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# ADVANCED PROPELLANT
# MANAGEMENT SYSTEM FOR
# FOR
# SPACECRAFT PROPULSION SYSTEMS

## SUMMARY REPORT

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# ADVANCED PROPELLANT MANAGEMENT SYSTEM FOR SPACECRAFT PROPULSION SYSTEMS

## SUMMARY

September 1969

Prepared for

NASA Manned Spacecraft Center
Houston, Texas

Approved by

Daniel L. Balzer
Program Manager

MARTIN MARIETTA CORPORATION
Denver, Colorado 80201

## FOREWORD

This document is submitted in accordance with Appendix A of Contract NAS9-8939, dated 21 November 1968. The report summarizes the results of the contract study effort and represents the completion of the technical effort.

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

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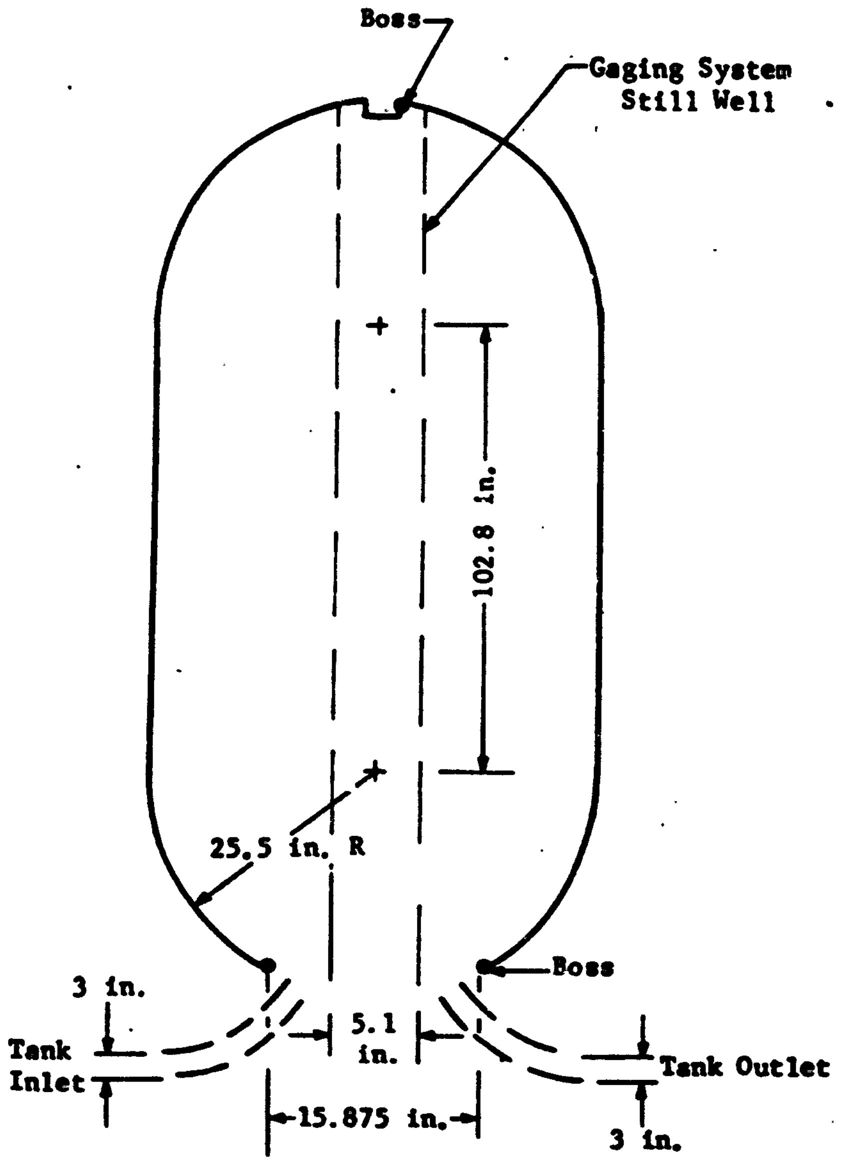


Fig. 1 Oxidizer and Fuel Tanks

Table 1 Propulsion System Characteristics

| | |
|---|---|
| Oxidizer | Nitrogen Tetroxide, $N_2O_4$ |
| Fuel | 50% N $O_4$ - 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 200 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 |
| -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 |

## III. RELATIONSHIP TO OTHER NASA EFFORTS

The results of this study were made possible through the use of information generated under numerous programs sponsored or conducted by virtually every NASA agency. In the study, basic analytical tools, design information, and experimental information that were generated during previous programs were brought together and applied to the selection and design of a propellant management system for a given set of requirements. Reports that were used during the study are included among the references presented in the three reports generated under this contract:

Advanced Propellant Management System for Spacecraft Propulsion Systems -

Phase I - Survey Study and Evaluation, February 1969,

Phase II - Detail Design Study, September 1969,

The Literature of Low-g Propellant Behavior, September 1969.

The study results have a dual significance to NASA programs. They relate to the current Apollo SPS in that they present a survey of propellant management systems for this application based on existing technology and indicate the type of system currently employed is a sound approach. Furthermore the study presents a design that would result in a significant improvement to the existing design and could be retrofitted to the current SPS. The new design is lighter by at least 20 lb per tank, depending on the changes incorporated, and provides a wider duty cycle capability while eliminating the requirement for propellant settling maneuvers.

In addition to the direct feedback to the Apollo SPS, the study results present meaningful conclusions with regard to the selection and design of propellant management systems for future spacecraft propulsion systems for a broad range of applications. Typical of these would be orbital shuttle craft, upper stages, and manned or large payload planetary and deep space vehicles.

While the study only considered earth storable propellants, much of the information and the design approach also apply to space storables and cryogens. This is particularly true for subcooled liquid storage with small heat leaks into the system.

## IV. METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

The initial task of the study was to survey all techniques for propellant management and evaluate them with respect to the system requirements. Since individual evaluation of specific techniques would be very time consuming, the approach was to divide the known methods into six categories for evaluation:

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

The category groupings were based on similar operational considerations of possible concepts within the categories. This permitted general evaluations that applied to the class of device in addition to more specific analysis of the most promising configurations within the categories. The number of different configurations evaluated was restricted to the minimum 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.

To minimize the possibility of obtaining a biased evaluation each grouping was studied independently. The objective was to evaluate the various techniques relative to the system criteria without intercategory comparisons that might influence the results. Based on the results of the evaluations, systems were recommended for the Phase II Detail Design Study.

In the Phase II study a detailed design and analysis of the selected propellant management concept was conducted. The approach was to analyze the design based upon existing criteria, where possible, and to verify the analysis by subscale experimental testing. The major areas considered most significant to successful operation of the expulsion device that were analyzed are:

1) Hydrostatic stability to axial and lateral accelerations;
2) Hydrodynamic stability to axial and lateral accelerations;

3) Effect of propellant resettle characteristics on liquid collection time;
4) Expulsion efficiency;
5) Outflow characteristics;
6) Compartment refill capability;
7) For the retrofit design, propellant siphoning during adverse acceleration environments.

