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MAY 77 G R WILLIAMSON, A SMITH, D MORSE

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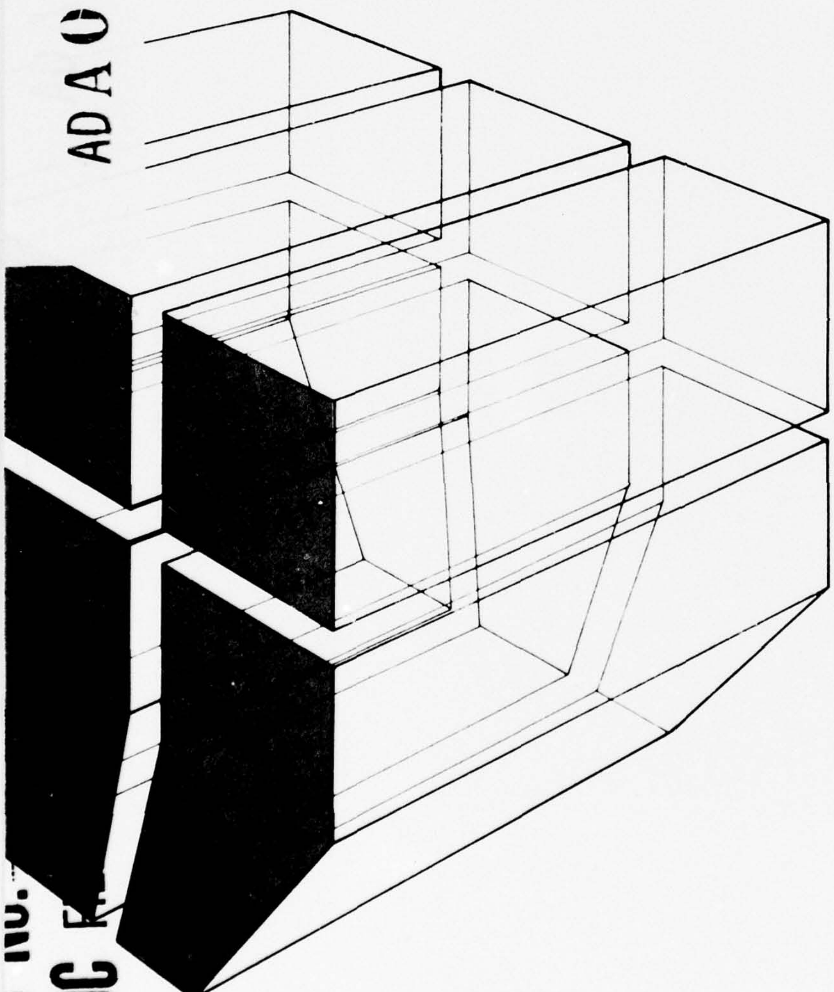
construction engineering research laboratory

TECHNICAL REPORT M-215
May 1977
Application of Fibrous Shotcrete for Construction in Theater of Operations

INFLATION/FOAM/SHOTCRETE SYSTEM FOR RAPID SHELTER CONSTRUCTION



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This report discusses an inflation/foam/shotcrete system for constructing hardened shelters in the theater of operations. The method was found to be rapid and low-cost, with a low skill level requirement. Five hemispherical domes of varying sizes and foam thicknesses were constructed and tested to determine their resistance to fire, ballistics, and simulated burial. Costs, man-hours, and skill levels required for construction are discussed.

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FOREWORD

This investigation was conducted by the U. S. Army Construction Engineering Research Laboratory (CERL) for the Directorate of Facilities Engineering, Office of the Chief of Engineers (OCE). The work was conducted under Project 4A162719AT41, "Design, Construction, and Operations and Maintenance Technology for Military Facilities"; Task 05, "Research for Base Development in the Theater of Operations"; Work Unit 001, "Application of Fibrous Shotcrete for Construction in Theater of Operations." The OCE Technical Monitor is R. Barnard.

The study was performed by the Construction Materials Branch, Materials and Science Division (MS). P. A. Howdyshell is Chief, Construction Materials Branch, and Dr. G. R. Williamson is Chief, MS.

COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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INFLATION/FOAM/SHOTCRETE SYSTEM FOR RAPID SHELTER CONSTRUCTION

1 INTRODUCTION

Background

Inflation forming procedures for constructing concrete domes have been in use for several years. A patented technique developed by Dr. D. Bini[1] uses a complicated system of springs and reinforcing bars. A similar system developed by the U. S. Army Construction Engineering Research Laboratory (CERL) substitutes steel fibers for Bini's spring-reinforcing system. The CERL technique was successful for domes up to 15-ft (4.6 m) in diameter;[2] however, the inflated system of fresh concrete became unstable for larger domes. Since procedures for stabilizing the larger domes during construction were considered too cumbersome for theater of operations (TO) construction, CERL was tasked with developing a simpler, more practical system for constructing hardened shelters—one which would combine the inflation system with polyurethane foam and steel fiber shotcrete.

Objective

The objective of this investigation was to develop a field-operational system for constructing hardened shelters in the TO. The system must be rapid, economical, and possess low skill requirements and minimum shipping volume.

Approach

Five steel-fiber-reinforced concrete domes were fabricated by the inflation/foam/shotcrete system. Three were 15 ft (4.6 m) in diameter by 7 ft (2.1 m) high, one was 18 ft (5.5 m) in diameter by 10 ft (3.1 m) high, and one was 28 ft (8.5 m) in diameter by 14 ft (4.3 m) high. The fabrication was performed in three steps: (1) a membrane was inflated to a predetermined height; (2) the membrane was sprayed with polyurethane foam to a specified thickness; and (3) the foam was sprayed with steel fiber shotcrete to a specified thickness depending on the application.

[1]D. Bini, "Technologies for R&E Construction by Pneumatic Lifting," *Proceedings 8th International Congress on R&E Precast Concrete Industry*, Stresa, Italy (May 1975).

[2]G. Batson, D. Naus, and G. Williamson, "Inflation Forming of Steel Fiber Reinforced Concrete," *Proceedings RILEM Symposium on Fiber Reinforced Cement and Concrete*, London, England (September 1975).

Costs, man-hours, skill levels, and times required for construction were noted, as were the domes' resistance to fire, ballistics, and simulated burial. The usefulness of foam/shotcreting as a repair technique was also examined.

