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SAMSO TR 69-213 VOL. I

CLOSURE ANALYSIS AND TEST STUDY
VOLUME I

PROJECT SUMMARY
AND
ABSTRACT OF FINDINGS

TECHNICAL REPORT NO. 4171-1

31 JULY 1969

Prepared for

DEPARTMENT OF THE AIR FORCE
SPACE AND MISSILE SYSTEMS ORGANIZATION
AIR FORCE SYSTEMS COMMAND
NORTON AIR FORCE BASE, CALIFORNIA

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THE RALPH M. PARSONS COMPANY

ENGINEERS-CONSTRUCTORS

LOS ANGELES
NEW YORK

FOREWORD

This final report, which is composed of Volumes I through VIII, contains the results of a research study conducted by The Ralph M. Parsons Company under the direction of John E. McCarney. The Ralph M. Parsons Company personnel making significant technical contribution to this effort include David M. Hopper, Philip R. Sands, Richard C. Mayer, and Philip Mannes.

The study was performed from 1 June 1967 to 31 July 1969 under Contract No. F04694-67-C-0105 for the Department of the Air Force, Space and Missile Systems Organization (AFSC), Norton Air Force Base, California 92409. The SAMSO project officers were Maj G. W. Barnes, Capt F. G. Harms, and 1st Lt H. S. Yoshioka. The Aerospace Corporation provided systems engineering and technical direction, with Warren Pfefferle acting as Technical Director.

This technical report has been reviewed and is approved.

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CLOSURE ANALYSIS AND TEST STUDY

INDEX OF VOLUMES

VOLUME I

PROJECT SUMMARY AND ABSTRACT OF FINDINGS

ABSTRACT

This report contains a summary of all activities and significant findings associated with, or emanating from, the Closure Analysis and Test Study. Candidate closure operating concepts consisting of the closure structure, bearing support, debris removal/handling system, actuation system, power system, and closure locking system are presented, and factors influencing the selection of two final configurations are discussed.

The results of the radiation analysis and the subscale operating, static and dynamic tests, which were conducted to establish credibility of the selected closure subsystem designs, are presented, together with study conclusions emanating from these tasks.

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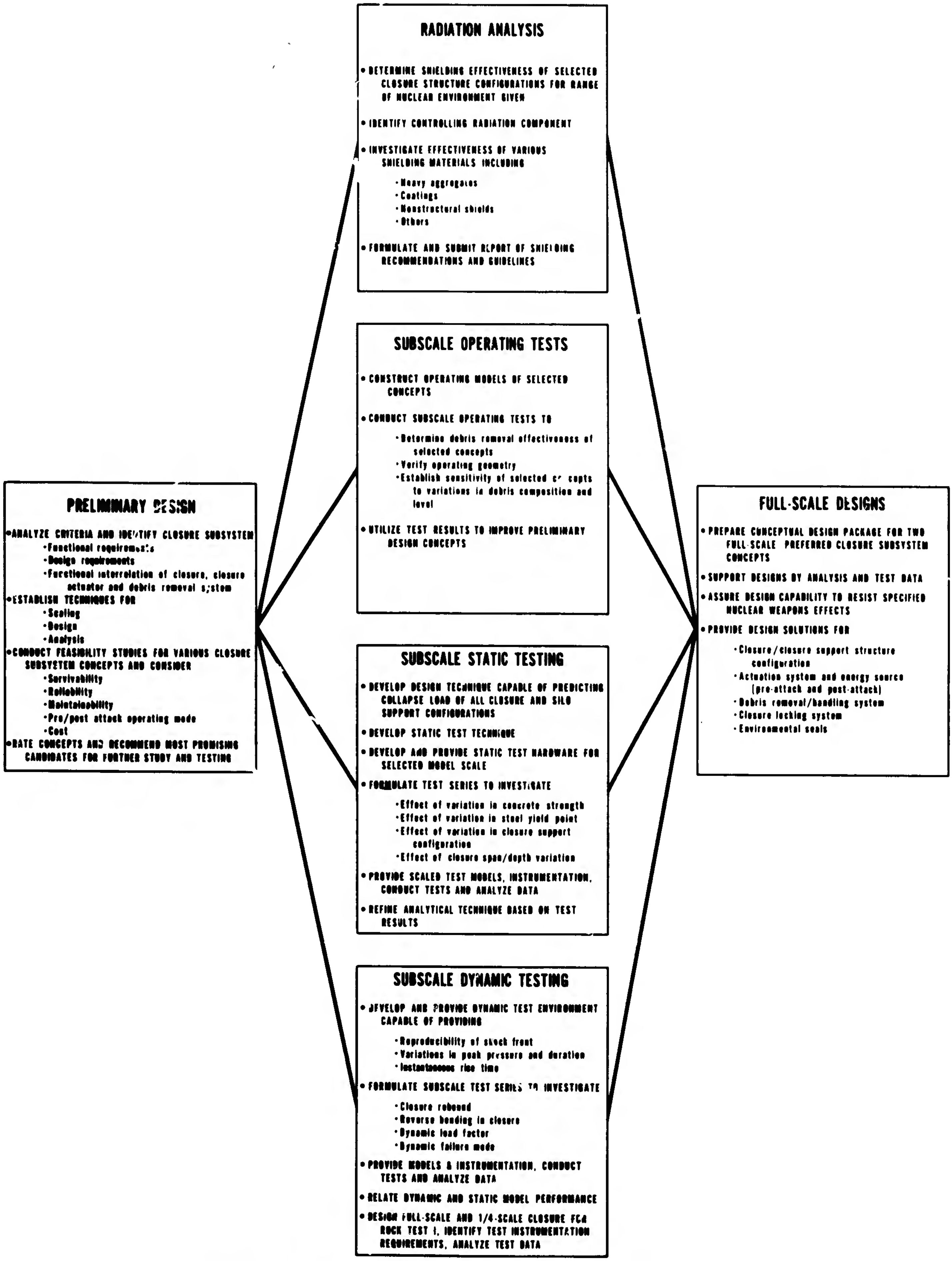
1.0 INTRODUCTION

The purpose of the Closure Analysis and Test Study (AF Contract No. F04694-67-C-0105) was to provide a technological base that would support the credibility of conceptual designs for functionally integrated closure subsystems for hardened advanced missile launch facilities. The closure subsystem was defined as consisting of the closure structure, closure supporting interface structure, closure actuation mechanism and debris removal mechanism. To achieve the specified end result, the Contract Work Statement defined a number of independent, yet interrelated, tasks to be accomplished. The study tasks and design goals are summarized in Figure 1-1. As indicated schematically, each task provided information to, or utilized information from, other study tasks; the pertinent findings then provided the technical basis for the conceptual design for two feasible closure subsystems.

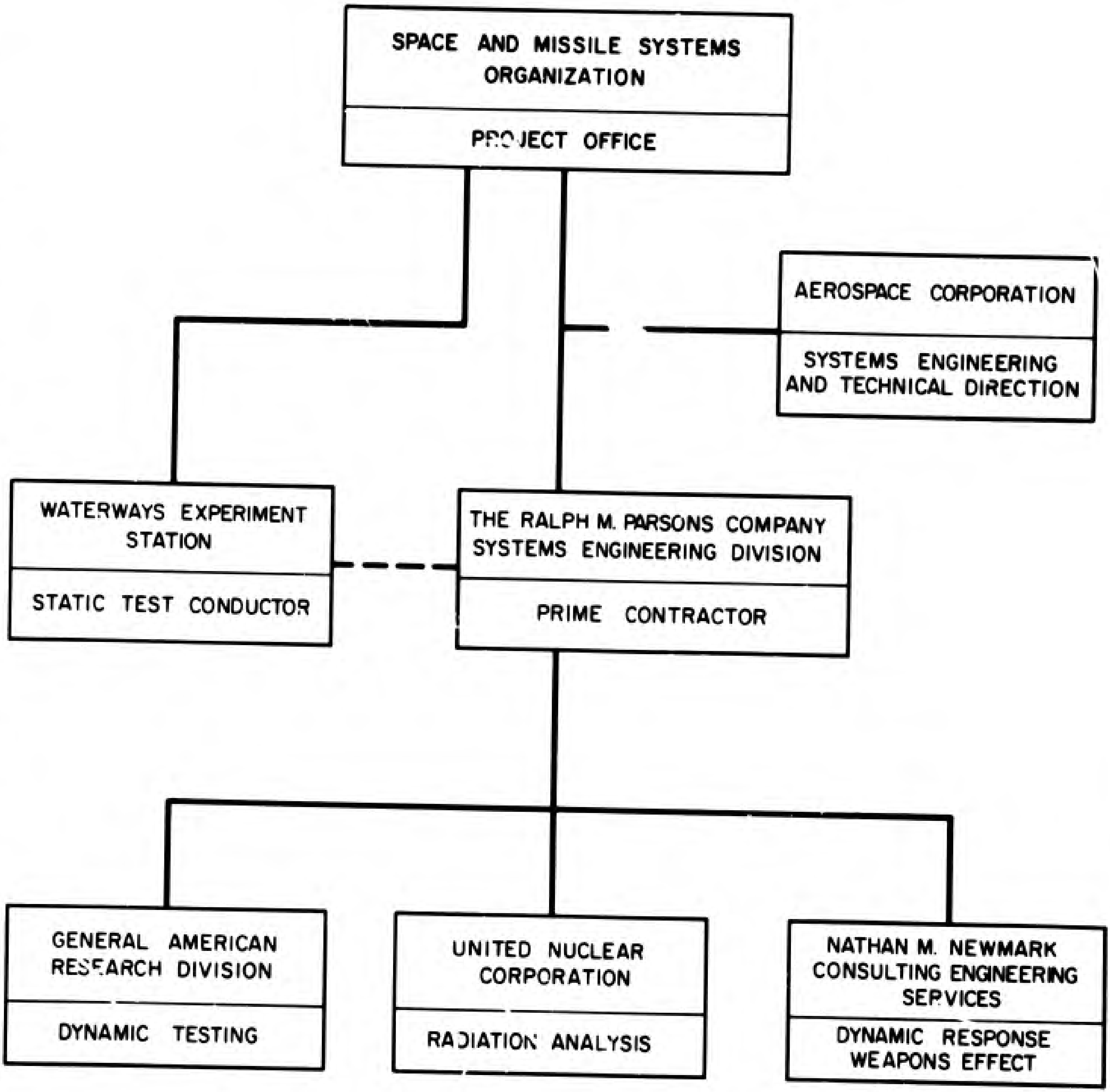
To ensure that adequate capability would be available to solve the broad range of problems posed by the work statement, Parsons assembled a team of technical subcontractors consisting of General American Research Division; Nathan M. Newmark, Consulting Engineering Services; and United Nuclear Corporation. The Waterways Experiment Station at Vicksburg, Mississippi, was retained by SAMSO as Static Test Conductor. The project organization and primary responsibility of the participants are shown on Figure 1-2.

This report would be incomplete without acknowledging the significant contributions made to this project by Parsons technical associates, Waterways Experiment Station and the SAMSO/Aerospace project leaders. Without exception, these firms and agencies exhibited the highest order of



TASK DESCRIPTIONS - CLOSURE ANALYSIS AND TEST STUDY

FIGURE 1-1



PROJECT ORGANIZATION

FIGURE 1-2

technical competence, enthusiasm, and a genuine determination to contribute meaningfully to the project. The assistance provided The Ralph M. Parsons Company by the study team members is deeply appreciated.

The material contained in this volume summarizes the major findings of the Closure Analysis and Test Study, and is intended to provide a general overview of the project goals and accomplishments. Supporting test data and analytical investigations undertaken to establish the credibility of the material presented herein are contained in the remainder of the report, Volumes II through VIII.

The entire report consists of the following documents:

Volume I - Project Summary and Abstract of Findings

Volume II - Technical Report

Volume III - Appendix 1 - Radiation Analysis for Closure Analysis and Test Program (CLASSIFIED - SRD)

Volume IV - Appendix 2 - Subscale Static Test Report

Volume V - Appendix 3 - Subscale Operating Test Report

Volume VI - Appendix 4 - Subscale Dynamic Test Report

Volume VII - Appendix 5 - Test Hardware Description and Data

Volume VIII - Appendix 6 - Closure Analysis and Test Study Criteria (CLASSIFIED - SRD)

The material emanating from the Closure Analysis and Test Study has been so compiled to make the study results meaningful and convenient for the widest possible range of readers. Volume II contains a complete discussion of all study activities and shows the interrelationship of the study tasks. Each appendix listed is a separate and completely independent report, providing detailed information relative to that phase of the study indicated in the title. It is hoped that this format will allow readers of varying areas of interest to utilize the presented material in an efficient manner.

2.0 SUMMARY OF ACCOMPLISHMENTS AND FINDINGS

The significant results of the Closure Analysis and Test Study are summarized as follows:

- The credibility of producing an integrated closure subsystem capable of surviving the nuclear weapons* effects postulated for advanced weapon systems, such as the Hard Rock Silo Development Program, has been demonstrated.
- Both rigorous and manual design techniques capable of accurately predicting the ultimate static load capacity of composite closure structures have been developed.
- The composite closure structure, i.e., a thick cylindrical section consisting of a circular steel bottom plate attached to a circular steel shell and filled with concrete, is a highly efficient structural member.
- Closure structures and silo bearing supports capable of resisting uniform loads in excess of 25,000 psi applied to the total closure area are now available.
- For the structural elements designed and tested in this program, the "one-time" dynamic load capacity of the composite closure structure is at least as great as the static load capacity.
- Composite closure structures can safely resist repeated dynamic loading although the relationship between safe repeated loading levels and maximum one-time dynamic load capacity is not yet known.

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* Refer to page 4-3.

- A static loading device with a capability of 12 million pounds has been developed and remains available to other researchers.
- The radiation attenuation provided by the composite closure structure is adequate to provide the necessary in-silo environment without resorting to more exotic radiation shielding materials than normal concrete and low carbon steel.
- Closure subsystems capable of operating through 15 feet of debris have been developed, and it is considered feasible to provide capability to operate through 50 feet of debris if necessary.
- A full-scale closure and bearing support structure designed by the techniques developed in this study has survived the simulated dynamic design environment provided by AFWL in Rock Test I.
- The post-attack energy required to actuate the closure subsystem can be efficiently provided by ballistic actuators utilizing state-of-the-art technology.
- Future static testing is required in order to precisely determine the relative effects of the side shell and the bottom plate on closure load capacity and to establish an empirical representation of closure support load capacity.
- Future dynamic testing is required to determine degradation in the load capacity of closure/closure support structures subjected to repeated loadings and to establish an empirical representation of closure/closure support dynamic load capacity.
- It is necessary to initiate a test program which will identify the influence of the expected nuclear environment on the material properties of closure structural elements.

3.0 STUDY APPROACH

To ensure adequate consideration of all system elements, the Closure Analysis and Test Study was organized and conducted essentially as a systems engineering effort. However, discipline generally implied by a systems engineering effort was not considered necessary, nor even particularly desirable, to a research project. As a result, senior engineers, analysts, staff personnel, and technical subcontractors were organized into a flexible and coordinated working group which de-emphasized the boundaries usually apparent when several engineering disciplines and companies are required to work together. An important aspect of the study team was its ability to conceive novel design solutions, weigh the technical and/or financial advantages that would accrue if the design approach were successful, and then, on the basis of overall study effectiveness, accept the technical risks attendant with the development of an untried method.

Many of the innovations shown in the selected designs and in the analytical and testing techniques presented in this report resulted from this coordinated approach. Joint sessions were held regularly to identify solutions to specific problem areas. Some of the ideas resulting from these sessions reflected a high order of ingenuity requiring only standard engineering procedures to be developed into workable solutions. It must be emphasized that, without the utilization of the full resources of all project (and supporting) personnel, this project could not have provided solutions to the rather formidable technical problems posed by the work statement.

Following is a brief description of the order of, and, to some extent, the method of approach to, the project effort. It is included to acquaint the reader with the overall scope of the project, and with the plan of action followed in the project efforts. Additional detail is provided in Volume II, Technical Report.

- A design requirements analysis was performed immediately following contract award. Requirements expressed and implied in the Contract Work Statement and the classified criteria were evaluated, leading to a Requirements Baseline Document which guided the early concept development efforts.
- Concept studies followed in which a total of 11 closure system actuation/geometrical concepts were developed. Additional efforts led to the development of concepts for locking, debris removal/exclusion and environmental sealing. Preliminary structural designs were developed through the methods then available. Tradeoff studies were performed and preferred concepts were selected for further study.
- A preliminary radiation analysis of the more promising concepts was made and design details were adjusted as necessary to improve the shielding capability. A comprehensive analysis was then made to develop radiation shielding guidelines.
- Phase I closure and silo static test specimens were designed on the basis of the preliminary structural analysis and then scaled to approximately 1/6 scale. All models were of composite concrete/steel

design, and were designed to fail at predicted loads. Designs were executed for a total of 15 tests: seven closure/silo combinations, six closures on low friction supports, and two closures on high friction (rigid) supports.

- A parametric study of static loading methods was made in an effort to devise a technique capable of producing the high unit and total loads required by the tests. This effort resulted in the development and fabrication of a 12-million-pound static test fixture capable of hydrostatically loading a test envelope of up to 52 inches diameter by 111 inches high. This test fixture utilizes the Central Firing Station at the Waterways Experiment Station, Vicksburg, Mississippi, as a reaction structure.
- Approximation techniques and rigorous analytical methods were developed to enable the prediction of load capacities of the composite structural elements to be tested. The Phase I static test specimens were designed on the basis of the approximation technique in an early stage of development. Phase II static test specimen designs and load predictions necessitated a broadening and upgrading of the basic techniques which were abetted by analysis of the Phase I results. These efforts resulted in the validated analytical approaches presented further in this report.
- A total of 41 subscale static tests were conducted at the Waterways Experiment Station test facility in two phases. These tests encompassed a broad range of test parameters and variables, at ultimate load capacities ranging from 1000 psi to 23,000 psi. Included in the

test variables were steel yield strength and thicknesses, concrete strength, span-to-depth ratios, support stiffness and friction, bearing width and configuration symmetry, and silo configurations. These variables were applied to both closure and silo test specimens.

- A total of 11 subscale dynamic tests were conducted on small-scale composite test specimens. These tests evaluated the effects of load and time variations on identical models in a closed-end shock tube. Pressure variations ranged from 2000 to 8000 psi. The surviving models were tested statically in an effort to establish the correlation between static and dynamic failure modes and loads.
- Tests of three subscale operating models were conducted to validate the basic design concepts and to determine the efficiency of each concept as a debris exclusion system. Concepts tested include the Rise and Rotate, Rise and Tilt, and the Single Hinge. Test variables consisted of variations in (simulated) debris characteristics including fineness and physical state (dry, wet and frozen).
- The integrated closure system design efforts concentrated on the development of two concepts: the Single Hinge and the Rise and Rotate. The structural design of both concepts reflects the experience gained in composite structural design through the study effort. The mechanical designs are conventional and uncomplicated and should possess high reliability.

