BELL AEROSYSTEMS COMPANY
DIVISION OF BELL AEROSPACE CORPORATION

APOLLO RCS POSITIVE EXPULSION TANKAGE PRODUCT IMPROVEMENT PROGRAM

FINAL REPORT - TASK A

EVOLUTION OF APOLLO-TYPE POSITIVE EXPULSION PROPELLANT TANKAGE

Bell Report No. 8514-927002
26 September 1969

(Supersedes Initial Submittal of 12-31-67)

By

Robert K. Anderson and Elvin J. Ecelbarger

Prepared Under Contract No. NAS9-7182

By

Bell Aerosystems Company
Buffalo, New York

For

National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas

NASA CR ...

BELL AEROSYSTEMS COMPANY
DIVISION OF BELL AEROSPACE CORPORATION

19

APOLLO RCS POSITIVE EXPULSION TANKAGE PRODUCT IMPROVEMENT PROGRAM

FINAL REPORT - TASK A

EVOLUTION OF APOLLO-TYPE POSITIVE EXPULSION PROPELLANT TANKAGE

Bell Report No. 8514-927002
26 September 1969

(Supersedes Initial Submittal of 12-31-67)

By

Robert K. Anderson and Elvin J. Ecelbarger

Prepared Under Contract No. NAS9-7182

By

Bell Aerosystems Company
Buffalo, New York

For

National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas

FOREWORD

This report is one of a series of task reports which present the results of a program performed by Bell Aerosystems Company during the period July 1967 through September 1969 under Contract NAS9-7182 for the National Aeronautics and Space Administration, Manned Spacecraft Center. Mr. Darrell Kendrick was Technical Monitor of the program for NASA. The Bell Aerosystems Program Manager was Mr. R. K. Anderson.

The purpose of the program was to improve and update the Apollo RCS positive expulsion propellant tank assemblies in the areas of performance, reliability and mission duration. The program effort was divided into the following major tasks, each of which is reported separately:

Task A - Historical Summary Report - A chronological summary of the evolution of the Command, Service, Lunar Module and other related tankage was prepared. This summary includes data on all configurations considered under the applicable programs and describes related IR&D work at Bell Aerosystems.

Task B - Long Term Compatibility Testing - The purpose of this task was to determine the useful operating lifetime of the Apollo Configuration RCS tanks as applicable to a mission of extended duration with a specific goal of 12 months. This task consisted of the following sub-tasks:

B-1: Tank Assembly Storage: Three tank assemblies were stored with propellant (N_2O_4, MMH, 50/50 fuel blend) for 12 months at operating pressure. At the end of this time each tank was subjected to a complete propellant expulsion followed by disassembly and evaluation.

B-2: Bladder Material Compatibility Testing: Teflon bladder material specimens were subjected to rolling of buckled fold tests after 24 hours, six months, and 12 months exposure to N_2O_4, MMH and 50/50 fuel.

B-3: External Flange Seal Evaluation: The effect of initial flange bolt tightening and retightening techniques on the rate of torque decay during a one-year shelf storage period was evaluated.

Task C - Correlation of Referee Fluid and Propellant in Vibration Testing - The objective of this task was to verify that vibration testing of the Apollo type bladder with referee fluid is representative of vibration testing with actual propellants. To develop a correlation with sufficient accuracy, the following three areas of testing were pursued:

C-1: Vibration tests were conducted with referee fluid in a plexiglass tank to define the response characteristics of the bladder as affected by ullage level, direction of excitation and vibration input level.

C-2: Rolling of buckled fold tests were conducted on bladder material specimens to compare endurance in referee fluids with endurance in propellants.

C-3: Full scale vibration testing was performed on a Lunar Module RCS oxidizer tank with N_2O_4.

Task D - Elimination of Permeation and Bubble Formation - The objective of this task was the elimination or reduction of bladder permeation and the associated problem of bubble formation within the bladder. This task included two principal areas of effort:

D-1: Development of Permeation Barrier: This sub-task consisted of design and fabrication of a Teflon bladder with an aluminum foil laminate as a permeation barrier. This bladder, which was of the Service Module oxidizer configuration, was also designed to function in an undersized configuration.

D-2: Elimination of Bubble Formation in Current Apollo Bladder Configuration: Experiments were conducted on both model and full-scale tanks to examine bubble formation phenomena as a function of such variables as temperature, pressure and ullage level. Data from these tests were used to provide an emperical basis to better understand the mechanisms involved and the effect of each on bubble formation.

Task E - Solution of Command Module and Service Module Oxidizer Repositioning Problem - The objective of this task was to increase expulsion cycle life of these bladders by eliminating damage due to post-expulsion repositioning.

E-1: Service Module Oxidizer Bladder: The approach used to solve this problem was the use of an undersized configuration similar to that used on the Lunar Module RCS tanks to solve the same problem.

E-2: Command Module Bladder: This problem was associated with the twist mechanism involved in a horizontally mounted tank during the fill cycle. A solution to this problem could not be found within the constraints of the program.

Task F - Integration and Verification of Solutions - The objective of this task was to devise a series of formal tests to demonstrate compliance of design changes from Tasks D-1 and E with the requirements of the applicable Apollo contractor procurement specification.

Service Module oxidizer bladders of the undersized configuration with an aluminum foil laminate were subjected to Qualification level vibration testing and were to be subjected to 20-propellant expulsion cycles. However, problems occurred during vibration testing which resulted in bladder failure and this task could not be completed within the limits of this program.

Since the Command Module bladder twist problem was not solved (Task E-2), no Command Module tank testing was performed in Task F.

This report covers the effort performing under Task A. The other major tasks are reported individually as follows:

Task	Report Number	Title
B	8514-928004	Long Term Compatibility Testing
C	8514-928005	Correlation of Referee Fluid and Propellant Vibration Testing
D	8514-928003	Elimination of Permeation and Bubble Formation
E	8514-928006	Solution of Command Module and Service Module Repositioning Problems
F	8514-928007	Integration and Verification Testing

ACKNOWLEDGEMENT

The preparation and format of this report are largely the product of its co-author, Mr. E. Ecelbarger, Supervisor of Technical Documentation for Bell Aerosystems' Structural Systems Department.

The scope, details, and historical accuracy of the contents of this report were made possible by many Bell Aerosystems employees who contributed their time and efforts, even though some are no longer associated with the Apollo and other tankage programs reported herein. Their wholehearted and generous cooperation is greatly appreciated. Principal among these contributors are:

Mr. T. Maurer
Mr. J. Z. Colt
Mr. L. M. Thompson
Mr. C. T. Kessing
Mr. T. Glynn
Mr. J. T. Pillittere
Mr. J. Wolf
Mr. S. A. Mekarski
Mr. R. A. Peltier
Mr. C. A. Armontrout
Mr. W. Page
Mr. R. J. Szpakowski

PREFACE

This report was prepared by Bell Aerosystems Company in response to Task A of NASA Contract NAS9-7182, "Apollo Command Module, Service Module, and Lunar Module RCS Positive Expulsion Tankage Product Improvement Program."

The objective of this program, Bell Model No. 8514, is to improve and upgrade the Apollo RCS tankage in the areas of performance, reliability, and mission duration.

The purpose of this report is to provide a summary of the total effort on each of the mainstream Apollo-type tankage and associated programs and in addition show the relationships between them. This effort encompasses ten separate programs during the period of October 1962 to December 1968. These programs were aligned to a common technology concept; however, they were individual contracts performed for different contractors. Although the programs were conducted on a common basis, each program had its own sequence of events.

The information in this report is presented to document technical activity and show the chronological sequence of events. The intent is to report this activity in sufficient detail so that future repetition of effort can be avoided. Although there is an abundance of test information, detailed test results are included only if they were significant for tank assembly design or performance.

The report is organized in sections as follows:

SECTION I - INTRODUCTION

This section briefly identifies and describes the Bell supplied positive expulsion propellant tankage used on the Apollo vehicle and the experience base existing at the inception of these programs.

SECTION II - APOLLO TYPE TANKAGE CONTRACT SUMMARY

This section describes the common technology or "commonality" concept used as a basis for the five mainstream tankage programs and identifies the five associated projects which were used to supplement them. The chronological and technical relationships of these ten programs are presented and in addition pertinent reference information regarding the tank assembly testing and physical and performance characteristics are included in tables and illustrations.

SECTION III - MAINSTREAM TANKAGE AND ASSOCIATED PROGRAM HISTORIES

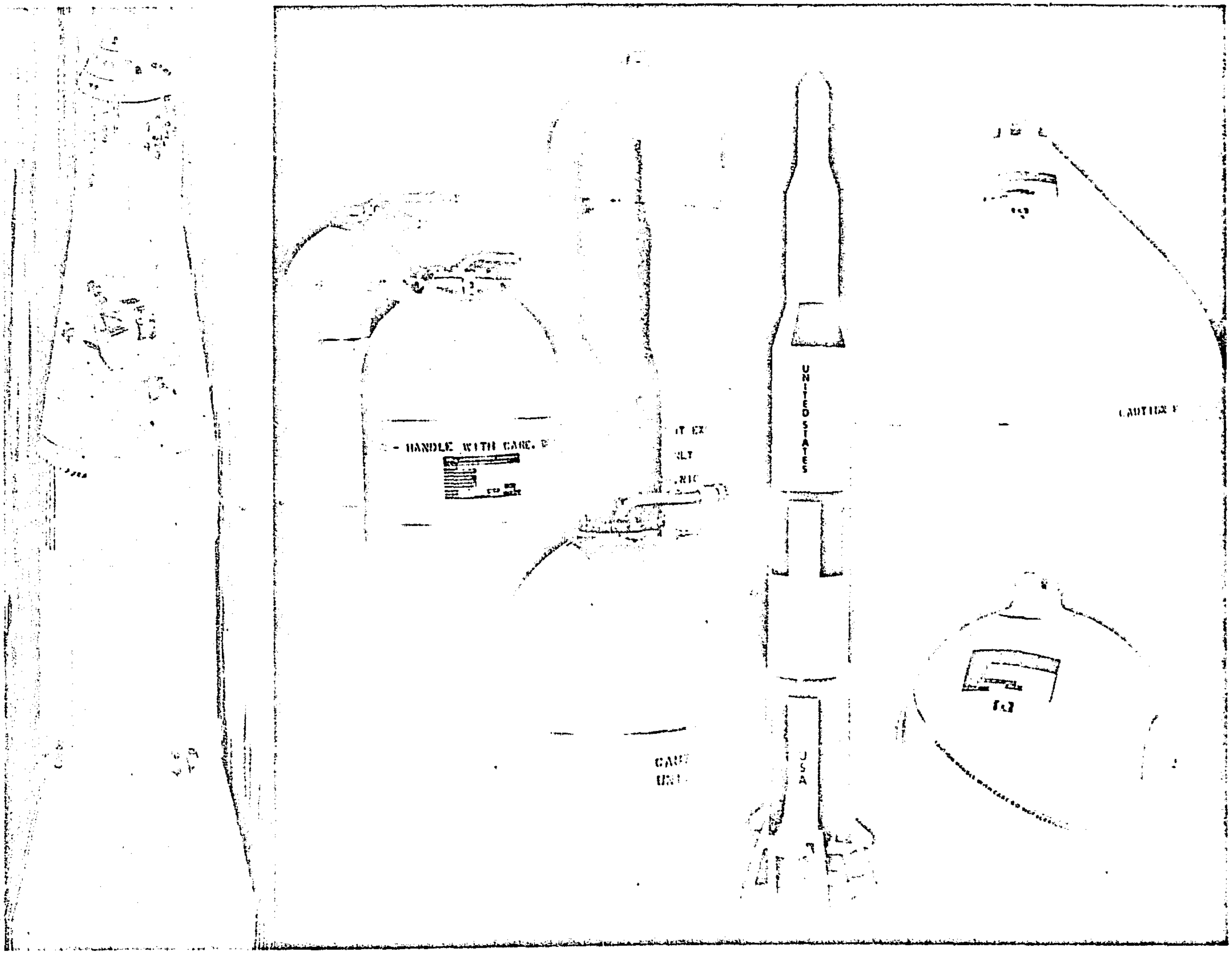
Because of the basic individuality of the programs, a separate subsection is used for each program. Each subsection contains a chronological history for a particular program with specific reference to events on other programs only when they had significant bearing on the activity. The chronological occurrence of major events and detailed test sequencing for the mainstream programs is presented in charts for reference use, and the supporting text includes at least mention of all salient points.

SECTION IV - MANUFACTURING AND QUALITY CONTROL

The information in this section is organized by component to document the major fabrication and assembly activity.

SECTION V - RELIABILITY

The reliability summary is generalized for all programs with the Lunar Module tankage used for specific reference.



APOLLO POSITIVE EXPULSION TANKAGE

CONTENTS

Section		Page
I	INTRODUCTION	1-1
	A. Apollo Positive Expulsion Tankage Definition	1-1
	B. Positive Expulsion Tankage Description	1-2
	C. Pre-Apollo Positive Expulsion Technology at Bell	1-2
	1. Research and Study Programs	1-5
	2. Design, Development, and Production Experience	1-6
II	APOLLO TYPE TANKAGE CONTRACT SUMMARIES	2-1
III	MAINSTREAM TANKAGE AND ASSOCIATED PROGRAM HISTORIES	3-1
	A. Model 8271 Command and Service Module Program Histories	3-1
	1. Proposal and Specification Activity	3-1
	2. Design and Development	3-2
	3. Development Testing	3-7
	a. Material Testing	3-7
	b. Plexiglass Tank Test Program	3-9
	c. Initial Prototype (DVT) Test Program	3-10
	d. Development Test	3-11
	e. Confidence Level Testing - Oversize Bladders	3-15
	f. Confidence Level Test Failure Investigations	3-16
	g. Pre-DVT Testing	3-20
	h. Alternate Design Activity	3-22
	i. Single-Ply Teflon Bladder Development	3-30
	j. Design Verification Testing (DVT)	3-34
	k. Additional DVT and Development Testing	3-38
	4. Qualification Configuration Formal Testing	3-45
	a. Service Module Tank Assembly Testing	3-45
	b. Command Module Tank Assembly Testing	3-52
	c. Propellant Exposure Testing	3-64
	d. Propellant Storage	3-65
	B. Model 8339 LM RCS Tankage Program	3-66
	1. Initial Design	3-66
	2. Design Development	3-66
	a. Diffuser Assembly	3-66
	b. Tank Shell	3-68
	c. Bladder	3-70

CONTENTS (CONT)

Section		Page
III (cont)	3. Design Verification and Overstress Testing	3-81
	a. Purpose	3-81
	b. Summary	3-81
	c. Test Sequence	3-82
	d. Test Results	3-82
	e. Summation	3-87
	4. Qualification Testing	3-89
	a. Summary	3-89
	b. Sequence of Testing	3-89
	c. Test Results	3-89
	5. Supplemental Testing	3-90
	a. Vibration and Shock Testing of Fuel Tank With Propellant	3-90
	6. Final Design Configuration	3-94
	C. Model 8400 Saturn SIVB Tankage Program	3-95
	1. Design	3-95
	2. Testing	3-97
	a. Development Testing	3-97
	b. Qualification Testing	3-106
	D. Model 8330 - Lunar Orbiter Positive Expulsion Tankage Program	3-109
	E. Associated Program Histories	3-114
	1. Bell Model 8460 - Design Criteria and Quality Control Studies for Teflon Expulsion Bladders	3-114
	2. Apollo Titanium - N_2O_4 Stress Corrosion Investigation.	3-116
	3. Bell Model 2312 - Service Module Aluminum Tank Shell.	3-119
	4. Bell Model 8508 - Nitrogen Tetroxide Exposure Test Programs	3-120
	5. Bell Funded R & D Bladder Material Programs	3-123
	a. Purpose.	3-123
	b. Elastomeric Bladder Material.	3-123
	c. Improved Teflon Bladder Material.	3-125
	d. Permeation Barrier Development	3-126

CONTENTS (CONT)

Section		Page
IV	MANUFACTURING AND QUALITY CONTROL	4-1
	A. Tank Shell Fabrication	4-2
	1. Processing Sequence	4-2
	2. Fabrication Problems	4-4
	a. Wall Thickness	4-4
	b. Mismatch	4-5
	c. Porosity	4-5
	d. Weld Bead Height, Width and Drop Through	4-6
	B. Bladder Fabrication	4-6
	1. Processing Sequence	4-6
	2. Fabrication Problems	4-8
	C. Diffuser Assembly Fabrication	4-9
	1. Bimetallic Joints	4-10
	2. Flange-to-Cone Weld	4-10
	3. Drilling	4-11
	4. Tube -to-Cone Weld	4-11
	5. Bleed Tube Weld	4-12
	D. Assembly and Acceptance Test	4-13
V	RELIABILITY	5-1
	A. Program Control	5-1
	B. Failure Mode and Effect Analyses	5-1
	C. Qualitative and Quantitative Analysis	5-2
	D. Reliability Block Diagrams	5-2

FIGURES

No.		Page
I-1	Typical Apollo Type Tank Assembly	1-3
I-2	Apollo Propellant Tank - Major Components.	1-4
I-3	Model 8101 Agena SPS Tank Assemblies	1-9
II-1	Apollo Positive Expulsion Propellant Tankage and Associated Programs	2-2
II-2	Command Module Tank Assemblies	2-8
II-3	Service Module Tank Assemblies.	2-9
II-4	Lunar Module RCS Tank Assemblies	2-10
II-5	Saturn APS Tank Assemblies.	2-11
III-1	Model 8271 Command, Service Module Tankage Program History	3-3
III-2	Model 8271 3-Ply Oversize Bladder Test Summary	3-14
III-3	Model 8271 Design Alternatives Development Test Summary . .	3-24
III-4	Model 8271 DVT and Development Test Summary	3-35
III-5	Model 8271 Command and Service Module Test History.	3-46
III-6	Model 8339 Lunar Module Tankage - Program History	3-67
III-7	Model 8339 Lunar Module Test History - Undersized Bladder Configuration.	3-76
III-8	Model 8400 Saturn SIVB Program History	3-96
III-9	Model 8330 Lunar Orbiter Program History.	3-110
III-10	Types of Expulsion Bladder Compositions	3-124
V-1	Typical Positive Expulsion Tankage Functional Block Diagram.	5-4
V-2	Lunar Module - Exploded View.	5-5
V-3	Reliability Logic (Block) Diagram, Positive Expulsion Tank, Typical.	5-6

TABLES

No.		Page
II-1	Apollo-Type Positive Expulsion Tankage - Physical Characteristics	2-5
II-2	Apollo-Type Positive Expulsion Tankage - Qualification Test Sequence	2-6
II-3	Apollo-Type Positive Expulsion Tankage - Qualification Dynamic Test Requirements	2-7
III-1	Expulsion Test Sequence	3-88
III-2	Lunar Orbiter Propulsion System Flight History	3-113
V-1	Typical Failure Mode and Effects Analyses	5-7
V-2	Propellant Expulsion Data Summary - Apollo Type Tank Assemblies	5-13
V-3	Propellant Expulsion Data Breakdown	5-14

SECTION I

INTRODUCTION

A. APOLLO POSITIVE EXPULSION TANKAGE DEFINITION

The NASA vehicle for the Apollo mission uses a total of 31 positive expulsion tanks supplied by Bell Aerosystems Company. These tanks are located in the command module, service module, lunar module, and Saturn IVB stage as shown in the frontispiece. Of these, three are lunar module water tanks containing cooling water for the environmental system and drinking water for the crew. The remaining 28 tanks are used for propellant as follows:

The command module tanks, supplied to North American Rockwell, contain the propellants for the reaction control system used for reentry maneuvers. The command module uses two fuel and two oxidizer tanks.

The service module tanks are also supplied to North American Rockwell and contain the propellants for the reaction control system used for positioning, orientation, and stabilization of the spacecraft during flight to and from the moon. The service modules use eight fuel and eight oxidizer tanks, of which four of each are of the command module configuration.

The lunar module tanks, supplied to Grumman Aircraft Engineering Company, contain the propellants for the reaction control systems used for positioning, orientation, and stabilization of the lunar module during descent to the lunar surface and ascent to and docking with the orbiting spacecraft. Two fuel and two oxidizer tanks are used on each lunar module.

The Saturn IVB positive expulsion tanks, supplied to McDonnell Douglas Company, contain the propellants for the auxiliary propulsion system which is used for ullage and attitude adjustment during powered flight, earth orbit, and translunar coast. Two oxidizer and two fuel tanks are used on each vehicle.

In addition to the Apollo vehicle, a modified version of the command module tankage was supplied to the Boeing Company for use on the Lunar Orbiter spacecraft. This tankage operated flawlessly during the five orbiter missions.

B. POSITIVE EXPULSION TANKAGE DESCRIPTION

Positive expulsion systems are necessary to provide continuous propellant flow to the engines regardless of vehicle position, environmental and dynamic forces, or zero gravity conditions where the propellant tends to float in the tank or cling to the tank wall instead of flowing naturally toward the tank outlet.

Each Apollo propellant tank (see Figures I-1 and I-2) has a titanium shell, Teflon bladder, and metal diffuser assembly. The propellant is contained inside the bladder. A pressurizing port is provided on the tank shell and a propellant outlet port and liquid bleed tube are incorporated in the diffuser assembly. The tank is capable of supplying propellant upon demand and will function from full propellant load conditions to propellant exhaustion. The propellant is loaded into the bladder through the propellant outlet port, When the bladder is full, gas is applied to the pressurizing port of the tank to pressurize the area between the tank shell and the outside of the bladder. The required amount of ullage is drained through the propellant outlet or bleed port and then the ports are closed. The tank is then ready to provide propellant to the reaction control subsystem upon demand. When demand for propellant is made, the pressurizing gas causes the bladder to collapse around the diffuser tube and the propellant is expelled through the propellant outlet port.

C. PRE-APOLLO POSITIVE EXPULSION TECHNOLOGY AT BELL

Activity in the field of positive expulsion propellant tankage started with the X-series of rocket aircraft in 1945 when the need arose for tankage which would positively and continuously supply propellant to the reaction control engines regardless of vehicle position and dynamic forces. A piston type expulsion tank was developed for the Bell X-1B research airplane and served as the expulsion device for the first known reaction control system.

After this initial endeavor, special emphasis was placed on positive expulsion devices. Early progress included the development and production of pressurization and propellant feed systems for the Kingfisher, Meteor, Shrike, and Rascal projects. These early systems were developed for a wide variety of propellants and provided important design and fabrication experience.

Positive expulsion technology began advancing at a very rapid pace in the late 1950's with initiation of the early manned and unmanned space programs. It was during this period that stringent weight, envelope, and efficiency requirements were imposed. In addition, the requirement for multicycle capability was necessary in most applications to permit actual system checkout firings and an abort capability

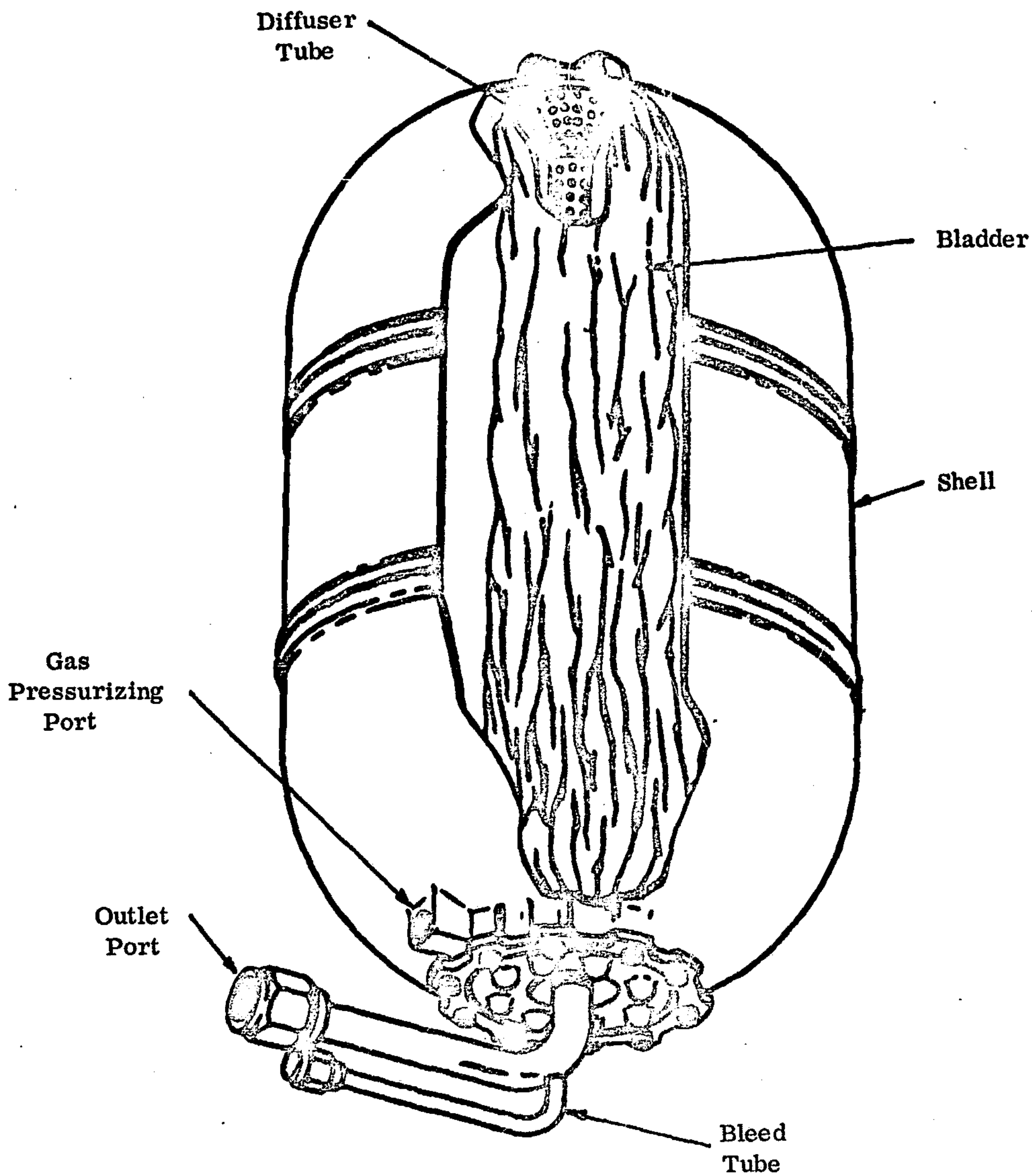


FIGURE I-1 TYPICAL APOLLO TYPE TANK ASSEMBLY

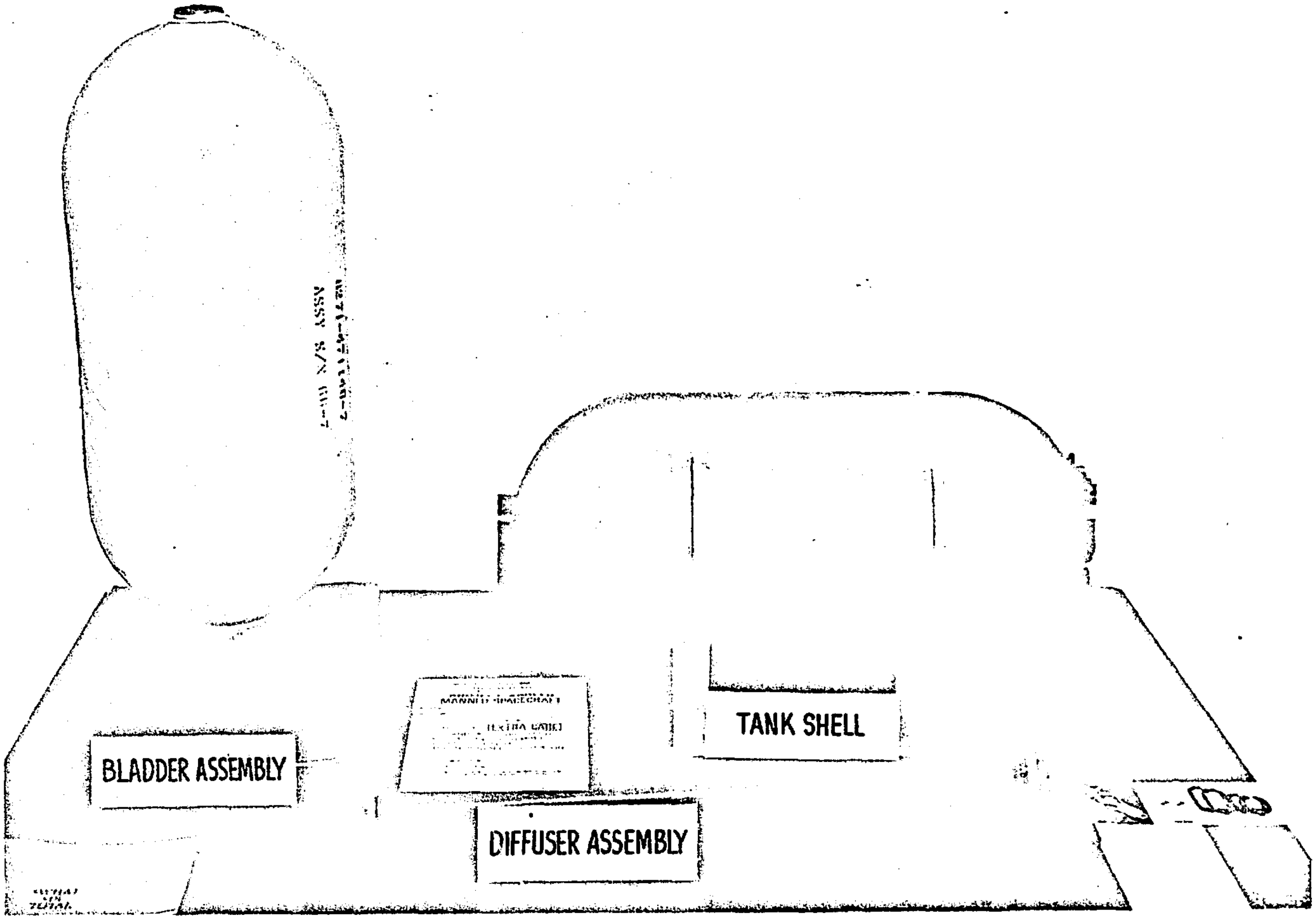


FIGURE I-2 APOLLO PROPELLANT TANK - MAJOR COMPONENTS prior to the actual mission cycle. This requirement necessitated the use of elastomeric bladders in the Mercury and Centaur hydrogen peroxide control systems and Teflon bladders for the Agena secondary propulsion system.

The pre-Apollo experience, at this point, separated into two areas: research and study programs for advanced positive expulsion concepts and design, development, and delivery contracts for positive expulsion tankage for flight vehicles.

1. RESEARCH AND STUDY PROGRAMS

The following is a summary of the major research programs in progress or completed by Bell at the inception of the Apollo program and depicts the background and experience used for the Apollo design:

Shipboard Storage of Liquid Rocket Propellant Tanks (U.S. Navy) - An experimental investigation was conducted in 1956 for the shipboard storage of liquid rocket propellant tanks using Teflon and butyl bladders. Propellants were stored in these tanks under shipboard conditions for one year and at the end of this period the propellants were expelled. Experience was acquired in the storage, handling, system design, and fabrication problems associated with positive expulsion systems.

Studies For Storage of Propellants in Space Environment (U.S. Air Force) A research and development program was performed to investigate the problems of materials compatibility, servicing, storing and transferring N_2O_4, UDMH, and N_2H_4 under environmental conditions simulating those encountered in missile and space vehicle use.

Titan II Storable Propellants (U.S. Air Force) - A storable propellant combination of N_2O_4 as the oxidizer and a nominal 50/50 blend of UDMH and N_2H_4 as the fuel was selected for the Titan II ballistic missile. These propellants were studied and the resultant data on physical properties, materials compatibility, handling, safety, and flammability and explosivity hazards were published in handbook form. Information compiled from industry and government data and from trade literature, was supplemented by laboratory tests conducted at Bell Aerosystems and the U.S. Bureau of Mines.

Research on Zero-Gravity Positive Expulsion Techniques (NASA) - This contract was awarded in 1961 for the purpose of establishing a compendium of design information on all known methods and advanced ideas for achieving positive expulsion. The program consisted of documenting Bell experience and ideas for expulsion techniques and supplementing this information with a literature search and industry-wide survey.

Follow-On Research on Current and Advanced Positive Expulsion Devices (NASA) - This design study program was initiated in 1962 to evaluate metallic positive expulsion devices and to select the device having the greatest potential for manned applications. An industry-wide survey was conducted to ascertain the state-of-the-art in development of expulsion devices. Of the approaches studied, the metal bellows concept proved to be the most promising method of expulsion within state-of-the-art capability for use in the more stringent operating regimes of long-term missions.

Advanced Research on Positive Expulsion Techniques (U.S. Air Force) - This program (classified Secret) was initiated in 1962 for research on advanced expulsion and orientation techniques. All conceivable methods were investigated and actual tests were conducted on surface force and electrostatic field devices to evaluate the most feasible concepts.

Bell Aerosystems IR & D - Company-funded programs were conducted to evaluate expulsion device materials. Candidate materials were evaluated on a sample basis and aluminum foil and electro-deposited nickel bladders were fabricated and tested.

2. DESIGN, DEVELOPMENT, AND PRODUCTION EXPERIENCE

Although the research programs were important for advancing the technology, the ultimate objective was the application of these techniques for specific missions and vehicles. Bell produced tankage which included spherical, cylindrical, and torus-type configurations with metals, elastromeric, and plastic materials used for the expulsion device. The following is a summary of the major hardware programs in progress or completed by Bell at the inception of the Apollo program:

Shrike Missile Program - Collapsing bladders fabricated from Buna-N and KEL-F for use with JP-4 and WFNA proved successful on all flight tests.

Rascal Missile Program - Buna-N bladders, fabricated for use in the main fuel tank, were successfully proven during flight.

Mercury Reaction Control System - The Mercury program provided Bell with the first opportunity to produce positive expulsion tankage for manned operation in a space environment. Three toroidal tanks were used to supply the 90% hydrogen peroxide for the reaction control systems. One tank was used for the automatic system, one for the manual, and one for reentry reserve. A spherical auxiliary tank was designed and tested but was not needed for the system. The collapsing bladders were fabricated from 9711 silicone rubber and the shells of 6061 aluminum. The diffuser assembly consisted of a Teflon tube with aluminum end plates. The bladder assembly design was unique in that the bladder and diffuser were assembled into a bladder assembly and tested for integrity prior to installation into the shell. These tank assemblies were used very successfully on all Mercury flights.

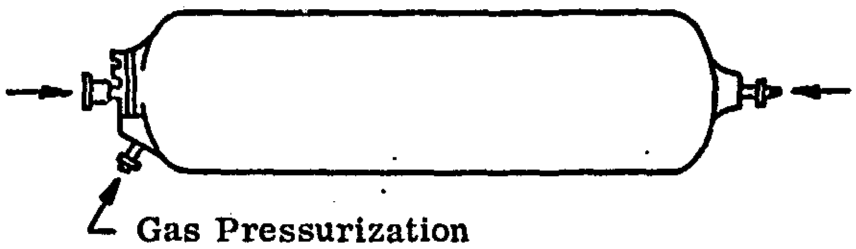
Centaur Program - Two spherical collapsing bladder configurations were provided for use in the attitude and ullage control system and auxiliary power system. These tanks used silicone bladders and aluminum shells.

Dyna-Soar - A cylindrical collapsing bladder configuration, consisting of a silicone bladder and an aluminum shell, was developed and tested for the Dyna-Soar vehicle.

Metallic Devices - Bell was very active in evaluating metallic expulsion devices which included reversing diaphragms, convoluted expanding diaphragms, and bellows. Several variations of these devices were fabricated and tested,and valuable information on performance characteristics and fabrication techniques was required.

Agena Secondary Propulsion System Tankage (Model 8101) - The tank assemblies produced for this program were the first qualified Teflon bladder positive expulsion tanks,and the experience acquired was directly applicable to the Apollo tankage. During the Rascal program, Bell had attempted to develop seamed bladders fabricated from KEL-F and Teflon. This approach was abandoned after a short development study because of problems encountered at the required - 65°F operating temperature and difficulty in fabricating the seamed configuration. Since the Agena program used MON as the oxidizer,it was apparent Teflon would have to be used for the bladder as it was the only non-metallic material that was compatible with this oxidizer. The design approach was directed toward a seamless construction and initial effort was to develop a fabrication technique. The spray dispersion method proposed by Dilectrix Corporation was chosen and Bell engineering worked with Dilectrix to adapt this technique to the fabrication of Agena seamless bladders. During development, bladders were fabricated in various thicknesses and compositions of TFE and FEP Teflon. The original approach included fabricating bladders of TFE and bladders of FEP in thicknesses of 5 to 10 mils. These bladders were not adequate because of the 0 to 100°F operating temperature requirement. Teflon FEP provided a good permeation barrier but lacked the capability to withstand repeated cycling at the higher temperatures. Teflon TFE was able to meet the cycling requirement at the higher temperature but was very susceptable to brittle failures at the lower temperatures. The problem was solved by using a laminate construction consisting of a layer of FEP applied over a layer of TFE. This construction method resulted in a bladder material which operated with the best characteristics of each type of Teflon. In addition, a bladder was fabricated using a codispersion, or mixture, of TFE and FEP. This fabrication technique resulted in a bladder material which acted much the same as a TFE bladder in that it lacked low temperature cycle capability and was highly permeable. The fabrication method had not been perfected at this time and the resulting bladder was of low quality. This approach was abandoned for the Agena program. Laminated bladders were fabricated in various thicknesses and ratios of TFE and FEP. These configurations were tested and evaluated to determine the most suitable bladder composition for life cycle and performance characteristics within the required temperature range. The most feasible configuration proved to be a single-ply 6-mil bladder composed of 3 mils TFE and 3 mils FEP. This tankage (see Figure I-3) successfully completed qualification testing and operated successfully during actual space flights. The Agena tankage was built for two separate systems; one with vertically mounted tanks and one with horizontally mounted tanks. Mechanical devices were installed inside the bladders for the horizontal configuration to control bladder folding and thus prevent bladder twist and random fold patterns.

In addition to the expulsion and dynamic tests performed during the mainstream program, several supporting investigations were performed to evaluate performance and design capabilities in the areas of compatibility, permeation, gas transmission, and radiation. Toward the end of the Agena tank program, a new design was developed as a product improvement type effort. The new design was the 3 mil, 3-ply bladder which consisted of 3 bladders, each 1.5 mils TFE and 1.5 mils FEP nested together. This design was based on the concept that the center bladder would be the primary film and the inside and outside bladders would serve as radius formers to prevent the sharp three-corner folds which had caused several pinhole failures on the single-ply bladders. The concept was successfully demonstrated during testing of pipe sections; however, the one bladder that was fabricated had very limited testing when the Agena SPS program ended.



Tank Assembly	Fuel	Oxidizer
Propellant	UDMH	N_2O_4 + 10% NO
Volume (in.^{3})	3000	1970
Diameter (in.)	10.1	10.1
Length (in.)	46.2	32.7
Weight (lb)	13.76	11.02
Working Pressure (psig)	225	225
Expulsion Efficiency (%)	98	98
Cycle Life (Expulsion)	10	10
Shell		
Material	Al. 6061-T6	Al. 6061-T6
Thickness (in.)	0.053	0.053
Bladder		
Material	Teflon TFE/FEP	Teflon TFE/FEP
Thickness (in.)	0.006	0.006

FIGURE I-3 MODEL 8101 AGENA SPS TANK ASSEMBLIES

SECTION II

APOLLO TYPE TANKAGE CONTRACT SUMMARIES

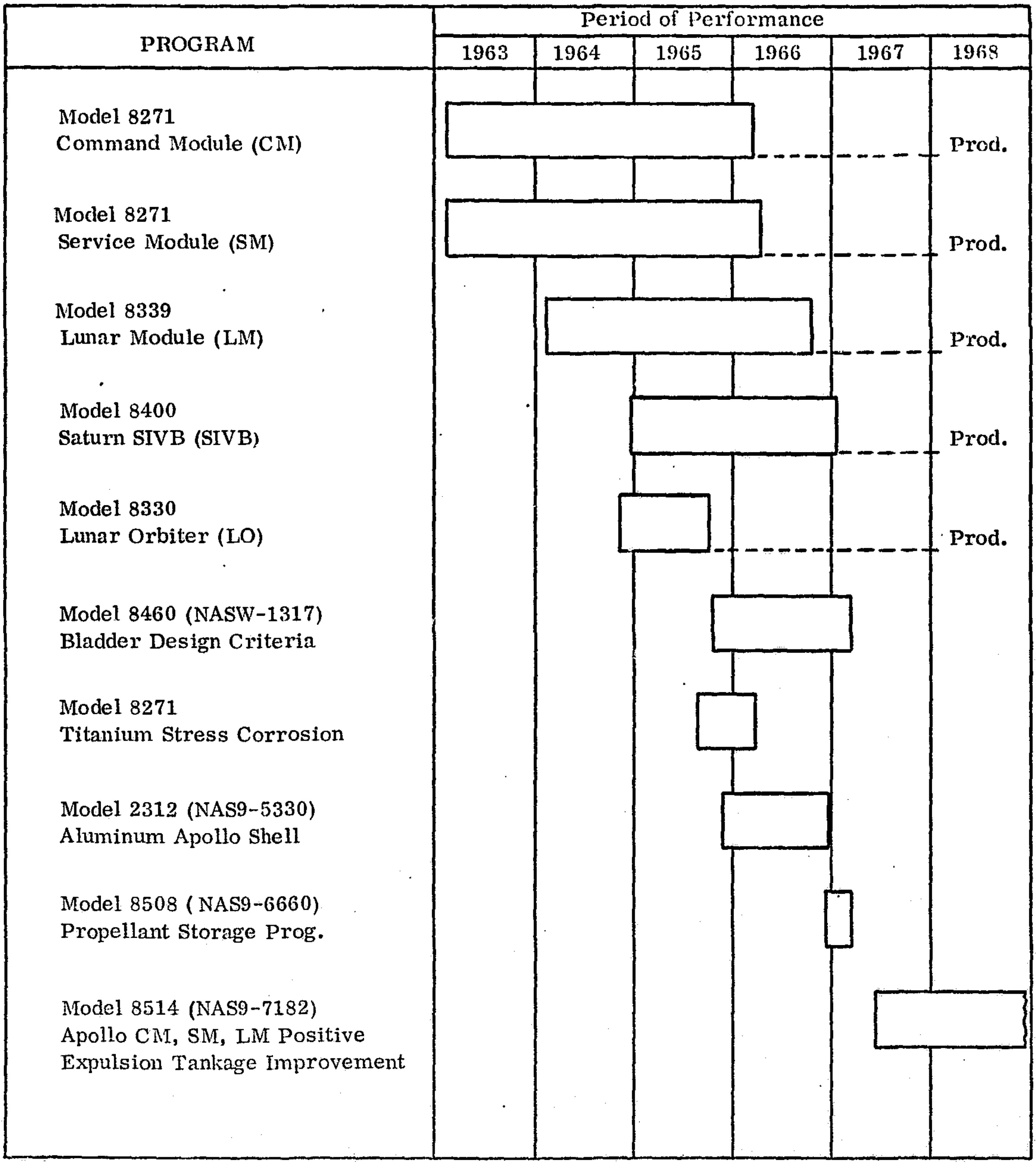
In addition to the mainstream Apollo propellant tankage programs discussed in Section I, there are five other programs that are directly related to the Apollo tankage effort. These programs are as follows:

Model 8460:	Teflon Bladder Design Criteria Study
Model 8271:	Titanium Stress Corrosion Investigation
Model 2312:	Service Module Aluminum Tank Shell
Model 8508:	Nitrogen Tetroxide Exposure Test Program
Model 8514:	Apollo CM, SM, LM RCS Positive Expulsion Tankage Product Improvement Program

The chronological relationship of the Apollo type programs is shown in Figure II-1. The indicated time periods for the five mainstream programs cover the effort from contact go-ahead to the completion of qualification and overstress testing. Hardware deliveries and supporting effort continued after these periods.

The Apollo type tankage effort started with the Model 8271 Command Module (CM) and Service Module (SM) tankage. The CM has a low L/D ratio and is used in the horizontal position, whereas the SM has a higher L/D ratio and is used in the vertical position. The overall approach was to have commonality, insofar as was practicable, not only between the oxidizer and fuel tanks but also between the CM and SM. The starting point was the common 12.5 inch diameter of the shells. It was planned that the only differences between the four tanks would be the length required to account for the differences in volume and wall thickness variations for pressure requirements. The commonality concept encompassed all areas including design, fabrication, and test to provide common usage of parts and facilities. Therefore, a change to solve a particular problem on one tank could not be made until it was evaluated for possible detrimental effects on the other configurations. This concept was continued throughout the CM and SM program so that the final configured tanks, aside from the planned length difference, are basically the same except for thickened ends on the CMO bladder.

FIGURE II-1 APOLLO POSITIVE EXPULSION PROPELLANT TANKAGE AND ASSOCIATED PROGRAMS



The Model 8339 Lunar Module (LM)tanks were designed to be common with the SM tank configuration except for the required additional length and the larger diameter outlet tubing required for interface with the system plumbing. This program was instituted before the SM design was finalized and, as a result, was extended concurrently with SM development. The full size single-ply bladder design adopted for the SM was applied to LM. This design was not completely suitable for the LM tanks because of the larger L/D ratio and corresponding bladder repositioning problem. A development program was conducted to solve the repositioning problem and the solution was attained with a 6 mil single-ply bladder with a diametrally undersized cylindrical section. This undersized bladder design is the only basic deviation from the commonality concept established between the LM and SM tankage.

The Model 8400 Saturn SIVB fuel and oxidizer tanks are the same size as the LM oxidizer tank which was used as the basic design. The design was modified to the extent that a stainless steel diffuser was used instead of aluminum (no bimetallic joint). Tube fittings were installed on the port tubing and an additional gas port was incorporated at the blind end of the tank.

The Model 8330 Lunar Orbiter (LO) program originally utilized the CM tanks; however, two major modifications were incorporated during the program. The first change was the use of a thick-walled shell for the oxidizer tank to retard stress corrosion for the duration of the LO mission. This approach was taken because the stress corrosion problem had not been solved at the time LO tankage was being delivered. The second major modification was the addition of an aluminum foil laminate in the oxidizer bladder as a permeation barrier against saturation of the oxidizer with pressurizing gas during the mission.

The titanium/N_2O_4 stress corrosion investigation was performed as part of the Model 8271 program. This investigation was started because of a failure of an SMO tank during storage with N_2O_4. The failure was verified immediately by additional testing of titanium shells with N_2O_4. The resulting failures emphasized the existence of a compatibility problem not only with the positive expulsion tanks but also with all types of titanium tankage. The investigation disclosed that stress corrosion occurs if NO is lacking in the N_2O_4. The problem was eliminated by controlling the amount of nitric oxide in the N_2O_4,and this "fix" was applied to all programs by adoption of NASA Specification MSCPPD-2.

The Model 8460 Teflon Bladder Design Criteria Program was instituted separately and paralleled the mainstream tankage programs. During the development phases of these programs a wide variety of bladder failures occurred. Since failure modes could not readily be determined, there was a need for a fundamental engineering study of bladder design, operation, and quality control. This program was established to determine design and quality criteria to enable evaluation of the main stream tankage.

The Model 8538 N_2O_4/Titanium Exposure Test Program was established to supplement the information acquired on the Titanium/N_2O_4 stress corrosion program. This test program was performed to extend confidence in the Apollo grade N_2O_4 by checking the effects of temperature cycling and sloshing during a propellant storage period of 30 days.

The Model 2312 Apollo Aluminum Shell Program was implemented to provide an Apollo type tank shell fabricated from aluminum and capable of withstanding external pressure. The existing thin wall titanium shells are designed for the lowest possible structural weight and will not withstand external pressure. The aluminum tank shells are functionally interchangeable with the SM oxidizer configuration.

The Model 8514 Apollo CM, SM, and LM Positive Expulsion Tankage Product Improvement Program, under which this report is being written, is currently in progress with the objective of improving and upgrading the tank assemblies in the areas of performance, reliability, and mission duration.

Although the concept of common technology between tank programs was adhered to as much as possible, it was necessary to deviate in instances dictated by tank size and individual program specifications. Comparisons of the physical characteristics and operational and test requirements for the five tankage programs is shown in Tables II-1, II-2, II-3. Exploded views showing the latest configurations for the CM, SM, LM, and SIVB tankage are presented in Figures II-2, II-3, II-4, and II-5. The configurations shown in these views are those delivered by Bell for use on the manned Apollo missions.