Mode of Technology Transfer

The inflation/foam/shotcrete system may be included in TM 5-855-1, *Fundamentals of Protective Design (Non-Nuclear)*,[3] FM 5-15, *Field Fortifications*,[4] and TM 5-1300, *Structures to Resist the Effects of Accidental Explosions*.[5]

2 EQUIPMENT AND MATERIALS

Equipment

All equipment used in the inflation/foam/shotcrete construction system, except the foam and shotcreting equipment, is part of the Table of Organization and Equipment (TOE) of the Engineer Combat Battalion, Heavy. The latter pieces are standard shelf items with long histories of reliable performance. The equipment required and the approximate 1976 cost, if applicable, are as follows:

1. Foam mixing chambers and spray gun, $5000 (Figure 1)

2. Shotcrete machine and nozzle (dry process), $7500 (Figure 2)

3. Concrete mixer (any type), (TOE)

4. 600 cfm (17 m^3/min) air compressor at 90 psi (0.621 N/mm^2), (TOE)

5. 20 cfm (0.57 m^3/min) air compressor, (TOE)

6. Snorkel truck, (TOE).

[3]*Protective Design: Fundamentals of Protective Design (Non-Nuclear)*, TM 5-855-1 (Department of the Army, 19 July 1965).

[4]*Field Fortifications*, FM 5-15 (Department of the Army, 27 June 1972).

[5]*Structures to Resist the Effects of Accidental Explosions*, TM 5-1300 (Department of the Army, 15 July 1969).

Materials

1. Polyurethane foam, \$1.70/cu ft (\$60.03/m^3) (2.5 lb/ft^3 [40.05 kg/m^3])

2. Reinforced polyethylene membrane (.008 in. [.20 mm] thickness), \$0.04 per sq ft (\$0.43/m^2)

3. Mold release, any type

4. Steel fibers, \$0.23/lb (\$0.51/kg); minimum yield, 70 ksi (483 N/mm^2)

5. Cement, sand, gravel, and water, \$25/cu yd (\$33/m^3)

6. Accelerators, if desired, any type.

The polyurethane foam used in this system has a specific weight of 2 pcf (32 kg/m^3), and develops a tensile and compressive strength of approximately 30 psi (.207 N/mm^2). The foam is a two-component system of polyol and isocyanate. The two materials are supplied in 55 gal (.21 m^3) drums and, when combined, undergo a volume expansion of 30 to 1. The foaming agent is freon. The insulation factor for 3 in. (.076 m) of polyurethane foam is U = 0.037 (R = 27.27). The type of foam used in this system requires a minimum spraying temperature of 45 to 50°F (7 to 10°C).

A recommended shotcrete design mix per cubic yard is as follows:

Cement—750 lb (445 kg/m^3)

Fine aggregate—1000 lb (593 kg/m^3)

Coarse aggregate, 3/8-in. (10-mm) mix—1200 lb (712 kg/m^3)

Steel fibers—200 lb (119 kg/m^3)

Water—as required

Accelerator—as specified.

This design mix will produce concrete with 28-day properties as follows: flexural strength, 1100 psi (7.584 N/mm^2); compressive strength, 6000 psi (41.369 N/mm^2); split tensile strength, 900 psi (6.205 N/mm^2); Young's Modulus, 3.8×10^6 psi (26 200 N/mm^2); and Poisson's ratio, 0.18.

The shotcrete process produces excellent fiber distribution, with the major fiber reinforcement in the two planar directions where the strength requirements are maximum (Figure 3). Table 1 shows the ballistic resistance of 3-in. (.076-m)-thick steel fiber concrete.[6]

Table 1
Ballistic Resistance of 3-In (.076-m)-Thick Steel Fiber Shotcrete

Complete Protection From:

Weapon	Range
M67 hand grenade	5 ft (1.5 m)
81-mm mortar	15 ft (4.6 m)
M16 rifle Ball ammo, M193, 5.66 mm	50 yd (45.7 m)
M73 30-caliber machine gun Ball ammo, M80, 7.62 mm	50 yd (45.7 m)
45-caliber pistol Ball ammo, M1911	10 yd (9.1 m)

3 PROCEDURE

The procedure for using the inflation/foam/shotcrete system to construct shelters is as follows:

1. Obtain membranes in the shape of the structure desired. These membranes may be elastic or nonelastic, but the preshaped nonelastic type is recommended. Figure 4 shows an inflated nonelastic reinforced polyethylene membrane 28 ft (8.5 m) in diameter and 14 ft (4.3 m) high. A flat lower membrane, slightly larger than the structure's diameter, is used in addition to the shaped membrane.

2. Prepare a ring beam of the proper diameter. Figures 5 and 6 show a segmented ring beam of fiberglass-reinforced polyester and polyurethane foam. This ring is portable and reusable. Concrete ring beams or concrete slabs which become part of the floor for the structure can also be used.

3. Attach the lower membrane, if used, to the ring beam with metal strapping, then place the preshaped

---

[6] D. J. Naus and G. R. Williamson, *Ballistics Tests of Fibrous Concrete Dome and Plate Specimens*, Technical Report M-179/ADA025209 (CERL, April 1976).

(or elastic) upper membrane over the lower membrane (Figure 7).

4. Inflate the upper membrane and spray it with polyurethane foam to a predetermined thickness, with a minimum of 3 in. (.076 m) (Figure 8). The larger the span, the greater thickness of foam required. Six inches (.15 m) of foam was used for the 28-ft (8.5-m)-diameter dome, while only 3 in. (.076 m) was required for the 15-ft (4.6-m) domes.

5. Begin shotcreting immediately after completion of the foam spraying. If the structures are small, shotcreting can be performed from a platform; a snorkel truck is recommended for larger structures (Figure 9). The shotcreting should be a continuous process to minimize cold jointing. The final thickness of the structure is a function of the shape and intended use. Figures 10 (a) and (b) show completed domes.

6. Create openings in the structure by applying a form to the inflated membrane as shown in Figure 11, by applying a form to the foam as shown in Figure 12, or by cutting through the completed structure as shown in Figure 13.

7. Use the same curing procedures for concrete placed by the shotcreting process (pneumatically) as for ordinary concrete.

8. Use conventional reinforcing bars and wire mesh when analysis indicates that the steel-fiber-reinforced concrete cannot carry the design loads (Figure 14).

4 RESULTS AND DISCUSSION

Structures Constructed

CERL has completed five hemispherical domes using the inflation/foam/shotcrete system. A description of each is given in Table 2. The three 15-ft (4.6-m)-diameter domes were made with various foam thicknesses to determine the minimum thickness required for shotcreting. It was found that the 1.5-in. (.038-m)-thick dome No. 1 could not withstand the pressure from the shotcrete nozzle and deformed as shown in Figure 15. A 3-in (.076-m)-thick dome proved sufficient for the 15-ft (4.6-m)-diameter structure.