Analyses were conducted in sufficient detail for each of the areas to yield a high confidence design. The experimental verification of the analysis consisted of conducting subscale experiments at scaled operational conditions to show that the design would function as predicted. No attempt was made to define limits, only to establish satisfactory operation at the required design points.

In addition to the propellant management system study, a separate task to conduct a literature survey update on low-g fluid mechanics was conducted. The approach taken on this task was to compile all the publications on low-g fluid mechanics and heat transfer since January 1967. The articles were then reviewed and the more pertinent ones identified with general comments concerning their significance.

## V. BASIC DATA GENERATED AND SIGNIFICANT RESULTS

The results from the Phase I and Phase II portions of this study will be presented separately in this section. Only a brief discussion of the analysis used and end results obtained will be presented. More detailed discussion of the supporting work leading to the conclusions can be found in the appropriate phase report.

### A. PHASE I

During this phase of the program the various types of expulsion systems were evaluated for the given advanced mission requirements. Each system was judged on the following criteria:

Adaptability;
Reliability;
State-of-art;
Weight;
Development time and cost;
Expulsion efficiency;
Passive operation;
Propellant slosh control;
Series tankage capability;
Pressurant gas ingestion;
Adaptability to varying acceleration gaging system.

A summary of the evaluations of the more important techniques is presented in Table 2. Significant aspects of the summary are:

1) The only systems that approach the 10-lb design goal are capillary systems;
2) The only system capable of retrofit to the existing tankage is a capillary system;
3) The only systems capable of very high cycle life (>100) are bellows and capillary systems;
4) The only system capable of adaptation to series tankage is a capillary system.

Based on the evaluations, only capillary retention systems were recommended for the Phase II Detail Design Study.

## B. PHASE II

In Phase II the recommended capillary concepts from Phase I were selected for the detail design study. The initial task was to finalize design details as structural mounting requirements, compartment sizes, and capillary structure effective pore sizes, and configurations. Figures 2 and 3 show the final configurations with major components identified for the no-hardware-change design and the no-hardware-limitation design, respectively.

The systems were designed to perform the mission requirements as outlined. In most cases a minimum design safety factor of two was used, i.e., the theoretical failure point was at least twice the actual required operating point. In general in the design of a capillary system the perforated material pore size will be determined by the most severe environmental aspect with the resultant design exhibiting a considerable margin of safety for the other environmental conditions. For the coverplates in the system the critical sizing condition is the lateral steady-state acceleration of 0.009 g. The criteria used to define the stability of this condition is the retention capability of the capillary structure. The capillary pore must be small enough to prevent gas penetration against the hydrostatic pressure difference developed across the coverplate due to the lateral acceleration.

Table 2 Propellant Control Systems Evaluation Summary

| Technique / Criteria | Nonmetallic | | Metallic* | | 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† | 10.7 - 18.7 | 94† | 91† |
| 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 Rank Redesign | Retrofit Possible | Extensive Tank Redesign | Extensive Tank Redesign |
| Duty Cycle Limitations | None | None | None | None | No. Restarts Constrained | 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‡ | 1 | 1 | 5 | 4 | 1 | 3 | 2 |
| Development Time and Cost‡ | 2 | 2 | 4 | 3 | 1 | 4 | 3 |

*All metallic systems are rated based upon titanium construction.

†Tank weight additions due to configuration change not included.