4.0 KEY STUDY RESULTS

The Closure Analysis and Test Study has resulted in several significant findings relative to the design of an advanced silo closure system. Broadly, these findings indicate viable solutions to problems attendant to the design of a closure operating/debris management system required to survive a close-in nuclear attach. Insight has been gained into the fundamental behavior of composite structural systems under combined states of stress, and methods of predicting this behavior have been developed. These methods have been validated by both full-scale and subscale experiment.

The remainder of this section is devoted to a summary of the more significant findings of the study. A detailed presentation may be found in Volume II, Technical Report.

4.1 Integrated Closure System Design

The primary purpose of the Closure Analysis and Test Study, as stated in the Contract Work Statement, was to establish a technological base necessary to support the credibility of conceptual designs for a functionally integrated closure system capable of remaining operational following exposure to very severe nuclear attack environments. This very broad requirement, when considered in respect to the nuclear attack criteria (Volume VIII, CLASSIFIED), resulted in several intensive study efforts to develop rationalized solutions in each of the several areas of interest, and an integrated effort to marry the discrete solutions into viable system concepts. The factors most influencing the development of a preferred system concept were structural response, radiation shielding, debris exclusion and, in a broad sense, system simplicity. The impact of each of these factors had to be thoroughly assessed before meaningful system solutions could be developed.

Structural response, or the ability of the structural system to withstand high-impulse loadings from overpressure, shock and thermal input, can be seen to be of major importance within the elevated threat regime considered. Since our study criteria required consideration of a composite concrete/steel closure configuration, the symmetry of the closure proper had to be persevered in any of the operating geometries considered. Analysis and experiments supported the contention that the load capacity of the closure was significantly enhanced by a circular confining steel shell. Under high axial loads the shell induces a combined state of stress, increasing the load capacity of the section in proportion to the strength of the shell. The system then, to benefit from this effort, must preserve the circular shape of the closure and limit asymmetry to the extent possible.

Radiation shielding requirements influence the mass of the closure and impose limitations upon the peripheral clearances to minimize gap streaming effects. For the study overpressure design level and the external radiation level specified, the thickness of concrete required for structural adequacy is approximately that required to provide the radiation attenuation. By providing a heavier steel bottom plate and side shell and higher strength concrete, it would be possible to reduce the thickness of the closure while maintaining the required structural capacity. However, special shielding materials would then be required and the fabrication complexity of the closure would be increased. As no apparent system advantage accrues as a result of a reduced closure thickness, it is recommended that the required radiation attenuation be provided by plain concrete. The thermal environment requires the inclusion of a surface layer of ablative material or the inclusion of an additional sacrificial thickness of concrete

Requirements for a sacrificial layer add approximately 10 percent to the total weight of the structure. Additionally, the locations and construction of steel structural members and operating attachments must be carefully chosen if heat influence and partial shielding effects are to be avoided. The reader is advised that a low confidence level should be assigned to our ability to predict the effect of the radiated thermal energy and the internal heating caused by neutron and gamma ray energy absorption on the structural properties of the closure materials.* With present-day understanding of material properties, it is impossible to define the behavior of concrete or steel under the combined pressure, thermal and radiation environment. Thus, it is mandatory that a detailed experimental program be implemented to obtain the necessary empirical data to support the development of a rational design techniques.

A significant portion of the conceptual system design effort was expended in developing system geometry that would ensure successful post-attack opening under the specified debris level and would also prevent debris from entering the missile silo. Several different methods of providing debris protection were considered, including plowing or blasting the debris off prior to opening, and providing debris pits to receive the debris during opening. The preferred concepts, however, utilize the closure itself as a debris removal mechanism and maintain the required clear fly-through

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* Refer to page 2-1.

envelope by extending an elevating shield which becomes an extension of the launch tube. This launch tube extension, or debris shield as it is referred to hereinafter, is provided with a cover which is opened just to missile launch.

The factor of system simplicity, or complexity, is of course relative to the alternates, and is difficult to assess against an absolute standard. For the purposes of a technological study, however, such an absolute assessment is seldom necessary and decisions can be based on judgment, as opposed to statistics. In rating the relative merits of competing concepts, we therefore adopted a rather straightforward policy which, in essence, stated: "Simple is good; complex is bad." The preferred concept under this system possessed the greatest number of "good" features and the fewest number of "bad." Of course, the evaluation assumed that either "good" or "bad" would function as designed. While reliability was not a specific constraint upon our development efforts, this approach provided a measure of discipline by assuring that the least complex concepts received the maximum emphasis.

A concentrated effort was expended to produce subsystem concepts that were relatively insensitive to variations in design criteria and whose geometry provided the capacity to accommodate an increase in threat levels. Concepts possessing these features received higher ratings in the evaluation procedure. Initially all system conceptual designs were evaluated on the basis of post-attack hydraulic operation. However, the evaluation of the hydraulic actuation system identified the following subsystem deficiencies:

(1) The space required to house the hydraulic pumps, reservoirs, and control equipment would cause an inordinate increase in the size, cost, and complexity of the launcher facility.

(2) Providing the post-attack electrical horsepower to operate the hydraulic system appeared unfeasible on the basis of cost and total weapon system reliability.

(3) Because of the complexity of the hydraulic control equipment and interconnecting piping, achieving the desired reliability would be costly and expensive.

Because of the problems associated with hydraulic actuation, all conceptual design on this actuation method was ceased and an investigation of the practicability of a gas generator power source was initiated. Two basic system concepts were considered: a gas generator to provide actuation power by pressurizing a hydraulic accumulator, and a gas generator discharging directly into the closure actuators. The pressurized accumulator concept was discarded as problems (1) and (3), previously discussed for the hydraulic system, still remained. The recommended post-attack actuation power system consists of gas generators discharging directly into the closure actuators. A system of this type should incorporate the following features:

(1) Prevent the gas generator from sensing variations in opening loads by discharging the gas through a sonic nozzle into the actuator. This greatly simplifies the design of the gas generator as case pressure, mass flow rate and burn time are the design conditions to be met.

(2) Because the sonic nozzle will reduce the delivered pressure to one-half the gas generator case pressure, the gas generator should be operated at a relatively high pressure in the interest of system efficiency. The preferred designs shown in Volume II require a gas generator operating pressure of 11,000 psi. Propellants capable of stable operation coupled with reasonable flame temperatures at this pressure level are currently available.

(3) The portion of the actuator down stream of the piston should be filled with fluid which will be discharged through an orifice as the piston is raised by the gas pressure. This feature will damp out transients in piston velocity caused by (unpredictable) variations in the closure load time history.

The recommended pre-attack actuation method is that of pressurizing the actuators with an inert high pressure (approximately 2000 psi) gas. The high pressure gas storage tanks could be located on-site or provided in a maintenance trailer. The propellant grain in the gas generators should be isolated from maintenance pressurization cycles by means of a metal blowout disk located downstream of the nozzle. The disk will prevent grain degradation due to the pressure cycling and the possibility of water vapor in the gas.

4.1.1 Concepts Considered

In the course of our studies eleven integrated closure concepts have been developed, each intended to satisfy the gross functional requirements. A brief description of the operation of each, together with illustrations and results of the concept analysis, follows. Expanded descriptions of these concepts are included in Volume II, Section 3, of this report.

Concept 1 - Single Bascule (Figure 4-1)

The closure covers the silo and a debris pit, and is actuated by two telescoping hydraulic cylinders. The covered debris shield is raised above grade by a hydraulically operated cable assembly mechanism, and the shield cover is then opened by a ballistic actuator.

This concept was eliminated because of the possibility of frozen debris bridging the debris pit and the requirement for very heavy retractable members to support the debris pit cover.

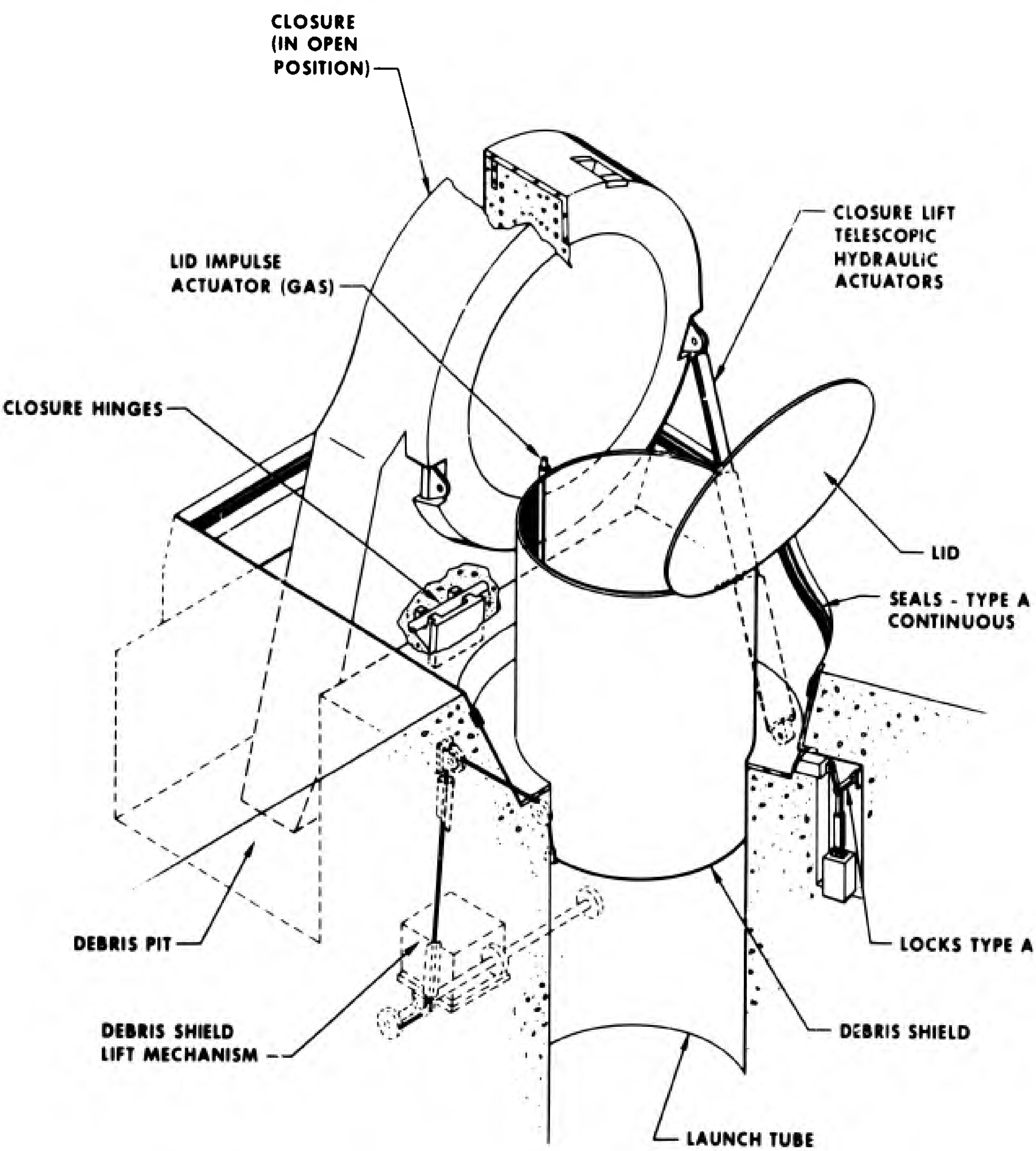
Concept 2 - Rise and Tilt - Preliminary (Figure 4-2)

The cylindrical closure is connected to a heavy debris shield by means of two tilt links and two tilt actuators. The closure and shield are raised by eight lift actuators to a position where the shield clears the debris. At this point the closure is tilted by the tipping actuator to clear the silo.

Because of the large silo diameter required to clear the tilting actuators and the resulting increase in closure thickness required to provide structural capacity, this concept was eliminated in favor of Concept 10, which is a revised version of Concept 2, with essentially the same operating geometry.

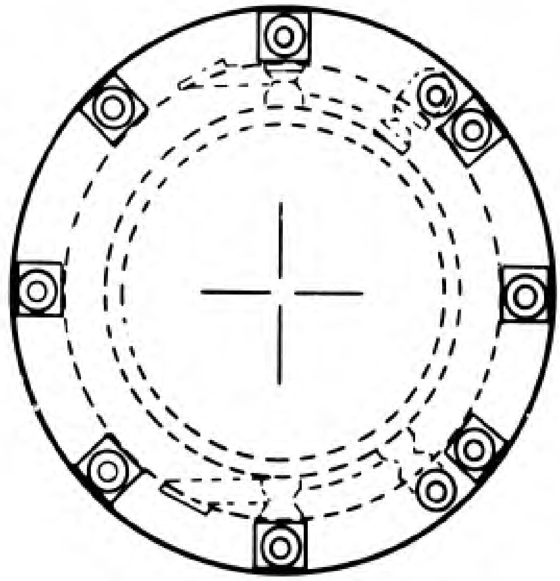
Concept 3 - Rise and Rotate (Figure 4-3)

The closure is raised by a single actuator designed to permit the closure to cantilever from the main support column. During the lift cycle, the debris shield is raised by means of a direct mechanical connection with the closure. At the desired elevation, the debris shield is latched in place, the closure rotated, and the debris shield cover opened.



CONCEPT 1 - SINGLE BASCULE

FIGURE 4-1



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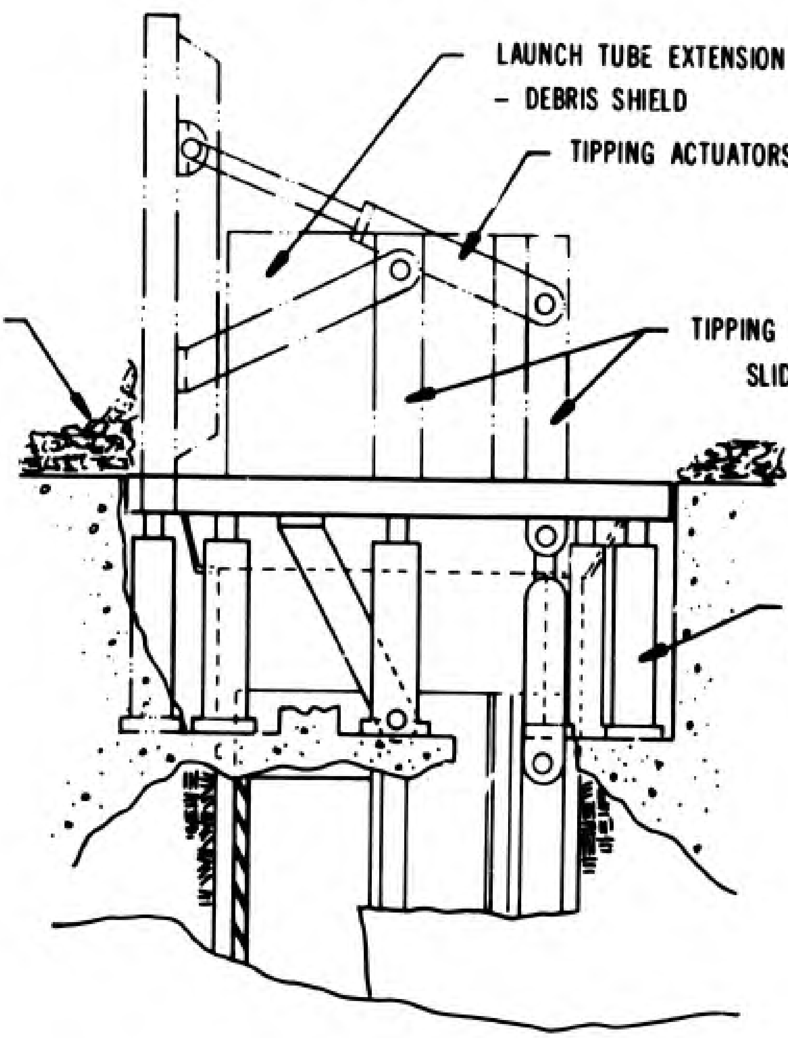
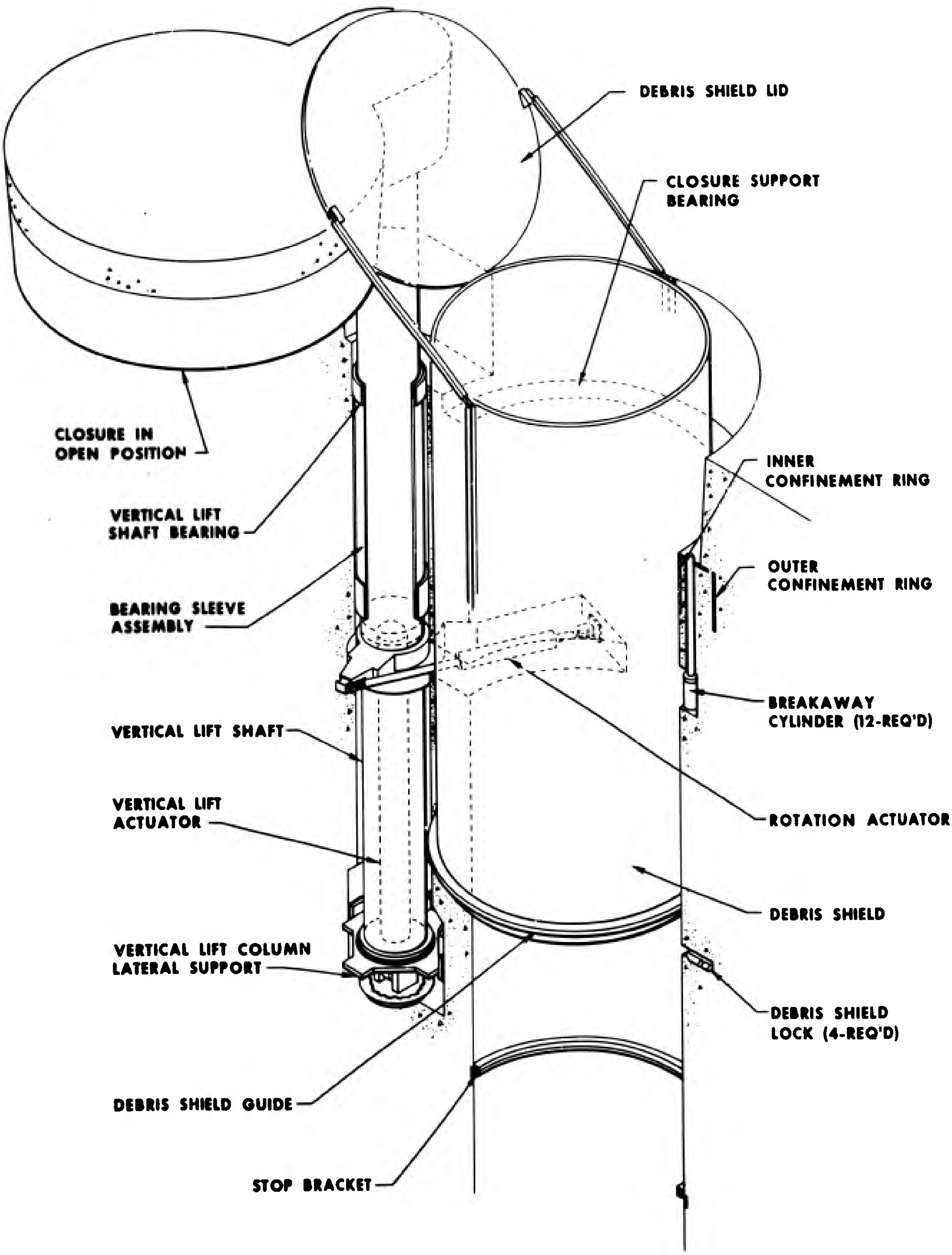


SECTION

CONCEPT 2 - RISE AND TILT - PRELIMINARY

FIGURE 4-2



CONCEPT 3 - RISE AND ROTATE

FIGURE 4-3

This concept was selected for preliminary design as it appeared to meet the functional requirements. Additional design efforts led to several changes in this concept. Details of the revised concept are contained in Volume II, Section 7, of this report.

