<table>
<thead>
<tr>
<th>AD NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD487118</td>
</tr>
</tbody>
</table>

**LIMITATION CHANGES**

**TO:**
Approved for public release; distribution is unlimited.

**FROM:**
Distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; AUG 1966. Other requests shall be referred to Arnold Engineering Development Center, Arnold AFB, TN.

**AUTHORITY**
AFAPL ltr, 12 Apr 1972
VACUUM DEPLOYMENT TEST
OF A LARGE EXPANDABLE
AEROSPACE SHELTER

F. W. Nelms
ARO, Inc.

August 1966

This document is subject to special export controls
and each transmittal to foreign governments or foreign
nationals may be made only with prior approval of
AFAPL or AEDC.

PROPERTY OF U. S. AIR FORCE
AEDC LIBRARY
AF 40(600)1200

AEROSPACE ENVIRONMENTAL FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE
NOTICES

When U. S. Government drawings specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, or in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Qualified users may obtain copies of this report from the Defense Documentation Center.

References to named commercial products in this report are not to be considered in any sense as an endorsement of the product by the United States Air Force or the Government.
VACUUM DEPLOYMENT TEST
OF A LARGE EXPANDABLE
AEROSPACE SHELTER

F. W. Nelms
ARO, Inc.

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of AFAPL or AEDC.
FOREWORD

The work reported herein was done at the request of the Air Force Aero-Propulsion Laboratory (AFAPL), Research and Technology Division (RTD), Air Force Systems Command (AFSC), Wright-Patterson Air Force Base, Ohio, under Program Element 62405214, Project 8170.

The expandable, self-rigidizing structure tested for AFAPL was designed by GCA Viron Division, a division of GCA Corporation, Minneapolis, Minnesota. Viron furnished the fabric portion of the structure, AFAPL fabricated the bulkheads, and Viron and ARO, Inc. assembled the structure. The design and fabrication accomplished by Viron for AFAPL was under Contract AF33(615)-2115. The cognizant contract monitor was Mr. Fred Forbes, APFT, WPAFB, Ohio.

The results of the test presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center, (AEDC), AFSC, Arnold Air Force Station, Tennessee, under Contract AF40(600)-1200. The test was conducted from March 17 to 29, 1966 under ARO Project No. SM0602, and the manuscript was submitted for publication on June 2, 1966.

This technical report has been reviewed and is approved.

James N. McCready
Major, USAF
AF Representative, AEF
Directorate of Test

Leonard T. Glaser
Colonel, USAF
Director of Test
ABSTRACT

A 10-ft-diam by 25-ft-long, expandable, self-rigidizing, cylindrical aerospace shelter was impregnated with a water setting resin and packaged for deployment in a vacuum of $10^{-4}$ torr in the Mark I Aerospace Environmental Chamber. Deployment of the structure occurred at an excessively high, uncontrolled rate. The test article and support equipment suffered extensive damage, which prevented continuation of the test in the vacuum. The Mark I chamber was returned to atmospheric conditions, and the structure was rigidized.
CONTENTS

ABSTRACT ................................................................. iii
I. INTRODUCTION ......................................................... 1
II. APPARATUS ............................................................. 1
III. PROCEDURE ........................................................... 4
IV. RESULTS ................................................................. 5
V. CONCLUSIONS ........................................................... 7

ILLUSTRATIONS

Figure

1. Mark I Schematic .................................................. 9
2. Mark I Facility Arrangement ....................................... 10
3. Chamber Pressure, Shakedown Run ............................... 11
4. Chamber Pressure, Rigidization Run .............................. 12
5. Packaged Expandable Aerospace Shelter ......................... 13
6. Deployed Expandable Aerospace Shelter ......................... 14
7. Cross Section of Fabric Cylinder Wall ............................ 15
8. Catalyst Container and Valves on Packaged Shelter ........... 16
9. Packaged Shelter and Gemini Model .............................. 17
10. Expanded Shelter during Rigidization ............................ 18
11. Expanded and Pressurized Shelter in Handling Fixture ...... 19
12. Expandable Shelter Evacuation and Pressurization Schematic .. 20
13. Cross Section of Cylinder Showing Floor Position .......... 21
14. Shelter Configuration 1.125 sec after Explosive Bolts Fired .... 22
15. Shelter Configuration 2.33 sec after Explosive Bolts Fired .... 22
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>Expanded and Rigidized Shelter</td>
<td>23</td>
</tr>
<tr>
<td>17</td>
<td>Inside of Lower Bulkhead after Shelter Rigidization</td>
<td>24</td>
</tr>
</tbody>
</table>
SECTION I
INTRODUCTION

The possible use of expandable structures in the manned space program is discussed in "Aerospace Expandable Structures Conference Transactions," AFAPL-TR-65-108, May 25-27, 1965, Minneapolis, Minnesota. The basic concept of the structures is characterized by a packaged vehicle many times smaller than its deployed configuration.