The versatility of the inflation/foam/shotcrete system permits the construction of structures of any thickness. The thickness of the dome is a function of its intended use. If the structure is to be relocatable, its weight must be kept within the capacity of the lifting equipment (i.e., helicopter, crane, etc.). Temporary structures can be constructed of foam only, or foam with shotcrete less than 1 in. (.025 m) thick. Hardened structures, or structures designed to resist heavy loads, may require more than 6 in. (.152 m). The various thicknesses are achieved without any alteration in the foam or shotcrete process, merely by increasing the time of foaming or shotcreting.

Comparison With Current AFCS Structures

Material costs varied with the thickness of the foam and shotcrete, but Table 2 shows that structures can be built at material costs less than \$3/sq ft (\$32.29/m^2).

Table 2
Dome Construction Summary

No.	Diameter, Ft (m)	Height, Ft (m)	Foam, In. (m)	Shotcrete, In. (m)	Time to Foam, Hr	Time to Shotcrete, Hr	Total Time to Construct, Hr	Area, Sq Ft (m^2)	Man-Hours*	Material Cost, \$	Material Cost, \$/Sq Ft (m^2)
1	15 (4.6)	7 (2.1)	1.5 (.038)	2.5 (.064)	1.0	1.5	2.5	177 (16.4)	20	280	1.58 (17.01)
2	15 (4.6)	7 (2.1)	3.0 (.076)	2.5 (.064)	1.5	1.5	3.0	177 (16.4)	23	360	2.03 (21.85)
3	15 (4.6)	7 (2.1)	5.0 (.127)	2.5 (.064)	2.0	1.5	3.5	177 (16.4)	23	450	2.54 (27.34)
4	18 (5.5)	10 (3.0)	6.0 (.152)	3.0 (.076)	2.0	2.0	4.0	255 (23.7)	25	850	3.50 (37.67)
5	28 (8.5)	14 (4.3)	6.0 (.152)	2.0 (.051)	8.0	6.5	14.5	616 (57.2)	74	1700	2.80 (30.14)

*Does not include preparation of reusable ring beams.

Table 3
Comparison of Inflation/Foam/Shotcrete Structure With AFCS Building

Item	AFCS TM 5-301 20 ft × 20 ft (6.1 m × 6.1 m) wood frame and wood floor	*Inflation/Foam/Shotcrete 22 ft (6.7 m) diameter x 11 ft (3.4 m) high, 3 in. (.076 m) thick, 3 in. (.076 m) concrete floor
Area	400 sq ft (37.2 m^2)	415 sq ft (38.6 m^2)
Weight	6 tons (5443 kg)	16 tons (14 515 kg)
Cost	$1021	$1010
Shipping volume	520 cu ft (14.7 m^3)	112 cu ft (3.2 m^3)
	Construction man-hours	
Horizontal	5	8
Vertical	220	72
General	40	8
TOTAL	265	86

*Does not include shipping of sand and gravel.

Table 3 compares an inflation/foam/shotcrete structure with a building of equal area as described in TM 5-301, 2, 3.[7] The shotcrete system requires one-third the man-hours and one-fourth the shipping volume. The shotcrete dome provides some ballistics resistance, as shown in Table 1, whereas the AFCS timber building does not.

Dome Tests

Relocatability

Figure 16 shows dome No. 4, 18 ft (5.5 m) in diameter by 10 ft (3.1 m) high, being lifted from the construction platform by a truck-mounted crane. The dome is 2.5 to 3 in. (.064 to .076 m) thick and weighs approximately 10 tons (9072 kg). It is reinforced solely with 1 volume percent of steel fibers. Only four lift points were required to move the dome 75 ft (22.9 m) into position for testing. This demonstrates that domes of this type are relocatable and can be transported by truck or helicopter from a general production facility.

[7] *Army Facilities Component System*, TM 5-301, 2, 3 (Department of the Army, 28 September 1973).

Simulated Burial

Dome No. 4 was covered with 70 tons (63 503 kg) of sand to simulate 4-ft (1.22-m) underground burial. The dome was ringed with sand bags to contain the sand and then loaded as shown in Figure 17. Dial gages mounted inside the dome to monitor the long-term deformations show that essentially no deformation has occurred since the initial deformations that resulted from the application of the load. The dome has been under load for 15 months.

Fireproofing

Polyurethane foam is a flammable material requiring some type of fireproof coating or covering. CERL has tested several types of materials and found that 1/16-in. (1.6-mm)-thick plaster made of one part cement to two parts sand is sufficient to fireproof the foam.[8] Corner fire tests conducted on full-scale panels with the plaster coating showed that the foam did not become involved

[8] Alvin Smith, *Fire/Flammability Test of Polyurethane Foams and Protective Coatings*, Technical Report M-129/ADA 009702 (CERL, July 1976).

until 8 minutes after ignition of the fire source. Very little involvement occurred during the following 17 minutes to the conclusion of the test. However, although plaster provides the required fireproofing, it cannot be considered the final answer to the problem since the large difference between the coefficients of expansion of the plaster and the foam can eventually cause the plaster to flake off.

The inside of dome No. 2 was coated with 1/8 in. (3.2 mm) of glass-fiber-reinforced cement and subjected to natural temperatures varying from 0 to 90°F (−17.8 to +32.2°C). The material is still intact after 10 months of exposure, with only minor shrinkage cracks. Tests of other types of fireproof coatings are continuing.

Production Data

Dry shotcrete machines can be purchased with a rated capacity of 2 to 12 cu yd/hr (1.5 to 9.2 m^3/hr). The actual production rate will depend upon the application, however. The CERL equipment is rated at 9 cu yd/hr (6.9 m^3/hr), but the actual rate attained was 2 to 3 cu yd/hr (1.5 to 2.3 m^3/hr). The primary reason for the lower-than-capacity production rate was the incorporation of fibers into the mix. Another reason was the technician's lack of familiarity with the equipment. However, experience has shown that a rate of 4 to 5 cu yd/hr (3.1 to 3.8 m^3/hr) of fibrous shotcrete is readily attainable during dome construction.

The foam- spraying equipment used in this study will mix and spray 60 gal (.23 m^3) of the liquid per hour, which foams into 200 to 225 cu ft (5.7 to 6.4 m^3). This study has shown that the average technician can produce 135 to 150 cu ft of foam per hour (3.8 to 4.2 m^3/hr) after only a few hours of instruction.

Mixing Alternatives

Blending the steel fibers with the cement and aggregate presents no problems since all materials are mixed dry. Mixing can be accomplished by batching all ingredients into a transit mixer at a central batch plant, by charging the mixer at the site using a conveyor belt, or by use of a concrete mobile as shown in Figure 18. It is also possible to perform the shotcreting operation using the standard 16-cu ft (.45-m^3) trailer-mounted concrete mixer that is part of the TOE of the Engineer Combat Battalion, Heavy; however, production rates are much lower than when a transit mixer is used.

