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9. ABSTRACT
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In 1962 the University of Michigan received a USAID grant to explore the potential of foam plastics for solving housing problems in developing nations. A feasibility study completed in 1962 (see PN-AAD-174) established the desirability of investigating the use of foam plastics as structural material. The project was conducted in two phases. The first phase involved experimentation to obtain information on a variety of foam plastics. Several structural systems were established as scale models before two structural concepts were selected for full-scale construction and testing. One concept involved application of spray polyurethane foam on a folding wood lattice armature. The other concept involved production of large structural components made of paper-laminated polyurethane foam board. During the second phase of the project, four prototype structures representing different techniques were built. One consisted of seven umbrella-shaped components made of sprayed polyurethane foam. A second was a two-story structure made of triangulated bents of folded paper-laminated polyurethane foam board. A third consisted of four square umbrella-shaped components made of flexible foam coated with reinforced polyester. The fourth was a room-sized unit in which polyurethane foam board served as the mandrel for filament-wound polyester. The research program also investigated requirements for production and marketing of chemicals and foam plastic products for structures and building components in underdeveloped countries. The major recommendation stemming from the project was

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that AID collaborate with the U.S. plastics industry in sponsoring construction and evaluation of suitable prototype dwelling units in developing countries. Interim reports of the project activities during 1964 and 1965 are available as PN-ADD-177 through PN-AAD-182.

AID/csd-288
IUD-M

Dr Urquhart
Report

PN-AAD-178

ARCHITECTURAL RESEARCH LABORATORY - THE UNIVERSITY OF MICHIGAN

Interim report: to the Agency for International Development
on ORA project 05687
for the period July 1963 through June 1964

# RESEARCH ON STRUCTURAL SYSTEMS UTILIZING THE FOAM PLASTICS AS A STRUCTURAL MATERIAL FOR HOUSING IN UNDERDEVELOPED AREAS

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## SUMMARY

Structural work conducted by the project staff ranges from the design development of foam plastics structures to the investigation of structural systems which are still experimental. The major emphasis during this phase of the project has been geared towards the use rather than the nature of materials. The research objective has been to obtain as much data as possible on the structural potential of foam plastics within the limitations of time and budget.

Since foam plastics are presently being used primarily for insulation, and only to a minor degree structurally as in the case of sandwich panels, existing testing methods and data regarding these materials are inadequate for an understanding of structural behavior. Therefore, in the absence of standard procedures, testing methods frequently had to be designed to fit the various experiments. Such testing has been in the interest of establishing better correlation between a specific material and its full-scale structural application.

The project has actively solicited the interest of the plastics industry in contributing its resources towards the AID-sponsored research. Direct contact was established with approximately 100 companies. Of the organizations which voiced an interest in this research activity, twelve have contributed to the experimental development of structural systems while thirty other concerns have offered materials and technical information.

Inquiries about the project have been received from various parts of the world. To maintain public interest in the project and to keep industry and organizations informed on progress, papers describing the project have been delivered at various conferences. Articles have also been prepared for publication along with several news releases.


## INTRODUCTORY PHASE

The feasibility study intended to explore the "Potential Use of Foam Plastics for Housing in Underdeveloped Areas" was concluded by the end of February 1963 as ORA project 05215 and a report was published under the same title. The initial printing of 500 copies was exhausted within 7 months. A second printing of 500 copies is nearing exhaustion as requests continue to be received from inquirors in both this country and abroad.

The project was temporarily extended through June 1963 and the project staff operated under a hardship fund set up by the University in order to maintain continuity of research between ORA project 05215 and the present ORA project 05687. During this period, priorities as to the course of research to be pursued were established on the basis of the most promising possibilities for early application. Thus, two materials were selected for initial investigation: (1) polystyrene foam, whose technology is

well advanced, and (2) polyurethane foam produced between paper skins, which offers a fair amount of quality control and unique structural possibilities.

At the same time, arrangements were made with Dow Chemical Company regarding the first of these materials, and with Union Carbide Corporation regarding the second, for direct collaboration as well as for contributions of materials and technology. A head start was achieved through the erection of a polystyrene dome structure before the end of June 1963. This test structure was turned into a usable building the following month.

## PROCEDURE

Since in sponsoring this project, the AID goal is to promote the establishment of an industrial base for the production of low-cost housing in the developing countries, it was thought important that a basis for communication and collaboration with industry and concerns interested in such housing should be established. The active participation of the chemical industry was sought not only because its resources are essential in conducting this project but also in order to encourage the establishment of production facilities abroad. The latter is a prerequisite for any early application of research findings.

The possibility of a foreign market opening up through AID sponsorship provided the necessary incentive for industry to make its resources available to the project. To stimulate industrial research and development in the direction of the AID goal, however, there had to be a demonstration of how the various foam plastics should be used structurally as new solutions to building problems.

It was decided that the investigation should cover as wide a range of structural systems as possible. Since the time alloted for this purpose was rather short, it was also decided that the project should concentrate on those systems whose potential could be demonstrated with the least demand on available time and resources. Full development of a system usually requires a sizeable amount of industrial investment and this cannot come to pass unless its potentials are demonstrated first. The emphasis has therefore been on potentials and what can be most readily achieved.

## STRUCTURAL RESEARCH AND DEVELOPMENT

Five structural systems were explored during this period. The range of investigation has varied from the erection of a usable structure to the most preliminary kind of experimentation. Four systems have been developed to the point where their potential is demonstrable and where further research and development is justified in terms of structural analysis, chemistry, and production.

This work has comprised (1) the erection of a dome with polystyrene foam by the "spiral generation" process, (2) the development of structural components with

paper-skin polyurethane foam panels, (3) the spray application of polyurethane foam on a "folding armature" structure, and (4) the erection of structural components made by rigidizing flexible polyurethane foam. A description of this work illustrated with a series of photographs takes the form of an article prepared for the Journal of Cellular Plastics and is attached as Appendix A.

Drawings and detailed information regarding the erection procedure of the polystyrene foam dome through the "spiral generation" process are attached as Appendix B. This full-scale experiment provided a demonstration of the potential of foam plastics for the creation of high quality and economic structures.

A report on the analysis and testing conducted to determine the design of structural bents made of paper-skin polyurethane-foam panels is attached as Appendix C. Drawings and specifications for the erection of a two-story test structure have been completed and a testing program has been set up to establish a better understanding of the behavior of this panel material.

Model studies are under way to explore the potential of the "folded armature" system using polyurethane spray and to determine the influence of shell form on the behavior of the structure. At the same time a testing program has been set up to explore creep characteristics of various foam plastics samples. Additional data will have to be obtained before a comprehensive report on this subject can be prepared.

Although the system based on the rigidizing of flexible foam is at an early stage of development, it holds great promise for early application. One of the drawbacks to date has been the maximum width (56 inches) in which the reticulated flexible foam can be obtained. Reticulation, a process which removes the surface films (windows) from the cell structure of the foam greatly improves the tensile and stretch strength of the material besides creating a material which can be economically impregnated with resin. It is believed that wider structural components can be obtained by using an adhesive which has stretch characteristics similar to that of the foam.

Another concept being explored is the creation of structures by inflating flexible membranes with polyurethane foam. After some preliminary experimentation which illustrated the various problems that had to be overcome, it was decided to suspend temporarily any further development of this system and to concentrate on the other four.

Since foam plastics are already being used as the core material for sandwich panels and can also be introduced in that form in developing countries, a theoretical study was undertaken to establish the economic relationship between the panel skins and core. This study is attached as Appendix D.

On the basis of research to date, indications are that foam plastics can contribute both to the industrialization of underdeveloped countries and to the realization of low-cost dwelling units, provided suitable structures and systems are developed which will exploit to the fullest the properties inherent in foam plastics.

PUBLICITY AND PUBLICATIONS

More than 400 inquiries have already been handled by the project staff. Also, visits and interviews are continually being arranged with representatives of industrial concerns who are interested in coming here to inspect the project accomplishments. Such inquiries have been received from many other parts of the world, notably Brazil, Colombia, Finland, Germany, Ghana, Israel, Italy, Samoa Islands and the United Kingdom.

Articles referring to the project have appeared in technical and trade journals as well as in newspapers. Particularly noteworthy: Development Research Digest, July 1963; International Asbestos Cement Review, October 1963; AIA Journal, January 1964; Chemical Week, 27 June 1964.