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

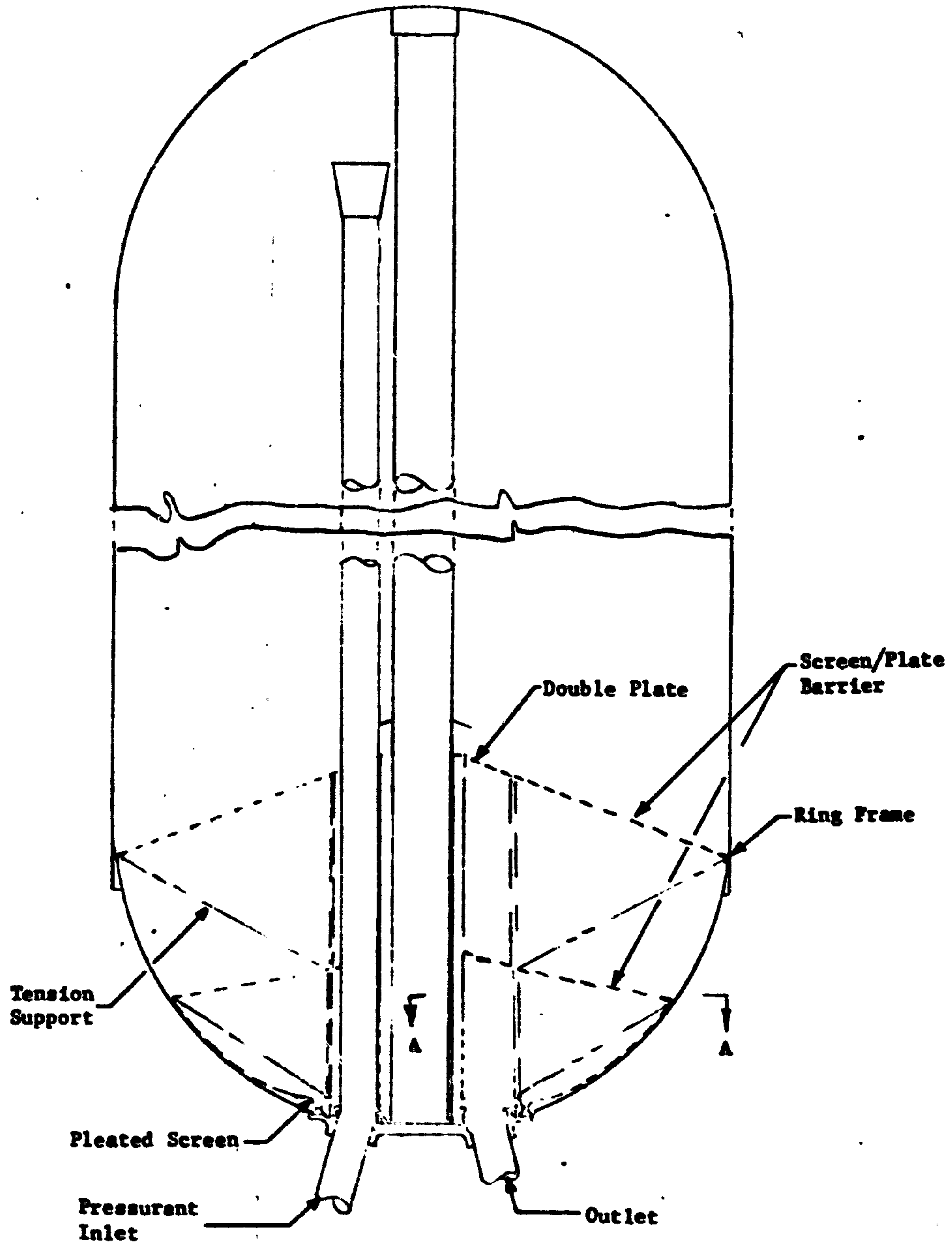


Fig. 2 Retrofit Capillary Design

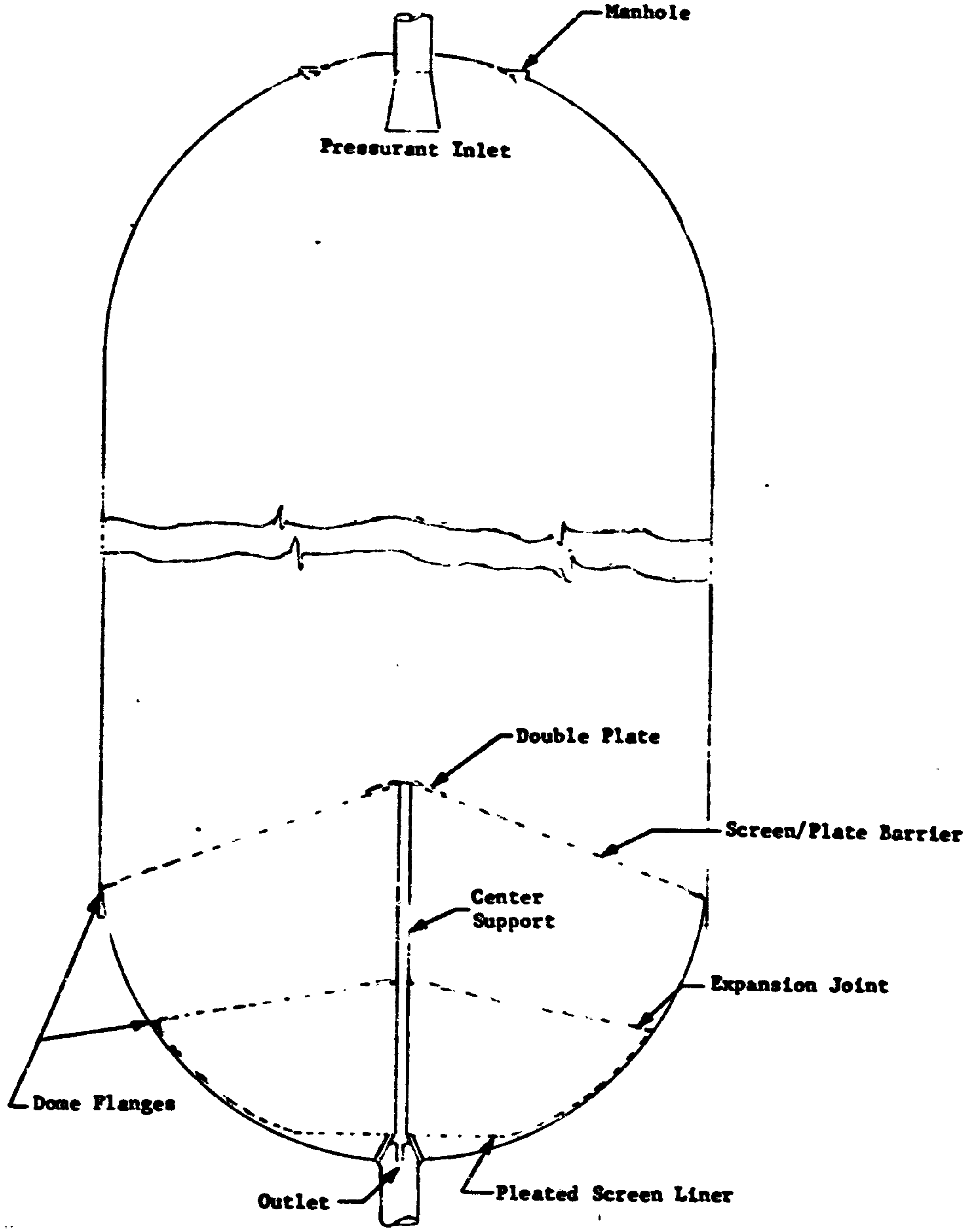


Fig. 3 No-Hardware-Limitaion Capillary Design

$$\frac{2\sigma\varphi}{r} = \rho g h \qquad [1]$$

where

$\varphi$ = function of contact angle and pore configuration,

$\sigma$ = liquid surface tension,

$r$ = radius of curvature of liquid/vapor interface in pore,

$\rho$ = liquid density,

$g$ = system acceleration,

$h$ = exposed height along acceleration vector.

For the system to be stable, the maximum capillary retention capability of the capillary barrier must be greater than the pressure difference developed across the barrier. For an ideal circular pore the maximum retention capability is when the radius of curvature of the interface equals the pore radius.

$$\Delta P_c = \frac{2\sigma}{r_p} \qquad [2]$$

where $r_p$ = pore radius. Therefore the pore size for stability can be defined in terms of the system environment by rearranging Eq [1] and [2].

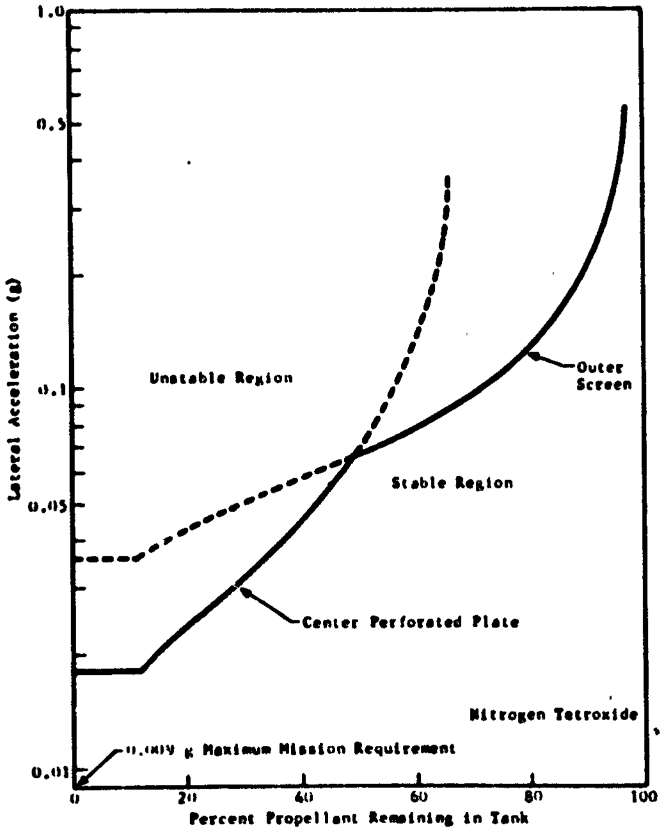


Fig. 4 Compartment Lateral Acceleration Retention Capability

$$r_p = \frac{2\sigma\varphi}{\rho g h}\left[\frac{1}{z}\right] \qquad [3]$$

where z = design safety factor. The stability of the coverplate as a function of the lateral acceleration is shown in Fig. 4 for the selected design pore size of 0.020 diameter center collar and 30 x 250 mesh outer periphery.