This report covers the assembly, resin impregnation, and deployment of an expandable, cylinder-type aerospace shelter whose dimensions after rigidization were approximately 10 ft in diameter by 25 ft long. The cylindrical portion, constructed of woven fiber glass flutes sandwiched between layers of urethane-coated nylon, was 18 ft long. This cylindrical section was terminated by two 10-ft-diam aspheric fiber glass and epoxy bulkheads, which also served as the structure's canister before deployment. The test objective was to determine if the vehicle would deploy and rigidize in a simulated space environment and to record the deployment and rigidization with motion-picture photography.

SECTION II
APPARATUS

2.1 MARK I, AEROSPACE ENVIRONMENTAL CHAMBER

2.1.1 General Description

Mark I, in which the tests were conducted, consists of a large cylindrical vacuum tank, pumping systems, thermal environmental systems, vibration system, controls, and instrumentation suitable for conducting tests on large space vehicles. A schematic of the facility is shown in Fig. 1. The chamber and associated equipment areas are shown in Fig. 2. The chamber is contained in a room 68 by 68 by 109 ft high. Service areas within the building provide space for test article buildup and equipment maintenance.

The Mark I chamber (Fig. 2) is a cylindrical vessel 42 ft in diameter and 82 ft in height with 0.875-in. thick walls and 1.5-in. thick elliptical heads. The chamber shell is constructed of 304L stainless steel for low outgassing and for good corrosion resistance.
The inside working dimensions of the chamber are 35 ft in diameter and 65 ft in height. Vehicle entrance to the chamber is through a 20-ft-diam hatch located in the top of the chamber. Personnel access to the chamber is through a hatch 7 ft in diameter near the bottom of the chamber.

Three pumping systems are available for evacuating the Mark I chamber: (1) a three-stage increment of the Propulsion Wind Tunnel Facility (PWT) plenum evacuation system, (2) a conventional vacuum pumping system consisting of roughing pumps, forepumps, booster pumps, and diffusion pumps, and (3) a cryopumping system cooled by a 90-kw liquid nitrogen and a 7.5-kw gaseous helium system.

2.1.2 Pumping System Used for this Test

The pumping system used for this test consisted of two 850-cfm roughing pumps and ten mechanical forepumps to evacuate the chamber from atmosphere to 15 torr, where two 4000-cfm Roots blowers were started; at $10^{-1}$ torr, four booster pumps were placed in operation; and at $10^{-2}$ torr the roughing pumps and Roots blowers were valved out and eleven 32-in. diffusion pumps were placed in operation. Approximately 1200 ft$^2$ of LN$_2$ cryopumping surface was used. Figures 3 and 4 show the pumpdown curves obtained with this system.

2.2 TEST ARTICLE STRUCTURE

The test article is shown in the packaged and deployed condition in Figs. 5 and 6, respectively. The structure is similar to the models tested earlier in the Aerospace Research Chamber (12V). 1

The domed bulkheads which served as the predeployment canister were constructed of fiber glass and epoxy. Each bulkhead weighed approximately 1000 lb and was 10 ft in diameter by approximately 3.5 ft deep.

The fiber glass fabric was of a sandwich-type construction with the fluted core parallel to the axis of the cylinder (Fig. 7). Elements of the fiber glass fabric sandwich consist of a 26-oz/yd$^2$ inner facing fabric,

---

an 8-oz/yd² core fabric, and a 10-oz/yd² outer facing fabric. The outer covering was identical to the urethane-coated bladder fabric except that it was not pigmented. Fiber glass sections of the fabric sandwich were joined continuously at the flute lines by an integral weaving process. The bonds between the pigmented urethane-coated bladder, the 0.25-in.-thick foam rubber, the fiber glass, and the urethane-coated nylon outer covering were made with flexible adhesives (Fig. 7). An O-ring seal was used between the two halves of the canister which were restrained by a large spring-loaded ring clamp. The clamp was released by the simultaneous firing of two explosive bolts positioned 180 deg apart on the periphery of the canister's 10-ft diameter.

