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AN EVALUATION OF THE MONOLITHIC DOME CONSTRUCTION METHOD FOR BIOLOGICAL CONTAINMENT STRUCTURES [1, 2]

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ABSTRACT

A monolithic dome was built as a residential structure using a previously developed airform technique. The building consisted of an outer airtight form, polyurethane foam insulation, and reinforced concrete. Except for the airform kit, locally available materials were used for construction using several alternatives and options applicable to this kind of building. The process and options were evaluated relative to their application for the production of biological containment facilities. It was concluded that the monolithic dome building technique is an effective alternative to conventional methods.

LITERATURE REVIEW

Required characteristics of a functional biological containment building have been outlined in several publications over the last 30 years (Kuehne 1973, Phillips 1967, U.S. Department of Health and Human Services 1993, U.S. Department of Agriculture ARS 1991.) Sealed concrete walls, floors, and ceilings have been specified along with directional filtered airflow. The sealing of penetrations currently range from statements such as "Penetrations in these surfaces are sealed, or capable of being sealed to facilitate decontamination." (U.S. Department of Health and Human Services 1993) to extensive pressure decay testing procedures which require airtightness to an extreme degree (U.S. Department of Agriculture ARS 1991). In the pressure decay testing requirement, sealing must be so complete that at a beginning pressure of 2" (5 cm) w.g. (water gauge), the rate must not exceed 7% (logarithmic of pressure against time) per minute over a 20 minute time period. This is a difficult standard to attain using conventional building designs and techniques.

The procedures for producing a monolithic dome are described in an article by one of the originators of the process (South 1990). A circular concrete footing is first constructed. A fabric form is then attached to the footing and inflated with air pressure. Two to five inches of polyurethane foam are then sprayed onto the inside of the form after which reinforcing steel (rebar) is attached to the foam. Last, concrete is sprayed over the foam and steel (Figure 1). The procedure may be modified if insulation is not desired by using a different kind of airform and placing the steel and concrete on the outside of the form (South 1995).

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Monolithic domes have potential for extreme airtightness as shown by their use for fruit storage in Stockton California (Anonymous 1990, Schmidt 1989). An atmosphere of 98% nitrogen and 2% oxygen at near freezing temperatures has been maintained in two 230 foot (70 meter) diameter domes to suspend the aging of fruit. Each dome contains 42,000 square feet (3902 sq. meters) of floor space, illustrating that massive airtight structures are possible. The key to the degree of airtightness is in the urethane foam and the seamless quality of sprayed on concrete.

Construction costs for this kind of structure are relatively low. The Stockton, California domes cost approximately $20.00 per square foot (.09 square meter). For residential use, finished dome costs were estimated in the range of $25.00 to $35.00 per square foot (Zimmerman 1992). In industrial use such as the storage of large quantities of fertilizer, it is estimated that domes require 50 percent less concrete, reinforcing, and footing than do conventional walls (South 1991). With the addition of airtight doors, HEPA filters (High Efficiency Particulate Air Filters),airlocks, and the necessary control equipment, the cost of a finished containment structure may be below the usual cost of such buildings due to the savings on the building shell.

High structural integrity is a highly desirable feature of a containment building. It has been estimated that a monolithic dome with proper earth sheltering will withstand bomb blasts more effectively than conventional structures (Barbier 1994). One chemical company chose to use a monolithic dome to store large quantities of material and makes the following statement: "The strength and stability of domes make them virtually immune to climatic catastrophe, or earthquakes, as well as to fire, or corrosion hazards." (Wood 1995). For environmental reasons, a state highway department uses a dome for salt storage on the basis of the estimation that 80 to 90 percent of environmental problems associated with the use of salt on roads is due to improper storage (Anonymous 1988).

Energy efficiency of building designs should be considered and is high in monolithic domes. The R-value of a typical dome is considered to be 35, but may effectively be higher due to the effect of thermal mass (South 1990). The energy saving features of domes are summarized by an architect who states, "Domes embody the virtues of simplicity, economy, and energy conservation, and enclose the maximum amount of space with the least surface area. It is this surface area which consists of building materials, and comprises the exterior skin of the building through which heat is gained, or lost. This is the essence of dome efficiency." (Zimmerman 1992).

With the exception of the airform kit, locally available materials are all that is needed to produce a dome. The expertise required to manage the alternative methods of construction may be developed through video tapes and classes taught by experienced dome builders (Neighbor 1995).