The enclosed volume was determined by the 50 restarts, 1-sec duration mission requirement. The total volume is 22 cu ft with the lower compartment containing 6 cu ft of this volume. In an actual condition this is probably extremely conservative since restarts with bulk liquid contact on the barrier surface would not consume liquid from the reservoir and some propellant refill would occur even under pulse mode operation. However to avoid possible limitations of application by defining the duty cycle burn durations and sequencing in detail, a worst-case conservative approach was used for sizing. Fewer restarts (~15) or a more detailed duty cycle definition could result in elimination of the upper coverplate. The functioning of the lower compartment is completely independent of the upper retention barrier. The upper barrier merely retains a liquid reservoir at the lower compartment that will supply propellant feed prior to main propellant settling. Only the lower compartment provides the gas-free negative and zero-g outflow capability. Propellant feed from the upper to lower compartment is acceleration dependent. Liquid contact with the lower coverplate is established only by virtue of the liquid interface shape in low-g or by positive-g settling.

The lower compartment maximum size is limited by the liner capillary retention capability. The worst-case condition that determines the design is near the terminal drain condition when the system positive axial acceleration is a maximum. The liner must prevent gas penetration from the compartment into the annular outflow region as illustrated in Fig. 5. The pressure drop across the liner is:

$$\Delta P = \Delta P_H + \Delta P_f \qquad [4]$$

where

$\Delta P_H$ = hydrostatic pressure term,

$\Delta P_f$ = viscous losses across liner.

In this case solving for the pore size required to retain the pressure drop for a 22-cu-ft capacity reservoir yields an answer that is not within the current or anticipated future capillary liner material capabilities. Therefore a multiple reservoir system was required. The best compromise in existing capillary materials was selected (250 x 1370 Dutch Twill mesh) and the maximum compartment size calculated based on its flow resistance and retention characteristics.

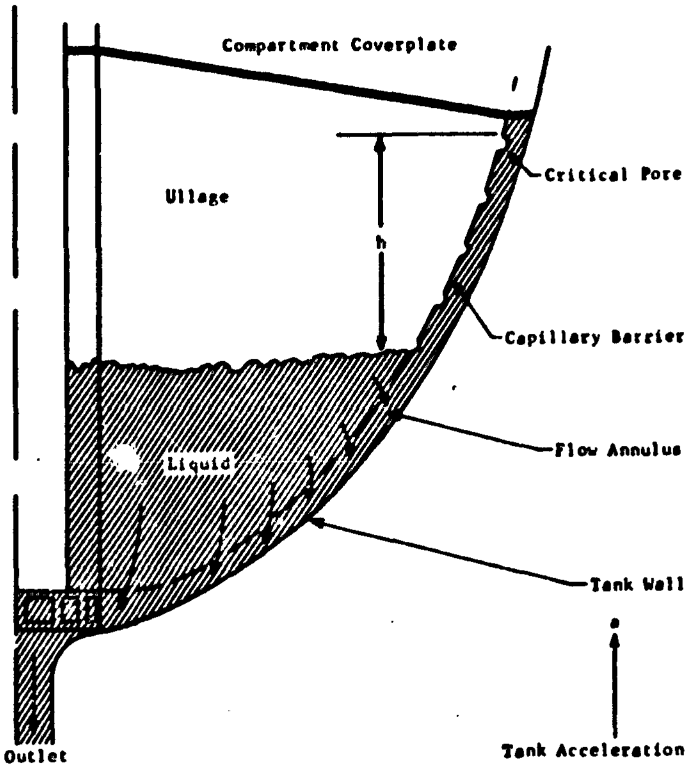


**Fig. 5 Schematic of Screen Liner during Terminal Drain**

An additional design consideration for the no-hardware-modification system was to prevent siphoning from the propellant compartments through the gaging system stillwell. Unless provisions are incorporated to uncouple the liquid compartments from the stillwell, under certain combinations of environmental conditions it would be possible to pump all of the liquid from the compartments through the stillwell. The approach in this design was to isolate the compartments from the stillwell by use of an annular volume around the stillwell that could be drained to provide an ullage path to the stillwell base. A screen capillary flow channel around the periphery of the channel base permits complete drainage of the annulus and stillwell into the retention compartments during terminal outflow.

Analysis and subscale testing were conducted on the designs to define their operational characteristics and verify the predicted performance. The specific areas investigated were:

1) Hydrostatic retention;
2) Hydrodynamic stability;
3) Resettle and liquid collection;
4) Trap refill characteristics;
5) Zero-g interface tests;
6) Expulsion efficiency at terminal draining;
7) Siphoning (applicable to no-hardware-change configuration only).

Hydrostatic Retention - The interface stability characteristics of the capillary systems are characterized by the Bond Number

$$Bo = \frac{\rho a r_p^2}{\sigma} \qquad [5]$$

where a is the system acceleration normal to the liquid/gas interface. The critical Bond number for stability is approximately 0.84. The Bond number for various elements in the design at significant acceleration levels is presented in the following tabulation.

| Element | Accel (g) | Bond Number | | Stability |
|---|---|---|---|---|
| | | $N_2O_4$ | A-50 | |
| Coverplate | 7.35 | 0.27 | 0.15 | Yes |
| Holes | 1.0 | 0.04 | 0.02 | Yes |
| (0.021 in. D) | 0.2 | 0.007 | 0.004 | Yes |
| Stillwell | 0.2 | 420 | 230 | No |
| (5 in. D) | $10^{-5}$ | 0.02 | 0.01 | Yes |
| Tank | 0.2 | 40,000 | 20,000 | No |
| (51 in. D) | $10^{-5}$ | 2.2 | 1.2 | No |

The maximum retention capability of the capillary structures can be represented by the following equation:

$$\Delta P = \frac{2\sigma\varphi}{r_p} \qquad [6]$$

The retention capability of the capillary elements as determined by bubble point testing and the resulting $\varphi$ value as defined in Eq [6] are given in the following tabulation.