The fiber glass sandwich section was impregnated with a resin which was activated by water vapor. Figure 8 shows the catalyst container and the two solenoid valves used to control the catalyst flow rate to the fiber glass fabric sandwich section. Two 2500-w heaters were installed in the container to maintain the proper catalyst temperature.

2.3 TEST CONFIGURATIONS

Two test configurations were used in the test. The first, for a shakedown run, had no resin in the fiber glass. The second configuration was used in the rigidization test.

The first configuration was an assembly of the nonresin-impregnated aerospace shelter and a full-scale model of the Gemini vehicle (Fig. 9). The purpose of using this assembly was threefold.

1. The "shakedown run" would provide an operational check of the Mark I chamber and all required support equipment.

2. All test article functions except the rigidization could be checked in the actual test environment.

3. Since the deployment of the test article was expected to occur in the same manner for both runs, motion pictures of the shelter-Gemini model assembly were made during the shakedown so that the model, which contributed significantly to the chamber pumping system gas load, could be removed for the rigidization run.

Strain-gage-type load cells were installed in the four support stands to monitor the test article's overall weight. They also indicated the amount of lifting load transmitted to the upper bulkhead from the overhead crane immediately prior to deployment via the support cables and a mechanical, vacuum tight feed through. The predeployment load on the
upper bulkhead was intended to prevent the bulkhead from falling back after initial deployment onto the fabric and lower bulkhead flange and possibly damaging the fabric.

The second configuration, the resin-impregnated shelter minus the Gemini model, is shown during installation (Fig. 8). The expanded cylinder during rigidization is shown in Fig. 10.

2.4 INSTRUMENTATION

The chamber pressure was monitored with two alphatron and two ionization gages. Copper constantan thermocouples were used to monitor the LN₂ liner temperatures, the three solenoid operated valves' temperatures, and the catalyst temperature. Four strain-gage-type load cells were used to monitor the weight of the test article (Fig. 8). Transducers were used to make the required pressure measurements. All data were recorded using a strip chart recorder and a 25-channel data logger system. Two cameras were used to provide the motion-picture coverage of the deployment and rigidization. These cameras were mounted outside the chamber and viewed the test article through portholes. One of the cameras was mounted to view the side of the extended cylinder and provided 400-frame/sec coverage for the first 10 sec of its operation, then shifted automatically to 24-frame/sec coverage. The second camera was mounted on top of the chamber and operated at 24 frame/sec. A closed-circuit television camera located inside the chamber was used to monitor the deployment of the test article.

SECTION III
PROCEDURE

3.1 PREPARATION OF THE TEST ARTICLE

The assembly of the 10-ft-diam by 25-ft-long, expandable, cylinder-type aerospace shelter was accomplished by Viron and ARO employees in the sixth floor buildup area of Mark I. After assembly, the cylinder's bladder and outer covering were leak checked using ammonia gas and a phenol indicator. The shelter was then packaged for the shakedown run. After completion of the shakedown run, the expandable structure was removed from the chamber, returned to the sixth floor buildup area, and then prepared for resin impregnation. Figure 11 shows the shelter and the handling stand used for the resin impregnation. The shelter was inflated to a pressure of 6 in. of water. This pressure provided the
rigidity required to maintain the shelter's shape in the horizontal position. Three equally spaced, 2-in.-diam by 12-ft-long tubes were inserted into the fluted portion of the fabric section to disperse the resin. A polyethylene covering was used to seal the entire nylon and fiber glass fabric portion from the water vapor in the atmosphere. The space between the polyethylene covering and the fabric portion of the cylinder was purged with dry nitrogen to ensure that no moisture would be introduced to the resin during impregnation. A vacuum pump was attached to the fiber glass section to enhance the flow of resin throughout the fluted section.

After resin impregnation was completed, the cylinder was packaged. The two bulkheads which served as the canister were brought together and fastened with a spring-loaded clamp and the two explosive bolts. The packaged shelter was then installed in the test chamber.