Skill Requirement

The most important skill requirement of the dry shotcrete operation is the nozzle operator, who controls the water content and thus the water/cement ratio of the mix. Nozzle operation can be learned in just a few hours by any lower-graded technician (GS 3-4); however, additional hours of practice are required to develop competence. This is also true of the foam spray equipment operation; however, operation of the air compressors, concrete mixer, and shotcrete machine requires minimum skill and can be learned very rapidly.

Foam/Shotcreting as a Repair Technique

As stated previously, dome No. 1 (1.5 in. [.038 m] of foam) was deformed by the high pressure of the shotcrete nozzle as shown in Figure 15. This dome was used to demonstrate the foam/shotcrete system's capability for rapidly repairing deteriorated or damaged structures of any type.

The material encompassing the deformation was removed by breaking it out with a 2-lb (.91 kg) hammer. Thin, flexible wood slats were then nailed into the foam on the underside of the dome as shown in Figure 19 to approximate the curvature of the dome. The opening was then covered with ordinary fly screen and sprayed with foam (Figure 20). The repaired area was sprayed with shotcrete to complete the repair (Figure 21). The entire repair was accomplished within 1 hour.

5 CONCLUSIONS AND RECOMMENDATIONS

1. The inflation/foam/shotcrete system is a rapid, low cost, and low skill system for constructing shelters.

2. The system can produce temporary or permanent construction, with any degree of hardening desired.

3. The foam/shotcrete system can be used to rapidly repair deteriorated or damaged structures of all types.

4. Dome-shaped structures can be constructed to be transportable by crane or helicopter.

It is recommended that:

1. The inflation/foam/shotcrete system be applied to non-dome-shaped structures.

2. Ballistics tests be conducted to determine the thickness requirements to resist 50-caliber and 20-mm weapons.

3. A demonstration be conducted using field troops to assess the utility of the system.

Any Federal agency desiring additional information or assistance in using the inflation/foam/shotcrete system may contact:

Dr. G. R. Williamson or
Mr. Al Smith
U. S. Army Construction Engineering Research Laboratory
P. O. Box 4005
Champaign, IL 61820
Phone, Commercial 217-352-6511
FTS 958-7362 or 7413

APPENDIX:

MATERIAL SUPPLIERS

The following is a list of the suppliers from whom the equipment and material used in this study were purchased. All of the items listed are also available from other manufacturers.

SHOTCRETE:

Reed Guncrete Equipment

Halco Incorporated
Conquip Division
3005 N. 7th Street & Trafficway
Kansas City, KS 66115

Contact: Mr. Hal Kalousek

Steel Fibers

U. S. Steel
600 Grant Street
Pittsburgh, PA 15230

Contact: Mr. Richard Pfister

Accelerator

Sigunite
Sika Chemical Corporation
2510 Dempster Avenue
DesPlaines, IL 60016

FOAM:

Gusmer Spray Equipment (Model FF)

Gusmer Corporation
Route 18 and Spring Valley Road
Old Bridge, NY 08857

Contact: Mr. Paul White

Foam Material System (2 pcf polyurethane)

MoBay Chemical Company
Penn Lincoln Parkway West
Pittsburgh, PA 15205
412-923-2700

Contact: Mr. Dave Lambert

MEMBRANE: ELASTIC

Tuftane (ca .020 thick)

B. F. Goodrich
9921 Brecksville Road
Brecksville, OH 44141
216-526-4311

Contact: Mr. Harry Davis

MEMBRANE: NONELASTIC

Reinforced Polyethylene (Loretex)

American Bleached Goods
Division of Chane and Earley Inc.
1460 Broadway
New York, NY 10036

Contact: Mr. Don Wilmarth

MOLD RELEASE

Brulin Sp 169

Brulin & Co., Inc.
P. O. Box 270-B
Indianapolis, IN 46206

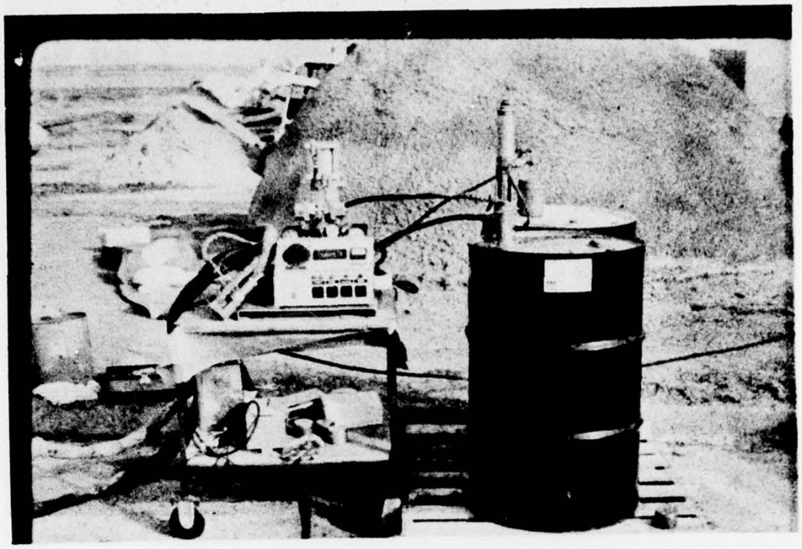


Figure 1. Polyurethane foam spraying equipment. Included are two compressed air operated pumps, a heating and mixing unit, and the spray gun.