MATERIALS AND METHODS

Generally standard materials and methods of monolithic dome construction were used. Variations and options chosen are listed in the following sections.

Airform Kits

The airform kit was obtained from Monolithic Constructors, Italy, Texas. The kit consisted of a 40 ft. (12 meter) diameter form along with reinforcing steel (rebar) anchors. The form was ordered in the shape of a half sphere with no custom window, or door augmentations.

Polyurethane Foam

Sprayed on polyurethane foam insulation was of a type using a two part process in which Diphenymethane-4,4'-diisocyanate was mixed with blended polyol resin.

Reinforcing Steel

Steel in the foundation and slab was 5/8 inch (16 mm) and 1/2 inch (13 mm) grade 40 rebar. In the dome shell, 1/2 inch (13 mm) and 3/8 inch (9.5 mm) grade 60 rebar was used.

Concrete

In the foundation and slab a standard 5 sack (470 pound cement per cubic yard), (214 kg cement per .76 cubic meter) concrete foundation mix was used. Concrete used in the dome shell was a 9 sack per cubic yard (.7647 cubic meter) mix. This was made up of 846 pounds (385 kg) Portland cement, 2182 pounds (992 kg) sand, 394 pounds (179 kg) 3/8 inch (1 cm) maximum diameter gravel, 1.5 pounds (.7 kg) plastic fibers and 4 ounces (118 ml) air entraining agent delivered at a 2" (5 cm) slump ready for the addition of water to pumping consistency. For the final coat of concrete, the gravel was eliminated and sand substituted.

CONSTRUCTION PROCEDURE

The footing and slab were constructed at the same time using a ringbeam configuration for steel in the footings and a grid pattern for steel in the slab. Polyurethane foam as applied in two layers to a total thickness of 3 inches (7.6 cm). Concrete was applied by the shotcrete (wet) process over a period of four days. Each day from 0.5 inch (1.25 cm) to 1.5 inch (3.8 cm) of concrete was added to the structure. This was done by standing on the floor, or from up to three layers of 5 foot (1.5 meter) scaffolding at a maximum distance of 6 feet (1.8 Meter) from the nozzle tip to the wall. The design specified the application of at least 6 inches (10 cm) of concrete at the wall base tapering to at least 2 inches (5 cm) at the top of the dome. Following the last application of concrete, blowers were left on for 8 hours and then shut off. The airlock was then left closed for 30 days to allow curing of the concrete.

To provide a smooth finished surface, a layer of cement based plaster was later hand applied and finished. This was primed with water based acrylic latex and finish coated with acrylic latex enamel.

PRESSURE TESTING AND DURABILITY OBSERVATIONS

Pressure Testing

Coarse pressure testing was the only pressure testing possible on this project. Deflection of a sheet of builders plastic taped over a window opening was audibly measured as a door was closed. Later after the installation of sealed, non-operable windows, air movement was audibly measured following the rapid closing of the door and the resultant compression of air in the interior of the dome. It was not possible to do a pressure decay test on the structure.

Structural Observations

Twenty-four months following the completion of the dome, observations were made concerning durability. The floor and shell were examined for cracks and the surface of the airform was checked for deterioration due to weathering.

Testing of Insulation

The dome was tested for the effectiveness of the insulation during winter temperatures. Two 1500 watt electric heaters were run for approximately a month while qualitatively measuring the room temperature.

Results

Closing of a normally gasketed residential door produced pressure sufficient to cause plastic covering a window hole in the exterior of the dome to produce an audibly detectable deflection. During the closing of the door later with permanent windows in place, air could be heard rushing between the door and the jamb for approximately two seconds after the door was shut. Air leaks were small enough in number so that combined with the insulation on the building, only minimal heat was required to keep the dome at close to habitable room temperature (15 to 20 C using only the two 1500 watt heaters.

The structure remained sound following completion. No major cracks formed in the dome shell. More cracks occurred in the slab than in the shell. The airform remained in about the same condition as when new, not showing any noticeable deterioration from the weather.