TABLE II-1

APOLLO-TYPE POSITIVE EXPULSION TANKAGE - PHYSICAL CHARACTERISTICS

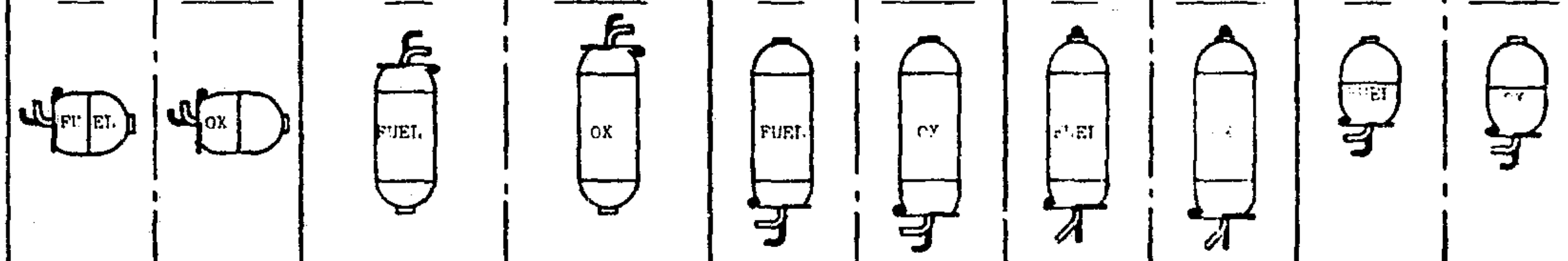
[illegible]	COMMAND MODULE		SERVICE MODULE		LUNAR MODULE		SATURN SIVB		LUNAR ORBITER	
Bell Aeros. Model No.	8271		8271		8339		8400		8330	
Prime Contrac.					NAS9-1100		NAS7-101		NAS1-3800	
Customer	NAA/SID		NAA/SID		Grumman		Douglas		Boeing	
Customer P. O. No.	M4J3XA-406027		M4J3XA-406027		2-24462-[illegible]		DAC A[illegible]		N66[illegible]63	
	FUEL	OXIDIZER	FUEL	OXIDIZER	FUEL	OXIDIZER	FUEL	OXIDIZER	FUEL	OXIDIZER
										
Bell Aerosystems Drawing No.	8271-471153	8271-471154	8271-471151	8271-471152	8339-471101	8339-471102	[illegible]-471[illegible]01	84[illegible]-471[illegible]01	8330-471001	8330-471071
No. of Tanks/Vehicle	2	2	4(+4 CMF)	4(+4 CMO)	2	2	2	2	2	2
Flange Orientation (on pad)	Horizontal	Horizontal	2 Up/2 Down (Horiz)	2 Up/2 Down (Up)	Down	Down	Down	Down	Down	Down
Propellant	MMH	N_2O_4	MMH	N_2O_4	50/50	N_2O_4	MMH	N_2O_4	50/50	N_2O_4
Pressurant	He		He		He		He		N_2	
Tank Total Volume (in^3)	1462	1783	2241	2844	3308	4115	4115	4115	1462	1783
Propellant Max. Flow Rate (lb/sec)	0.33	0.66	0.22	0.44	0.44	0.88	0.55	0.92	0.06	0.112
Propellant Specification Load (lb)	45.2	89.2	69.0	137.0	103.5	203.7	115	160	46.4	89.2
Propellant Ullage (lb)	1.2	3.7	4.5	11.2	4.5	11.3	15	55	1.2	3.7
Propellant Full Load (lb)	46.4	92.9	73.[illegible]	148.2	[illegible]	[illegible]	130	215	47.6	92.9
Pressures: Burst (psig)	540		372		375		550		540	
Proof (psig)	480		331		333		41[illegible]		480	
Max. Op. (psig)	360		248		250		27[illegible]		236	
Nominal (psig)	289		179		181		[illegible]		190	
Temperature: Max. Op. (°F)	105		85		100		1[illegible]		85	
Min. Op. (°F)	40		40		40		4[illegible]		40	
Shell: Fabricator	Airite		Airite		Airite		Bell		Bell	
Overall Length (in)	17.3	19.9	23.7	28.6	32.2	38.8	38.9		17.3	19.9
I.D. (in)	12.5		12.5		12.5		12.5		12.5	
Head Thickness (in)	.027		.022		.022		.028		.027	.055
Cyl. Thickness (in)	-		.022		.025	.032	.029		-	
Weight (lb)	4.50	4.93	5.02	5.65	6.45	8.1[illegible]	8.90		4.50	4.93
Diffuser: Type	LSV		LSV		LSV		LSV Blind End Gas Port		LSV	
Material	Al		Al		Al		S.S.		Al	
Tube O.D. (in)	5/8		5/8		3/4		3/4		5/8	
Weight (lb)	1.57	1.59	1.57	1.61			4.47			
Bladder: Material	TFE/FEP		TFE/FEP		TFE/FEP		TFE/FEP		TFE/FEP	TFE/Al/FEP
Thickness	6 mil	6 mil (9 mil Ends)	6 mil		6 mil		6 mil		6 mil	6 mil
Tank Assembly Weight (lb)	7.20	7.90	7.90	8.70	10.09	12.17	15.75		7.20	10.97
Status: Test	Qualified		Qualified		Qualified		Qualified		Qualified	

TABLE II-2

APOLLO-TYPE POSITIVE EXPULSION TANKAGE - QUALIFICATION TEST SEQUENCE

COMMAND MODULE - MODEL 8271	SERVICE MODULE - MODEL 8271	LUNAR MODULE - MODEL 8339	SATURN SIVB - MODEL 8400	LUNAR ORBITER - MODEL 8330
<u>Fuel Unit P1</u> Acceptance Test - Tank Assy Vib. (X & Y) Slosh - Horizontal Acceleration Exp. (No. 1) Amb. Exp. (No. 2 thru 16) Hot Exp. (No. 17 & 18) Cold Exp. (No. 19 & 20) Jettison (2) Off Limits - Amb. Exp. (50 Max) <u>Fuel Unit P2</u> Acceptance Test - Shell Pressure Cycle Acceptance Test - Tank Assy Amb. Exp. (No. 1 thru 15) Vib. (Random) (X & Z) Acceleration Exp. (No. 16) Hot Exp. (No. 17 & 18) Cold Exp. (No. 19 & 20) Volume Verification Jettison Off Limits - Vib. (Random)	<u>Fuel Unit P1</u> Acceptance Test - Tank Assy Vib. Amb. Exp. (No. 1 thru 16) Hot Exp. (No. 17 & 18) Cold Exp. (No. 19 & 20) Off Limits: Hot Exp. (2) Cold Exp. (2) Amb. Exp. (46) <u>Fuel Unit P2</u> Acceptance Test - Shell Press. Cycle (2700 NWP, 300MWP) Acceptance Test - Tank Assy Amb. Exp. (No. 1 thru 16) Vib. (Random) Hot Exp. (No. 17 & 18) Cold Exp. (No. 19 & 20) Off Limits: Hot Exp. (2) Cold Exp. (2) Vib. (Random) (Y-Axis)	<u>Fuel Units P3 and P4</u> Acceptance Test Temperature Extremes *Vib. & Shock (F, 3/4, 1/2) *Acceleration *Slosh - Vertical Ambient (16) Hot Exp. (2) Cold Exp. (2) Bladder Removal Pressure Cycle Burst	<u>Fuel Unit P1</u> Acceptance Test 5 Dry Cycles (N_2) Prop. Exposure (1 Amb. Exp.) Vib. & Shock Ambient Exp. (7) Cold Exp. (1) Hot Exp. (1) Amb. Exp. (8) Cold Exp. (1) Hot Exp. (1) Press. Cycle (500 Cycles) Bladder Removal Burst	<u>Fuel Unit</u> Acceptance Test Vib. Internal ΔP Test Functional Test (Pulse Exp. No. 1 & 2) Amb. Exp. (3 thru 8) Amb. Exp. (9 thru 16) Volume Verification Hot Exp. (17 & 18) Cold Exp. (19 & 20) Slosh Overstress: Full ΔP Exp. (21) Thermal Cycling
<u>Oxidizer Unit P1</u> Acceptance Test - Tank Assy Vib. (X & Y) Slosh - Horizontal Acceleration Exp. (No. 1) Amb. Exp. (No. 2 thru 16) Cold Exp. (No. 17 & 18) Hot Exp. (No. 19 & 20) Off Limits - Amb. Exp. (50 Max) <u>Oxidizer Unit P2</u> Acceptance Test - Shell Pressure Cycle Acceptance Test - Tank Assy Amb. Exp. (No. 1 thru 15) Vib. (Random) (X & Z) Acceleration Exp. (No. 16) Cold Exp. (No. 17 & 18) Hot Exp. (No. 19 & 20) Volume Verification Off Limits - Vib. (Random)	<u>Oxidizer Units P1 and P2</u> Acceptance Test Amb. Exp. (No. 1 thru 4) Vib. (X & Y) Slosh - Vertical Cold Exp. Hot Exp. Off Limits: <u>Unit P1</u> Vib. (Random) <u>Unit P2</u> Amb. Exp. (To Failure)	<u>Oxidizer Units P1 and P2</u> Acceptance Test Temperature Extremes *Vib. & Shock (F, 3/4, 1/2) *Acceleration *Slosh - Vertical Ambient (16) Hot Exp. (2) Cold Exp. (2) Bladder Removal Press. Cycle (2700 NWP, 300 MWP) Burst	<u>Oxidizer Unit P2</u> Acceptance Test 5 Dry Cycles (N_2) Prop. Exposure (1 Amb. Exp.) Vib. & Shock Amb. Exp. (7) Cold Exp. (1) Hot Exp. (1) Amb. Exp. (8) Cold Exp. (1) Hot Exp. (1) Press. Cycle (500 Cycles) Bladder Removal Burst	<u>Oxidizer Unit</u> Acceptance Test Vib. Internal ΔP Test Functional Test (Pulse Exp. (No. 1 & 2) Amb. Exp. (3 thru 8) Amb. Exp. (9 thru 16) Cold Exp. (17 & 18) Volume Verification Hot Exp. (19 & 20) Overstress: Full ΔP Exp. (21) Thermal Cycling

* Test Sequence Optional

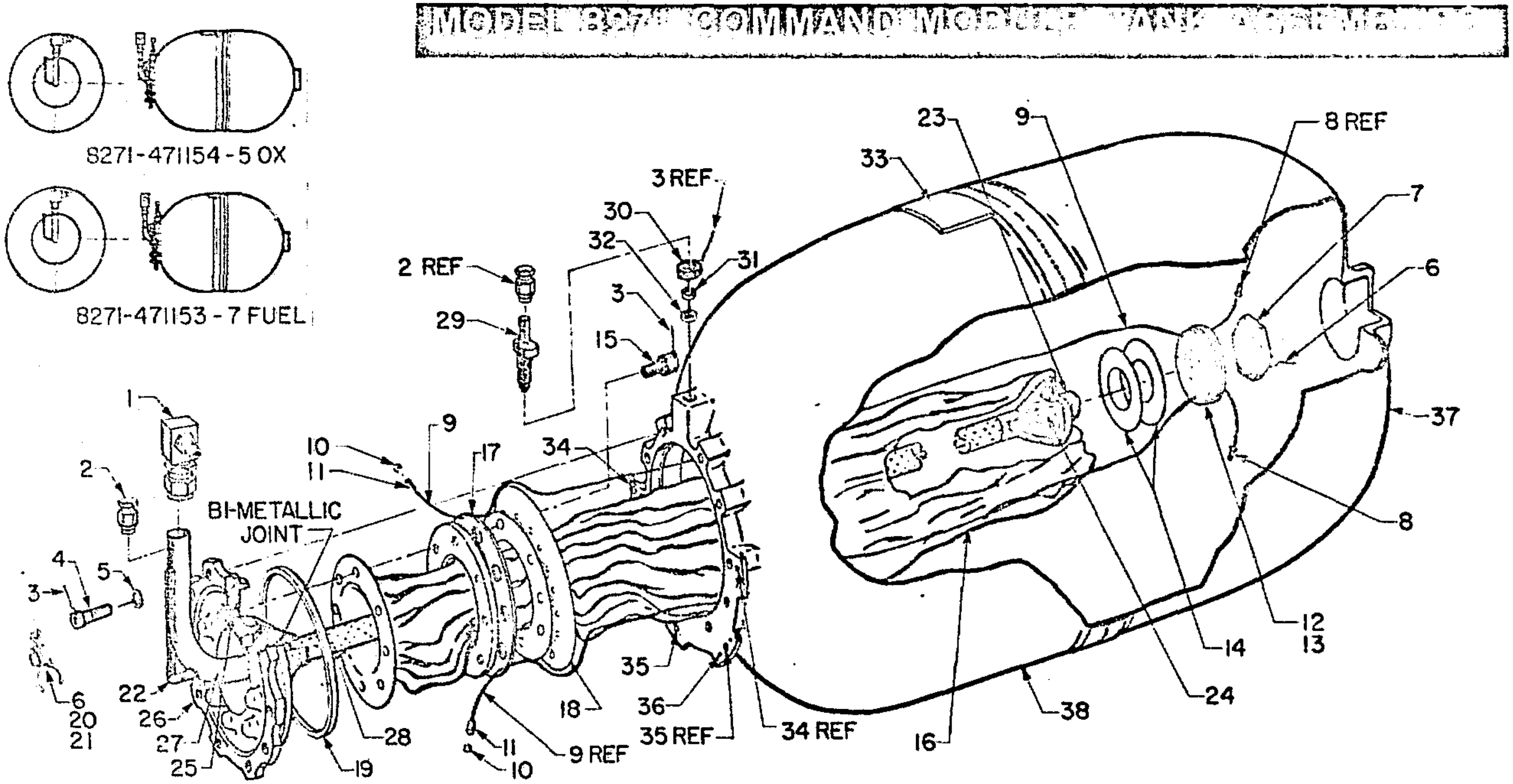
TABLE II-3

APOLLO-TYPE POSITIVE EXPULSION TANKAGE - QUALIFICATION DYNAMIC TEST REQUIREMENTS

	COMMAND MODULE		SERVICE MODULE		LUNAR MODULE			SATURN SIVB		LUNAR ORBITER	
	FUEL	OXIDIZER	FUEL	OXIDIZER	FUEL		OXIDIZER	FUEL	OXIDIZER	FUEL	OXIDIZER
VIBRATION											
Test Liquid	water/alch	meth. chlor.	water/alch	meth. chlor.	inhib. water		Freon - TF/alch	MMH	N_2O_4	Isoprop water	Freon-TF/meth.
Liquid Load - Full (lb)	46.4	92.9	73.5	148.6	119		234	130	215		
Ullage (lb) (%)	1.2 (2.6)	3.7 (3.9)	3.8 (5.2)	10.5 (7.1)	[illegible] (4.2)		18 (7.7)	15 (11.5)	55 (25.6)		
Liquid Load - Net (lb)	45.2	89.2	69.7	138.1	113		216	115	[illegible]		
Orientation & Axes Mounting	Horizontal X Plus Y or Z Rigid		Vertical X Plus Y or Z Rigid		Vertical X, Y, Z Customer			Vertical Custom		Vertical X, Y, Z Rigid	
					LAUNCH (FULL)	DESCENT (3/4 FULL)	ASCENT (1/2 FULL)				
SINE	Res. sweep 5-2000 cps at ±2 g pk max.		Res. sweep 5-2000 cps at ±2 g pk max.		Res.sweep 5-2000 cps at ±2 g pk max. Rate: 3 oct./min cps 5- 16 .20 DA 16- 250 2.5 g 250- 420 .0008 DA 420-1000 7.0 g 1000-2000 9.0 g Time: 5.8 min	Res.sweep 5-2000 cps at ±2 pk max. Rate: 1 oct./min cps 5- 17 .13 DA 17-310 2.0 g 310-500 .00039 DA 500-2000 5.2 g Time: 17.3 min	Res.sweep 15-2000 cps at 1 g cps Same as Descent Time: 17.3 min	Rate: 3 oct./min cps 5- 47 .031 DA 47- 220 3.6 g pk 220- 295 .0014 DA 295-2000 6.2 g pk Time: 5.8 min		Res.sweep 5-2000 cps at ±2 pk max. Rate: 4 oct./min Time: 4.3 min	
RANDOM	15 sec random burst .008 g^2/cps at 10 cps with lin. inc. to .10 g^2/cps at 80 cps. Constant .10 g^2/cps from 80 cps to 2000 cps. Time: 15 min		.035 g^2/cps at 10 cps with lin. inc. to .35 g^2/cps at 100 cps Constant to 250 cps with a lin. dec. to .03 g^2/cps at 2000 cps Time: 15 min		cps 10- 23 12 db/oct. rise to 23- 80 .025 g^2/cps 80-100 12 db/oct. rise to 100-1000 .06 g^2/cps 1000-1200 12 db/oct. rolloff to 1200-2000 .025g^2/cps Total g RMS - 9.2 Time: 5 min	cps 10- 20 12 db/oct. rise to 20-100 .034 g^2/cps 100-120 12 db/oct. rolloff to 120-2000 .017 g^2/cps Total g RMS - [illegible] Time: 12.5 min	cps Same as Descent Time: 8.5 min	cps 20- 85 .025 g^2/cps 85- 280 6.5 db/oct. 280-1000 .31 g^2/cps 1000-2000 12 db/oct. Time: 30 sec +3 min		15 sec random burst at low level acceleration spectral density 1.2 grms for 80 sec 7.4 grms for 50 sec 15.0 grms for 40 sec 20.4 grms for 40 sec Time: 2[illegible] sec	
SHOCK Orientation (Axes) Liquid Load Input No. of Shocks						Vertical (X,Y,Z) 3/4 full 15 g 11±1 ms rise, 1 ±1 ms fall [illegible] each axis		Vertical full 22 g 10±2 ms half sine [illegible] each axis			
SLOSH Test Liquid Orientation (Axes) Liquid Load Input (500~)	water/alch Horizontal (X-axis) 1/2 full 2.7 cps at 0.3 DA	meth chlor. Horizontal (X-axis) 1/2 full 2.6 cps at 0.325 DA	Oxid. tank only N_2O_4 at 40°F Vertical (Z) 1/3 full 2.3 cps at 0.041 DA		Water Vertical (Y) 1/3 full 3.0 cps at .22 DA		[illegible].2 cps at .19 DA			Water in Flex.Tank (not qual) Vertical (lateral slosh) [illegible] 2.[illegible] cps 3.4 cps 2.[illegible]cps [illegible] [illegible] cyc. each level [illegible]	
ACCELERATION Orientation (Axes) Liquid Load Input (Time)	Horizontal (X & Y or Z) full 28 g (5 min) Plus Accel-exp., lateral, 20 to 2 g				Horizontal(+X & -X) full 8.5 g (5 min)						

BELL AEROSYSTEMS COMPANY
DIVISION OF BELL AEROSPACE CORPORATION

MODEL 827[illegible] COMMAND MO[illegible] TANK [illegible]



TANK ASSEMBLY
[illegible]

1. [illegible]
2. CAP ASSEMBLY [illegible]
3. [illegible] (STAINLESS STEEL)
4. BOLT 8271-471319 (15 REQ'D) [illegible]
5. WASHER [illegible] (STAINLESS STEEL 347)

BLADDER ASSEMBLY
[illegible]

6. LOCKWASHER MS [illegible] (STAINLESS STEEL)
7. NUT [illegible] (STAINLESS STEEL 347)
8. [illegible] (STAINLESS STEEL [illegible])

VENT LINE ASSEMBLY
[illegible]

9. VENT LINE [illegible] (TEFLON TFE)

EYELET RETAINER 8271-471[illegible]-1

10. COVER 8271-471[illegible] (TEFLON TFE)
11. [illegible] (TEFLON TFE)

RETAINER GASKET 8271-471[illegible]

12. GASKET 8271-47[illegible]-3 (TEFLON TFE)
13. WASHER 8271-471[illegible]-3 (ALUMINUM [illegible])
14. PAD 8271-471[illegible] (12 REQ'D) (TEFLON TFE)
15. [illegible]
16. [illegible]
17. [illegible]
18. [illegible]
19. GASKET [illegible]

DIFFUSER ASSEMBLY
[illegible] (STAINLESS STEEL 347, ALUMINUM [illegible], STAINLESS STEEL [illegible], UNICHROME STEEL [illegible])

CLAMP ASSEMBLY
8271-471197-1 (UNICHROME STEEL [illegible] PLASTIC)

20. SCREW [illegible] (STAINLESS STEEL)
21. WASHER AN [illegible] (STAINLESS STEEL)
22. [illegible] TUBE 8271-47[illegible] FUEL 8271-47[illegible] (STAINLESS STEEL 347)
23. RETAINER ASSEMBLY 8271-471207-13 (ALUMINUM [illegible])
24. BUSHING 8271-471[illegible]-1 (TEFLON TFE)
25. INSERT MS [illegible] REQ'D) (STAINLESS STEEL [illegible])

DIFFUSER FLANGE ASSEMBLY
[illegible]

DIFFUSER FLANGE 8271-471235-17 (ALUMINUM 6061)

26. FLANGE 8271-471235-7
27. ELBOW 8271-471230-3
28. DIFFUSER TUBE 8271-471208-17 FUEL 8271-471208-19 OXIDIZER (ALUMINUM 6061)
29. FITTING 8271-471276-7 (STAINLESS STEEL 304L)
30. NUT 8271-471249-1 (STAINLESS STEEL)
31. GASKET 402-4 (TEFLON)
32. GASKET 8271-471245-1 (TEFLON TFE)
33. [illegible]

TANK SHELL ASSEMBLY
8271-47[illegible] FUEL
8271-47[illegible] OXIDIZER
(TITANIUM Ti6AL-4V)

34. NUT PLATE NAS 687C4 (2 REQ'D) (STAINLESS STEEL)
35. NUT PLATE NAS 685C4 (2 REQ'D) (STAINLESS STEEL)
36.* RIVET MS 20427[illegible] (8 REQ'D) (STAINLESS STEEL)
37. [illegible] END TANK SECTION 8271-471012-1 FUEL 8271-471012-3 OXIDIZER (TITANIUM Ti6AL-4V)
38. FLANGE END TANK SECTION 8271-471011-5 FUEL 8271-471011-7 OXIDIZER (TITANIUM Ti6AL-4V)

FIGURE II-2

MODEL 8271 SERVICE MODULE [illegible]

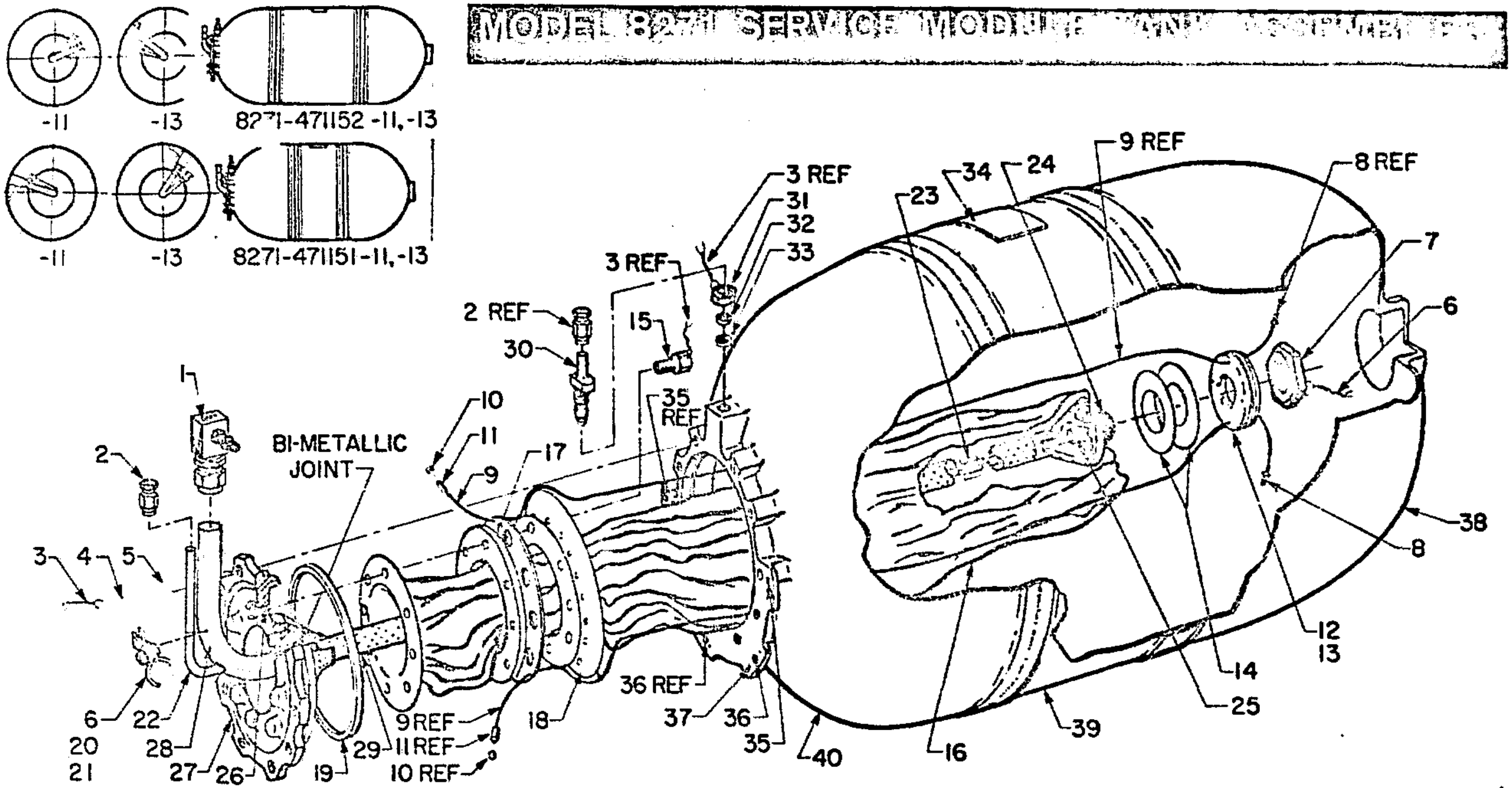


FIGURE II-3

TANK ASSEMBLY
- 8271-471151-11, -13 FUEL
- 8271-471152-11, -13 OXIDIZER

1. CLOSURE ASSEMBLY 8271-471272-1 (ALUMINUM, TEFLON TFE, STAINLESS STEEL, NYLON)
2. CAP ASSEMBLY 7Y400-C (NYLON)
3. LOCKWIRE MS 20995C20 (STAINLESS STEEL)
4. BOLT 8271-471019-3 (10 REQ'D) (TITANIUM)
5. WASHER AN960-C416L (10 REQ'D) (STAINLESS STEEL 347)

BLADDER ASSEMBLY
- 8271-471150-13 FUEL
- 8271-471155-15 OXIDIZER

6. LOCKWIRE MS 20995C32 (STAINLESS STEEL)
7. NUT 8271-471023-3 (STAINLESS STEEL 347)
8. EYELET 8271-471141-1 (2 REQ'D) (STAINLESS STEEL 304)

VENT LINE ASSEMBLY
- 8271-471127-5 FUEL (2 REQ'D)
- 8271-471127-7 OXIDIZER (2 REQ'D)

9. VENT LINE
   - 8271-471127-13 FUEL
   - 8271-471127-15 OXIDIZER
   - (TEFLON TFE)

EYELET RETAINERS 8271-471131-1

10. COVER 8271-471141-3 (TEFLON TFE)
11. HOUSING 8271-471131-5 (TEFLON TFE)

RETAINER WASHER 8271-471144-3

12. GASKET 8271-471346-1 (TEFLON TFE)
13. WASHER 8271-471120-1 (ALUMINUM 6061-T6)
14. PAD 8271-471112-1 (2 REQ'D) (TEFLON TFE)
15. BOLT 8271-471114-1 (6 REQ'D) (STAINLESS STEEL 347)
16. BLADDER
    - 8271-471148-5 FUEL
    - 8271-471148-7 OXIDIZER
    - (TEFLON TFE/FEP)
17. PIN 8271-471117-1 (ALUMINUM 6061)
18. PAD 8271-471247-1 (TEFLON TFE/FEP)
19. GASKET 8271-471025-1 (TEFLON TFE)

DIFFUSER ASSEMBLY
- 8271-471233-17 FUEL
- 8271-471233-19 OXIDIZER
- (STAINLESS STEEL 347, ALUMINUM 6061, STAINLESS STEEL HELICOIL, UNICHROME STEEL CLAD)

CLAMP ASSEMBLY
- 8271-471197-1 OXIDIZER
- 8271-471197-2 FUEL
- (UNICHROME STEEL CLAD, PLASTIC)

20. SCREW 6Z2A1032-6 (STAINLESS STEEL)
21. WASHER AN 960C10L (STAINLESS STEEL)
22. BLEED TUBE
    - 8271-471212-19 FUEL
    - 8271-471212-21 OXIDIZER
    - (STAINLESS STEEL 347)
23. SPACER 8271-471216-1 (TEFLON TFE)
24. RETAINER ASSEMBLY 8271-471207-13 (ALUMINUM 6061-T6)
25. BUSHING 8271-471213-1 (TEFLON TFE)
26. INSERT MS 122041 (6 REQ'D) (STAINLESS STEEL HELICOIL)

DIFFUSER FLANGE ASSEMBLY
- 8271-471241-27 FUEL
- 8271-471241-29 OXIDIZER
- (ALUMINUM 6061)

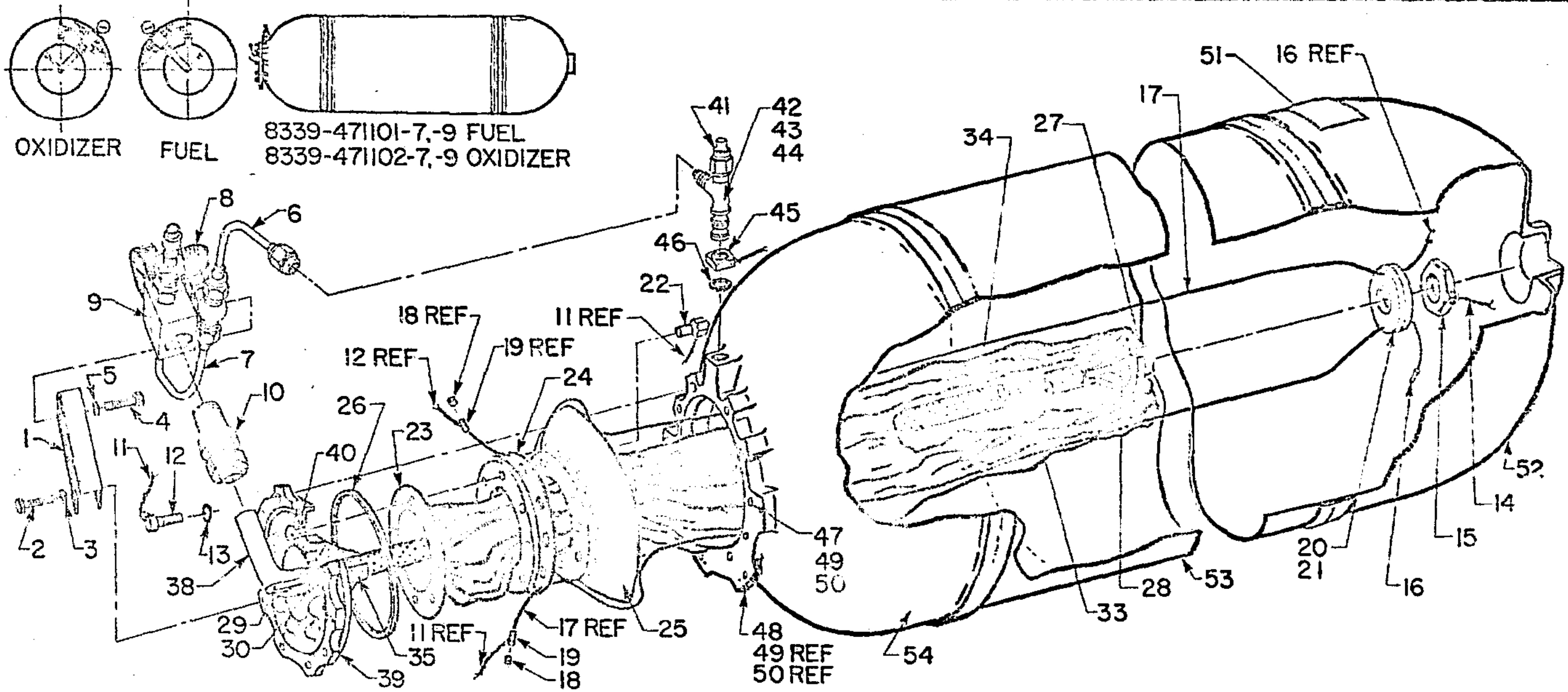
DIFFUSER FLANGE 8271-471235-17 (ALUMINUM 6061)

27. FLANGE 8271-471205-7
28. ELBOW 8271-471230-3
29. DIFFUSER TUBE
    - 8271-471209-33 FUEL
    - 8271-471209-35 OXIDIZER
    - (ALUMINUM 6061)
30. FITTING 8271-471026-7 (STAINLESS STEEL 304L)
31. NUT 8271-471049-1 (STAINLESS STEEL)
32. GASKET 402-8 (TEFLON)
33. GASKET 8271-471045-1 (TEFLON TFE)
34. [illegible]

TANK SHELL ASSEMBLY
- 8271-471035-9 FUEL
- 8271-471036-11 OXIDIZER
- (TITANIUM Ti6AL-4V)

35. NUT PLATE NAS 687C4 (2 REQ'D) (STAINLESS STEEL)
36. NUT PLATE NAS 686C4 (2 REQ'D) (STAINLESS STEEL)
37. RIVET MS 20427F3-6 (4 REQ'D) (STAINLESS STEEL)
38. CLOSED END TANK SECTION 8271-471030-1 (TITANIUM 6AL-4V)
39. CYLINDER TANK SECTION
    - 8271-471019-1 FUEL
    - 8271-471019-3 OXIDIZER
    - (TITANIUM 6AL-4V)
40. FLANGE END TANK SECTION 8271-471017-1 (TITANIUM 6AL-4V)

MODEL 8339 LUNAR MODULE RCS TANK ASSEMBLIES



LUNAR MODULE REACTION CONTROL SYSTEM TANK
- 8339-471101-7 FUEL
- 8339-471102-7 OXIDIZER
- 8339-471101-9 FUEL (PEENED SHELL)
- 8339-471102-9 OXIDIZER (PEENED SHELL)

1. BRACKET 8339-471064-1 (ALUMINUM 2024-T3)
2. BOLT AN3-4 (STEEL)
3. WASHER AN960C10L (STAINLESS STEEL)
4. BOLT AN4-3 (STEEL)
5. WASHER AN960C10L (STAINLESS STEEL)

VALVE ASSEMBLY
- 8339-471062-1 FUEL
- 8339-471062-3 OXIDIZER

6. TUBE ASSEMBLY 8339-471067-1
   - REF TUBE 8339-471067-3 (STAINLESS STEEL 347)
   - REF NUT MS21921-4C (2 REQ'D) (STAINLESS STEEL)
   - REF SLEEVE MS21922-4C (2 REQ'D) (STAINLESS STEEL)
7. TUBE ASSEMBLY 8339-471068-1
   - REF TUBE 8339-471068-3 (STAINLESS STEEL 347)
   - REF NUT MS21921-4C (2 REQ'D) (STAINLESS STEEL)
   - REF SLEEVE MS21922-4C (2 REQ'D) (STAINLESS STEEL)
8. VALVE 32RA
9. PLUG ASSEMBLY 8339-471060-3
   - REF GAGE FIGURE 2500
   - REF VALVE MS 28889-1
   - REF UNION AN 815-4S
   - REF GASKET 402-4
   - REF FILTER ASSEMBLY 8339-471062-1
   - REF FITTING 8339-471064-3
10. MALE CONNECTOR 7Y1210-12 (NYLON)

TANK ASSEMBLY
- 8339-471103-3 FUEL
- 8339-471104-3 OXIDIZER
- 8339-471103-5 FUEL (PEENED SHELL)
- 8339-471104-5 OXIDIZER (PEENED SHELL)

11. LOCKWIRE MS 20995C20 (STAINLESS STEEL)
12. BOLT 8271-471019-1 (10 REQ'D) (TITANIUM)
13. GASKET AN900-C10L (10 REQ'D) (STAINLESS STEEL)

BLADDER ASSEMBLY
- 8339-471051-5 FUEL
- 8339-471052-5 OXIDIZER

14. LOCKWIRE MS 20995C32 (STAINLESS STEEL)
15. NUT 8271-471021-3 (STAINLESS STEEL 347)

VENT LINE ASSEMBLY
- 8339-471027-1 FUEL (2 REQ'D)
- 8339-471027-3 OXIDIZER (2 REQ'D)

16. EYELET 8271-471141-1 (2 REQ'D) (STAINLESS STEEL 304)
17. VENT LINE (TEFLON TFE)
    - 8339-471027-5 FUEL (TEFLON TFE)
    - 8339-471027-7 OXIDIZER (TEFLON TFE)

EYELET RETAINER ASSEMBLY 8271-471131-1

18. COVER 8271-471131-3 (TEFLON TFE)
19. HOUSING 8271-471131-5 (TEFLON TFE)

RETAINER WASHER ASSEMBLY 8271-471142-1

20. GASKET 8271-471028-1 (TEFLON TFE)
21. WASHER 8271-471120-1 (ALUMINUM 6061-T6)
22. BOLT 8271-471114-1 (6 REQ'D) (STAINLESS STEEL 347)
23. BLADDER
    - 8339-471050-1 FUEL
    - 8339-471050-3 OXIDIZER
    - (TEFLON TFE/FEP)
24. RING 8271-471117-1 (ALUMINUM 6061)
25. PAD 8271-471249-1 (TEFLON TFE/FEP)
26. GASKET 8271-471025-1 (TEFLON TFE)

DIFFUSER ASSEMBLY
- 8339-471054-5 FUEL
- 8339-471054-3 OXIDIZER

27. RETAINER ASSEMBLY 8339-471057-1 (ALUMINUM 6061-T6)
28. BUSHING 8271-471213-1 (TEFLON TFE)

FLANGE ASSEMBLY
- 8339-471056-3 FUEL
- 8339-471056-3 OXIDIZER

BLEED TUBE ASSEMBLY
- 8339-471059-9 FUEL
- 8339-471059-11 OXIDIZER

29. TUBE
    - 8339-471059-13 FUEL
    - 8339-471059-15 OXIDIZER
    - (STAINLESS STEEL 347)
30. CAP 2Y500 C (NYLON)
31. NOT USED
32. NOT USED
33. SPACER 8339-471058-1 (TEFLON TFE)
34. DIFFUSER TUBE
    - 8339-471036-1 FUEL
    - 8339-471036-3 OXIDIZER
    - (ALUMINUM 6061-T61)

DIFFUSER ELBOW ASSEMBLY 8339-471042-3

OUTLET ASSEMBLY 8339-471032-3 (STAINLESS STEEL)

35. CONE 8339-471034-1 (ALUMINUM)

ELBOW ASSEMBLY 8339-471041-5

36. NOT USED
37. NOT USED
38. TUBE 8339-471041-7 (STAINLESS STEEL 347)
39. FLANGE 8339-471041-1 (ALUMINUM 6061-T6)
40. INSERT MS 21209 [illegible] (STAINLESS STEEL HELICOIL)

GAS INLET FITTING ASSEMBLY 8339-471069-1

41. CAP ASSEMBLY AL929-4S (STAINLESS STEEL)
42. FILTER RETAINER 8240-472063-1 (STAINLESS STEEL)
43. DISC 5-35 223-1-50 (STAINLESS STEEL)
44. TEE FITTING 8339-471069-3 (STAINLESS STEEL)
45. NUT 8271-471349-1 (STAINLESS STEEL)
46. GASKET 402-4 (TEFLON)

TANK SHELL ASSEMBLY
- [illegible]
- [illegible]
- [illegible] (PEENED SHELL)
- [illegible] OXIDIZER (PEENED SHELL)

47. NUT PLATE [illegible] (STAINLESS STEEL)
48. NUT PLATE [illegible] (2 REQ'D) (STAINLESS STEEL)
49. [illegible] (STAINLESS STEEL)
50. RIVET MS 20426-[illegible] (REQ'D) (STAINLESS STEEL)
51. IDENTIFICATION PLATE
    - 8339-471[illegible] FUEL
    - 8339-471[illegible] OXIDIZER
    - (ALUMINUM [illegible])
52. [illegible] TANK SECTION 8339-471[illegible]-3 (TITANIUM [illegible])
53. [illegible] SECTION
    - [illegible] FUEL
    - [illegible] OXIDIZER
    - (TITANIUM [illegible])
54. [illegible] TANK SECTION 8339-471011-3 (TITANIUM [illegible])

BELL AEROSYSTEMS COMPANY
DIVISION OF BELL AEROSPACE CORPORATION

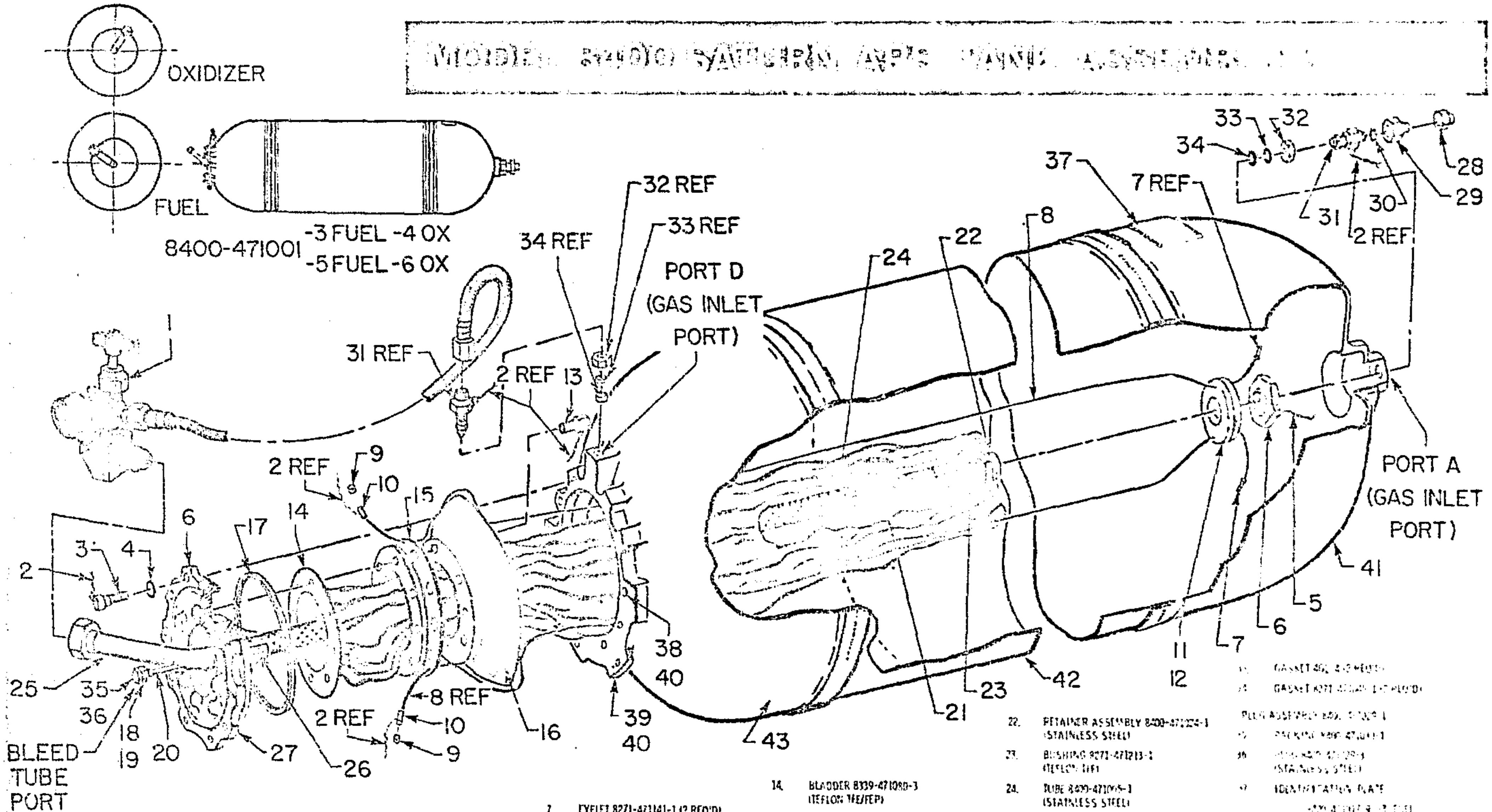


FIGURE II-5

APS BLADDER EXPULSION TANK

8400-471001-3 FUEL
8400-471001-4 OXIDIZER
8400-471001-5 FUEL (PEENED SHELL)
8400-471001-6 OXIDIZER (PEENED SHELL)

1. CLOSURE ASSEMBLY
8400-471036-1 FUEL -2 OX
REF. VALVE MS 25429-1
REF. GAGE FIGURE [illegible]
REF. HOSE ASSEMBLY 40837-20
REF. VALVE [illegible]
REF. CAP ASSEMBLY AN929-12S
REF. PACKING MS 29511-017
REF. FILTER ASSEMBLY 8339-471062-1
REF. PLATE DESIGNATION [illegible]
REF. MANIFOLD
8400-471037-1 FUEL
8400-471037-2 OXIDIZER
(BRASS)

TANK ASSEMBLY
8400-471002-3 FUEL
8400-471002-4 OXIDIZER
8400-471002-5 FUEL (PEENED SHELL)
8400-471002-6 OXIDIZER (PEENED SHELL)

2. LOCKWIRE MS 20995C20
(STAINLESS STEEL)

3. BOLT 674-12F (10 REQ'D)

4. WASHER AN960-C416L (10 REQ'D)
(STAINLESS STEEL)

BLADDER ASSEMBLY
8400-471003-3 FUEL
8400-471003-4 OXIDIZER

5. LOCKWIRE MS 20995C32
(STAINLESS STEEL)

6. NUT 8400-471027-1
(STAINLESS STEEL 347)

7. EYELET 8271-471141-1 (2 REQ'D)
(STAINLESS STEEL)

VENT LINE ASSEMBLY 8339-471027-? (2 REQ'D)

8. VENT LINE 8339-?71027-7
(TEFLON TFE)

EYELET RETAINER 8271-471131

9. COVER 8271-471131-3
(TEFLON TFE)

10. HOUSING 8271-471131-5
(TEFLON TFE)

RETAINER WASHER ASSEMBLY 8400-471019-3

11. GASKET 8400-471022-1
(TEFLON TFE)

12. WASHER 8400-471021-3
(STAINLESS STEEL 347)

13. BOLT 8400-471025-1 (8 REQ'D)
(STAINLESS STEEL 347)

14. BLADDER 8339-471080-3
(TEFLON TFE/FEP)

15. RETAINER RING 8400-471023-1
(STAINLESS STEEL 347)

16. PAD 8271-471249-1
(TEFLON TFE/FEP)

17. GASKET 8271-471025-1
(TEFLON TFE)

DIFFUSER ASSEMBLY
8400-471004-3 FUEL
8400-471004-4 OXIDIZER

BLEED TUBE ASSEMBLY 8400-471025-1

18. NUT MC 124C3
(STAINLESS STEEL)

19. SLEEVE MC 124C4
(STAINLESS STEEL)

20. TUBE 8400-471025-3
(STAINLESS STEEL 347)

21. SPACER 8339-471059-1
(TEFLON TFE)

22. RETAINER ASSEMBLY 8400-471024-1
(STAINLESS STEEL)

23. BUSHING 8271-471213-1
(TEFLON TFE)

24. TUBE 8400-471005-1
(STAINLESS STEEL)

FLANGE ASSEMBLY
8400-471006-1 FUEL
8400-471006-2 OXIDIZER
(STAINLESS STEEL)

25. TUBE 8400-471008-1
(STAINLESS STEEL)

26. CONE 8400-471009-1
(STAINLESS STEEL)

27. FLANGE 8400-471007-1
(STAINLESS STEEL)

28. CAP ASSEMBLY AN929-3S
(STAINLESS STEEL)

29. BUSHING AN [illegible]
(STAINLESS STEEL)

30. PACKING MS29779-4

31. FITTING 8400-471020-3 (2 REQ'D)
(STAINLESS STEEL 347)

32. NUT [illegible]-4S (2 REQ'D)
(STAINLESS STEEL)

33. GASKET [illegible] (2 REQ'D)

34. GASKET 8271-[illegible] (2 REQ'D)

PLUG ASSEMBLY 8400-[illegible]

35. PACKING 8400-47[illegible]

36. [illegible] 8400-47[illegible]
(STAINLESS STEEL)

37. IDENTIFICATION PLATE
[illegible]

TANK SHELL ASSEMBLY
8400-471013-[illegible]
[illegible]

38. NUT PLATE NAS [illegible] (2 REQ'D)
(STAINLESS STEEL)

39. NUT PLATE NAS [illegible]
(STAINLESS STEEL)

40. RIVETS [illegible]
(STAINLESS STEEL)

41. [illegible] TANK SECTION 8400-471013-1
(TITANIUM [illegible])

42. CYLINDER TANK SECTION 8400-471015-1
(TITANIUM [illegible])

43. [illegible] TANK SECTION 8400-471011-1
(TITANIUM (6AL-4V)

SECTION III

MAINSTREAM TANKAGE AND ASSOCIATED PROGRAM HISTORIES

A. MODEL 8271 - COMMAND AND SERVICE MODULE PROGRAM HISTORIES

1. Proposal and Specification Activity

The request for proposal for positive expulsion tankage for the Apollo Command and Service Module RCS systems was received in October 1962.

In November, Bell proposed the following tank assembly configurations in response to the specification requirements:

	CM	SM
Shell	Aluminum	Aluminum
Diffuser	Aluminum	Aluminum
Bladder Type	Expanding	Collapsing
Bladder Material:		
Fuel	Butyl	Butyl
Oxidizer	3-ply Teflon	3-ply Teflon

In January 1963, Bell requested that collapsing bladders be used in the command module because of the difficulty anticipated with the elaborate tunnel arrangement required for liquid transfer with expanding bladders. The use of titanium for the tank shells was considered at this time; however, Bell objected to this approach because of the reported shock sensitivity of titanium when used with the highly reactive oxidizers.

The contract was awarded in January 1963 and new procurement specifications were released in February. Bell submitted a new proposal in March in response to the revised requirements. The proposed program covered a 27-month schedule with the following configurations:

	CM	SM
Shell	Titanium	Titanium
Diffuser	Aluminum	Aluminum
Bladder Type	Expanding	Collapsing
Bladder Material:		
Fuel	Butyl	Butyl
Oxidizer	3-ply Teflon	3-ply Teflon

The proposal was reviewed and a coordination meeting was held to discuss schedule and technical problems. The schedule was reduced from 27 to 15 months and the development program was eliminated except for basic essential plexiglass tank testing. The go-ahead was given in March with efforts directed toward tailoring everything to achieve the shortened schedule.

Early in April the decision was made to use Teflon bladders and stainless steel diffuser tubes in both the oxidizer and fuel tanks. The use of Teflon fuel bladders eliminated the need for parallel testing of the fuel and oxidizer tanks because of the difference in bladder configuration. By using the same design most testing could be accomplished on a worst case basis. The use of a stainless steel outlet was required for the brazed connection with the system plumbing.

In May, Bell submitted a proposal for the required 15-month program based on the following tank assembly configurations:

	CM	SM
Shell	Titanium	Titanium
Diffuser	Stainless Steel	Stainless Steel
Bladder Type	Collapsing	Collapsing
Bladder Material	3-ply Teflon	3-ply Teflon

This program excluded all development testing except for basic plexiglass tank testing and simulated bladder testing on material samples and "pipe" sections. The design verification test program was to be initiated on a "high-risk" basis as soon as prototype hardware could be designed and fabricated. The resulting program effort is shown in Figure III-1.

2. Design and Development

The design effort started with program go-ahead and changes were incorporated as they were made. All drawings were released by the end of May 1963. The service and command module tanks were designed to use interchangeable parts whenever practicable, and the required fabrication techniques were within the state-of-the-art. Vendor evaluation was in progress during the design effort to establish existing capabilities and insure that the design was buildable.

Pressure vessel fabricators were evaluated to establish the existing capabilities for fabricating tank shells of aluminum, stainless steel, and titanium. Specifications (Book-form drawings) were prepared which contained all the detailed requirements for the titanium shells. These were the thinnest-walled pressure vessels known at that time and, as a result, the requirements were extremely stringent to insure structural integrity. Trade-off studies were completed to establish acceptable limits based on industry capability and a reasonable advancement of the state-of-the-art. As a result of these evaluations Airite was selected to fabricate the shells.

MODEL 8271 COMMAND AND SERVIC[E

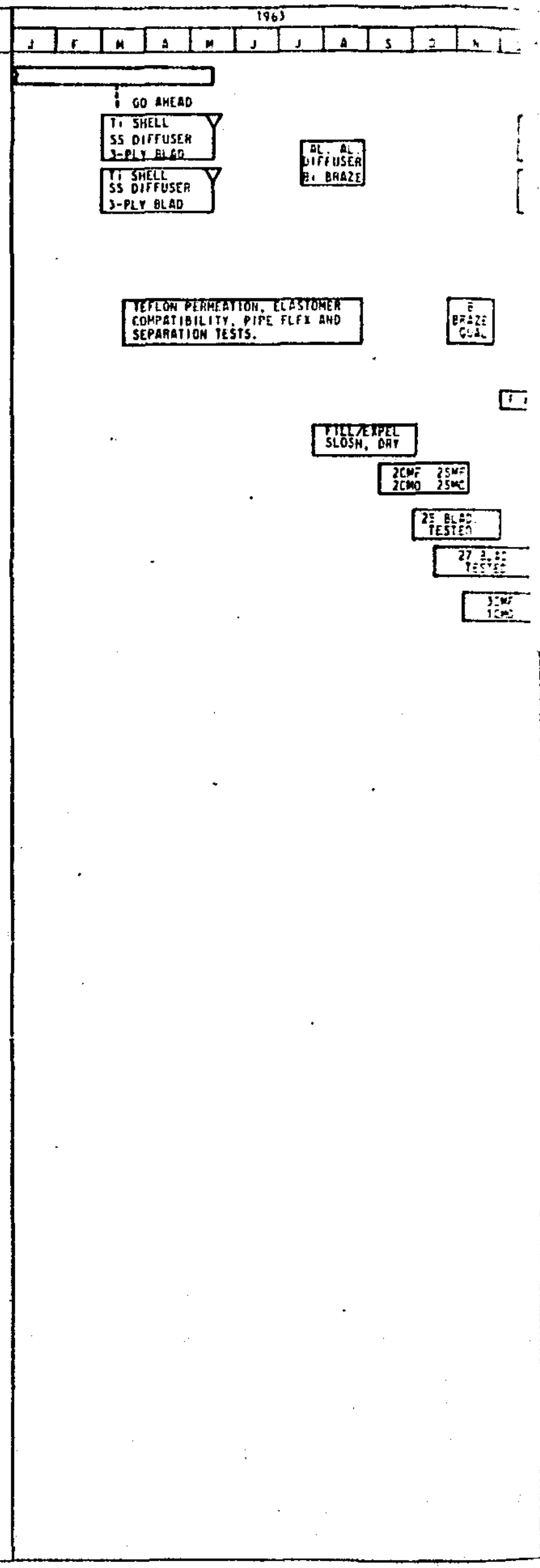
I PROPOSAL AND SPECIFICATION ACTIVITY

II DESIGN
A. COMMAND MODULE
B. SERVICE MODULE

III TESTING
A. MATERIALS
B. DYNAMICS DEVELOPMENT
C. 3-PLY BLADDER PROGRAM
1. PLEXIGLASS TANK/BLADDER
2. ORIGINAL DVT PROGRAM
3. BLADDER TWIST EVALUATION
a. PLEXIGLASS TANK
b. METAL TANKS
4. OVERSIZE BLADDER CONFIGURATION
a. DEVELOPMENT
b. CONFIDENCE LEVEL TESTING
(1) COMMAND MODULE
(2) SERVICE MODULE

D. 1-PLY 6-MIL BLADDER PROGRAM
1. DEVELOPMENT
a. COMMAND MODULE
b. SERVICE MODULE
2. DESIGN VERIFICATION TEST
a. COMMAND MODULE FUEL
b. COMMAND MODULE OXIDIZER
c. SERVICE MODULE FUEL
d. SERVICE MODULE OXIDIZER
3. COMMAND MODULE DEVELOPMENT
a. CM FUEL
b. CM OXIDIZER
4. QUALIFICATION LEVEL & OFF-LIMIT PROGRAM
a. COMMAND MODULE FUEL (DVT)
b. COMMAND MODULE OXIDIZER (DVT)
c. SERVICE MODULE FUEL (QUAL)
d. SERVICE MODULE OXIDIZER (QUAL)
e. SERVICE MODULE OXIDIZER (CERTIFICATION)
5. DESIGN SUBSTANTION-COMMAND MODULE
6. PROPELLANT EXPOSURE
a. SERVICE MODULE FUEL
b. SERVICE MODULE OXIDIZER

E. PROPELLANT STORAGE
a. N_2O_4 STORAGE - 10 TANKS
b. FUEL (MMH & 50150) STORAGE
c. TITANIUM/ N_2O_4 STRESS CORROSION PROG.