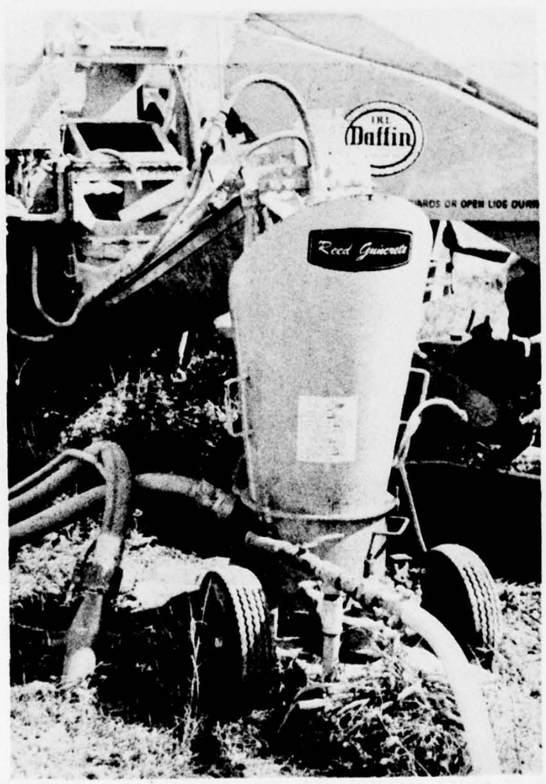
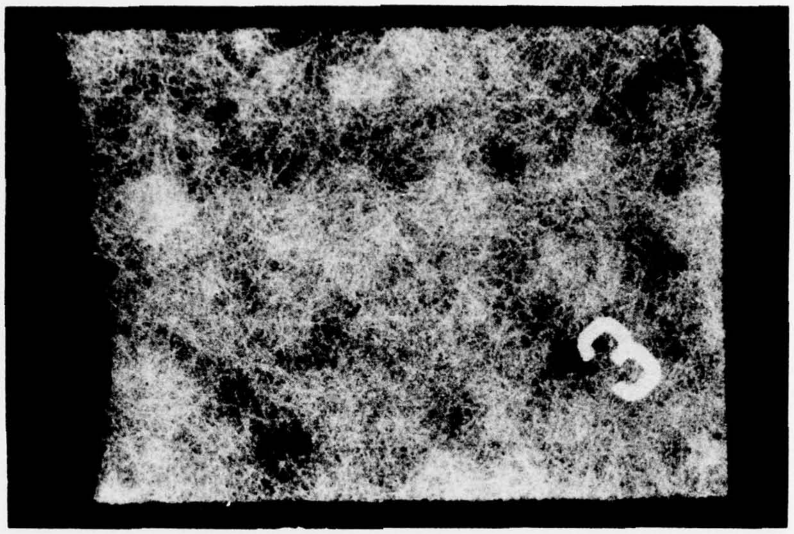


Figure 2. Dry shotcrete machine with nozzle.



(a) Plan view.

(b) Edge view.

Figure 3. Radiograph of piece of steel-fiber-reinforced shotcrete with 1.5 volume percent of fibers.

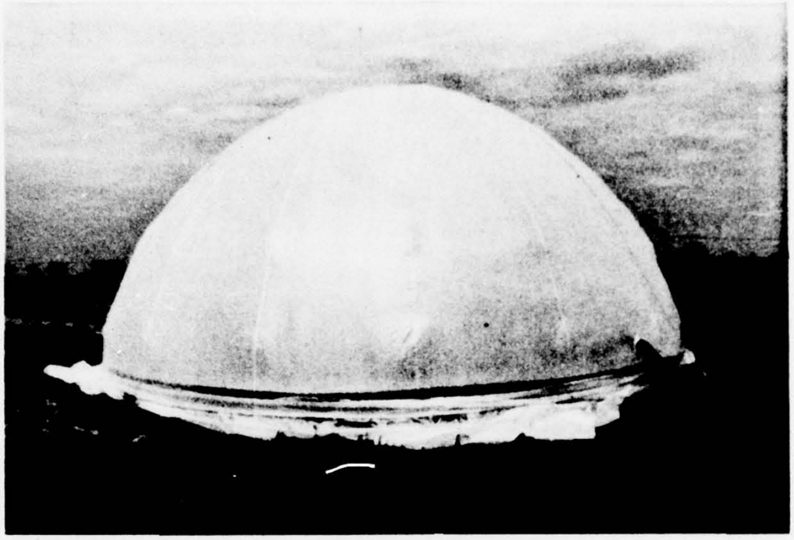


Figure 4. Reinforced polyethylene membrane in fully inflated position – 28 ft (8.5 m) diameter by 14 ft (4.3 m) high. Note small 20 cu ft (.57 m^3)/min blower unit at lower right.

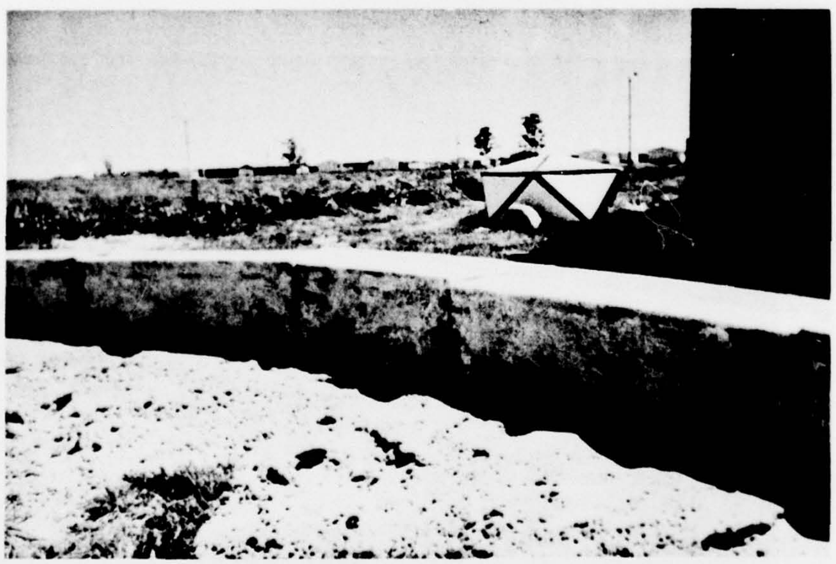


Figure 5. Segments of polyurethane foam/glass reinforced polyester ring beam for 28-ft (8.5-m)-diameter dome.

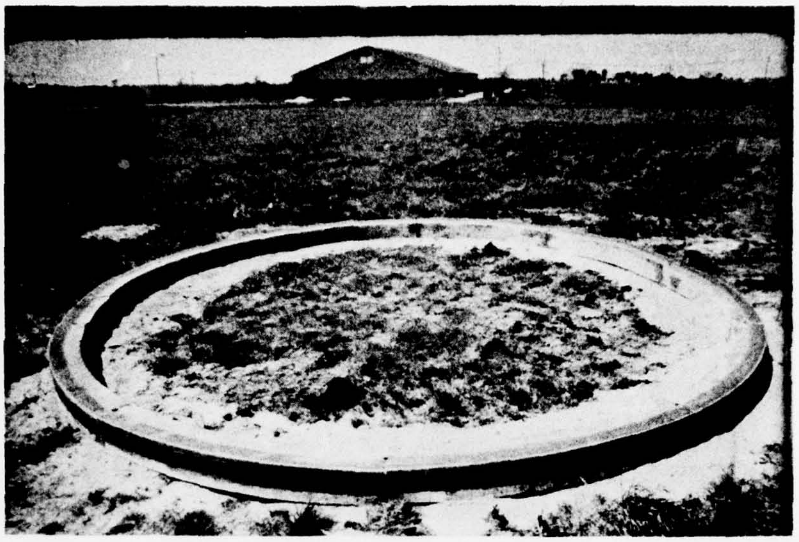


Figure 6. Full 28-ft (8.5-m)-diameter ring beam in position to receive membrane.