Two papers have been presented on the over-all objectives of the project: (1) at the conference on foam plastics, co-sponsored by the U. S. Army Natick Laboratories and the Committee on Foam Plastics of the National Academy of Sciences, in Boston, in April 1964; (2) at the conference of the Association of the Collegiate Schools of Architecture, in Miami, in May 1963. The former was published in a volume containing the proceedings of the conference under the title: Foam Plastics, PB 181576, U. S. Department of Commerce, Office of Technical Services, 1963.

A paper on the economy of sandwich panels (see Appendix D) was presented at the conference of the Society of Plastics Engineers, in Buffalo, in May 1964. This paper was published in the June 1964 issue of Modern Plastics.

A paper on the structural development work has been prepared for the International Conference on Cellular Plastics to be held in New York in September 1964; this paper is to be published in the January 1965 issue of the Journal of Cellular Plastics (see Appendix A). Two other papers have been prepared for the conference on cellular plastics to be held at The University of Michigan in August 1964. The project has also been invited to submit a paper for the meeting of the Conseil International du Bâtiment (CIB) to be held in Copenhagen in August 1965.

CONTRIBUTIONS

Major contributors to this early phase of the project have been Dow Chemical Company, Union Carbide Corporation, and Wyandotte Chemicals Company. Their contributions include materials, manpower and equipment, technical assistance and

development work. Equipment for foam and glass fiber applications was donated to the University by Binks Manufacturing Company and Pyles Industries. Materials essential for the erection of the experimental structures were contributed by Kimberly Clark Company, Raymond Company and Scott Paper Company. Information and technical assistance has also been obtained from Atlas Chemical Industries, E. I. du Pont de Nemours and Company, Farbenfabriken Bayer A. G., and Mobay Company.

Working relationships have been established with approximately 30 other concerns who have offered to assist the project in various areas.

## GRADUATE TRAINING PROGRAM

Two graduate students from Yugoslavia under AID fellowship -- Ivan Petrovic and Anton Polensek -- were trained by the project staff in the use of foam plastics materials. Mr. Petrovic is presently employed in England by Imperial Chemical Industries as a staff architect to further explore the potential of plastics in building.

Appendix A

# STRUCTURAL RESEARCH AND DEVELOPMENT

# Architectural Research in the Use of Foam Plastics

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**ABSTRACT**

*This program of research is being sponsored by the Agency for International Development of the U. S. Department of State in the interest of exploring the possibility of using foam plastics as a basic structural material for application in underdeveloped areas of the world. The preliminary investigation included a study of the mechanical properties of cellular plastics, methods for producing such materials (alone or in combination with other materials), as well as erection techniques which could result from the use of these materials. On the basis of this investigation certain conclusions were reached as to the kinds of structures which would make logical use of foam plastics, utilizing their unique properties and designing around their shortcomings.*

## Research Objectives

The program of research on foam plastics conducted at the University of Michigan which is sponsored by the Agency for International Development of the United States Department of State, is aimed at exploring the feasibility of using these materials for housing in underdeveloped areas of the world (1).

This article presents certain aspects of the research program which followed the feasibility study. The task at present is to investigate the potentials of foam plastics as a structural material. Our approach to structure has been molded by this objective, to wit, the extent to which foam plastics can contribute to the resolution of the housing problem in underdeveloped areas. This means that the ideal solution from the viewpoint of structural engineering may be far from being feasible for introduction in the less developed countries, not only because of cost, but also because of limitations in required production facilities and skills.

Although no specific country and no specific conditions have yet entered the picture, the fact that most developing nations are within a tropical or semi-tropical zone has been taken into consideration. In short, continuous exposure to high heat and humidity rather than extreme variations in temperatures may more often than not be the main problem. Also, resistance to high winds and impact from falling objects rather than long-term sustained loads may constitute the critical design factors.

It was decided quite early that we should avoid trying to design or develop a universal house. This, it was believed, would be a snare and a delusion. Plastics offer great versatility in both application and production. This advantage has been recognized in the production of other items, and should not be overlooked or wasted with respect to housing. The objective should always be to develop the proper total system (design, production, and marketing) and to make whatever adjustments may be needed within the system to enable it to cover the widest possible range of housing requirements in each developing country.

The selection of materials and systems in each case should be done by thorough survey and analysis. Conditions which may give the edge to a material or a structural system in one country may be completely different or unsuitable in another. The materials and structural shapes that will ultimately prove best suited for a specific area will depend on a number of social, economic, technical, or environmental factors, even though the first selection may have to be decided only on the basis of presently available production facilities. Also, new breakthrough, in the technology of plastics (which can be anticipated) and the developments of new markets for a material (which would lower its cost) may completely reverse present day assumptions.

Consequently, we are investigating as wide a range of structures as possible within the limitations of time and resources. The four structures that have been selected for presentation illustrate the work presently under way. They include (example 1) the architectural application of a system already developed by a chemical company, (example 2) the development of a structure based on the properties of a composite material, (example 3) the application of a technique to a method for the erection of shelter, and (example 4) the investigation of a new idea for the erection of structural components. Other avenues of structural development have also been selected for further exploration. Of special interest are the possibilities offered for the production of structural components or total structures through vacuum-forming, filament-winding, and foam-inflating of flexible membranes.

Reprinted from the Journal of CELLULAR PLASTICS, January 1965, Vol. 1, No. 1

## Approach to Structure

To determine which structural systems are the most promising for further development, experimental structures have to be erected which make a logical use of the materials at hand. One cannot design intelligently with any material unless facts are available as to its properties, the shapes and sizes in which it can be obtained, and the possibilities of erecting the basic parts and assembling them into a final structure. More importantly, in order to establish a correlation between materials and structure, performance data must be obtained from actual application in the field. Creative design imagination is not stimulated by lack of familiarity with a material, and the plastics are not familiar materials in the same sense as concrete, brick, steel, lumber, and the other structural materials which architects and engineers have been using traditionally.

Before any meaningful design data can be developed, more research in the chemistry and production of these materials will be necessary to eliminate some of their present qualitative inconsistencies and to improve their overall performance. The low ultimate strength of low density plastics should not be allowed to inhibit their structural application. A material with inferior mechanical properties may turn out not to be difficult or impossible or uneconomical when properly used in structural design. It has to be kept in mind that the geometry of a structural section and the overall geometry of the total structure are major influencing factors. However, inconsistencies in the quality of certain foams, will have to be reduced to acceptable levels to avoid unpleasant surprises in construction.

In addition, more research is needed to determine more accurately the physical properties of foams and to what extent these can be improved through chemistry or better quality control. Especially, very little is known about the creep characteristics of cellular plastics. This phenomenon, also referred to as plastic flow, has presented us with some serious problems in certain instances, while in others it does not appear to be of any consequence. More information on this subject is needed, since even minor plastic deformations could lower the stability of a structure. This is particularly true in the case of fairly flat shells which can be very sensitive to changes in curvature caused by plastic deformations, as we have discovered in a recent experiment.

Through the erection of test structures and other experimentation with materials we have been trying to determine the influence of certain unknown factors in foam plastics on a structural form. This has been done in order to identify areas where additional research and development work is needed to improve performance standards. At the same time we are trying to establish the extent to which the present weaknesses and inconsistencies of the materials can be compensated through corrective measures within a structure.

To determine priorities in our structural research and development work, we have approached the problem from three directions. (1) Through the preliminary investigation of the mechanical properties of foam plastics, assumptions were drawn as to the kinds of structures which would be most logical from the structural engineer's point of view. (2) A similar investigation of production methods revealed the shapes and sizes as well as the kinds of structures (and structural components) that may most readily be obtained. (3) Finally, various possible erection techniques were suggested and these also limited the ways in which structures could be developed.

Without going into the details of structural analysis, if we accept the premise that certain problems related to the physical properties of foams can be resolved by industry and we turn our attention to basic mechanical properties, it becomes apparent that the fundamental limitation in structural design lies in the low modulus of elasticity of the plastic materials. The flexural stiffness of a structure will depend on the quantity EI, where E is the modulus of elasticity and I is the moment of inertia. The E value is an inherent property of the material. The I on the other hand does not depend on the material but on its distribution in the structure; in other words, on the structural geometry.

Since we must deal with relatively low E values, the only way we can eliminate excessive deformations is by increasing the structural stiffness through geometry. This will also lead to the reduction of stresses within the structure. Low stress values in the structure are essential not only because of the low material strengths, but also because creep seems to depend upon the stress level of the material.