FOLDOUT FRAME /

...RVICE MODULE TANKAGE PROGRAM HISTORY

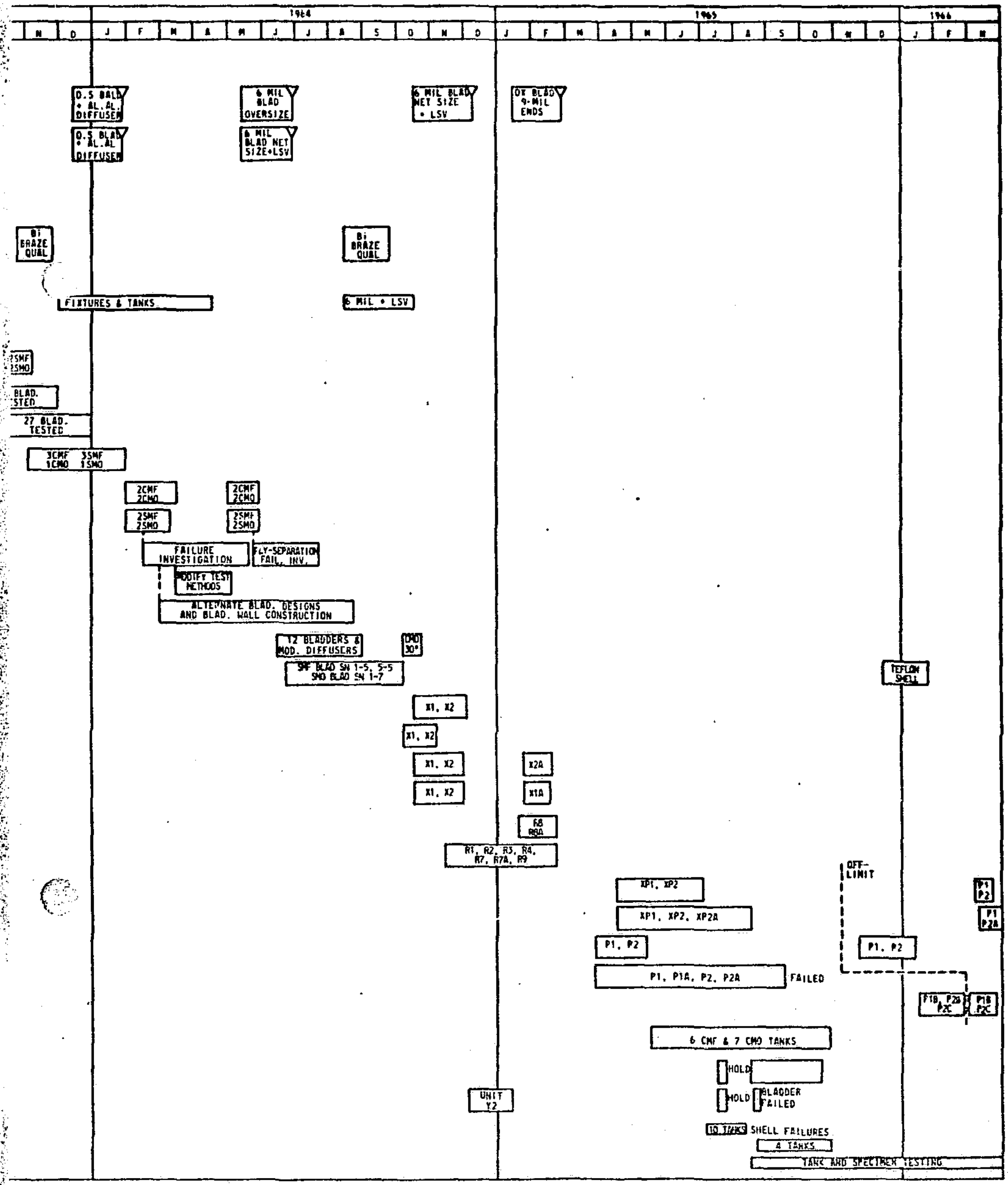


FIGURE III-1

FOLDOUT FRAME 2

All known Teflon bladder fabricators were surveyed for their ability to perform to the bladder fabrication requirements. As a result of these evaluations, Dilectrix Corporation was selected as the Teflon bladder vendor.

The selection of the vendor for the butyl bladder had not been completed at the time the decision was made to use Teflon instead of butyl for the fuel bladders. The state-of-the-art capability had been established and the most advanced fabricators were working with Bell during the material development program. These vendors also participated later in the program when butyl bladders were fabricated as part of an alternate bladder design effort.

Additional effort during this time included designs for an aluminum shell and titanium diffuser assemblies.

By July 1963, the design was considered 100% complete since all drawings had been released and the formal design review was completed. Minor changes had been made to the drawings during fabrication of the initial prototype hardware to ease manufacture. At this time, weight reduction became a major factor. Design changes were made to save weight at the sacrifice of interchangeability of CM and SM parts and extending fabrication times. These changes included reducing the wall thicknesses of the diffuser, retainer, and the SM flange. In addition, an evaluation was performed to check the feasibility of changing to an aluminum diffuser assembly. The change to aluminum bladder hardware was initiated and the design was completed in September. This design included the stainless-steel-to-aluminum bimetallic joint on the outlet port tubing to provide the stainless steel tube required for brazing to the system plumbing. Bi-braze Corporation was selected as the vendor and Bell personnel began working with them immediately to establish design parameters and fabrication techniques. Since this was a dissimilar metal union, compatibility tests were performed immediately and a qualification program was subsequently completed.

In October 1963, vent lines were added to the design. The vent lines are external to the bladder and provide a passageway for gas to bleed from the blind end of the tank to the helium inlet port. The need for the vent lines as servicing aids was established during plexiglass testing when difficulty in venting the gas was encountered while draining the tank in the vertical flange-down position. At that time there was a requirement for repetitive expulsion cycling (50 cycles), one-third of which were in the vertical flange-down position. This 3-position requirement was for both the command and service module. For this reason, the vent lines were incorporated in both the CM and SM configurations.

In November, a new weight reduction program was initiated to substantially reduce the tank assembly weight. Excess material was removed from the shell boss and the aluminum diffuser hardware was incorporated.

During this same period, the bladder design was changed as a result of rupture type failures during the DVT program. The failures were caused by twist, and a failure investigation and bladder development program resulted in the oversize (added length) bladder as a quick solution to the problem. This solution was advantageous because it had a minimum effect on other components, the shortest possible impact on fabrication schedule, and allowed use of existing hardware and tooling. The bladder length increases were as follows:

CMF	2.60 inches
CMO	3.73 inches
SMF	4.84 inches
SMO	4.00 inches

These length increases resulted in only one new bladder size because the existing bladder configurations were adjusted as follows:

CMF	bladder was deleted
CMO	bladder used in CMF tank
SMF	bladder used in CMO tank
SMO	bladder used in SMF tank

New oversize SMO bladder designed

Drawings for the new tank assemblies were released in January 1964 with the following configuration:

	CM	SM
Shell	Titanium	Titanium
Diffuser	Aluminum	Aluminum
Bladder (oversize)	3-ply Teflon	3-ply Teflon

This design was modified, after drawing release, to add Teflon buffer pads at each end of the bladder to prevent bladder damage from adjacent metal hardware. This type of damage had occurred during vibration testing in the development program.

A confidence level test program was initiated on two tank assemblies of each configuration. The command module tank assemblies were tested in the horizontal position only and demonstrated excellent cycle life capability. Three of the four service module tanks failed prematurely. A large scale failure investigation was started and the test cell and procedures were modified. During this period, alternate bladder design activity was started. Two tanks of each configuration were again subjected to testing to demonstrate confidence in the capability to pass the design verification test requirements. The CM tanks were tested in the horizontal position and the SM tank in the vertical (both flange-up and flange-down) position. All eight tanks failed because of low efficiency, inability to achieve repeatable loads, or high leakage. The failures on the oxidizer tank resulted from ply separation.

Several alternate bladder designs were completed and included the following:

- Elastomer/metal/Teflon
- Teflon cloth/Teflon film/Teflon cloth
- Teflon cloth/Teflon Film/aluminum foil
- Redundant 3-ply TFE film
- Redundant 3-ply FEP film
- Teflon film (6 mil)/Teflon cloth (9 mil)
- 3-ply Teflon (5 mil TFE/3 mil FEP/ 5 mil TFE)
- 1-ply Teflon (3 mil TFE/3 mil FEP)

The last three bladder designs were fabricated and tested. In addition, a diffuser assembly which included a liquid side vent (bleed tube) was fabricated and tested in conjunction with the 3-ply and single-ply bladder configurations. These tests were conducted with both oversize and net size* bladders.

The ply separation problem was unsolved and the decision was made to incorporate the single-ply bladder. This design was based on the success of SMF bladder SN 1-5. The design was changed in June 1964 to the following configurations:

	CM	SM
Shell	Titanium	Titanium
Diffuser	Aluminum	Aluminum with Bleed Tube
Bladder	1-ply Teflon (oversize)	1-ply Teflon (net size)

The bleed tube was incorporated into the service module design to facilitate loading and purging, but was not approved for the CM configurations. The bleed tube in the SM diffuser required a new bi-braze joint configuration which was subsequently qualified.

The decision was made to start DVT testing of these configurations without further development; two tank assemblies of each configuration were tested. These tanks failed to meet the specification requirements of 50 expulsions and expulsion efficiency of 99% at a ΔP of 2 psi; however, the test results indicated that a cycle life of 20 expulsions at an efficiency of 98% at 2 psi ΔP, could be attained on all but the CMO configuration. The CMO cycle life was low and efficiency was poor, especially during the high temperature expulsions.

A development program was initiated for the CMO configuration on the R-series tanks. As a result, the diffuser was modified as to number and location of holes. In addition, the liquid bleed tube and net size bladder were added. Additional

* Net size means nominally the same size as the inside dimensions of the shell.

development testing of CMO unit R9 showed that the expulsion efficiency was increased with heavy (9 mil) ends on the bladder. This design change was added to the CMO configuration in February 1965. The configurations at this time were as follows:

	CM	SM
Shell	Titanium	Titanium
Diffuser	Aluminum LSV	Aluminum LSV
Bladder	1-ply Teflon (6 mil) net size (ox: 9 mil ends)	1-ply Teflon (6 mil) net size

This design remains fixed except for minor changes such as thickening the SM diffuser flange so that it is common with the CM configuration.

3. Development Testing

All development testing was eliminated from the planned program with the exception of material and plexiglass tank testing. However, the original high-risk design verification test program was unsuccessful and a great deal of additional testing was performed prior to establishing the final tank configurations. From a historical approach all testing prior to formal qualification type testing on the final configurations is included as development testing.

a. Material Testing

The planned material testing was initiated in March 1963 to test butyl and Teflon bladder material samples for propellant compatibility, permeation, and gas transmission. In addition, 3-ply Teflon test pipes were tested for cycle life and ply separation.

(1) Butyl Material Tests

Samples of nine different elastomeric compounds were tested to determine compatibility with the MMH and 50/50 blend fuels. The original plan was to test the samples after various periods of immersion in the propellant. This plan was modified because of the decision to use Teflon bladders instead of butyl in the fuel tankage. All of the compounds exhibited good compatibility in both fuels after immersion periods of 7 and 28 days.

(2) Teflon Material Tests

(a) Gas Transmission

Gas transmission rates were established by testing 1-ply, 3 mil and 3-ply samples in air, N_2O_4, MMH, and 50/50 blend fuel. The tests were conducted at ambient temperatures using a modified ASTM D 1434-58 apparatus.

(b) Cycle Life and Ply Separation

This testing was performed on three 3-ply, 3 mil Teflon test pipes at 150 psi ΔP and room temperature with N_2O_4 and MMH. One pipe completed 100 cycles in MMH, and each of the other pipes completed 100 cycles in N_2O_4. Under static conditions an accumulation of N_2O_4 was detected between the plies; however, there was no evidence of ply separation during flex testing.

(c) Permeation

Permeation tests were performed at various temperatures on 3-ply, 3 mil specimens using the NASA permeation test apparatus with N_2O_4.

(d) Compatibility

The decision to use Teflon bladders in the fuel tanks necessitated compatibility checks of Teflon with MMH. Specimens of 3 mil material showed no significant change in properties after immersion in MMH for 21 days at temperatures of 75 and 105°F.

(3) Bi-Braze Joint

The aluminum/stainless steel joint was subjected to exhaustive testing because of the normal restriction on the use of dissimilar metals and possible resulting galvanic corrosion.

(a) Compatibility

Joint assemblies were immersed in N_2O_4 at a temperature of 105°F for a period of 63 days with no deleterious effects on the hardware.

(b) Qualification Testing

The original bimetallic joint consisted of a section of aluminum tube joined to a section of stainless steel tubing. Ten tube assemblies successfully completed individual qualification test sequences and demonstrated the ability to meet the design requirements. Testing included hydrostatic proof pressure, helium leakage, thermal cycling, fatigue cycling, tension, vibration, burst, and metallographic analysis. The detailed test results are contained in Bell Report No. 8271-927003.

The joint design was modified when the tank assembly design was changed to include a liquid side vent diffuser, and a new qualification program was performed in August of 1964. The new design consisted of a curved section of stainless steel tube joined to an aluminum cone. Five test units successfully completed a qualification test sequence similar to that performed on the previous configuration. The detailed test results are contained in Bell Report No. 8271-927006.

b. Plexiglass Tank Test Program

Plexiglass test tanks were designed and fabricated for the command and service modules with extra center sections so they could be used for either the fuel or oxidizer configurations. These tanks permitted visual observation of the action of the 3-ply bladder; however, testing was limited to simulated propellants at a maximum pressure of 40 psig. The test series for each configuration consisted of slosh, loading and expelling, and drying evaluations.

(1) Load and Expulsion

This testing was performed on each configuration to refine the procedures and demonstrate the capability of being loaded and expelled in all three attitudes - horizontal, vertical flange-down, and vertical flange-up. The vacuum loading technique was used on all configurations. A problem arose in servicing in the vertical flange-down position because of the inability to vent the gas trapped between the bladder and shell. The problem had been anticipated because of experience from previous programs. The addition of vent lines alleviated the problem.

The CMF configuration was subjected to life cycle testing to demonstrate the 50-cycle capability with all tests performed at a maximum temperature of 40°F. Thirty-six expulsions (16 horizontal, 17 vertical flange-up, 3 vertical flange-down) were completed prior to bladder failure. The failure was caused by the low temperature effects coupled with the twisting action noted during the horizontal cycles.

A new bladder was installed and 50 cycles were completed as follows:

8 expulsions at 40°F horizontal
8 expulsions at 70°F horizontal
17 expulsions at 70°F vertical, flange-up
17 expulsions at 70°F vertical, flange-down

(2) Slosh

All four configurations were subjected to low frequency vibration scans to establish the major liquid natural frequencies. The tests were completed without incident.

(3) Drying Evaluation

Vacuum drying techniques for use during production acceptance test were evaluated using methylene chloride and methyl alcohol at ambient and low temperatures.

c. Initial Prototype (DVT) Test Program

This program, started in September 1963 before completion of the plexiglass tank testing, was the initial testing on the prototype metal tank assemblies. The testing was performed in accordance with the then current specification sequence and requirements. The expulsion cycle demonstration required 50 propellant expulsions, each of which was conducted with a differential pressure of full tank assembly operating pressure across the bladder at the end of the expulsion. In addition, each configuration was tested in all three attitudes and at high, ambient, and low temperatures. Eight tank assemblies, two of each configuration, were to be subjected to the DVT sequence and, in addition, one CMF and one SMO tank shell were to be pressure cycled and burst. The test results of each configuration were as follows:

CMO Unit X1 completed 16 propellant expulsion cycles including 8 at 40°F in the horizontal position and 8 at 70°F in the vertical flange-up position. During fill for the 17th expulsion, after changing to the flange-down position, a failure was evident. The bladder was torn through all three plies and had the appearance of being burst. The tank assembly was refurbished with a new bladder and held for future testing.

CMO Unit X2 completed acceleration and started vibration testing when the bladder failed. The tank assembly had been fully loaded in accordance with the requirements and the internal pressure buildup during vibration forced the bladder against the edges of the holes in the "showerhead" ring causing the failure. The procedures were changed to allow proper ullage capacity during testing and, as a result of this failure, Teflon buffer pads were added to each end of the bladder to protect it from damage by the bladder hardware. These pads were tested during vibration development and were incorporated into the design in December 1964.

CMF Unit X1 was held pending solutions to the other tank failures and was later used in the bladder development program.

CMF Unit X2 completed acceleration testing prior to the start of the vibration testing. During the random vibration run the helium port fitting fractured because of improper fixturing. The fixtures were modified and the tank assembly was refurbished for future testing.

CMF Unit X3 completed the specified 3000 pressure cycles prior to being burst. The resulting burst pressure was 1049 psig. *

SMF Units X1 and X2 were not tested. The units were held for future testing.

SMO Units X1 and X2 were not tested because of the bladder failures encountered with the command module configurations.

SMO Unit X3 completed the required 3000 pressure cycles and was burst at a pressure of 567 psig. *

d. Development Test

Although the original development program had been deleted, it became necessary to reinstate a development effort because of the twisting type bladder failures and vibration fixturing problems. All design verification testing was stopped and development programs were established in each of these areas:

(1) Dynamics Development

This program was initiated in November 1963 to solve the tank assembly and fixture problems encountered during DVT where bladder failures had occurred during vibration with the box type fixtures. The original plan was to test the tank assemblies concurrent with the evaluation of redesigned fixtures and optimized equalization techniques. The scope of the program was expanded to include evaluation of tank assemblies with aluminum diffusers and oversize bladders.

(a) Fixture Redesign

Each tank assembly was to be vibrated in three axes - one longitudinal and two lateral. During the original DVT testing, problems arose on trying to equalize because of the fixturing. Several companies and laboratories were consulted regarding fixture design and random vibration equalization techniques. As a result, new fixtures were designed - circular plate for the command module, and tubular type for the service module.

(b) Tank Assembly/Fixture Testing

The command module units tested with the box type fixture during DVT resulted in bladder failures during the random equalization runs. Three additional units, one fuel and two oxidizer, were tested with the circular plate

* (Additional burst test data were obtained in November 1963 by burst testing of one CMO and one CMF shell which had been rejected because of excessive porosity and mismatch. The resulting burst pressures, after completion of pressure cycling, were 920 and 1020 psig, respectively.)

fixture. The fuel unit was tested successfully; however, the first oxidizer unit test resulted in a bladder failure during endurance testing. A second oxidizer test with an oversize bladder was successful except for mounting bolt problems.

All service module testing was performed using the tubular fixtures. Six test units, three fuel and three oxidizer, were tested. One fuel and one oxidizer without bladders were used for lateral axis fixture checkout. Mounting bolt problems were encountered and the necessary modifications were made. Some mounting bolt problems were evident during testing of the remaining four units; however,the tank assemblies successfully withstood the required vibration inputs. New high-strength bolts were used for subsequent testing.

(2) Bladder Development

This program was undertaken to solve the twisting problem as quickly as possible with minimum effect on the hardware configuration. The effort was directed toward procedural changes which would negate the effects of twisting and minor hardware modifications which would prevent twist or failures due to twist. Potential hardware changes included the following:

- Controlled-fold devices
- Finned diffuser
- Multiple vent lines
- Undersized bladder
- Oversize (length) bladders
- Liquid side vent (bleed tube) diffuser

In addition, the bladder fabrication process was monitored and evaluated to determine if the twist was inherent because of the technique of spraying a rotating mandrel. This theory was not substantiated by the investigation. Approximately 50 bladder tests were performed in both plexiglass and metal tanks during this development program. The hardware and procedural modifications were first tested in plexiglass tanks with simulated propellant and then, if a concept showed potential, it was tested in the metal tanks with propellant.

(a) Procedural Changes

Attempts were made to prevent rupture type failures resulting from twisting by controlling load pressures and flow rates. In addition, repositioning by cycling the bladder with gas prior to each load was attempted. Several variations and combinations of gas cycling, pressure, and evacuation techniques were attempted with the tank assembly in each of the three required orientations. A satisfactory procedure was established for the command module tanks and the 50-cycle requirement was demonstrated on four tanks of each configuration, using water as the test liquid. These procedures did not alleviate the twist problem in the longer service module tank assemblies.

(b) Controlled-Fold Devices

Activity on these devices was limited to a design effort. No workable design was established because of the tank assembly configuration and the susceptability of the bladder material to damage from mechanical restraining devices.

(c) Finned Diffuser Tube

A diffuser assembly with anti-twist fins attached longitudinally to the diffuser tube was fabricated and tested in plexiglass and metal tank assemblies. This concept showed some potential but no further testing was performed because of the success of the oversized bladder described below.

(d) Multiple Vent Lines

A bladder assembly was built up with eight (instead of the standard two) vent lines to prevent localized gas pockets and permit more uniform gas flow between the bladder and shell. Testing in the plexiglass tank indicated that there was no improvement in the twist problem with this configuration.

(e) Undersize Bladder

A CMF bladder was shrunk so that it was approximately 1/8-inch undersize. This unit was tested in the plexiglass tank at very low pressure and successfully completed 50 cycles with little twist; however, the concept was abandoned because it was felt that the undersize characteristics would be lost because of stretching.

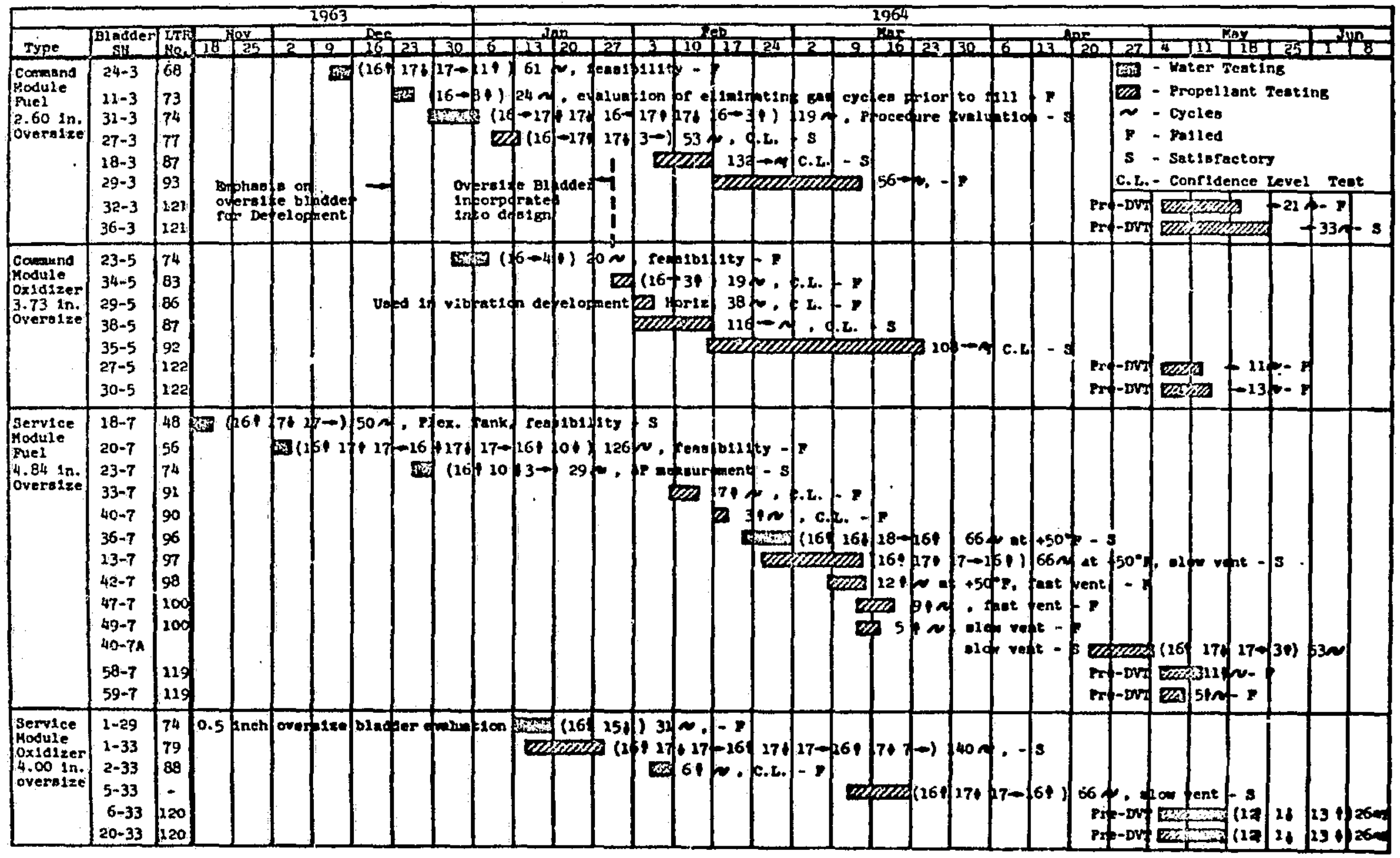
(f) Liquid Side Vent Diffuser

A diffuser was modified to include a liquid side vent (bleed) tube to permit liquid loading with the bladder expanded. This concept eliminates the vacuum loading technique for the vertical position and facilitates servicing. One test of 33 cycles was performed in the plexiglass tank with minimal twist. No additional testing was performed at this time because this concept was not applicable to the horizontal loading requirements of the command module configuration.

(g) Oversize Bladder

The oversize bladder concept was based on the idea that the additional length would permit twisting without the burst-type failures. A test summary is presented in Figure III-2. The first trial was testing of a SMO bladder in the SMF plexiglass tank. Fifty cycles were completed without failure. A new SMO bladder was installed in a metal tank and 126 water expulsions were completed at standard pressures and flow rates before bladder failure. The next test was a CMO bladder in a CMF metal tank which completed 61 water expulsions prior to failure. Testing of these units was performed in all three attitudes.

FIGURE III-2 MODEL 8271 3-PLY OVERSIZE BLADDER TEST SUMMARY



Based on the success of these tests, emphasis was placed on the oversize bladder as a solution to the twist failures. The oversize configuration resulted in a minimum effect on other components and had minimum effect on the schedule because existing hardware and tooling could be used. The additional bladder lengths were attained by using the CMO bladder in the CMF tank, the SMF bladder in the CMO tank, the SMO bladder in the SMF tank, and a new oversize bladder in the SMO tank. The other concepts were abandoned so that hardware and effort could be concentrated on meeting the program schedule with the oversize design. During December 1963, additional oversize bladders were tested with water to refine loading and servicing procedures and acquire cycle life data. This testing demonstrated that the 50 expulsion cycle life was attainable. Testing in January 1964 was delayed until additional bladders of the required configurations could be fabricated for use in confidence level testing.

e. Confidence Level Testing-Oversize Bladders

This test program was started in January 1964 with successful completion of 53 cycles in all three attitudes at 50°F on a CMF tank (Bladder SN 27-3). The aluminum diffuser and oversize bladder were incorporated into the design based on this test coupled with the results of the development program. The intent of this program was to establish a level of confidence in the ability to pass the DVT 50-cycle requirement by testing two units of each configuration to the specification expulsion requirements, except all testing was performed at 50°F.

(1) Command Module

The first CMO unit (Bladder SN 34-5) failed after 19 cycles, of which the last three were vertical. The previous expulsion test with water (Bladder SN 23-5) had resulted in failure after 20 cycles with the last four vertical. Based on the results of these tests it was decided to test four additional command module tanks to failure with the tests performed at 50°F in the horizontal position only. The results were as follows:

CMF (Bladder SN 18-3) completed 132 MMH expulsions in the horizontal position without failure.

CMF (Bladder SN 29-3) completed 56 MMH expulsions in the horizontal position prior to failure.

CMO (Bladder SN 29-5) had previously completed the DVT vibration test during vibration development. Since the unit was available, expulsion testing was performed prior to disassembly and refurbishment. The unit completed 38 N_2O_4 expulsions in the horizontal position prior to failure.

CMO (Bladder SN 38-5) completed 116 horizontal expulsions with N_2O_4 without failure.

CMO (Bladder SN 35-5) completed 108 horizontal expulsions with N_2O_4 without failure.

The results of these tests indicated that the 50-cycle life requirement was easily attainable if the testing was performed in the horizontal attitude.

(2) Service Module

Previous expulsion testing with water had indicated good cycle life. The propellant testing in all three attitudes was started on the oxidizer tanks and the first test was very successful. The results of the four confidence level tests were as follows:

SMO (Bladder SN 1-33) completed 140 N_2O_4 expulsions without failure.

SMO (Bladder SN 2-33) failed after completion of six vertical expulsions.

SMF (Bladder SN 33-7) failed after seven vertical expulsions.

SMF (Bladder SN 40-7) failed after three vertical expulsions.

The confidence level testing of the service module configurations was stopped and a thorough investigation of the three premature failures was started.

f. Confidence Level Test Failure Investigations

The investigation of the Service Module bladder failures was initiated immediately. A very extensive compilation of variables which could occur in fabrication, assembly, and test was assembled in matrix form for bladders that were tested without failing versus bladders which failed prematurely. This matrix of variables failed to determine conclusively the cause of failure; however, many possibilities such as raw material problems, bladder fabrication, faulty hardware, and assembly methods were eliminated. The variables which remained as possible causes of failure were the effects of 50/50 fuel blend on the bladder material and the low temperature and high humidity encountered during assembly, shipping, and storage. The 50/50 fuel blend was investigated because with one exception all premature failures occurred during tests with this propellant. The one exception was the failure of a service module oxidizer bladder that appeared to have been damaged during assembly. The material, heat transfer effects, test procedures, design, and instrumentation accuracy were scrutinized for any possible detrimental conditions that may have induced the bladder failures. A bladder development plan, divided into the following tasks, was formulated and a concentrated effort was initiated to establish the corrective action required to eliminate the cause of failure:

- Analytical Studies - This category included a malfunction analysis, weight measurement study, investigation of critical parameters, and an independent test data analysis.
- Laboratory Testing - Tests were performed to evaluate 50/50 blend fuel characteristics and Teflon gas transmission.
- 3-Ply Bladder Testing - To support other areas of the investigation.
- Design Alternatives - Diffusers and bladders. (This effort was performed concurrently with the failure investigation and is discussed in detail in succeeding sections of this report.)

(1) Analytical Studies

(a) Malfunction Analysis

This analysis, conducted to determine the effect of test equipment and instrumentation on the test, resulted in several changes to the test procedure and modification of the test cell.

(b) Weight Measurement

This study was conducted to determine the most accurate and reliable methods of measuring weight, flow, and pressure drop. As a result, the test stands were modified and more accurate and reliable methods of weight measurement were incorporated into the test procedure. The scales were changed and the test data reduction procedures were revised to insure optimum accuracy in measuring expulsion efficiency.

(c) Test Data Analysis

A separate reliability review of existing test data and specification requirements was completed. This information was used in the modification of the test cell and procedures.

(d) Analytical Investigation of Critical Parameters

This investigation was conducted to determine the procedural changes necessary to eliminate or minimize the problems caused by thermodynamic effects encountered during expulsion cycling. Computer studies were conducted for the service module tanks by varying the rate of post-expulsion venting. The results of six cases were analyzed to determine the effect of the venting rate on tank and bladder temperature. The results proved the possibility of encountering extremely low temperatures during the venting and evacuation processes. The procedures were refined to provide precise control and monitoring of temperatures during all phases of testing.

(2) Laboratory Testing

(a) Gas Transmission Testing

This series of ASTM permeation tests was conducted on 3-ply, 3 mil Teflon material using helium as the permeant. Tests were conducted on material with a pinhole in one, two, and three plies in addition to tests on material in the as-received condition. The purpose of the tests was to establish a realistic leakage rate for each of the bladders and a criteria for detecting the occurrence of a pinhole in a bladder. The test results are contained in Bell Report No. 8271-928018.

(b) Propellant Investigation

Laboratory tests of 50/50 fuel blend were conducted to support the bladder failure investigation. The following areas were investigated:

- Freezing and thawing characteristics of 50/50 blend and mixtures of 50/50 blend with Freon-TF, isopropanol, and water under normal and reduced pressures.
- Impact sensitivity of crystals resulting from these mixtures.
- Effects of absorbed 50/50 fuel blend on bladder material subjected to freezing.
- Impact sensitivity of bladder material containing absorbed propellant mixtures cooled below their freezing points.
- Formulation of crystals during simulated oxidizer or fuel diffuser tube decontamination at reduced pressure.

These investigations were completed but the results did not provide evidence of the cause of bladder failures in the service module tanks. This program was later extended to further investigate the compatibility of Teflon and propellants.

(3) 3-Ply Bladder Testing

Tank assembly expulsion testing was performed to simulate the SMF failures and support the analytical and laboratory evaluation results.

(a) Failure Simulation Tests

Three SMF tank assemblies were tested in an attempt to duplicate the premature failures which occurred during confidence level testing. The tests were as follows:

SMF (Bladder SN 36-7) was expulsion tested with water in a prototype tank assembly at 50°F in the DVT attitudes using the same diffuser and bladder hardware which had been used with Bladder SN 40-7. The unit completed 66 expulsions without failure.

SMF (Bladder SN 13-7) was expulsion tested with 50/50 blend at 50°F in the DVT attitudes under carefully controlled assembly and test conditions. and completed 66 expulsions without failure. The post-expulsion vent time was controlled to prevent the low temperature conditions associated with rapid venting.

SMF (Bladder SN 42-7) was expulsion tested with 50/50 blend at 50°F in the DVT attitudes. The conditions prevailing during testing of the confidence level tanks which failed were duplicated as closely as possible. This included fast venting. Bladder failure occurred after 12 expulsions.

(b) Tank Assembly Testing to Support Evaluations

Three major tank tests with propellant were performed to support preliminary analytical and laboratory evaluations. These tests were performed mainly to check procedural and test cell changes associated with temperature conditions resulting from post-expulsion venting.

SMF (Bladder SN 47-7) failed after nine expulsions during fast vent evaluation.

SMF (Bladder SN 49-7) failed after five cycles during slow vent evaluation.

SMO (Bladder SN 5-33) completed 66 expulsions without failure during slow vent evaluation.

After these tests, tank assembly testing was stopped until the analytical and laboratory investigations were completed. After the final procedural changes were made, one additional tank assembly test was conducted to determine the effects of slow venting and terminating the expulsion at a differential pressure of 2 psi instead of full tank pressure.

SMF (Bladder SN 40-7A) successfully completed a total of 53 propellant expulsions in all three required attitudes without failure. Fifty expulsions were performed at 50°F and three at 40°F.

The test was terminated to permit the start of Pre-DVT testing on all four tank configurations.

g. Pre-DVT Testing

(1) Test Plan

The laboratory experimental tests and analytical investigations had been completed and, as a result, the test equipment and procedures were modified to insure data accuracy and control temperature to prevent freezing. Failure criteria were established for tank assembly expulsion cycling as follows:

- Loaded weight repeatable within one pound of propellant
- Residual load repeatable.
- Flow trace not erratic.

In addition, the requirement was changed so that the command module tanks were tested in the horizontal position and service module in the vertical (flange-down and flange-up) position.

(2) Test Results

Eight tank assemblies, two of each configuration, were subjected to the DVT expulsion test sequence. The results for each test unit were as follows (See Figure III-2):

CMF (Bladder SN 32-3) completed 21 cycles in the horizontal attitude before testing was terminated because of excessive leakage rate.

CMF (Bladder SN 36-3) completed 33 cycles in the horizontal attitude before the test was terminated. Evaluation disclosed that the bladder had twisted approximately 140°, and ply separation was evident between the middle and outer plies.

CMO (Bladder SN 27-5) completed 11 cycles in the horizontal attitude before the test was terminated because of excessive load weight deviation and low expulsion efficiency. Subsequent evaluation disclosed considerable ply separation.

CMO (Bladder SN 30-5) completed 13 cycles in the horizontal attitude before testing was terminated because of excessive load weight deviation and low expulsion efficiency.

SMF (Bladder SN 58-7) completed 11 cycles in the vertical, flange-up attitude before testing was terminated because of erratic flow indications and continuous high residual weights.

SMF (Bladder SN 59-7) completed 5 cycles in the vertical, flange-up attitude before testing was terminated because of a failure during loading.

SMO (Bladder SN 6-33) completed 12 cycles in the vertical, flange-up attitude and 14 cycles in the vertical, flange-down attitude before testing was terminated because of excessive load weight deviation.

SMO (Bladder SN 20-33) completed 12 cycles in the vertical, flange-up attitude and 14 cycles in the vertical flange-down attitude before testing was terminated because of excessive load weight deviation.

(3) Failure Investigation

Failure was indicated early in the testing. The service module fuel tanks had high leakage rates and liquid on the gas side of the bladder. The discrepancies in the service and command module oxidizer tanks were caused by ply separation. Inspection of the bladders after disassembly showed that the outer plies failed because of twisting or tearing and the inner plies contained pinholes. Expulsion testing was stopped to conduct further laboratory type tests to investigate the compatibility of Teflon with the propellants under varying storage periods and temperatures and the mechanics of ply-separation. Prior to the completion of this testing, the decision to change to an alternate configuration was made.

(a) Ply-Separation Testing

Ply-Separation tests were initiated for the following reasons:

- Establish an expulsion procedure to prevent occurrence of ply-separation.
- Establish a method of removing vapor from between the plies.
- Determine amount of ply-separation occurring under various conditions.

Testing was performed on 3-ply Teflon "pipes" using N_2O_4 at various temperatures ranging from 60 to 105°F. The ply separation increased with temperature and soak time. An additional test with MMH at a temperature of 105°F revealed that the separation was negligible compared to N_2O_4. Efforts to prevent or efficiently remove propellant vapor from between the plies was unsuccessful both in "pipe" and tank assembly testing. As a result of this problem, the decision was made to change from the 3-ply to the single ply bladder.

(b) Teflon/Propellant Studies

Tests were performed to acquire specific data on the physical properties of Teflon laminate materials after exposure to various propellants for varying time periods. Although the emphasis was on 6 mil and 3 mil (1-ply and 3-ply) laminate material, samples of 4 and 5 mil were also tested. The primary testing was performed with N_2O_4, MMH, and 50/50 blend; however, data was acquired from testing with N_2H_4, UDMH, air, and water. The tests were conducted to determine the effect of fluid on materials as a function of temperature and time. The resulting data established the following limits for optimum bladder performance:

Propellant	Minimum Temperature
N_2O_4	+50°F
MMH	+45°F
50/50	+55°F

h. Alternate Design Activity

Shortly after the bladder failures in the confidence level test program, an alternate design program was initiated with the effort paralleling the failure investigation and other testing. The purpose of this program was to develop an alternate configuration which could be used if the failure investigation resulted in the necessity for a major design change. The following concepts were considered for evaluation:

- New Bladder Construction

  Three ply Teflon (5 mil/3 mil/5 mil)
  Single ply Teflon/Teflon Cloth (6 mil/? mil)
  Single ply Teflon (3 mil TFE/3 mil FEP)
  Single ply elastromeric
  Advanced combinations of Teflon, cloth, metal, and elastromers

- Diffuser Hardware

  Liquid side vent (bleed tube)
  Controlled-fold devices

- Metallic Devices

  Bellows
  Convoluted diaphragms

(1) Design

A design for a liquid side vent diffuser was completed in addition to the following bladder alternatives:

- Elastromer/Al. foil/Teflon film
- Teflon film/Teflon cloth
- Teflon cloth/Teflon film/Teflon cloth
- Teflon cloth/Teflon film/Al. foil/Teflon cloth
- 3 redundant films, each film 2 mil TFE
- 3 redundant films, each film 3 mil TFE
- 3-ply Teflon (5 mil/3 mil/5 mil)
- 1-ply elastomeric
- 1-ply Teflon (3 mil TFE/3 mil FEP)

(2) Testing

A summary of the alternate design testing is shown in Figure III-3.

(a) Three-Ply Teflon (5 mil/3 mil/5 mil)

Two oversize bladders were tested as follows:

SMF (Bladder SN 1-93) completed 18 cycles with 50/50 fuel blend (six cycles in each attitude). Low expulsion efficiency was indicated after the second cycle. Inspection after disassembly revealed pinholes in the inner ply.

FIGURE III-3 MODEL 8271 DESIGN ALTERNATIVES DEVELOPMENT TEST SUMMARY

Tank Config.	Blad Size	Blad S/N	Bladder Part No.	Bladder Construction	LTR No.	1964 (Apr, May, Jun, Jul, Aug, Sep)
C/M Fuel	Net	1-1	8271-471148-1	6 mil Teflon (3 TFE/3 FEP) LSV	137	Plex. Tank ■ Fill Evaluation
	O.S.	28-3	8271-471030-3	3 ply, 3 mil Teflon LSV	143	Plex. Tank / Metal Tank ■ 9~ Modified Diffuser - Twist and expulsion effc'y eval. ■ 9~ Modified Diffuser-ΔP and expulsion effc'y eval.
	O.S.	51-3	8271-471030-3	3 ply, 3 mil Teflon	145	■ 3~ Helium/Ply separation
	O.S.	50-3	8271-471030-3	3 ply, 3 mil Teflon Mod. Diffuser	154	■ 3 Vacuum Test
C/M Oxidizer	Net	1-3	8271-471148-3	6 mil Teflon (3 TFE/3 FEP) LSV	136	Plex. Tank ■→ 24 ~ S; Metal Tank ■ →107 ~ (Last 25 ~ at 40°F) - S
	O.S.	2-5	8271-471148-5	6 mil Teflon (3 TFE/3 FEP) LSV	146	■ Helium gas entrapment
					148	■ 9~ Modified diffuser - Twist and ΔP eval.
					144	Plex. Tank ■ 10~ Evaluate expulsion efficiency and twist.
	O.S.	76-5	8271-471030-5	3 ply, 3 mil Teflon	147	Plex. Tank ■ Eval. of effect of ply separation on ΔP and flow.
	Net	3-3	8271-471-148-3	6 mil Teflon (3TFE/3FEP) Mod. Diffuser	151	■ } 8 ~ Expulsion efficiency using diffusers modified as to number of holes and location and size of holes.
	Net	1-3	8271-471-148-3	6 mil Teflon (3TFE/3FEP) Mod. Diffuser	151	■
	O.S.	2-5	8271-471-148-5	6 mil Teflon (3TFE/3FEP) Mod. Diffuser	151	■
S/M Fuel	O.S.	1-93	8271-471030-93	3-ply Teflon (5 mil/3 mil/5 mil)	105	▨ (6↓ 6↓ 6→) 18 ~ at 40°F (Erratic flow noted on 3rd and subsequent expulsions) - F
	O.S.	2-93	8271-471030-93	3-ply Teflon (5 mil/3 mil/5 mil)	110	▨ (16↓ 17↓ 17→ 3↓) 53~, 50 at 70°F, 3 at 40°F (Tested in parallel with SN40-7A, controlled vent and ΔP (2 psi) - S
	O.S.	1-1	8271-471130-1	Teflon film/Teflon cloth (6 mil/9 mil)	106	■ 3 ~ at 40°F - F
	Net	1-5	8271-471148-5	6 mil Teflon (3 TFE/3 FEP) - LSV	134	▨ (12↓ 13↓ 11↓) 36~ (34~ at 65°F, 2~ at 55°F) - F (Hardware Failure)
	Net	40-5	8271-471030-5	3 ply, 3 mil Teflon - LSV	129	Plex. Tank ■ (5↓ 5↓) 10 ~ (Twist and vertical displacement observation) - S
	Net	5-5	8271-471148-5	6 mil Teflon (3 TFE/3 FEP) - LSV	155	▨ 16~ Life cycle test
S/M Oxidizer	Net	2-1	8271-471130-1	Teflon film/Teflon cloth (6 mil/9 mil)	107	■ (5↓ 5↓ 5→) 15 ~ Plex. Tank - To observe folding characteristics, no twist noted. - S
	Net	2-1	8271-471130-1	Teflon film/Teflon cloth (6 mil/9 mil)		▨ 9 ~ Metal Tank Film separated from cloth - F
	Net	35-7	8271-471030-7	3-ply, 3 mil Teflon - LSV	112	■ (16↓ 16↓) 32 ~ - F
	Net	1-7	8271-471148-7	6 mil Teflon (3TFE/3FEP) LSV	135	■ (12↓ 12↓) 24~ (21 ~ at 65±5°F, 3 ~ at 43 to 55°F) - F
	Net	51-7	8271-471030-7	3 ply, 3 mil Teflon - LSV	104	■ (50↓ 50↓) 100 ~ Plex. Tank - (outer ply failed cycle 21, middle ply failed cycle 32) - S
	O.S.	31-33	8271-471030-33	3 ply, 3 mil Teflon - LSV	149	■ 15~ at 65°F - F

Legend:
- ▨ Water Testing
- ■ Propellant Testing
- ~ Cycles
- F Failed
- S Satisfactory
- LSV Liquid Side Vent

SMF (Bladder SN 2-93) completed 53 cycles with 50/50 fuel blend without failure. The first 50 cycles were conducted at +50°F and the last three at +40°F. Vent cycle was controlled to limit temperature drop and expulsion terminated at a ΔP of 2 psi. This bladder was tested in parallel with SN 40-7A.

These results supported by flex and ply separation tests on "pipe" sections indicated that this configuration had no apparent advantage over the 3-ply, 3 mil construction.

(b) Teflon Film/Teflon Cloth (6 mil/9 mil)

Two Teflon film/Teflon cloth bladders were tested as follows:

SMF (Bladder SN 1-1) oversize bladder failed after third expulsion with 50/50 fuel blend. Inspection revealed a small crack in the inner film.

SMO (Bladder SN 2-1) completed 15 water expulsions in the plexiglass tank as a net size bladder. Five cycles were conducted in each attitude to observe folding. There was no evidence of twisting. The bladder was then installed in the metal tank and completed nine N_2O_4 expulsions. Inspection revealed leakage at a seam.

These results coupled with the information acquired from testing three "pipe" sections indicated that this construction was not adequate.

(c) Elastomeric Bladders

A single-ply elastomeric bladder development program was established and fabrication was initiated at the following three vendors:

Stillman Rubber Company
Thiokol Chemical Corp., Reaction Motors Div.
Dilectrix Corp.

Specimens of the elastomeric compounds were tested for compatibility in 50/50 blend, MMH, and N_2O_4 concurrently with the fabrication development. The compounds tested were as follows:

SR617-75 (Stillman)
SR634-70 (Stillman)
EPR132 (Thiokol)
Parco 823-70 (Dilectrix)

Numerous delays in the planned program resulted from fabrication problems. Stillman used the core molding technique for bladder fabrication and several tooling problems arose. A total of 25 bladders were fabricated. Three of these were shipped to Bell; however, none were suitable for testing. In addition to the core molding development, Stillman fabricated samples to evaluate the vacuum bag-molding process. Dilectrix effort consisted of the development of a vacuum bag-molding process using Parco 823-70 Butyl compound. A total of three bladders were fabricated. The last one was shipped to Bell but was not tested. Thiokol effort was limited to fabrication of seamed specimens for bonding compatibility testing. The elastomeric program was stopped because of the decision to use the single-ply Teflon bladders.

(d) Liquid Side Vent (Bleed Tube) Diffuser

Service module testing with 3-ply, 3 mil bladders was performed to evaluate twist and vertical displacement of the bladder using diffusers modified to include the bleed tube. Bladders were tested in both the oversize and net size configuration as discussed as follows:

SMO (Bladder SN 61-7): A net size bladder assembled with a modified diffuser tube and a liquid side vent completed 100 vertical water expulsions (50 flange-up, 50 flange-down). The two outer plies had failed prior to the 33rd cycle, but testing was continued to observe twist.

SMO (Bladder SN 35-7): A net size bladder assembled with liquid side vent diffuser failed after 32 vertical water expulsions (16 flange-up, 16 flange-down) were completed.

SMF (Bladder SN 40-5): A net size bladder with a liquid side vent was tested to observe filling procedure and bladder behavior. This unit completed five flange-up and five flange-down water cycles in a plexiglass tank. The fill procedure was satisfactory and measured maximum twist was 3/8-inch clockwise and twist following the 10th expulsion was 1/4-inch clockwise.

SMO (Bladder SN 31-33): An oversize bladder completed 15 propellant expulsions to compare with liquid side vent performance of a 3-ply bladder with a single-ply bladder. Results showed that the loaded weight could not be reproduced from cycle to cycle with the three-ply bladder. The outer ply tore around the top spherical radius.

This testing successfully demonstrated the usefulness of the liquid bleed tube for the service module configuration. This concept was further proven during testing with the single-ply bladder.

Command module expulsion tests using 3-ply and single-ply bladders were performed to establish servicing procedures and evaluate performance characteristics of the liquid side vent diffuser for the command module configuration. The results are as follows:

CMF (Bladder SN 1-1): This single-ply net size bladder was assembled with a liquid side vent diffuser tube. The bladder was tested in the plexiglass tank to develop a procedure for horizontal loading with the bladder expanded with gas that is vented during load. The tests were unsuccessful. Additional tests were conducted using standard evacuation loading procedure and expelling to determine ΔP characteristics of the new diffuser tube.

CMO (Bladder SN 1-3): This net size single-ply 6 mil bladder was assembled in a plexiglass tank with a liquid side vent and cycled for the purpose of measuring bladder twist. Twenty-five cycles were completed with water as the test fluid in a horizontal attitude. The maximum measured twist on the first cycle was 1-3/8 inches. The measured twist following the 25th expulsion was 1/8-inch in a counter-clockwise direction. This bladder was then assembled into a metal tank and subjected to an additional 107 water cycles (the last 25 at 40°F) without failure.

CMF (Bladder SN 28-3): Water expulsion tests with an oversize 3-ply bladder and LSV diffuser (holes in cone) were conducted to compare twist and expulsion efficiency with standard diffuser tube data. Nine cycles were completed in the plexiglass tank with the maximum twist being 11 inches. The bladder assembly was installed in the metal tank and nine cycles were completed to check ΔP and expulsion efficiency. The ΔP was reproducible with minimum expulsion efficiency at ΔP of 2 psi being 96.6%.

CMO (Bladder SN 2-5): This single-ply oversize bladder was subjected to a series of the following three separate tests:

The first test was to evaluate the effect of helium on gas entrapment with a single ply bladder. This test was performed for comparison with a similar test on a 3-ply oversize bladder (CMF Bladder SN 51-3). This bladder had been tested to evaluate the effect of helium on ply separation and gas entrapment with a 3-ply, oversize bladder in MMH. It was found by flowing through a gas trap that the permeation of helium prior to the bladder fill cycle contributes to gas trapped in bladder.

The second test consisted of water expulsion tests to study the effect of flowing through the diffuser cones only (holes in tube were masked). Nine cycles were completed in this condition and the results showed that the amount of twist was reduced by expelling through the holes in the cones, but the ΔP was much greater (5 psi vs 1 psi).

The third test consisted of water expulsion tests to study expulsion efficiency and twist using an oversize single ply bladder with the liquid side vent diffuser tube. Ten expulsions were completed in the plexiglass tank. Twist and ΔP were recorded on the first nine cycles. On the 10th cycle an air bubble was intentionally introduced with the liquid load to test flow stability. The flow trace did not become erratic until approximately midway through the expulsion.

CMO (Bladder SN 76-5): This 3-ply oversize bladder was subjected to water expulsion tests in the plexiglass tank with a standard diffuser tube to evaluate the effect of ply separation on ΔP and flow. Gas was injected between plies prior to the expulsions. The results showed that with a small amount of gas (55 in.^{3}) between plies there was little effect on expulsion efficiency; however, with a large amount of gas (308 in.^{3}) between plies, there was a decided decrease in expulsion efficiency.

No additional command module testing was performed to evaluate the liquid side vent diffuser at this time. Additional single-ply testing was performed with standard diffusers.

(e) Single-Ply 6 mil Teflon Bladders

(1) Service Module

SMF (Bladder SN 1-5): This net size bladder completed 36 expulsions with 50/50 blend (23 flange-up and 13 flange-down) with the last two cycles at 55°F. Examination of the bladder following failure disclosed a 360° cut at the retainer end caused by failure of the press fit joint of the diffuser. The bladder displayed no other failure. The unit exhibited good load repeatability and low residual weight at 2 psi ΔP.

SMO (Bladder SN 1-7): This net size bladder completed 24 propellant cycles (12 flange-up and 12 flange-down). Excessive leakage following the 24th cycle forced conclusion of this test. Subsequent investigation disclosed severe crazing at the flange end hemispherical section. Available data indicated repeatable loading and expulsion efficiency between 98.4% and 98.8% at 2 psi ΔP. The last three cycles were conducted at propellant temperatures of 55°F, 52°F and 43°F, respectively.

SMF (Bladder SN 5-5): This unit completed 30 expulsion cycles with 50/50 blend (22 at 70°F, 4 at 85°F, 1 at 50°F, and 3 at 40°F). Evidence of failure was disclosed during the leakage test after cycle No. 30. Investigation after removal of the bladder from the tank revealed one pinhole on the neck of the bladder at the flange end. The expulsion efficiency at a ΔP of 2 psi was as follows:

Cycle	Position	Average Efficiency
1-11	flange-up	98.8%
12-24	flange-down	99.0%
25-29	flange-up	98.7%
30	flange-down	98.5%

The 6 mil bladder (net size) and liquid bleed tube were incorporated into the service module design as a result of the first two tests (Bladders 1-5 and 1-7). This decision was substantiated by the testing of Bladder 5-5.