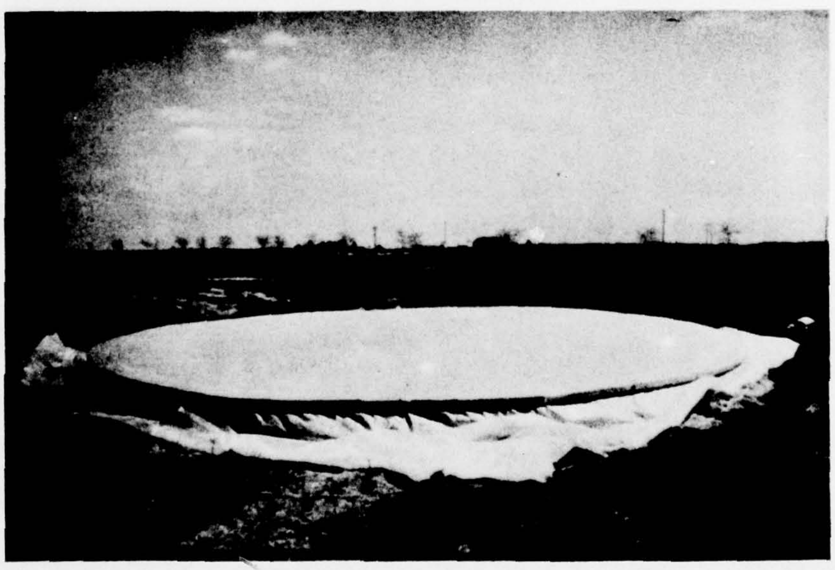


Figure 7(a). Lower membrane banded into position for 28-ft (8.5-m) dome.

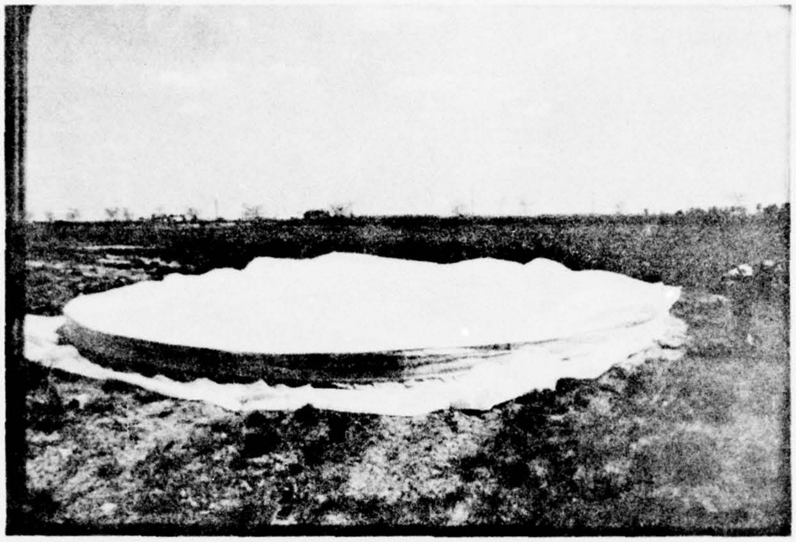


Figure 7(b). Upper membrane banded into position, ready for inflation.

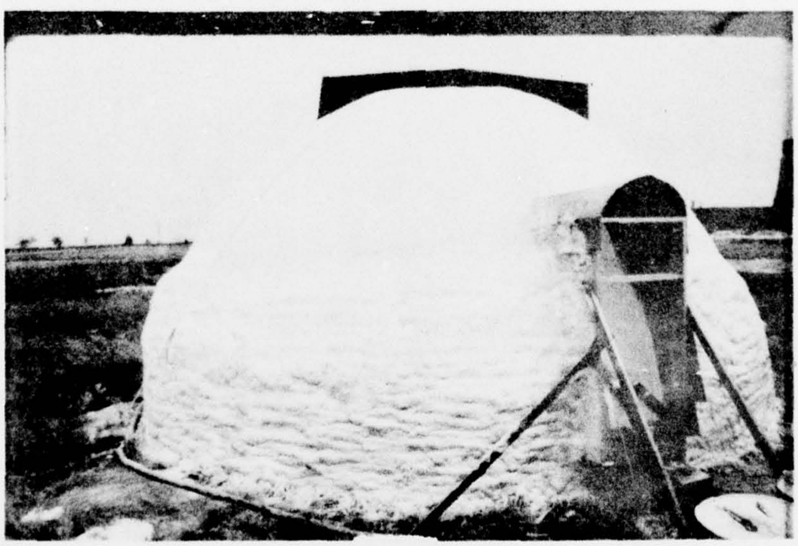


Figure 8. Twenty-eight-ft (8.5-m)-diameter membrane partially sprayed with polyurethane foam.

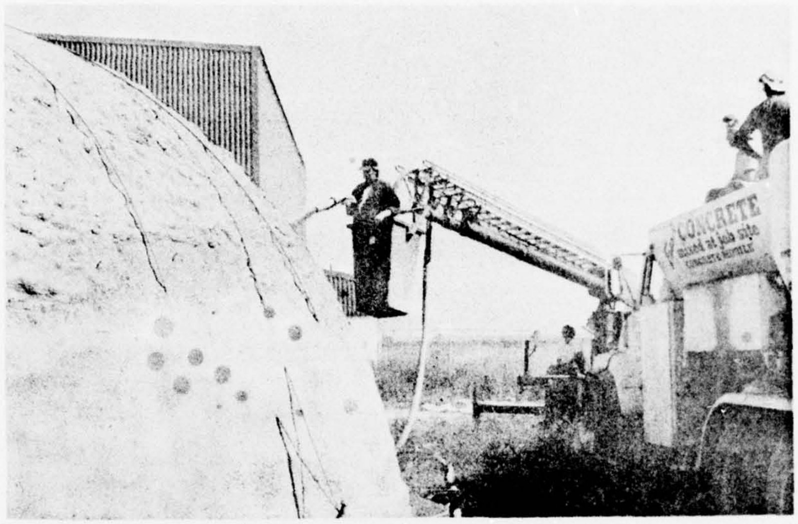


Figure 9. Shotcreting 28-ft (8.5-m)-diameter by 14-ft (4.3-m)-high dome with use of snorkel crane.