It is apparent that the foam plastic structures which offer the largest potential are those in which stress levels are kept low by the distribution of loads throughout the structure, and where load and stress concentrations are avoided as much as possible. Therefore, the structural solutions we have sought have been within the family of "surface structures," especially shells and folded plates, which have such characteristics.

Through further analysis involving the basic families of internal stresses, theoretical solutions can be obtained which will be fairly ideal from a purely structural viewpoint. However, these solutions may be far from ideal with regard to application, especially so far as our particular project is concerned.

The possibilities and limitations imposed by presently available production methods are major factors influencing the structural solutions we are seeking. Such factors relate both to the form of the structure as well as to the form in which materials can be used. Finally, factors relating to the erection of a structure must also be considered, not only because of limitations which may be imposed, at least initially, by the lack of facilities and skills, but also because the nature of these materials

presents some unique possibilities for the erection of structures, which may affect considerably their cost in place.

The great advantage of plastics is that, as synthetics, they can be made according to a wide range of performance specifications. This in turn allows one either to start with a material and then develop a structure, or to start with a structural concept and then develop the necessary material. In either case, during this initial stage of research, a major objective should be to discover what new architectural solutions are being made possible through the introduction of these new materials.

The examples that follow illustrate structures in varying degrees of development. With the exception of the first example which is being tested for long-term performance, the structures have been erected for the primary purpose of obtaining information regarding their behavior. It is still too early to release the data which is continuously being collected through measurement and observation. This information is looked upon only as a guide to assist us in developing a second generation of test structures freed from certain present shortcomings.

## Example 1: Erection of a Dome with Polystyrene Foam by the "Spiral Generation" Process

The "Spiral Generation" process* was demonstrated to us by the Dow Chemical Company in the spring of 1963. The process involves the use of a specially designed machine which bends, places, and fastens boards of plastic foam together in a predetermined shape. A variety of shapes can be produced by programming the machine. The machine head is mounted on a boom which turns around on a pivot mechanism. As the generation process begins, foam board material is placed in the machine head which then forms and seals it, layer upon layer, into a rising structural spiral. This development truly constitutes a landmark in building technology, since it is the first system to produce an architectural structure totally by a machine.

After examining a number of experimental structures which had been erected on company grounds and discussing the data which had been obtained thus far, we suggested the design and erection of a building for public use. Our objective was to study and resolve various architectural detail problems, and to obtain data on actual costs, weathering properties of polystyrene foam bearing a light coating of paint, public acceptability, and most important, the effect of public use on the structure's durability.

A local golf club's need for a temporary club facility became the vehicle for a full-scale field test structure. The club provided the site and assumed responsibility for all construction with the exception of the polystyrene shell. Dow contributed the materials*, equipment and erection crew for the latter. The structure, encompassing a dome 45 feet in diameter, was designed by our project staff to meet the program requirements.

In erecting this structure a one-foot wide by three-foot deep trench was first excavated corresponding to the diameter of the dome. The trench was bridged at intervals by 2 x 4 inch wood blocks which supported a base ring made from angle iron (*Figure 1a*). A starter strip of foam was then attached to the base ring and the spiral generation process began (*Figure 1b*). The dome, consisting of boards 4 inches thick with an approximate density of 2 pounds per cubic foot, was constructed in less than 12 hours by two men (*Figure 1c*).

Following its completion, the dome was lowered into the trench by approximately 30 students using ropes connected to the base ring (*Figure 1d*). After the dome had been lowered and the trench backfilled with earth (fully on the outside and partly on the inside), all openings were marked, cut and reinforced around the edges with fiberglass cloth and epoxy resin (*Figures 1e, 1f and 1g*). At the same time a few of the end joints between the foam plastics found to be still partly open were sealed with epoxy resin and ground glass. The floor slab was then poured and its edge was anchored to the dome.

The dome exterior was painted with a mixture of latex paint and vermiculite. This operation was accomplished in short order by simply bringing the paint from the inside to the top of the dome, letting it flow down on the exterior surface and distributing it evenly by rotating a squeegee (*Figure 1h*). Vermiculite was added to the latex paint in order to provide a fairly rough surface that would be somewhat unpleasant to the touch and thus discourage people from picking at the surface of the structure. One can call it a psychological coating. The interior surface was treated with a similar but somewhat heavier coating. Window glass for the exterior walls was cut and placed in wooden mullions. The joint between the dome and the glass was made watertight and flexible by using a polyethylene foam gasket made in our laboratory and bonded with contact cement to the dome's interior surface (*Figures 1i and 1j*).

The structure has been under close observation for over a year now and has so far performed very well. A few small cracks occurred at the area of contact with two window mullions but these were easily repaired with epoxy resin. These cracks probably occurred because of the way the mullions had been installed. In general any damage to the dome's surface can be easily repaired.

Public reaction to the structure has been good. No one has felt that the building is too fragile or too experimental, or that it is a cheap substitute for conventional construction. There is no evidence of damage to the outside or inside coating of the structure. This is very encouraging,

* Invented by Donald R. Wright, an engineer in the long-range plastics application laboratory of the Dow Chemical Company. Until this system is more fully developed the company is carefully controlling its application.

* "Styrofoam FR", paints, and various secondary materials.

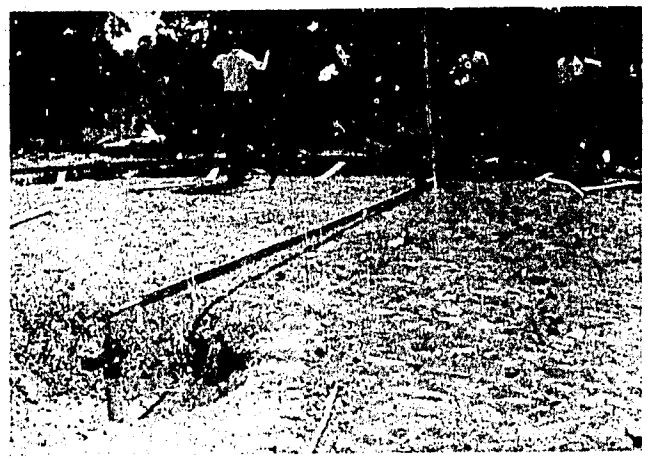

Figure 1A

Figure 1B

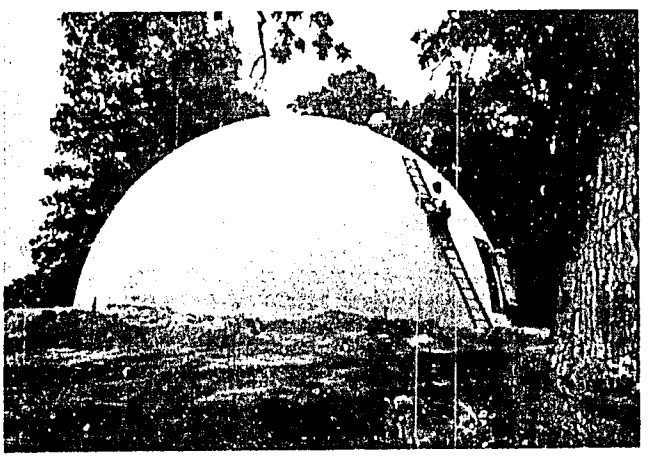

Figure 1C

Figure 1D

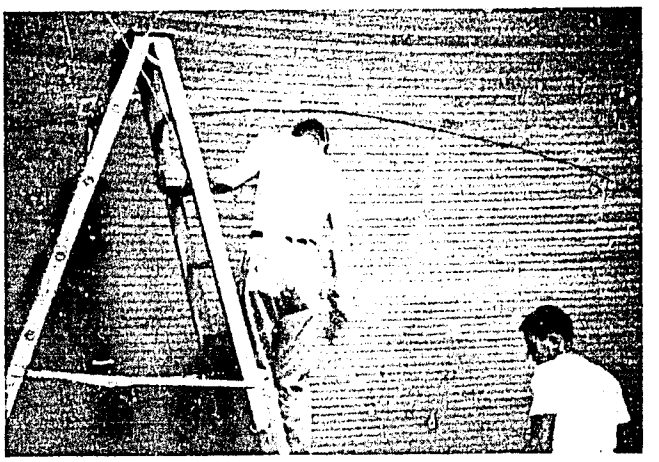

Figure 1E

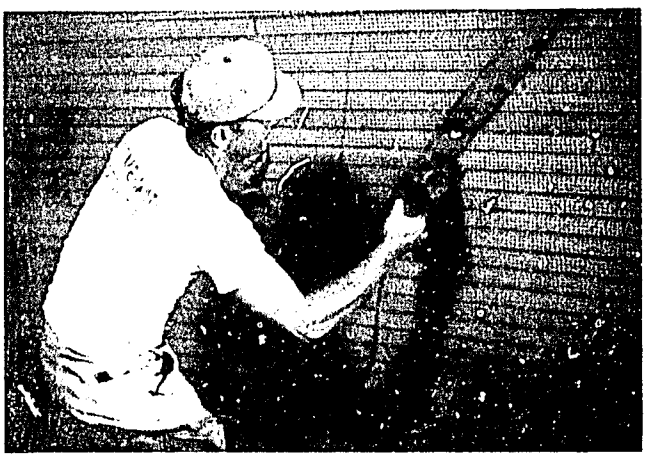

Figure 1F

since one of the things we hoped to learn was whether it was possible to protect a low-density foam structure by a coating of paint. Even though at times there have been over a hundred persons in the building, no one has tried to test it with fingernail, pocket knives and lighted cigarettes. The surface texture apparently serves to discourage such exploration.