DISCUSSION

Results of the construction of the dome show that there is a potential for this kind of dome to be used successfully for biological containment building construction. As indicated by the results of the door closure testing, the airtightness required for pressure decay testing is nearly achieved after a dome is finished. One author of this paper has been through the pressure decay testing and sealing process with a conventional building and reports that the degree of airtightness achieved after the initial dome construction was comparably achieved in the conventional building only following days of preliminary leak detection and sealing. Pressure decay testing was beyond the resources available for this project. Had it been reasonable to do more extensive sealing of openings and penetrations, there is a high possibility that the USDA tests would have been passed with minimal effort. Energy efficiency was confirmed in the winter heating of the dome. The lack of major cracks in the shell indicates that the structure is permanent and durable. The lack of noticeable weathering of the airform indicates that it should last for several years before requiring recoating. Interior wall finishes using paint may be adequate to permit airtightness and cleaning initially, but consideration should be given to the use of a flexible polymer finish to compensate for cracks if they should eventually occur. With the addition of air locks, specialized HVAC equipment, airtight doors, and a small amount of additional sealing of penetrations, this structure could be modified to meet the requirements for containment in Ag BSL-3 construction with much less work than with a conventional building (U.S. Department of Agriculture ARS 1991).

There are several reasons that monolithic domes should be seriously considered as assets to any attempts toward ultimate biosafety. Other types of buildings, while able to pass a pressure decay test immediately following construction, would most likely not pass a year later due to settling of foundations and resultant cracks in the containment envelope. Preliminary evidence is that monolithic domes will remain structurally stable for extended periods of time. Reinforced concrete combined with the dome shape is extremely strong. There would be much less likelihood of a break in containment due to earthquakes, or severe weather than with a conventional building. The recent terrorist bombings around the world also indicate the need for extreme structural security of any laboratory in which dangerous biological agents are present.

Concern has been raised by some about the risks to domes during construction as a result of power failures. The most critical time appears to be while foam only ,or foam and untied rebar are supported by only air pressure. One builder reported that after all of the rebar on a 50 foot (15 meter) diameter dome had been placed and tightly tied, power was down on both a portable generator and the utility company for about half an hour. The dome did not suffer any noticeable damage during this time (Vaughn 1995). This might not have been the case before all rebar was tied, or if the power had been lost later during shotcrete application. The necessity for back-up emergency power is thus obvious during construction.

Potential uses for monolithic domes as containment structures are numerous. Small animal research work could be done under conditions which more closely approximate wild outdoor, or agricultural conditions than do isolator cages, or small floor pens. For large animal disease work monolithic domes provide walls which may stand the abuse of large animals and offer open spaces needed for exercise. Aerosol testing as applied to the development of defensive devices against chemical and biological warfare agents might be done in large domes. Due to the insulating qualities of the shells, the attaining of high, or low temperatures would be easily accomplished. The strength of this kind of construction would also allow either above, or below sea level altitudes to be simulated through the use of high pressure supply, or exhaust fans.

Since the security offered by monolithic domes is unequaled for the amount of money required to produce them, they should be ideal for new research and treatment facilities required by government and health organizations. To produce a structure by conventional methods with as much durability as a concrete dome could require much more than available funding. Although research and health funding is decreasing, the need for affordable containment is increasing. Patients requiring isolation due to antibiotic resistant respiratory infections and those who need to be protected from infection due to immune system disfunction continue to become greater in number. Buildings located in areas away from the general population might be advocated, but it would be more effective to place the treatment centers close to the problems in areas of dense population. An affordable place to house these patients is available in monolithic domes.

There are other non-biocontainment applications for monolithic domes. Large exercise areas might be built to train athletes, or the military for performance at various air pressures and temperatures. Where large cleanrooms are required for medical and electronics parts manufacturing, isolation domes may be an answer as to how to supply hundreds of thousands of square feet of unobstructed, clean, isolated, affordable space. Durable, affordable, energy efficient homes, schools, factories and churches, may also be provided through this technology.

FIGURE 1 (A-E)

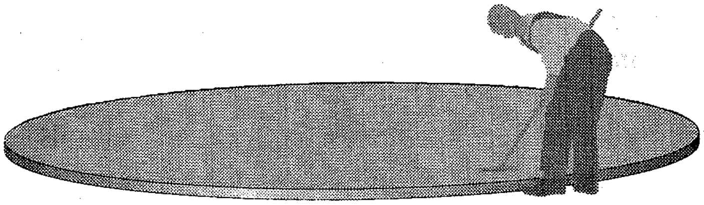

Fig 1a — Foundation is constructed.