<u>Concept 4 - Vertical Rise and Slide</u> (Figure 4-4)

A rectangular closure and attached debris shield are raised on a drawer/slide-type frame to an elevation above the anticipated debris level. Impulse actuators slide the closure clear of the missile flight path, and the debris shield cover is blown open by a cold-charge impulse actuator.

This concept was eliminated because of the heavy gear required for maintenance of the closure and access to the silo.

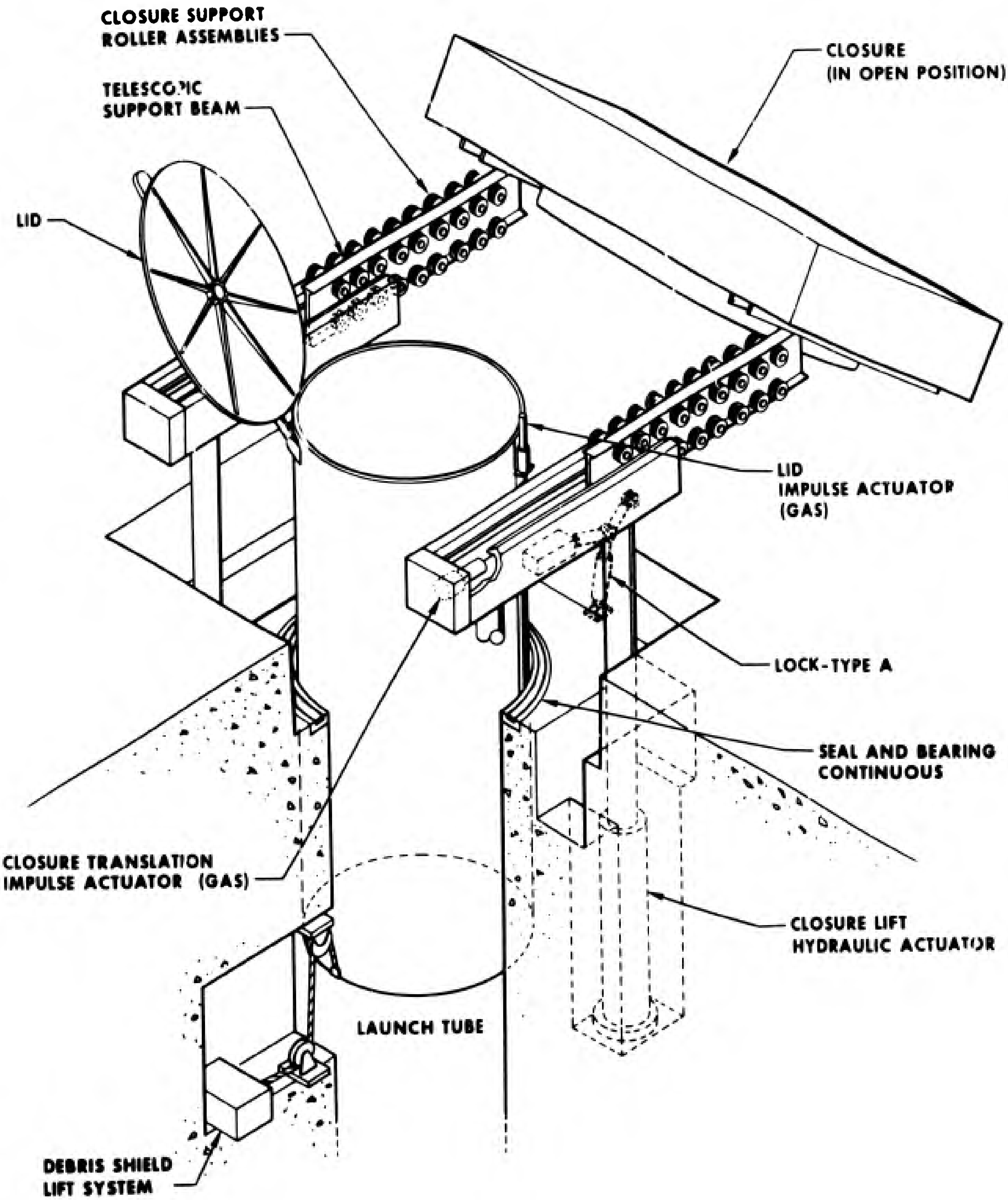
<u>Concept 5 - Horizontal Sliding With Cover</u> (Figure 4-5)

A rectangular closure and adjacent debris pit are sequenced to elevate the debris pit cover, and the main closure slides into the cleared area by means of impulse actuators. The debris shield is then raised and the cover opened by an impulse actuator.

This concept was eliminated because of the requirement for two independently actuated closures and the possibility of the main closure not clearing the silo due to debris buildup in the debris pocket, as well as the possibility of frozen debris bridging the main closure opening.

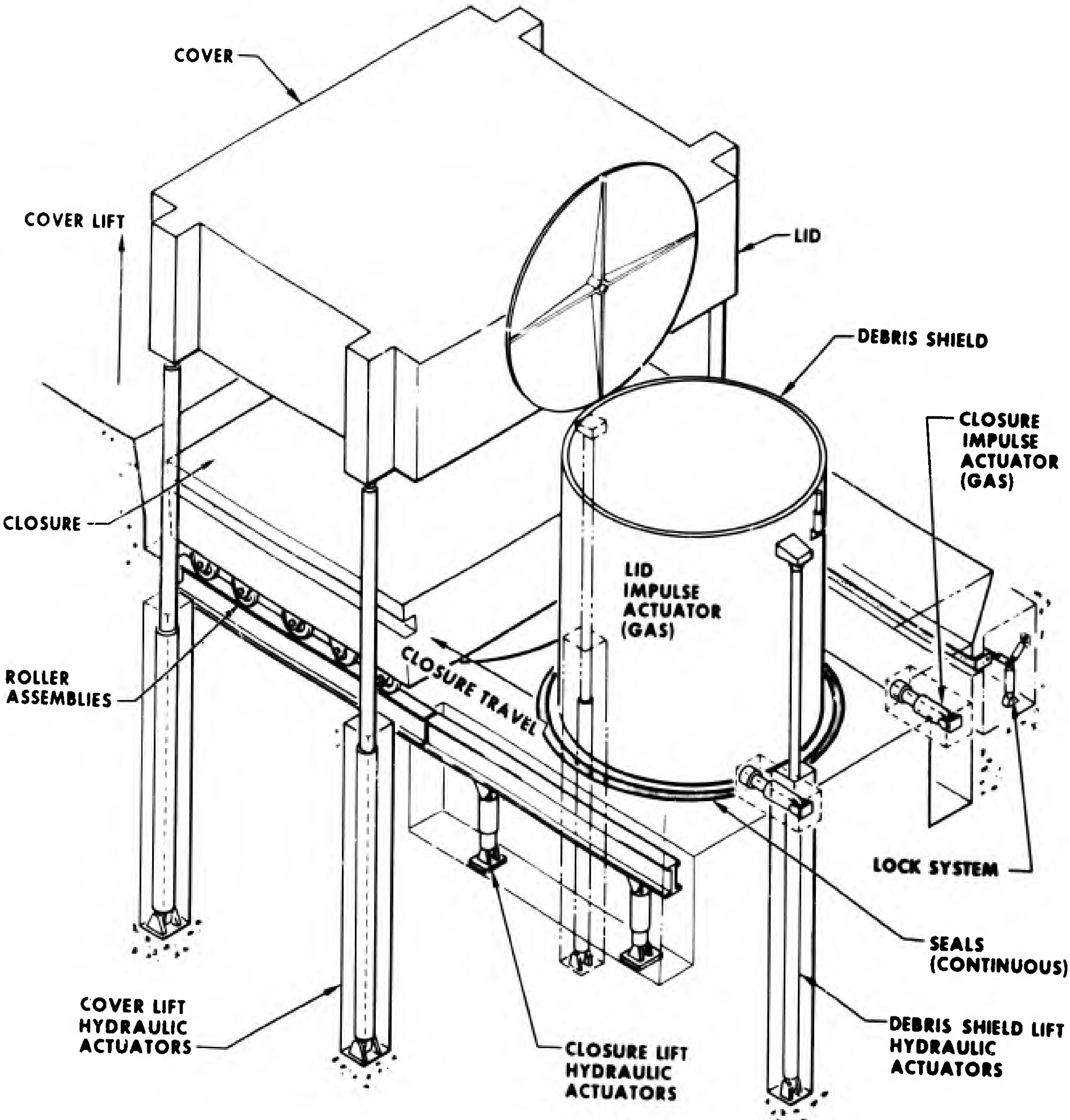
<u>Concept 6 - Single Leaf Pivot</u> (Figure 4-6)

This system is similar to Concept 1 (Single Bascule) except that the debris pit cover is extended to provide a counterweight effect, thereby reducing the amount of stored energy required. The debris shield is raised above grade by a cable mechanism attached to the closure. The shield cover is opened by means of an impulse actuator.



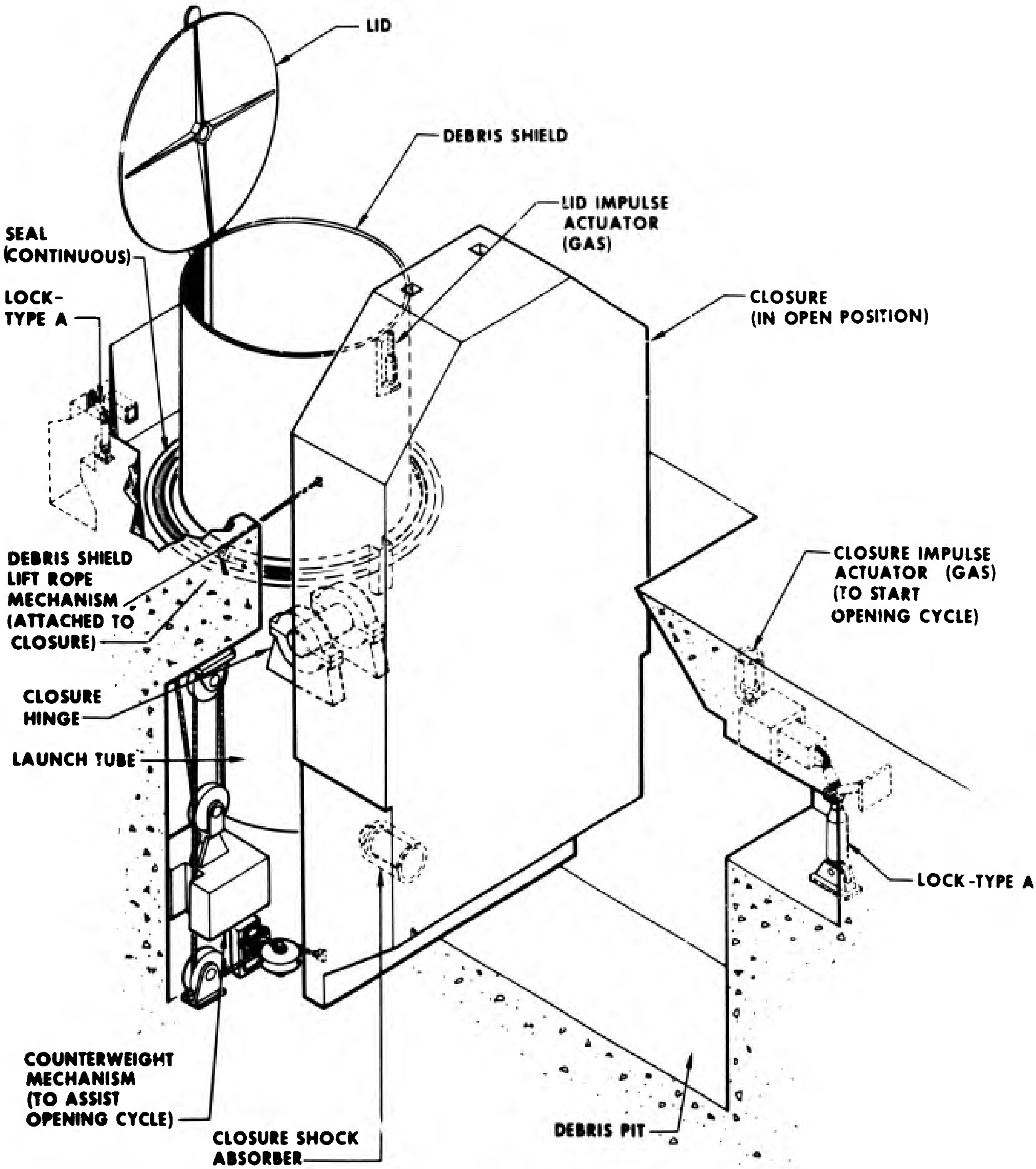
CONCEPT 4 - VERTICAL RISE AND SLIDE

FIGURE 4-4



CONCEPT 5 - HORIZONTAL SLIDING WITH COVER

FIGURE 4-5



CONCEPT 6 - SINGLE LEAF PIVOT

FIGURE 4-6

This concept was eliminated because of the possibility of frozen debris bridging the debris pit and the requirement for very heavy retractable members to support the debris pit cover.

Concept 7 - Revolving Turret (Figure 4-7)

In this concept the main closure is rotated rather than elevated. A radiation plug is lowered into the debris pit, a debris shield is raised to clear the remaining debris, and the main closure is rotated to uncover the silo.

This system was eliminated because of the possibility of frozen debris bridging the debris shield.

Concept 8 - Oblique Lift and Eject (Figure 4-8)

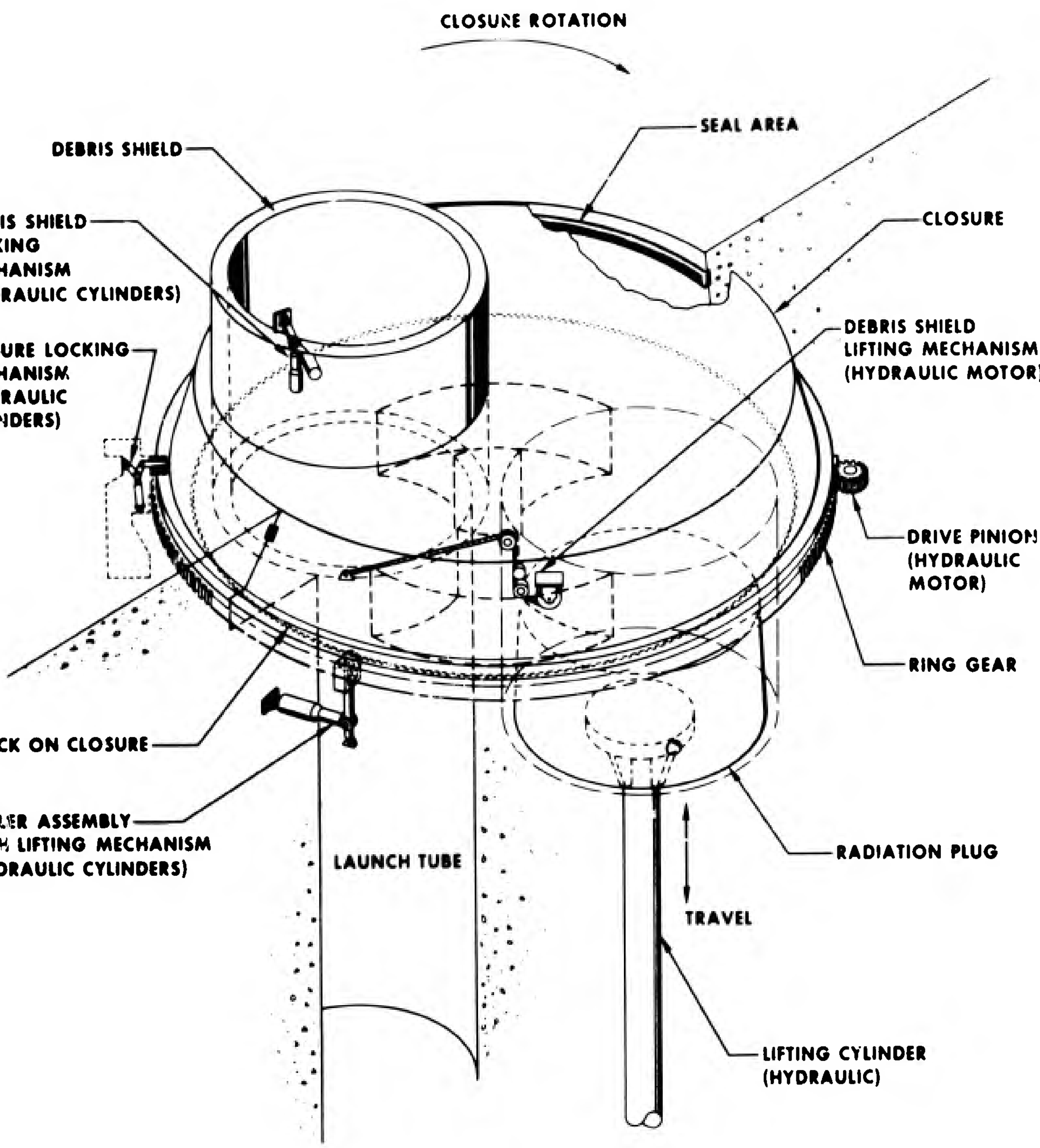
This concept uses a combination two-stage telescoping ram and a large-volume compressed air cylinder to engage and lift the closure. Compressed air is released when the ram is fully extended, propelling the closure clear of the silo opening. An extended trough catches the falling debris and routes it into an internal debris pit. The debris trough is then retracted and the silo is cleared for launch.

This concept was eliminated because of the number of complex and sequential operations required as well as the necessity for heavy handling gear for closure replacement during operational and maintenance cycles.