It is apparent that the "Spiral Generation" process is unique, not only in concept but in its versatility. It derives its principal advantage from a well integrated use of a relatively simplified equipment and the economic use of materials. It affords a continuous system of rapid erection and is capable of producing structures which enjoy a high strength to weight ratio.

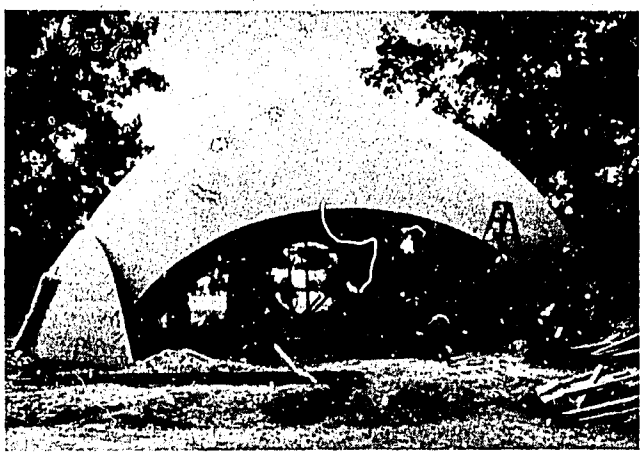

Figure 1G

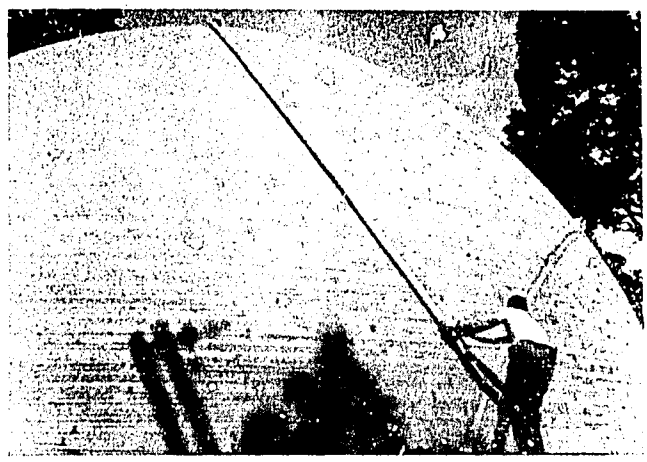

Figure 1H

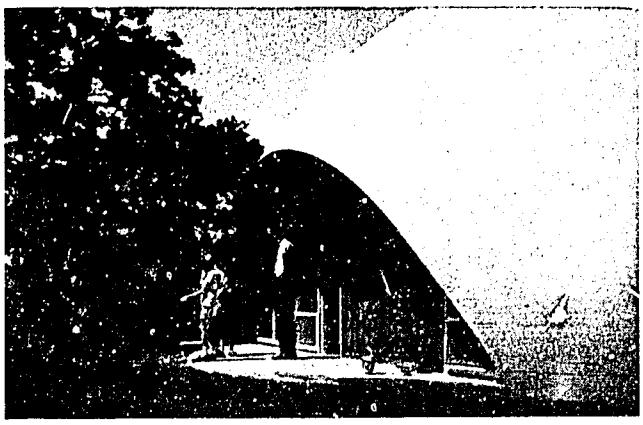

Figure 1I

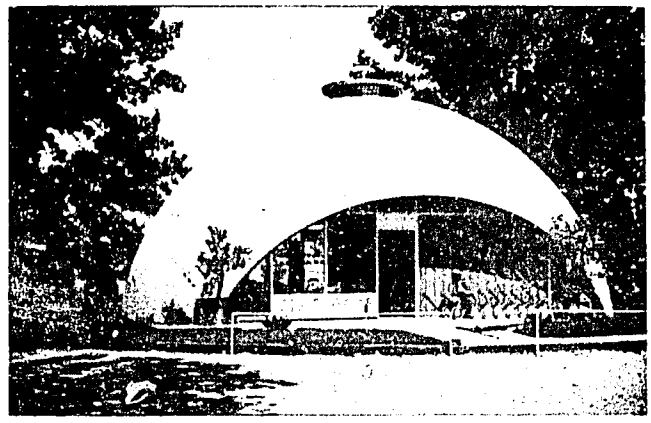

Figure 1J

## Example 2: Development of Structures with Paper Skin Polyurethane Foam Panels

In this case, the unique properties of the material and its method of production became the basis for the development of a structural system. The material is a urethane foam board surfaced on each side with kraft paper which can be coated with a variety of materials to meet structural and weathering requirements.

Today a number of companies are producing this material with some variation in the system of production. In general it is a continuous process in which the skins, introduced in rolls, go through a machine at the same rate as the foam that is being produced. The liquid foam components are uniformly distributed between the two skins. The unexpanded foam and skin sandwich moves through a form work or a dye where the foam expands. The material, after passing through a heat-curing operation, is cut to the desired length.

When the system and the material was first presented to us at the research center of Union Carbide Corporation, we became intrigued with its possibilities for use in folded plate construction. After initial investigation of the mechanical properties of the material with varying thicknesses of the foam core and a variety of skin coatings, it was decided to develop folded plate and curvilinear structural components which would utilize the ease with which the material can be scored and bent, as a production factor determining the ultimate shape of the structure. Also it was thought desirable from a production standpoint that structural systems should be developed which could be produced adding equipment to the end of the line which produces the board.

With these ends in mind, three structural systems were developed*. One system takes the form of triangulated bents or components that can be prefabricated and field-assembled to create the floor, walls and roof of a building (*Figure 2a*). The second is similar in principle but resembles an airplane wing in its cross section, being made up of units that are shipped as flat sheets and then spread apart by the insertion of spreaders at the building site (*Figure 2b*). A third system utilizes simple semicircular sections that can be easily assembled in the field (*Figure 2c*).

Full-scale test bents of these three structures were constructed and tested. After preliminary testing it became apparent that the triangular cross section had the greatest potential since it could conceivably be used as a floor. This also suggested the possibility of a two-story structure being developed with a flat roof.

* Materials for this work and for the erection of the final test structure were produced by the Technifoam process and contributed to the project by Union Carbide.