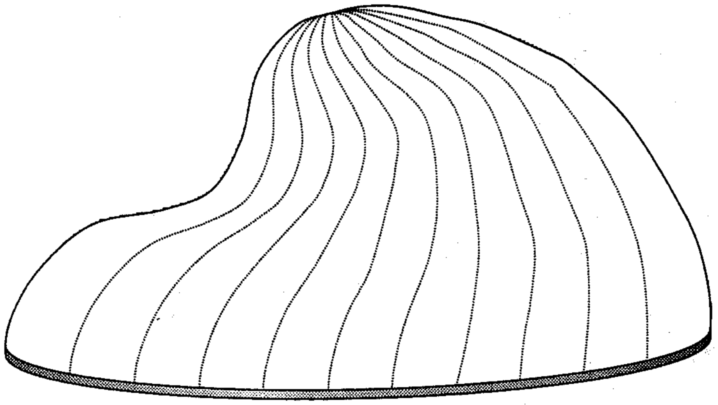

Fig 1b — Airform is attached and inflated.

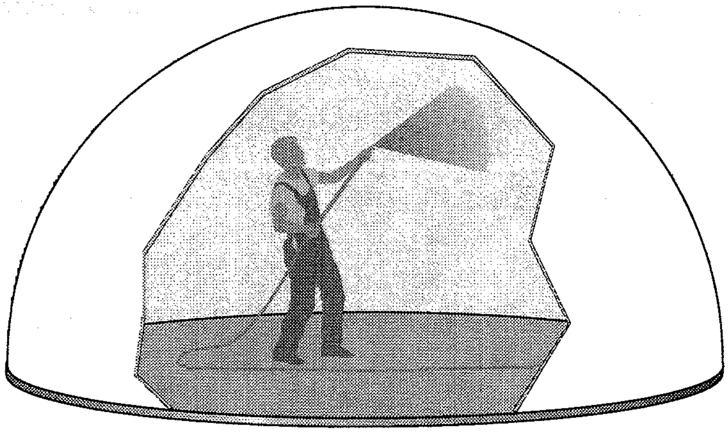

Fig 1c — Polyurethane foam is applied.

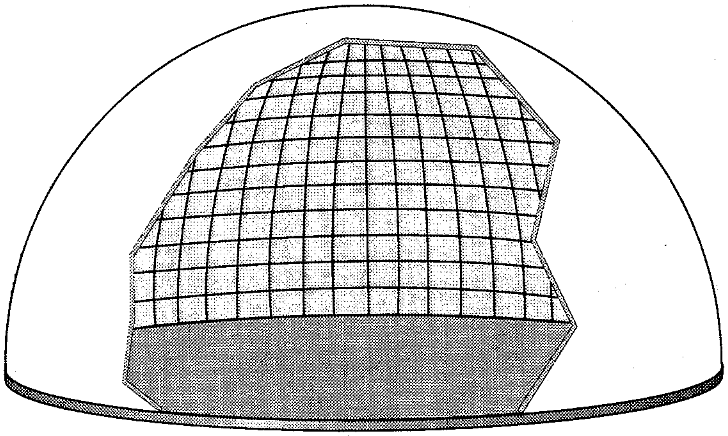

Fig 1d — Rebar is hung and tied.

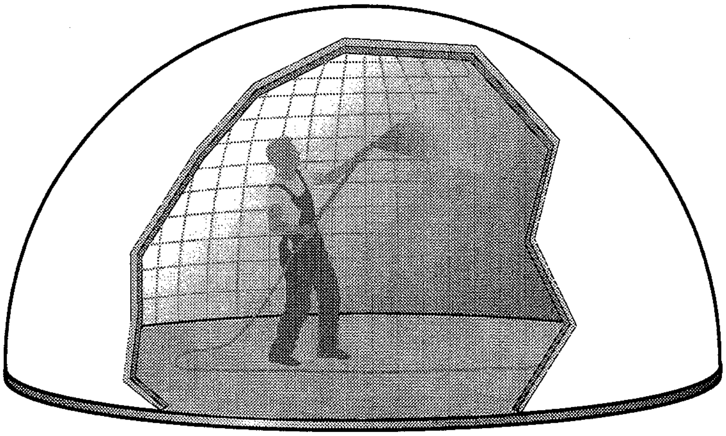

Fig 1e — Shotcrete is applied.

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