(2) Command Module

Three single-ply bladders had been tested previously as part of the command module liquid side vent diffuser testing. In order to define the diffuser assembly and bladder configuration for the command module units, a test series was conducted to measure ΔP versus expulsion efficiency. The testing was done in a command module oxidizer tank, using both full-size and oversize single-ply, 6 mil Teflon (TFE/FEP) bladders. Three bladders (SN 3-3, 1-3, and 2-5) completed a total of 68 water expulsions using four types of diffuser configurations. These tests indicated that the optimum technical configuration consists of diffuser hardware having holes in both the flange and retainer cones. However, to permit the reworking of a considerable amount of existing hardware, a configuration having holes in the retainer cone only was selected. To make this compromise configuration acceptable from the standpoint of repeatability of the ΔP versus expulsion efficiency curve, the use of an oversized bladder was required. Therefore, an oversized single-ply, 6 mil bladder and hardware having 216 holes in the retainer cone was selected as the configuration for the command module tanks. In addition, a test series was conducted with MMH in a command module fuel tank (Bladder SN 50-3) to evaluate methods and establish procedures for pulling a vacuum at 28 inches of mercury without letting the bladder and associated hardware temperature drop below +40°F.

i. Single-Ply Teflon Bladder Development

(1) Dynamic Testing

A new dynamic test program was required to demonstrate the following capabilities:

- New acceleration-expulsion requirement for command module tankage
- Slosh with propellant
- Slosh and vibration of single-ply bladder
- Vibration of oversize bladder
- Vibration of liquid side vent diffuser

(a) Acceleration-Expulsion

A CMF tank assembly with an oversize bladder (SN 44-3), and a CMO tank assembly with an oversize bladder (SN 46-5) were tested to evaluate the expulsion capability of command module tanks during acceleration. The tanks were subjected to a 20 g acceleration force in the X-axis (longitudinal) with the expulsion tube facing the center of rotation. The tanks were loaded to more than 75% of propellant capacity with simulated propellants and the gas side was pressurized to 287 $^{+0}_{-5}$ psig with helium. The liquids were expelled at specified flow rates in a series of flow bursts which were terminated at 60, 40, and 25 percent of maximum propellant capacity and when the pressure differential between the gas and the liquid sides, due to expulsion, reached 2 psig. Both bladders were intact after the testing.

A CMO tank with a single-ply bladder (SN 7-5) was subjected to a 28 g acceleration force. The acceleration force was applied perpendicular to the longitudinal X-axis for a period of 5 minutes. The tank assembly was then tested to evaluate the expulsion capability of the command module tanks while being subjected to a 20 g acceleration force perpendicular to the longitudinal X-axis. The outlet port faced forward with respect to the direction of rotation and the outlet tube pointed toward the center of rotation. The expulsion was accomplished in three flow bursts which were terminated at 58.5, 38, and 21.2% of propellant capacity. The pressure differential following the third flow burst was 4.68 psi. The test was completed without damage to the tank structure or the bladder. This tank attitude was found to be more detrimental to the performance of the unit than when the 20 g acceleration force was applied along the X-axis.

(b) Slosh

Two service module tanks with 3-ply oversize bladders were tested to evaluate slosh with propellant. The results were as follows:

SMO (Bladder SN 22-33): The unit was loaded to 1/3 capacity with nitrogen tetroxide and the gas side pressurized to 25 psig with helium. The tank was positioned with the diffuser tube horizontal and subjected to 500 slosh cycles in the direction of the diffuser tube at 0.94 cps with 2.41 inches peak-to-peak input. The tank was then subjected to 500 slosh cycles at 2.0 cps with 0.53 inch peak-to-peak input in a direction perpendicular to the diffuser tube.

SMF (Bladder SN 46-7): The unit was loaded to 1/3 capacity with 50/50 blend and pressurized to 25 psig with helium. The tank was subjected to 500 slosh cycles in the direction of the diffuser tube at 0.95 cps with 2.36 inches peak-to-peak input. The tank was then repositioned so that the diffuser tube was vertical and subjected to 500 slosh cycles at 1.90 cps with 0.59 inch peak-to-peak input in a direction perpendicular to the diffuser tube.

Slosh testing in the plexiglass tanks was performed with simulated propellant to test the resonant frequencies of the new single-ply configurations. A 6 mil single-ply net size SMO bladder and a 6 mil single-ply oversize CMO bladder were sloshed in a plexiglass tank to establish resonances. The data indicated that the major liquid slosh frequencies were higher and the liquid responses lower with the single-ply bladder than they were for corresponding configurations using 3-ply bladders. Based on these comparisons, the respective major liquid slosh frequencies for the SMF and CMF were extrapolated as follows:

Unit	Attitude	Input Axis relative to diffuser	Major Slosh Frequency (cps)
CMF	Horiz.	Parallel	2.7 estimated
	Horiz.	Perpendicular	3.0 estimated
CMO	Horiz.	Parallel	2.6
	Horiz.	Perpendicular	2.8
SMF	Horiz.	Parallel	1.55 estimated
	Vert.	Perpendicular	2.9
SMO	Horiz.	Parallel	0.9
	Vert.	Perpendicular	2.3

(c) Vibration

CMF (Bladder SN 44-3) tank assembly was subjected to vibration inputs in three axes to complete the evaluation of oversize bladders. The sinusoidal survey and random vibration tests for the longitudinal axis were conducted in an adjustable fixture using a Teflon rod connector on the blind end. Lateral axis vibration was conducted in a circular plate type fixture. During the tests 45 $^{+5}_{-0}$ psig helium was trapped on the gas side of the tank. DVT level inputs were used for all three axes of vibration with no evidence of failure.

SMO (Bladder SN 4-7) tank assembly was tested to determine the capability of the single-ply bladder and liquid-side vent diffuser to withstand the DVT vibration environment. The 15-minute longitudinal X-axis sine and random vibration was successfully completed. Problems were encountered in maintaining mounting bolt torque during lateral axis vibration. A bladder failure was indicated after approximately 7 minutes of Z-axis random vibration. Inspection of the bladder after disassembly revealed a 1/4-inch failure near a flange bolt. The buffer pads at this end of the tank were rolled up and an investigation showed that the pads could roll because of mislocation during assembly. As a result the buffer pad was redesigned.

SMO (Bladder SN 7-7) was a repeat of the previous test with a single-ply bladder, liquid side vent, and a redesigned buffer pad. The unit was subjected to the DVT spectrum random vibration and failure occurred again during the lateral vibration (Z-axis) portion of the test. Upon disassembly, a bladder failure was found very nearly in the same location as in the previous test. The redesigned pad was in excellent condition. A procedural change was initiated consisting of:

- Vibrating while the tank is pressurized to the operating pressure of 179 psig
- Introducing the lateral input while the tank is oriented in the vertical attitude, either flange-up or flange-down. Previous SM tanks were vibrated in horizontal position.

These conditions correspond to the operational conditions which exist in the vehicle. The tank assembly was refurbished with a new bladder (SN 8-7), pressurized to 179 psig, and mounted on the C-210 vibrator with the tank assembly in the vertical position. The tank assembly was subjected to the DVT vibration inputs in all three axes, with the lateral Z and Y axes vibration applied with the tank assembly in the vertical attitude. Post-test inspection of the tank assembly revealed no structural damage to the tank or bladder.

(2) Off-Horizontal Expulsion Tests - Command Module

A development series of tests were conducted with CMO configurations to determine expulsion efficiencies when the tank is oriented 30° from the horizontal position. Eighteen expulsions were completed using water as the test fluid. The configurations tested were as follows:

- Oversize bladder (SN 2-5) with hardware having holes in the retainer cone and diffuser tube only
- Net size bladder (SN 5-3) with hardware having holes in the retainer cone and diffuser tube only

Tests were conducted both in the flange-down and flange-up attitudes. The expulsion efficiencies for the oversize bladder tests were good and did not differ significantly from the results obtained in the horizontal attitude. For the net size bladder in the flange-down attitude at 30° orientation the expulsion efficiencies were low and non-repeatable from expulsion to expulsion. For the flange-up position the expulsion efficiencies were practically identical to the high values obtained in the horizontal position.

j. Design Verification Testing (DVT)

Design verification testing was initiated on four tank assemblies of each configuration. The configurations were as follows:

Service Module	-	Single-ply bladder (net size) Liquid side vent diffuser
Command Module	-	Single-ply bladder (oversize) Standard diffuser with holes in retainer cone and tube only

The command module tanks were tested in the horizontal position and the service module tanks in the vertical flange-up and flange-down positions.

The test results (see Figure III-4) for each unit were as follows:

CMF Unit X-1: The tank assembly completed acceptance testing, vibration testing, 13 expulsion cycles with propellant (9 ambient and 4 high temperature), and acceleration testing which included an additional ambient expulsion cycle with simulated propellant. Four expulsions were then completed at low temperature and four at high temperature prior to bladder failure. The tank had accumulated a total of 30 bladder cycles including 21 propellant expulsions, one acceleration expulsion and eight gas cycles. Inspection after disassembly revealed a tear at the flange end of the bladder.

CMF Unit X-2: The tank assembly completed the acceptance test and 25 expulsions (9 ambient, 4 hot, and 12 ambient, for a total of 25 bladder cycles during expulsion cycle testing). Bladder failure was indicated at the completion of the 25th expulsion (30th bladder cycle). Inspection disclosed a pinhole at the point of tangency between the cylindrical and hemispherical sections of the bladder at the retainer end.

BELL AEROSYSTEMS COMPANY
DIVISION OF BELL AEROSPACE CORPORATION

FIGURE III-4 MODEL 8271 DVT AND DEVELOPMENT TEST SUMMARY

TEST	TANK	TEST UNIT	TANK S/N	BLAD S/N	CONFIGURATION	OCTOBER 1964	NOVEMBER 1964	DECEMBER 1964	JANUARY 1965	FEBRUARY 1965
DVT	CNF	X-1	16	4-3	8271-471103-5	B/U, VIB., E.C.	ACCEL., EC	Failed on Cycle No. 30		
DVT	CNF	X-2	30	21-3	8271-471103-5	B/U, E.C.	Failed on Cycle No. 30			
DVT	CMO	X-1	0003	10-5	8271-471104-5	B/U, VIB., E.C.	Failed on Cycle No. 12			
DVT	CMO	X-2	16	6-5	8271-471104-5	B/U, E.C.	Failed on Cycle No. 17			
DVT	SMF	X-1	2	21-5	8271-471151-1		B/U, VIB., E.C.	Failed on Cycle No. 6		
DVT	SMF	X-2	8	22-5	8271-471151-1	B/U, E.C.		Failed on Cycle No. 32		
DVT	S[illegible]	X-1	16	6-7	8271-471152-1		B/U, SLOSH	Failed		
DVT	SMO	X-2	5	5-7	8271-471152-1	B/U, E.C.		Failed on Cycle No. 30		
DEV	CMO	R-1	8	30-5	8271-471104-5		B/U, E.C.	Failed on Cycle No. 17		
DEV	CMO	R-2	0003	16-3	Full size blad		B/U, E.C.	PLEX, [illegible] Efficiency Evaluation		
DEV	CMO	R-3	16	25-3	ISV Full size blad		B/U, E.C.	Failed on Cycle No. 7		
DEV	CMO	R-4	Plex	2-5			E.C. Gas Entrapment Investigation			
DEV	CMO	R-7	Plex	1-3	ISV Full size blad			E.C.	Diffuser [illegible] Pattern Investigation	
DEV	CMO	R-7A	Plex	1-3	Mod. Diffuser				EC Efficiency Evaluation	
DEV	CMO	R-7A	0003	27-3					EC Failed on Cycle No. 27	
DEV	CMO	R-7A	0003	34-3					B/U [illegible] Acceleration-expulsion Evaluation	
DEV	CMF	R-8	30	2-1	Same as R-7A				B/U, E.C. Failed on Cycle No. 35	
DEV	CMO	R-9	8	42-3	Heavy end blad				B/U, E.C., FUEL VIB	Bladder Failed
DEV	CMO	-	Plex	43-3	Heavy end blad				Efficiency Evaluation	
DEV	CMO	-	Plex	16-3	Mech Restrainers				Efficiency Evaluation	
DEV	SMO	Y-2	5	13-7	8271-471152-1			SLOSH, Prop. Exposure	Shell failed after 23rd day	
DEV	CMF	R-8A	30	3-1	Same as R-8				VIB	Bladder Failed
DVT	SMF	X-2	8	17-5	8271-471151-1				B/U, E.C.	Failed on Cycle No. 19
DVT	SMO	X-1	16	15-7	8271-471152-1				B/U, VIB Helium Port and Bolt Failure	VIB Bladder Failed

CMO Unit X-1: The tank assembly completed acceptance testing, vibration testing, and a total of 10 expulsion cycles (9 ambient and one high temperature) for a total of 12 bladder cycles. Bladder failure was indicated at the completion of the 10th expulsion. Inspection of the bladder disclosed a pinhole plus considerable high stress area at the flange neck.

CMO Unit X-2: The tank assembly completed the acceptance test and 11 expulsions (9 ambient and 2 hot) for a total of 17 bladder cycles. Bladder failure was indicated upon completion of expulsion No. 11. Inspection of the bladder revealed a large tear at the flange end of the bladder.

SMF Unit X-1: The tank assembly completed the acceptance test, vibration testing, and six ambient expulsion cycles prior to failure. Inspection disclosed a pinhole in the bladder at the retainer ring area with evidence of deformation of the bladder material in the same area. The diffuser tube was broken approximately 3/16-inch from the flange cone weld. The diffuser failed during vibration testing and caused the subsequent bladder failure. The diffuser fracture was traced to the mounting arrangement of the tank assembly in the vibration fixture during lateral axis testing which caused the tank shell to vibrate at a frequency approximately the same as the resonant frequency of the diffuser tube. This condition caused excessive amplification and produced the failure.

SMF Unit X-2: The tank assembly completed the acceptance test and a total of 32 expulsions (26 ambient, 4 hot, 2 cold) for a total of 32 bladder cycles. Bladder failure was evident upon completion of the 32nd cycle which was an ambient cycle carried out to full bladder ΔP at shutdown. Inspection of the bladder disclosed a 1/16-inch crescent shaped hole near the retainer end of the bladder.

SMO Unit X-1: The tank assembly was acceptance tested and subjected to low temperature slosh testing. Subsequent to slosh testing, bladder failure was evident. Inspection disclosed a pinhole approximately seven inches from the flange-end of the bladder.

SMO Unit X-2: The tank assembly completed acceptance test and 28 expulsions (24 ambient and 4 hot) for a total of 30 bladder cycles. Bladder failure was indicated upon completion of the 28th expulsion cycle. Inspection disclosed a pinhole leak surrounded by a porous area and several highly stressed spots near the retainer end of the bladder.

The failures encountered during design verification testing showed that the existing service and command module configurations were incapable of meeting the following specification performance requirements:

- Cycle Life of 50 expulsions
- Expulsion Efficiency of 99% at 2 psi ΔP

The test results showed that there is a consistency in bladder life before failure and that the performance characteristics are repeatable. The test history, in terms of cycle life and expulsion efficiency obtained from the DVT and previous applicable development tests, was as follows:

EXPULSION EFFICIENCY-DVT TESTING

	Ambient Temp.	High Temp.	Low Temp.
CMO	97.3%	87.8%	
CMF	98.0%	98.1%	98.0%
SMO	98.8%	98.9%	
SMF	99.0%	98.5%	98.9%

CYCLE TESTING - COMMAND MODULE

	Dynamic Testing	Ambient Expul.	105°F Expul.	40°F Expul.	Total Expul.
Proc. Req.		24	8	6	38
CMF (X-1)	Vibr.-Accel.	14	4	4	22
CMF (X-2)	-	20	4	1	25
CMO (X-1)	Vibr.	9	1		10
CMO (X-2)	-	9	2		11

CYCLE TESTING - SERVICE MODULE

	Dynamic Testing	Ambient Expul.	85°F Expul.	40°F Expul.	Total Expul.
Proc. Req.		36	8	6	50
SMF (X-2)	-	26	4	2	32
SMF (1-5)	-	36			36
SMF (5-5)	-	22	4	4	30
SMO (X-1)	Slosh				
SMO (X-2)	-	24	4		28
SMO (1-7)	-	21		3	24

It appeared that a cycle life in excess of 20 expulsions was attainable repeatably with the service module configuration. This life expectancy was based on a sample of four tanks, 2 DVT and 2 development, which completed 32, 28, 30, and 24 cycles before failure. In addition, the test results indicated that an expulsion efficiency of 98 percent at 2 psi Δ P could be consistently attained.

The command module units were more marginal in cycle life as shown by the X1 and X2 fuel units which demonstrated a life of 22 and 25 expulsions, respectively. The oxidizer units X1 and X2 indicated that the command module oxidizer configuration (oversize bladder plus a diffuser having holes in the retainer cone plus the tube) did not possess the capability to survive the four required high temperature expulsion cycles. The results seemed to indicate that the combination of N_2O_4 and heating to a high temperature has a deleterious effect on bladder life and expulsion efficiency.

Based on these results, the expulsion cycle capability for these configurations was established at 20 expulsions which included the high and low temperature tests. These criteria were used in subsequent tests. In addition, test programs were established for the following purposes:

- Command Module - substantiate design changes which increase performance and life of CMO configuration.
- Service Module - perform tests to show capabilities which had not been demonstrated because of the early failures in DVT.

k. Additional DVT and Development Testing

(1) Service Module

Two service module units were subjected to additional design verification testing to demonstrate performance capabilities which were not performed because of the failures encountered during the DVT test program which ended in December 1964.

SMF Unit X-2: The unit completed a total of 19 expulsion cycles (12 ambient, 4 high temperature and 3 low temperature) before bladder failure. However, bladder helium leakage rates exceeded the specified 210 cc/15 minutes following the fourth high temperature test (expulsion No. 16).

SMO Unit X-1: The tank assembly was subjected to Y-axis, flange-down, vibration. After 11 minutes and 15 seconds of the run, one of the flange mounting bolts and the helium port fitting were broken. The tank was then drained and the helium port fitting and bolt were replaced. Subsequently, both a tank assembly and bladder leak check were performed with acceptable leakage rates. The tank was then reinstalled in the fixture and the remaining 3 minutes and 45 seconds of Y-axis random vibration were completed. The tank was then drained and reinstalled in preparation for Z-axis vibration. Upon filling, liquid appeared on the gas side of the tank indicating the bladder had failed.

A development unit was tested to demonstrate the capability of performing the propellant exposure and revised slosh test. The results are as follows:

SMO Unit Y-2: This unit successfully completed slosh testing at 37°F with the tank in the vertical position and slosh inputs in the lateral axis. The specification requirements had been changed to require that the test be conducted with the major axis in the vertical position and the reciprocating motion applied perpendicular to the longitudinal axis. The slosh failure during DVT (SMO Unit X-1) had occurred with the tank horizontal and inputs parallel to the longitudinal axis.

The unit was subjected to propellant exposure testing with N_2O_4 at a temperature of +105°F. Tank shell failure was indicated after 23 days of exposure. The failure was located in the parent metal of the cylindrical section, approximately 1-inch from the weld, and consisted of four crack areas. All the cracks did not penetrate through the shell thickness, and salt deposits were found on the internal surface of the shell in the vicinity of the failure. This unit had been exposed to propellant for a total of 49 days because of previous testing.

(2) Command Module Oxidizer Tank Development

A test program was initiated on the R-series tanks to provide data to evaluate changes tailored to increase the performance of the CMO tanks.

The occurrence of both DVT CMO unit failures during high temperature testing indicated that N_2O_4 heated to the high temperature within the propellant tank had a deleterious effect on bladder life. Low expulsion efficiency always accompanied the high temperature tests. Since this phenomenon occurs when gas pockets are located inside the bladder, it was conjectured that inert pressurizing gas plus N_2O_4 vapors accumulated during the heating cycle and caused the bladder and expulsion efficiency degradation.* Therefore, two development units (R-1 and R-2) were subjected to testing with the following major test modification:

- The N_2O_4 was thoroughly degassed before loading and the pressurizing gas on the load tank was changed from nitrogen to helium.
- After the expulsion at high temperature, the propellant assembly was cooled to ambient temperature after the bladder was expanded to the tank wall to prevent severe high temperature, high pressure folds.

CMO Unit R-1: The tank assembly (standard diffuser and oversize bladder) was subjected to expulsion testing with N_2O_4. Twelve expulsions (9 ambient and 3 hot) were completed for a total of 17 bladder cycles. Bladder failure occurred upon completion of expulsion No. 12.

CMO Unit R-2: This unit (standard diffuser and net-size bladder) completed 20 expulsion cycles with N_2O_4 (9 ambient, 4 hot, 4 cold, 1 ambient, and 2 ambient pulsed). No bladder damage was incurred; however, the expulsion efficiency was quite low (approximately 90%) and an appreciable decrease in expulsion efficiency was noted at the higher temperature. The tank was then subjected to flow checks with Freon-TF, both at rated tank pressure and at 20 psig, to determine the effect of pressure variation and the expulsion medium upon the expulsion characteristics. The pressure variable seemed to have no measureable effect upon expulsion efficiency; however the Freon-TF appeared to give efficiencies somewhere between N_2O_4 at ambient and high temperature.

* CMO Unit R-4: Expulsion tests with water in the plexiglass tank were made to observe the effect of gas in the propellant upon bladder folding and expulsion characteristics. Two ambient expulsions were made as follows: One with the tank loaded normally with no gas in bladder, and one with the tank loaded normally and then approximately 100 cu in. of water displaced by gas in the bladder. These tests were repeated at 105°F.

Because of the unsatisfactory high temperature life cycle performance of the CMO configuration, a redesign was initiated. Since the R-2 unit with a net size bladder had demonstrated acceptable life cycle characteristics but poor expulsion efficiency, the decision was made to change the configuration to include holes in the flange cone as well as the retainer cone of the diffuser plus using a net-size bladder. Simultaneously with this change, the liquid side vent provisions were incorporated into the design. A development model liquid side vent configuration assembly (R-3) was built which incorporated a 3/16-inch liquid side vent tube within a 5/8-inch diameter diffuser tube (.049 inch wall). A Teflon spacer was inserted between the liquid side vent tube and the diffuser tube. There were 216, .032-inch holes in the retainer cone and 150 in the flange cone. This unit was tested as follows:

> CMO Unit R-3: This unit (net-size bladder) completed a total of seven ambient expulsions with N_2O_4 prior to bladder failure. Several excessive residuals were obtained and expulsion efficiency varied from approximately 93 to 99% at a ΔP of 2 psi. The bladder failure occurred at the retainer hemispherical portion of the bladder. The U-shape appearance of the failure, plus the location of other highly stress areas in the same vicinity, indicated that severe folding and creasing must have occurred.

Since the most obvious hydraulic difference between R-2 and R-3 units was the reduced flow area of the R-3 caused by the insertion of the bleed tube plus the Teflon support spacer it was believed that this premature failure was related to an unbalanced pressure distribution along the diffuser tube. The folding patterns of R-2 and R-3 were observed with net-size bladders in a plexiglass tank during horizontal expulsion to determine whether any noticeable difference could be detected. Colored Freon-TF was used to simulate the density of N_2O_4. No noticeable difference in the folding patterns could be discerned. The R-3 unit was then modified to an R-7 configuration which consisted of replacing the .094 inch wall diffuser tube with a .028 inch wall and removing the Teflon spacer. This made the tube cross-sectional flow area practically equivalent to that of R-2. This unit was assembled with a full size bladder, and a total of 23 expulsions with Freon-TF were completed to study diffuser hole patterns which were varied by taping the diffuser. Expulsion efficiencies of approximately 97% were obtained; however, the fold sequence and severity of the creases looked similar to that observed with R-2 and R-3.

The severity of the folds at the retainer raised the possibility of bladder degradation. Since earlier twist investigations showed that an improvement was produced if all the diffuser tube holes were closed, a test was performed on the

R-7 net-size bladder configuration flowing only through the cones with the diffuser tube holes masked. This was tested in a plexiglass tank with freon and the terminal fold pattern was improved relative to the basic R-7 test. The severe creases and folds near the retainer were not in evidence; however, the expulsion efficiency decreased to a range of 93 to 98%.

The objective was to obtain more repeatable and higher expulsion efficiency while maintaining the fold pattern.

The local flow rate is controlled primarily by the pressure drop within the bladder filled channels which lead to openings in the diffuser, in addition to the drop through the diffuser holes left uncovered by the bladder. Two tests were performed in a plexiglass tank to further localize the effects of bladder resistance versus diffuser hole resistance. The results are as follows:

- A Teflon catenary tube was installed between the cones of the basic R-7 diffuser to eliminate the effect of varying flow resistance caused by bladder folding. The expulsion efficiency with this modification was repeatable and high (> 98%).
- A concentric cone made of perforated metal was constructed around the retainer cone of the R-2 unit, to assess the effect of retainer cone open area. The test results indicated an improvement in expulsion efficiency of approximately 3% over that obtained on Unit R-2.

The test results indicated that both the bladder and the diffuser tube resistances determined the expulsion efficiency and the fold pattern; however, the bladder resistance was dominant in producing the terminal high pressure rise.

CMO Unit R-7A: After the plexiglass tank efficiency testing, Unit R-7A was assembled with a metal shell and a liquid side vent diffuser with enlarged (.040 inch) holes in the retainer and flange cones. A total of 18 expulsion cycles with N_2O_4 were completed on this unit prior to bladder failure. These included 14 ambient (2 of which were at low flow condition) and 4 high temperature cycles. The tank was refurbished with a new bladder, SN 34-3, and subjected to testing to determine the expulsion characteristics during acceleration. Four 2g constant acceleration expulsion tests were performed without structural damage. Expulsion efficiencies, based on a minimum differential pressure of 3 psi, varied from 90.7 to 92.7%.

A command module fuel tank assembly (R-8) was assembled with the same configuration as CMO Unit R-7A (net-size bladder and liquid side vent diffuser with .040 inch holes in the cones).

CMF Unit R-8: Twenty expulsion cycles were performed with MMH in accordance with the established DVT Procedure (12 ambient including 2 pulsed, 4 hot, and 4 cold). Expulsion No. 21 was the fuel jettison test in which the tank was emptied in approximately 7 seconds. Bladder failure was encountered at the end of the jettison test. The unit demonstrated more than 98% expulsion efficiency at 2 psi Δ P at specified flow rates and temperatures. This R-8 configuration was selected as the DVT configuration.

CMF Unit R-8A: Unit R-8 was redesignated R-8A after refurbishment with a new bladder subsequent to the fuel jettison test. The refurbished unit was subjected to an acceleration-expulsion (20g to 2g) test and demonstrated an expulsion efficiency of 98.5% at 2g with a ΔP of 2 psi. The tank was then subjected to DVT level vibration inputs and successfully passed sine and random vibration in the X-axis. However, during pretest service for Y-axis vibration, bladder failure was encountered.

The command module oxidizer unit presented a major problem because of the limited life cycle capability and low expulsion efficiency experienced during high (105°F) temperature heating and expulsion. Testing on the R-series tanks showed that the bladder folding pattern had to be controlled so that the ends did not collapse and prevent propellant flow through the flange and retainer cones. Two approaches were taken to prevent the bladder ends from collapsing prematurely:

1. Internal mechanical restraint
2. Inherent bladder structural restraint

CMO - Mechanical Restrainers: Two expulsions were made with Freon-TF in the plexiglass tank using a net-size bladder, SN 16-3. Three 1/4-inch flexible Teflon tubes were installed longitudinally, 120° apart, along the diffuser tube. Each tube formed a loop with the center of the loop approximately three inches from the diffuser tube. An expulsion efficiency approximately 4 percent greater than that obtained without the restrainers was experienced in both tests.

CMO - Heavy Wall Bladder - Six expulsions were made with Freon-TF in the plexiglass tank using a net-size bladder having a 6 mil cross section in the cylindrical section and 9 mil cross section in the hemispherical ends. The expulsion efficiency was approximately 4 percent greater than that obtained with the standard 6 mil bladder.

Based on the successful results of the plexiglass tank testing, a development unit (R-9) was assembled with the liquid side vent diffuser (same as R-8A) and thickened-end bladder for testing to the DVT sequence.

CMO Unit R-9: A total of 21 expulsion cycles were completed in the following sequence; 11 ambient, 2 high temperature, 4 low temperature, and 2 high temperature with N_2O_4 plus one acceleration expulsion at 2g and one at 1g with simulated propellant. The tank was then subjected to DVT level vibration inputs in all three axes. Upon completion of the final axis (Z-axis) bladder failure was noted. The expulsion efficiency at low and ambient temperature was greater than 98%, while at 105°F the efficiency was about 94%. The efficiency decreased to about 96% during 2g acceleration.

Based on the results of testing on this unit, the R-9 design was selected as the configuration for formal testing.

4. Qualification Configuration Formal Testing

All development effort was stopped in March 1965 and preparation was made to start formal testing on all four tank configurations. These were as follows:

Configuration	Bell Part No.
Service Module Fuel	8271-471151-1
Service Module Oxidizer	8271-471152-1
Command Module Fuel	8271-471153-1
Command Module Oxidizer	8271-471154-1

The sequence of events and tests are shown in Figure III-5.

Two tank assemblies of each configuration were to be subjected to the qualification and off-limit test sequence specified in the following North American Aviation specifications, as modified by the specification control drawing (SCD):

Configuration	NAA Specification	NAA SCD
Service Module Fuel	MC 282-0008	ME 282-0008
Service Module Oxidizer	MC 282-0004	ME 282-0004
Command Module Fuel	MC 282-0007	ME 282-0007
Command Module Oxidizer	MC 282-0006	ME 282-0006

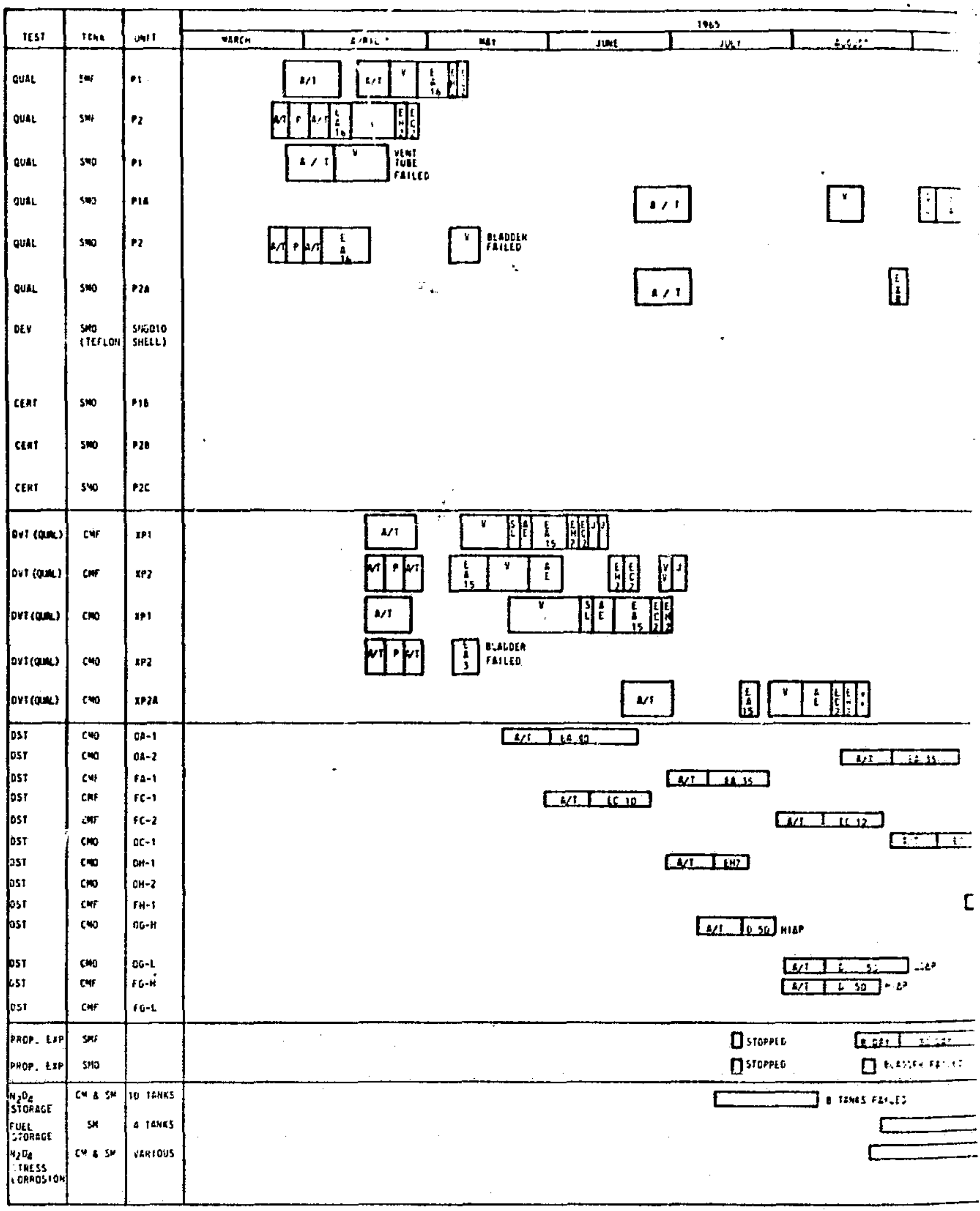
The final sequence of tests for each unit is shown in Table II-2. The dynamic test levels are shown in Table II-3.

Qualification testing was conducted to demonstrate tank conformance to the specification requirements. Off-limit testing was then performed on the same test units to accrue additional test data for reliability assessment, and to verify critical environmental and functional design margins by testing to failure. Other formal testing included design substantiation testing to provide supplemental data on the command module tank performance, and propellant exposure testing on the service module configurations. The propellant storage program was a separate program which resulted from the titanium/N_2O_4 stress corrosion problem.

a. Service Module Tank Assembly Testing

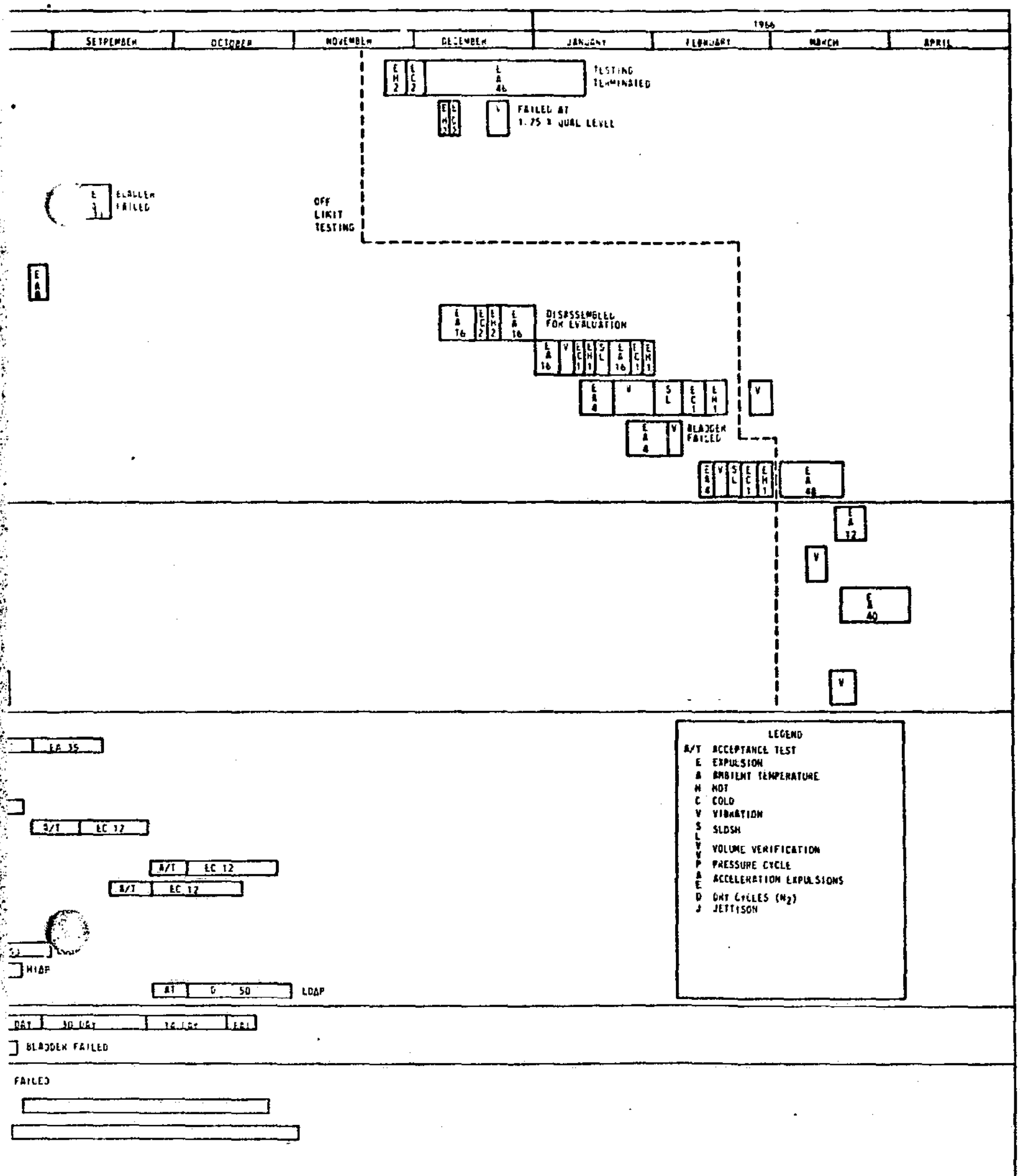
The service module tests were performed with the tank assembly in the vertical position. Expulsion testing was performed with the tank assembly oriented flange-up for half of the tests and flange-down for the remainder. Dynamic testing was planned so that both attitudes would be tested in each axis insofar as was

FIGURE III-5 MODEL 8271 COMMAND AND SERVICE MODU



FOLDOUT FRAME 1

MODULE TEST HISTORY - QUALIFICATION CONFIGURATIONS



FOLDOUT FRAME 2

practicable; however, off-limit testing was performed in the attitude deemed most detrimental to the unit. Vibration testing was performed using simulated propellant, and water was used for shell pressure cycle testing. All other testing was accomplished with actual propellant - N_2O_4 oxidizer and 50/50 blend fuel.

Expulsion cycling was performed at nominal operating pressure (179 psig) to demonstrate conformance to the following requirements:

Cycle Life - 20 expulsions consisting of 16 at ambient temperature (65 to 75°F), 2 at low temperature (35 to 40°F), and 2 at high temperature (85 to 90°F).

Expulsion Efficiency - Demonstrate efficiency of 98% at a ΔP of 2 psi at high flow rate and 99% at a ΔP of 2 psi at low flow rate. The extra low flow demonstration was performed only if the 99% requirement was not attained at the high flow rate.

(1) Service Module Fuel Qualification

Qualification testing of two SMF tank assemblies was performed in accordance with the procedures contained in Bell Report 8271-928007, Revision A. Unit P-1 successfully completed the test series consisting of vibration in two axes, 16 ambient expulsions, 2 high temperature expulsions, and 2 low temperature expulsions. Unit P-2 successfully completed the test series consisting of shell pressure cycling, 16 ambient expulsions, vibration in two axes, 2 high temperature expulsions, and 2 low temperature expulsions.

(a) Vibration

Each unit was subjected to vibration testing in two axes. The P-1 unit vibration was conducted in the flange-down position for the X-axis and flange-up position for the Y-axis. Unit P-2 vibration was conducted in the flange-down position for the X-axis and the Z-axis. Unit P-1 was subjected to a 2 g sinusoidal survey and random vibration while the P-2 unit was subjected to random vibration only. This testing was completed without incident.

(b) Expulsion Cycling

The tank assemblies were subjected to propellant expulsion tests with all expulsion requirements accomplished successfully. The mean expulsion efficiency for both tanks was in excess of 99% for both attitudes at all temperature conditions, and no significant difference in expulsion efficiency or characteristics due to temperature or attitude was noted.

Tank	Attitude	Temperature		
		Low	Ambient	High
P-1	Flange-Up	-	99.2%	99.3%
P-1	Flange-Down	99.4%	99.3%	-
P-2	Flange-Up	99.0%	99.2%	-
P-2	Flange-Down	-	99.3%	99.1%

The detailed results of the Qualification Test Program are contained in Bell Report No. 8271-928034.

(2) Service Module Fuel Off-Limit Testing

Upon successful completion of qualification testing, the two test units were subjected to off-limit testing in accordance with the procedures specified in Bell Report No. 8271-928015. Unit P-1, after completing the required 20 expulsions during qualification testing, completed an additional 2 hot expulsions, 2 cold expulsions and 46 ambient expulsions for a total of 70 expulsions without bladder failure. Unit P-2, after completing 20 expulsions during qualification testing, completed 2 hot expulsions and 2 cold expulsions for a total of 24 expulsions without bladder failure. The tank was then subjected to random vibration in the lateral axis, flange-down,for 5 minutes at 1.5 times the qualification level,and 5 minutes at 1.75 times the qualification level prior to failure.

The testing was successfully completed with the SMF tank assemblies exhibiting a substantial functional design margin in the number of bladder cycles available for expulsion. The detailed test results are contained in Bell Report No. 8271-928046.

(3) Service Module Oxidizer Qualification

Two SMO tanks were originally started in the qualification sequence in accordance with the procedures contained in Bell Report No. 8271-928007, Revision A. The original two test units P1 and P2 were unsuccessful. Unit P1 completed sine and random vibration testing in the X and Y-axes. X-rays taken after the test revealed no structural damage. Loading for the next test could not be accomplished and a subsequent investigation disclosed a bleed tube failure in the weld area. The welding procedures and inspection methods were revised to prevent recurrence of this type of failure. Unit P2 completed 16 ambient temperature propellant expulsions and then testing was stopped because of the bleed tube failure of unit P1. Testing was resumed and the unit completed the X-axis vibration test. While re-expanding the bladder for the Z-axis test a bladder failure was indicated. The results of the failure investigation are contained in Bell Report No. 8271-928031.

The two test units were refurbished into units P1A and P2A, and the qualification test sequence was started in accordance with Revision B of the procedure. These refurbished units also failed to meet the life cycle requirements. Unit P1A successfully completed vibration in the X and Y-axes, slosh testing, and eleven ambient temperature expulsions prior to bladder failure. The results of the failure investigation are contained in Bell Report No. 8271-928048. Unit P2A completed eight ambient temperature expulsions before bladder failure. The details of the failure are contained in Bell Report No. 8271-928047.

(4) Service Module Oxidizer Development

Testing was stopped at this point and the units were not refurbished pending a solution to the SMO configuration problem. The SMF tank assemblies had successfully completed qualification testing and the only difference between the fuel and oxidizer tanks was propellant used and tank length. The additional length of the SMO tank over the successful SMF configuration made it marginal,regarding normal repositioning of the bladder upon re-expansion after an expulsion,because of greater friction between the bladder and tank wall. A development effort was initiated which consisted of the following efforts:

- Teflon coating the inside of the shell to reduce the friction coefficient,thus permitting the bladder to slide on the tank wall and reduce biaxial stresses necessary to lift the bladder
- Mechanical smoothing of the inside of the shell to reduce friction
- Bladder redesign with undersized center section to eliminate wall friction during bladder expansion

Tests showed that mechanical polishing for reduced friction was marginal and impractical; however, experiments indicated that a Teflon lined shell offered a solution to the repositioning problem. At this time Teflon coated shells were being fabricated for use on the titanium/N_2O_4 stress corrosion program to determine if the Teflon lining would serve as a barrier to retard the stress corrosion. One of these shells SMO,SN0010 was assembled for propellant expulsion testing. The unit successfully completed 16 ambient temperature, 2 cold, 2 hot, and 16 additional ambient temperature expulsions without failure. The unit was disassembled for evaluation and the decision was made to reassemble the tank with a new bladder and subject it to the qualification test series. Based on the success of this unit, all other design and development activity was stopped.

The refurbished test unit was subjected to the qualification test sequence plus additional expulsion testing. The unit successfully completed 16 ambient temperature expulsions prior to qualification vibration. During vibration the old configuration bleed tube, which had been used because of the unavailability of production configuration diffusers, failed; however, testing was continued by using the command module style vacuum loading technique. Vibration was completed and the unit then successfully completed one cold and one hot expulsion, slosh, 16 ambient temperature expulsions, one cold and one hot expulsion without bladder failure. All expulsion efficiencies were above 99%.

Although the first series of tests on the Teflon coated shell indicated that it would meet the qualification test requirements, an analysis of the schedule indicated that refurbishment of flight line tanks could not be accomplished in time for use. The existing test data from units P1, P2, P1A, and P2A provided a basis for a reduction in the required number of expulsion cycles. As a result, a certification program, designed to demonstrate the capability of the SMO configuration of performing to the lowered requirements, was initiated shortly after the beginning of the second test series on the Teflon-lined shell.

(5) Service Module Oxidizer Certification Testing

Certification testing was accomplished on two SMO tank assemblies to demonstrate that they were capable of performing to the modified qualification test requirements of the North American Aviation specifications. The testing was performed in accordance with the procedures contained in Bell Report No. 8271-928045. Unit P1B successfully completed the test series consisting of four ambient propellant expulsions, vibration in two axes, slosh test, one low temperature propellant expulsion, and one high temperature expulsion. Unit P2B failed during vibration test after completing the four ambient propellant expulsions. The unit was refurbished as unit P2C and successfully completed the test series consisting of four ambient propellant expulsions, vibration in two axes, slosh test, one low temperature propellant expulsion, and one high temperature propellant expulsion.

(a) Vibration

Units P1B and P2C were subjected to random vibration testing in the Y-axis lateral, flange-up and the X-axis longitudinal, flange-down position. During the X-axis test on unit P2C, the Teflon bushing at the boss end became dislodged. The test was stopped, the bushing was reinstalled, and the test was completed.

(b) Slosh

Slosh testing was successfully performed on both the P1B and the P2C units. The units were installed in the flange-up attitude, loaded to 50% capacity with nitrogen tetroxide, and subjected to 500 slosh cycles at ambient temperature.

(c) Expulsion Cycling

Each of the units P1B and P2C were subjected to propellant expulsion cycling to demonstrate the following:

Cycle Life - Perform six expulsions consisting of four ambient temperature expulsions,flange-down, one low temperature expulsion,flange-up, and one high temperature expulsion,flange-up. An additional three expulsions were accomplished during emptying after the X-axis vibration, Y-axis vibration, and the slosh test.

Loadability - To demonstrate the ability to load the units to the acceptance test volume-weight equivalent ±1.0 pound.

Expulsion Efficiency - To demonstrate an expulsion efficiency of at least 98% at 2 psi differential pressure.

Each of the test units completed the four expulsions at ambient temperature with expulsion efficiencies at 2 psi ΔP ranging from 99.5 to 99.6 for the P1B unit and from 99.1 to 99.7 for the P2C unit. Each unit then successfully completed one low temperature and one high temperature expulsion in the flange-up altitude. The expulsion efficiencies for the low temperature expulsions for P1B and P2C were 99.5 and 99.4, respectively. The expulsion efficiencies for the high temperature expulsion for the P1B and P2C units were 99.6 and 99.8, respectively. The detailed test results are contained in Bell Report No. 8271-928049.

(6) Service Module Oxidizer Off-Limit Testing

After completion of certification testing, SMO units P1B and P2C were subjected to off-limit testing in accordance with the procedures specified in Bell Report No. 8271-928015. Unit P1B, which had completed certification testing, was then subjected to random vibration in the lateral Y-axis, flange-down attitude, for 5 minutes at 1.0 times certification level and 5 minutes at 1.5 times certification level. Unit P2C, after completing certification testing, was subjected to 48 additional ambient temperature propellant expulsions without bladder failure.

(a) Vibration

Vibration testing of unit P1B was performed at 14.8 g rms (qualification level) for 5 minutes without damage. The assembly was then subjected to 22.2 g rms (1.5 qualification level) for the planned 5 minutes. Cracks were noted in the tank flange at the completion of the test. This tank shell had been subjected to qualification level vibration prior to the certification and off-limit test program. The exposure time to full level random vibration (14.8 g) was 45 minutes in the longitudinal X-axis and 50 minutes in the lateral Y-axis. In addition, the shell completed the scheduled 5 minutes at 15% full level vibration in the lateral Y-axis.

(b) Expulsion Cycling

Expulsion cycle testing was performed on unit P2C at a temperature of 70°F to demonstrate the following capability:

Cycle Life - The number of expulsions which may be performed prior to failure.

Expulsion Efficiency - To demonstrate an expulsion efficiency greater than 98% at 2 psi differential pressure.

The unit was installed in the flange-up attitude for 4 expulsions and then in the flange-down attitude for 4 expulsions. This sequence was continued until a total of 48 off-limit expulsions had been completed without failure. The average expulsion efficiency for the 48 expulsions was 99.3% and varied from 99.2 to 99.5%. All efficiencies were within the specification requirements. The detailed test results are contained in Bell Report No. 8271-928050.

b. Command Module Tank Assembly Testing

All command module tests were performed with the tank assembly in the horizontal position. Vibration, acceleration, and acceleration-expulsion were performed using simulated propellant; water was used for shell pressure cycling. All other testing was conducted with actual propellant - N_2O_4 oxidizer and MMH fuel.

Expulsion cycling was performed at nominal operating pressure (289 psig) to demonstrate the following capabilities:

Cycle Life - 20 expulsions consisting of 16 at ambient temperature (65 to 75°F), 2 at high temperature (105 to 110°F), and 2 at low temperature (35 to 40°F). The expulsion during acceleration expulsion was counted as one of the ambient temperature expulsions.

Expulsion Efficiency

Fuel - Demonstrate an efficiency of 98% at a ΔP of 2 psi at high flow rate,and 99% at a ΔP of 2 psi at low flow rate. The extra, low flow demonstration was to be performed only if the 99% requirement was not attained at the high flow rate.

Oxidizer - Demonstrate an efficiency of 98% at a ΔP of 2 psi at high flow rate except for high temperature. High temperature requirement is 93% at 2 psi ΔP.

The qualification test program on the fuel and oxidizer tank assemblies originated as design verification testing; however, all testing was performed in accordance with the qualification requirements of the North American specifications as specified in the Bell Qualification Test Procedure. The only change was the addition of slosh testing to the test sequence.

(1) Command Module Fuel Qualification

Two command module fuel tank assemblies were tested in accordance with the qualification test procedures contained in Bell Report No. 8271-928008, Revision B.

Unit XP-1 completed the required test series which consisted of acceptance test, vibration, slosh, acceleration, acceleration-expulsion, 15 ambient-temperature propellant expulsions, 2 high-temperature expulsions, 2 low-temperature expulsions, and jettison testing. The helium and nitrogen leakage rates exceeded specification limits after the second high temperature expulsion; however, the remaining tests were completed with no appreciable increase in the leakage rate. A second jettison test was conducted with an orifice resized to reduce the jettison time.

Unit XP-2 successfully completed the required test series which consisted of shell acceptance test, pressure cycle test, tank assembly acceptance test, 15 ambient-temperature expulsions, vibration, acceleration, acceleration-expulsion, 2 high-temperature expulsions, 2 low-temperature expulsions, volume verification, and jettison testing.

(a) Vibration

Each unit successfully completed vibration testing in the longitudinal X-axis and one lateral axis while mounted in the horizontal position. Unit XP-1 was tested in the longitudinal X-axis and lateral Y-axis. The test for each axis consisted of a sinusoidal sweep and a 15-minute random test. Unit XP-2 testing was performed in the longitudinal X-axis and lateral Z-axis. The test for each axis consisted of a 15-second random burst and a 15-minute random test.

(b) Acceleration

Acceleration and acceleration-expulsion testing was performed by subjecting each unit to a 28 g acceleration test for 5 minutes in each of two horizontal axes: the first was with the X-axis extending radially from the center of rotation,and the second was with the X-axis perpendicular to the rotary arm. In the second test the outlet faced forward with respect to the direction of rotation and the outlet tube pointed towards the center of rotation. Upon completion of the second 5-minute acceleration test, the units were subjected to the acceleration-expulsion test without changing the tank orientation. The expulsion was performed while the tank assembly was under acceleration forces dimishing from 20 g to 2 g. The required expulsion efficiency was 96% at a ΔP of 2 psi and 2 g acceleration. The acceleration-expulsion plan consisted of flow bursts at varying g levels separated by periods of no flow while the g level was being decreased.

Unit XP-1 completed the test satisfactorily and without damage to tank or bladder. However, because of an incorrectly calibrated accelerometer the lateral axis acceleration test was conducted at 31.2 g instead of a scheduled 28 g,and the acceleration expulsion test was conducted from 21.5 to 5.2 g instead of a scheduled 20 to 2 g. An expulsion efficiency of 93.4% was realized at a ΔP of 2 psi at an acceleration level of 5.3 g at the tank center of gravity. The low expulsion efficiency of 93.4% is attributed to the higher than scheduled acceleration level.

Unit XP-2 completed the tests without discrepancy and without damage to tank or bladder. Expulsion efficiency was established to be 98.3% at a ΔP of 2 psi,and an acceleration level of 3.3 g at the tank center of gravity.

(c) Slosh

Slosh testing was performed on the XP-1 unit only. The unit was loaded to approximately 50% capacity with monomethylhydrazine and tested in the horizontal position. The test consisted of 500 slosh cycles at 2.7 cps with a .3-inch peak-to-peak input.

(d) Expulsion Cycling

Each test unit was subjected to 15 ambient temperature propellant expulsions. These expulsions included 2 high ΔP tests in which the tank assemblies were subjected to approximately 300 psi differential across the bladder in both the collapsed and expanded conditions. The units exhibited normal expulsion characteristics during all 15 cycles. The expulsion efficiency range for unit XP-1 was 98.60 to 99.19 percent while unit XP-2 varied from 98.42 to 98.70 percent.