| Element | Bubble Pressure (Methanol Test Fluid) | $\varphi$ |
|---|---|---|
| Coverplate Single Layer (0.024 in. D) | 0.021 psi | 1.0 |
| Double Layer (0.024 in. D holes 0.019 in. gap) | 0.032 psi* | 1.47 (based on single pore surface) |
| 30 x 250 mesh | 0.094 psi* | 0.728 (based on 100μ equivalent pore size) |
| 250 x 1370 mesh | 0.505 psi* | 0.701 (based on 18μ equivalent pore size) |
| *Tested after fabrication into test model hardware | | |

Hydrodynamic Stability - The criterion for establishing the dynamic stability of the capillary system coverplates is the Weber number:

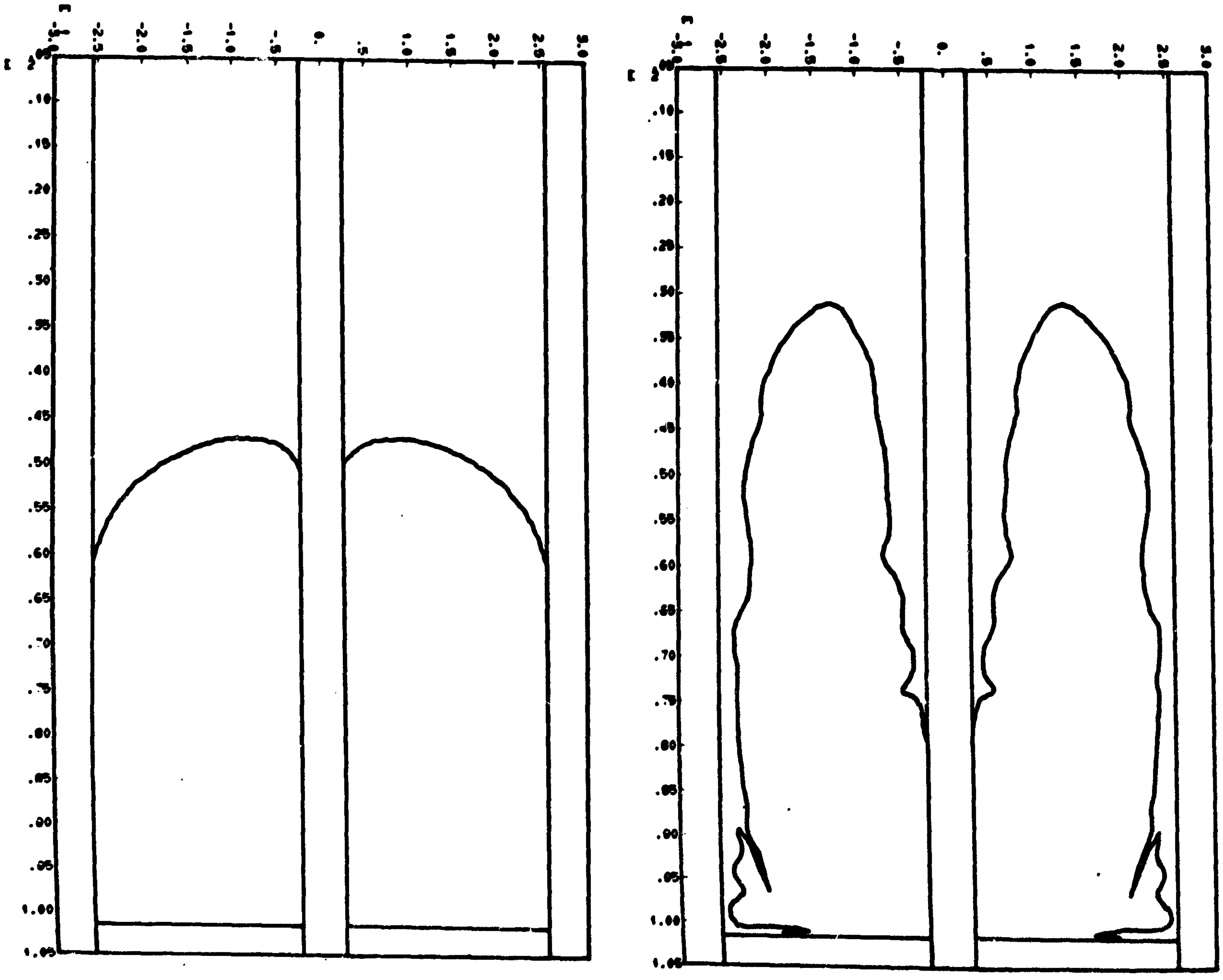
$$We = \frac{\rho v^2 r_p}{\sigma} \qquad [7]$$

where v is the liquid velocity at the pore. Analysis and experimental testing verify the stability of the coverplates due to the lateral excitation. A modified form of the Weber number has been used to establish stability during rotational maneuvers:

$$We = \frac{\rho \dot{\theta}^2 R^3}{\sigma} \qquad [8]$$

where $\dot{\theta}$ is the angular velocity and R is the tank radius. Testing in this mode was not conducted, but comparison with previous data verifies stability of the coverplate design.

Resettle and Liquid Collection - An analysis using a Martin Marietta-modified version of the Marker and Cell computer program was conducted to establish the resettle flow characteristics at engine thrust initiation in the cylindrical tank with the center stillwell. The initial interface configuration and flow profile is shown in Fig. 6. Of special interest is the fact that the primary flow occurs along the wall.

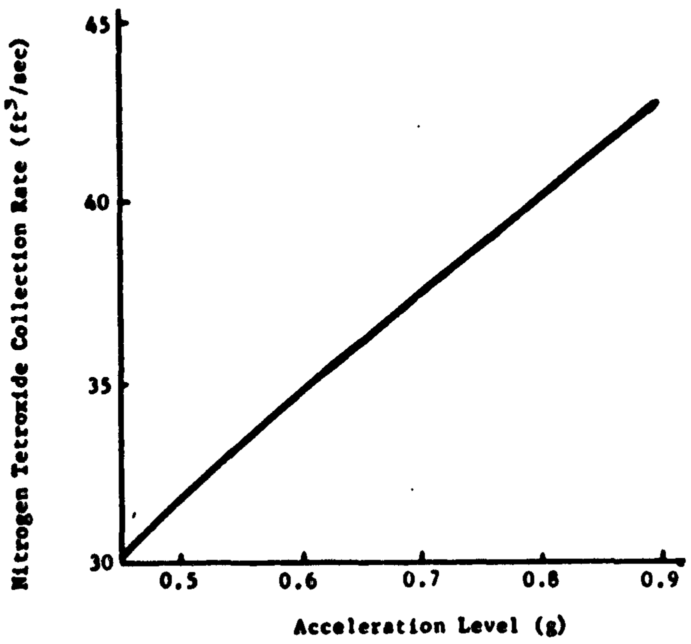


**(a) Initial Interface in $10^{-5}$ g Environment**

**(b) Interface 0.75 sec after Initiation of 0.6-g Resettle Acceleration**

Fig. 6 Propellant Resettle Characteristics

A primary consideration in proper sizing of the retention system is to establish when the liquid collection rate from propellant settling is sufficient to supply the steady-state engine feed rate. An empirically based simplified mathematical model was used to predict the rates shown in Fig. 7. These results indicate that the required flow is established well before the design-based allowable value of 1 sec. Qualitative