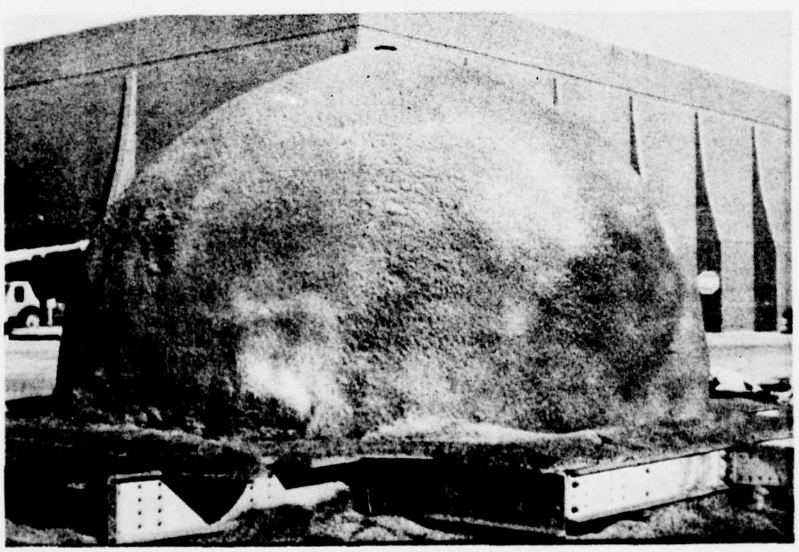


Figure 10(a). View of completed 18-ft (5.5-m)-diameter by 10-ft (3.0-m)-high steel fiber shotcrete dome.

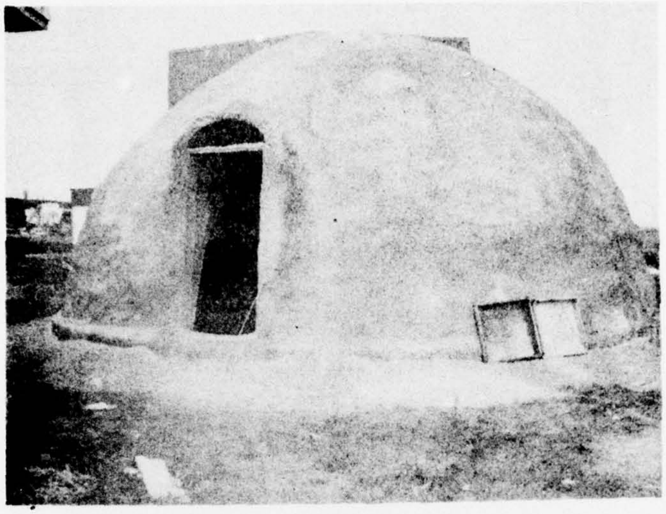


Figure 10(b). Completed 28-ft (8.5-m)-diameter by 14-ft (4.3-m)-high steel fiber shotcrete dome. The dome consists of 6-in (.15-m)-thick polyurethane foam and 2 to 3 in. (.051 to .076 m) of 1.5 volume percent steel fiber shotcrete.

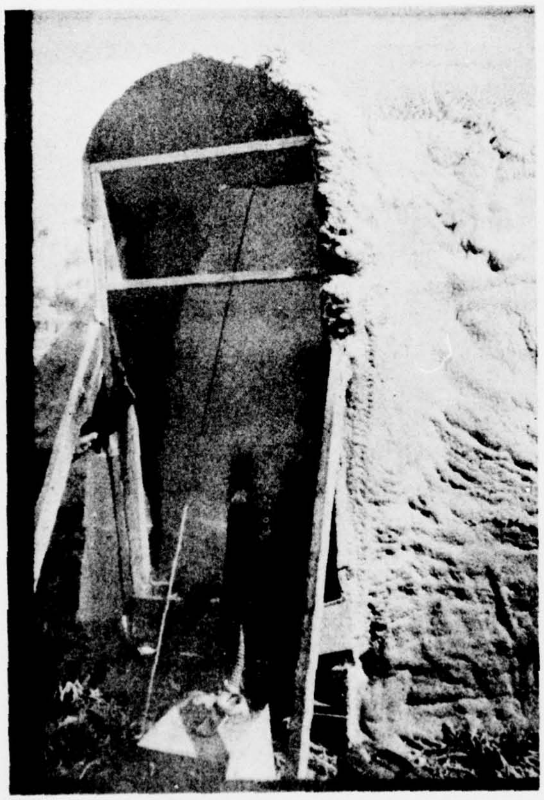


Figure 11. Cardboard form attached directly to inflated membrane to provide opening into 28-ft (8.5-m)-diameter dome.

Figure 12. Opening into 15-ft (4.6-m)-diameter by 7-ft (2.1-m)-high dome made by placing wood form directly on the foam shell and then shotcreting around it. Cover of form has been removed.

Figure 13. Opening cut into 15-ft (4.6-m)-diameter by 7-ft (2.1-m)-high steel fiber shotcrete dome with demolition saw. The foam and shotcrete are each 3 in. (.076 m) thick.

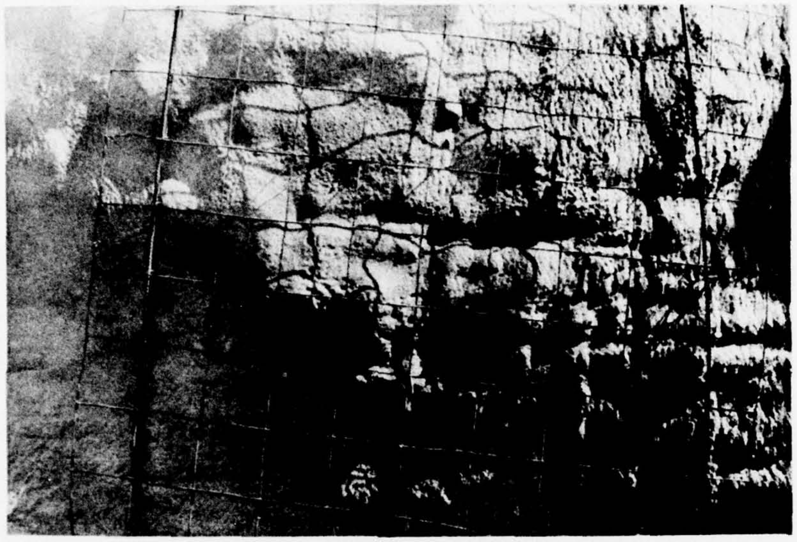


Figure 14. Segment of 28-ft (8.5-m)-diameter dome was reinforced with No. 4 reinforcing bars and 6/6-10/10 wire mesh to demonstrate the utility of this type of reinforcing if it should be required.