Each unit completed two high temperature expulsions. Unit XP-1 showed normal expulsion characteristics with expulsion efficiencies of 98.16% and 99.11%. The helium bladder leakage rate increased above the allowable after the second expulsion; however, authorization was given to proceed with testing. Unit XP-2 completed the two high temperature tests with expulsion efficiencies of 99.12 and 99.23 percent.

Each unit was then subjected to two low-temperature expulsions. Unit XP-1 had expulsion efficiencies of 96.42 and 96.93 percent which did not meet the required efficiency of 98%. These apparently low efficiencies were caused by weighing errors due to condensation forming on the tank because of low temperature and high relative humidity. The required pulse durations, ranging from 100 milliseconds to 30 seconds at both specification low and high flow rates, were executed during the second low temperature test. Unit XP-2 completed the two low temperature tests satisfactorily with expulsion efficiencies of 98.18 and 98.23 percent. Pulse testing was performed on the second low temperature expulsion.

(e) Volume Verification

Volume verification was performed only on the XP-2 unit to verify that the volume, as determined by pressure rise, was in accordance with the specification requirements. The pressure increased to 87 psig which was within the specification limit of 205 psig.

(f) Jettison

Jettison blowdown tests were performed to demonstrate the capability of the units to expel the specification liquid volume within 15 seconds using helium gas at a pressure of 130 psig and a temperature of -10°F. Unit XP-1 was subjected to the jettison test with a resultant expulsion time of 21.4 seconds. The jettison vent orifice was enlarged and the test was repeated. The expulsion time for the second test was 12.8 seconds. Unit XP-2 successfully completed the jettison test with an expulsion time of 12.0 seconds.

The units successfully completed the qualification test series, with the specified variations. A detailed report on qualification testing is contained in Bell Report No. 8271-928037.

(2) Command Module Fuel Off-Limit Testing

After successful completion of the qualification test series the two test units were subjected to off-limit testing in accordance with the procedures specified in Bell Report No. 8271-928016. Unit XP1, which previously had completed the qualification test series, completed an additional 12 ambient expulsions during off-limit testing prior to failure. Unit XP-2, after completing the qualification test series was subjected to random vibration in the longitudinal X-axis for 5 minutes each at 21.0, 24.5, 28.0 and 31.5 g rms without failure during off-limit testing.

(a) Expulsion Cycling

Unit XP-1 completed a total of 12 off-limit ambient temperature expulsion cycles with expulsion efficiencies ranging from 98.8 to 99.2% and an average of 99.1%.

(b) Vibration

Unit XP-2 was subjected to random vibration in the longitudinal X-axis with the diffuser tube horizontal. The input to the assembly started at 21.0 g rms, 50% above the qualification test (14.0 g rms), and was increased in 25% increments to 31.5 g rms (225% of 14.0 g rms) with runs of 5 minutes performed at each level. The tank assembly completed the tests at all input levels without damage to the tank or bladder.

The detailed results of off-limit testing are contained in Bell Report No. 8271-928051.

(3) Command Module Oxidizer Qualification

Two command module oxidizer tanks were tested in accordance with the qualification test procedures contained in Bell Report No. 8271-928008, Revisions A and B.

Unit XP-1 completed the required test series which consisted of acceptance test, vibration, slosh, acceleration/acceleration-expulsion, 15 ambient temperature propellant expulsions, 2 low-temperature expulsions, and 2 high-temperature expulsions. Tank assembly designated XP-2 successfully completed the shell acceptance test, pressure cycle test, tank assembly acceptance test; however, the bladder failed following the third ambient expulsion of the test series. Post-failure examination revealed that the bladder had fabrication irregularities. The unit was refurbished with a new bladder and was designated unit XP-2A. This unit successfully completed the required test series which consisted of acceptance test, 15 ambient temperature propellant expulsions, vibration,acceleration/acceleration-expulsion, 2 low temperature expulsions, 2 high temperature expulsions, and volume verification.

(a) Vibration

Each unit was subjected to vibration testing in the longitudinal X-axis and a lateral axis with the units mounted in the horizontal position. Unit XP-1 testing was performed in the longitudinal X-axis and lateral Y-axis. The test for each axis consisted of a sinusoidal sweep and a 15-minute random vibration test. Unit XP-2A was tested in the longitudinal X-axis and lateral Z-axis. The test for each axis consisted of a 15-second random burst and a 15-minute random vibration test.

(b) Acceleration

Acceleration and acceleration-expulsion testing was performed by subjecting each unit to a 28 g acceleration test for 5 minutes in each of two horizontal axes: the first was with the X-axis extending radially from the center of rotation and the second was with the X-axis perpendicular to the rotary arm. In the second test the outlet faced forward with respect to the direction of rotation and the outlet tube pointed towards the center of rotation. Upon completion of the second 5-minute acceleration test the units were subjected to the acceleration-expulsion test without changing the tank orientation. The expulsion was performed while the tank assembly was under acceleration forces diminishing from 20 g to 2 g. The required expulsion efficiency was 96% at a ΔP of 2 psi and 2 g acceleration.

Unit XP-1 satisfactorily completed the testing without damage to tank or bladder. However, the acceleration-expulsion test was conducted from 20.0 to 6.3 g instead of a scheduled 20 to 2 g. An expulsion efficiency of 92.2% was realized at a ΔP of 2 psi at an acceleration level of 6.3 g at the tank center of gravity. The low expulsion efficiency of 92.2% was attributed to the higher-than-scheduled acceleration level.

Unit XP-2A was tested without damage to tank or bladder; however, the acceleration test was conducted from 20.0 to 6.8 g rather than scheduled 20.0 to 2.0 g. Expulsion efficiency was determined to be 94.2% at a ΔP of 2 psi and an acceleration level of 6.8 g at the tank center of gravity.

(c) Slosh

Slosh testing was performed on the XP-1 unit only with the unit loaded to approximately 50% capacity with nitrogen tetroxide. The test consisted of 500 slosh cycles at 2.6 cps with a .3-inch peak-to-peak input with the unit in the horizontal position.

(d) Expulsion Cycling

Units XP-1 and XP-2 were subjected to 15 ambient temperature expulsions and both units exhibited normal expulsion characteristics during all 15 cycles. Expulsion efficiency ranged between 98.61 and 98.85% for unit XP-1 and between 98.53 and 98.76% for unit XP-2A.

Each unit completed two low temperature expulsions. The resulting expulsion efficiencies for unit XP-1 were 97.49 and 97.84%, which did not meet the required efficiency of 98%. These apparently low efficiencies were caused by a change in weight due to condensation forming on the tank because of low temperature and high relative humidity. The first low temperature test was pulsed and the required pulse durations were executed. Unit XP-2A completed the two low temperature tests satisfactorily with expulsion efficiencies of 98.33 and 98.03%. Pulse testing was performed and the required pulse-width durations were executed.

Each unit was subjected to two high temperature expulsions and both showed normal expulsion characteristics during the tests. The expulsion efficiency for unit XP-1 was 96.18% and 98.89%. The efficiency for unit XP-2A was 92.40% and 91.68%.

(e) Volume Verification

Volume verification was performed on the XP-2A unit only to verify that the volume was in accordance with the specification requirements. The pressure increase to 80 psig was within the specification allowable of 205 psig. Test units XP-1 and XP-2A successfully completed the required test series, with the slight explainable expulsion efficiency variations during acceleration-expulsion and low and high temperature expulsion testing. The detailed results of the testing are contained in Bell Report No. 8271-928038.

(4) Command Module Oxidizer Off-Limit Testing

After successful completion of the qualification test series, the two test units were subjected to off-limit testing in accordance with the procedures specified in Bell Report No. 8271-928016. Unit P1, which previously had completed the required qualification test series, completed an additional 50 ambient expulsions during off-limit testing without failure. Unit P2A, after completing the required qualification test series, was subjected to off-limit random vibration in the longitudinal X-axis for 5 minutes each at 21.0, 24.5, 28.0 and 31.5 rms without failure.

(a) Expulsion Cycling

Unit XP-1 completed a total of 50 off-limit ambient temperature expulsion cycles without failure. The expulsion efficiency ranged from 98.9 to 99.8% with an average of 99.1%. All efficiencies were over the minimum requirement of 98%.

(b) Vibration

Unit P2A was subjected to random vibration in the longitudinal X-axis with the diffuser tube in the horizontal position. The input to the assembly started at 21.0 g rms (50% above the qualification test level of 14.0g rms) with runs of 5 minutes performed at each level. The tank assembly completed the tests at all input levels without damage to the tank or bladder.

The detailed results of off-limit testing are contained in Bell Report No. 8271-928052.

(5) Command Module Design Substantiation Testing

The design substantiation test program was a supplemental engineering test program considered necessary because of the limited test data available regarding the performance capabilities of the command module fuel and oxidizer configurations. The purpose of the test program was to determine the operational limits of the qualification configuration tank design under various test environments and to establish limits and criteria by which remaining bladder life could be predicted, that is, total bladder cycle life and curves of helium and nitrogen leakage rates versus number of operational cycles. The methods and test procedures used for this program were in accordance with the procedures established for use in the qualification test program and as specified in Bell Report No. 8271-928030.

Thirteen command module positive expulsion propellant tank assemblies were subjected to the test series which consisted of propellant expulsion and gas cycle testing. The six fuel and seven oxidizer tank assemblies completed the test program with three units failing to complete the scheduled test series. The quantity of hardware used in the testing was minimized by using four tank assemblies, 2 fuel and 2 oxidizer, and refurbishing them with new bladders as required to complete the test series. The required tests were as follows:

- Propellant Expulsion, ambient temperature
- Propellant Expulsion, cold temperature
- Propellant Expulsion, high temperature
- Gas Expulsion, ambient temperature, low ΔP
- Gas Expulsion, ambient temperature, high ΔP

The propellant expulsions were performed using nitrogen tetroxide in the oxidizer units and monomethylhydrazine in the fuel units. Dry cycle testing was performed with nitrogen as the simulated propellant and pressurant. The failure criteria were patterned after the criteria used for qualification testing except that the allowable nitrogen leakage rate of the bladder was doubled to permit acquiring additional cycle life and leakage rate data prior to removing a unit from test.

Propellant expulsion testing was conducted on 4 fuel and 5 oxidizer tank assemblies in the horizontal attitude using normal operating pressure and flow rates. The original plan, which consisted of the following items, was executed with only minor changes:

Cycle Life - Establish cycle life capability at the required temperatures by performing tests as follows:

- Ambient temperature - subject 2 oxidizer and 1 fuel unit to a total of 35 expulsions each.
- Low temperature - subject 1 oxidizer and 2 fuel units to a total of 12 expulsions each.
- High temperature - subject 2 oxidizer and 1 fuel unit to a total of 12 expulsions each.

Expulsion Efficiency - Demonstrate the following efficiencies during life cycle testing:

- Demonstrate an expulsion efficiency of 98% at a ΔP of 2 psi at the high flow rate for all expulsions except the high temperature oxidizer where the efficiency requirement is 93%.

- Demonstrate an expulsion efficiency of 99% at shutdown at the low flow rate for all expulsions by performing an additional "squeeze" on the bladder. This test was not required if an efficiency of 99% was achieved at the high flow rate.

Leakage Tests - Establish criteria for predicting remaining bladder life by performing helium and nitrogen bladder leakage tests alternately throughout the testing.

(a) Ambient Temperature Expulsions

The test plan required subjecting one fuel and two oxidizer units to a total of 35 expulsions at a temperature of 70°F on each unit. Essentially, this plan was completed as scheduled.

Unit FA1 completed the 35 scheduled expulsions with an expulsion efficiency mean value of 98.7%. The secondary expulsion at the low flow rate was required on four of the 35 expulsions. Unit OA1 exceeded planned requirements by completing 40 ambient propellant expulsions, whereas 35 were originally scheduled. The additional five were performed to evaluate an increasing leakage rate trend. The expulsion efficiency mean value was 98.5% and the range of 97.9 to 98.8% demonstrated compliance with the required 98% level. The low flow expulsion efficiency mean value was 99.1%. The low flow expulsion was not performed on 9 cycles where the high flow rate had demonstrated the 99% expulsion efficiency.

Unit OA2 completed the 35 scheduled ambient propellant expulsions with expulsion efficiencies above the required 98% for all 35 cycles. The low flow expulsion efficiency mean value of 99.1% was above the required 99%. The low flow was not performed on 19 expulsions since a 99% expulsion efficiency was demonstrated at high flow shutdown.

(b) High Temperature Expulsion

The test plan required subjecting one fuel and two oxidizer units to a total of 12 expulsions at a temperature of 105°F on each unit.

Unit FH1 successfully completed the scheduled 12 high temperature expulsions with expulsion efficiencies at the high flow rate shutdown exceeding 99% on each cycle.

Unit OH1: completed 7 of the 12 scheduled high temperature expulsions. Leakage rates were above the allowable limits after expulsion No. 3,but testing was continued to obtain cycle life versus leakage rate data. All high flow rate efficiencies exceeded the required 93%, with the mean value 95.4% and the range 93.6 to 98.8%. The low flow expulsion was required on 6 cycles and all were greater than the specified 99%. The mean value was 99.5% and the range was 99.2 to 99.9%.

Unit OH2 completed the scheduled 12 high temperature expulsions; however, leakage rate exceeded the allowable limit after expulsion No. 10. The expulsion efficiency mean value was 97.6% and the range of 95.8 to 98.9% showed performance greater than the required 93% for all cycles. The low flow expulsion was performed on 10 cycles and the expulsion efficiency mean was 99.6% with a range of 99.5% to 99.8%.

(c) Low Temperature Expulsions

The test plan required subjecting two fuel and one oxidizer unit to a total of 12 expulsions, each at a temperature of 35°F.

Unit FC1 completed 10 of the scheduled 12 cold propellant expulsions. The leakage test rates following expulsions No. 8, 9, and 10 were above the allowable limits. The expulsion efficiency mean value was 97.9% and the range was 96.7 to 98.4%. The low flow mean expulsion efficiency was 99.0% with a range of 98.6 to 99.2%. The low efficiency which resulted during 5 expulsions can be attributed to weighing error caused by condensation on the cool tank from the humid atmosphere.

Unit FC2 completed the scheduled 12 cold propellant expulsions. The expulsion efficiency mean was 97.3%; range was 95.5 to 98.3%. The low flowrate expulsion efficiency mean value was 98.6% with a range of 97.9 to 99.6%.

Unit OC1: successfully completed 7 of the scheduled 12 cold propellant expulsions. The expulsion efficiency mean value was 98.2% with a range of 97.8 to 98.3%. The low flow rate expulsion efficiency mean was 98.9% with a range of 98.5 to 99.1% for the 5 expulsions where low flow was required.

(d) Gas Cycle Testing

Gas cycle testing was performed on four test units. The purpose of the testing was to determine the life cycle capability of the tank assemblies without the influence of propellants, and to obtain data on helium and nitrogen leakage rates versus number of cycles. Each test unit completed 50 cycles as scheduled, and nitrogen and helium bladder leakage tests were performed alternately on each fourth cycle. The testing was performed in the temperature range of 65 to 95°F with an expulsion pressure of 287 psig. Nitrogen gas was used as the pressurant and as "simulated propellant" for the liquid side of the bladder.

(e) Low ΔP Tests

One fuel and one oxidizer unit were subjected to the low ΔP test series. The test was designed to subject the bladder to the same action as an expulsion without using a test liquid. Each expulsion was terminated at an indicated ΔP of 3.5 to 4 psi. Units OGL and FGL completed the scheduled 50 cycles, with helium leakage rates within the specified limits throughout the testing.

(f) High ΔP Tests

One fuel and one oxidizer unit were subjected to the high ΔP test series. The test was designed to subject the bladder to a ΔP of 287 psi at the end of the cycle. Units OGH and FGH completed the scheduled 50 cycles, with helium and nitrogen leakage rates within the required limits throughout the test series.

(g) Conclusions

No direct correlation could be made between helium leakage rate and nitrogen leakage rate data. The helium leakage test provides the necessary sensitivity to accurately monitor changes in bladder permeation characteristics; however, there appears to be no way to relate bladder leakage rate to number of bladder cycles to predict subsequent bladder service life or failure. The detailed results of the design substantiation testing are contained in Bell Report No. 8271-928039.

c. Propellant Exposure Testing

(1) Service Module Fuel

One tank assembly was subjected to propellant exposure testing to demonstrate that the service module fuel tank assembly is capable of performing properly afte an extended period of exposure to a 50/50 blend of hydrazine-unsymmetrical dimethylhydrazine, and that creep requirements as specified in North American Aviation procurement Specification MC 282-0008, would not be exceeded. The test procedures are specified in Bell Report No. 8271-928024. The tank assembly was installed but testing was not started immediately because of the rupture of shells in the 10-tank storage program. The test was started about a month later and the tank assembly successfully completed the required test series which consisted of the following:

- 8-day fill and drain test
- 30-day exposure and creep test
- 14-day drained storage
- duty-cycle demonstration

The leakage rates were within the allowable limits at the completion of testing and indicated that there was no material degradation or damage to the test unit. All expulsion requirements were met during the duty cycle at the end of the exposure period. Measurements of the tank assembly during the 30-day exposure test indicated no measurable creep resulting from the high pressure and temperature during the test period.

Samples of the helium taken from the gas side of the bladder during the test to measure propellant permeation showed that the ullage space does not become saturated by the fuel in the 30-day period. Samples of the propellant taken from the liquid side of the bladder during the test to measure gas transmission properties of the bladder indicated that the helium content of the fuel was approximately .0016% by weight at the end of the 30-days. This compared favorably with North American Aviation data. The detailed test results are contained in Bell Report No. 8271-928041.

(2) Service Module Oxidizer

The SMO unit was installed for testing at the same time as the fuel unit but testing was stopped because of the rupture of tanks during the 10-tank storage program. Testing was resumed on this unit but bladder failure occurred during reloading for the test. The test was not repeated because sufficient data was acquired during the titanium N_2O_4 stress corrosion storage program.

d. Propellant Storage

The N_2O_4 ten-tank storage, fuel (MMH and 50/50 blend) storage, and the resulting activity under the titanium - N_2O_4 stress corrosion programs originated and were administered as part of the Bell Model 8271 Apollo Tankage Program. Because of the magnitude and industry-wide impact of the stress corrosion investigation, it is covered separately in this section as an associated program.

B. MODEL 8339 LM RCS TANKAGE PROGRAM

1. INITIAL DESIGN

In February 1964, initial go-ahead was received from Grumman Aircraft Engineering Company to supply positive expulsion tankage for the Lunar Module RCS propulsion system which uses 50/50 blend fuel and N_2O_4 oxidizer. The resulting program is shown in Figure III-6.

The design was governed by a contractual requirement of commonality to the Apollo RCS tankage with limited exceptions based on specification requirements or customer preference. Consequently, the initial design released in April 1964 was identical to that of Apollo with the following exceptions:

- The cylindrical length was increased to accommodate the greater volume of propellant required.
- Tank shell thickness was altered to comply with the pressure and dynamic requirements of GAEC.
- The liquid bleed tube was incorporated into the initial diffuser design. This was not yet common with Apollo because,although this addition had been proposed by Bell for the Apollo tanks, it was not approved by North American until June 1964 for service module tanks and December 1964 for command module tanks.
- Diffuser outlet, bleed tube, and helium inlet port fittings were 304L stainless steel with tube fittings installed.
- Diffuser and propellant outlet were fabricated from 3/4-inch O.D. tubing with the outlet tube having a wall thickness of 0.020 inch.

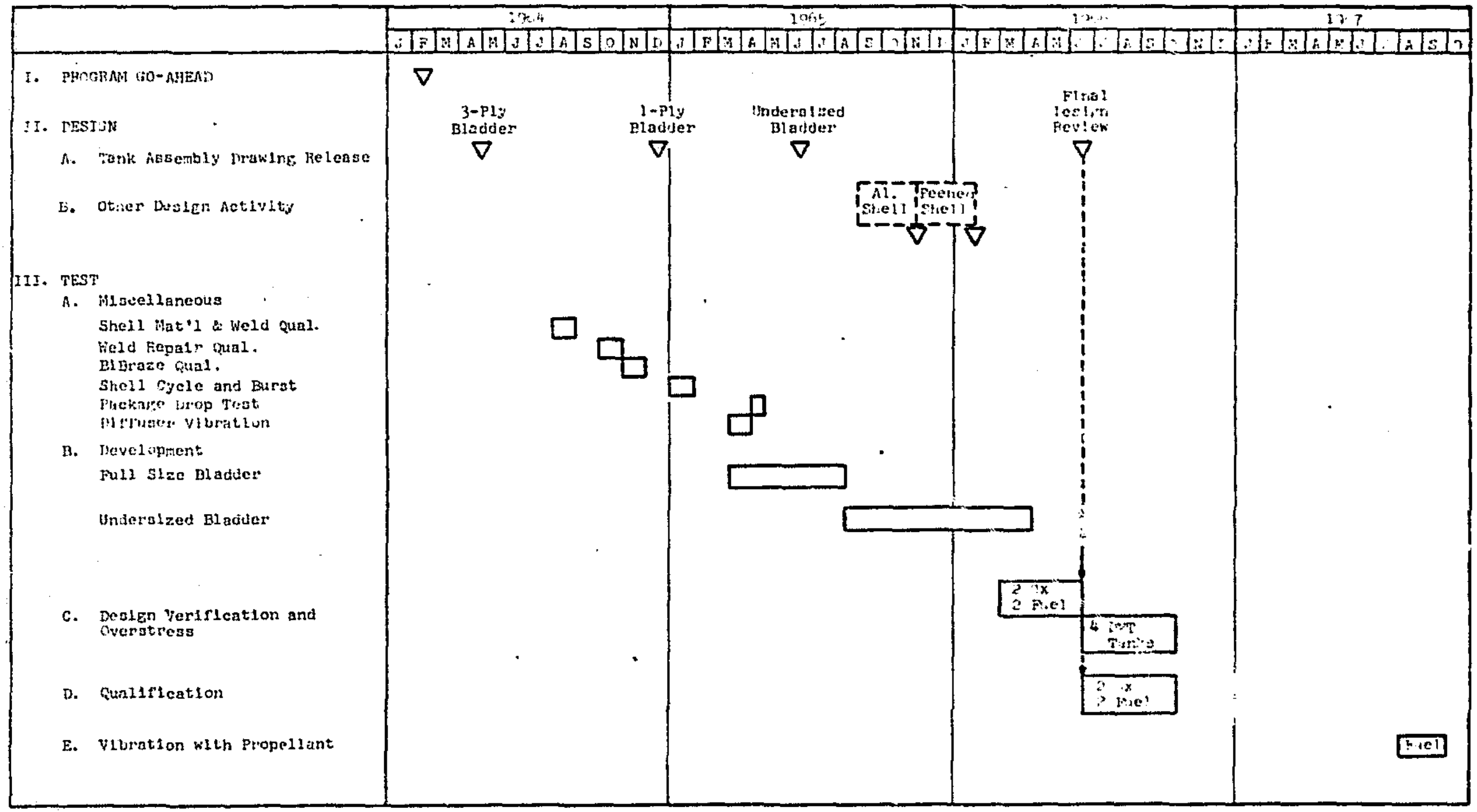
Procurement activity was started for shells, bladders and diffuser material in April 1964.

2. DESIGN DEVELOPMENT

a. Diffuser Assembly

Fabrication of diffuser assemblies was initially delayed because of difficulty in obtaining 304L stainless tubing that met GAEC specification requirements. The tubing was received in August 1964,and fabrication of diffusers proceeded.

FIGURE III-6 MODEL 8339 LUNAR MODULE TANKAGE - PROGRAM HISTORY



In November 1964, five propellant outlet assemblies were tested to qualify the Bi-braze joint. All of the units successfully completed the testing which included proof pressure, helium leakage, temperature cycle, fatigue cycle, vibration, helium leakage, burst, and shear strength tests. This testing is reported in detail in Bell Report No. 8339-910001.

Meanwhile, during diffuser fabrication, cracking was experienced in the propellant bleed tube in the area of weldment to the outlet tube. This was caused by the boron content of the 304L stainless. This problem was alleviated by limiting the boron content to 0.003%. Additional problems were encountered with the Bi-braze joint. It was difficult to obtain a good coating of the 304L outlet tube with aluminum during the Bi-braze process. Also the tube corroded in the vicinity of the Bi-braze joint because of sensitization from the brazing process. As a result, Bell recommended the use of 347 stainless tubing on the basis of its resistance to sensitization and demonstrated success on the Apollo Command and Service Module assemblies. Grumman approved this recommendation and the change was made.

Diffuser vibration testing was conducted on one fuel and one oxidizer diffuser assembly to establish structural adequacy of these components. Each diffuser was tested in the longitudinal and one lateral axis at qualification vibration test levels and up to 1.5 qualification levels. Both tubes successfully passed the testing which is reported in detail in Bell Report No. 8339-928004.

In April 1965, the tank assembly design was changed to require cut-off of outlet tube, bleed tube and helium inlet port tube prior to delivery to Grumman. A few tanks, however, were delivered with tube fittings for breadboard testing.

b. Tank Shell

(1) Structural Analysis

Structural and preliminary dynamic analyses were performed in April 1964 to verify the shell design and are reported in detail in Bell reports 8339-941001 and 8339-941002. The preliminary dynamic analysis was conducted in conjunction with similar analyses performed at Grumman in order to determine the dynamic response of the tanks in the LM dynamic environments, not only on rigid supports but also on supports which incorporated the flexibility factors of the vehicle mounting brackets.

(2) Process Qualification

The LM tank shells are of the same materials and construction as the Apollo shells except for cylindrical length and shell thickness. Therefore, to expedite the test program, the first 20 shells were fabricated in accordance with Apollo material and process controls while qualification of material and welding processes were being performed to Grumman specification requirements. This qualification was completed in August 1964. Subsequent problems encountered with weld mismatch on shells were solved by changing the weld backup ring. This resulted in a penalty weld qualification test in November 1964. The twenty-first and all subsequent shells (including all those of qualification and flight configuration) were fabricated to the LM specification requirements. A weld repair process for the shell was successfully qualified; however, no weld repair has been performed on any LM shell.

(3) Burst Test

Fatigue cycle and burst tests were performed on one fuel and one oxidizer shell in January 1965 to verify the structural adequacy of the tank shell design early in the program.

A total of 3000 hydrostatic pressure cycles consisting of repeated series of 270 cycles from 0 to 180 psig, followed by 30 cycles from 0 to 250 psig, with a pressure rise time of 1.25 ±.25 seconds, was performed on each shell. This was followed by hydrostatic proof pressure test at 333 psig and a burst test. There was no permanent set at proof pressure. Burst pressures were 615 psig for the fuel shell and 818 psig for the oxidizer shell. These results compared favorably with theoretical values of 620 psig and 825 psig for the fuel and oxidizer shells, respectively. These values greatly exceeded the specification requirement of 375 psig because of the design considerations necessary to meet the specified dynamic requirements.

(4) Vibration Testing

Vibration testing of one fuel and one oxidizer tank assembly was conducted in the period of May to August 1965. This testing was accomplished to check the vibration fixtures and test procedures and to determine the structural adequacy of the tank assemblies, vehicle mounting brackets, and propellant gaging system under qualification level vibration inputs. Original design full-size bladders were used for these tests to establish the structural adequacy of the tankage and support system early in the program. Each tank was subjected to sinusoidal and random vibration in each of the three orthogonal axes. The tanks were loaded to specification propellant volume with substitute liquids. The fuel was simulated using a mixture of 1.06 parts of isopropanol to 1.0 part distilled water by weight. Freon-TF mixed with 5% methanol by weight was used to simulate the oxidizer.

The fuel bladder failed after completion of X-axis sine and random and Y-axis sine vibration. An equipment problem during the latter test resulted in a severe overtest condition which contributed to bladder failure. The bladder was replaced and the Y- and Z-axis testing was completed. The oxidizer tank completed all the testing without incident. The fuel and oxidizer tank assemblies, fixtures, and vehicle mounting brackets proved satisfactory. The Gianini propellant gaging blankets did not fail although they showed crazed areas around the screws used to hold the halves of the blanket together. All bladders used for the test were severely damaged; however, only one failed and this was apparently caused by the overtest condition. Grumman was requested to re-examine the projected mission vibration environments from the standpoint of reducing the qualification level vibration requirements.

(5) Alternate Designs

When the problem of titanium stress corrosion with N_2O_4 occurred on Apollo, Grumman requested that Bell initiate a design effort for an aluminum tank shell. Three aluminum alloys (6061, 2219 and 2014) were investigated for possible use and preliminary shell drawings were made. This effort was stopped in November 1965 when internal peening of titanium shells was found to be an effective deterrant of stress corrosion with N_2O_4. Requirements for glass bead peening of shells were then established in December 1965, and three oxidizer and three fuel tank shells were sent to NASA Langley Research Center for peening. After peening, these shells were returned to Bell and subsequently used in tank assemblies which were delivered to Grumman. The subsequent adoption of N_2O_4 with a controlled NO content as an effective stress corrosion inhibiting measure precluded further use of peened tank shells on the LM RCS tankage.

c. Bladder

(1) Initial Design and Test

In conformance with the commonality concept, the original bladder design released in April 1964 was the 3 mil 3-ply configuration which was the current Apollo design. However, procurement of this configuration was stopped in June 1964 because of problems on the Apollo program. In December 1964, after the full size 6 mil single-ply bladder was adopted for Apollo with successful testing, the LM design was changed to this configuration and bladder procurement was again initiated.

In March 1965, the first single-ply full size bladder was tested in a plexiglass tank to determine if the increased length over that of the Apollo tank would affect bladder behavior. One expulsion was made in the vertical flange-down attitude on an oxidizer bladder using Freon-TF as the expulsion medium. After completion of the expulsion, the bladder was re-expanded and the tank filled to capacity in preparation for the next expulsion. At this point the bladder failed in the top (retainer) hemisphere. The failure consisted of two small slits in the retainer hemisphere. These slits were in areas of numerous striations and stress cracks. There was also a small puncture in the cylindrical section caused by a foreign particle on the outside of the bladder.

A thorough investigation of the stress failure in the upper hemisphere of the bladder was conducted. The failure mechanism was identified as biaxial stress imposed during post-expulsion re-expansion of the bladder. This condition resulted from the fact that as liquid is expelled from the tank the bladder material is displaced downward and, at the end of the expulsion, becomes trapped in the bottom of the tank in the form of deep folds. During subsequent gas re-expansion of the bladder the cylindrical section expands first and engages the tank wall. In the case of the LM tanks the length/diameter ratio resulted in bladder-to-wall friction forces exceeding the available lifting forces provided by bladder internal pressure. This resulted in yielding of the top hemisphere of the bladder. Bladder fabrication was stopped in April 1965,pending resolution of this problem.

During the investigation, additional plexiglass tank tests were conducted in which various techniques, such as simultaneously pressurizing both inside and outside of the bladder, were attempted in an effort to effect bladder recovery. None resulted in complete recovery unless the tank assembly was inverted prior to expansion. The use of lubricants between the bladder and tank shell was also unsuccessful.

Results of additional tests disclosed that expulsion of not more than 50% of the loadable volume of propellant resulted in satisfactory post-expulsion bladder recovery. As a result, a limited number of tanks with full size bladders were delivered to Grumman for limited testing pending resolution of the positioning problem.

(2) Design Development

As a result of the bladder failure,a bladder design and development program was initiated in April 1965. The program was conducted simultaneously along two parallel lines of effort, bladder redesign and adaptation of existing hardware and servicing procedures.

(a) Adaptation of Existing Design

(i) Mechanical Restrainers and Increased Venting

It seemed apparent that if the bladder could be restrained at the retainer end to minimize or eliminate its downward displacement, the recovery problem could be circumvented. In addition, during previous plexiglass expulsion tests, the bladder was observed to be fluttering near the bottom of the tank. This observation led to the premise that the standard 0.028 inch thick monofilament vent lines were providing insufficient area for gas passage between the bladder and tank wall resulting in the bladder being forced from the wall by pressure differential between the bottom and top of the tank. No flutter had been observed during tests made with the tank inverted to the flange-up attitude which placed the gas inlet port at the top of the tank. It also had been observed that post-expulsion expansion of the bladder in the flange-up attitude resulted in approximately 50% greater bladder recovery than experienced in the normal flange-down attitude with the gas port at the bottom of the tank. Thus it was hypothesized that restriction of gas passage between the bladder and tank wall, during bladder expansion, was a contributory factor in preventing bladder recovery.

Two Teflon restrainers (a 3.8 inch diameter disc and a $2\frac{3}{4}$ x 5-inch oval) were made and each was tested in an oxidizer plexiglass tank. The size limitation of the restrainers was dictated by the inside diameter of the bladder neck (2 inches) and the tank flange opening (4 inches). Non-rigid restrainers were not considered, since they would necessarily be of the metallic finger type and experience on the Agena program proved these to be detrimental to bladder life.

To increase tank venting capability, braided vent cords were substituted for the standard .028 inch monofilament Teflon vent lines. A series of plexiglass tank tests was conducted utilizing Teflon restrainers and braided vent cords, both singly and in combination, to establish the effect of each on bladder recovery. During these tests an additional gas port was installed on the retainer (top) end of the plexiglass tank to study pressure differential across the bladder.

The use of restrainers during these tests resulted in only partial improvement in bladder recovery. During testing it was observed that as the bladder collapsed during an expulsion it did not follow the contour of the restrainer, but the material "bridged" between the restrainer and the diffuser. Thus, it was felt that this unsupported area of the bladder would yield and fail when subjected to full tank differential pressure at the end of a complete expulsion. The elliptical restrainer was installed in a metal tank shell and a full expulsion was made at rated tank pressure. The bladder failed at the end of propellant flow when it became subjected to a differential pressure equal to the tank pressure. The failure occurred in the unsupported area just below the restrainer.

Although increasing the tank venting capacity by use of the braided vent cords effectively eliminated bladder "flutter" during expulsion tests, negligible improvement in bladder recovery was experienced during re-expansion. Test results also indicated that the use of standard vent cords during bladder re-expansion did not result in restriction of gas passage to a detrimental degree.

In attempting to reorient the bladder between tests, it was discovered that if the top vent was opened and 1.0 psig pressure was applied suddenly to the gas port while the bladder was expanded to 0.5 psig, full bladder recovery was experienced. However, since the deliverable tank did not have a vent port at the retainer end and since system weight and space restrictions could not allow the extra plumbing required for the added port, this solution could not be applied to the LM tankage. This information, however, was applied to the Saturn SIVB program which does have a gas port at the retainer end of the tank.

A detailed report of these tests is contained in Bell Report No. 8339-928014.

(ii) Teflon Coating of Tank Shell

The possibility of reducing bladder-to-tank friction through application of a Teflon coating to the inside of the shell was investigated. Analysis disclosed that the maximum tolerable coefficient of friction between the bladder and shell on the LM oxidizer tank is 0.124. Laboratory tests showed that the coefficient between Teflon-FEP and TFE is 0.17 and between FEP and FEP is 0.26. For this reason no further consideration was given to coating of LM tank with Teflon.

(iii) Liquid Fill and Buoyancy

Re-expansion of the bladder with propellant in lieu of gas resulted in successful reorientation in seven out of ten tests. The bladder failed to recover in the remaining three tests. For this reason the liquid fill technique is considered unreliable. Tests performed using the buoyancy effect to "float" the bladder upward in the tank, using first a heavy gas (carbon dioxide) and second a liquid (water), were unsuccessful. These tests are reported in detail in Bell Report No. 8339-928012.

(iv) Undersized Sleeve

The initial purpose of the undersized sleeve design was to determine the practicability of a bladder design with an undersized cylindrical section. A standard full-size oxidizer bladder was restricted for 19 inches of its cylindrical length by a Teflon sleeve which was 3.2% undersized, diametrally. Expulsion testing in the vertical flange-down attitude resulted in complete bladder recovery each time and showed not only that the undersized bladder design concept was feasible, but also indicated that utilization of an undersized sleeve with a full size bladder might be a workable alternate or substitute for the undersized bladder.

Consequently, a second phase of testing was undertaken to demonstrate the capability of an undersized sleeve in all three expulsion attitudes (flange-down, flange-up, and horizontal). To accomplish this, the sleeve was reworked to a configuration which could be adapted to a standard metal tank and twelve additional expulsions were performed. The bladder recovered completely each time it was re-expanded. The sleeve had no measureable effect on tank performance or expulsion efficiency.

During these tests the sleeve was stressed to the tank wall 16 times for a total of approximately 70 hours. Post-test measurements of the sleeve indicated that this accumulated stressing resulted in a 0.65% increase in sleeve diameter and a 0.26% decrease in its length. These tests clearly demonstrated the practicability of both the undersized bladder and the undersized sleeve as satisfactory solutions to the problem of bladder-to-tank orientation. A detailed report of this testing is contained in Bell Report No. 8339-928013.

(b) Bladder Redesign

(i) Stiffening of Cylindrical Section of Bladder

A study was made into the possibility of stiffening the cylindrical section of the bladder so that it would not fold so drastically during expulsion and would delay in contacting the tank wall during re-expansion. Consideration was given both to ribbing and increased material thickness in the center section. Neither of these concepts was considered to be beneficial for the following reasons:

- Downward displacement is the result of inward folding of the hemispherical portion of the bladder, not the cylindrical portion.
- Any increase in stiffness in the cylindrical section, which would not be detrimental to tank performance, would still result in contact between this section of the bladder and the tank wall before the hemispherical ends could expand sufficiently to result in full bladder recovery.

(ii) Undersized Bladder

(aa) Design

As a result of the successful bladder positioning using an undersized sleeve, the LM bladder design was altered so that the diameter of the cylindrical portion is 2% less than the inside diameter of the tank shell. In addition, the material thickness at the retainer end of the bladder was increased to 9 mil for a 2-inch diameter at the retainer,tapering gradually to the normal 6 mil thickness at a diameter of 4 inches from the end. The latter change was the result of observed stress marks in full size bladders, due to bridging between the retainer washer and the retainer boss of the tank in tests conducted during the initial bladder failure investigation. The additional bladder thickness in this area allowed removal of the Teflon buffer pads at the retainer end of the bladder.

Laboratory testing was conducted on bladder material specimens to validate the design concept. Tensile, creep, stress relaxation and strain recovery tests verified that the bladder material would recover elastically after repeated subjection to 2% uniaxial strain. Exposure of specimens to oxidizer, fuel, and flush fluids did not adversely affect the stress-strain characteristics of the material after outgassing.

In order for the undersized bladder design to function successfully, extremely tight diametral tolerances had to be met during fabrication. Since mandrel dissolving results in differential shrinkage of the bladder, due to the nature of the dissolving process, an additional processing step was required. A bladder sizing oven was designed to support the bladder in its natural shape while heating it uniformly to a predetermined temperature level,to obtain desired shrinkage of the bladder. Testing of several scrap bladders in the oven established that a uniform shrinkage of 2% will be obtained if the bladder is heated to, and stabilized at, a temperature of 200 to 210°F. Of course, tight control over mandrel dimensions was also required to maintain a consistent, preshrinkage size of the bladders. Special equipment and techniques were developed to obtain accurate measurement of bladder diameter and length when expanded with an internal pressure equivalent to 8.2 inches of water.

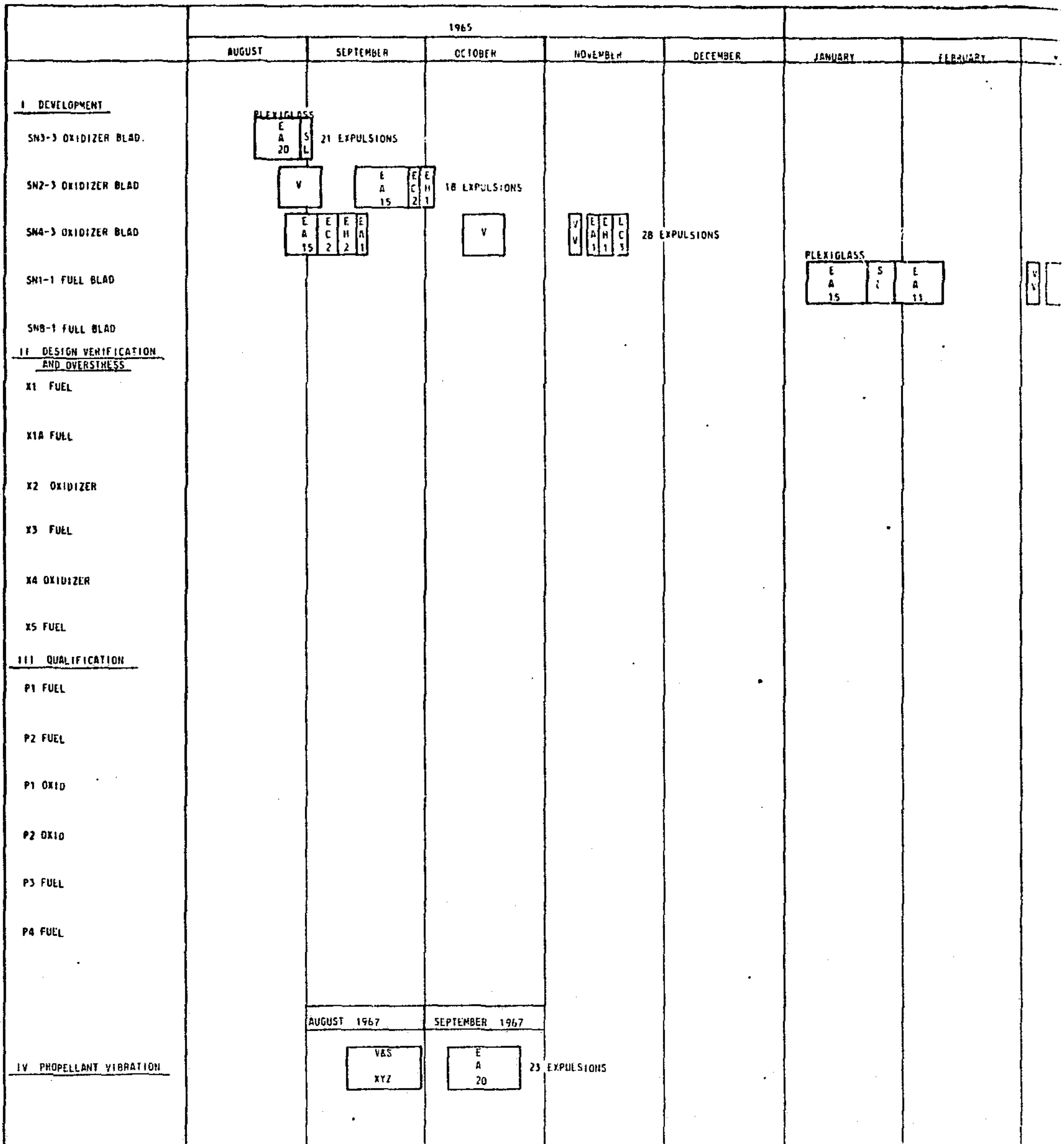
(ab) Test

After the fabrication process had been established, three undersized bladders of the oxidizer tank size were procured and tested as follows (See Figure III-7):

(i) Oxidizer Bladder SN 3-3

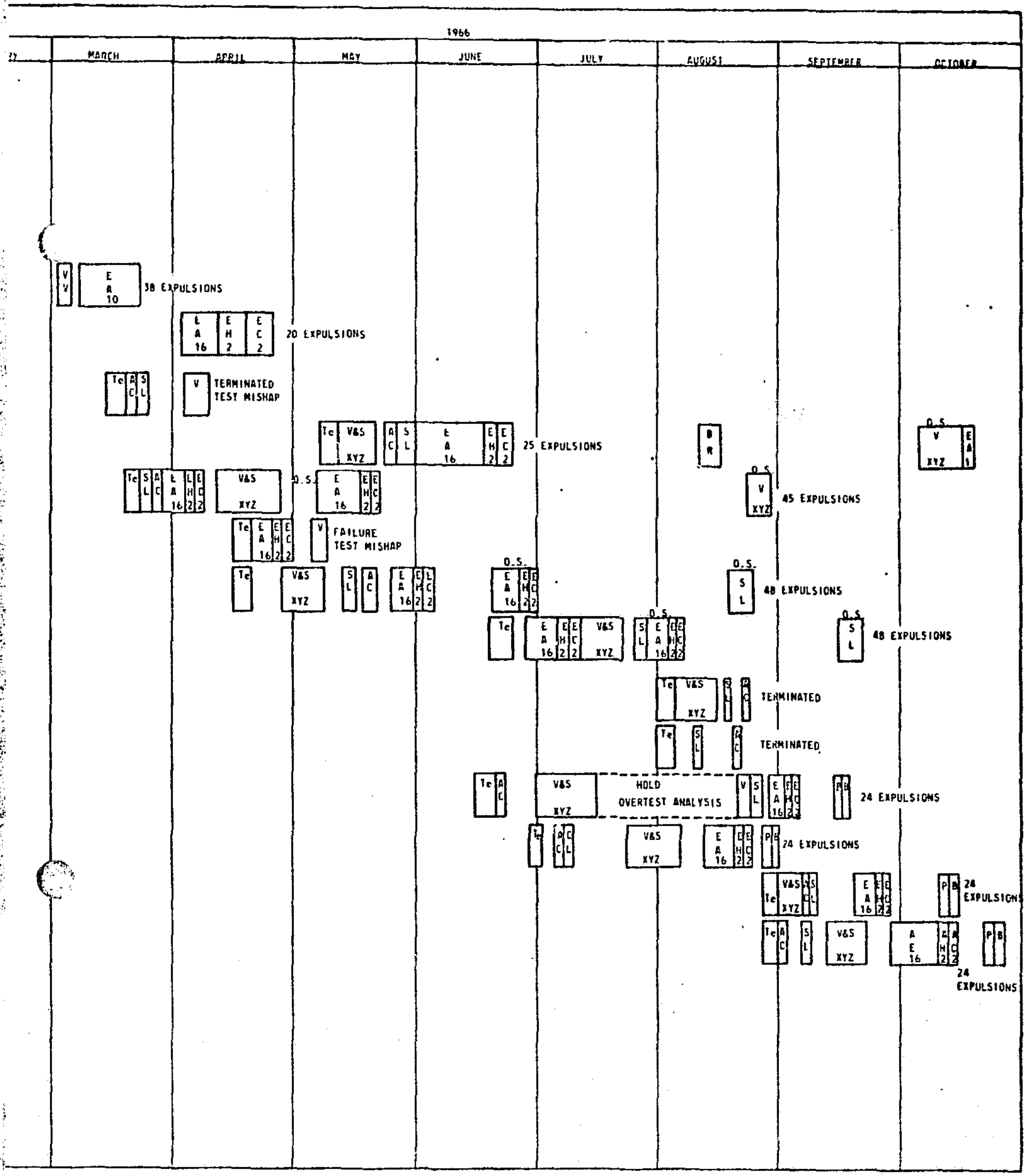
(aa) Expulsion Testing - This bladder was subjected to 20 expulsions with Freon-TF in a plexiglass tank, in both vertical and horizontal attitudes, with complete bladder recovery after each expulsion. Visual examination of the bladder disclosed no evidence of stresses as a result of these

FIGURE III-7 · 8339 LUNAR MODULE TEST HISTORY -



FOLDOUT FRAME

TORY - UNDERSIZED BLADDER CONFIGURATION



FOLDOUT FRAME 2

tests. It should be noted that regardless of the expulsion attitude all loading and servicing of the LM tanks is performed in the vertical, flange-down, attitude to simulate vehicle use. Expulsion efficiency at a tank assembly ΔP of 2 psi varied from 98.9 to 99.2% in the vertical attitude and from 90.8 to 93.5% in the horizontal attitude.

(ab) Slosh Testing - After expulsion testing, the bladder was subjected to slosh testing in a plexiglass tank to establish the fundamental slosh mode in the vertical attitude when filled to 1/3 capacity and subjected to 0.1 g input perpendicular to the longitudinal axis. The fundamental slosh frequency was established at 3.2 cps. After a 500 cycle slosh endurance test, the bladder was examined with no observable evidence of stress damage.

As a result of the successful performance of this bladder, the remaining two bladders were assembled into prototype oxidizer tanks for testing.

(ii) Oxidizer Bladder SN 2-3

This bladder was subjected to vibration in all three axes to the original LM dynamic requirements. This was followed by 18 propellant expulsions in the vertical attitude after which the bladder failed. The failure consisted of a 1/4-inch rupture in the flange end caused by bi-axial stress. Measurement of the bladder disclosed that it was approximately 1/4-inch shorter than the tank shell and 3/8-inch shorter than its "as fabricated" length. This represented a one percent decrease in bladder length due to repeated flexure during test. This length decrease resulted in the bladder being stretched longitudinally in order to fill the tank shell after the cylindrical section engaged the tank wall.

Although the post-vibration bladder leakage tests showed that the bladder had not been functionally impaired by this test, it was removed from the tank prior to the expulsion test and examined for vibration damage. A number of stressed areas were found in the upper (retainer) hemisphere in the ullage portion of the bladder. Although these stresses were not nearly as severe as those found previously on the full size bladders, they appeared to be sufficiently damaging to adversely affect the subsequent cycle life of the bladder. As a result, Grumman revised the vibration requirements of the specification to more nearly approximate the mission requirements. All subsequent testing was performed to the new requirements.

(iii) Oxidizer Bladder SN 4-3

This bladder started testing simultaneously with bladder SN 2-3 and was subjected to 20 propellant expulsions, vibration in all 3 axes to the new vibration requirements, volume verification and an additional 5 expulsions prior to bladder failure.

(aa) Propellant Expulsion Testing - The initial 20 expulsions consisted of 15 vertical at 70°F, 2 vertical at 35°F, 2 vertical at 105°F, and one horizontal at 70°F. Of the vertical tests, 10 were made in the flange-down attitude and 9 in the flange-up attitude. After vibration and volume verification testing, one pulsed expulsion at 70°F was made in the vertical flange-down attitude followed by four horizontal tests, one at 105°F and 3 at 35°F. During the last three expulsions, the helium pressurant gas was -20°F for the last 10% of each expulsion and each expulsion was allowed to proceed until full tank assembly differential pressure was imposed across the bladder. During normal expulsion testing of a repetitive nature, the tests are automatically terminated when tank assembly ΔP reaches an indicated value of 3 to 4 psi. Expulsion efficiency of the tank in the vertical attitude exceeded 99% at a tank assembly ΔP of 2 psi which exceeded the specification requirement of 95%. In the horizontal attitude, however, efficiency ranged from 94.2 to 96.8% for the low temperature tests and 89.7% for the high temperature test. The lower efficiency in the horizontal attitude was expected and supported results obtained on the Apollo tank program. Grumman has since revised the specification to lower the minimum horizontal expulsion efficiency to 87% and raised the maximum differential pressure at all attitudes to 2.5 psi.

(ab) Vibration Testing - The unit successfully completed all 3 axes of vibration in accordance with the new specification requirements. The bladder was removed from the shell and examined both before and after vibration testing and exhibited no evidence of damage due to the vibration test. A few small stress areas which were found at each end of the bladder prior to vibration test were not altered in appearance after the test.

(ac) Volume Verification Test - This test was conducted to demonstrate compliance with the specification requirement that the tank, when loaded with propellant to specified capacity at 65°F and pressurized to 25 psig, shall not exceed an internal pressure of 130 psia when heated to a stabilized temperature of 100°F. The actual test pressure was 100 psia which was well within the specified limit.

(ad) Failure Analysis - The bladder failure was determined to have been caused by rolling of a tightly compressed buckled fold in an area previously weakened by biaxial stress. The tightly compressed buckled fold resulted from the last three low temperature horizontal expulsions being allowed to progress to full tank assembly differential pressure. Measurements of the bladder disclosed that, like bladder SN 2-3, it had decreased one percent in length from the as-fabricated condition and was approximately 3/16-inch shorter than the tank shell. It was obvious that this was the cause of the biaxial stress damage in both ends of the bladder which was identical to the damage experienced by bladder SN 2-3.

At this time bladder S/N 3-3, which had been used in the plexiglass tank tests, was measured and also proved to have shrunk approximately one percent in length. However, since its original length was greater than that of the other two bladders, it was approximately 1/8-inch shorter than the tank and consequently did not have the severe biaxial stress marks. In the "as fabricated" condition all three bladders were 1/8 to 1/4-inch longer than the tank shells after the sizing operation.

The undersized bladder design was changed to require the bladder length to be a minimum of 1% longer than the maximum allowable internal length of the tank shell. Procurement of undersized bladders of the new length for test and delivery was started in December 1965.

(iv) Fuel Bladder S/N 1-1

This was the first of two undersized fuel bladders of the new length to be tested. The tests performed on this bladder consisted of 26 expulsions and slosh testing in a plexiglass tank, volume verification, and 10 propellant expulsions prior to bladder failure.

