missiles and Space Company, 30 June 1967.

Miller, R. A.: Title Classified. R454-164-2, Aero-General Corporation, January 1964.

Muraca, R. F., J. S. Whittick, and A. A. Koch: Development of Techniques to Improve Bladder Materials and Test Methods. Final Report SRI Project PRD-6068, Stanford Research Institute, Menlo Park, California, 17 June 1968.

Nye, H. H. and D. W. Moorman: Lunar Orbiter Velocity Control System. Journal of Spacecraft and Rockets, Vol 5, No. 2, February 1968.

Orbital Refueling and Checkout Study. Final Report T1-51-67-21, Vol III, Part 1, Lockheed Missiles and Space Company, Sunnyvale, California, 12 February 1968.

Petriello, J. V.: Modifications in Fluorocarbon Bladder Structures in Improving Flexibility and Impermeability. Joint AIAA/Aerospace Corporation Symposium, Low Gravity Propellant Orientation and Expulsion, 21-23 May 1968.

Pope, D. H. and V. E. Isakson: Positive Expulsion of Cryogenic Liquids. Report No. 14252, Beech Aircraft Corporation, Boulder, Colorado, March 1964.

Porter, R. N.: The Fabrication of Seamless Teflon Propellant Expulsion Bladders. Technical Report No. 32-914, Jet Propulsion Laboratory, Pasadena, California, 15 June 1966.

Porter, R. N. and H. B. Stanford: Propellant Expulsion in Unmanned Spacecraft, SAE Air Transport and Space Meeting, April 1964.

Program 706 Task 4 MPU Bladder Development. Report No. SSD-TDR-63-278, Radio Corporation of America, Burlington, Massachusetts, 4 November 1963.

Properties of Ardeform Material and Ardeform Experience. Arde, Inc., Paramus, New Jersey.

Putt, W. J.: Experience with Teflon Positive Expulsion Bladders for the Surveyor Vernier Propulsion System. Joint AIAA/Aerospace Corporation Symposium, Low Gravity Propellant Orientation and Expulsion, 21-23 May 1968.

Schmitz, B. W., T. A. Groudle and J. H. Kelley: Development of the Post-Injection Propulsion System for the Mariner C Spacecraft. Technical Report No. 32-830, Jet Propulsion Laboratory, Pasadena, California, 1 April 1966.

Space Vehicle Applications. Technical Note 8500-950008, Bell Aerosystems, October 1965.

Stanford, H. B.: The Measured Permeability to Nitrogen Tetroxide of Some Potential Bladder Materials. Technical Memorandum No. 33-123, Jet Propulsion Laboratory, Pasadena, California, 24 March 1963.

Telecon: Mr. R. Lark, NASA LeRC, and Mr. D. Balzer, Martin Marietta Corporation, January 1969.

Trimble, E. F.: *Fabricating, Testing, Cleaning and Shipping Daco 1A67911 Expulsion Tanks*. SC-39262. Sealol, Inc., November 1965.

Vango, S. P.: *Compatibility and Permeability of Nitroso Rubber*. Space Programs Summary No. 37-34, Vol IV, pp 206-207, Jet Propulsion Laboratory, Pasadena, California, 31 August 1965.

Vango, S. P.: *Determination of Permeability of Cast Teflon Sheet to Nitrogen Tetroxide and Hydrazine*. Technical Memorandum No. 33-55, Jet Propulsion Laboratory, Pasadena, California, 15 June 1966.

Walsh, James R.: *Metal Bellows Reservoirs*, Metal Bellows Corporation, a Zurn Company.

Wendt, D. A.: *Engineering Memorandum*. Solar Corporation, a Division of International Harvester Company, June 1968.