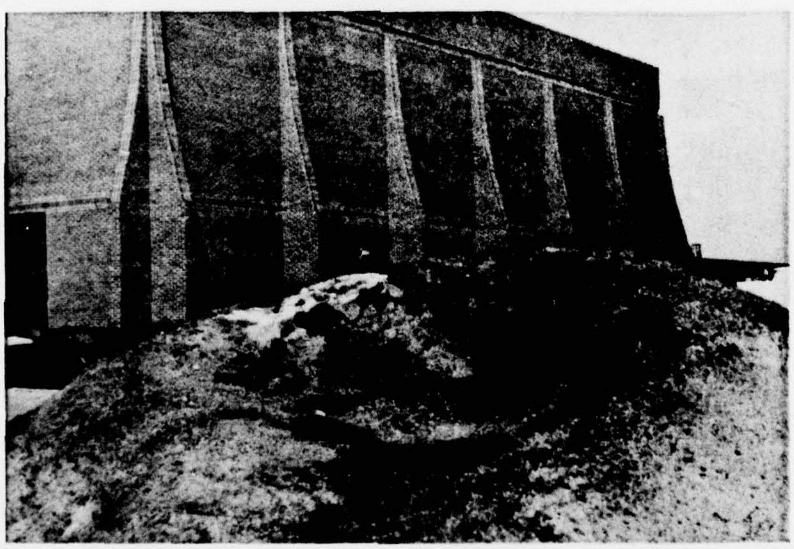


Figure 15. Deformation of the 1.5-in (.038-m)-thick polyurethane foam dome resulting from high pressure of shotcrete.

Figure 16. Eighteen-ft (5.5-m)-diameter by 10-ft (3.0-m)-high dome being lifted from construction platform by truck crane for placement into position for testing.

Figure 17. View of 18-ft (5.5-m)-diameter dome being loaded with 70 tons (63 503 kg) of sand to simulate a 4-ft (1.2-m) underground burial.

Figure 18. Batching of steel fiber concrete mix. Equipment required is a concrete mobile, a shotcrete machine, 600 cu ft (17 m^3) /min air compressor, and a truck-mounted snorkel crane.

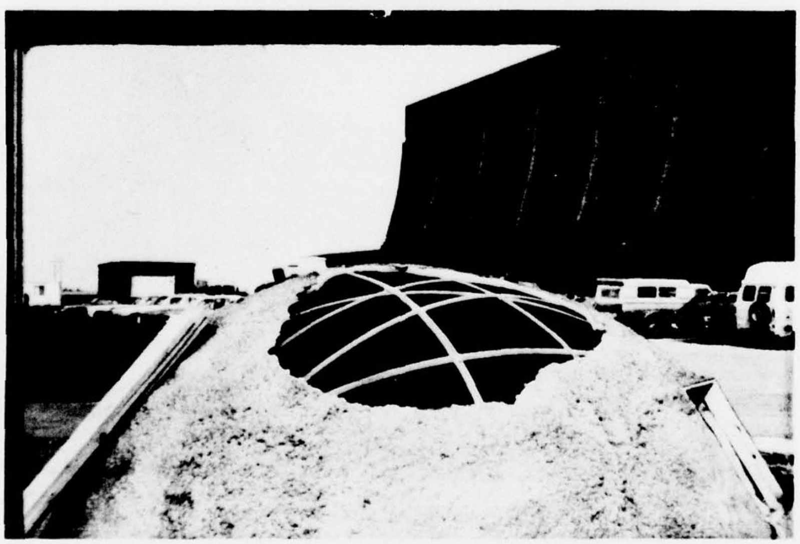
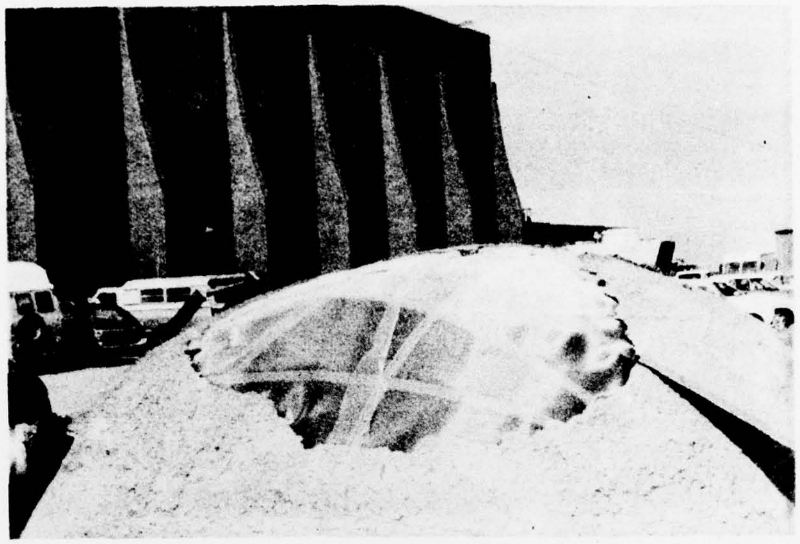


Figure 19. Deformed dome of Figure 15 being repaired using the foam/shotcrete system. This view shows the old material removed and flexible wood slats placed to curvature of dome.



(a) Screen in place ready for foaming.

(b) Foam being applied to screen.

Figure 20. Further steps of repair process.

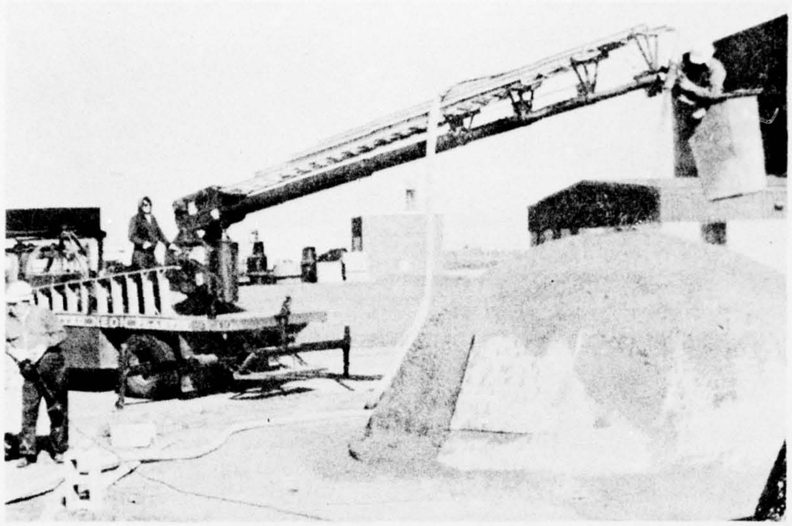


Figure 21. Shotcreting foam patch to complete repair of 15-ft (4.6-m)-diameter dome.

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