Concept 9 - Trap Door (Figure 4-9)

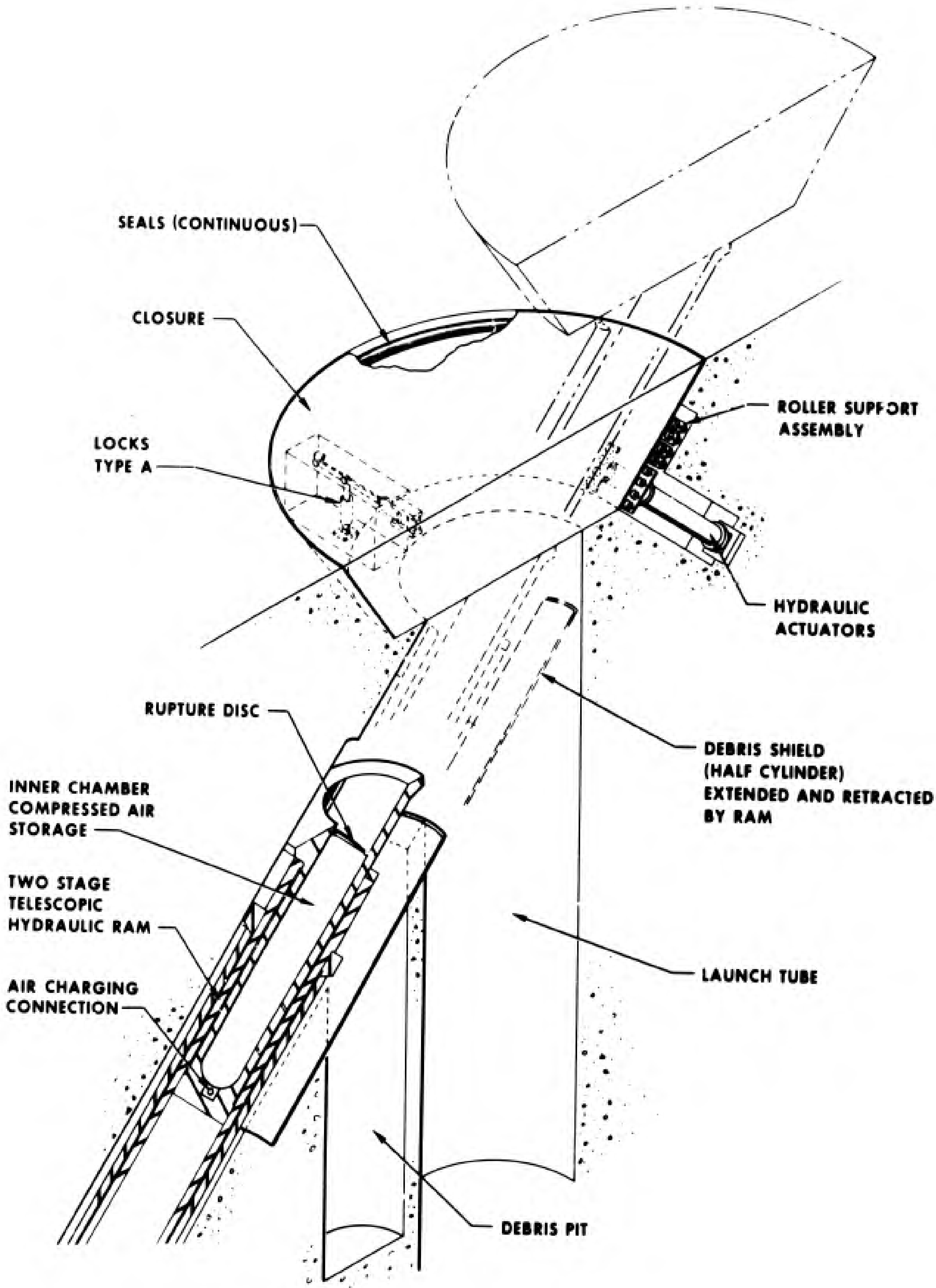
The closure is hinged so that it swings down into the silo. A debris diverter channels debris into the internal debris pit. The diverter which acts as a silo cover is then removed to clear the silo for launch.

This concept was eliminated because of the possibility of frozen debris bridging the silo opening.



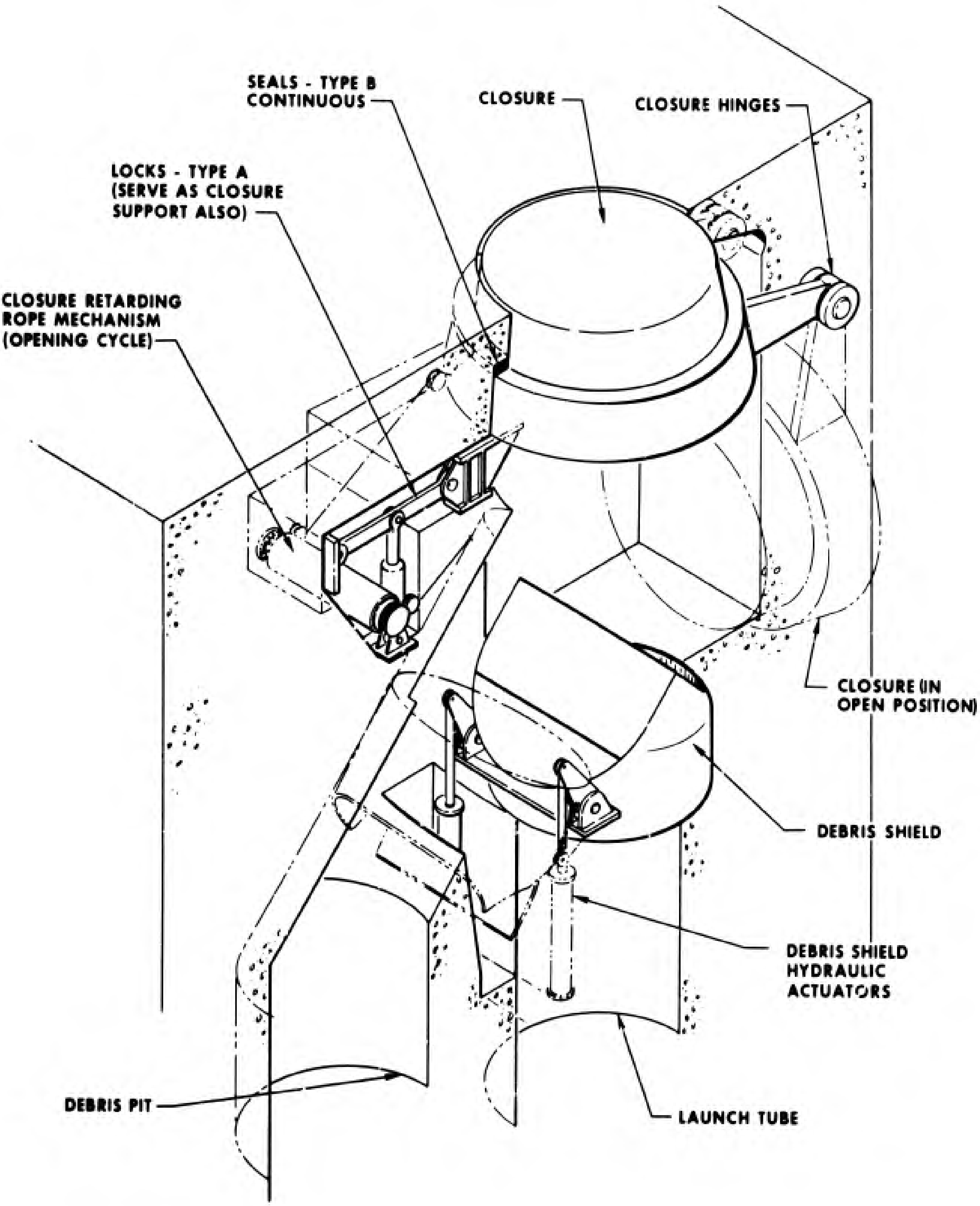
CONCEPT 7 - REVOLVING TURRET

FIGURE 4-7



CONCEPT 8 - OBLIQUE LIFT AND EJECT

FIGURE 4-8



CONCEPT 9 - TRAP DOOR

FIGURE 4-9

Concept 10 - Rise and Tilt - Final (Figure 4-10)

This concept has essentially the same operating geometry as Concept 2. The closure is raised vertically by four actuators with the debris shield following closely. At an elevation above the anticipated debris depth, the closure hinge actuators are stopped and the tilt actuators continue to rotate the closure to clear the missile flight path, and the debris shield cover is opened.

This concept was eliminated because of the difficulty of synchronizing the four actuators with any system that could approach the reliability of a concept using a single actuator.

Concept 11 - Single Hinge (Figure 4-11)

Operation of the closure is similar to that of Concept 1, except that the single actuator is located between the hinge and the closure center of gravity.

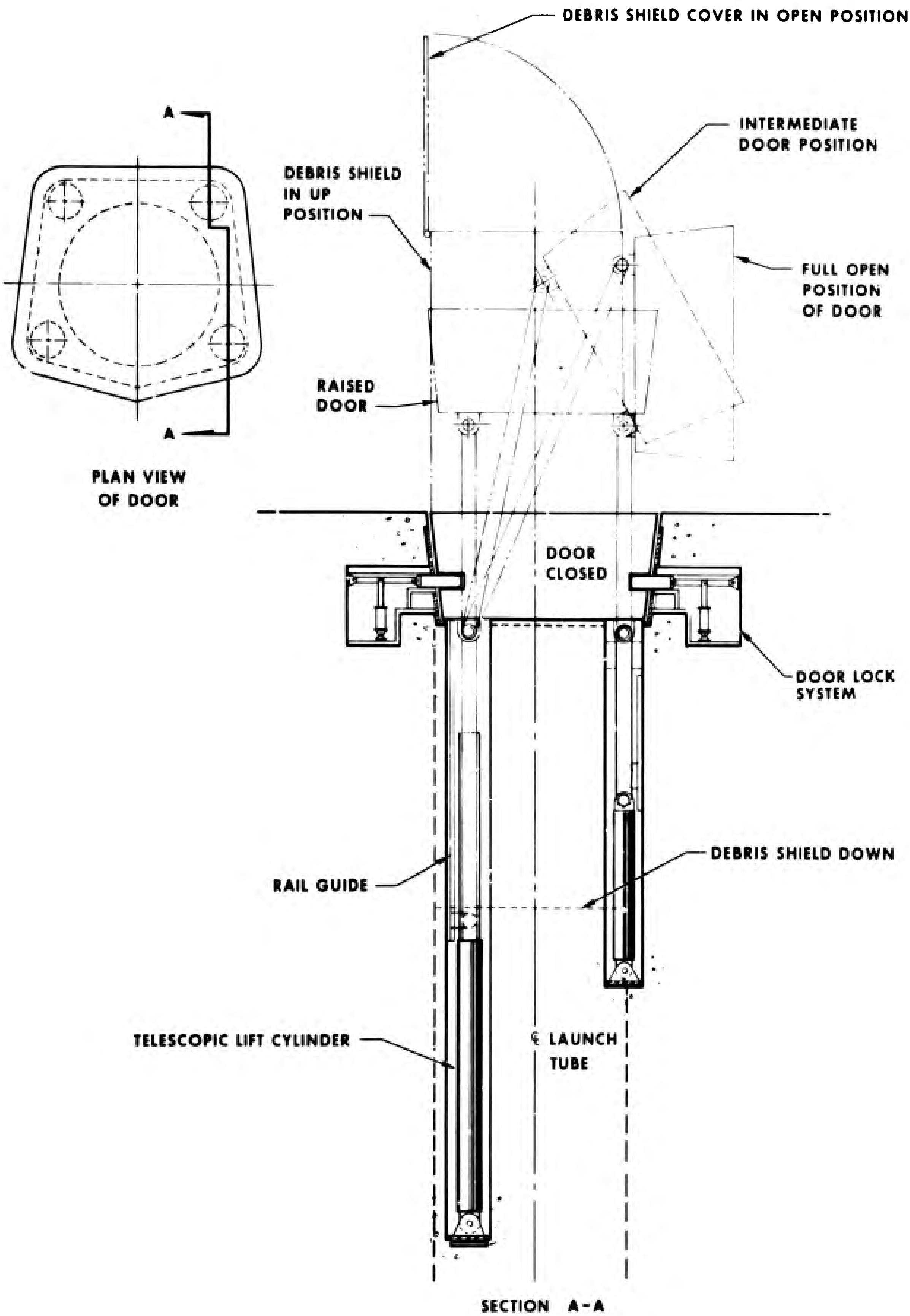
The debris shield, driven by hydraulic master/slave actuators, follows the closure opening very closely. During the last portion of the closure opening cycle, the debris shield lid is opened mechanically.

This concept was selected for preliminary design, and additional details may be found in Volume II, Section 7, of this report.

4.1.2 Selected Concepts

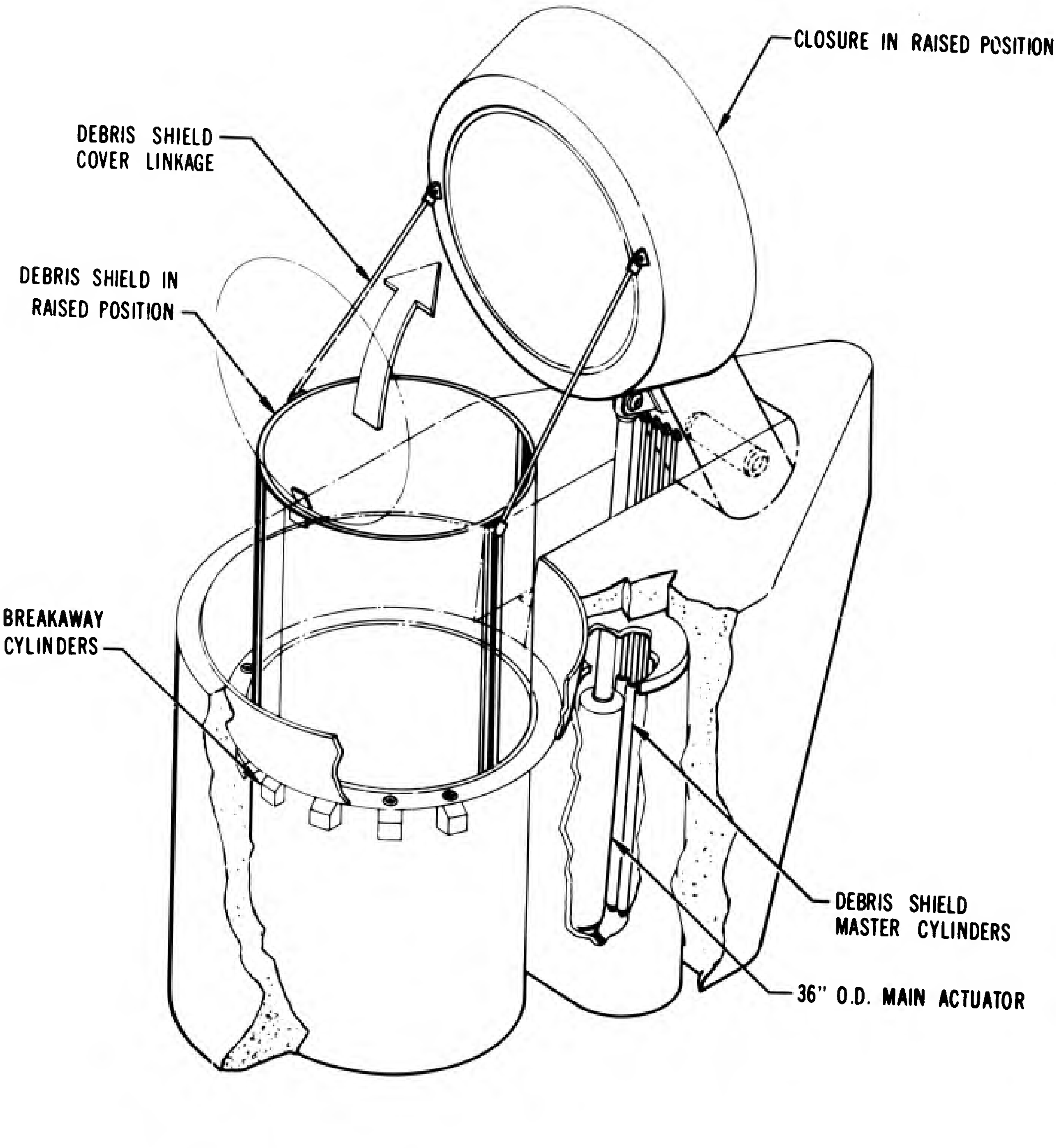
Single Hinge Concept

This design consists of an axisymmetric closure connected to a hinge point by a narrow composite beam. The closure is powered by a single actuator attached midway between the hinge and the closure center of gravity, and opens through an angle of approximately 76 degrees. A debris shield contained within the silo is raised simultaneously by means of a hydraulic



CONCEPT 10 - RISE AND TILT - FINAL

FIGURE 4-10



CONCEPT 11 - SINGLE HINGE

FIGURE 4-11

master/slave cylinder arrangement, with the master cylinders attached to the closure and powered by the closure opening motion. The fluid displaced from the master cylinders drives the slave cylinders attached to the debris shield raising the shield. At the completion of the shield elevation, the shield cover is raised by a mechanical linkage between the shield and closure during the remainder of the closure opening cycle.

In the closed position, the closure is restrained against rebound loads by an annular lock system which operates similar to a spring collet. Horizontal motions of the closure structure are accommodated by registry of the closure into the bearing support structure.

Short-stroke, high-force breakaway actuators are provided to assist in the initial motion of the closure through compacted, wet, or frozen debris.

System power is supplied by two solid propellant gas generators: one supplies the collet lock actuator system, and the other supplies the breakaway and main actuator systems. The collet lock actuators are pressurized approximately one second before the main and breakaway actuators. Sufficient force is available in the breakaway actuators to force the closure open in the event of a lock system failure.

<u>Rise and Rotate Concept</u>

This design is similar to the Single Hinge Concept in many of its functional components, i.e., axisymmetric closure, covered debris shield, breakaway actuators, collet lock, and power supply. The essential difference is in the opening mode.

The closure rises vertically, cantilevered on a heavy column, to an elevation greater than that of the anticipated debris depth, and is then rotated to clear the missile flight path. The column is povered by a single actuator for the raise cycle and by a second actuator for the rotate cycle. The debris shield is raised by the closure during elevation, latched in position at the end of the raise cycle, and disengaged from the closure during the rotate cycle. At the end of the rotate cycle, the shield cover master cylinders are pressurized, driving slave cylinders which open the cover.

4.2 Radiation Analysis

In order to establish the relative efficiency and accuracy of manual versus rigorous analytical procedures, three methods of radiation shielding analysis were employed during the course of this study. First, manual calculations were used to make a preliminary estimate of the minimum amount of ordinary concrete required to provide the necessary radiation attenuation. The dominant radiation component which necessitated this thickness was identified. After a preliminary closure design was generated on the basis of both preliminary radiation and structural analysis, detailed computer calculations of two types were used to evaluate the adequacy of the selected design. One-dimensional transport S_n calculations were made using the United Nuclear Corporation ANISN computer code, and, in addition, three-dimensional Monte Carlo transport calculations were performed on each radiation component using the UNC-SAM-2 code.

Comparisons were made between results of the two computer methods of calculation and also with results of the manual method. All three methods indicated that the shielding provided by the preliminary closure design (90.25 in. of reinforced concrete) was more than adequate to meet the required in-silo environment. The calculations predicting silo radiation levels showed agreement within the range of 10 to 50 percent, which is excellent correlation considering that large attenuation factors are involved. The 50-percent variation in predicted silo radiation level corresponds to a variation in shielding thickness of approximately 2 inches. It was concluded that the less expensive manual calculations described fully in Volume IV are adequate for calculation of radiation attenuation through the composite closure structure.

As the final closure design provided greater attenuation than the preliminary design, because of structural considerations a rigorous analysis of the final closure structure was not performed.