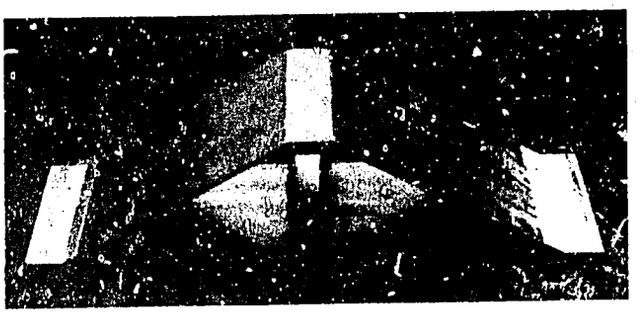

Figure 2A

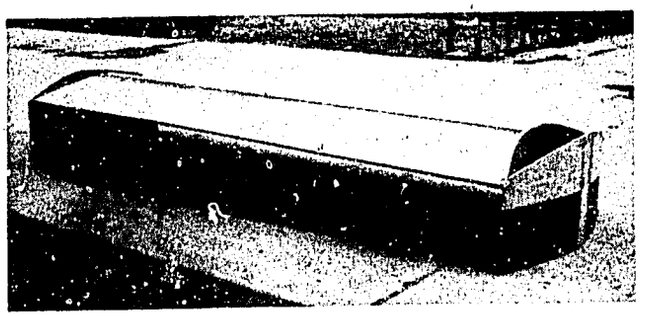

Figure 2B

Figure 2C

Figure 2D

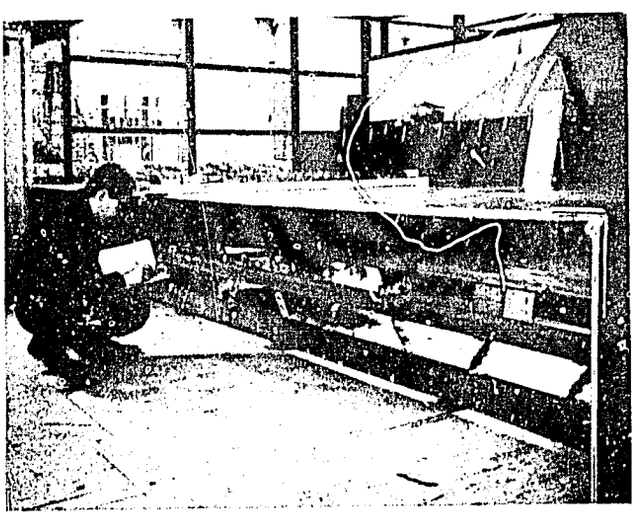

Figure 2E

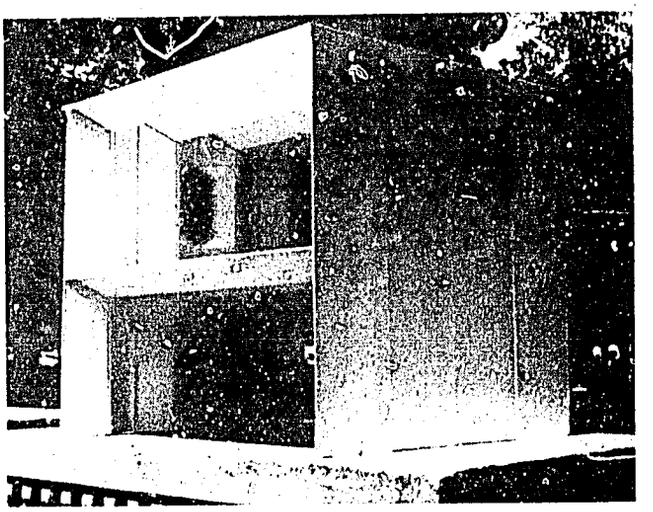

Figure 2F

Following initial study of a variety of cross sections which would produce adequate structural strength and rigidity, a test bent was constructed from urethane foam board ⅜" thick with an approximate foam density of 2.6 pounds per cubic foot. All paper surfaces of the board were impregnated with polyester resin*. Polyester resin was also used in conjunction with fiberglass tape to join the various parts of the structure together. The bent is 16 feet long, 5 feet wide and 12 inches deep. The cross section is the same for the horizontal beam and the vertical supports (*Figures 2d and 2e*).

The test procedure was designed to accomplish three things: (1) to establish the capacity of the section within an arbitrary allowable deflection; (2) to provide accurate information on the elastic behavior of the structure; (3) to establish the pattern of behavior for plastic deflection of foam and polyester paper composites. The test bent was loaded, and its deflection recorded. Assuming an allowable deflection of 1/240th of the span, the structure was found capable of carrying about 25 pounds per square foot. The internal stresses in the paper skins at this load level were found to be well within the limits of the material.

After having determined the elastic behavior of the structure, a test was then set up to find out whether there are unique characteristics in its plastic flow or creep behavior. Our objective was not only to arrive at precise conclusions which would permit prediction of design, but also to evaluate the significance of plastic flow on this particular structural cross section created from this particular material. The test bent used for this experiment was the same as that used for the elastic experiments. The structure was given a total load of 1470 pounds (18.4 P.S.F.) distributed over the surface. The

* "Raybond" contributed by Raymond Company.

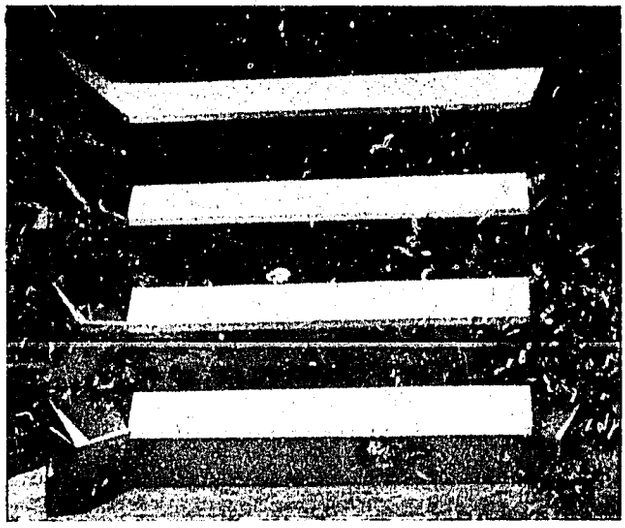

Figure 2G

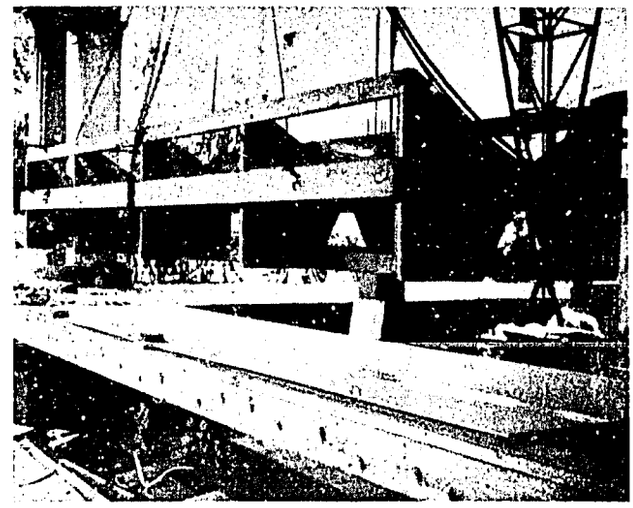

Figure 2H

load remained in place for 167 hours and was then removed. During this period readings of 10 dial gauges were recorded at a variety of intervals. Although the results of the tests are not absolutely conclusive, much of the data shows that the plot of plastic deflections against elapsed time follows a curve which seems to be leveling off.

A unique property of the structure was discovered when the loads were removed at the end of the test period. Virtually all of the elastic deflection was recovered immediately. Following this initial recovery, the structure continued to recover plastically almost all of the deformations that had accumulated over the study period. This behavior is not typical of conventional materials which, once deformed plastically, stay deformed plastically. Further investigation is needed to find out exactly what has caused this. Other experiments have been set up to explore this question and are currently in progress.

The results of this study on the test bent show that the design of substantial and durable structures utilizing paper skin urethane foam are not only feasible but relatively uncomplicated. Since the performance of the test structure was highly encouraging, we decided that a full-scale test structure should be designed and constructed.

Drawings and specifications have been completed for a 2-story test structure made up of four 4-foot bents with an 18 foot span (*Figures 2f and 2g*). The necessary materials have been produced and received. At the time of writing this article we are in the process of constructing this structure at the Architectural Research Laboratory in Ann Arbor. The footings have already been poured in place and an assembly templet has been constructed for the production of the bents (*Figure 2h*). These bents, which are light enough to be handled by two men, will be glued together. The outer surface will be coated with pigmented polyester and the floor will be covered with an impact resistant material.

The ease with which a panel material of this nature can be scored and bent opens up new possibilities for the realization of folded plate structures. From a production standpoint, the properties of urethane foam are utilized efficiently to create a sandwich panel by a continuous mechanical process which can be adjusted to meet a variety of specifications. A variety of materials obtainable in rolls may be used for the skins. However, paper seems to be one of the best suited for this purpose, because structural properties can easily be added through secondary applications depending on performance requirements within the structure.

## Example 3: Spray Application on a "Folding Armature" Structure

Although some preliminary experimentation with urethane spray had made us skeptical of the practicability of spray-on techniques for the erection of structures in the field (because of the dependance on suitable environmental conditions and the difficulty of maintaining uniformity of control over the material and its appearance), it was felt nevertheless that the method merits further investigation since it is a system representative of foam plastics technology. The transportability of the system and the ease of creating varying thicknesses offer definite advantages. Besides, it is possible to control to a degree environmental factors in the field, and the other disadvantages may be overcome through skilled application, or even better, through automation of the spray process.