3.2 TEST PROCEDURE

The Mark I chamber was evacuated to the low $10^{-6}$ torr range for the shakedown run and to the low $10^{-4}$ torr range for the actual test. The higher pressure for the actual test was a result of the outgassing load (primarily resin-solvent vapor) from the test article. After the chamber pressure had stabilized and a final scan had been made of all the sensors, the motion-picture cameras were started. Approximately 2 sec later the explosive bolts were fired to initiate the deployment of the test article. After firing of the explosive bolts, the procedure was to have been to deploy the cylinder slowly by filling the bladder with CO$_2$ to a pressure of 6 in. of water. Figure 12 is a diagram of the CO$_2$ piping and valving arrangement. After complete deployment the catalyst solenoid valves were to be operated as required to release the catalyst at approximately 20 lb/hr. The vapor distribution solenoid valves were to be used to release excess catalyst and solvent vapor. Pressure was to be maintained in the bladder at 6 in. of water until the rigidization process was completed.

SECTION IV
RESULTS

4.1 SHAKEDOWN RUN

During the shakedown run pumpdown, a base pressure of $4 \times 10^{-6}$ torr was reached. Figure 3 indicates that a pumping time of nearly 13 hr was required to attain this pressure. Deployment of the shelter was performed using CO$_2$ to pressurize the bladder section to approximately
16 torr. At this pressure, the shelter was fully expanded and supported the Gemini model without assistance from the support cables.

Motion pictures were made of the shelter-Gemini model assembly's deployment and expansion. Shelter internal pressures, several test article component temperatures, and the load cells' output were monitored during the run. All indications were that the chamber, its support equipment, and the test article would perform satisfactorily at the required chamber test pressure and temperature during the rigidization run.

4.2 RIGIDIZATION TEST RUN

A base pressure of $4 \times 10^{-4}$ torr was attained in approximately 8 hr for the test of the resin-impregnated cylinder. The chamber pressure was limited because of the large gas load presented by the approximately 240 lb of solvent (butyl acetate) in the 600 lb of resin-solvent mixture used to impregnate the fiber glass section of the cylinder.

The test run was not completely successful. All systems operated normally until immediately after the firing of the explosive bolts. Complete deployment of the cylinder occurred almost immediately after the bolts released the restraining ring. The cylinder expanded unevenly, bending and leaning toward the side containing the heavy, eccentrically positioned floor. Figure 13 shows the shelter floor location. The expansion rate and the asymmetrical weight distribution caused the almost fully expanded shelter to fall to the chamber floor. The bending moments on the load cells in the support stands destroyed the cells. The pressure transducers, catalyst valves, and catalyst tank were torn from the upper bulkhead when it struck the floor and side of the chamber. Figure 14 shows the shelter 1.125 sec after deployment began. Figure 15 shows the upper bulkhead striking the floor and chamber wall 2.33 sec after deployment began. The violent deployment with its resultant damage precluded continuation of the test with the expanded cylinder resting horizontally on the chamber floor. The chamber was returned to atmospheric pressure. The cylinder was positioned with its longitudinal axis vertical and was pressurized to 8 in. of water gage. Rigidization of the resin-impregnated fiber glass section of the shelter was then accomplished at ambient conditions. Figure 16 shows the rigidized cylinder after removal from the chamber.

The shelter was inspected immediately after removal from the chamber. Although no structural strength tests were conducted, the fabric section was examined closely and was found to be very hard and completely rigidized. Most of the damage suffered during the violent deployment and fall
was to the interior portion of the shelter. The bladder was torn from
the lower bulkhead, and the fiber glass floor supports were cracked at
the support-to-bulkhead joints. Figure 17 shows the interior of the
lower portion of the cylinder and the bottom bulkhead.

The pressure in the resin-saturated fluted fiber glass section of the
fabric cylinder was 13 in. of water prior to deployment of the shelter.
Although this pressure was higher than desired, the decision was made
to deploy since indications were that pressure would not be reduced
significantly during an extended period of pumping.

The cause of the expansion of the cylinder to its full length in such a
violent manner was traced directly to the high pressure in the volume
between the bladder and outer covering, which contained the 600 lb of
resin-solvent mixture. Analysis of the data and subsequent work done
by the resin suppliers indicate that approximately 63 percent of the
solvent (150 lb) should have been removed from the resin-impregnated
fabric to prevent the violent deployment. It is quite unlikely that this
amount of solvent could have been pumped by the chamber pumping
system in a reasonable time since the lower portion of the cylinder con-
tained a substantial amount of resin in the liquid phase that could very
well have been trapped within the folds of the packaged fabric, thereby
preventing the solvent from vaporizing.

One method of reducing the amount of solvent in the impregnated
fabric would be to purge the fluted area with dry nitrogen until the
required reduction in the solvent content is attained. To keep the resin
solids suspended homogeneously in the impregnated fabric after drying
with nitrogen, the resin suppliers recommend minute amounts of certain
inert additives in the resin-solvent mixture.