Analysis was performed to assess the benefits to be derived through use of enhanced shielding materials. Through use of dense aggregate concretes such as magnetite, barites, or ferrophosphorous, or a combination of ordinary concrete and dense material such as steel or depleted uranium, the thickness of the shield can be reduced roughly in inverse proportion to density. However, little, if any, weight reduction is realized. Both weight and thickness could be reduced through use of a combination of preferred neutron interaction materials such as lithium hydride or polyethylene at the top, in conjunction with high density materials at the bottom. Unfortunately, these special materials, in addition to being relatively expensive, do not offer the structural strength and chemical stability required to meet the environmental conditions, and hence do not appear feasible.

The relative cost and shielding worth of a number of materials were assessed and are presented in Volume II (Section 4.0). Ordinary concrete was found to be the most economical shielding material by a considerable margin. Next in line is magnetite concrete which offers approximately a 25-percent reduction in thickness for a threefold increase in cost.

The energy deposition profile through the closure resulting from radiation attenuation was calculated and combined with the effects of incident thermal and X-ray radiation in order to estimate the surface ablation effects and the internal damage level. Unfortunately, insufficient experimental data concerning thermal damage to concrete or other materials under these severe exposure conditions is available to provide a basis for making a credible prediction of the amount of damage to be expected. It is recommended that this phenomenon be investigated on an accelerated basis so that sufficient test data will be available to support the formulation of a rational prediction method.

The possibility of excessive radiation leakage through a closure gap due to looseness of fit was evaluated and design guidelines were established. In general, the requirements for adequate design are not conflicting with mechanical constraints. The gap and degree of offset with respect to the inside silo wall were satisfactory for both the preliminary and final design closures, although layout of the breakaway cylinders required special consideration to avoid a potential problem.

On the basis of these study results, a recommended procedure for approaching future closure shielding design problems is presented in Volume II (Section 4.0).

4.3 Subscale Static Tests and Analysis

4.3.1 Basis for Model Designs

a. Introduction

In accordance with work statement requirements, preliminary full-scale structural designs for both reinforced concrete and composite closures were developed concurrently with subsystem concept investigations. The subsystem concepts were then evaluated to determine the impact on operating characteristics caused by each type of closure structure. On this basis, it was determined that the reinforced concrete design would impact the subsystem concepts in the following manner:

(1) The wider bearing width required for the reinforced concrete design increased the mass of this closure approximately 50 percent over the composite design.

(2) Because of the increase in area caused by the wider bearing width, the weight and volume of debris to be handled increased proportionately with closure mass.

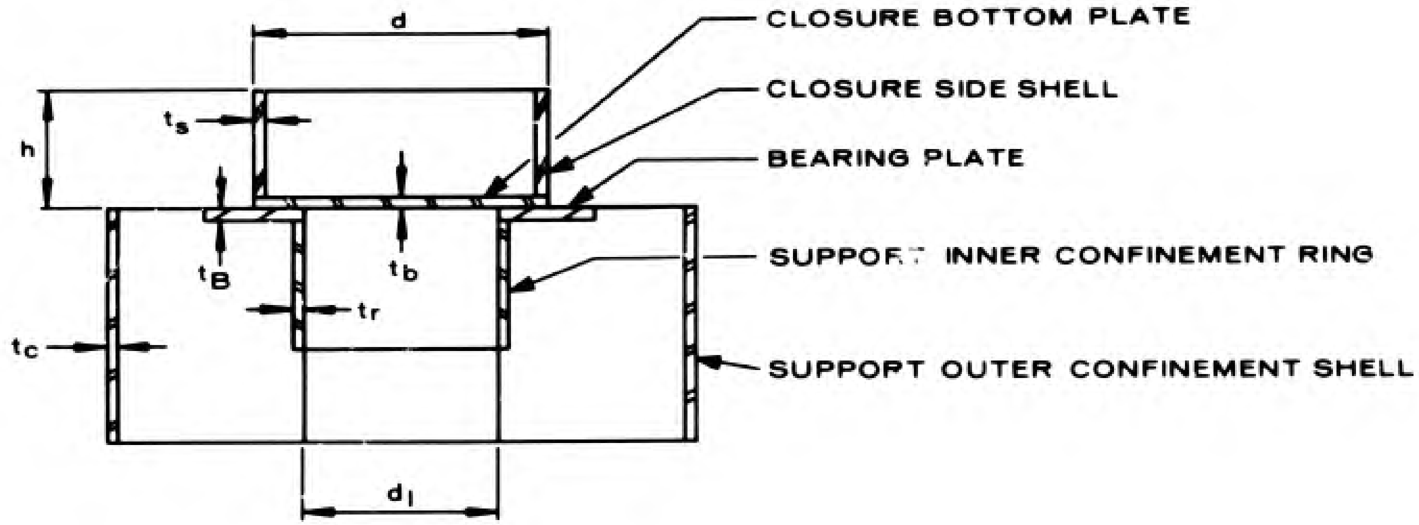
(3) Because of (1) and (2) above, the actuation equipment size and horsepower requirements would increase markedly if a reinforced concrete closure were selected.

(4) The reinforced concrete design appeared to be costly and difficult to construct because of the high percentage of steel required.

Although the above listing of subsystem disadvantages attributable to the reinforced concrete design was rather formidable, the composite closure suffered from a serious defect as well. This was the low confidence level assigned to the accuracy of the preliminary calculations for the composite design. However, after considering the subsystem advantages that would accrue from the composite structure, Parsons recommended that the reinforced concrete closure be eliminated from further consideration. SAMSO/Aerospace concurred and the general closure/support configuration shown in Figure 4-12 evolved.

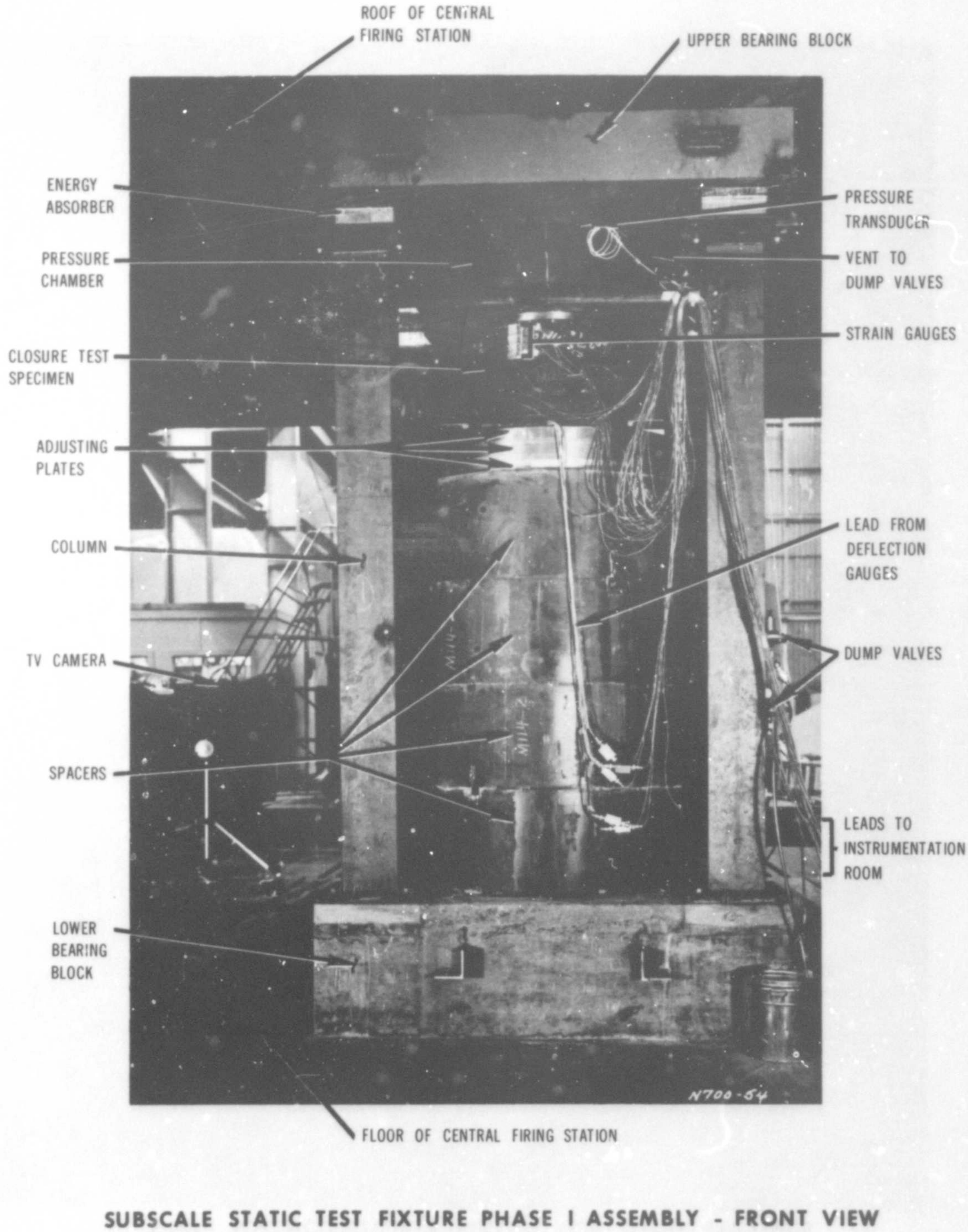
b. Phase I Testing

In Phase I of the static test series, models were proportioned by simplified manual design procedures to provide data points within the load range of the test apparatus designed by Parsons. It was thus necessary to limit model load capacity to 12 million pounds. A basic closure diameter of 32-1/4 inches was selected which would allow approximately 15,000 psi to be applied to the model surface. The configuration of the static test fixture, the static test fixture control panel, and a typical test model ready for insertion into the fixture are shown in Figures 4-13, 4-14 and 4-15, respectively. A complete description of the test apparatus is included in Volume VII.



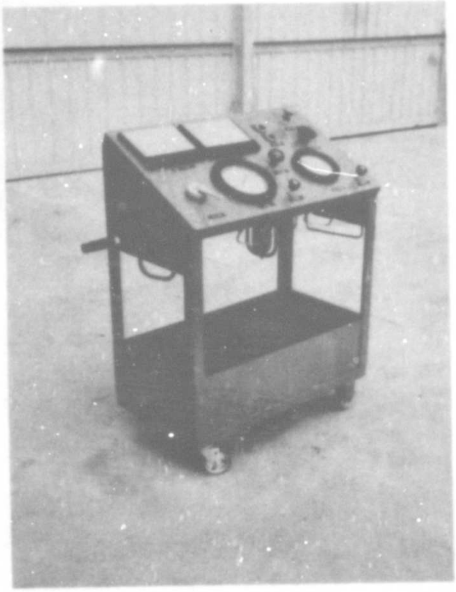
CLOSURE/SUPPORT CONFIGURATION

FIGURE 4-12



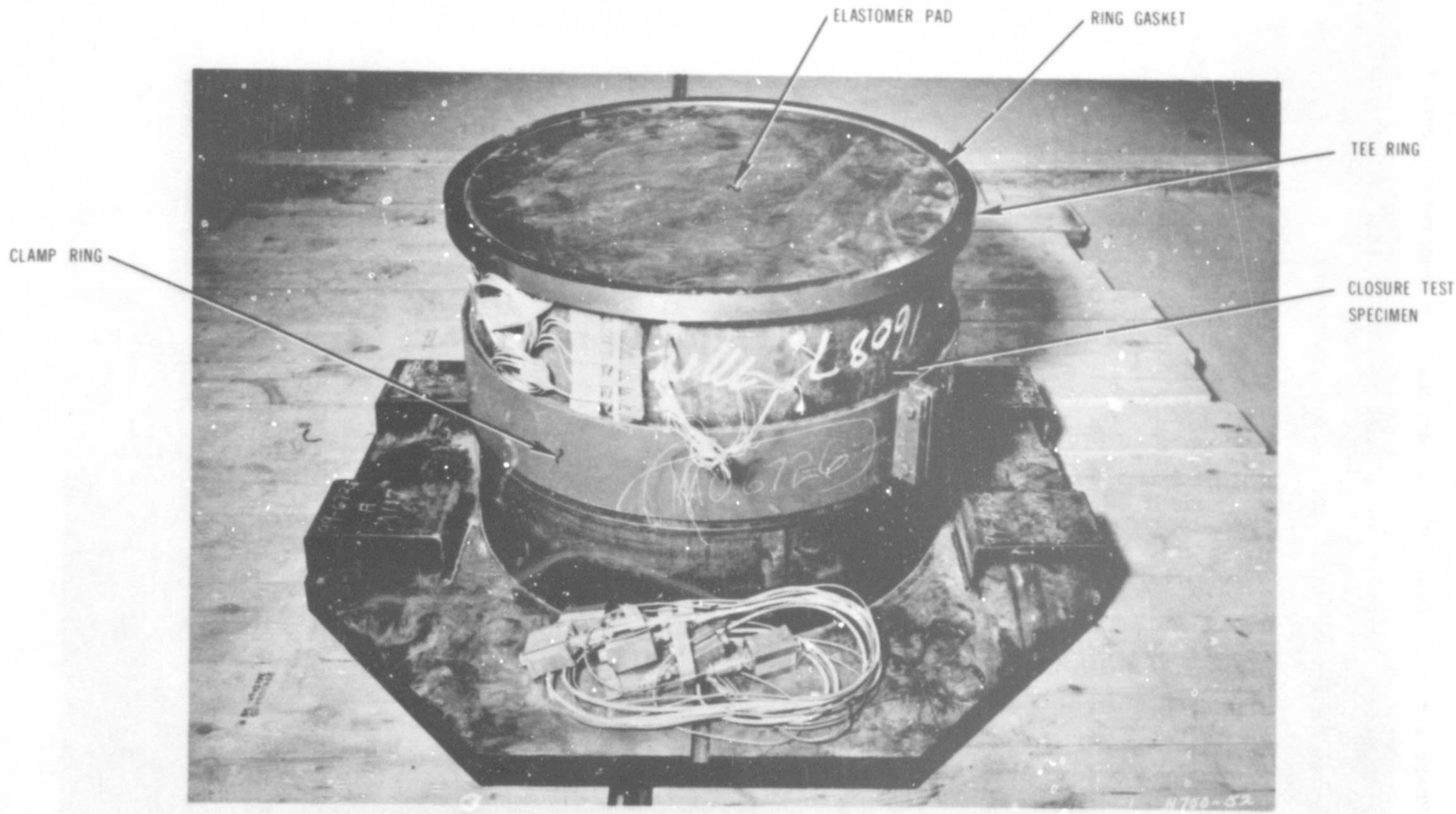
SUBSCALE STATIC TEST FIXTURE PHASE I ASSEMBLY - FRONT VIEW

FIGURE 4-13



SUBSCALE STATIC TEST FIXTURE REMOTE CONTROL PANEL

FIGURE 4-14



SUBSCALE STATIC TEST PROGRAM CLOSURE TEST SPECIMEN ASSEMBLY

FIGURE 4-15

In the Phase I models designed by Parsons, the concrete strength and the steel strength were held constant as well as the overall dimensions. Steel plate thicknesses in the closures and silo support were varied to provide the required variations in load capacities. The effect of support friction and stiffness was examined by testing closure models on low and high friction rigid supports as well as on idealized closure support structures. Predictions of failure load capacities were made for all test structure configurations. Predictions versus actual load capacity are shown in Table 4-1.

A model similar to one tested by the University of Illinois in a previous test program was scaled up and tested to investigate the effect of scale factor on load capacity and to relate the Closure Analysis and Test program to the work of previous researchers. Duplicate tests were performed on this model and on one other configuration to establish the reproducibility of test results.

c. Phase II Testing

In the Phase II static testing, the results of Phase I were used to modify the manual design procedure for proportioning closure models and for predicting failure load capacities of closure and closure/support combinations. A pause in the testing allowed time to select future models to examine critical parameters identified in the first phase of static testing. In Phase II, the effect on model load capacity caused by varying the following parameters was examined:

- Span-to-depth ratio
- Bearing width

TABLE 4-1

MANUAL LOAD PREDICTIONS

Test Number	Load Capacity, ksi		% Error
	Actual	Predicted	
1	2.6	2.5	0
2	2.6	2.5	0
3	3.4	4.5	32
4	3.6	4.5	25
5	3.2	4.5	40
6	3.0	4.5	50
7	4.7	4.5	4
8	6.4	9.0	40
9	3.8	5.0	32
10	6.8	10.0	47
11	4.1	5.0	22
12	2.9	9.0	200
13	8.8	12.0	36
14	4.2	4.5	7
15	2.8	9.0	220

- Closure side shell thickness
- Closure bottom plate thickness
- Silo bearing plate thickness
- Support outer confinement shell thickness
- Support inner confinement ring thickness
- Bearing launch configuration
- Concrete strength
- Steel strength
- Reduced support friction
- Closure/closure support interaction phenomena

4.3.2 Significant Test Findings

For the span-to-depth ratios under consideration, the total load capacity and the mode of closure failure changes as the confining plate load capacities are varied. With low strength steel plates, yielding of the side shell occurs, accompanied by a catastrophic shear failure in the concrete section; with high strength steel plates, the observed failure is quite ductile, consisting of a yielding of the steel side shell and local failure of the concrete in the bearing area. If the closure confining shell is properly selected, high bearing stresses can be safely resisted.

The tensile load capacity of the steel side shell influences the mode of failure and the total collapse load to a greater degree than does the plate strength of the bottom plate.

For the closure supporting structures tested, the tensile load capacity of the outer steel shell influenced the total support load capacity to a far greater degree than did variation in the thickness of the inner confining ring or the bearing ring.

The total load capacity of the closure and its supporting structure is influenced by the interaction of the two structures. Under static loading, the closure and its support act to some degree as one structure; failure in one of the structural elements may precipitate failure in the other element. The interaction phenomenon requires additional study.

The following effects of parametric variations were noted:

- A 50-percent variation from the nominal span-to-depth ratio of 2/1 has a minimum effect on the total load capacity of representative closures
- Up to a critical strain point, the ultimate (IID/2/1127) steel strength in the shell is of greater significance than is steel stiffness
- For a given steel shell thickness, the load capacity of the closure varies as a function of the concrete strength
- The outside shells of both the closure and the closure support are of primary design importance

4.3.3 Analytical Techniques and Assumptions

a. Manual Design Technique

A manual design technique was initially developed to grossly proportion static test models. The approach considered three modes of closure response. A total capacity was determined based on an assumed failure shear stress at one-half the closure thickness from the support. A bending capacity was determined based on the resistive moment capacity of the concrete and closure bottom plate. The bearing strength was determined based on the assumed maximum concrete bearing capacity available, taking into account the additional strength due to the confinement provided by the steel side shell. The prediction of total load capacity and failure mode was based on the lowest failure.

The support structure was designed assuming that both vertical and radial load components would be induced from the closure structure. The support outer confinement shell was proportioned to withstand the radially induced load component, while the support inner confinement ring was proportioned to effectively increase the allowable concrete bearing stress in the support structures.

The manual technique gave only fair results in comparison with the experiments. This is to be expected in light of the complex three-dimensional nature of the actual problem.

b. Finite-Element Analysis

A nonlinear finite-element computer analysis was undertaken utilizing an axially symmetric element configuration. The well-known von-Mises criterion of failure was implemented for the steel, and a criterion which took into account the hydrostatic as well as the deviatoric stress components was used for concrete. The criterion for concrete thus took into account the fact that concrete does not have great strength in tension but yet has high strength in a triaxial state of compression.