An essential element in a spray application is the "background," i.e., the formgiving surface against which the foam components are to be sprayed. After investigating various possibilities, we devised for this purpose a lightweight wood lattice armature. This armature, capable of being folded, is easily transported to a building site and quickly erected. It is made in such a way that it can be laid out flat on the ground and then pulled into a double curved structural shape.

A one-third- full-size model of the armature was first constructed in the laboratory and its behavior studied. A full-size 28-foot square armature was

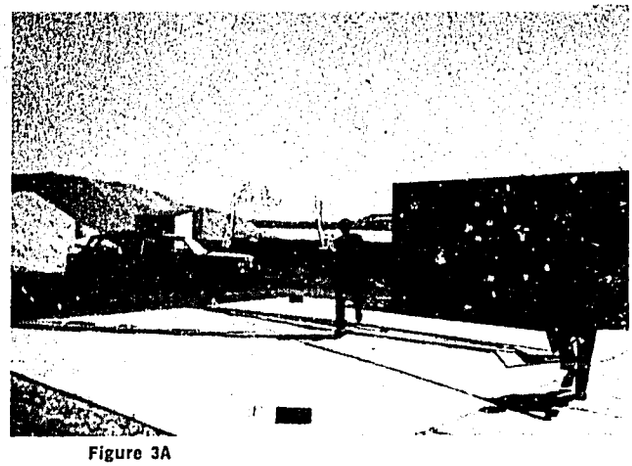

Figure 3A

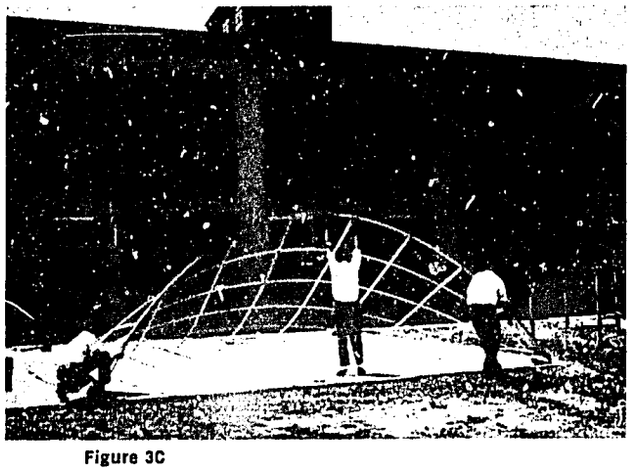

Figure 3C

then constructed which when erected into its final structural form produces approximately a 21-foot square dome structure supported on four points. This armature was erected and taken down four times in the course of working out various problems and the technique of erection.

In May 1964 a spray structure utilizing the armature was erected in collaboration with Wyandotte Chemicals Corporation on the company's grounds. A concrete slab with appropriate anchors was prepared and construction started soon thereafter.

The folding armature was transported in four sections which were bolted together on the slab (*Figures 3a and 3b*). Then, using tension chords, each of the 4 edge members were alternately bent into shape, and temporary tension ties were placed across each of the supporting legs of the structure to pull it into its final shape (*Figures 3c, 3d, and 3e*). Each of the edges was then reinforced, and the entire structure covered with a stapled-on nylon-reinforced paper skin* (*Figures 3f and 3g*). One-half of the surface was sprayed for experimental purposes with a moisture-curing urethane resin** (*Figure 3h*). The foam was then sprayed on the structure*** (*Figures 3i, 3j, and 3k*). The density of the foam was close to 2½ pounds a cubic foot, and some 700 pounds of foam were used to produce a structure approximately 4 inches thick. It

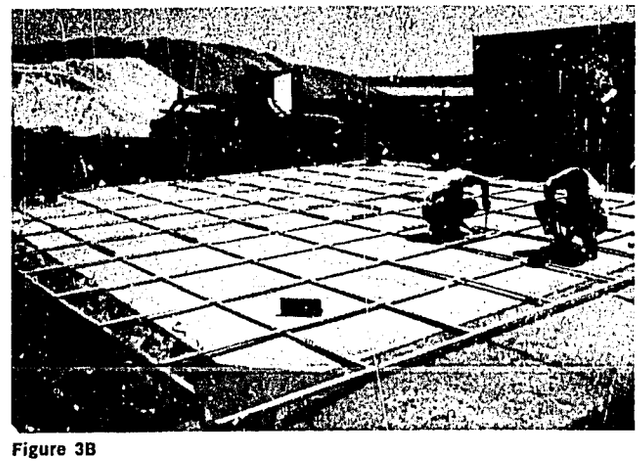

Figure 3B

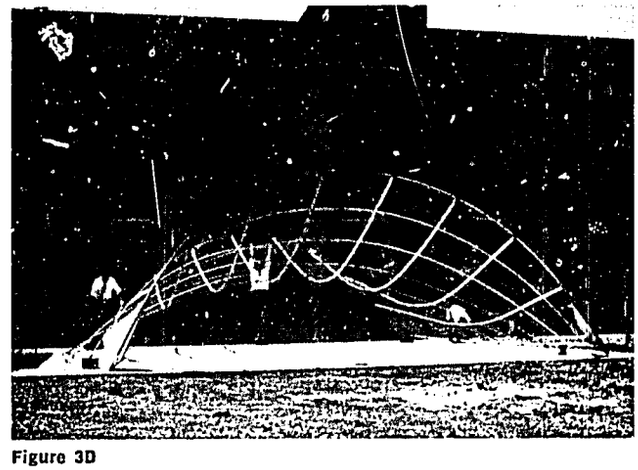

Figure 3D

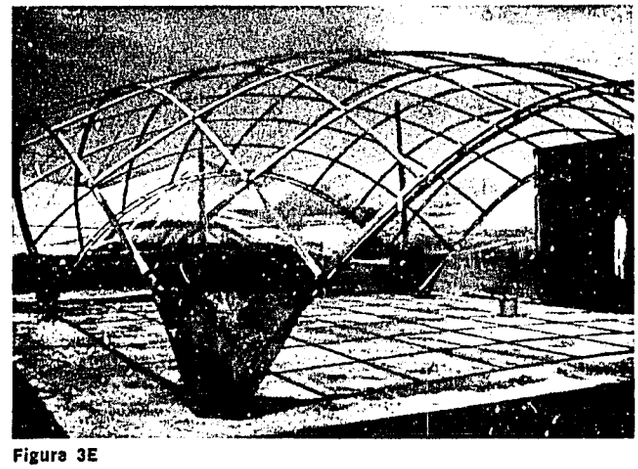

Figure 3E

took almost 8 man-hours to complete the spraying. The surface appearance of the structure was quite good and much more acceptable than in our initial experiments (*Figure 3l.*)

Our original approach to the design of the structure had been to consider the wood armature only as a formwork on which the foam was to be

* "Kaycell," contributed by Kimberly Clark Company

** Developed by Wyandotte

*** A Binks Model 18FM spray gun was used

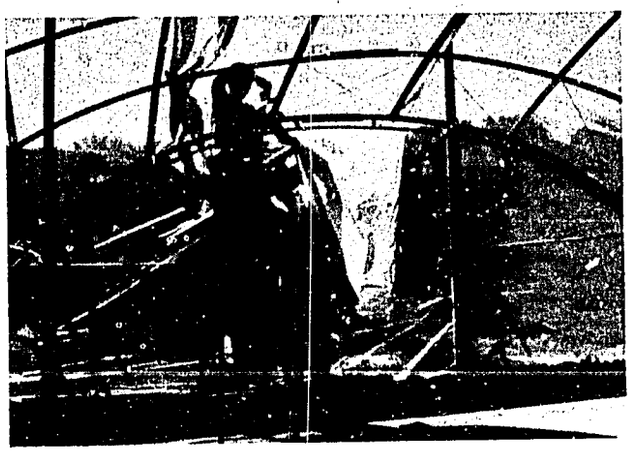

Figure 3F

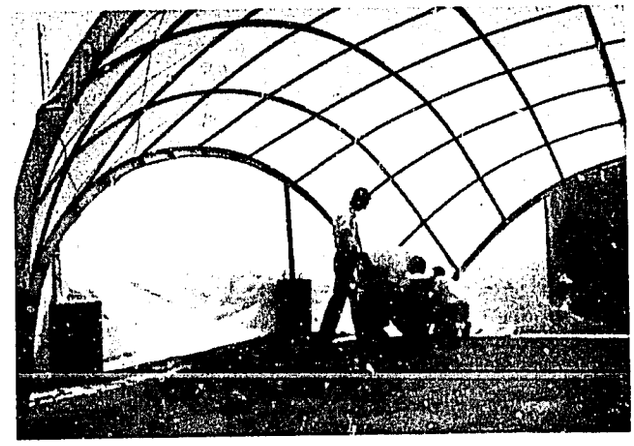

Figure 3G

sprayed. Model studies indicated that the armature was not capable of taking the total weight of the foam and therefore the sequence of the spraying operation became an important consideration in the construction of the structure. First the buttress portion and then the peripheral section were sprayed. Thus the foam began working structually as the armature was being sprayed. There were several unexpected problems, some of which resulted from design considerations and others from the construction methods. First, the dead load of the foaming caused an initial distortion in the structure which had not been anticipated. Secondly, inadequate edge stiffnesses caused higher stress levels in the buttress portions of the shell than were anticipated. This was probably due to the fact that the edge members were not foamed to the final thickness prior to foaming the rest of the shell.