Fig, 7 Propellant Collection Rate on Capillary Compartment Coverplate

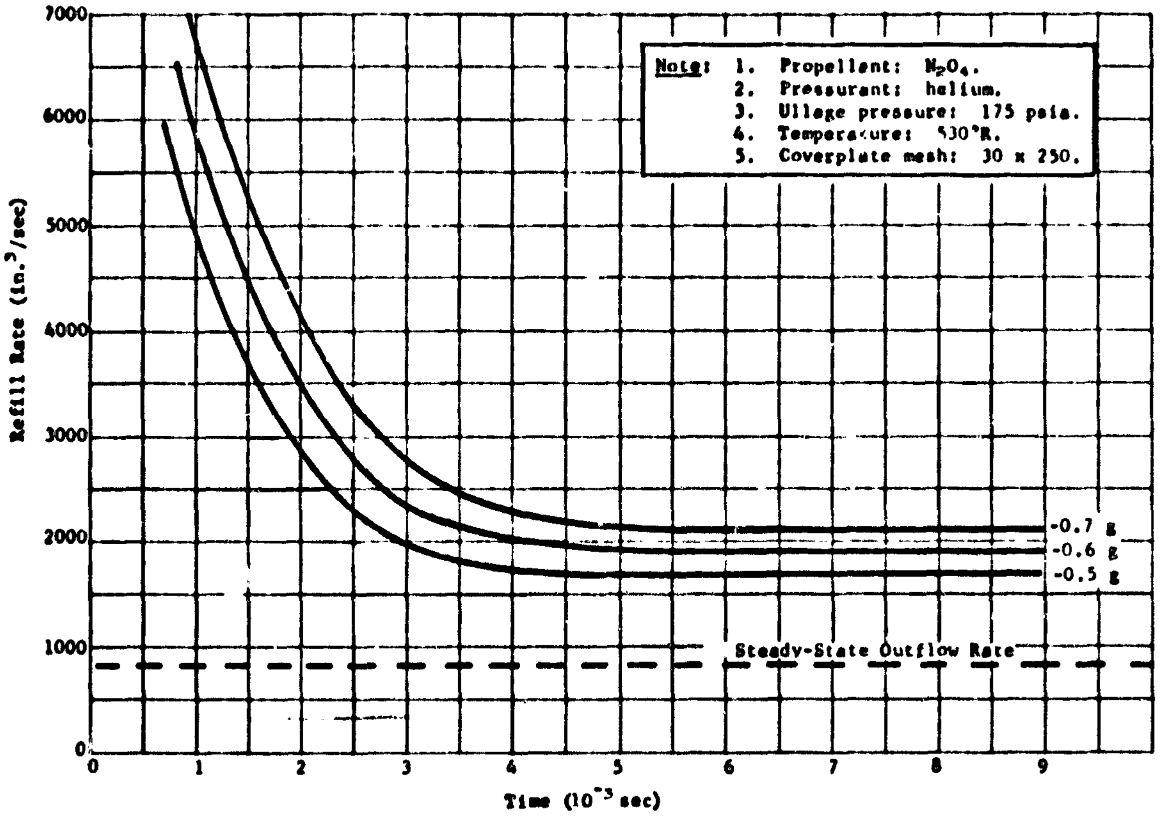
subscale tests verified that little rebound occurred at impact of the resettle propellant and that large liquid collection rates do exist. These tests also demonstrated the effectiveness of the capillary barriers to separate the two phase turbulent fluid caused by impact on the upper coverplate and maintain a rather quiescent single-phase liquid reservoir in the compartments.

Trap Refill Characteristics - A mathematical model describing the propellant flow characteristics across the retention compartment coverplates was constructed. The model was used to predict the refill flow rates shown in Fig. 8 for the retention compartments during thrusting. Subscale testing verified compartment refill.

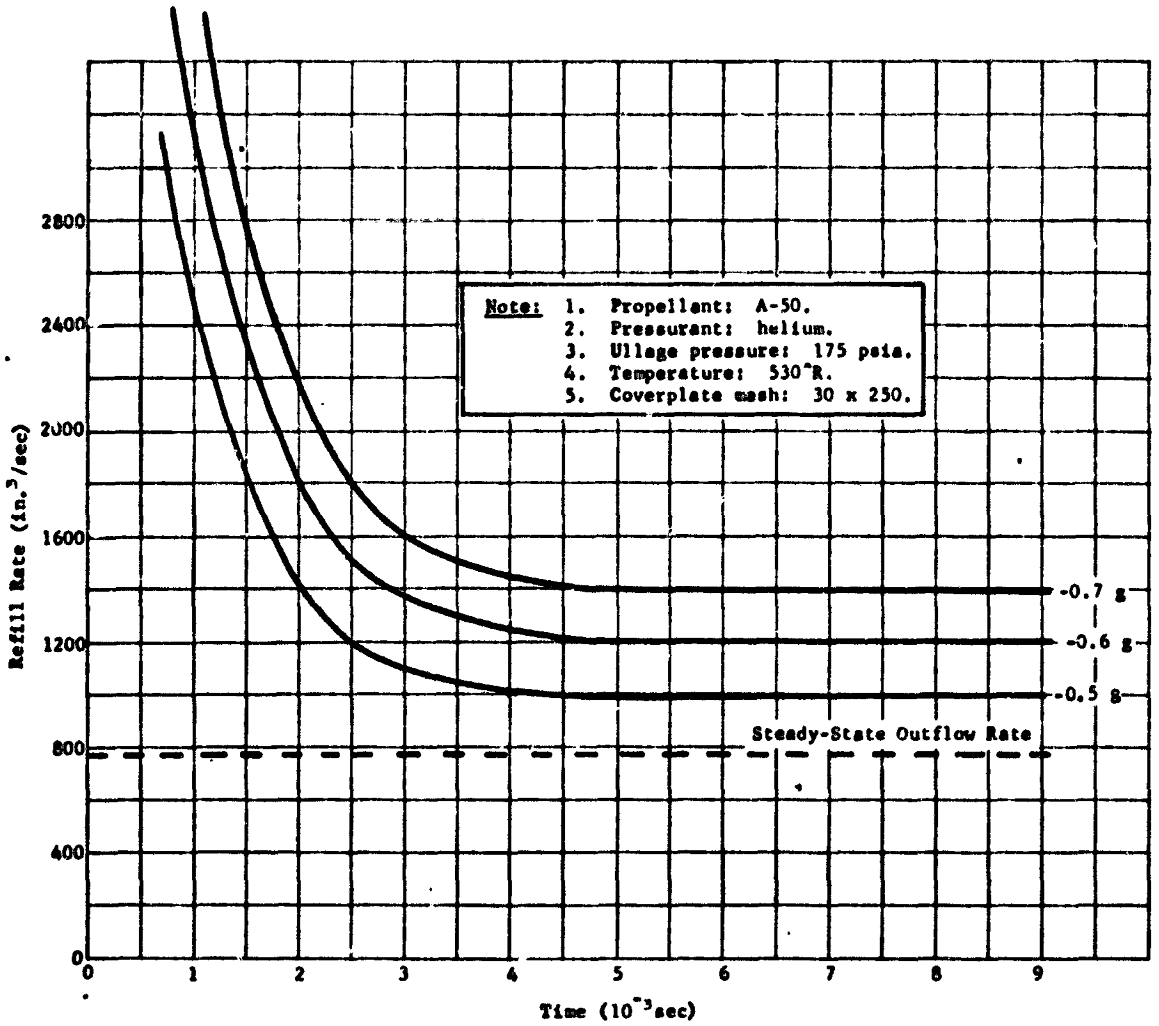
Zero-G Interface Tests - Analysis and experimental testing were conducted to determine the zero-g equilibrium liquid/gas interface in the lower compartment at the time of engine start initiation for partially empty conditions. The liquid-to-screen liner contact area is a critical parameter in the design of the compartment to prevent vapor pullthrough during engine start. Results showed that the contact area on the liner portion is substantial with sufficient area to permit outflow without breakdown for very small propellant volumes.