As shown in Table 4-2, the load capacities predicted using the finite-element technique agreed very well with those observed experimentally.

TABLE 4-2

FINITE-ELEMENT LOAD PREDICTIONS

Test Number	Description	Load Capacity, psi		% Error
		Actual	Predicted	
(3,4)	Closure on low friction support 40 ksi steel	3500	3750	7.1
8	Closure on silo support structure	6400	6250	2.3
21	Closure on low friction support 160 ksi steel	7250	7250	0

c. Empirical Relation

Based on a regression analysis of the test data, the collapse load Q of the closure structures tested on low friction supports can be expressed in the functional form shown below.

The prediction function has the form:

$$Q = B_o + B_1 \left(\frac{t_s}{d_1} f_s\right) + B_2 \left(\frac{t_b}{d_1} f_s\right) + B_3 \left(f'_c\right)$$

where f_s = steel yield strength

f'_c = unconfined concrete strength

B_o, B_1, B_2, B_3 = the linear regression coefficients

and the other parameters are as defined in Figure 4-16.

LEGEND

CLOSURE

- d DIAMETER
- h DEPTH
- t_s SIDE SHELL THICKNESS
- t_b BOTTOM PLATE THICKNESS

CLOSURE SUPPORT

FOUNDATION

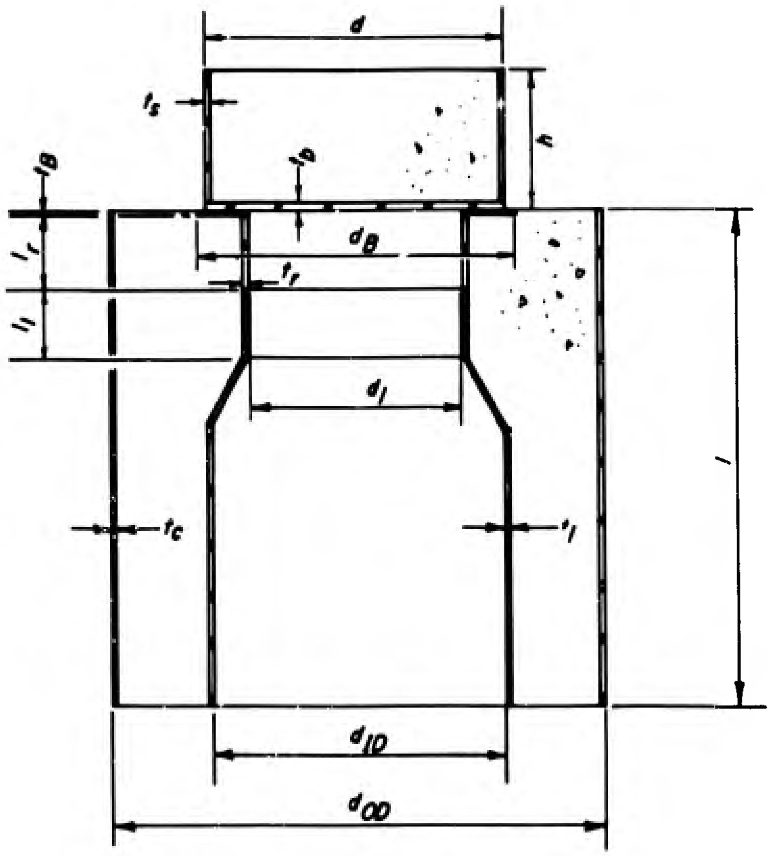
- d_l CLEAR INSIDE DIAMETER OF SUPPORT UNDER CLOSURE
- l TOTAL DEPTH
- d_{OD} OUTSIDE DIAMETER
- d_{ID} CLEAR INSIDE DIAMETER OF LOWER PORTION

BEARING ASSEMBLY

- d_B OUTSIDE DIAMETER OF BEARING RING
- t_B BEARING PLATE THICKNESS
- l_r VERTICAL DIMENSION OF BEARING SHELL
- t_r BEARING SHELL THICKNESS

LINER AND CONFINING SHELL

- t_l LINER PLATE THICKNESS
- l_l VERTICAL DIMENSION OF LINER PLATE
- t_c OUTER SHELL THICKNESS



STATIC TEST SPECIMENS

FIGURE 4-16

Using 23 sets of sampling data available, the regression coefficients B_o, B_1, B_2, and B_3 were determined using a multiple regression and correlation analysis. Their values were:

$$B_o = 0.40$$

$$B_1 = 4.9$$

$$B_2 = 2.3$$

$$B_3 = 0.23$$

The above constants are to be used in conjunction with stresses in kips per square inch. The following limits must be considered in light of the experimental data available:

$$1.3 \leq \frac{h}{d} \leq 3.5$$

$$0.00 \leq \frac{t_b}{d} \;\&\; \frac{t_s}{d} \leq 0.03$$

$$36 \text{ ksi} \leq f_s \leq 70 \text{ ksi}$$

$$3 \text{ ksi} \leq f'_c \leq 12 \text{ ksi}$$

This prediction function when compared with the low friction test data yields a multiple regression coefficient of 0.92, which shows extremely good correlation, especially in light of the small sample size of the test data. Predicted load capacities utilizing the regression analysis formula versus observed test results are depicted in Table 4-3.

TABLE 4-3

REGRESSION ANALYSIS LOAD PREDICTIONS

Test No.	Load Capacity, ksi		% Error
	Actual	Predicted	
(1,2)	2.6	2.2	15
(3,4)	3.5	3.3	6
7*/	4.7	3.3	30
8*/	6.4	5.6	12
13	8.8	8.0	9
14*/	4.2	3.3	21
16	5.5	4.7	22
17	3.7	3.3	11
18	2.8	2.6	7
19	5.5	5.6	2
20	6.6	7.0	6
21	7.3	10.2**/	40
22	4.9	4.9	0
23	6.4	5.6	12
24	3.4	3.3	3
25	3.3	3.3	0
26	1.0	1.0	0
27	1.1	1.0	10
28	4.1	3.3	19
29	8.3	8.0	4
30	6.8	8.0	18

*/ Test on bearing other than low friction support.

**/ Extrapolated region.

4.3.4 Applicability to Full-Scale Design

The static test data should be directly relatable to full-size structures since no materials were scaled and all stresses and pressures should be equivalent in the model and the full-size structure. Difficulties encountered in using the data for full-size dynamically loaded closure structures occur in the determination of the actual dynamic load factor in predicting the degradation in load capacity caused by repeated dynamic loading, and also in predicting the dynamic failure mode. However, it is recommended that the one-time dynamic load capacity be considered to be at least equal to the static failure load.

4.4 Subscale Operating Tests and Analysis

The purposes of the subscale operating tests and analysis element of the program were (1) to demonstrate that the Rise and Rotate, Rise and Tilt and Single Hinge closure concepts could or could not operate successfully under simulated post-attack debris conditions with respect to their opening and debris removal/exclusion features, (2) to develop additional engineering data regarding debris characteristics, and (3) to recommend changes and improvements in design leading to the selection of a preferred closure system concept.

Debris is defined as the material ejected from the crater formed by a nuclear weapons burst. On the basis of the criteria furnished, it is assumed that the surface of the silo closure and its surroundings could be covered with an infinite expanse of debris following an attack.

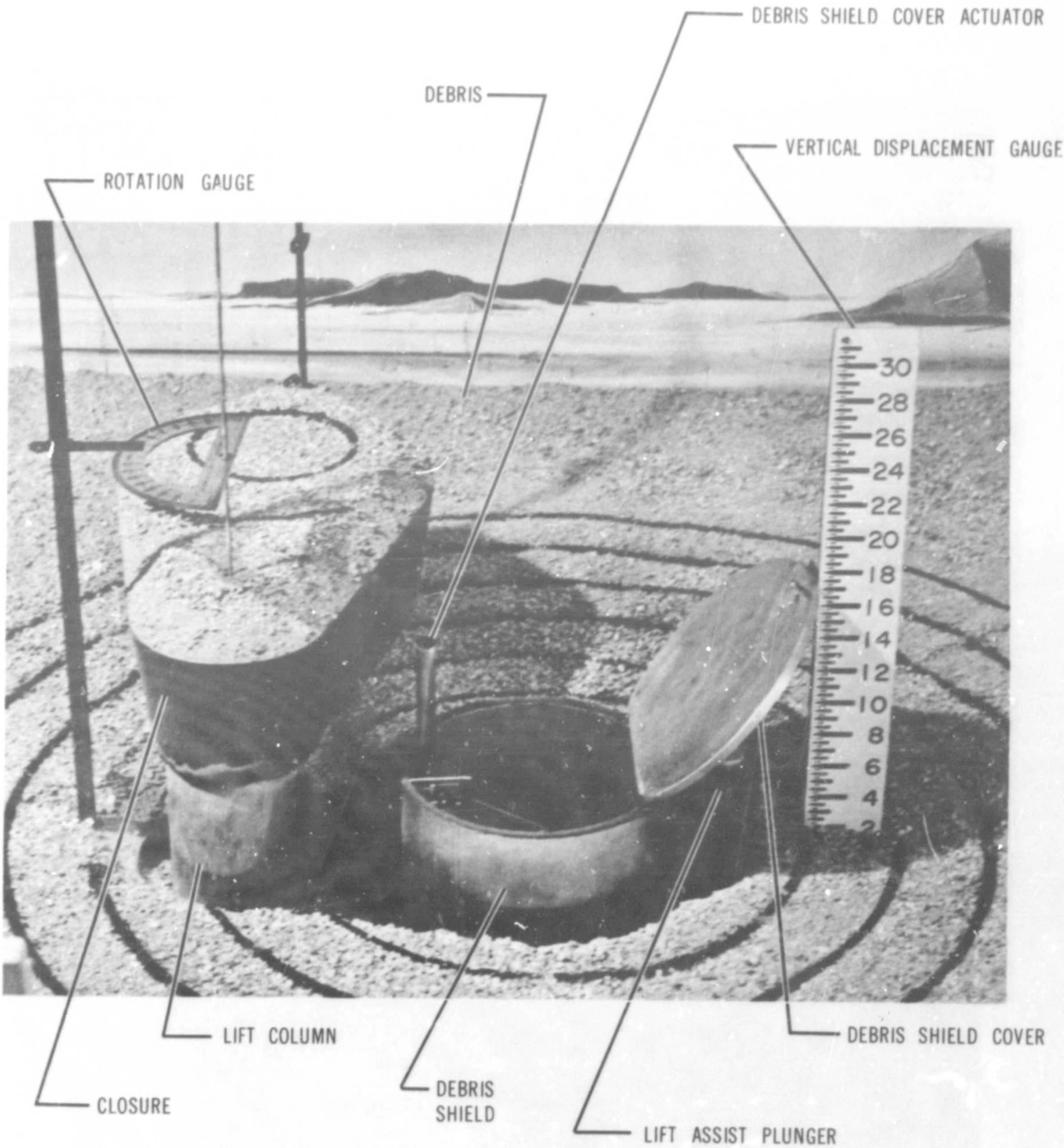
Basic requirements of the closure system are that it must protect the missile from windborne and blast-induced debris, be capable of reliable operation even though buried under debris, and must positively prevent debris from falling into the launch tube as the closure is opened.

Reliable, accurate predictions of the physical properties and depths of the debris are not available, and there is little documented experimental data covering these effects. In addition, natural environmental effects such as rain or freezing temperatures impose the requirements that the closure system must be capable of reliable operation under dry, wet, or frozen debris conditions.

Accordingly, a series of subscale operating tests and studies were conducted to investigate parametrically the functional operation and debris removal/exclusion capabilities of the selected closure system under several types of debris, including dry solids, wet solids, and frozen debris, and under varying depths of debris ranging from zero up to a depth where the system no longer functioned satisfactorily. The subscale operating tests are fully described in Volume VI (Appendix 4).

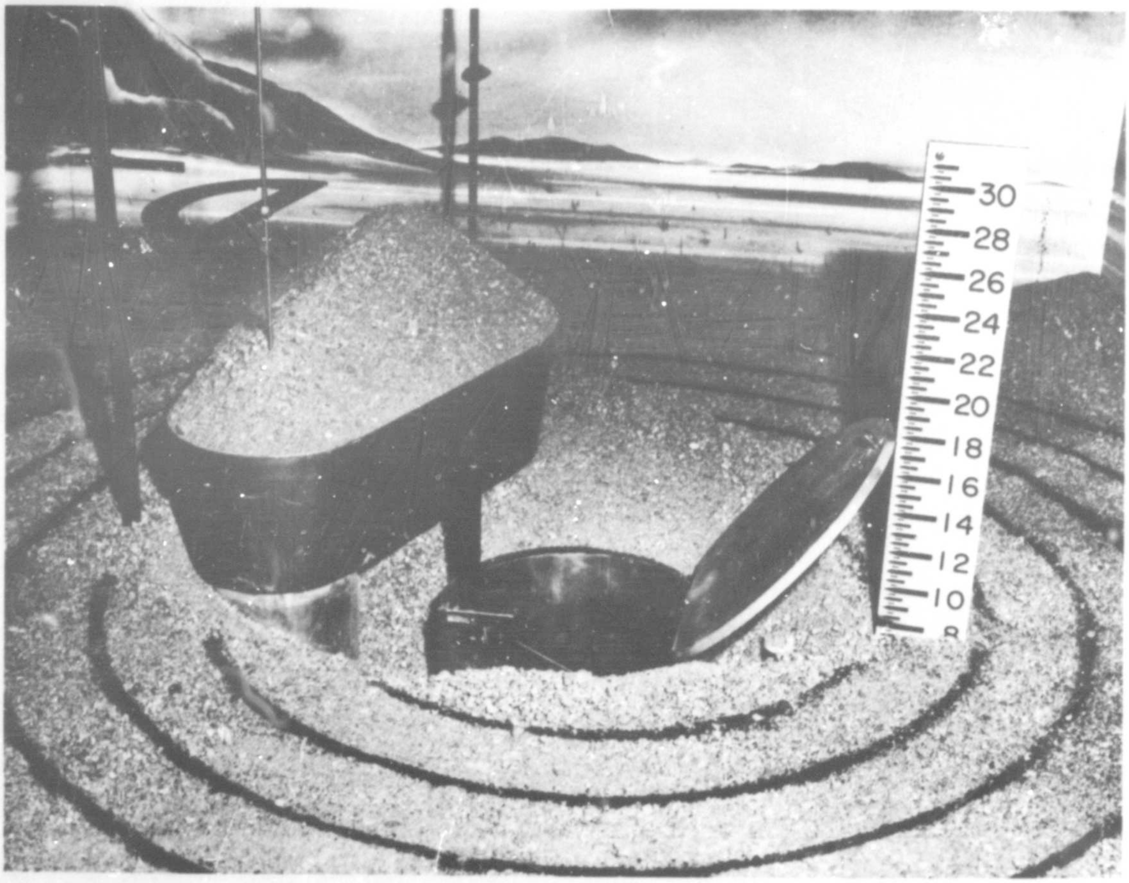
The conclusion of a typical test is shown in Figure 4-17. The illustration following (Figures 4-18 through 4-27) depict the parametric nature of the tests.

Test runs of models of each of the three concepts under comparable depths of dry sand are shown in Figures 4-18, 4-19 and 4-20. Test results of the Rise and Rotate concept when buried under other types of debris are illustrated in Figures 4-21 through 4-25. The test conclusions of the Rise and Rotate and Single Hinge configurations at the comparable maximum test depth for dry solids debris are depicted in Figures 4-26 and 4-27.