Figure 3H

Measurements were made of the structure two weeks after the foaming had been completed. At this time there seemed to be noticeable movements, particularly in the buttress section. Three weeks later the structure was measured again. At this time there was considerable movement, particularly at the top of the edge support which had come down approximately six inches. It was noted also that the shape of the curve of the edge member had changed considerably, becoming much flatter.

During the three-week period between the first and second measurements, a small but accurate wire model of the armature was constructed and carefully tested in an attempt to predict more precisely the nature of the behavior of the structure. From the study of this small test model we were able to see that the primary failure of the structure would occur in the buttress section and if the edge member was adequately stiffened, a secondary failure would occur due to buckling of the domical portion

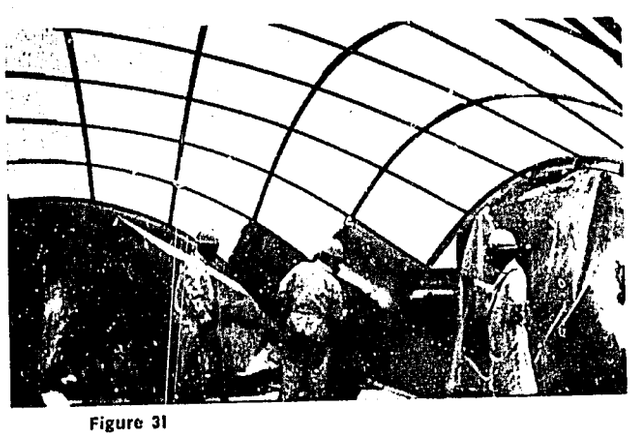

Figure 3I

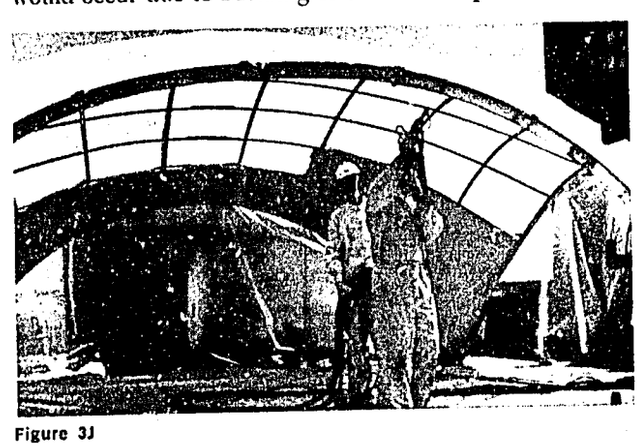

Figure 3J

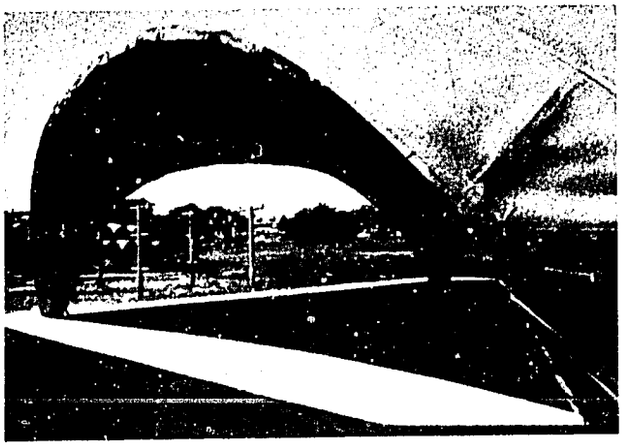

Figure 3K

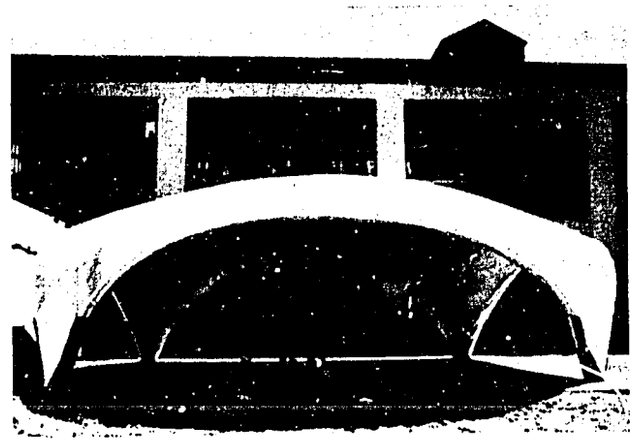

Figure 3L

of the shell. Also, during this period several tests were run on samples of the urethane foam which had been sprayed on the dome. These tests were run in hopes of finding the cause of the slow deformation of the structure under its own weight.

Compression, flexural, shear, and creep studies were also conducted. It was found that the material had a considerable higher strength parallel to the direction of rise. Compression strength perpendicular to the direction rise was approximately 20 lbs. per square inch and the compressive strength parallel to the direction rise was more than 40 lbs. per square inch. Creep studies revealed that even at relatively low stress levels plastic deformations continued for considerable time without reaching a plateau. These creep characteristics became a particular problem in the higher stressed buttress portion of the dome where they caused successive increase in deformations and stress levels.

We therefore decided to put the structure back into its original shape and reinforce the edge members so that the stress levels in the foam would be lowered. This was done in the belief that the lower stress levels in the structure would produce acceptable levels of plastic deformations over a long period of time. Further measurements and tests will continue throughout the summer.

This first experimental structure has demonstrated the feasibility of using spray foam technology in the field for easily erected structural units. With the information obtained from the tests of the first structure and additional model tests on the armature, we feel confident that a second test structure which will be built in the fall will be free from the defects of the first. In the proposed second structure we anticipate that the stronger edge member in combination with a major tension tie within the armature will reduce stress concentrations. We also anticipate the use of a higher density foam formulation which should produce acceptable levels of long term deformations. Much work needs to be done on the nature of creep properties of foam plastics in general.

## Example 4: Structure Made by Rigidizing Flexible Urethane Foam

One of the structural concepts under consideration has been the possibility of erecting double-curved surfaces by rigidizing flexible membranes after they have been stretched to the desired shape. Several experiments were conducted at small model scale using such materials as nylon jersey and glass cloth in combination with epoxy, polyester, and urethane resins (*Figure 4a*).