Expulsion Efficiency - The expulsion efficiency of the capillary system was calculated. The trapped volume residuals are less than 0.5% of the total tank volume for both designs. An analysis was conducted to ensure the compartment coverplates would drain completely during a terminal burn before gas penetration into the outlet. The model was a modified version of the one used for the trap refill analysis. Results of the analysis, Fig. 9, show that complete draining will occur. Subscale model tests also showed complete drainage from the compartments.

Analysis was also performed of the terminal draining from the lower compartment liner to determine the point at which liner breakdown would occur. The analysis, as well as subscale testing, showed complete drainage of the liner before gas penetration.



(a) Oxidizer



(b) Fuel

Fig. 8 Compartment Refill Flow Rate

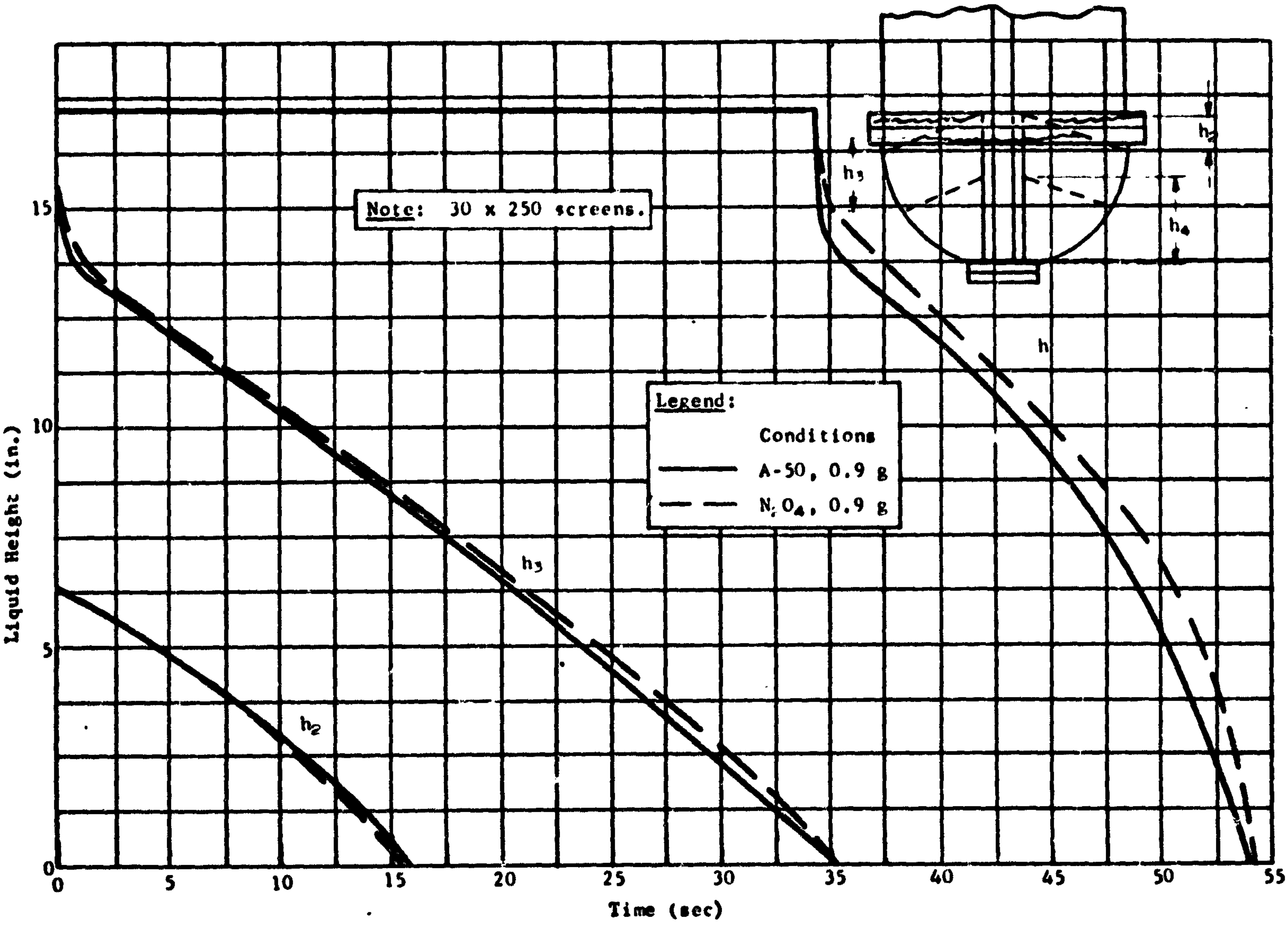


Fig. 9 Liquid Draining Hist ries

Siphoning - An analysis of the potential siphoning of propellants from the retention compartments during negative thrusting was performed for the system with the stillwell in the center, no-hardware-change configuration, Fig. 2. The results of the analysis are shown in Fig. 10. It was not reasonable to design the system to prevent siphoning completely, however as the results show, little fluid is lost even at the maximum negative acceleration of 0.2 g with a full standpipe for the initial condition.