SUBSCALE OPERATING TESTS
TEST ARRANGEMENT

FIGURE 4-17

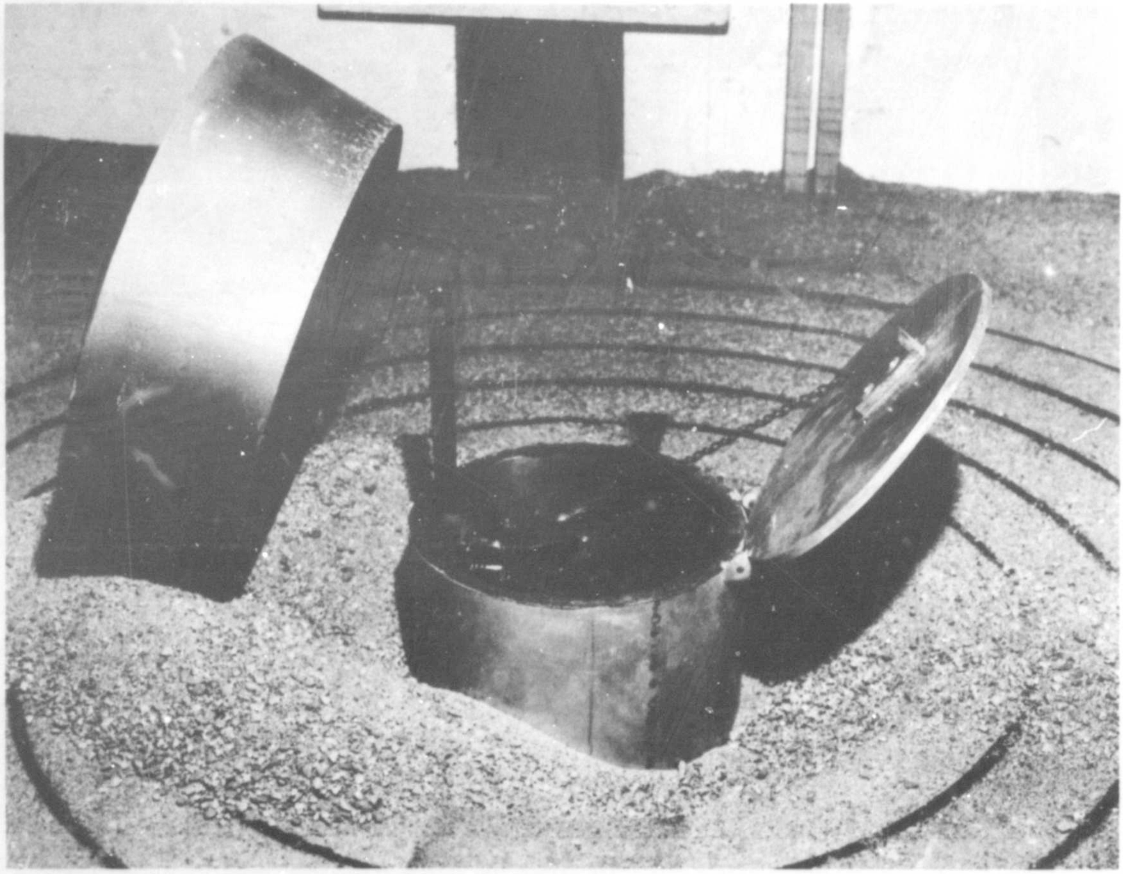


RISE AND ROTATE CONCEPT - DRY SAND

FIGURE 4-18

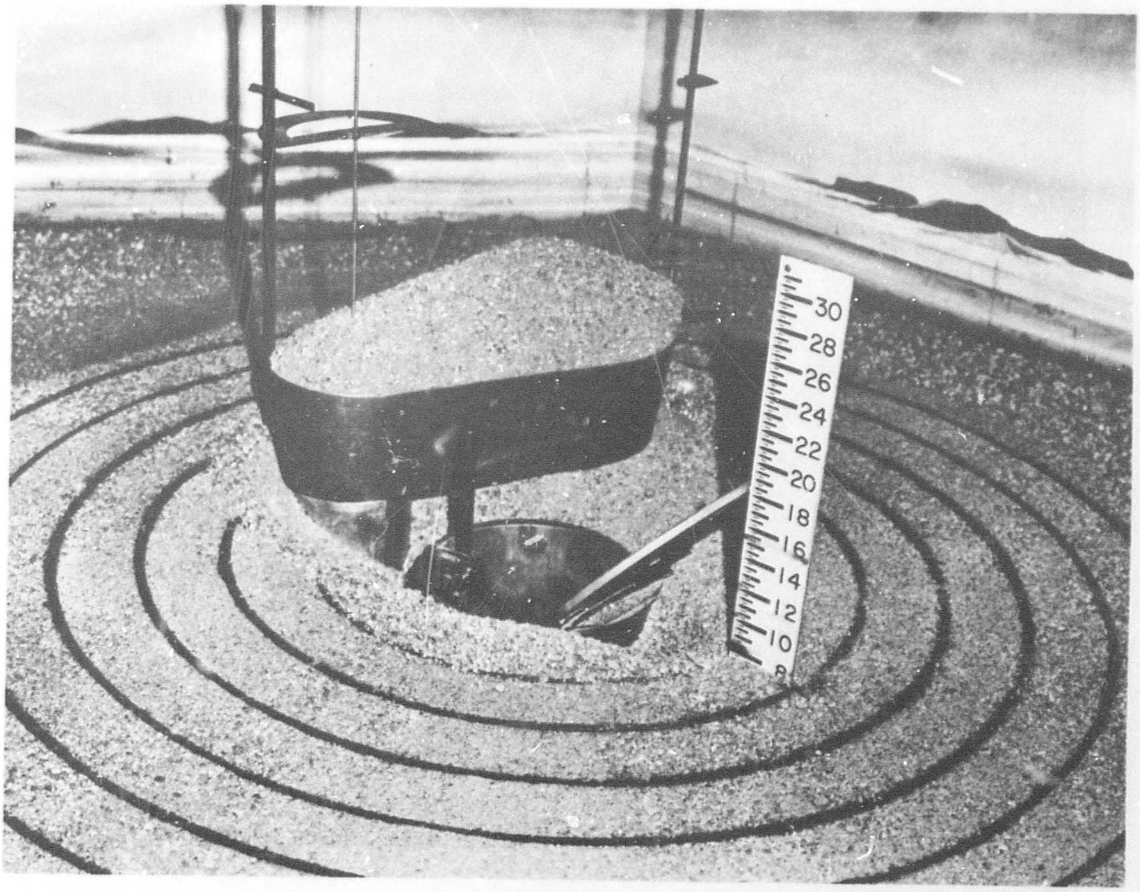
RISE AND TILT CONCEPT - DRY SAND

FIGURE 4-19



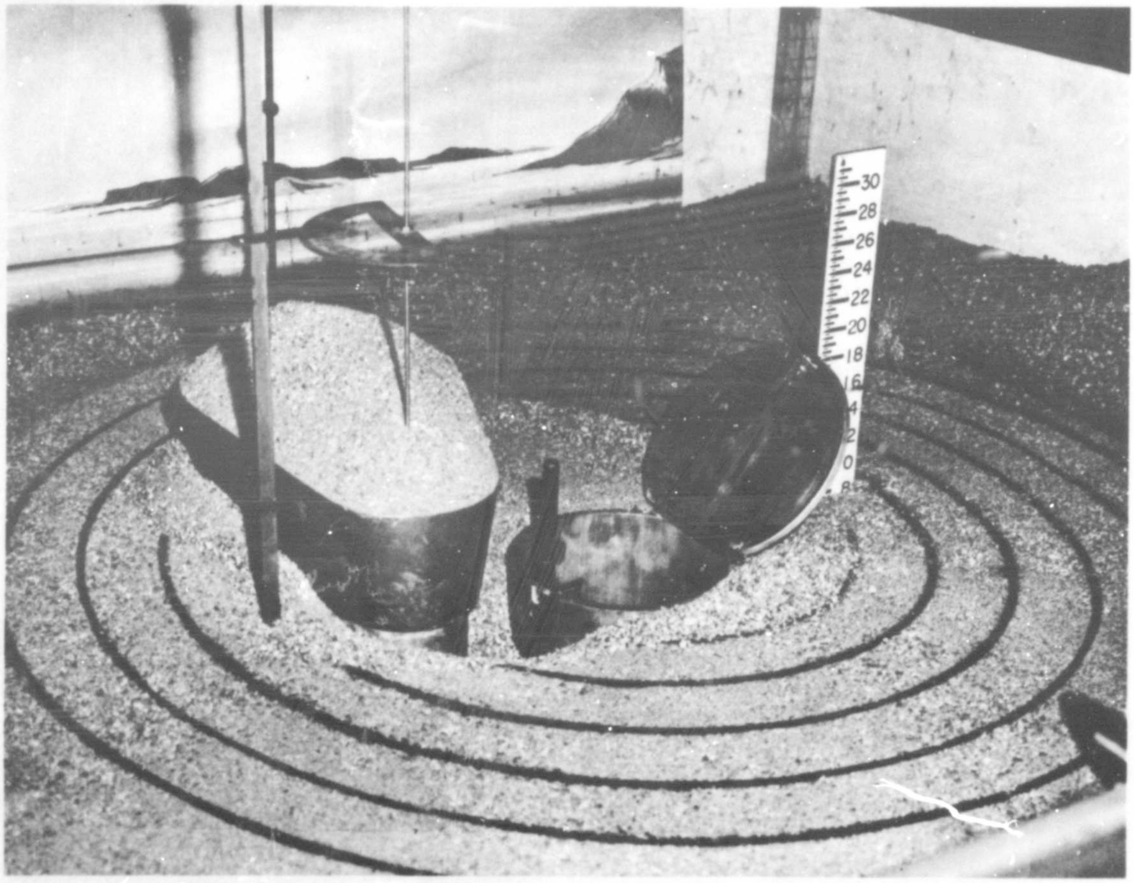
SINGLE HINGE CONCEPT - DRY SAND

FIGURE 4-20



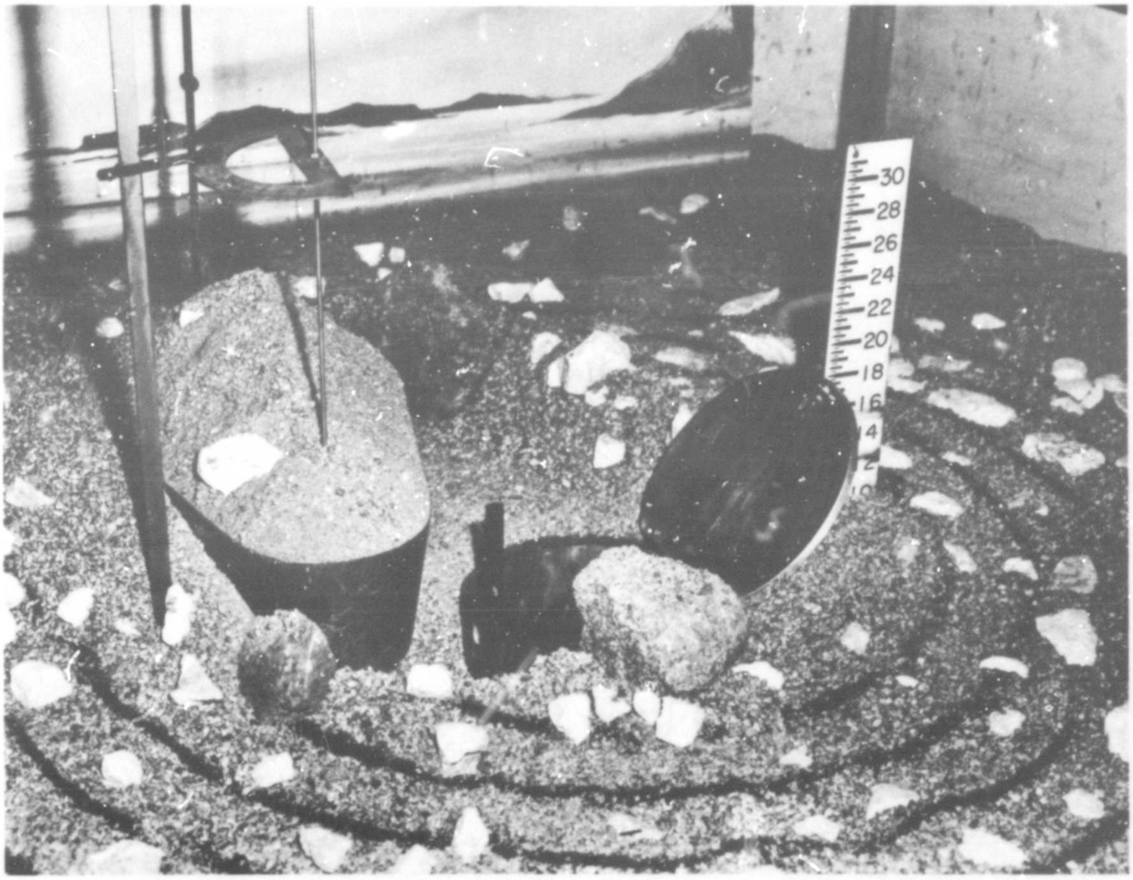
RISE AND ROTATE CONCEPT - DRY GRAVEL

FIGURE 4-21



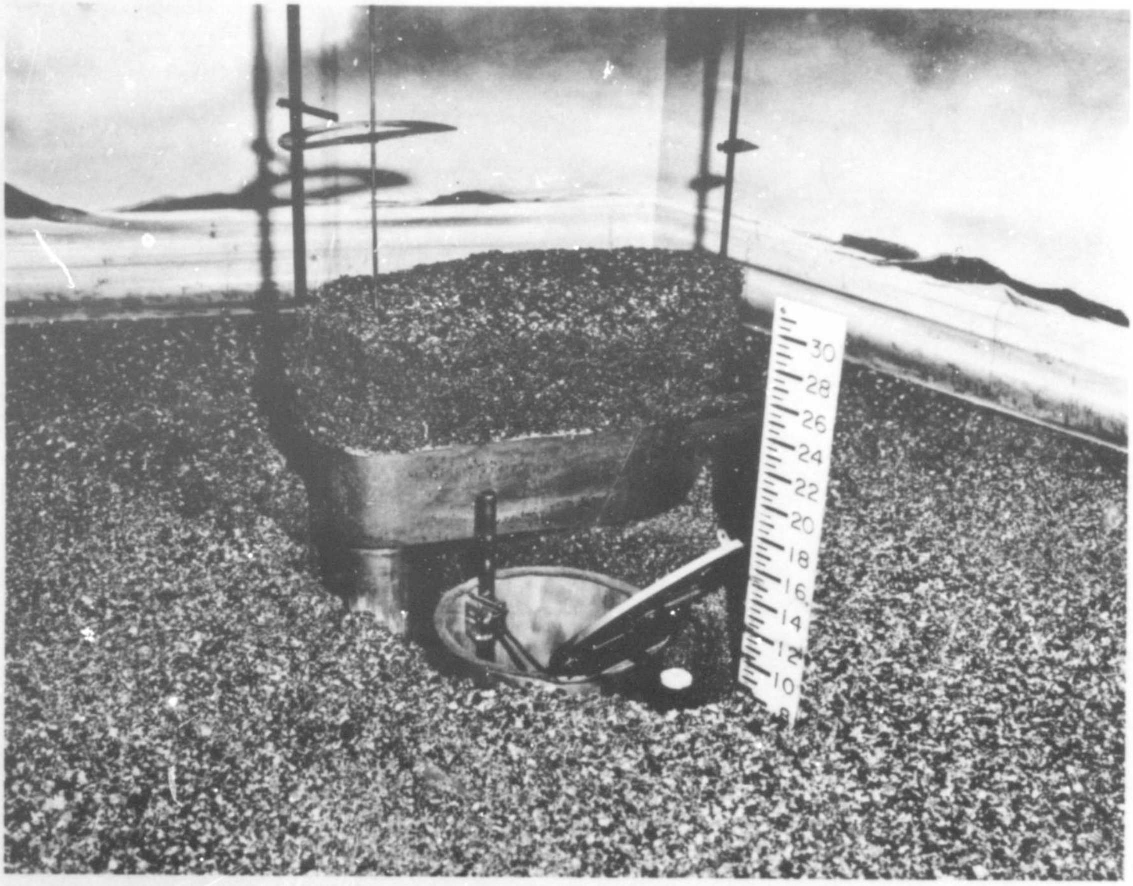
RISE AND ROTATE CONCEPT - DRY SAND AND GRAVEL