(aa) Plexiglass Tank Expulsion Testing - Seven expulsions (6 vertical and one horizontal) were made with inhibited water to study bladder behavior and performance with a liquid approximately the density of fuel. All expulsions, including the horizontal test, showed an expulsion efficiency greater than 99% at a ΔP of 2 psi. An additional 19 expulsions were made with Freon-TF to check performance of the new bladder length with a liquid which approximates oxidizer in density and physical effects on the bladder material. The latter group of tests included expulsions made at various attitudes between vertical and horizontal to establish a relationship between test attitude and expulsion efficiency. The range of efficiency at $\Delta P = 2$ psi was as follows:

Attitude	No. of Tests	Range of Efficiency
Vertical ±60° (Flange-down or up)	12	97.8 to 99.4%
75% from Vertical	2	96.9 to 97.8%
Horizontal	5	94.7 to 97.8%

(ab) Plexiglass Tank Slosh Testing - Between the fifteenth and sixteenth expulsion tests, a slosh test was conducted to establish the fundamental slosh mode of the fuel tank under the same conditions as described for the slosh test of oxidizer bladder S/N 3-3. The fundamental slosh frequency was established at 3.0 cps.

When the bladder was removed from the plexiglass tank after the final expulsion and visually examined, some apparently minor stress points were noted principally in the upper (retainer) hemisphere and several long longitudinal creases were found in the cylindrical portion of the bladder. In addition, there were many short creases and folds distributed in random fashion all over the bladder. However, no severe damage could be found and the bladder helium leakage rate after the final test was no greater than its pretest rate. The bladder was therefore installed into a metal shell and prepared for propellant testing.

(ac) Volume Verification Testing - This test was conducted for the same purpose as described previously for oxidizer bladder SN 4-3. Prior to this test, however, Grumman changed the initial and final pressures to 40 psig and 145 psia, respectively. The actual test pressure was 111 psia which was well within the specified limit.

(ad) Propellant Expulsion Testing - A total of 10 vertical propellant expulsions at 70°F were completed successfully. Bladder failure occurred while the bladder was being expanded in preparation for propellant loading for the 11th expulsion. Performance of the tank assembly was satisfactory throughout the 10 expulsions and there was no indication of impending failure prior to the actual occurrence.

(ae) Failure Analysis - Examination of the bladder disclosed a 0.023 inch rupture located in the retainer hemisphere of the bladder. The cause of the failure was rolling of a buckled fold in an area which had previously been damaged by repetitive rolling of a buckled fold. The principal cause of failure was considered to be the large number of slosh impulses experienced during plexiglass tank slosh tests. A study of test records indicated that between 6,000 and 10,000 slosh impulses had been imparted to the bladder during the frequency survey to establish the critical slosh modes. In addition, the bladder had experienced a total of 38 expulsion cycles (including 2 during slosh test) with three different fluids as well as extra handling during removal from the plexiglass tank and installation into the metal tank. Since the bladder had accumulated such a varied and rigorous test history, the failure was not considered to constitute an inadequacy in design or fabrication.

(v) Fuel Bladder SN 8-1

(aa) Propellant Expulsion Test - Although fuel bladder SN 1-1 accumulated a total of 38 expulsions, in addition to extensive slosh testing, it did not complete the 20 expulsions in fuel required by the specification. Bladder SN 8-1 was assembled into a tank and subjected to these 20 expulsions to demonstrate that the fuel bladder configuration is capable of meeting the propellant expulsion performance and durability requirements of the specification.

The unit performed satisfactorily throughout the 20 expulsions which consisted of 16 vertical at 70°F, 2 vertical at 100°F, 1 vertical at 35°F, and one horizontal at 35°F with helium pressurant introduced at -20°F during the last 10% of the expulsion. The final (horizontal) expulsion was allowed to proceed until full tank assembly ΔP was impressed across the bladder. Expulsion efficiency during all tests exceeded 99% at a tank assembly ΔP of 2 psi.

The bladder was removed from the tank following the last expulsion and visually examined for evidence of damage or deterioration. The bladder was found to be in excellent condition with little or no visible evidence of damage due to testing.

(ac) Conclusion

These tests proved that successful post-expulsion bladder-to-tank shell orientation can be achieved repeatedly through use of a bladder which is 1.5 to 2% undersized in the cylindrical section and at least one percent longer than the inside of the shell to allow for flexure shrinkage. However, detailed servicing procedures must be used and strictly adhered to in order to assure repeated success.

A detailed report of the undersized bladder development testing described herein is contained in Bell Report No. 8339-928025.

3. DESIGN VERIFICATION AND OVERSTRESS TESTING

a. Purpose

Design Verification Testing (DVT) was performed to provide reasonable confidence that the design of the LM RCS tankage would satisfy the performance requirements of the procurement specification, by conducting the specified tests, and to establish the design margin for the tankage by performing the specified overstress tests. DVT testing was performed in the period of March to June 1966. Overstress testing was completed in October 1966. (See Figure III-7).

b. Summary

Design verification testing of four tank assemblies, two fuel and two oxidizer, was performed in accordance with the procedures contained in Bell Report No. 8339-928016. The original fuel tank assemblies (Units X1 and X3) were removed from the test series because of test mishaps during vibration test. In addition, Unit X1 had been assembled without a Teflon bleed tube support. These tank assemblies were replaced by two new fuel units designated X1A and X5.

All four test units successfully completed the required Design Verification Test Program (at qualification test level) in accordance with the specification requirements and approved procedures. Tests conducted on each unit consisted of temperature extremes storage, followed by acceleration, slosh, shock, vibration and expulsion in varying sequences.

In addition, overstress tests were performed on each of the units as follows to establish the margin above the reliability boundary:

X1A Fuel	X2 Oxidizer	X4 Oxidizer	X5 Fuel
Bladder Replacement Vibration	20 Expulsions Vibration	20 Expulsions Slosh	20 Expulsions Slosh

c. Test Sequence

The chronological sequence of tests for each unit was as follows:

	X1A Fuel	X5 Fuel	X2 Oxidizer	X4 Oxidizer
Qualification Level				
Acceptance Test	1	1	1	1
Temp. Extreme	2	2	2	2
Vibration/Shock	3	4	6	3
Acceleration	4	5	4	5
Slosh	5	6	3	4
Expulsions (20)	6	3	5	6
Overstress				
Expulsions	-	1	1	1
Slosh	-	2	-	2
Vibration	1	-	2	-

d. Test Results

(1) Temperature Storage Testing

This test was performed on each of six tank assemblies as the first test in the DVT series. Each unit was subjected to the storage conditions while in a nonoperating state with the bladder pressurized internally to 20 $^{+3}_{-0}$ psig. The units were maintained at a temperature of $-20\,^{+0}_{-5}\,°F$ and held at this temperature for 12 hours before being conditioned to room temperature. At this point a helium bladder leakage test and a tank assembly leak test were performed. The unit was then conditioned to a temperature of $160\,^{+5}_{-0}\,°F$ and maintained at this temperature for 12 hours before being conditioned to room temperature. The helium bladder leakage test and tank assembly leakage tests were repeated at this point.

(a) Unit X2

This unit was the first to be tested and excessive flange leakage was evident after the initial (-20°F) storage period. An investigation disclosed that the residual torque on the flange bolts varied considerably, and the gap between the flange and shell varied 0.010 inch indicating improper assembly technique. As a result of this failure the acceptance test procedure was revised to more rigidly control the bolt tightening operation by including specific instructions for attaining the required torque values in uniform incremental steps. The bolts were tightened in accordance with the revised procedure and Unit X2 was again subjected to the temperature storage test and successfully completed the test.

(b) Units X1 and X3

These two tank assemblies successfully completed temperature storage testing; however, both assemblies were overtested during subsequent testing and were replaced by Units X1A and X5.

(c) Units X1A, X4, and X5

All three test units successfully completed the temperature storage test.

(8) Dynamic Testing

All four DVT test units were subjected to acceleration, slosh, vibration and shock tests. While undergoing the dynamic environments, the following liquids were used to simulate the propellants:

Oxidizer:	Freon-TF mixed with $3\,^{+2}_{-0}\%$ methyl alcohol by volume.
Fuel:	Distilled water inhibited with 0.1% chromic acid by weight.

The units were pressurized to 250 psig with nitrogen for all dynamic testing except Launch/Boost vibration which was accomplished at a pressure of 40 psig.

(a) Slosh

The tank assemblies were mounted directly to the test fixture (hard mounted) for slosh testing and were installed on the slosh machine in the vertical flange-down attitude. The units were loaded to 1/3-specification volume and were subjected to 500 slosh impulses along the Y-axis at the following input levels:

Tank	Frequency	Input Displacement
Oxidizer	3.2 cps	0.19 inch DA
Fuel	3.0 cps	0.22 inch DA

All four test units successfully completed the DVT slosh testing.

Upon completion of the DVT test series, overstress slosh testing was performed on Fuel Unit X5 and Oxidizer Unit X4. The overstress conditions were as follows:

1.33 Qualification Level - 300 cycles
Oxidizer X4: 3.2 cps at .25 inch DA
Fuel X5: 3.0 cps at .29 inch DA

1.67 Qualification Level - 100 cycles
Oxidizer X4: 3.2 cps at .32 inch DA
Fuel X5: 3.0 cps at .37 inch DA

2.0 Qualification Level - 50 cycles
Oxidizer X4: 3.2 cps at .38 inch DA
Fuel X5: 3.0 cps at .44 inch DA

Both tank assemblies successfully completed overstress slosh tests.

It should be noted that at the completion of each slosh test the liquid was forced from the tank by collapsing the bladder, thus constituting an added expulsion cycle on the bladder.

(b) Acceleration

Each unit was mounted on Grumman support brackets, loaded to specification volume, and mounted on the centrifuge with the +X-axis horizontal and extending radially outward from the center of rotation. An acceleration force of 8.5 g was applied for 5 minutes. The unit was then turned so that the -X-axis extended radially outward from the center of rotation and the 8.5 g acceleration force was applied for 5 minutes. All four test units successfully completed acceleration testing with no indication of damage.

(c) Vibration and Shock

(i) Test Conditions

All four tank assemblies were installed on the Grumman support brackets and mounted in the vertical flange-down attitude for vibration and shock testing. The testing included launch and boost level vibration, lunar descent level vibration (and shock), and lunar ascent level vibration. Each level was performed in all three mutually perpendicular axes. Each unit was tested at all required levels in one axis and then was drained and leak tested prior to starting the next axis. The sequence of events for each axis was as follows:

- The unit was loaded to specification capacity and pressurized to 40 psig for launch/boost vibration. Upon completion of this vibration level, the pressure was reduced to 5 psig and sufficient liquid was drained to leave 75% of specification volume loaded in the tank. The tank was then pressurized to 250 psig and vibrated in accordance with the descent level requirements. With the 75% load and 250 psig pressure in tank, the assembly was given three 15 g shock pulses first in the plus, then in the minus direction along the axis of vibration. Pressure was vented to 5 ±.5 psig and the unit was visually inspected.
- Following the shock test, sufficient liquid was drained to leave 50% of specification volume in the unit. The tank was pressurized to 250 psig and vibrated in accordance with the lunar ascent requirements. The liquid was then expelled by collapsing the bladder and the tank and brackets were visually examined for evidence of damage. A helium leakage test was conducted to evaluate internal bladder assembly damage. It should be noted that the expulsion of liquid after each axis of vibration constituted an additional 3-expulsion cycles for each tank during vibration test.
- After completion of all three axes of vibration and shock testing, each unit was subjected to a tank assembly leakage test and then was X-rayed for possible structural damage.

Overstress vibration on the X1A fuel and X2 oxidizer units was performed with inputs at 1.33, 1.67, and 2.0 times qualification levels while loaded to specification volume. The tank assembly was drained and a helium leakage test was conducted after test in each axis.

(ii) Test Results

All four units successfully completed qualification level vibration and shock testing. It was planned to replace the bladders on X1A fuel and X2 oxidizer units prior to overstress vibration. The planned replacement was accomplished on X1A,and the unit satisfactorily withstood the entire overstress vibration sequence with no evidence of damage to the test unit or the vehicle mounting brackets.

The planned bladder replacement was not accomplished on X2, prior to overstress vibration, in order to determine the ultimate life of the bladder. During overstress vibration, bladder failure was indicated after Y-axis testing at the 1.33 level. This bladder had previously withstood all qualification level tests, overstress expulsion tests and Z-axis overstress vibration tests at the 1.33 level. Testing was continued and the tank shell ruptured during the last scheduled axis of overstress vibration test. Failure occurred near the end of the X-axis sinusoidal sweep at 2.0 times qualification level.

(3) Expulsion Cycle Testing

(a) Test Conditions

All four test units successfully completed the series of expulsions specified in Table III-1. Nitrogen tetroxide was used in the oxidizer units and hydrazine/UDMH blend in the fuel units. The tests were conducted in accordance with the specified conditions of temperature, flow rate, flow duration, and shutdown ΔP. The testing series demonstrated the capability of the tank assembly to meet the following performance requirements:

- Cycle Life - Twenty propellant expulsion cycles comprised of 16 at ambient temperature (65° to 75°F), 2 at high (100° to 105°F), and 2 at low temperature (35° to 40°F).
- Pulsed Flow - Ability to expel propellant in flow bursts of various durations. This was performed on the eighth, ambient, flange-down expulsion.
- Expulsion Efficiency Vertical - Demonstrate an expulsion efficiency of 95% at a ΔP= 2.5 psi at all flow and temperature conditions specified with the tank in a vertical attitude.
- Expulsion Efficiency Horizontal - Demonstrate the ability to expel a minimum of 87% of capacity in the horizontal attitude. This was demonstrated

on the 20th expulsion of each unit. This expulsion was made at 35 $^{+5}_{-0}$°F, except that the pressurizing gas was conditioned to -20 ±5°F during the last 10% (high flow) portion of the expulsion. The expulsion was allowed to run to completion of flow so that full ΔP was impressed across the bladder.

The specification requirement that the tank assembly be capable of expelling 99% of its propellant capacity, in any attitude at a ΔP of full operating pressure, was not demonstrated since all expulsions, with the exception of Expulsion No. 20 on each unit, were terminated at a ΔP of 3 to 5 psi. However, data indicated an efficiency greater than 98% at a Δp of 2 psi. Extrapolation of the expulsion curves indicated that the tank assembly is capable of meeting this requirement.

Overstress expulsion testing was performed on three units (X2, X4, and X5) after the DVT test series was completed. This overstress testing consisted of repeating the expulsion sequence specified in Table III-1. All three units successfully completed the additional 20 expulsions. Overstress expulsion testing was not performed on fuel tank X1A because bladder leakage rate was high after the initial 20 expulsions. Although the bladder had not failed at this point, it was considered desirable to remove it and identify, if possible, the nature of the degradation. Inspection showed a severe stress mark in the upper (retainer) hemisphere which subsequently failed in biaxial stress when inflated after removal from the tank. Rupture did not occur until the bladder was inflated to a pressure of 1 psig while unrestrained.

e. Summation

The Lunar Module RCS positive expulsion propellant tank design demonstrated its adequacy to fulfill the intended mission. All four test units successfully completed the qualification test levels of the Design Verification Test Program. The added reliability margin indicated by the overstress testing provided a high degree of confidence that the tank design is able to meet all the qualification test requirements of the Grumman Procurement Specification. A detailed report of this testing is contained in Bell Report No. 8339-928024.

A formal design review was held with Grumman in June 1966 after completion of qualification level testing of the DVT Program. At this review the design configuration was frozen in preparation for entry into formal qualification testing.

TABLE III-1 EXPULSION TEST SEQUENCE

Test	Flange Orientation	Temperature (°F)
Leakage - Helium	Down	70 ±5
*Expulsion No. 1 thru 8	Down	70 ±5
Leakage - Helium	Down	70 ±5
Expulsion No. 9 thru 16	Up	70 ±5
Leakage - Helium	Down	70 ±5
Expulsion No. 17	Down	100^{+5}_{-0}
Leakage - Helium	Down	70 ±5
Expulsion No. 18	Up	100^{+5}_{-0}
Leakage - Helium	Down	70 ±5
Expulsion No. 19	Down	35^{+5}_{-0}
Leakage - Helium	Down	70 ±5
**Expulsion No. 20	Horizontal	35^{+5}_{-0}
Leakage - Helium	Down	70 ±5

* Expulsion No. 8 pulsed.

** Expulsion No. 20 performed so that during the last 10% of the expulsion (high-flow portion) the pressurizing gas was at a temperature of -20 ±5°F and the expulsion proceeded to full tank ΔP.

NOTE

The low medium, and high flow rate capability was demonstrated on Expulsions No. 1, 9, 17, 18, 19, and 20 as follows:

Low flow rate to 60% expulsion
Medium flow rate 30% expulsion
High flow rate 10% expulsion

All other expulsions were performed at the high flow rate only.

4. QUALIFICATION TESTING

a. Summary

Qualification testing of four tank assemblies, two fuel and two oxidizer, was performed during the period of June to October 1966. The two original fuel tanks were removed from test due to handling damage to the propellant outlet tubes and were replaced by two new fuel units. All four test units successfully completed the required qualification test in compliance with the specification requirements and according to the test procedures contained in Bell Report No. 8339-928022. (See Figure III-7.)

b. Sequence of Testing

The chronological sequence of testing for each unit was as follows:

	P1 Oxidizer	P2 Oxidizer	P3 Fuel	P4 Fuel
Acceptance Test	1	1	1	1
Temperature Extremes	2	2	2	2
Acceleration	3	4	4	3
Vibration & Shock (3 axes)	4	5	3	5
Slosh	5	3	5	4
Propellant Expulsions (20)	6	6	6	6
Bladder Removal	7	7	7	7
Pressure Cycle	8	8	8	8
Burst	9	9	9	9

c. Test Results

All four units successfully completed all the tests. The temperature extreme, acceleration, vibration, shock, slosh and 20 propellant expulsions were conducted in the same manner as the qualification level portion of DVT testing described earlier in this section. In addition, each unit was subjected to fatigue pressure cycle and burst testing.

(1) Pressure Cycle and Burst Testing

Upon completion of expulsion testing the units were disassembled and the bladders removed. They were then reassembled without bladders and subjected to pressure cycle testing. Each unit was loaded with distilled water and cycled from 0 to 181 to 0 psig for 270 cycles with a pressure rise time of 1.25 ±0.25 seconds. The pressure was increased to 250 ±10 psig and the unit was cycled from 0 to 250 to 0 psig for 30 cycles with a pressure rise time of 1.25 ±0.25 seconds. This sequence was repeated until a total of 3000 cycles were completed. All four units successfully completed the test. Each unit was then subjected to hydrostatic proof and burst testing with the following results:

Unit	Initial Yield Pressure (psig)	Burst Pressure (psig)
Oxidizer Tank P1	560	767
Oxidizer Tank P2	570	775
Fuel Tank P3	460	589
Fuel Tank P4	490	622

Design requirements for the fuel and oxidizer shells are as follows:

Nominal Working Pressure	181 psig
Maximum Working Pressure	250 psig
Proof Pressure	333 psig
Burst Pressure	375 psig

The actual burst pressures substantially exceeded the design burst requirement because dynamic loading requirements of the specification had to be considered in the design of the tank shells.

5. SUPPLEMENTAL TESTING

a. Vibration and Shock Testing of Fuel Tank With Propellant

(1) Background

Although the LM RCS tankage was successfully qualified, it was recommended in the Qualification Report that one fuel and one oxidizer tank be subjected to vibration and shock testing at qualification levels with actual propellant.

Information developed on the NASw-1317 contract raised a serious question concerning the validity of dynamic testing with the specified simulated propellant. There was a reasonable amount of evidence that, through the interplay of actual propellants and the Teflon bladder material, the cycle life of the bladder may be lower than that experienced when using alternate test fluids.

For this reason it was deemed advisable to demonstrate satisfactory bladder cycle life using actual propellants in order to remove any uncertainty and increase confidence in the ability of the tank assemblies to meet mission requirements.

In June 1967, Bell received contractual go-ahead to perform vibration and shock testing of one LM RCS fuel tank with propellant. This test was to be followed by 20 propellant expulsion cycles at 70°F in the vertical flange-down attitude.

(2) Test Description

The required tests were performed in August and September 1967 on one fuel tank designated R-1. Vibration and shock tests were performed at Wyle Laboratories; Norco, California test facility. The propellant expulsions were performed at Bell. At the request of Grumman, a gas bubble formation test was performed between expulsions No. 5 and No. 6.

(a) Pretest Checkout and Calibration

Prior to the testing of unit R1, a fuel tank without bladder was subjected to launch and boost vibration levels in all three axes. This tank was fully loaded with distilled water inhibited by 0.1 percent by weight of chromic acid. Nitrogen was used as the pressurizing gas. This test was conducted to establish input control techniques to provide necessary input level modifications imposed by maximum response criteria. In addition, this test provided a checkout of the equipment and procedure and provided familiarization for test personnel prior to tank assembly testing.

(b) Vibration and Shock Testing

Vibration and shock testing was performed to the qualification test requirements except that 50/50 fuel blend was used in place of the substitute propellant. The vibration testing was completed without incident. Satisfactory shock impulses could not always be obtained, due to equipment limitations, but this was not considered to be significant since shock testing is primarily a measure of the structural adequacy of the unit while the bladder, being flexible, is more sensitive to number of flexures than to degree of flexure.

(c) Expulsion Cycle Testing

Twenty propellant expulsions were performed with the tank assembly in the vertical flange-down attitude at 70°F. All expulsions were terminated automatically at a tank assembly ΔP of 2 psi with the exception of expulsion number 20. This test was allowed to proceed until full tank assembly differential pressure was impressed across the bladder.

(d) Gas Bubble Formation Test

Following expulsion No. 5 and the subsequent bladder leakage test, Grumman requested that the tank assembly be loaded to specification volume and stored with a 40 psig helium pad at room temperature to determine the extent, if any, of gas bubble formation on the liquid side of the bladder. This request was complied within the following manner:

1/ The tank assembly was loaded, ullage was drained, and 42 psig helium trapped on the gas side of the bladder.

2/ After approximately 84 hours, the trapped pressure had decreased to 25 psig. The pressure was increased again to 40 psig and the upper portion of the tank assembly was X-rayed to determine bladder position and to detect the presence of a liquid-gas interface.

3/ The top of the bladder was then vented through the bleed port and into a gas sampler, while maintaining 40 psig on the gas side of the bladder.

4/ The upper portion of the tank assembly was then X-rayed to detect any change in bladder position as a result of the rebleeding.

5/ The sample obtained in step 3/ was analyzed for helium content.

The results of this test were as follows:

1/ A study of the X-ray made prior to rebleeding disclosed no visible gas entrapment at the top of the bladder. The X-ray made after rebleeding showed no visible change in bladder position or folds when compared to the original X-ray, thus indicating that no discernible gas bubble existed within the bladder.

2/ A 20 cc gas bubble was collected in the sampler at a sample pressure of 38.5 psig. Spectrophotometric analysis disclosed that 5.9 cc of this bubble was helium. The remaining 14.1 cc was probably propellant vapors trapped at the top of the bladder during the tank assembly loading operation, since post-load ullage was drained from the outlet tube at the bottom of the tank rather than from the bleed tube at the top of the tank.

These results led to the conclusion that prelaunch bubble formation within the bladder is essentially negligible in the case of the LM RCS fuel tank, since the 5.9 cc bubble would be compressed to approximately 1.66 cc at a nominal tank working pressure of 181 psig. Since the bubble formation test was merely an extension of the primary test program, the following variables existed which could not be fully controlled or quantatively evaluated for their effects on bubble size:

1/ Some of the 5.9 cc of helium in the sampler was in solution in the fuel and went out of solution when the fuel, at 40 psig in the tank, was bled into the sampler. Solubility data of helium in 50/50 fuel blend indicates that the entire 5.9 cc could have come out of solution with the 1.5 psi drop in pressure which occurred when the tank was bled.

2/ Some of the 5.9 cc of helium may have been part of the trapped gas at the top of the tank after loading, since ullage was not drained from the bleed tube at the top, but from the outlet tube at the bottom. (Helium is used to supply back-pressure to keep the bladder expanded during loading.)

3/ The pressure drop from 40 psig to 25 psig, that occurred during the test, cannot be attributed entirely to helium permeating the bladder and dissolving in the fuel. Based on the solubility of helium in 50/50 fuel, the pressure should have dropped only to 34.9 psig. It would appear that the remaining decrease of 10 psi was probably due to minor leakage in the test system.

4/ Although the bladder had been purged and subjected to a helium leak check prior to loading for this test, it had been exposed to fuel for three days prior to this test and traces of fuel may have been still present within the bladder membrane. It is possible that gas permeation rate subsequent to the initial loading of a dry bladder may be different.

Since the size of the helium bubble proved to be comparatively innocuous during this test, it seems apparent that if any or all of the above variables were applied, the result would still be effectively negligible.

(3) Conclusions and Recommendations

The LM RCS fuel tank assembly successfully completed vibration and expulsion testing with actual propellant with no significant degradation of the bladder.

The results of this test program yielded a high level of confidence in the capability of the fuel tank assembly to successfully meet the Apollo mission requirements.

Although there appears to be no significant prelaunch gas bubble problem in the fuel tank, it was recommended that the following conditions be met during prelaunch servicing for both fuel and oxidizer tanks:

1/ Post-load ullage be drained from the bleed tube.

2/ A rebleed through the bleed tube be made, if possible, within 24 hours of launch or at least 24 hours after loading.

3/ The tank be pressurized to working pressure as soon as feasible after rebleeding.

A detailed report of this testing is contained in Bell Report No. 8339-928027.

6. FINAL DESIGN CONFIGURATION

The final design configuration which was qualified and delivered as flight hardware is shown in Figure II-4 and may be generally described as follows:

Titanium tank shell - not peened (except for 3 oxidizer and 3 fuel tanks with peened shells which were delivered to Grumman as flightworthy hardware).

Diffuser assembly of the same materials as Apollo RCS diffusers. Diffuser and outlet tube 3/4 inch O.D. and bleed tube 3/16-inch O.D.

Undersized bladder with no buffer pad at the retainer end.

Shipping closure with provisions for expanding the undersized bladder during shipping and relaxing the bladder during storage.

Deliverable tank configuration has no helium inlet port fitting. A shipping closure fitting is substituted.

C. MODEL 8400 SATURN SIVB TANKAGE PROGRAM

1. DESIGN

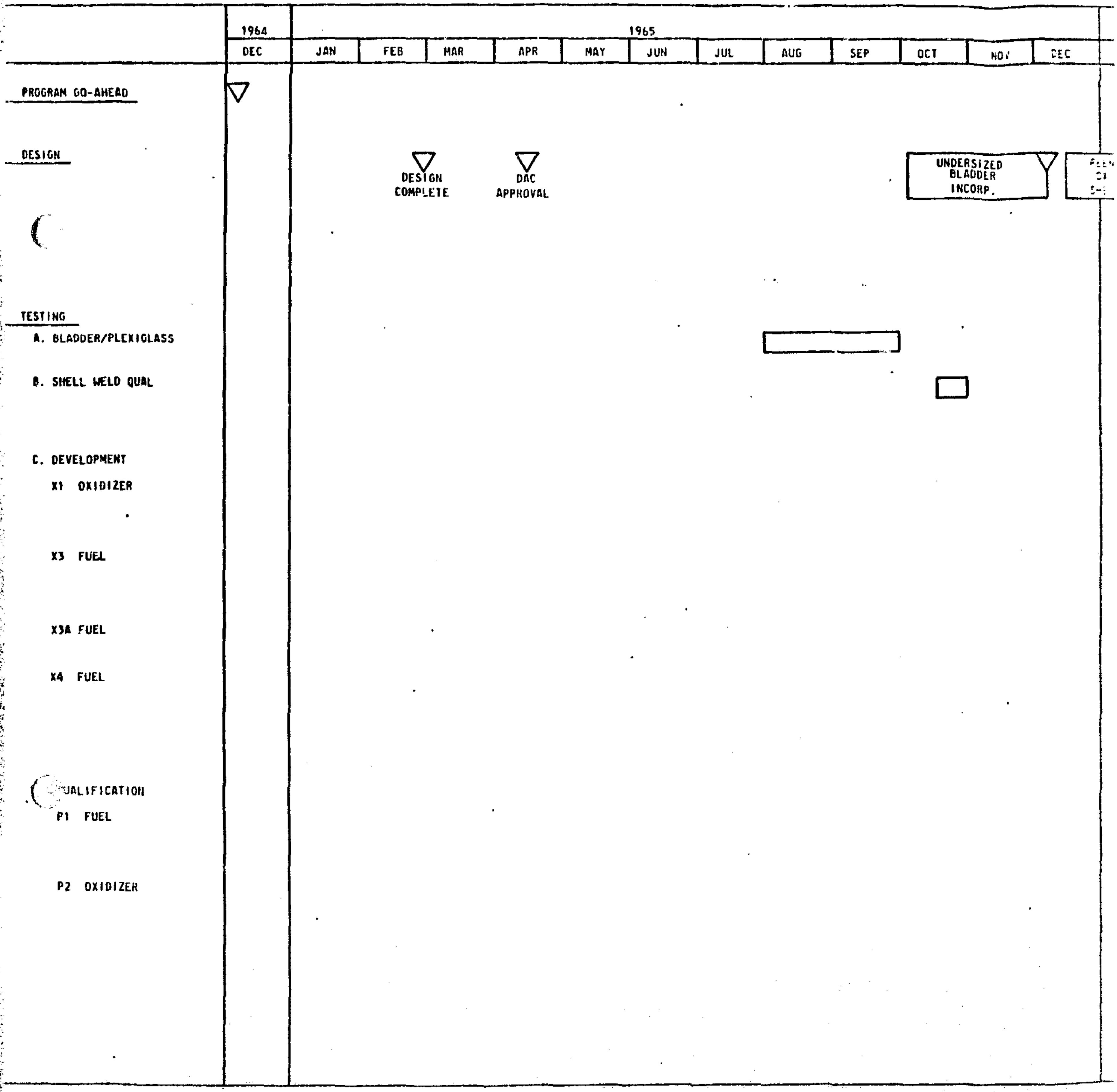
In December 1964, Bell received contractual go-ahead to supply positive expulsion tankage for the Saturn SIVB Auxiliary Propulsion System. Each system includes two fuel tanks for use with MMH, and two oxidizer tanks for use with N_2O_4. The fuel and oxidizer tanks are the same size and were based originally on the Lunar Module oxidizer tank configuration except that the SIVB design contained an additional gas pressurization port at the blind end of the tank for greater ease in purging and servicing the gas side of the bladder. Since this tank is always operated in the vertical flange-down position, this port became the primary pressurization point. The resulting program is shown in Figure III-8. Shortly after initiation of design effort Bell was directed to incorporate the following additional changes:

- Higher burst pressure (550 psig)
- All stainless steel (347) diffuser assembly
- Tube fittings and MC flares on propellant outlet and bleed tubes

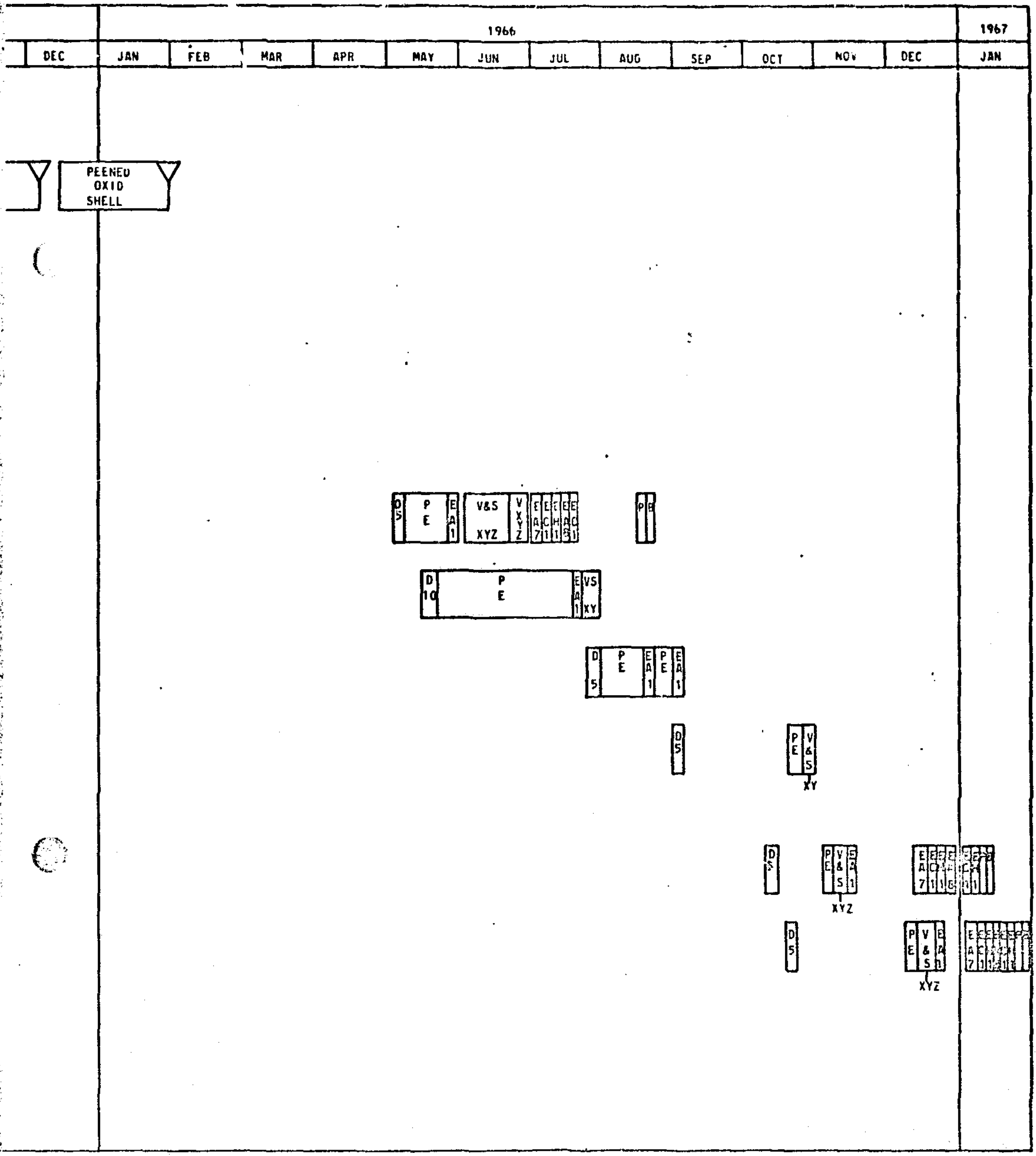
Preliminary release of the final design configuration was made in March 1965 with formal release following in April. During this period the Lunar Module tank program started plexiglass tank testing and experienced a bladder failure due to bladder-to-tank shell friction during post-expulsion repositioning of the bladder. Since the SIVB tank design utilized the then current LM oxidizer full size single-ply bladder, a temporary hold was imposed on bladder fabrication for the SIVB program pending resolution of the problem. Meanwhile, limited development testing was initiated with a plexiglass tank to evaluate the effect of various purge and servicing procedures on bladder behavior. During these tests it was found that post-expulsion repositioning of a full-size bladder is possible by pressurizing both the inside and outside of the bladder to an equal value and control-venting the blind-end gas port to create a low pressure area at the top of the tank. Consequently, twelve tank assemblies were assembled with full-size bladders and delivered to Douglas as an interim configuration for testing purposes.

In the summer of 1965 an undersized bladder configuration proved successful in overcoming the LM repositioning problem and was incorporated into the LM tank design. In the fall of 1965 the SIVB tank design was altered to incorporate the undersized bladder. In conjunction with the incorporation of the undersized bladder, a shipping closure similar to that of LM was designed with a common line and a hand valve between the liquid and gas sides of the bladder. Since Douglas had need for such a device on the tanks after assembly into the propulsion system,

FIGURE III-8 MODEL 8400 SATURN SIVB



URN SIVB PROGRAM HISTORY



FOLDOUT FRAME 2

the closure installation envelope was redesigned to make it compatible with the SIVB installation. All SIVB APS tanks are now installed and serviced with closure assemblies installed.

During the Apollo stress corrosion investigation it was found that internal peening of titanium tank shells would retard stress corrosion caused by red N_2O_4. Since the specified oxidizer for the SIVB tankage at that time was red N_2O_4, eleven tank shells were internally glass-bead peened at the NASA Langley Research Center in February 1966. Three of the eleven peened shells were retained at Langley for testing, two were assigned for use on the development program at Bell, and the remaining six were assembled into oxidizer tank assemblies and delivered to Douglas. The subsequent adoption of N_2O_4 with a controlled NO content as an effective stress corrosion inhibiting measure precluded further use of peened oxidizer tank shells on the SIVB program until the summer of 1967. At this time Bell was directed to deliver all tank assemblies, both oxidizer and fuel, with internally peened shells. Tank shell and assembly drawings were changed to incorporate this requirement. Therefore, after fabrication at Bell, all SIVB tank shells are peened at Douglas then returned to Bell for assembly into tanks. Tanks which had been delivered were returned to Bell for disassembly and the shells returned to Douglas for peening. The shells were then returned to Bell for bladder replacement, reassembly, and acceptance testing.

In order to obtain more beneficial emissivity effects, the final design configuration also included a polished flange and polished tubing on both the propellant outlet port and the bleed port. These modifications were incorporated in March 1966. The final design configuration now in current delivery is the same as that of the LM oxidizer tank with the following exceptions:

- Thicker tank shell - glass bead peened on inner surface
- Stainless steel diffuser assembly
- Top gas port for servicing and pressurizing the bladder
- Polished diffuser flange and external tubing
- Shipping closure designed for storage and servicing on the APS Module
- "MC" flares on tube assemblies

2. TESTING

a. Development Testing

Development testing was limited to demonstration of compliance with requirements peculiar to the Saturn IVB APS program; therefore, requirements identical to those of the LM RCS tanks were not demonstrated. Additional objectives of development testing were to assist in establishing optimum GSE servicing procedures for Douglas, and to check out and refine test procedures and equipment prior to initiation of formal qualification testing. The development test program described in the succeeding paragraph was conducted in two phases. The first phase, which took place in August and September 1965, consisted of plexiglass tank testing to visually study bladder behavior. The second phase, tank assembly testing, was initiated in May 1966 and completed in November 1966.

(1) Plexiglass Tank Testing

The purpose of these tests was to establish and evaluate tank-to-bladder relationships by visual observation of bladder behavior under various conditions of liquid and gas flow. The specific test objectives were as follows:

- To study bladder behavior during liquid expulsion and gas re-expansion in the flange-down attitude while using the top (blind end) gas port for pressurizing and venting. Since none of the other tanks of the common technology "family" are equipped with this port, there was no prior test experience with this configuration.
- To evaluate servicing procedures for loading and bladder positioning.
- To study gas flow characteristics around the bladder and evaluate purge procedures for elimination of permeated liquids from the gas side of the bladder.

Since this phase of testing was begun before the undersized bladder design became established on the LM program, a full size bladder was used. A total of thirty-one plexiglass tank expulsions were made with the tank oriented in the vertical, flange-down attitude using Freon-TF as the expulsion medium. A detailed report of these tests is contained in Bell Report No. 8400-928015. The principal findings were as follows:

- Use of the additional gas port at the blind (top) end of the tank did not measurably affect bladder behavior, tank assembly ΔP, or expulsion efficiency during liquid expulsion. The only noticeable difference during expulsion testing was the absence of bladder "flutter" observed during LM tank expulsions in this attitude, due to passage of pressurant gas between the bladder and tank shell. Expulsion efficiency during these tests varied from 98.2 to 98.9% at a tank assembly differential pressure of 2 psi, which complied with the specification requirement of 97.5%.

- A successful method of repositioning a full-size bladder in a tank mounted in the vertical, flange-down attitude was attained by utilizing the additional blind end gas port as follows:

  1/ With the bladder in a collapsed condition, apply nitrogen gas at 25 psig regulated pressure, simultaneously, to the bottom gas port and propellant outlet port.

  2/ Allow the bladder to expand by controlled venting through the top gas port, maintaining a maximum differential pressure of 3 psi between the inlet gas pressure and the pressure at the top gas port.

- Elimination of liquids from the gas side of the bladder, by purging, did not prove to be practical within reasonable purge times and at pressures, temperatures and gas flow rates which would not be detrimental to the bladder. This is especially true of propellants with relatively low vapor pressure, such as MMH.

- After completion of 31 expulsions the bladder was completely functional and showed no measureable indication of degradation.

(2) Tank Assembly Testing

(a) Summary

Tank assembly testing was initiated in May 1966. Three tank assemblies, two oxidizer and one fuel, were scheduled for dry cycles, propellant exposure, dynamic testing, life cycles with propellant, and shell cycle and burst test. However, testing was cancelled on the second oxidizer tank.

(i) Oxidizer Tank X1

The tank successfully completed five dry cycles, 22 days propellant exposure, vibration and shock at specification level, vibration at reduced level, 19 expulsion cycles, and shell cycle and burst tests. Bladder failure occurred after propellant expulsion cycle 19.

(ii) Fuel Tank X3

The tank successfully completed 10 dry cycles, 33 days propellant exposure, and vibration and shock at specification level in the X and Y-axes. Excessive bladder leakage was indicated after vibration and shock in the Y-axis. The bladder was replaced and the tank (redesignated as X3A) was again put into test.

(iii) Fuel Tank X3A

The tank successfully completed five dry cycles, 25 days propellant exposure, and two expulsion cycles. Testing was suspended at this point by direction of Douglas.

Under the NASw-1317 program, an additional development unit, fuel tank X4, was assembled and tested in accordance with the qualification test requirements which included vibration with actual propellants. This tank was subjected to five dry bladder cycles, three-day propellant exposure and vibration and shock testing with actual propellant. After vibration and shock testing in two axes (X and Y) excessive bladder leakage occurred, indicating bladder failure.

(b) Test Results

(i) Dry Cycle Testing

Prior to any tests with propellants, a series of dry cycles was performed on each tank assembly. Prior to each dry expulsion the bladder was positioned in accordance with Douglas GSE procedures. Bladder leak checks were performed prior to the first dry cycle and after every five cycles.

(ii) Propellant Exposure Testing

(aa) Oxidizer Tank X1

This unit was scheduled for minimum mission requirements; therefore, the propellant exposure time for this unit was to be 10 days at varying temperature and pressure conditions. However, to reduce the time interval between completion of propellant exposure and initiation of dynamic testing, the propellant exposure time was extended to 22 days. At the completion of the 22-day propellant exposure, the temperature was reduced to ambient and an expulsion test was successfully completed.

(ab) Fuel Tank X3

The unit was originally scheduled for 30 days propellant exposure under varying temperature and pressure conditions. The time was extended to 34 days to gain supplemental information on gas formation on the liquid side of the bladder which occurred in a Model 8400 tank during checkout of an APS system at Douglas Aircraft. As part of the study, Douglas requested that fuel tank X3 be X-rayed for evidence of gas inside the bladder. The initial X-ray of tank X3 was taken after 27 days of exposure and after temperature and pressure cycling, and showed gas formation above the liquid inside the bladder. The gas was vented and, when analyzed, revealed 400 parts helium to one part nitrogen with a volume of approximately 3000 scc. However, since the exposure test was well under way prior to investigation for bubbles, little analytical information could be gained. After the gas was removed from inside the bladder, the temperature was lowered to +40°F for most of the remaining portion of the exposure test. X-rays were taken at approximately 8-hour intervals and no gas or vapor bubble was detected during this period of 7 days. A propellant expulsion performed at the end of this test appeared to be normal in every respect. During the exposure test the gas side was monitored for evidence of MMH permeation across the bladder and samples were taken at varying intervals. Analysis indicated that there was no MMH on the gas side of the bladder; however, evidence of methane and ammonia, which are products of dissociation of MMH, were obtained in amounts varying with time. Detailed results of this analysis are contained in Bell Report No. 8400-928012.

(ac) Fuel Tank X3A

In order to obtain more valid data for better understanding of the extent of the propellant permeation problem, an additional evaluation was made during the propellant exposure test on tank X3A under more rigidly controlled conditions. In this test propellant exposure was conducted in two parts using helium and then nitrogen as the pressurant. The test performed with helium had a duration of 22 days. Gas samplings on the liquid side were taken periodically for monitoring the possible formation of a gas bubble. X-rays were also taken to confirm the results of the sampling. A 56cc gas bubble was bled from the tank approximately 14 hours after loading. After the initial bubble was bled off, 7 days elapsed before another bubble became evident,at which time 192 cc of gas were bled from the tank. Analysis of propellant samples at this time indicated that the propellant was saturated with helium. It should be noted that during this 7-day period the tank was pressurized twice to 200 psig for 8-hour intervals and vented back to 35 psig, and the temperature was raised from 70°F to 105°F for approximately 3 days during this period. The gas bubble was bled from the tank at 75°F and at 35 psig. Three additional bubbles were bled from the tank, at one-week intervals, which were 53, 25, and 58 cc respectively. Again, it should be noted that pressures and temperatures were varied throughout the test period which most certainly drove gas in and out of solution and made impossible any assessment of the rate of bubble formation under any specific set of conditions.

In the second test, using nitrogen as the pressurizing gas, X-rays and samples were taken and evidence of a small gas bubble was observed in each gas sample. This test was conducted to determine whether the use of nitrogen would either eliminate the bubble or extend the time for the bubble to materialize. It was hypothesized, that since nitrogen has a molecule larger than helium it would not penetrate the bladder as fast as helium. Also, nitrogen is much more soluble in MMH than is helium. The results of the two tests, however, indicate that the use of nitrogen represents no significant improvement in this problem. A detailed report of the gas formation testing of fuel tank X3A is presented in Bell Report No. 8400-928010.

(iii) Vibration and Shock Testing

Vibration and shock testing were accomplished using vehicle mounting brackets supplied by Douglas. Freon-TF (mixed with 3 to 5% methanol by volume) was used for oxidizer tank X1 and inhibited water was used in fuel tank X3 as simulated propellants. Fuel tank X4 was tested with MMH. Original requirements included 12 minutes of random vibration in each axis. However, during the vibration fixture/mounting bracket evaluation extremely high temperatures were experienced at the top (retainer) end of the tank during X-axis vibration, due to a "pumping" action of the tank retainer boss within the Teflon bushing of the vehicle upper mounting bracket. This condition was alleviated, somewhat, by addition of an O-ring at the retainer end of the tank to limit the pumping motion and by lubricating the Teflon bushing with DuPont PR-240 AC grease. As an additional measure to help minimize temperature rise, the random vibration duration requirement was reduced from 12 to 5 minutes.

(aa) Oxidizer Tank X1

The tank completed vibration and shock testing in all three axes. During the five-minute random vibration in the first axis (X-axis), the temperature at the top end of the tank reached 180°F. To eliminate the temperature problem, the random endurance requirement was reduced to three minutes. After completion of this test the tank was subjected to an additional random vibration test at reduced levels in all 3 axes. For this test the tank was loaded to 10% of rated propellant volume and, while vibrating, pulsed expulsions at the rate of 2 per minute were conducted. A total of nine 60-millisecond pulses were made in each axis, expelling an average of 7.5 cc per pulse. The duration of each of these tests was approximately 5 minutes.

(ab) Fuel Tank X3

The tank was vibrated and shocked in the X-and Y-axes only. Bladder failure was encountered while servicing the tank in preparation for testing in the Z-axis. Laboratory investigation disclosed that the failure was of a fatigue type, resulting from repetitive rolling of buckled folds during vibration.

The results of the laboratory investigation were confirmed by a review of the dynamic test history of the tank. The test data indicated random vibration was conducted throughout the vibration frequency range of 0 to 2000 cps, instead of 20-2000 cps as required by the specification. Since the bladder/liquid system has a fundamental frequency in the range of 0-20 cps, this contributed to bladder fatigue. It was also determined that a great amount of test time was used to achieve equalization prior to random vibration testing in each axis. As a result, an excessive number of vibration cycles were accumulated on the bladder.

The dynamic test procedures were subsequently revised to omit any dynamic testing in the range of 0-20 cps for random vibration. Furthermore, attempts were to be made to minimize equalization time at frequencies under 100 cps, to reduce the accumulation of excessive vibration cycles on the bladder. The details of the failure investigation are contained in Bell Report No. 8400-928008. At this time, laboratory tests conducted on the NASw-1317 Program verified that the cycle life of Teflon bladder material in the rolling-of-buckled-fold mechanism is affected by the fluid medium which the bladder contains. For this reason, no further dynamic testing with simulated propellants was performed on this program.

(ac) Fuel Tank X4

The tank was vibration and shock tested with MMH and, like fuel tank X3, bladder failure was indicated after testing in the X-and Y-axes. Investigation disclosed that this failure was nearly identical to that of fuel tank X3. A review of test records from both tanks showed that a significant amount of vibration time had been accumulated on both bladders during random equalization runs, which were necessary to set up the equipment to provide vibration inputs within specified limits during the random vibration test. Thus, the bladders were subjected to a considerable amount of overtest in each axis prior to actual vibration at specification test levels.

While investigating the reason fo.: the difficulty in equalization during setup for random testing,it was found that the inside diameter of the Teflon bushing, which supported the top of the tank, was enlarging during the test. It was felt that this cumulative clearance between the tank retainer boss and the bushing resulted in some unrestricted motion at the top of the tank, thereby making the task of equalizing more difficult. It should be noted that when installed new the Teflon bushings have a slight interference fit on the retainer boss of the tank. A corrective action was implemented at this time to monitor bushing-to-boss clearance during any subsequent testing and to replace the top mounting bracket whenever the clearance became excessive.

(iv) Expulsion Cycle Testing

(aa) Oxidizer Tank X1

Expulsion testing was performed at ambient, high, and low temperatures at nominal tank pressures and flow rates. One ambient temperature expulsicn (80 to 90°F) had been previously accomplished after propellant exposure test. Seven ambient temperature (80 to 90°F), 1 low temperature (35 to 40°F), 1 high temperature (100 to 110°F), 8 ambient temperature and 1 low temperature expulsions were accomplished,in that order, during expulsion cycle testing. Expulsion efficiency on all tests exceeded the minimum specification requirement of 97.5% at a ΔP of 2 psi.

Following the last low temperature expulsion, which was the ninteenth propellant expulsion, excessive leakage was encountered during bladder expansion, indicating bladder failure. Investigation of this failure disclosed that, after the low temperature test, bladder expansion was accomplished before the bladder had been allowed to warm up. This resulted in a brittle rupture of the bladder at the apex of a double buckled fold. The test procedures for low temperature expulsions, which were based on Apollo and LM, required that the tank assembly be stabilized at room temperature prior to bladder expansion. However, the criterion for determining tank temperature was based on a thermocouple attached to the tank flange and was not truly indicative of bladder temperature. As a result of this failure the procedure was adjusted to more closely control tank assembly heating prior to bladder expansion.

In support of this failure investigation, laboratory tests were conducted with bladder material specimens soaked in water at temperatures of +35°F, +40°F, and +45°F. At each of these temperatures a buckled double fold was manually induced in ten specimens. The fold was then rolled out (re-expanded) at the same temperature. All specimens at +35°F and +40°F failed when re-expanded while none of the specimens at +45°F failed. Additional specimens were folded while immersed in water at +35°F and then unrolled after warming to room temperature. These specimens did not experience failure even when this process was repeated ten times on each specimen.

(ab) Fuel Tank X3

Only one expulsion was accomplished at ambient temperature following the propellant exposure. No additional expulsion cycles were accomplished on the fuel tank because of the forementioned failure during dynamic testing. Expulsion efficiency exceeded the requirement of 97.5% at a tank assembly ΔP of 2 psi.

(ac) Fuel Tank X3A

Expulsion cycling was restricted to two cycles following the propellant exposure tests. The first expulsion was performed with helium as the pressurant and the second with nitrogen. All further testing was suspended by direction from Douglas.

(v) Shell Pressure Cycle and Burst Test

(aa) Oxidizer Tank X1

After the bladder was removed, the tank shell was hydrostatically pressure cycled from 0 to 275 psig 500 times. This was followed by a burst test. No yielding occurred at design proof pressure of 413 psig. The actual burst pressure was 740 psig, with rupture occurring in the cylindrical section approximately 9 inches from the closed-end weld. Actual burst pressure compared favorably with theoretical burst for this unit of 760 psig,which indicates that glass bead peening of the shell interior had no measurable adverse effects upon burst pressure. No pressure cycle or burst testing was accomplished on fuel tanks during the development test program.

The tank assembly development testing is reported in detail in Bell Report No. 8400-928011.

(3) Conclusions

The oxidizer tank successfully completed all testing up to the final propellant expulsion cycle. It was concluded that the final expulsion cycle could have been successfully accomplished if bladder failure had not occurred due to a servicing error. The primary reason for failure of the fuel tank to complete dynamic testing was the excessive number of bladder fatigue cycles experienced during vibration test, principally during setup and equalization of the test equipment prior to random vibration test in each axis.

Also, although propellant expulsion cycle life was not demonstrated on the fuel tank, a reasonable confidence level did exist in the capability of the tank assembly to meet the expulsion requirements. This confidence stemmed from successful testing on the LM tank program which used hardware of similar configuration.

b. Qualification Testing

(1) Summary

Qualification testing of one fuel and one oxidizer tank assembly was started in October 1966, and completed in January 1967. Both tank assemblies successfully completed all tests which consisted of 5 dry cycles on the bladder using nitrogen gas as the pressurant, propellant exposure and dynamic tests, expulsion cycle testing, shell pressure cycle with bladder installed, and shell burst testing.

The dry cycles, propellant exposure, and dynamic tests were accomplished under NASA Contract NASw-1317. The propellant exposure and dynamic tests, using actual propellants, were conducted at Wyle Laboratory's Norco California Test Site. All other tests were performed at Bell's test facilities.