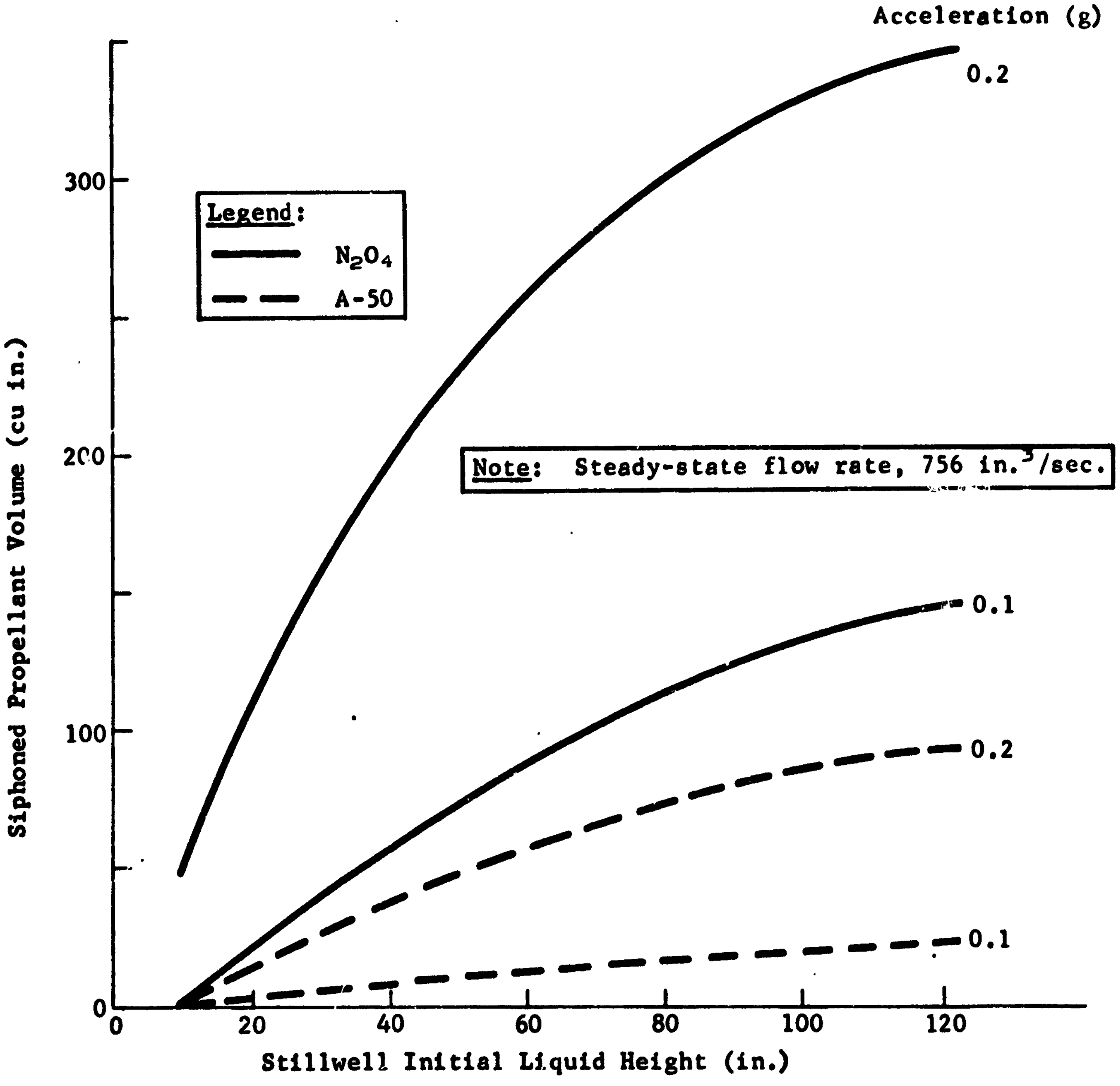


Fig. 10 Capillary Compartment Propellant Loss from Stillwell Siphoning Action

## VI. LIMITATIONS

The primary limitation of the study is the lack of detailed structural analysis. This is in part due to two factors, a need for more detailed system characteristics and a lack of design experience for structures of this type in large-scale tankage. A specific design area requiring further development is the Teflon seals around the periphery of the lower coverplate. This seal must effect an 18-micron equivalent pore seal around the tank circumference.

A transient analysis of the system start characteristics was not conducted. This type of analysis would require incorporating the details of a specific design feed system including line sizes, volumes, and valve responses to the capillary system. For a general application study of this type a meaningful dynamic analysis of the start transient is not possible. Such an analysis should be conducted for a specific system application to ensure that gas ingestion will not occur during engine start.

While there is little doubt that the configuration developed is a sound and workable concept, additional experimental data are required to establish design limits and detailed operational characteristics. The limitations of the experimental techniques and facilities could only provide a qualitative verification of predicted performance in most cases. However the analysis indicates the design is conservative for the mission requirements. A final design optimization would require full-scale hardware fabrication and test.

## VII. IMPLICATIONS FOR RESEARCH

While a considerable amount of analysis and experimentation has been conducted in the area of low-g fluid behavior, in most cases the results are limited to simple geometries and axisymmetric disturbances. In real applications this is rarely the situation. For programs of this type with complex geometries a heavily empirical approach is suggested. This requires an extensive experimental program to define the fluid characteristics in terms of design optimization. Such programs should be based on defining meaningful hardware design criteria rather than elaborate theoretical analysis of fluid behavior under ideal conditions. While theoretical analysis is valuable for defining the interrelationship of critical parameters, the apparent technology gap is not in the theory but in a strong experimental design base. Long term low-g test data on fluid behavior under orbital conditions is required in some cases to establish empirical relationships without the attendant shortcomings of low-g test time restrictions and scaling up from small test models. Another area for research is in the fabrication of capillary materials. Currently most of the work with porous materials is limited by the available materials and techniques developed for other technologies. Research into special weaving and forming procedures and new types of porous materials for the specific application to fluid management systems should be conducted. Improvements in material fabrication and types of materials fabricated could extend the capability and range of application for these devices.

## VIII. SUGGESTED ADDITIONAL EFFORT

Additional efforts that would enhance the results of this study or appear to be a logical extension of this work are:

- Investigate the impact of other propellants, especially space storables and cryogens, on the design of capillary propellant management systems;
- Conduct research into new approaches to obtain capillary structures with small effective pore sizes and low flow resistance;
- Develop wire weaving technology to cover a broader range of materials (e.g., aluminum and titanium in fine mesh at a reasonable cost);

- Determine the stability of the liquid/vapor interfaces in capillary barriers under high frequency vibrational environments;
- Conduct manufacturing technology programs to verify and/or develop fabrication techniques;
- Fabricate and install the proposed design into the existing Apollo propulsion system tankage and test it during a future flight.