FIGURE 4-22



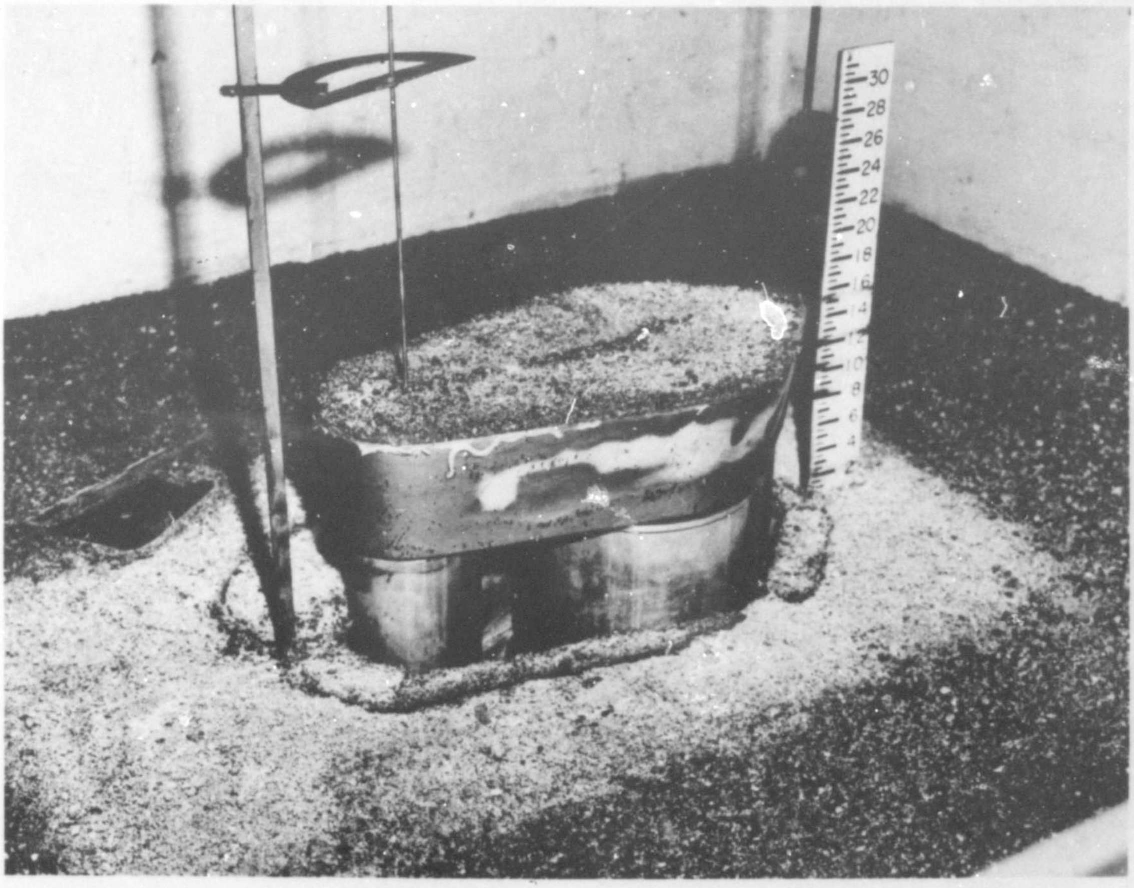
RISE AND ROTATE CONCEPT - DRY SAND, GRAVEL, AND BOULDERS

FIGURE 4-23



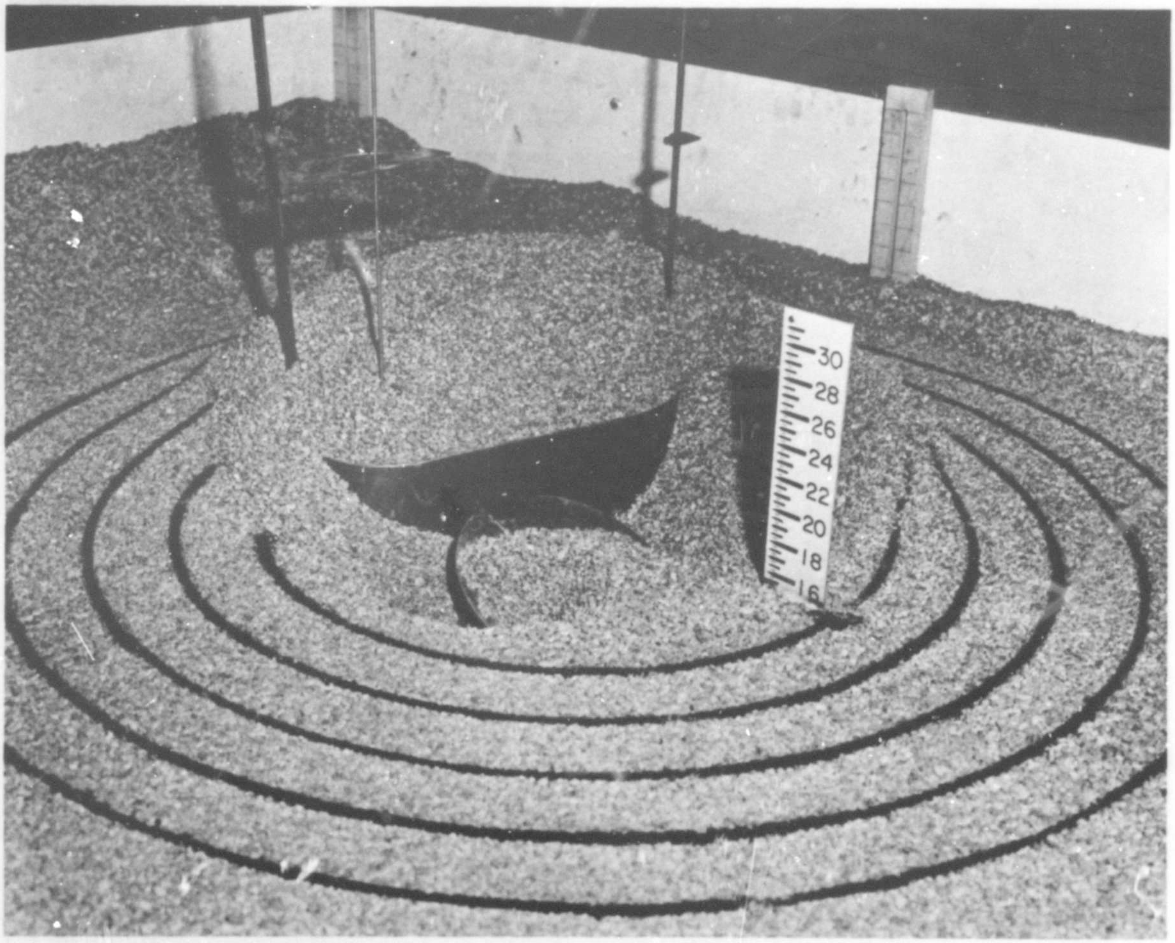
RISE AND ROTATE CONCEPT - WET SAND

FIGURE 4-24



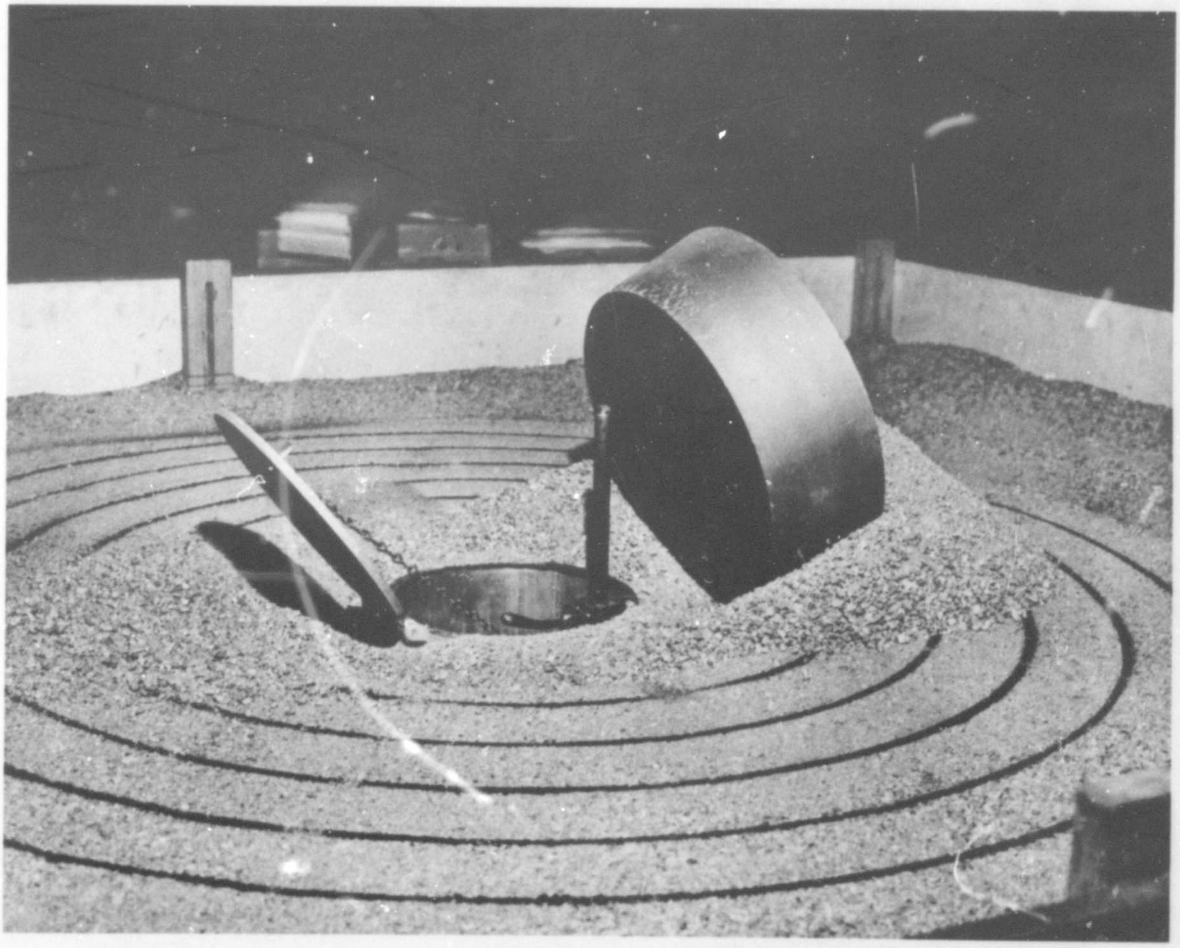
RISE AND ROTATE CONCEPT - FROZEN DEBRIS

FIGURE 4-25



RISE AND ROTATE CONCEPT - DRY GRAVEL

FIGURE 4-26



RISE AND ROTATE CONCEPT - DRY GRAVEL

FIGURE 4-27

The significant findings of the tests and related studies are:

- By the use of proper locks and seals, any of the configurations studied, when closed and locked, would provide adequate protection for the missile from windborne and blast-induced debris.
- A system that utilizes the opening action of the closure itself as the means of debris removal, thereby permitting its integration into the closure actuation mechanism, is sound and technically feasible.
- A debris shield that follows the opening action of the closure and is provided with a cover that opens at the end of the operating cycle is a desirable and effective means of preventing debris intrusion or fallback into the launch tube as the closure is opened.
- An auxiliary debris pit is not required nor effective for reliable operation of a debris handling and removal subsystem.
- The Rise and Rotate and the Single Hinge concepts demonstrated satisfactory operating and unfrozen debris handling capabilities and were selected as candidates for full-scale design.
- The Rise and Tilt configuration, as designed, exhibited inability to open fully under moderate debris depths, due to its compacting action on the debris, and was eliminated from further consideration.
- The magnitude of the high initial force required to overcome frozen debris is such that it was found more desirable to provide an auxiliary system of ice breakers to furnish the high initial force than to incorporate the added power requirements into the basic actuation system.

As the Contract Work Statement (Volume VIII, CLASSIFIED) specified no debris characteristics, for study purposes certain assumptions were made regarding the density, strength levels, and composition of the debris. In view of the parametric nature of the subscale operating tests, it was determined that commercially available sand and gravel could be used to demonstrate the opening and debris removal/exclusion capabilities of the three different closure concepts under varying depths and compositions of dry debris.

Linear scaling of the depth of debris used in the tests results in the following relationships:

$$\text{Scale factor (S)} = \frac{\text{size of model structure}}{\text{size of full-scale structure}}$$

$$\text{Length (model)} = \text{length (full-scale)} \times \text{scale factor (S)}$$

$$\text{Area (model)} = \text{area (full-scale)} \times \text{scale factor (S)}^2$$

$$\text{Volume (model)} = \text{volume (full-scale)} \times \text{scale factor (S)}^3$$

$$\text{Power (model)} = \text{power (full-scale)} \times \text{scale factor (S)}^4$$

$$\text{Time (model)} = \text{time (full-scale)}$$

Similar scale factors were assumed to be applicable to the relationship of the size and spacing of rocks used in the model tests to boulders which might be present in full-scale debris.

For tests conducted with frozen debris, it was assumed that the force required to shear ice is directly proportional to its depth and therefore scales linearly.

Assuming the debris criteria and scale factors to be valid, the tests provided a high confidence level in the operating and debris handling capabilities of the Rise and Rotate and the Single Hinge concepts under moderate depths (12-15 feet) of unfrozen debris.

As the power requirements of the full-scale system vary by the fourth power of the model scale factor, caution is necessary in attempting to extrapolate test data to the full-scale design since very small differences in model power requirements become highly exaggerated.

In addition, uncertainties persist regarding the physical properties of the debris under which the closure might be required to operate, and questions regarding the scaling of time and gravity effects on large debris particles are still unresolved.

4.5 Dynamic Tests and Analysis

4.5.1 Related Test Programs

At the onset of the Closure Analysis and Test Study program, only limited dynamic testing had been undertaken on closure models. The University of Illinois tested some 1/5-scale closure models with a dynamic gas pressure. Unfortunately, the rise time of the applied pressure pulse was so large, relative to the fundamental period of the tested models, that the loading was essentially static.

The Air Force has conducted HEST-type tests where subscale closure structures have been included in the test bed. The Hercules and Goliath tests were used to demonstrate the feasibility of closures designed to withstand high dynamic pressure loadings. Detailed data from these tests are not available at this time; therefore, the only conclusion that may be made relative to the Hercules and Goliath tests is that the majority of the subscale models survived the dynamic loads applied, which were severe but not well defined.

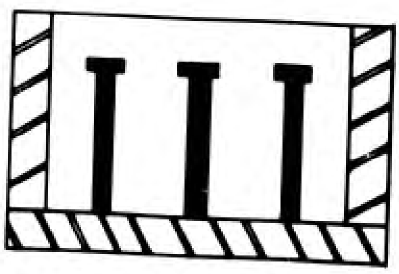
4.5.2 Test Descriptions

a. Shock Tube Tests

A series of subscale dynamic tests was performed for Parsons by General American Research Division (GARD) in a 12-inch diameter shock tube. Models were proportioned at approximately 1/18 scale to simulate one of the 1/7-scale static test models with a 0.5-inch outer shell and bottom plate. This model failed statically at a load of 5900 psi. It was decided that the models should be tested dynamically at pressures of 2000, 4000, 6000, and 8000 psi, and it was assumed that a model would be failed dynamically. However, as the series progressed, it became evident that the model exhibited a higher dynamic load capacity than had been anticipated.

A typical cross section of one of the test models is shown below. It will be noted that large (0.5 inch x 3 inch) weld studs are shown in the section. These studs were provided in order to eliminate concrete spalling from the shock wave passing through the closure.

Actual material strengths in the dynamic model were obtained and the static load capacity of the actual model was then predicted to be in excess of 8000 psi. Later static tests showed the static load capacity of the 1/18-scale models to be approximately 9500 psi.



It is a very difficult task to obtain reliable dynamic test records from small models such as were tested because the characteristic responses observed are often responses of the instrumentation and the test apparatus rather than responses of the models. Nevertheless, these small-scale tests are valuable since they do give a measure of total load capacity and provide a model which may be analyzed with its support as a means of checking dynamic response computations.

b. Rock Test I

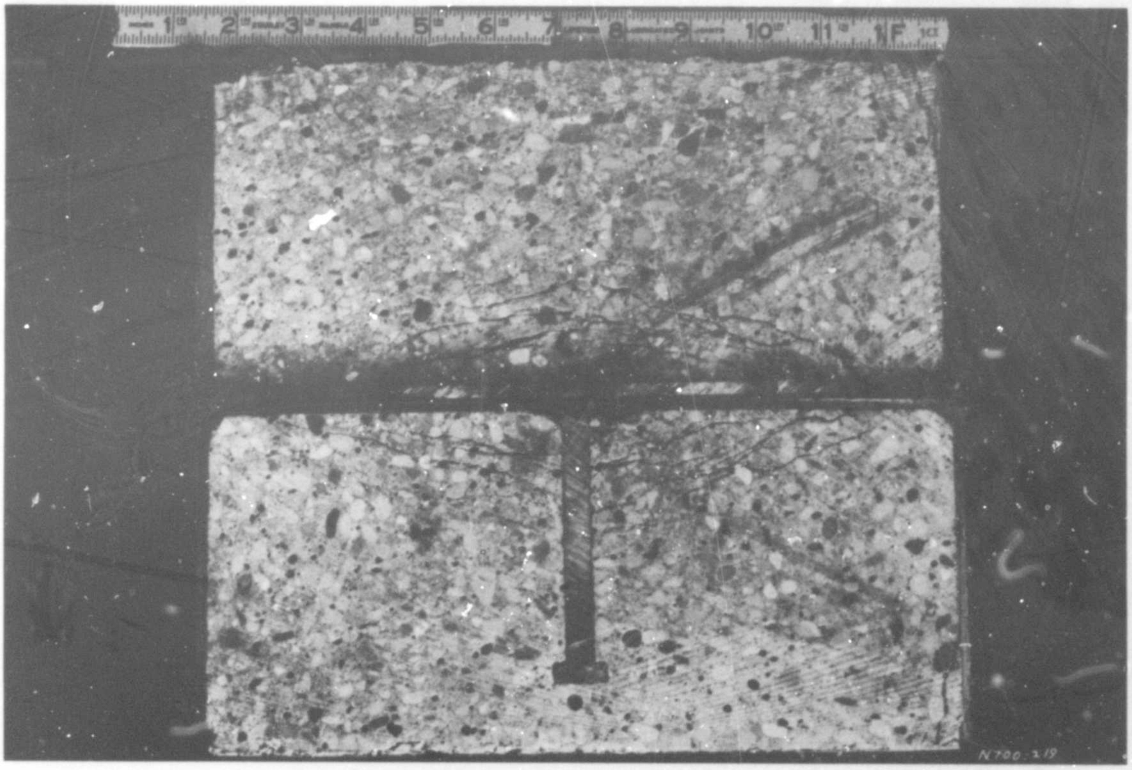
A full-size closure was designed by Parsons to be included in the Rock Test I event. Examination of the test data now available from the Air Force Weapons Laboratory (AFWL) shows that, for all practical purposes, the full-size Rock Test I closure remained eleastic, confirming the analytical predictions. No rebound was measured in the tie-down bolts.

Because of the format, the AFWL-supplied test data could not be used to correlate the dynamic analysis. When digital data records become available, a detailed examination may be carried out. Dynamic response data from a full-size closure structure will be most valuable even though the support conditions expected in an actual rock site are not identical to those in Rock Test I.

4.5.3 Significant Test Results

The dynamic tests performed in conjunction with the Closure Analysis and Test program were useful in providing a basis for comparing the accuracy of the analytical technique with the observed full-scale and subscale model response.

In addition, limited insight was gained relative to the static/dynamic load capacity of subscale models and the relationship between subscale and full-scale dynamic response. Figure 4-28 presents a photograph of a



SAMPLE CAT DYNAMIC TEST SPECIMEN SHOWING SCABBING

FIGURE 4-28

dynamically tested subscale model which has been sawed in two sections as part of the post-test model evaluation. It is believed the wedge-shaped crack near the top edge of the model was formed because of the reduced radial stiffness of the steel outer ring in this region, while the crack pattern in the lower central region of the model was caused by the shock wave propagation through the model. The model shown in Figure 4-28 was dynamically loaded four times at peak pressure levels of 2000, 4000 and 6000 psi. However, the load intensity causing or adding to the damage shown is not known.

The wedge-shaped crack has been observed in larger models designed and tested by Air Force Weapons Laboratory personnel in the Hercules, Goliath and Rock Test I test events. Post-test ultrasonic investigation of the full-scale Rock Test I closure provides evidence that the lower central region of that closure has also suffered distress. Thus it appears that the small-scale models tested in the Closure Analysis and Test Study were responding in a manner similar to much larger models, and that with sufficient additional testing the relationship between full-scale and subscale dynamic response could be established.

To determine the degradation in static load capacity caused by dynamic loadings, a model previously dynamically loaded to a peak pressure of 8000 psi was statically tested to destruction. The static load capacity of the previously dynamically loaded model was 9200 psi. This value compares with a load capacity of 9400 psi obtained by statically testing an identical model which had not been loaded in any way prior to the static test. Thus it appears that no static load degradation had accrued by dynamically testing the model to approximately 85 percent of its static load capacity.

4.5.4 Analytical Techniques and Correlation

Recently an analytical technique called the finite-element method has been developed as an efficient tool of the structural analyst. Arbitrary boundary conditions and material distributions are handled by this method with relative ease, since the analyst initially selects a physical mesh rather than writing differential equations of motion. The method is well described in recent papers. Essentially, it allows one to discretize a solid with a series of arbitrary interconnected elements. The potential energy of the system of elements is minimized, consistent with a compatible displacement field, the assumed boundary conditions, and the applied loads. The solution of the resulting simultaneous equations yields the displacements of the element node points due to a given set of applied loads. Element stresses are computed from the element node point displacements.

It has been shown that as the finite-element mesh becomes smaller, the analytical solution converges to the actual solution. However, relatively accurate solutions may be obtained using coarse meshes. This means that computer run times associated with finite-element solutions were small for those structures analyzed in this study.

An axisymmetric solids program was employed for the elastic dynamic response analysis. After initial conditions are selected, the dynamic response analysis may progress rather rapidly since only matrix multiplication is involved in the computational process.

As an example of the technique, an idealized shock tube containing a closure model was analyzed. The results of the analysis compared extremely well with the experimental results in both the time and frequency domain. The Rock Test I full-size closure model was also analyzed, but response data has not been available in a form useful for correlation.

4.5.5 Applicability to Full-Scale Design

Test evidence indicates that the finite-element technique provides sufficiently accurate dynamic response data for closure design purposes. Its use in conjunction with static test results allows the determination of economical closure sections to withstand high pressure loadings.

The dynamic test results directly tell several interesting stories. For all practical purposes, the use of a dynamic load factor greater than one appears unrealistic for design. It also appears that a 20-percent rebound steel provision for reverse bending is sufficient and that rigid body rebound as such is nonexistent.

At this time very little is known about the detailed dynamic response of closure structures. However, enough is known so that rational designs may be made. Although a dynamic load factor of one has been assumed adequate for design purposes, it is recommended that response analysis be performed for each special situation to verify this design assumption. Future refinements to analytical techniques, supported by adequate test data, will permit collapse load predictions to be made precisely, so that the proper design load factors may be selected with high confidence.

The response of closure structures is influenced by the actual pressure/time history of load application. Revisions in the estimates of the shape of this load curve would greatly influence closure design parameters.

Much work is still necessary in the field of closure dynamics. The effect of the horizontal stress wave must be considered in detail and experimental verification of the assumed failure modes is necessary before the problem can be completely solved.

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13. ABSTRACT

This report contains a summary of all activities and significant findings associated with, or emanating from, the Closure Analysis and Test Study. Candidate closure operating concepts consisting of the closure structure, bearing support, debris removal/handling system, actuation system, power system, and closure locking system are presented, and factors influencing the selection of two final configurations are discussed.

The results of the radiation analysis and the subscale operating, static and dyanamic tests~~, which were conducted to establish credibility of the selected closure subsystem designs~~, are presented, together with study conclusions emanating from these tasks.

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Gentlemen:

It is requested that the changes listed below be made in your copies of Volumes I, II and IV of Closure Analysis and Test Study, dated 31 July 1969.

On Page 4-39 of Volume I, "Project Summary and Abstract of Findings," Page 6-53 of Volume II, "Technical Report," and Page A2-218 of Volume IV, "Subscale Static Test Report," the value for the regression coefficient B_o is in error and should be corrected to read as $B_o = -0.40$, as shown below:

Incorrect	Correct
$B_o = 0.40$	$B_o = -0.40$
$B_1 = 4.9$	$B_1 = 4.9$
$B_2 = 2.3$	$B_2 = 2.3$
$B_3 = 0.23$	$B_3 = 0.23$

In addition, on Page A2-221 of Volume IV, "Subscale Static Test Report," the function "$Q = 0.40 + 4.9\left(\frac{t_s}{d_1} f_s\right) + 2.3\left(\frac{t_b}{d_1} f_s\right) + 0.23 f_c'$" should be corrected to read as follows:

$$"Q = -0.40 + 4.9\left(\frac{t_s}{d_1} f_s\right) + 2.3\left(\frac{t_b}{d_1} f_s\right) + 0.23 f_c'".$$