(2) Test Results

(a) Dry Cycle Tests

Prior to each of the 5 dry expulsions, the bladder was positioned in accordance with Douglas GSE positioning procedures. Bladder leak checks, using nitrogen and then helium, were performed prior to the first cycle and after the last cycle.

(b) Propellant Exposure and Dynamic Tests

Both fuel tank P1 and oxidizer tank P2 were filled to rated propellant load and subjected to a nominal four-day propellant exposure test. This test, which was programmed to simulate prelaunch conditions, was conducted with the tank assembly mounted in the vibration fixture on the shaker head just prior to X-axis vibration. At the end of exposure testing the test units were not drained, but were vented 12 to 48 hours prior to initiation of vibration test.

During propellant exposure test of the oxidizer tank an attempt was made to study gas formation inside the bladder. No valid data were obtained due to limitations in the sampling equipment and anomalous results from the outside laboratory which was contracted to perform the analyses.

The sequence of testing for fuel tank P1 consisted of sinusoidal and random vibration testing followed by shock testing in each of the three orthogonal axes (X, Y and Z) with the tank assembly pressurized to 200 psig. After dynamic testing in the final (Z) axis,an expulsion of 85% of the propellant load was made at 200 psig tank pressure and at approximately rated flow rate. This incomplete expulsion was specified to compensate for limitations in the expulsion equipment at Wyle's Norco facility which did not have accurate flow measuring capability, or the capability of automatically terminating flow in time to avoid impressing full tank pressure differential across the bladder.

The number of vibration cycles imposed on the bladder of fuel tank P1 during random equalization runs were reduced somewhat from those of X3 and X4 during the development phase,due to some extent to extremely close monitoring of the vibration control console settings and adjustment. The upper mounting bracket was replaced between the second and third axes due to increased clearance between the tank retainer boss and Teflon bushing. However, a great deal of difficulty was experienced in random equalization on this tank. In view of these difficulties, several meetings took place among personnel from NASA, Douglas, and Bell. At these meetings it was agreed to refurbish the vibration fixture and to modify the test procedures and specification requirements. The fixture refurbishment consisted of the following:

- Repair of several visual cracks in the fixture welds
- Dye penetrant check of all fixture weldments for evidence of other cracks.
- Installation of additional threaded bolt inserts for attaching the lateral axes adaptor to the fixture
- Refacing of the surface areas around the holes in the lateral axes adaptor

Procedure and specification requirement modifications consisted of the following:

- Inputs below 100 cps were to be attenuated as much as possible during initial random equalization attempts
- Representatives from NASA, Bell, and Douglas Aircraft Company were to give total on-the-spot concurrence as to the acceptability of some peaking and notching outside the ±3db level during full level portion of random equalization prior to the random endurance test.

- The three minute random vibration run at endurance level acceleration spectral density was to include the time of the approved equalization burst run at full level.
- The sequence of testing for all three axes was changed to be random vibration, sinusoidal, vibration and shock in order to minimize bracket bushing wear prior to random equalization.
- The sinusoidal sweep rate for all axes was to be changed to 3 octaves/minute,from 1 octave/minute
- The Douglas supplied 1B52219-1 Bracket was replaceable at the end of any axis of vibration with Douglas concurrence.

Dynamic testing of oxidizer tank P2 was completed successfully. The tank was subjected to the same test sequence as fuel tank P1 with the above modifications in procedures and requirements.

(c) Expulsion Cycle Testing

The fuel and oxidizer tanks were each subjected to a series of twenty propellant expulsion cycles. The first expulsion on each tank was performed at the end of Z-axis vibration and shock at Wyle Laboratory. Expulsions No. 2 through 20 were completed at Bell test facilities. The twenty cycles consisted of 16 ambient temperature (65-75°F), two high temperature (100 to 110°F), and two low temperature (35 to 45°F). Both tank assemblies completed all expulsion tests successfully. The required minimum expulsion efficiency of 97.5% at a ΔP of 2 psi was exceeded on all tests except the first expulsion on each tank at Wyle Laboratory which was manually terminated at 85% expulsion.

(d) Shell Pressure Cycle and Burst Test

Each test unit, with bladder installed, was hydrostatically pressure cycled from 0 to 275 psig for 500 cycles with a pressure rise time of 1.25± 0.25 seconds. The bladder was then removed and the shell and diffuser assembly subjected to a hydrostatic proof and burst test. There was no permanent set at design proof pressure of 413 psig. Burst pressures were 789 psig for the fuel tank and 779 psig for the oxidizer tank with failure initiation in the center of the cylindrical section in each case.

(3) Test Report

The detailed qualification test results are contained in Bell Report No. 8400-928014.

D. MODEL 8330 - LUNAR ORBITER POSITIVE EXPULSION TANKAGE PROGRAM

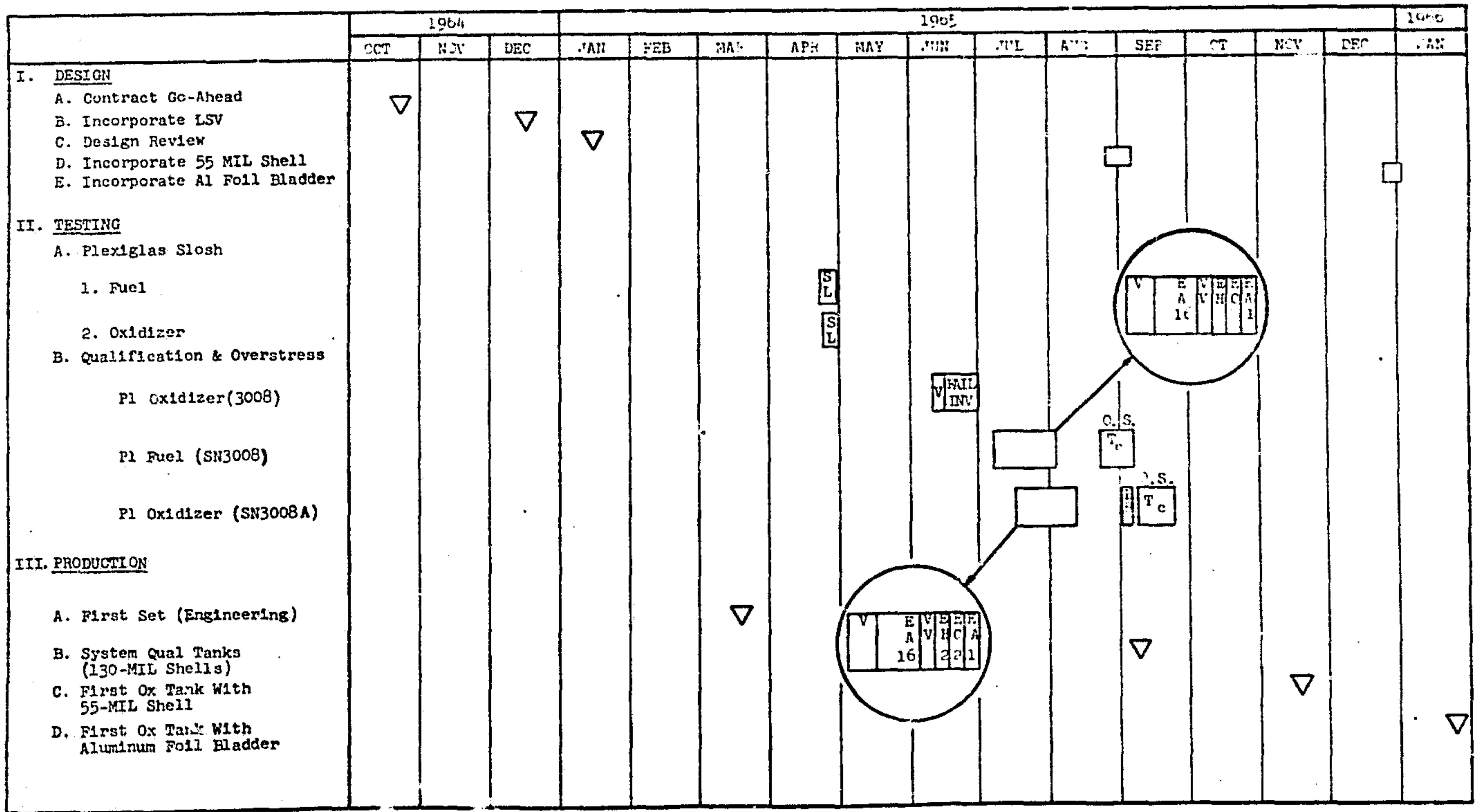
In March of 1964, Boeing and Bell started discussions concerning positive expulsion propellant tanks for the Lunar Orbiter Velocity Control System with particular attention given to use of the command module tank configuration. In June 1964, Boeing procured two fuel and two oxidizer command module tanks from Bell for engineering evaluation. These tank assemblies were transferred to Boeing with North American Aviation's concurrence and were replaced under the Boeing procurement.

At this time, Bell was engaged in a program to develop an in-house tank shell fabrication capability. This included development of processes and procedures, design and fabrication of tooling, and qualification of the weld for the command module fuel and oxidizer tank shells. In February of 1965, shells fabricated by Bell were fatigue cycled and burst tested and shortly thereafter a qualification report was submitted to North American and to Boeing for approval. In the absence of timely approval or disapproval action by North American, Boeing concurred that fabrication of tank shells by Bell would be satisfactory for the Lunar Orbiter Program.

In October 1964, Bell received a full go-ahead on the Lunar Orbiter positive expulsion propellant tank program. The resulting program is shown graphically in Figure III-9. The original program consisted of the procurement, fabrication, assembly and acceptance test of 21 fuel and 21 oxidizer tank assemblies of the existing command module configuration. This configuration consisted of titanium shells, aluminum diffusers, and oversize single-ply bladders. The tanks were to be assembled and acceptance tested in accordance with the command module procedures. Tank shells were to be fabricated by Bell and the design requirements of the Boeing specification were to be considered as design objectives to provide the latitude necessary for the commonality concept in the event of design changes on the command module program.

In December 1964, the liquid bleed tube and net size bladder were incorporated into the Command Module/Lunar Orbiter tank design. Progress on the program continued until February of 1965,at which time Boeing chose not to adopt the command module oxidizer bladder change which incorporated 9-mil ends. Because of this change,and because North American had not taken action to approve Bell as a source for tank shells, Boeing directed that Lunar Orbiter top assembly part numbers be established to provide configuration control.

FIGURE III-9 MODEL 8330 LUNAR ORBITER PROGRAM HISTORY



V - Vibration
SL - Slosh
EA - Expulsion, Ambient
VV - Volume Verification
EH - Expulsion, Hot
EC - Expulsion, Cold
OS - Overstress
TC - Temperature Cycling
BL - Bladder Replacement

In February 1965, Boeing made two major changes to the program. The first of these was to incorporate a vibration requirement into the acceptance test of each deliverable unit. The second change was the establishment of a test program designed to augment the command module qualification program in the area peculiar to the Lunar Orbiter mission. (The original intent of NASA/Langley and Boeing had been to conduct such unique testing at the vehicle qualification level.) A qualification test program consisting of expulsion and vibration testing plus overstress testing consisting of thermal cycling, were incorporated into the program. It was required that these tests be performed on one fuel and one oxidizer tank. The test program started in April 1965 with slosh testing of one fuel and one oxidizer bladder in plexiglass tanks for the purpose of establishing slosh modes for vibration. Qualification testing was started in June 1965 and a bladder failure occurred in the oxidizer tank during vibration testing. As a result of this failure, vibration levels were revised by Boeing and the qualification program was restarted in July 1965. Qualification and overstress testing of the fuel and oxidizer tanks was successfully completed in September 1965. The test results are contained in Bell Report 8330-928004.

The first set of tank assemblies was delivered to Boeing in March 1965. After the fifth set had been delivered a hold was placed upon deliveries pending completion of qualification testing. During this hold period (July 1965), the Apollo program experienced stress corrosion failure in the oxidizer tank shells and the stress corrosion investigation was started. Because of very tight schedule requirements, Boeing was unable to wait for the investigation to be completed. The immediate way to solve the problem was to keep the stress below the danger point by thickening the oxidizer tank walls. A set of boiler plate tanks with 130 mil thick walls was fabricated and delivered in support of Boeing spacecraft testing. Meanwhile, the flight configuration oxidizer tank design was changed to incorporate a 55 mil tank shell. While this redesign was being accomplished on the oxidizer assemblies, the remaining fuel assemblies were completed and delivered to Boeing. In November 1965, the first oxidizer assemblies incorporating the 55 mil shells were delivered and 12 assemblies of this configuration were placed into production.

In January 1966, the oxidizer bladder was redesigned to include aluminum foil to act as a permeation barrier and prevent saturation of the N_2O_4 with nitrogen gas during the mission. Twelve assemblies of this configuration were completed and shipped, to Boeing, consisting of both new assemblies off the production line and assemblies returned from Boeing for refurbishment. The laminate construction of this bladder consists of 2 mil TFE/1 mil FEP/1/4 mil Al foil/3 mil FEP. In May 1966, the last tank was shipped to Boeing, completing the project.

The Model 8330 tank assemblies were subsequently used on Lunar Orbiter Missions I through V. The fuel and oxidizer tanks performed flawlessly throughout the five missions in accomplishing a total of 29 velocity maneuvers. During Mission I and the 339 day mission II, the propellants were allowed to flow until completely expelled, demonstrating expulsion efficiencies of better than 99%. A summary of the propulsion system operation during each mission is presented in Table III-2.

TABLE III-2

LUNAR ORBITER PROPULSION SYSTEM FLIGHT HISTORY

MISSION	EVENT	LAUNCH DATE OR DAYS FROM LAUNCH	ENGINE BURN TIME (SEC)	PROPELLANT EXPELLED (LB)
I	Launch	August 10, 1966		276.8**
	Midcourse	2	32.1	11.7
	Injection	4	578.7	212.2
	Orbit Transfer	11	22.4	8.2
	Orbit Transfer	15	3.0	1.2
	Impact Maneuver	80	94.4	40.1*
II	Launch	Nov. 6, 1966		277.0**
	Midcourse	2	18.1	6.6
	Injection	4	611.6	222.4
	Orbit Transfer	9	17.4	6.4
	Inclination Change	32	61.3	22.0
	Orbit Phasing	159	3.2	1.2
	Orbit Transfer	233	4.6	1.7
	Impact Maneuver	339	35.5	15.5*
III	Launch	Feb. 5, 1967		275.9**
	Midcourse	2	4.3	1.6
	Injection	4	542.5	195.9
	Orbit Transfer	8	33.7	12.2
	Orbit Phasing	67	3.5	1.3
	Orbit Transfer	163	8.9	3.4
	Orbit Transfer	207	127.1	44.6
	Impact Maneuver	247	32.0	11.3
IV	Launch	May 4, 1967		276.3**
	Midcourse	1	52.7	19.1
	Injection	4	501.7	181.7
	Lower Perilune	32	117.9	43.2
	Lower Apolune	35	42.7	15.6
V	Launch	August 1, 1967		276.2**
	Midcourse	2	26.1	9.5
	Injection	4	498.1	181.8
	Orbit Transfer	6	10.8	4.0
	Orbit Transfer	8	152.9	55.6
	Orbit Phasing	70	40.8	15.0
	Impact Maneuver	182	16.4	6.3

*Engine valves opened until propellants were exhausted
** Propellants loaded at launch.

E. ASSOCIATED PROGRAM HISTORIES

1. BELL MODEL 8460 - DESIGN CRITERIA AND QUALITY CONTROL STUDIES FOR TEFLON EXPULSION BLADDERS

This program was performed between late 1965 and the early part of 1967 for the NASA Manned Spacecraft Center under Contract NASw-1317.

In the early development phases of the propellant expulsion tanks for the Apollo program, a variety of bladder failures occurred which could not be readily understood. Therefore, this program was established to determine bladder design and quality criteria for evaluating the expulsion units of the Apollo-type tankage. Another purpose of this study was to provide timely support to the main-stream Apollo tankage programs with respect to bladder performance and to recommend modifications in design, operational and test procedures, or quality control, if these would benefit function or reliability.

An extensive review was made of bladder failures which occurred in the development phases of the mainstream tankage programs. This review, in conjunction with prior analytical and experimental studies performed at Bell, identified and defined the failure modes of the Teflon bladders and hence aided in refinement of design criteria.

The following two failure modes were established as the principal limiting factors in bladder service life:

- Biaxial tension forces develop in the hemispherical sections of the bladder during filling and pressurization if the bladder is incorrectly positioned. These forces greatly extend local strains at fold and buckle sites to produce ruptures. In vertical tanks this condition is initiated by accumulation of bladder material at the bottom of the tank during expulsion. If the frictional resistance between the tank wall and the bladder is great enough, determined by the length of the tank, the bladder is unable to lift completely during pressurization and remains displaced. This causes large strains in the upper hemi-sphere as pressure forces this part of the bladder to the tank wall. In horizontal tanks, the bladder tends to twist, thereby folding the material and reducing the available bladder volume. If the twist angle is large enough, severe biaxial tension strains develop in the bladder hemispherical ends upon complete filling of the tank. These failure mechanisms had been identified on the mainstream tank programs and the findings of this program aided in their clarification and helped to quantitively establish critical stress loadings which result in this type of failure.

- Rolling of double fold motion is generated in the bladder during vibration, slosh, and fill and expulsion operations. This motion gradually fatigues the material at the site of the buckled fold. Since a large number of motion cycles are needed to develop a rupture, this failure mode is associated primarily with vibration.

Mechanical tests were performed which defined selected properties of Teflon-TFE, FEP and TFE/FEP laminates. The effects of temperature and fluid environment were particularly large in such tests as uniaxial tension and rolling of double folds. In the case of the latter tests, which were used to simulate the rolling of buckled fold failure mode in bladders, a large range of variation was found in the number of cycles to failure in given environments. The number of tests performed in this study did not permit statistical definition of the cycle life of the material in the various simulated and actual propellants, but the tests did indicate comparative performances. Material cycle life was high in Freon-TF, methylene chloride, and MMH; moderate durability was measured in N_2O_4; and a relatively low cycle life was measured in 50-50 fuel blend. Temperature had a pronounced effect on mechanical properties of the Teflon.

These findings resulted in the qualification, vibration and shock testing of the SATURN APS tankage with actual propellant in lieu of the alternate fluids originally specified. These tests, which were performed as part of this program, are described in Section III,C of this report.

The processing methods and controls used to fabricate Teflon bladders were reviewed and experimentation was conducted to determine the potential for increasing the service life of the material and obtaining improved uniformity. These studies indicated that quenching techniques can strongly influence the properties of Teflon-TFE. Rapid quenching after sintering decreased the crystallinity, which resulted in an order of magnitude increase in the rolling of double fold life of TFE in 50-50 fuel blend. The influence of other parameters such as spraying rates, sintering times, etc. were not investigated but it is possible that these may also have an appreciable effect on material constancy and performance in bladders.

This program is reported in detail in Bell Report No. 8460-933012.

2. APOLLO TITANIUM - N_2O_4 STRESS CORROSION INVESTIGATION

The effort on this program was performed by Bell under subcontract with the Space and Information Systems Division of North American Aviation under NASA Prime Contract NAS9-150. The original titanium - N_2O_4 stress corrosion problem occurred at Bell; however, it soon became apparent that this was an industry wide problem of serious magnitude. Bell was designated as the focal point for the investigation; however, the NASA agencies, Apollo prime contractors, and many other organizations materially participated in the program.

The failure of SMO Unit Y-2 (Shell SN 5) after 23 days exposure to N_2O_4 (MIL-P-26539) during the Model 8271 development program was the starting point of the stress corrosion program. A detailed investigation of this failure identified the cause as stress corrosion. The original theory was that the stress corrosion may have been caused by unintentional sensitizing of the titanium during fabrication of the tank shell.

A comprehensive series of tests was initiated on ten titanium 6A1-4V tank shells to determine if the initial failure was a random occurrence or if the titanium alloy and Specification N_2O_4 were incompatible. The ten tank shells were selected based on their fabrication dates so as to have shells fabricated both before and after failed shell SN 5. The selected tank shells were assembled without bladders and loaded with Specification N_2O_4. Eight of the ten tank shells failed in test and the remaining two shells were burst tested. One of the burst test shells ruptured above the design pressure but the second shell failed below the design burst pressure. Evidence of stress corrosion was found on the inside surface of all ten tank shells. The only differences noted among the shells were crack intensity and crack density.

The ten-tank storage program proved that a stress corrosion problem existed between the titanium 6A1-4V alloy and Specification N_2O_4 and established that the problem was not random in nature. The stress corrosion investigation at Bell was then directed to resolve the problem by determining the cause of the stress corrosion and/or to determine a practical solution to the problem.

Allison Division had successfully stored Specification N_2O_4 in titanium 6A1-4V alloy tanks. Compared with the failure at Bell (both using Specification N_2O_4), the Allison success indicated that the Bell fabrication process or handling used for the Apollo RCS tank shells was introducing some factor which resulted in stress corrosion. Chlorides were a prime suspect based on previous stress corrosion test results.

Bell Aerosystems Company representatives toured various manufacturers' facilities to discuss the stress corrosion problem, and several metallurgical meetings were held at Bell. Knowledgeable persons from government agencies, aerospace companies, and universities were present for discussions on the problem.

As the result of this work, several tank shells were treated and exposed to Specification N_2O_4. The titanium surface treatments evaluated included air furnace oxidation, anodizing, and Teflon coating. Only the Teflon-coated tank shells showed any promise of meeting the 30-day storage requirements of the Apollo RCS propellant tanks. The test effort also showed that galvanic action (aluminum/titanium couple), annealing, cleaning method, and heat treatment were not significant factors in the stress corrosion problem. Temperature was found to be an accelerating factor while stress level was found to be a lesser factor.

During this time, NASA/Langley Research Center undertook the evaluation of inducing residual compressive stress as a solution to the stress-corrosion problem. NASA/LRC demonstrated that glass bead peening of the tank shell internal surface was a candidate as a solution to the stress corrosion problem.

At the same time that these tank tests were being accomplished, Bell developed and utilized stressed titanium specimen testing which was representative of the tank shell failures. The stressed specimen testing evaluated titanium surface treatments and N_2O_4 additives. The results of the stressed titanium specimens in Specification N_2O_4 demonstrated that titanium surface treatments did not eliminate stress corrosion (with the possible exception of Teflon coating) and that fabrication processes were not significantly contributing to the cause of stress corrosion. The stress corrosion of commercially pure annealed titanium as well as material from an Allison tank demonstrated that the problem was not the result of the fabrication used on the Apollo RCS tank shells. Further evidence that the stress failure of Apollo RCS tank shells was not the result of fabrication processes was demonstrated by the failure of one Surveyor and two Gemini titanium tank shells at Bell after exposure to Specification N_2O_4 at Apollo stress and temperature requirements.

The possibility of determining an inhibitor which could be added to Specification N_2O_4 to stop the stress corrosion, was considered as a possible solution to the stress corrosion problem. The stressed titanium specimen testing program included the evaluation of various additives; i.e., water, nitric acid, nitrosyl chloride, silver nitrate, etc. Only limited testing of these additives was accomplished at the time NO was found to be an effective inhibitor, but some of these additives (e.g., nitric acid) also appeared to be effective in inhibiting stress corrosion.

The results of the test specimen and tank stress corrosion testing indicated that the stress corrosion attack of titanium was not the result of fabrication since commercially pure titanium was found to be as susceptible to attack as the 6Al-4V alloy. The fact that Bell Aerosystems-fabricated tanks did not fail in test at North American also indicated that processing was not the source of the stress corrosion problem. Greater attention was then given to the chemistry of Specification N_2O_4. Once again Bell made use of available information by contacting and meeting with knowledgeable persons from government agencies, aerospace companies, and universities.

The chemical approach considered not only the chemistry of Specification N_2O_4, but also the probable reactions occurring at the titanium surface. The principal goal of the chemistry approach remained the same as that held previously, which was to determine the cause and/or solution for the stress corrosion problem.

The presence of nitric oxide in Specification N_2O_4 was found to be a solution to the stress corrosion problem during the stressed specimen test program. A comparison of this finding with a check of the N_2O_4 used with the tanks that did not fail in test at North American Aviation/S&ID and with tanks that did fail in test at Wyle Laboratories, NASA/MSC, and Aerojet substantiated this fact.

A series of tank shell tests was initiated at Bell to confirm that the presence of nitric oxide did indeed effectively inhibit stress corrosion of the tank shells. Three tank shells were tested and all exceeded the 30-day requirement at temperatures in excess of the required 105°F.

To verify that the stress corrosion solution was not random in nature and that the presence of the Teflon bladder did not negate the solution, two bare wall tank shells and two tank assemblies with bladders were tested with N_2O_4 containing 0.030% NO. The test results verified that the presence of nitric oxide did inhibit the stress corrosion failure of the titanium 6Al-4V tank shells and that the presence of the bladder had no discernible effect.

This investigation culminated in the issuance of NASA Specification MSCPPD-2 for procurement of N_2O_4 with controlled NO content.

The detailed results of the tests and investigations are contained in the four volumes of Bell Report No. 8271-928060.

3. BELL MODEL 2312 - SERVICE MODULE ALUMINUM TANK SHELL

This program was performed from October 1965 to December 1966 under Contract NAS9-5330 for the NASA Manned Spacecraft Center. The effort included the design, fabrication and test of one tank shell plus production of four deliverable units.

The existing titanium command and service module RCS propellant tank shells are designed to have the lightest possible structural weight. As a result, these thin wall shells are not capable of withstanding complete internal evacuation because of low buckling strength. This program was established to develop and fabricate an aluminum alloy tank shell which was capable of withstanding complete internal evacuation and designed to be functionally and dimensionally interchangeable with the service module RCS oxidizer tank shell.

The design and fabrication of one test and four deliverable tank shells was completed. Detailed weight estimates showed that the 6061T6 aluminum alloy oxidizer tank shell would be approximately 1.40 lb heavier than the present 6A1-4V titanium oxidizer tank shell.

The structural adequacy of the aluminum shell was demonstrated by successful completion of an internal proof pressure test to 331 psig and an external proof pressure test to 22 psid. The burst test requirement of 372 psig was surpassed and the pressure was increased to 422 psig before failure occurred in the form of a small leak in the circumferential weld. The leak was sealed and an ultimate external pressure test was completed which successfully demonstrated that the external pressure requirement could be met. After passing the specified external pressure of 30 psid, the test was continued until an abrupt change in the slope of volumetric expansion versus external pressure occurred at 41 psid.

The design, fabrication, delivery, and test requirements of this program were successfully completed and a detailed account is presented in Bell Report No. D2312-950001.

4. BELL MODEL 8508 - NITROGEN TETROXIDE EXPOSURE TEST PROGRAM

This test program was performed in the early part of 1967, under Contract NAS9-6660, for the NASA Manned Spacecraft Center. The testing was designed to provide added confidence in the ability of the Apollo grade (green) N_2O_4 to prevent stress corrosion.

Two service module tank assemblies and a command module tank without a bladder were subjected to N_2O_4 storage conditions which simulated the more demanding aspects of a space mission in terms of potential problems with stress corrosion.

The two service module tank assemblies (R1 and R2) were loaded to approximately 50 percent capacity with N_2O_4 and pressurized with helium on the gas side. This condition allowed the N_2O_4 to permeate through the bladder and contact the highly stressed (90 ksi) areas of the titanium shells. These two units were stored for 30 days to determine if a large ullage volume (increased bladder permeation) would increase the possibility of stress corrosion of titanium at the specified test conditions. The presence of gas bubble formation within the bladders during the storage period was also studied. Tank R1 was tested at constant elevated temperature and pressure, and tank R2 at constant elevated pressure and variable temperature.

Test Unit R1 successfully completed 30 days of N_2O_4 exposure testing at a constant pressure of 288 ±28 psig and a constant temperature of 100 ±5°F. A gas bubble formed during testing as verified by the post-test X-rays.

Test Unit R2 successfully completed 30 days of N_2O_4 exposure testing at a constant pressure of 302 ±28 psig and a variable temperature of 60 ±5°F to 100 ±5°F. A gas bubble formed during testing.

The command module tank without a bladder (Unit R3) was half loaded and subjected to a 30-day storage and slosh test series to evaluate the possible effects of stress corrosion on titanium from propellant in motion at elevated temperature and pressure. It was considered possible at this time that the success of the Apollo grade N_2O_4 under static exposure conditions was due to protective films formed on the titanium and that these films could be washed off by liquid motion during a mission.

Test Unit R3 successfully completed 30 days of N_2O_4 exposure testing at a constant pressure of 388 ±38 psig and temperature of 100 ±5°F. The test unit was sloshed each normal working day at a rate of one cycle per second at 2 inches double amplitude (which is equivalent to 0.1 g loading). The test unit completed approximately 536,124 cycles or 1,072,128 sloshes during the test period.

The three units were subjected to hydrostatic burst test to determine the effects of prolonged nitrogen tetroxide exposure on titanium tank shells. The burst pressures were as follows:

	Minimum Required (psig)	Actual (psig)
Unit R1 (SMF)	372	650
Unit R2 (SMF)	372	603
Unit R3 (CMF)	540	1074

Metallurgical, chemical, and X-ray evaluations were made before, during, and after the testing to provide data in the following areas:

- Tank material before and after test
- Bladder position before and after test
- Propellant quality during loading and draining
- Analysis of permeants into gas
- Analysis of gas into propellant
- Bubble formation

Metallurgical analyses of the tank material showed no evidence of stress corrosion cracking or degradation of tank shell integrity. This was verified by the burst test results.

X-rays showed movement of the bladders to the wall confirming the results of chemical analyses and models describing bubble formation and growth. The bubble, which formed during test prior to propellant saturation, was rich in helium; however, quantitative analysis of the phenomenon was rendered impossible because of changes in the temperature and pressure during the test.

The only deterioration noted in propellant quality were decreases in NO (nitric oxide) content and an increase in dissolved helium content. The NO decay appeared to be a matter of sampling procedure and the results were within the limits of experimental accuracy.

Permeation of the bladder by propellant was obvious within four hours.

The detailed test and analytical results, contained in Bell Report No. 8508-928002, showed no problem on exposure of highly stressed (90 ksi) areas of titanium 6 Al-4V tanks to permeants from Apollo grade N_2O_4 (Specification NASA-MSC-PPD-2A),within the limits of the test program.

5. BELL FUNDED R & D BLADDER MATERIAL PROGRAMS

a. Purpose

Apollo tankage studies and experience showed that the Teflon expulsion bladders have limitations in cycle life during expulsion and vibration, and resistance to permeation of pressurizing gas and propellant. Increased cycle life is desirable to increase the reliability above that presently attainable with Teflon bladders; permeability is desirable to prevent the pressurizing gas from accumulating in the propellant side of the bladder. To achieve these features, Bell has been investigating improved and new materials and methods such as elastomers, improved Teflon, and permeation barriers.

b. Elastomeric Bladder Material

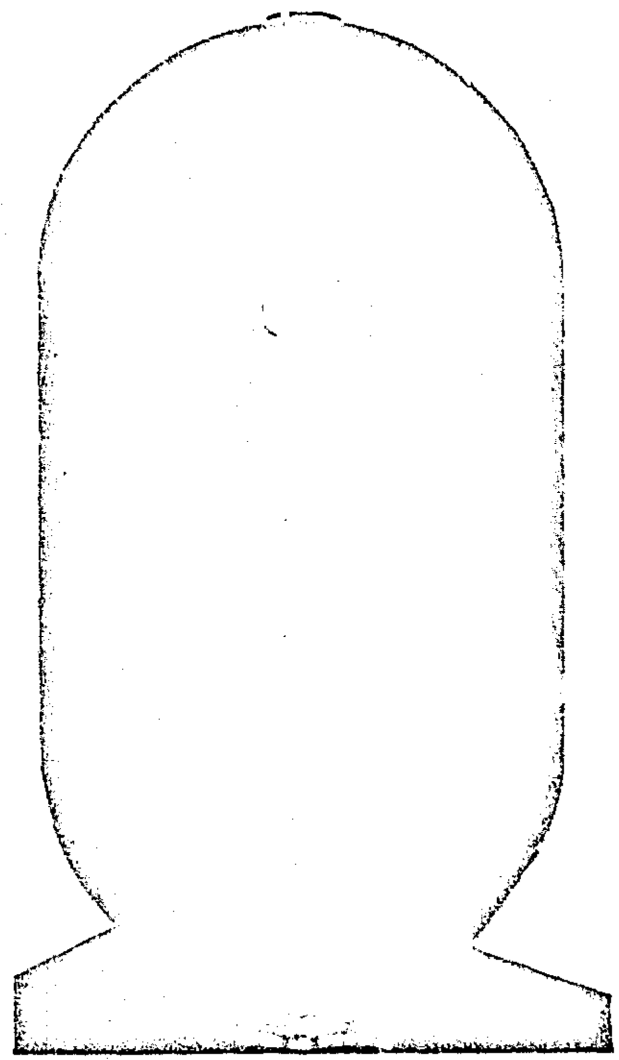
(1) Oxidizer Application

The need for an elastomeric material compatible with N_2O_4 and possessing the desired elastic strain capability for repeated folding and buckling, without material damage, resulted in intensive effort by Bell in development of nitroso rubber expulsion bladders. The development of optimum techniques and methods for compounding nitroso rubber for bladder application has been actively pursued since early 1966. This effort resulted in the fabrication of a 10-inch diameter spherical bladder by a spray dispersion technique. A photograph of the bladder is shown in Figure III-10.

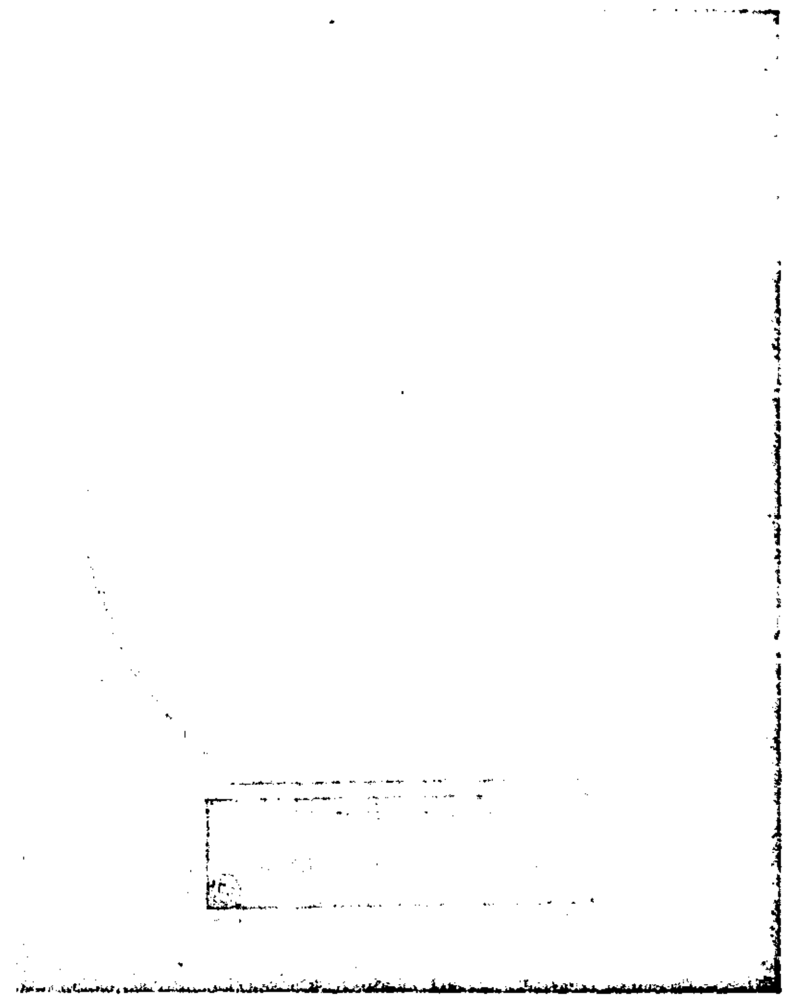
Although nitroso rubber yields the desired improvements in bladder cycle life, this material is highly permeable to N_2O_4, helium, and nitrogen. Thus, the effort in 1967 concentrated on the development of a nitroso rubber bladder having a metallic foil permeation barrier. The major problem encountered was insufficient adherence of the rubber bladder to the metallic foil. Although some degree of success was obtained, the adhesion problem was not completely solved and efforts were shifted in 1968 to the incorporation of a proprietory plastic permeation barrier (Vapolock) into the nitroso rubber. This barrier reduces the permeation rate of a nitroso rubber bladder, 10 fold. The 1968 program will culminate in the fabrication of several Nitroso/Vapolock 10-inch diameter bladders which will be subjected to storage and expulsion tests.

(2) Fuel Application

For several years elastromeric materials have been investigated for fuel bladder use. These materials include ethylene propylene copolymer (EPR), ethylene propylene terpolymer (EPT), and butyl rubbers. These elastomers were subjected to specimen compatibility tests in MMH and 50/50 fuel blend for



Redundant Film Bladder



Nitroso Rubber Bladder

FIGURE III-10 TYPES OF EXPULSION BLADDER COMPOSITIONS

1-day, 7-day, 28-day, and 63-day storage periods at 80°F. EPR and butyl rubbers were found to be equally satisfactory for use with fuel, except that EPR exhibited greater durability. EPT was found to be unsatisfactory. In addition to the specimen compatibility tests, 10-inch diameter spherical and hemispherical bladders were stored for 30 days in MMH at 80°F, with no adverse effects.

Based on the results of the material studies, work was continued in 1967 and 1968 in the development of EPR and butyl rubber bladders. Although some degree of success was achieved in incorporating a metallic barrier into these bladders, the metallic barrier was dropped in 1968 so that the full effort could be concentrated on the incorporation of Vapolock into the EPR bladders. To date, considerable success has been achieved and the 1968 program will culminate in the fabrication of several 10-inch diameter, hemispherical EPR/Vapolock bladders which will be used for propellant storage tests.

c. Improved Teflon Bladder Material

In an attempt to develop a Teflon bladder with an improved cycle life, redundant and codispersion films were investigated. The redundant film bladder, shown in Figure III-10, consisted of three-plies of TFE with graphite laminated between each ply. This provided for ply-to-ply slippage which, in turn, minimized sharp creases and folds. In addition, the use of graphite was intended to keep the plys intact and thus prevent the entrapment of gas between the plys. Results of specimen tests showed that the redundant film construction exhibited a cycle life three times greater than the 6 mil TFE/FEP laminate. The redundant film helium permeation rate was equivalent to that of the laminate, but the N_2O_4 permeation rate was five times greater. Because of the promising cycle life, an SMF size redundant film bladder was fabricated and successfully subjected to vibration, 14-day N_2O_4 storage, and 10-expulsion cycles. However, extensive delamination and entrapment of gas occurred between the plys. For this reason, the redundant film bladder concept has been discarded.

The codispersion material is a mixture of TFE and FEP sprayed and sintered together into a uniform film. Specimen testing of 3%, 5%, and 10% FEP loadings indicated that the only codispersion film that offered an advantage in fatigue cycle life, over the TFE/FEP laminate, was a codispersion film with a FEP loading of 5%. However, the helium permeation rate of the 5% FEP codispersion film was four times greater than that of the laminate, which made it undesirable as an alternate film construction.

d. Permeation Barrier Development

(1) Metallic

A technique for fabricating a Teflon bladder with a metallic permeation barrier was successfully employed during the Lunar Orbiter program. Company-sponsored research has established a +35°F expulsion cycle capability and a 17 expulsion cycle life capability at ambient temperature for the Teflon/metallic foil bladder. At the completion of 17 cycles with N_2O_4, the bladder leakage rate was 12 cc/15 minute of helium compared to 80-90 cc/15 minute of helium for an equivalent size TFE/FEP laminate bladder. Prior to cycling, the leakage rate was zero. The metallic permeation barrier effort is continuing with emphasis on the development of methods for depositing uniform nonporous metallic coatings on nonmetallic substrates.

(2) Nonmetallic

Experimental work in 1966 and 1967 resulted in the development of a proprietary plastic permeation barrier (Vapolock) which reduces the permeation rate of a Teflon bladder by a factor of 7 to 10. Development of optimum bladder/barrier fabrication techniques is continuing. The 1968 program will yield both nitroso and EPR bladders with the Vapolock permeation barrier.

SECTION IV

MANUFACTURING AND QUALITY CONTROL

At the inception of the Apollo tankage programs the plan for the command and service modules was to have all fabrication within existing capabilities for manufacturing and inspection techniques because of the extremely tight schedule limitations. In reality, the state-of-the-art had to be advanced in many areas because of the stringent specification requirements and continuous refinements to lower the weight and increase the reliability of the tankage.

The existing technology base at this time was the experience with the Model 8101 Agena SPS tankage, which was a low production item. The Apollo type tankage necessitated advancements in the following areas:

High Production Rates - The need for high production on a tight schedule basis required fabrication and inspection of components on an assembly line basis with elimination of all "model-shop" type operations. Special tooling, fixturing, and inspection equipment were devised to give repeatable results.

Titanium Shells - These were the thinnest-walled titanium pressure vessels known at that time. Fabrication, inspection, and handling techniques were refined to assure compliance with the stringent requirements and to minimize scrappage due to rejection or damage.

Teflon Bladders - Although the fabrication process was essentially the same as for the Agena SPS bladders, the Apollo tankage requirements led to much tighter fabrication control and many advancements in inspection techniques.

Diffuser Assemblies - The difficult welding and critical drilling operations required for this assembly, coupled with numerous design changes, resulted in continuous refinement of the fabrication and inspection operations. The use of the stainless steel-to-aluminum bimetallic joint added to the complexity of this component.

Assembly and Acceptance Test - Although Bell had produced other tankages with equally stringent cleanliness requirements, the production rate demands and configuration of the Apollo tankage necessitated major refinements in facilities, personnel training and specialized test and handling equipment.

Identification and Traceability - The stringent identification and traceability requirements required implementation of special procedures and controls to maintain a closed loop system on all aspects of the raw material, special processing, fabrication and testing.

The major fabrication problems were solved during the early stages of the command and service module programs. The solutions and advanced techniques were automatically implemented on the programs which followed.

A. Tank Shell Fabrication

The tank shells for the CM, SM, LM, SIVB, and LO tank assemblies are fabricated from titanium alloy. The 12.5 inch inside diameter is common to all configurations and the shells vary in length from 17.3 inches for the CMF to 38.8 inches for the LM oxidizer. The CM/LO tanks are made by joining two elongated hemispheres while the other configurations require the addition of a cylindrical section. The tank shells for the command and service module and the lunar module tankage were subcontracted to Sargent-Airite. During the early stages of these programs Bell developed an in-house capability for fabricating titanium shells and later manufactured all of the shells for the Lunar Orbiter and Saturn IVB.

1. Processing Sequence

Material for the Apollo shells is forged from billets of titanium 6A1-4V alloy which are rolled from ingots produced by double consumable electrode vacuum arc melting. Each billet is cut into forging multiples which are serialized and recorded as to location in the billet.

The forging multiples are heated to the required forging temperature with the temperatures and reduction ratio controlled to produce as fine a grain size as is practical. Specification limits are for equiaxed primary alpha particles to be predominantly ASTM No. 8, or finer, as determined by ASTM Practice E112. The hemispherical components are forged in a closed die and the cylindrical components are made from upset and pierced discs which are extruded and rolled to cylindrical shape.

The forgings are completely inspected and partially machined to remove excess material in heavy sections prior to solution heat treatment and stress relieving. Solution heat treatment is made at 1725°F for two hours followed by a water quench. Stress relieving is at 950°F for a maximum of two hours followed by air cooling to room temperature. The cylinders are rough machined before stress relief while the hemispheres are rough machined after stress relief.

The outside and inside diameters of the hemispheres are rough machined and then the inside diameters finish machined. The closed end hemisphere is finish turned on the outside diameter. The open end hemisphere is profile milled on a vertical mill and the flange contour is formed on a Hydrotel. The boss is then formed on a vertical mill, the outside diameter is finished on a tracer lathe, and the flange and gas port are drilled and tapped. The cylinders are rough bored and turned and finish bored and turned on an engine lathe with tracer. The O.D. of the cylinder has a profiled weld lip for fusion welding to an identical lip on the hemispheres. Measurements are made after each machining operation and recorded in terms of amount of metal removed per surface to assure that all surface contamination is removed during machining.

The parts are cleaned in preparation for welding to remove all surface defects and sub-surface conditions of oxidation, scale, grease, etc. The cleaning process includes submersion of components in a hot alkaline bath, scrubbing, rinsing with water, submerging in a 35-45% nitric acid bath, spray washing, and forced-air drying.

All welding is done on parts in the solution treated and stress relieved condition. The cleaned components are assembled in the weld chamber and the weld areas are inspected to assure the absence of all foreign particles. For the welding operation an expandable backup fixture is used and locating pins are employed to control alignment. Parts are first tack welded in a vacuum-purged inert atmosphere welding chamber. Tack welds are made in 16 places, approximately equally spaced using a skip sequence. After tacking, the assembly is TIG fusion welded with one continuous single pass. This procedure is performed so that craters or other stopping defects are prevented.

After welding, the assembly is cooled under inert gas flow before removal from the welding chamber. The backup fixture is removed and the shell assembly is inspected. Inspection criteria for the weldment include mismatch, penetration, porosity, bead width, buildup, and drop-through. The tank shells are then alkaline cleaned, water rinsed, placed in 35-45% nitric acid bath, spray washed, and dried.

The shells are aged at 1050°F for 2 hours to meet required properties. Forgings for each shell are selected on the basis of similar heat treat response and chemical composition, so final mechanical properties will be uniform. After aging, the shells are removed from the furnace and allowed to cool to room temperature.

A final surface treatment is performed to remove sufficient metal after aging to assure freedom from contamination resulting from aging. The process used is a modified 'Ti-Brite' process which is an electrolytic method of removing high temperature oxides and scale from titanium and its alloys.

After 'Ti-Briting', the shell flanges and bosses are finish machined to insure accuracy of mounting dimensions. The nut plates on the flange are riveted in place after final shell inspection.

Final inspection and acceptance test is made to insure conformance to the Bell Drawing requirements. It consists of the following:

Dimensional Check
Hydrostatic Test at proof pressure
Helium Leak Test
Radiographic Inspection
Fluorescent Penetrant Inspection

2. Fabrication Problems

It is believed that the Apollo tankage became the thinnest walled titanium pressure vessels ever fabricated on a production basis. Because of the relatively thin walls, imperfections such as nicks, dents, or scratches could not be tolerated. Special motivation training of personnel, and the use of special handling fixtures and containers, resulted in negligible loss or damage to tank shells or details despite the many handling operations required for fabrication and inspection.

Numerous problems were encountered during fabrication of the early command and service module shells. The following is a summary of fabrication problems which occurred during the early manufacturing period:

a. Wall Thickness

Maintaining the wall thickness of .022 +.000 -.005 inches resulted in a 25% rejection rate. The following corrective action was implemented which shortly reduced the rejection rate to 10% and eventually to less than 1% over the long-term:

Use of vacuum chucks to hold the thin wall hemispherical sections firmly in place during final machining operations.

Use of contour templates to assist the machine operator during intermediate setups.

Stress relieving of the parts after partial machining.

Thickness measurement of the hemispherical sections in 12 quadrants spaced one inch apart.

Use of special deep-throat micrometers as an added check of the Vidigage readings.

b. Mismatch

Mismatch between the mating surfaces of the closed-end and open-end hemispherical sections (and between the cylindrical section on service module tanks) resulted in a rejection rate of 33% on the first 30 shells fabricated. The following action reduced this rate to 15% within 3 months and eventually to less than 2%:

Use of internal and external backup rings to align and hold the hemispherical sections firmly in place during welding.

Implementation of special tools and techniques for proper measurement of mismatch after welding.

Use of special sizing rings to selectively measure and mate cylindrical and hemispherical sections.

c. Porosity

Rejection due to porosity, pore spacing, and inclusions amounted to more than 50% during the early stages of shell fabrication. The following were some of the pertinent factors that resulted in lowering the rejection rate to less than 5%:

Development and careful monitoring of special cleaning processes.

Establishment of a time limit between final cleaning and welding.

Preparation of the weld area by draw filing to remove oxide scale.

Special wrapping and packing procedures to maintain cleanliness level of parts awaiting welding.

Training and certification programs for welders and inspection personnel.

Establishment of rigid control of chemical composition and cleanliness level of cleaning solutions.

d. Weld Bead Height, Width and Drop Through

Failure to meet these requirements caused rejection rates in excess of 20% at the beginning of the shell fabrication process. They were reduced to less than 2% as a result of the following actions:

Refinement of the step-by-step weld procedure to tightly control voltage setting, current control, rotational speed of weld, and vacuum chamber environment.

Weld operator training and certification.

Tack welding at specific intervals prior to full single pass weld.

B. Bladder Fabrication

The bladders used on the Apollo type positive expulsion tanks are fabricated from laminated Teflon TFE and FEP, by Dilectrix Corporation, using the spray dispersion technique. The fabrication of the bladder is a rather unique process which consists of spraying and curing thin layers of Teflon onto an aluminum mandrel. After the layers are built up to the required thickness, the mandrel is removed chemically.

1. Processing Sequence

The soft aluminum mandrel is made up of two or three spun sections. These sections are welded together and the entire exterior is polished to a 32 RMS finish. The outside diameter, overall length and concentricity are precisely controlled since these dimensions control the size and shape of the completed bladder. The length and diameter of the mandrel are slightly oversize to compensate for bladder shrinkage encountered when the mandrel is dissolved.

The bladders are fabricated on an assembly line in a level C clean room environment. A maximum of three bladders may be processed simultaneously as an individual lot. A cylindrical mandrel is processed with each lot to produce a test "pipe" which is representative of the bladders in that lot. The test pipe is subjected to destructive testing to determine the physical properties of the lot of bladders which it represents.

The Teflon TFE is sprayed on the mandrel while it is rotating in a horizontal chuck. Each spray application deposits a layer approximately .00025 inches thick and, after each application, the Teflon is allowed to partially air dry. The Teflon-coated mandrel is then cured at approximately 670°F in a temperature controlled oven. After drying, it is removed from the oven and allowed to cool in preparation for the next application of spray dispersion. Approximately fifteen spray applications of the TFE laminate are used to attain the required 3 mil minimum thickness. Thickness measurements are made with a Dermitron and Permascope at specific intervals to assure completion to drawing thickness requirements. The spray cycle of applying the 3 mil of FEP is the same as for the TFE except that the oven-temperature for curing the FEP is approximately 560°F. When the required 6 mil thickness is attained, the mandrel is removed.

Dissolving the coated mandrel is accomplished using a caustic solution and sodium gluconate. Proper amounts of these chemicals are measured out into charges which are added to the dissolving tank slowly to limit the temperature of the dissolving solution. After the mandrel is completely dissolved, the bladder is removed and cleaned. After cleaning, the bladder is inflated to approximately 1/2 psig and dimensional measurements are checked with contour templates. At this point in the manufacturing cycle, the undersized bladders for LM and SIVB are subjected to an additional sizing operation. Upon completion of the sizing operation and corresponding dimensional inspection, the bladder flange is trimmed and the flange mounting holes are punched. The bladder is then placed in a special holding fixture, pressurized to 1 psig, and the entire surface is visually checked for leakage - first by water immersion and then by helium mass spectrometer leak tests.

After the leak test the bladder is visually inspected in accordance with a detailed procedure with the help of visual aid samples of actual bladder film which define acceptance and rejection criteria.

In preparation for shipment the bladder is placed into a polyethylene bag and a clean commercial rubber balloon, of sufficient size to support the entire bladder, is inflated inside the bladder to prevent collapse during shipment and storage.

2. Fabrication Problems

At the beginning of the Apollo program, bladders were of the 3 mil 3-ply construction. Several fabrication areas at Dilectrix had to be improved to maintain the level of cleanliness required on the Apollo program. Since the three individual plies had to be assembled and bonded at the butt and flange ends with no particulate matter between the plies, special laminar flow work areas were employed. The bonding or heat sealing of the ends required the designing of special dies and sealing techniques, as well as destructive testing of material samples, to assure repeatable and adequate bonding of all bladders. To assure strict compliance with the critical dimensional requirements of the bladder, special fit tanks were used and each bladder was tank fitted at the supplier's facility as part of final inspection. In the summer of 1964, the bladder design was changed to 6 mil single-ply and an entire new set of process and quality control procedures was generated.

Changes in various contractors' resident quality representatives caused a fairly high rejection rate of bladders in the final assembly stage because the acceptability of a bladder was based, in part, on visual inspection and consequently on judgment which varied between individuals. This lack of firm, positive acceptance and rejection criteria resulted in Bell and Dilectrix collaborating on preparation of a set of visual aid samples of acceptance and rejection criteria. A special procedure, Report No. 8339-928006, was written and a special illumination inspection fixture was developed to establish the same set of standards of inspection both at Bell and at Dilectrix. Implementation of these procedures resulted in a marked decrease in bladder rejection.

In the latter part of 1965, during the measurement of test pipe thickness at Bell, it was discovered that several test pipe specimens were slightly under the minimum 6 mil thickness requirement. Micrometer measurements were made on various bladders associated with the thin test pipes and the bladders were also found to be slightly under the drawing thickness requirements. An investigation disclosed that bladders that were exhibiting these defects were fabricated during a peak production period which required maximum loading of the electric curing ovens. Tests showed that this peak loading resulted in a decrease in line voltage, at the Dermitron thickness tester, to 95 volts which was too low for the voltage regulator tubes in the tester. Corrective action for this condition consisted of changeover in the power distributing circuits at Dilectrix and, in addition, providing a Sola-transformer in the source line of the Dermitron measuring device. In addition, more stringent controls were imposed on equipment calibration and servicing.