SECTION V
CONCLUSIONS

Deployment of the large aerospace shelter in a simulated space
environment was not successful; however, the shelter was rigidized
at atmospheric conditions. The violent expansion certainly was not
desirable, but it appeared that had the shelter been constrained to pre-
vent structural damage, a successful deployment and rigidization would
have been achieved. The dramatic, though undesirable, results of this
test graphically pointed to the need for further study and development of
rigidizing agents for expandable space shelters.
Fig. 1 Mark I Schematic
Fig. 3 Chamber Pressure, Shakedown Run
Fig. 4 Chamber Pressure, Rigidization Run
Fig. 6 Deployed Expandable Aerospace Shelter
Fig. 7 Cross Section of Fabric Cylinder Wall

- Fiber Glass Section
- Urethane-Coated Nylon Outer Covering
- Pigmented Urethane-Coated Bladder
- 1/4-in. thick Foam Rubber
Fig. 8 Catalyst Container and Valves on Packaged Shelter
Fig. 9 Packaged Shelter and Gemini Model
Fig. 10 Expanded Shelter during Rigidization
Fig. 11 Expanded and Pressurized Shelter in Handling Fixture
Fig. 12 Expandable Shelter Evacuation and Pressurization Schematic
Fig. 13 Cross Section of Cylinder Showing Floor Position
Fig. 14 Shelter Configuration 1.125 sec after Explosive Bolts Fired

Fig. 15 Shelter Configuration 2.33 sec after Explosive Bolts Fired
Fig. 16 Expanded and Rigidized Shelter
Fig. 17 Inside of Lower Bulkhead after Shelter Rigidization
A 10-ft-diam by 25-ft-long, expandable, self-rigidizing, cylindrical aerospace shelter was impregnated with a water setting resin and packaged for deployment in a vacuum of 10⁻⁴ torr in the Mark I Aerospace Environmental Chamber. Deployment of the structure occurred at an excessively high, uncontrolled rate. The test article and support equipment suffered extensive damage, which prevented continuation of the test in the vacuum. The Mark I chamber was returned to atmospheric conditions, and the structure was rigidized.
### INSTRUCTIONS

1. **ORIGINATING ACTIVITY:** Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization (corporate author) issuing the report.

2. **REPORT SECURITY CLASSIFICATION:** Enter the overall security classification of the report. Indicate whether “Restricted Data” is included. Marking is to be in accordance with appropriate security regulations.

3. **REPORT TITLE:** Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. **DESCRIPTIVE NOTES:** If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. **AUTHOR(S):** Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. **REPORT DATE:** Enter the date of the report as day, month, year, or month, year. If more than one date appears on the report, use date of publication.

7. **TOTAL NUMBER OF PAGES:** The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

8. **NUMBER OF REFERENCES:** Enter the total number of references cited in the report.

9. **CONTRACT OR GRANT NUMBER:** If appropriate, enter the applicable number of the contract or grant under which the report was written.

10. **REPORT DATE:** Enter the date of the report as day, month, year, or month, year. If more than one date appears on the report, use date of publication.

11. **TOTAL NUMBER OF PAGES:** The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

12. **NUMBER OF REFERENCES:** Enter the total number of references cited in the report.

13. **CONTRACT OR GRANT NUMBER:** If appropriate, enter the applicable number of the contract or grant under which the report was written.

14. **PROJECT NUMBER:** Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

15. **ORIGINATOR'S REPORT NUMBER(S):** Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

16. **OTHER REPORT NUMBER(S):** If the report has been assigned any other report numbers (either by the originator or by the sponsor), also enter this number(s).

17. **AVAILABILITY/LIMITATION NOTICES:** Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

   (1) “Qualified requesters may obtain copies of this report from DDC.”

   (2) “Foreign announcement and dissemination of this report by DDC is not authorized.”

   (3) “U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through DDC.”

   (4) “U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through DDC.”

   (5) “All distribution of this report is controlled. Qualified DDC users shall request through DDC.”

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

18. **SUPPLEMENTARY NOTES:** Use for additional explanatory notes.

19. **SPONSORING MILITARY ACTIVITY:** Enter the name of the departmental project office or laboratory sponsoring (paying for) the research and development. Include address.

20. **ABSTRACT:** Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as (F3), (S), (C), or (U).

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

21. **KEY WORDS:** Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.