Detailed measurements of approximately 150 bladders and test pipes during this investigation revealed that the standard 14 measuring points on the bladder profile 180° apart were not sufficient to assure compliance to drawing requirements. As a result, a semi-automatic process was developed which utilized an eddy current measuring device called the Permascope. This device was more accurate than the Dermitron and the thickness reading was indicated directly on the meter in mils.

The final concept resulted in utilizing the Permascope coupled with a strip chart recorder which gave an instantaneous and permanent recording of Teflon thickness the entire length of the bladder in any plane desired. Implementation of this new measuring technique on production bladders was initiated in July 1966 and is currently in use.

Concurrently, a program was conducted by Bell and Dilectrix to refine and optimize all the process specifications, inspections, and test procedures utilized in the fabrication of all Apollo type Teflon bladders for Bell. This effort culminated in the creation of Dilectrix Quality Document No. 166 which controls all phases of bladder fabrication, inspection and test.

This document became effective in April 1966 and there have been no subsequent problems requiring corrective action by Bell.

C. Diffuser Assembly Fabrication

The basic configuration of the diffuser assembly fostered complications in welding and inspection techniques. There are a total of five welds plus one bi-metallic brazing operation required for this assembly. In addition, drilling and deburring of the many holes (approximately 1000 for the SMO Configuration) required complete inspection to prevent surface discrepancies which could result in bladder damage.

The original diffuser tube assembly used on the CM and SM positive expulsion tanks was fabricated from 347 stainless steel. Problems were encountered in welding thin wall stainless steel tubing to the heavy section of the flange and retainer because of shrinking and distortion which made it extremely difficult to meet the critical concentricity requirements. While these problems were being resolved, weight restrictions imposed by North American necessitated a change to a lighter weight diffuser assembly. The redesigned diffuser assembly used 6061 aluminum alloy in lieu of stainless steel.

1. Bimetallic Joints

Since the interface to the spacecraft plumbing required stainless steel connections, the use of an aluminum/stainless steel bimetallic joint was required. Bi-Braze Corporation was selected to produce the bimetallic joint; however, this firm had no prior exposure to aerospace quality and reliability requirements. As a result Bell personnel were required to develop refined processes and controls. Despite the successful implementation of the controls, rather extensive destructive and nondestructive testing was required to assure reliability of this joint. The following tests and controls were implemented:

- Control of the aluminum alloy dip solution and furnace temperature.
- Proper sizing of the outlet tube O.D. diameter to the inside diameter of mating aluminum alloy.
- Lot control and corresponding destructive testing of 1/3 of each lot of 24 pieces.

Toward the latter part of 1964, the bimetallic joint configuration was changed to coincide with the introduction of the bleed tube to the diffuser assembly. The aluminum portion of the joint was machined as an integral part of the flange assembly and new tooling and holding fixtures were required at Bi-Braze. The first lots processed were rejected because of an excessive amount of braze spatter that was firmly attached to the stainless steel tubing in the area of the bleed tube weld. This problem was solved by modification of the holding fixtures and introduction of a special graphite masking operation which confined the bonding of the aluminum braze solution to the actual joint area. The new joint configuration increased the cost of the bimetallic assembly since it required precision machining and drilling operations. The destructive sampling plan at Bi-Braze and Bell consumed 33% of the hardware. Early in 1966, after careful review and analysis of the results of destructive tests performed on a total of over 500 bimetallic joints, during which no failures were detected, the number of destructive test pieces was reduced by 50 percent.

2. Flange-to-Cone Weld

Welding of the bimetallic zone assembly to the flange required rather heavy weld geometry in very close proximity to the stainless steel-aluminum joint. The first approach was to attempt to weld the joint with a single-pass weld; however the amount of current required for full penetration produced excessive heat and annealed the flange to the point that it would not respond to subsequent aging processes to attain the required T6 condition (45,000 psi tensile strength). In addition, full penetration at the root of the weld could not be achieved. As a result, the first lot of flange assemblies processed was rejected. An attempt to remedy this condition employed special large mass heat sinks to eliminate the annealing caused by welding plus packing the cavity of the cone adjacent to the bimetallic joint with weld foam heat absorber. The welding technique was changed to a two-pass weld which effectively solved the full root penetration problem. However, the weld foam heat absorber migrated to the joint and a high rejection rate due to porosity was encountered. Improvements in welding techniques and weld holding fixtures with a critically positioned heat sink ultimately resulted in eliminating the use of weld foam and satisfactorily reduced the rejection rate on this assembly.

3. Drilling

Due to a design change for improving expulsion efficiency, the cone of the flange assembly was modified by drilling .032 inch diameter holes similar to those in the diffuser tube. Drilling of these holes at an angle through the heavy wall portion near the base of the flange resulted in a high rate of rejection due to numerous broken drills. This high rejection rate was due to the configuration of the assembly and the inordinately large L/D of the drilled holes caused by the thickness of the material. This problem was solved by enlarging the cone holes to .040 inch and liquid honing the holes to chamfer the edges to protect the bladder.

The change to the .040 inch hole greatly reduced the number of broken drills; however, broken drills still occur occasionally. The rather lengthy chemical milling required to remove the small portions of broken drills imbedded in the thick portion of the flange cone resulted in some scrappage of flanges thus processed, because of corrosive pitting. A method of removing broken drills using electro-chemical drilling was developed and is currently being used successfully.

4. Tube-to-Cone Weld

The initial problem with this weld was in developing the proper techniques and fixtures to weld thin wall aluminum tubing to the heavy machined sections of the flange cone. Development of this process required a considerable amount of time and the first 16 production units had to be scrapped. Separate detailed procedures were specified for each joint configuration to control voltage, current, rotational speeds, type of filler wire, cleaning requirements, time limitations between the cleaning and welding operations, argon purge flow rates, and specific acceptance and rejection criteria. During the latter part of 1964, a total of 120 diffusers were fabricated of which 100 were acceptable as fabricated while the remaining 20 required rework.

At the end of 1964, a failure was experienced on a diffuser tube during vibration. The failure consisted of a break through the diffuser tube approximately 3/8-inch from the tube to cone weld at the center of the first set of .032 diameter holes. As a result of the failure investigation, this row of holes was deleted and certain acceptance criteria for the weld were changed. Prior to the failure, the requirement for this weldment was that the weld should not penetrate through the interior of the tube wall. After the failure, this requirement was changed to full penetration with reaming out of excessive drop through as required. An additional change required that the tensile strength, approximately 3/8-inch from the center of the weld, be 32,000 psi minimum. As a result, the heat affected zone adjacent to the weld had to be held to a minimum so as not to anneal the tube and prevent response to the subsequent aging after welding. Various heat sink and chill bars were tried but proved unsuccessful. Unsuccessful attempts were made to automate the weld so that faster rotational speeds could be used to minimize the heat affected zone. The problem was finally resolved by using Weld-Dun foam as a heat barrier. This process required packing the area adjacent to the weld with Weld-Dun foam just prior to welding and removing it immediately after and cleaning the material off. This method was used for approximately 18 months during which time 240 diffuser tube assemblies were fabricated. The rework rate, due to porosity, increased sharply with ultimate scrappage of approximately 7% due to unsuccessful rework.

The source of the porosity in the weld was traced to moisture emitted from the foam heat barrier. Special tests were conducted and meticulous fixturing and preweld preparation finally produced welds that were porosity free; however, the elaborate preparation proved to be too costly and time consuming. During this time, new welding equipment and advancements in welding technology resulted in a capability of making this weld without the use of foam while still meeting the tensile strength requirements adjacent to the weld. The rework rate due to porosity has decreased to approximately 1/8 of its former rate since the Weld Dun foam heat barrier was eliminated. There are still some rejections due to incomplete penetration, but the overall rejection rate has decreased to approximately 1/4 the original rate. The possibility of automating this weld is being explored to further increase the yield while still meeting all requirements for this particular weld.

5. Bleed Tube Weld

The configuration of this critical weld necessitates manual welding. Extreme care is required as the point of the actual weld through the stainless steel diffuser outlet tube is in the center of a 90° bend radius where the tubing is thinned because of metal stretchout, and also because of a dimpling process which is necessary to precisely locate the bleed tube. A bleed tube weld failure experienced early in qualification testing during vibration was resolved with the addition of a special buttering operation to reinforce the thinned out area by applying a weld bead around the periphery of the dimpled hole. This improvement rendered the weld joint structurally sound. This weld geometry has produced a high rate of rejection which necessitates a large amount of rework and repair. Several bleed tube welds that successfully passed acceptance test criteria at the diffuser assembly level were subsequently rejected during final tank assembly level acceptance tests. To correct this condition, Engineering drawings and detail test procedures were amended to subject the weldment to more stringent test requirements at the detail level, utilizing higher pressures and substituting helium gas and mass spectrometer leak detectors in lieu of nitrogen gas and water immersion tests.

Continuing efforts to reduce the rework rate of this weldment have yielded some improvements. In May of 1967, weld specifications were changed to provide a more positive argon gas purge during welding, and the welding electrode tip was changed to a smaller size, which provides greater accessibility to the weld.

D. Assembly and Acceptance Test

The stringent cleanliness requirements for the positive expulsion tankage dictate that the entire assembly and test operation be performed in a clean room environment.

When the Apollo program started, Bell was using clean room operations for other programs such as the Gemini/Agena secondary propulsion system. The facilities consisted of clean room trailers which were operating at the current state-of-the-art in clean room facilities and were adequate to meet the requirements for the Apollo tankage. Special ultrasonic equipment capable of cleaning the tank shell and associated hardware was designed and built since off-the-shelf commercial equipment of sufficient size was not available. Thorough cleaning of the bladder presented a unique problem because of the bladder shape, flexibility, and susceptability to handling damage. Special equipment was designed and fabricated which provided for spraying the bladder while it was held in an expanded but unstressed condition during the cleaning cycle.

This equipment and the related procedures proved adequate for cleaning the hardware to the required contamination levels; however some problems had to be resolved during the processing of early preproduction tank assemblies. The most notable of these were as follows:

1. The bladder, once assembled to the diffuser tube, had to remain exposed to the clean room environment for as much as three days in order to comply with the 24-hour retorque requirements for the sealing surfaces of the bladder. Due to the dielectric properties of Teflon, the bladder develops a high electrostatic charge which attracts whatever impurities are in the air near it. This tends to compromise the previous cleaning accomplished in the detail stage.

   To solve the problem several approaches were tried, such as the use of static brushes to neutralize the electrostatic charge and nylon bags to protect the bladder. The most effective approach, which was adopted as standard practice, was the use of a 5% methanol/Freon TF mixture to wipe off the surface of the bladder within one hour of installation into the tank shell. The alcohol neutralized the elastrostatic charge and permitted the particles to be freely wiped off. A final black light inspection was used to assure that the bladder was free from particulate matter just prior to installation into the tank shell.

2. Bladder folding for insertion into the tank shell is a very critical operation from the standpoint of causing bladder damage due to multiple folds and creases. It was necessary to develop an optimum folding technique which could be rigidly controlled to minimize the human variable which is inherent in such an operation. Various techniques were investigated, including a hot folding technique in which the folding was accomplished with the hardware stabilized at 105°F.

   An optimum folding technique was established in 1964 and a detailed step-by-step folding procedure, supplemented with a sequence of photographic visual aids, was formalized. This method, which is still in use on all the Apollo tank configurations, consists of a set pattern of folding in which the bladder is first folded from the retainer end toward the center section and then from the flange end toward the center section. This leaves all surplus bladder material in the center of the bladder which is the area of least stress concentration in the tank assembly. This operation is performed at room temperature.

A training program was established and assembly personnel were thoroughly trained to perform this critical operation.

In 1964,Bell's expanding involvement in spaceflight hardware including positive expulsion tankage with rigid cleanliness requirements necessitated an expansion of clean room facilities. As a result, a new facility was designed and constructed embodying the latest concepts in clean room technology. This new facility located in the main manufacturing building with easy access to the various support departments, became operational in September 1965. A primary consideration in the design and construction of this facility was special provisions and equipment for assembling and testing positive expulsion tanks for the Apollo program.

The new laminar flow clean room, which provides 2485 square feet of working space, provides an environment of Class 100 to 100,000 (Federal Standard 209) depending on the location within the room. This facility includes automatic equipment for obtaining particle count and non-volatile residue as well as continuous recording of temperature, humidity and positive pressure.

In addition to the laminar flow clean room, several laminar flow tunnels of Class 10,000 (Federal Standard 209) are utilized in the Functional Test department to provide contamination-free testing of tanks.

In the latter part of 1966, due to recent findings which indicated stress corrosion problems involving methanol and titanium, Bell was directed to stop using methanol on all positive expulsion tanks. The only place alcohol was used at that time in the tank programs was on the final wipe-off of the bladder assembly in order to remove the electrostatic charge on the bladder. From that point on, trichlorotrifluoroethane has been the only liquid allowed to perform this process. The resultant patented problem of electrostatic attraction of airborne particles by the bladder has been solved by use of an air ionizing unit installed in the clean room in the final assembly area.

During the course of the Apollo tankage programs, constant optimization of clean room procedures, equipment and techniques has been pursued with great emphasis on those applicable to Apollo and associated tankages. As a result, all assembly and test operations on the Command and Service Module tanks including the final envelope check and packaging for shipment are performed in the laminar flow clean room. Other tanks, such as the Lunar Module and Saturn, which require additional testing after assembly, are tested in a laminar flow tunnel of Class 10,000 (Federal Standard 209) prior to shipment.

On the Apollo tank programs all critical assembly operations, such as bladder folding and insertion, are performed in the Class 100 area of the laminar flow room.

SECTION V

RELIABILITY

A. PROGRAM CONTROL

Reliability programs were conducted during the Apollo tankage contracts from the initial design stages through qualification testing and hardware delivery. Effort was focused principally on achieving the specified reliability goal by implementation of tasks which would insure early recognition of problem areas and initiation of appropriate corrective actions. Although no specific reliability requirements were prescribed for the Lunar Orbiter program, testing was monitored for impact on the other programs.

Following a review of the preliminary design, a Functional Block Diagram (See Figure V-1) was prepared. Although the Apollo Spacecraft contains six slightly different tank configurations, the basic design is typical of each. Therefore, for convenience of discussion of the reliability aspects of Apollo type tanks, the Lunar Module tankage illustrated in Figure V-2 is used as a representative example and for correlation with remarks in the text, tables, and figures in this section. Pertinent differences are noted where applicable.

B. FAILURE MODE & EFFECTS ANALYSES

Failure Mode and Effects Analyses of the type shown in Table V-1 were conducted on the Apollo tank components indicated in Figures V-2 and V-3, to identify the "Assumed Failure", "Possible Cause", and the "Operational Effect" on the "Function" (equipment and system) and on the "Mission". Shown under "Function" are also those problems which may be encountered during various test phases. In this instance, the failure is isolated to the "Mission Lowest Affected Level". In all cases, except one, where a mission effect exists at all, the lowest affected level of assembly is the total tank assembly. The one exception is a crack in the diffuser tube (without a separation of parts).

"Failure Detection", as enumerated, relates to prelaunch conditions only. The assigned "Failure Class" is the worst case mission effect whenever a degree of failure is involved (e. g., leakage rates). Failure classes are:

I. Equipment inoperative or degraded to the extent that it will no longer perform its intended function.

II. Equipment slightly degraded (will function but possibly not within required limits)

III. Nuisance type failure (No mission effect)

The analysis is based upon an occurrence of a single failure mode. Two cases of a double malfunction are cited (A.I.2.b and C.III) for general information only.

C. QUALITATIVE AND QUANTITATIVE ANALYSIS

Surveillance of all testing was conducted throughout the program. Test results and data were reviewed and timely qualitative and quantitative analyses of tank assembly performance were generated. Analysis of the command module and service module tankage was reported qualitatively because of the relatively small amount of available data for each of the four tank configurations. During the Lunar Module and SIVB programs, quantitative analyses were also presented based on all applicable actual propellant expulsion data. The command module oxidizer tank data were excluded since this bladder has 9 mil thick hemispherical ends with a 6 mil cylindrical center section as opposed to the other tanks which contain bladders of uniform 6 mil thickness.

Table V-2 summarizes all propellant expulsion data, including the CMO, accumulated throughout the programs. The reliability at the 50% and 90% LCL is also presented; however, it should be noted that they are primarily a reflection of the small amount of data available for each configuration.

The periodic accumulation of all expulsion data (CMO excluded) as applied to the LM and SIVB quantitative analysis are contained in Table V-3. The data are shown beginning with April 1966 since all CM and SM formal testing ended at that time. As noted in the table, all discrepancies were carried as reliability failures (F) in the calculations until "Failure Recurrence Prevention" was established. That is, no observed "failures" were discounted until a thorough investigation was conducted and adequate corrective action (where applicable) was implemented.

D. RELIABILITY BLOCK DIAGRAMS

A typical Reliability Logic Block Diagram is presented in Figure V-3. The tank assembly was divided into three main subassemblies (tank, bladder, and diffuser assembly) with associated failure rates. Subdivisions are listed to correlate with the failure mode and effects analysis. The diagram is a simple series arrangement since no redundancy (parallelism) exists for the primary function of propellant expulsion. The two vent lines are servicing aids only.

Figure V-3 shows that the failure rates for the tank (A) and diffuser assembly (C) are insignificant in arriving at the tank assembly reliability. Tank assembly reliability, therefore, is primarily a function of the bladder failure rate and it has been adequately demonstrated that, given satisfactory pretest leakage checks and propellant loadings, successful complete expulsions can be effected repeatably on all configurations. The failure rates presented were established, as explained above, for the LM and SIVB programs. The attendant reliability is 0.9993 at a 50% LCL (or 0.9977 at 90%.)

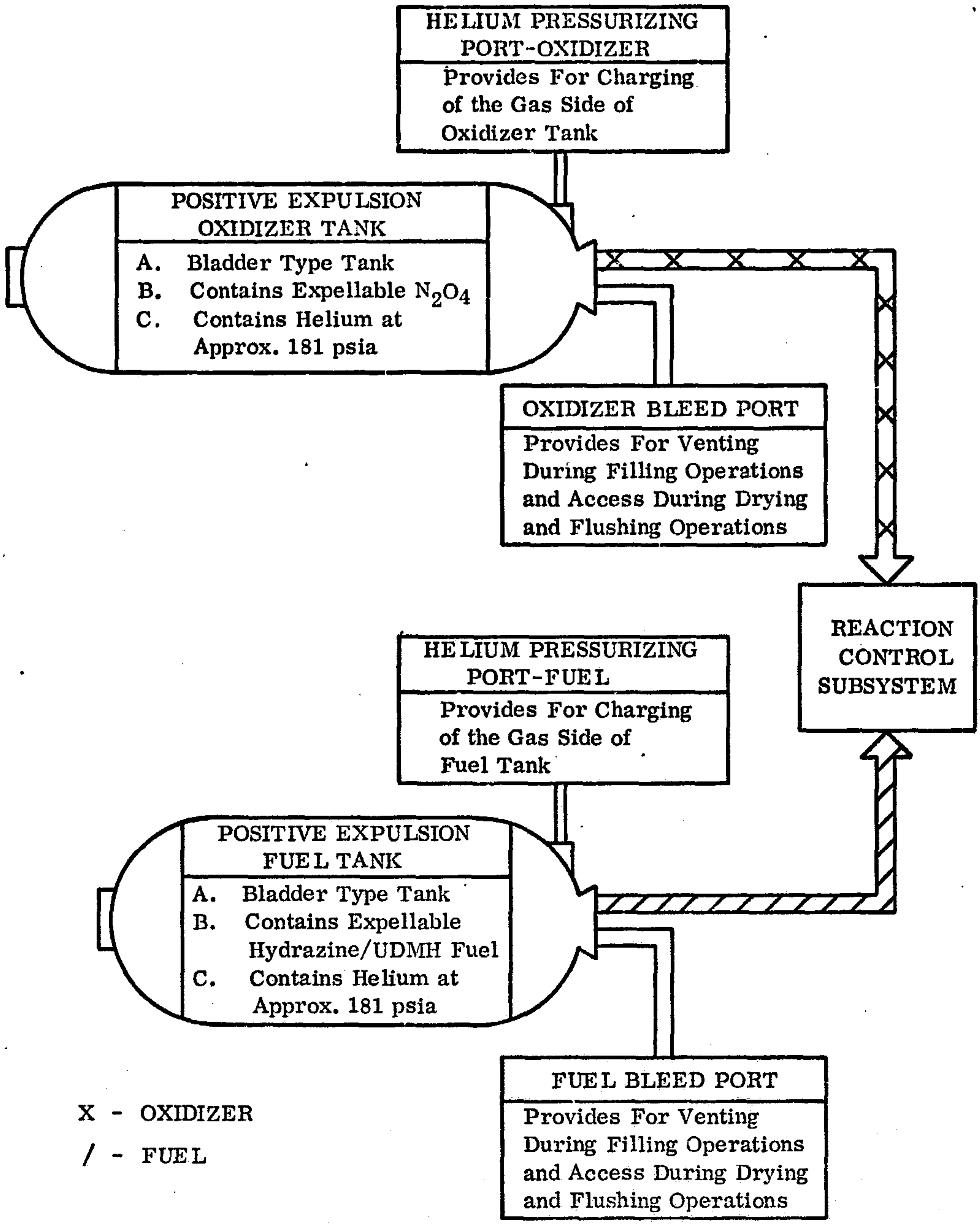
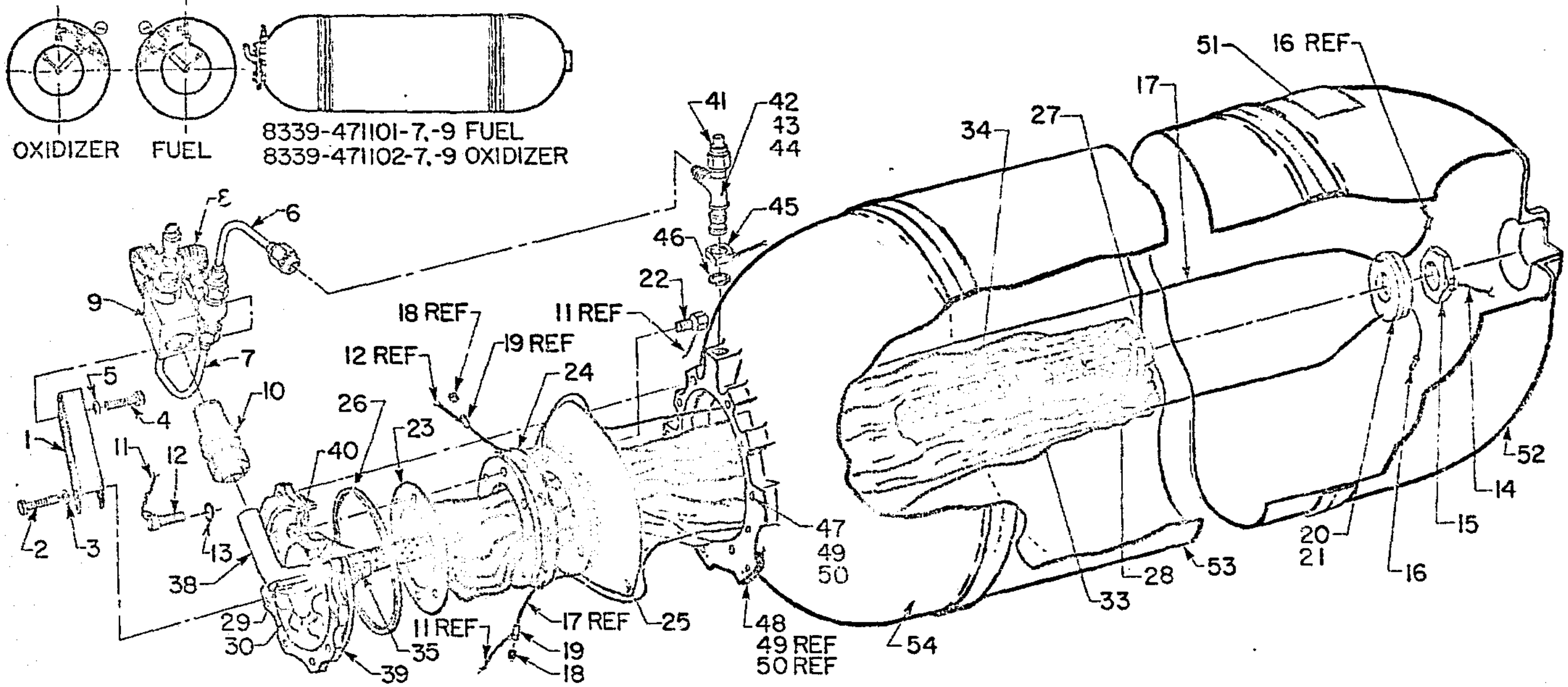


FIGURE V-1 TYPICAL POSITIVE EXPULSION TANKAGE FUNCTIONAL BLOCK DIAGRAM

MODEL 8339 LUNAR MODULE RCS TANK ASSEMBLIES



LUNAR MODULE REACTION CONTROL SYSTEM TANK
8339-471101-7 FUEL
8339-471102-7 OXIDIZER
8339-471101-9 FUEL (PLENED SHELL)
8339-471102-9 OXIDIZER (PLENED SHELL)

1. BRACKET 8339-[illegible] (ALUMINUM 2024-T3)
2. BOLT AN5-8 (STEEL)
3. WASHER AN960-[illegible] (STAINLESS STEEL)
4. BOLT AN3-2 (STEEL)
5. WASHER AN960-[illegible] (STAINLESS STEEL)

VALVE ASSEMBLY
8339-471072-1 FUEL
8339-471072-3 OXIDIZER

6. TUBE ASSEMBLY 8339-471067-1
REF TUBE 8339-471067-3 (STAINLESS STEEL 347)
REF NUT AN818-4C (2 REQ'D) (STAINLESS STEEL)
REF SLEEVE [illegible] (2 REQ'D) (STAINLESS STEEL)

7. TUBE ASSEMBLY 8339-471065-1
REF TUBE 8339-471065-3 (STAINLESS STEEL 347)
REF NUT AN818-4C (2 REQ'D) (STAINLESS STEEL)
REF SLEEVE MS 21419-4C (2 REQ'D) (STAINLESS STEEL)

8. VALVE 62581

9. PLUG ASSEMBLY 8339-471060-1
REF CAGE FIGURE P900
REF VALVE MS 28[illegible]-1
REF UNION AN 815-4S
REF GASKET 402-4
REF FILTER ASSEMBLY 8339-471062-1
REF FITTING 8339-471064-3

10. MALE CONNECTOR 7-1210-17 (NYLON)

TANK ASSEMBLY
8339-471103-3 FUEL
8339-471104-3 OXIDIZER
8339-471103-5 FUEL (PLENED SHELL)
8339-471104-5 OXIDIZER (PLENED SHELL)

11. LOCKWIRE MS 20995C20 (STAINLESS STEEL)
12. BOLT 8271-471[illegible]-1 (10 REQ'D) (TITANIUM)
13. WASHER AN960 [illegible] (10 REQ'D) (STAINLESS STEEL)

BLADDER ASSEMBLY
8339-471[illegible]-5 FUEL
8339-471059-5 OXIDIZER

14. LOCKWIRE MS 20995F32 (STAINLESS STEEL)
15. NUT 8271-471021-3 (STAINLESS STEEL 347)

VENT LINE ASSEMBLY
8339-471027-1 FUEL (2 REQ'D)
8339-471027-3 OXIDIZER (2 REQ'D)

16. EYELET 8271-471[illegible]-1 (2 REQ'D) (STAINLESS STEEL [illegible])
17. VENT LINE (TEFLON TFE)
8339-471027-5 FUEL (TEFLON TFE)
8339-471027-7 OXIDIZER (TEFLON TFE)

EYELET RETAINER ASSEMBLY 8271-471131-1
18. COVER 8271-471131-3 (TEFLON TFE)
19. HOUSING 8271-471131-5 (TEFLON TFE)

RETAINER [illegible] ASSEMBLY 8271-471[illegible]-1
20. GASKET 8271-471[illegible]-1 (TEFLON TFE)
21. WASHER 8271-471120-1 (ALUMINUM 6061-T6)
22. BOLT 8271-471114-1 (6 REQ'D) (STAINLESS STEEL 347)
23. BLADDER
8339-471080-1 FUEL
8339-471080-3 OXIDIZER
(TEFLON TFE/FEP)
24. RING 8271-471117-1 (ALUMINUM 6061)
25. PAD 8271-471[illegible]-1 (TEFLON TFE/FEP)
26. GASKET 8271-471125-1 (TEFLON TFE)

DIFFUSER ASSEMBLY
8339-4710[illegible]-3 FUEL
8339-4710[illegible]-3 OXIDIZER

27. RETAINER ASSEMBLY 8339-4710[illegible]-1 (ALUMINUM 6061-T6)
28. BUSHING 8271-471213-1 (TEFLON TFE)

FLANGE ASSEMBLY
8339-471055-3 FUEL
8339-471056-3 OXIDIZER

BLEED TUBE ASSEMBLY
8339-472037-9 FUEL
8339-471039-11 OXIDIZER

29. TUBE
8339-471059-33 FUEL
8339-4710[illegible]-35 OXIDIZER
(STAINLESS STEEL 347)
30. CAP 7Y36-C (NYLON)
31. NOT USED
32. NOT USED
33. SPACER 8339-471058-1 (TEFLON TFE)
34. DIFFUSER TUBE
8339-4710[illegible]-1 FUEL
8339-4710[illegible]-3 OXIDIZER
(ALUMINUM 6061-T6)

DIFFUSER ELBOW ASSEMBLY 8339-471042-3

OUTLET ASSEMBLY 8339-471032-3 (STAINLESS STEEL)

35. CONE 8339-471034-[illegible] (ALUMINUM)

ELBOW ASSEMBLY 8339-471031-5

36. NOT USED
37. NOT USED
38. TUBE 8339-471031-7 (STAINLESS STEEL 347)
39. FLANGE 8339-471033-1 (ALUMINUM 6061-T6)
40. INSERT MS [illegible] (8 REQ'D) (STAINLESS STEEL HELICOIL)

GAS INLET FITTING ASSEMBLY 8339-471069-1

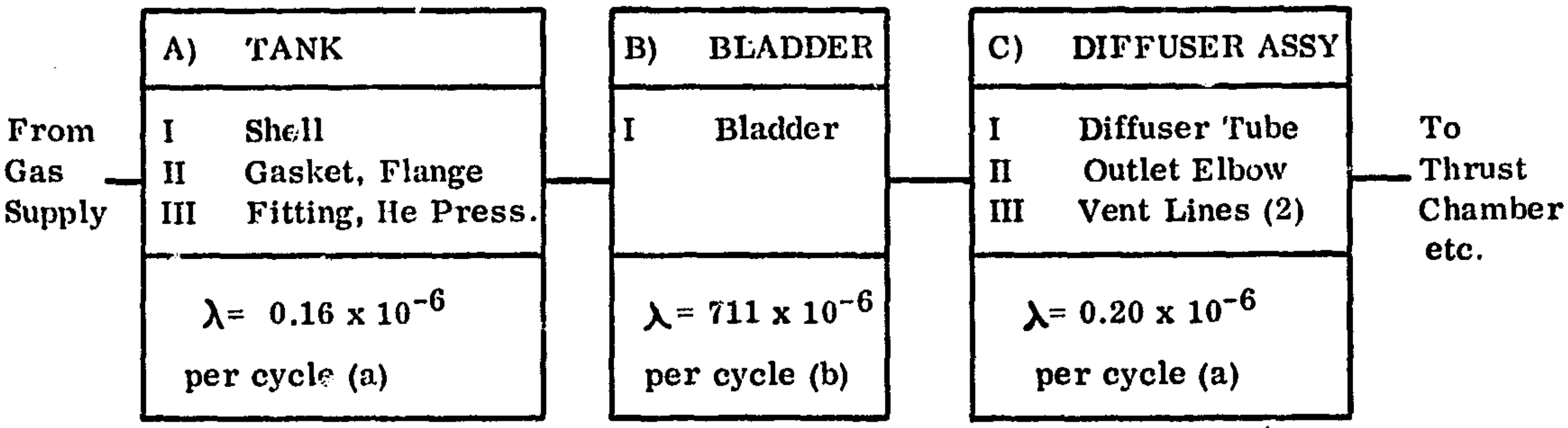
41. CAP ASSEMBLY AN929-4S (STAINLESS STEEL)
42. FILTER RETAINER 8250-472053-1 (STAINLESS STEEL)
43. DISC [illegible] (STAINLESS STEEL)
44. TEE FITTING 8339-471069-3 (STAINLESS STEEL)
45. NUT 8271-471[illegible]-1 (STAINLESS STEEL)
46. GASKET 402-4 (TEFLON)

TANK SHELL ASSEMBLY
8339-471110-1 FUEL
8339-471[illegible] OXIDIZER
8339-471[illegible] FUEL (PLENED SHELL)
8339-471[illegible] OXIDIZER (PLENED SHELL)

47. NUT PLATE NAS[illegible]-5 (2 REQ'D) (STAINLESS STEEL)
48. NUT PLATE NAS[illegible]-5 (2 REQ'D) (STAINLESS STEEL)
49. RIVET [illegible] (8 REQ'D) (STAINLESS STEEL)
50. RIVET [illegible] (8 REQ'D) (STAINLESS STEEL)
51. IDENTIFICATION PLATE
8339-471[illegible]-29 FUEL
8339-471[illegible]-31 OXIDIZER
(ALUMINUM [illegible])
52. [illegible] TANK SECTION 8339-471013-3 (TITANIUM [illegible])
53. [illegible] SECTION
8339-471[illegible] FUEL
8339-471[illegible] OXIDIZER
(TITANIUM [illegible])
54. [illegible] END TANK SECTION 8339-471011-3 (TITANIUM [illegible])

BELL AEROSYSTEMS COMPANY
DIVISION OF BELL AEROSPACE CORPORATION

FIGURE V-2



Tank Assembly Mission Failure Rate'

$\lambda = A + B + C$
711.4×10^{-6}/per cycle at 50% LCL
(or 2335 at 90%)
Tank Assembly Mission Reliability

R = 0.9993 at 50% LCL
(or 0.9977 at 90%)

NOTES:

(a) Estimated from BAC experienced combined with BUWEPS data published by NOL-CORONA.
(b) Calculated from BAC data: 985 propellant expulsions with zero reliability failures utilizing 42 tank assemblies (Models 8271, 8339 and 8400).

FIGURE V-3 RELIABILITY LOGIC (BLOCK) DIAGRAM, POSITIVE EXPULSION TANK, TYPICAL

TABLE V-I

TYPICAL FAILURE MODE AND EFFECTS ANALYSES

ITEM (REF. FIG. V-3)	PART NAME PART NUMBER (REF. FIG.V-2) ASSUMED FAILURE	POSSIBLE CAUSE	OPERATIONAL EFFECT: FUNCTION (EQUIPMENT & SYSTEM)	OPERATIONAL EFFECT: MISSION	MISSION LOWEST AFFECTED LEVEL	1) INHERENT COMPENSATION 2) FAILURE DETECTION 3) REMARKS	FAILURE CLASS (WORST CASE)
A	TANK						
I	Shell 8339-471110						
	1. External gas leakage through wall or welds	Porosity or cracks.	Overboard loss of helium pressurizing gas resulting in partial to complete loss of tank pressures. Decrease in operating duration	Partial to complete loss of tank (and source) pressure. Premature termination of mission.	Tank Assy.	1) Acceptance Tests: Hydro proof pressure check of each tank assy (minus bladder) at 333 psig (MEOP is 250 psig); Helium leak check at 250 psig; x-ray and dye check of all welds. 2) Pre-launch gas pressure check of tank assy at 250 psig (minus propellant). Loss of suppression pressure (40 psig) post propellant loading.	I
	2. Rupture	a. Overpressurization during servicing. b. Info only Double malfunction. Bladder leakage & use of incompatable oxidizer (or flush fluids e.g.methanol) could result in stress corrosion of shell.	Complete overboard loss of pressurizing gas and assembly operation at time of occurrence. Bladder rupture will probably also occur with overboard loss of propellant.	a. No effect since assembly would be replaced prior to launch. b. *Premature termination of mission*	a. None b. *Tank Assy.*	1) Acceptance Tests: Hydro proof pressure check of each tank assy (minus bladder) at 333 psig (MEOP is 250 psig & nom. is 181 psig). Design burst is 2.0 times nom. Helium leak check at 250 psig; X-ray and dye check of all welds. (re. double malf.)-only specified flush fluids, or peened shells must be used. 2) Pre launch visual/audio observations during pressurization. 3) Strict adherence to servicing procedures required. Double malfunctions are not normally considered. Included for information only.	III b.*I*
	3. Buckling	Internal vacuum (applicable to loading in horizontal attitude only - bleed tube partially effective).	Assembly may not hold a full load of propellant.	No effect since tank assy would be replaced prior to launch.	None	1) None 2) Pre launch visual or inability to load desired amount. 3) Strict adherence to service procedure required.	III
II	Gasket, Flange 8271-471025-1 1. External gas leakage at shell to flange gasket	1. Improper installation. 2. Loss of torque on 8271-471019-1 bolts.	Overboard loss of pressurizing gas resulting in a partial to complete loss of tank pressure. Decrease in operating duration.	Partial to complete loss of tank (and source) pressure. Premature termination of mission.	Tank Assy.	1) Acceptance Tests: Tank assy helium leak check at 250 psig. Serrations on flange provide a redundant sealing surface. Torque-retorque procedure minimizes possibility of leakage. Bolts lock-wired to minimize loss of torque.	I

TABLE V-I (CONT)

TYPICAL FAILURE MODE AND EFFECTS ANALYSES

ITEM (REF. FIG. V-3)	PART NAME PART NUMBER (REF. FIG.V-2) ASSUMED FAILURE	POSSIBLE CAUSE	OPERATIONAL EFFECT FUNCTION (EQUIP-MENT & SYSTEM)	OPERATIONAL EFFECT MISSION	MISSION LOWEST AFFECTED LEVEL	1) INHERENT COMPENSATION 2) FAILURE DETECTION 3) REMARKS	FAILURE CLASS (WORST CASE)
A (CONT)							
II						2) Pre launch gas pressure check of tank assembly at 250 psig (minus propellant). Loss of suppression pressure (40 psig) after propellant loading. 3) New gasket must be used if tank is disassembled.	
III	Helium Port Fitting (where applicable) 8339-471026-1						
	1. External gas leakage	Incorrect installation of parts or defective fitting or gaskets(two)	Overboard loss of pressurizing gas resulting in a partial to complete loss of tank pressure. Decrease in operating duration.	Partial to complete loss of tank (and source) pressure. Premature termination of mission.	Tank Assy	1) Acceptance Tests: Hydro proof pressure check of each tank assy (minus bladder) at 333 psig and a helium leak check at 250 psig assure that fitting is not defective. A second 250 psig helium check is subsequently performed during the acceptance tests after removal and reinstallation of fitting with new gaskets. Two gaskets are used, providing redundant seals, therefore both must leak. 2) Pre launch gas pressure check of tank assy at 250 psig (minus propellant). Loss of suppression pressure after propellant loading. 3) New gaskets must be used if disassembly occurs.	I
B	BLADDER						
I	Bladder 8339-471080						
	1. Leakage due to pinhole leaks or small cuts.	Mishandling, contamination, twisting or wearout.	Propellant (liquid) and/or gas transfer or interchange may occur which could result in assy performance degradation from:	Premature termination of mission depending on degree and duration of leakage since:	Tank Assy	1) Acceptance Tests: Helium leak check of bladder at 10 psig, liquid to gas side after final assembly. Assembling conducted in clean room for contamination control. 2) Pre launch helium leak check of bladder at 10 psig.	I
	a. Leakage of pressurizing gas (helium) to liquid side.		a. Excessive gas dilution of propellant. See also B.I.3.a (Gas Bubble)	a. Thrust chamber(s) performance may be out of specification.			

TABLE V-I (CONT)

TYPICAL FAILURE MODE AND EFFECTS ANALYSES

ITEM REF. FIG. V-3)	PART NAME PART NUMBER (REF. FIG. V-2) ASSUMED FAILURE	POSSIBLE CAUSE	OPERATIONAL EFFECT FUNCTION (EQUIPMENT & SYSTEM)	OPERATIONAL EFFECT MISSION	MISSION LOWEST AFFECTED LEVEL	1) INHERENT COMPENSATION 2) FAILURE DETECTION 3) REMARKS	FAILURE CLASS (WORST CASE)
B I	(CONT) b. Leakage of propellant (liquid) to gas side.		b. Trapping of some propellant on gas side thereby reducing expulsion efficiency.	b. Expulsion efficiency will be less than specification.		Observations for odor or vapors at gas port during propellant Loading. 3) Strict adherence to established procedures will eliminate discrepancies due to mishandling, or twisting during installation. Twisting during horizontal expulsion can possibly present a problem from the standpoint of horizontal reloading for subsequent expulsions only. Wearout is a problem only from use outside of spec limits (vibration, expulsions etc.).	
	2. Leakage due to bladder loosening from hardware at either end. (8271-471144-1 retainer washer & 8271-471117-1 ring)	Loss of torque	Transfer of propellant to gas side where it will be trapped, thereby reducing the assy expulsion efficiency-amount dependent upon degree and duration of leakage.	Premature termination of mission depending on degree and duration of leakage.	Tank Assy	1) Acceptance Tests: Helium leak checks at 28 inches of water pressure (mounted on diffuser) with mass spectrometer and also water immersion. Helium leak check at 10 psig after final assembly. Serrations on washer and ring provide redundant seals. Torque retorque procedure compensates for cold flow. Lockwiring of 8271-471021-3 retainer nut and 8271-471114-1 ring bolts minimizes loss of torque. 2) Pre launch helium leak checks of bladder at 10 psig. Observations for odor or vapors, at gas port, during propellant loading.	I
	3. Leakage due to permeation	Basic bladder material design	Note: Similar to B.I.1, however quantitites transferred are much less, and only the propellant vapors (not liquid) are involved in (b) below. Assembly performance degradation may result from:	Premature termination of mission depending on degree and duration of permeation since:		1) Acceptance Tests: Helium leak check of bladder at 10 psig, liquid to gas side, after final assembly assures that permeation is within specification requirements.	

TABLE V-I (CONT)

TYPICAL FAILURE MODE AND EFFECTS ANALYSES

ITEM REF. FIG. V-3)	PART NUMBER PART NAME (REF. FIG. V-2) ASSUMED FAILURE	POSSIBLE CAUSE	OPERATIONAL EFFECT: FUNCTION (EQUIP-MENT & SYSTEM)	OPERATIONAL EFFECT: MISSION	MISSION LOWEST AFFECTED LEVEL	1) INHERENT COMPENSATION 2) FAILURE DETECTION 3) REMARKS	FAILURE CLASS (WORST CASE)
B I	3 (CONT) a. Permeation of gas to liquid side.		a. Gas bubble formation (following permeation and propellant saturation by dissolution) which in effect is an undesirable foreign element capable of being expelled from the tank assy.	a. Thrust Chamber(s) ignition run and shutdown characteristics may be adversely affected.	a. Tank Assy.	2) Pre launch helium leak check of bladder at 10 psig. 3) Re-bleeding and increasing the helium pressure to operating level pre launch is an effective means of retarding gas bubble formation.	a. I
	b. Permeation of propellant vapors to gas side.		b. No effect	b. No effect	b. None		b. NA
	4. Rupture of Bladder	Mishandling or twisting during assembling. Undue stress experienced during propellant loading or from operational shrinkage (wrinkles.)	Propellant and gas interchange resulting in erratic and unpredictable assy. operation and a decrease in expulsion efficiency.	Premature termination of mission.	Tank Assy	1) Acceptance Tests: Visual observations, while pressurized, after assembling bladder to diffuser should detect any twist. Helium leak check of bladder at 10 psig after final assembly affords assurance of probable freedom from handling or twisting discrepancies. The 8339-471080 bladder is specifically designed to minimize possibility of undue stresses resulting from propellant loading or operational shrinkage. 2) Pre launch helium leakage check of bladder at 10 psig. Observations for odor or vapors, at gas port, during propellant loading. 3) Strict adherence to established procedures will eliminate possibility of rupture due to mishandling or twisting.	I

TABLE V-I (CONT)

TYPICAL FAILURE MODE AND EFFECTS ANALYSES

ITEM (REF. FIG. V-3)	PART NAME PART NUMBER (REF. FIG.V-2) ASSUMED FAILURE	POSSIBLE CAUSE	OPERATIONAL EFFECT: FUNCTION (EQUIPMENT & SYSTEM)	OPERATIONAL EFFECT: MISSION	MISSION LOWEST AFFECTED LEVEL	1) INHERENT COMPENSATION 2) FAILURE DETECTION 3) REMARKS	FAILURE CLASS (WORST CASE)
C	DIFFUSER ASSEMBLY 8339-471053-3 Fuel 8339-471054-3 (Oxid)						
I	Diffuser Tube 8339-471036						
	1. Crack or fracture at 8339-471034-1 outlet end cone or at 8339-471057-5 retainer cone.	Defective weld. Mishandling of parts.	a. None for crack or fracture only. b. If the retainer shifts (separation of parts at fracture) the bladder might be cut on the retainer boss circumference or rough edges of either fracture. If bladder is cut propellant transfer will result with a decrease in expulsion efficiency.	a. None for fracture only. b. Possible premature termination of the mission with complete separation	a. Diffuser b. Tank Assy	1) Acceptance Tests: All welds are x-rayed and dye checked at diffuser assy level. The outlet holes must be located outside of the weld heat affected zones. 2) Visual inspection prior to final assembly. 3) Strict adherence to established procedures will preclude transmission of torque to welded joints during retainer nut installation. The bleed tube & spacer will tend to limit diffuser tube movements if separation of parts occurs.	a. III b. I
II	Outlet Elbow Tube 8339-471031						
	1. Crack or fracture at bimetallic joint or of weld at the 8339-471059 bleed tube.	Defective joint. Defective weld. Mis[illegible] handling of parts.	[illegible] loss of propellant resulting in [illegible] to complete loss of propellant supply depending on degree and duration of leakage. A large leak can also reduce the flow rate below specification requirements.	Premature termination of mission due to available propellant volumn and/or thrust chamber mixture ratio being out of specification.	Tank Assy	1) Acceptance Tests: Hydro proof pressure check at tank assy. level (minus bladder at 333 psig; Helium leak check at 250 psig. X-ray and dye check of welds. Bimetal joint samples are subjected to temperature cycling, fatigue (pressure) cycling, helium leakage check, shear strength and metallographic examination. 2) Pre launch gas pressure check of tank assy at 250 psig (minus propellant). Observation for odor, fumes liquid or loss of suppression pressure during & after propellant loading.	I

TABLE V-I (CONT)

TYPICAL FAILURE MODE AND EFFECTS ANALYSES

ITEM (REF. FIG. V-3)	PART NAME PART NUMBER (REF. FIG.V-2) ASSUMED FAILURE	POSSIBLE CAUSE	OPERATIONAL EFFECT FUNCTION (EQUIP-MENT & SYSTEM)	OPERATIONAL EFFECT MISSION	MISSION LOWEST AFFECTED LEVEL	1) INHERENT COMPENSATION 2) FAILURE DETECTION 3) REMARKS	FAILURE CLASS (WORST CASE)
C (CONT)							
III	(CONT)						
	2. Insufficient slack (one or both)	Incorrect lines or installation.	Line (s) would cut the bladder. Lines and bladder would be replaced prior to shipment.	No effect	None	1) Lines are oversize to provide sufficient slack, are controlled by PN for each tank size and are installed with bladder inflated to visually assure that they are not taut. 2) Excessive bladder leakage would be detected during initial assembly and acceptance testing.	III

BELL AEROSYSTEMS COMPANY
DIVISION OF BELL AEROSPACE CORPORATION

TABLE V-2

PROPELLANT EXPULSION DATA SUMMARY - APOLLO TYPE TANK ASSEMBLIES

Program	Type T/A*	No. Of Assys	No. Of Expul's	Test Period	Relia. Fails.	at 50% LCL $\lambda \times 10^{-6}$/cyc	R/cyc	at 90% LCL $\lambda \times 10^{-6}$/cyc	R/cyc
Apollo RCS	SMF	7	217	6/64 - 1/66	0	3226	.9968	10599	.9894
	SMO	10	230	6/64 - 3/66	0	3043	.997	10000	.9900
	CMF	7	145	1/65 - 3/66	0	4828	.9952	15862	.9841
	CMO	9	209	2/65 - 4/66	0	3349	.9967	11005	.9890
LM RCS	Oxid	6	163	8/65 - 9/66	0	4294	.9957	14110	.9859
	Fuel	8	170	3/66 - 9/67	0	4118	.9959	13529	.9865
SIVB APS	Oxid	2	39	5/66 - 1/67	0	17949	.9821	58974	.9410
	Fuel	2	21	6/66 - 1/67	0	33333	.9667	109523	.8905

* All tank and bladder assy's are final configuration except two of the six LM Oxid bladders. These were of the undersize cylindrical section type but did not have a) the heavier area at the retainer washer and b) were not sized to assure a 1% greater than tank length, as did the final design.

TABLE V-3

PROPELLANT EXPULSION DATA BREAKDOWN

MODEL	T/A	PHASE	T/A SN	F/A SN	THRU APR 66	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC	JAN 67	SEPT
Apollo 8271	SMP	R&D	-	1-5	36 NR e										
		R&D		5-5	30 NRa,c										
		DVT	X 2	22-5	32 NR c										
		DVT	X-1	21-5	6 NRg,a										
		DVT	X 2	17-5	19 NR e										
		QT&O-L	P-1	53-5	70										
		CT&O-L	P 2	50-5	24 NRg,c										
	SMO	R&D	-	1-7	24										
		DVT	X-2	5-7	28 NRc,e										
		QT	P-2	24-7	16 F	NR 1									
		CT	P 2A	50-7	8 F	NF 1									
		QT	P-1A	68-7	12 F	NR 1									
		Teflon Coated Shell		90-7	36										
		" " "		66-7	36 NRg,h,e										
		CT	P-1B	72-7	9 NR h,e										
		CT	P 2F	104-7	4 NR c										
		CT&O-L	P-2C	102-7	57										
	CMF	R&D	R-8	2-1	21 NR c										
		DVT	P-1	5-1	34 NR f,c										
		DST	FC-1	17-1	10 NR c										
		DVT	P-2	6-1	21										
		DST	FA-1	40-1	35										
		DST	FC 2	60-1	12										
		DST	FH-1	76-1	12										
LM 8339	Oxid	Dev.	-	2-3	18 NR a,e										
		Dev.	-	4-3	25 NF d,c										
		DVT&OS	X-2	2-3	20	20									
		DVT&OS	X 4	11-3		18	22 NRf,e								
		QT	P-1	51-3					17	3					
		QT	P-2	58-3					20						
	Fuel	Dev.	-	1-1	10 NR d,e										
		Dev.	-	8-1	20										
		DVT	X 1A	17-1			18(+2) F	(F)	(F)	(F)	(F)	NRf(+2)			
		DVT	X 3	11-1	19	1									
		DVT&OS	X-5	18-1			16	11	13						
		CT	P 3	31-1						20					
		QT	P-4	29-1						2	18				
		Special	R-1	42-1											20
SIVB 8400	Oxid	Dev.	X-1	21-3		1	2	16 F	NRa,e						
		CT	P 2	96-3									1	19	
	Fuel	Dev.	X-3	41-3			1 F	(F)	(F)	(F)	(F)	NRa,c,e			
		QT	P-1	75-3								1	17	2	
Sub Total					-	40	59	27	50	25	18	3	18	21	20
Total Expuls./No. of Assys					704/30	744/32	803/35	830/35	880/37	905/39	923/39	926/40	944/41	965/41	985/42
F - Relia. Fail.					3	3	0	3	2	2	2	0	0	0	0
Bladder Fail. Rate x 10^{-6}/cyc at					5256	941	3362	4458	3068	2983	2925	756	742	725	711
Reliability/Cyc (50% LCL)					.9947	.9991	.9966	.9955	.9969	.9970	.9971	.9992	.9993	.9993	.9993

LEGEND & FAILURE/ CORRECTION ACTION REP.

Phase Designation -

DVT - Design Verification Test
QT - Qualification Test
O-L - Off-Limits
CT - Certification Test
DST - Design Substantiation Test
Dev.- Development
OS - Overstress Test
Special - Dyn.'s W/Prop. Prior to Expulsions

F - Discrepancy carried as a reliability failure during period of investigation.
NR - Investigation completed. Failure (F) determined to be Non-Reliability (NR) type due to one or more of following:

a) Human or Procedure Error or Test Equipment
b) Data misinterpreted
c) Subjected to O-L or OS testing
d) Subjected to excessive prior tests
e) Corrective Action re. procedure or design precludes recurrence.
f) Damage only, not a failure
g) Hardware failure or discrepancy
h) Failed in Dyn. pre or post expulsion test.
i) Corrective Action recommended based on additional testing.