This idea was translated into flexible foams, but there appeared to be too many difficulties involved in producing sizable components by impregnating them after they had been shaped. When Wyan-

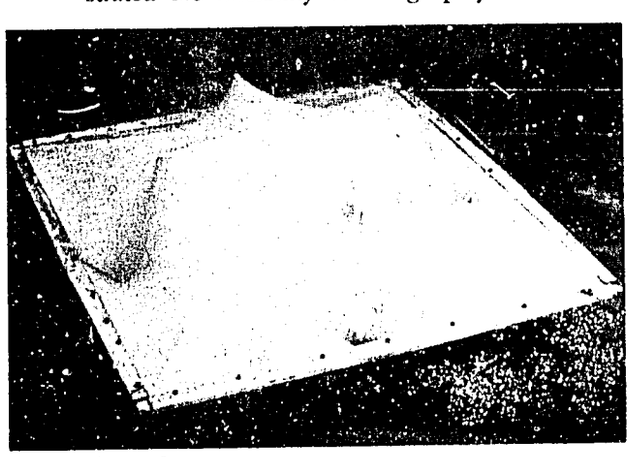

Figure 4A

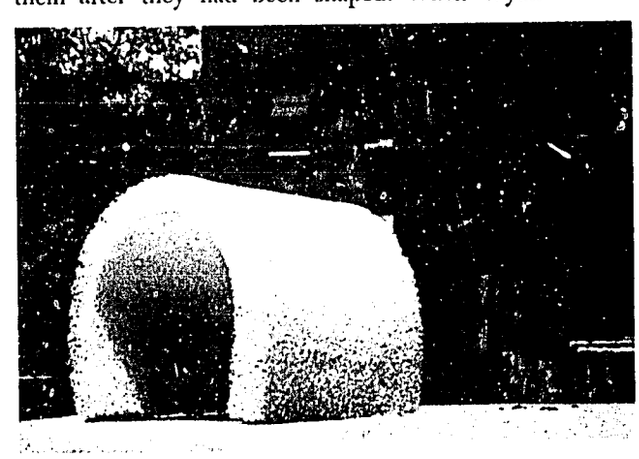

Figure 4B

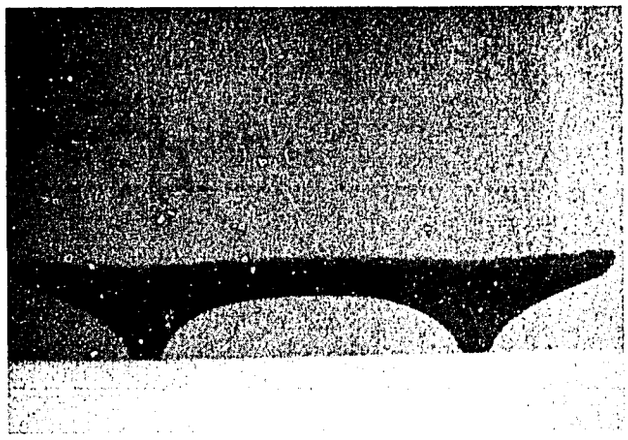

Figure 4C

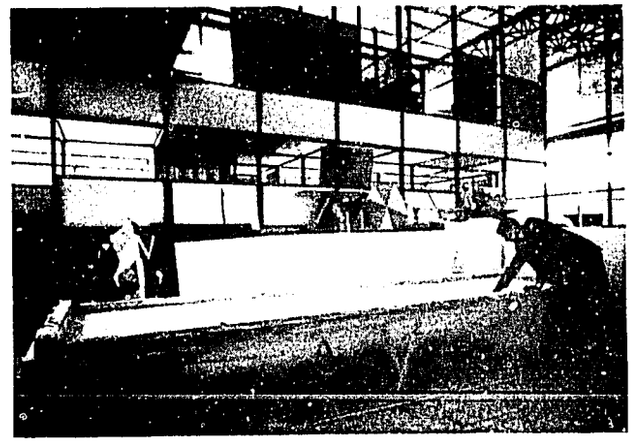

Figure 4D

dotte presented us with the moisture-curing urethane resin mentioned in the previous example, the thought occurred that the flexible components might be pre-impregnated. This brought the concept closer to the realm of feasibility, Thus we could envision the possibility that component parts of a structure might even be pre-impregnated under controlled environmental conditions, sealed into a moisture-free bag and stored until needed. At that time, they would be pulled out, erected into final shapes, and allowed to cure by atmospheric moisture.

After some searching to find a proper material for rigidization we decided on a reticulated flexible urethane foam having a fairly large cell structure.*

Small samples were prepared by impregnating this foam with the moisture-curing resin, removing the excess resin, and allowing it to cure (*Figure 4b*). Since this impregnation technique offered little technical difficulty, we decided to build a full-scale test structure. The material at hand served to produce two identical structural components. This was done by clamping a sheet of this foam (4 x 16 feet, 1 inch thick) in a wooden frame, and then pulling down two points to produce a warped structural component (*Figures 4c and 4d*).

As this paper is being prepared, arrangements are being made to spray both surfaces with chopped fiberglass and polyester resin. We intend to erect a test structure outside the Architectural Research Laboratory by joining the two structural components and supporting them on four tubular columns. Although it is still in the very early stage of development we feel that this process holds fruitful potentials for the future.

## Summary

Our program of research explores various possibilities for utilizing cellular plastics as structural materials in their own right rather than as substitutes for other materials. Questions to be answered are: What new structural solutions become possible through their logical use and application? How can these solutions best contribute towards the resolution of the housing problem in the underdeveloped areas of the world? Maybe the best is still not good enough, but in an age of chemistry it seems worthwhile to find out.

* "Scottfoam" contributed by the Scott Paper Company.

## Acknowledgments

This research is being conducted with my colleagues; Harold J. Borkin, J. Sterling Crandall, Robert M. Darvas, James L. Haecker, C. Theodore Larson, and Willard A. Oberdick. In addition to the companies already mentioned in the text and whose collaboration has made this work possible, we should like to express our sincere appreciation to Atlas Chemical Industries, E. I. du Pont de Nemours and Company, Mobay Company, and Pyles Industries for their assistance during this beginning phase of our project, as well as to the entire plastics industry for the information and the resources made available to us.

## References

1. "The Potential Use of Foam Plastics for Housing in Underdeveloped Areas," Architectural Research Laboratory, The University of Michigan, Ann Arbor, March 1963.

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## Stephen C. A. Paraskevopoulos

Prof. Stephen Parsakevopoulos was born in Athens, Greece on May 21, 1926. He became a U.S. citizen in May 1963.

He was graduated from the National Technical University of Athens in 1951 with a Dipl. Ing. degree; and he received a M. Arch. from The University of Michigan in 1954.

His professional background includes architectural practice and building studies in Athens, Greece and Ann Arbor, Michigan, consultant on social and economic aspects of housing and resident architect in Indonesia for the United Nations, and architectural hospital consultant at The University of Michigan.

From 1955-1956 he was a visiting lecturer at the University of Michigan; from 1956-1960 he was an assistant professor; from 1960-64 he was an associate professor and he is currently a professor, Dept. of Architecture, The University of Michigan.

He has participated in the University's research programs: "Unistrut Space-Frame System" and "School Environments Research" directed by Prof. C. T. Larson; and is directing the project on "Foam Plastics for Housing in Underdeveloped Areas."

Appendix B

# ERECTION OF A POLYSTYRENE FOAM DOME

ERECTION OF A PLASTIC DOME BY THE DOW "SPIRAL GENERATION" PROCESS

As a case-study under ORA project 05687, sponsored by the Agency for International Development, a styrofoam plastic dome has been erected on a site outside Ann Arbor and is now being used as a temporary clubhouse by Webster Golflands, Inc.

Preparation of the site for erection of the 45-foot diameter dome was started on Monday, 24 June, 1963. One-half day was required for unloading of equipment and assembling of a base ring. The site was leveled and a circular trench 40 inches deep and approximately 2 feet wide was dug prior to erection of the generating equipment. Actual generation of the styrofoam shell took twelve hours to complete. At intervals during the succeeding five days, the exterior of the shell was sealed with epoxy resin, sanded, painted and all cut lines were located. The dome was then lowered into the previously prepared trench.

Between 3 July and 15 July the interior rough carpentry work was accomplished. Structural mullions were installed along with the mechanical service facilities. During the period from 15 July to 25 July the interior of the shell was completed: leaks were sealed, all patched surfaces sanded, all cut edges reinforced, and the styrofoam ventilating monitor at the top of the structure was put in place.

The completed structure is shown in Figure 1.

## The "Spiral Generation" Process

This system is based on the use of a specially designed machine which bends, places, and fastens pieces of prefoamed plastic together in a predetermined path to form an integral structure. Although so far the system has been utilized mostly for the generation of structural domes, a variety of shapes can be produced by modifying the layout or locus of points followed by the machine in its generating course.

The only power supply required is a single-phase 110 - 220 volt system. Depending upon the size of the structural shape to be generated, the weight and bulk of the equipment may vary; this, however, should not cause any difficulty in the machine's handling or in its portability.

The machine head is attached to the end of a lightweight structural boom which is secured to a mechanism which controls the machine's path and thus predetermines the shape of the structure. The machine-head end of the boom is supported on the structure as it is being generated and the balance of the boom's weight is taken by the centroid or pivot mechanism. As the generation begins, foamed material is placed in the machine head which then forms it and seals it into a rising structural spiral. The process is continued until the entire structure has been generated.

## Materials

Although Styrofoam has been used to generate the structures currently in use use, other foams capable of being heat-sealed could be employed with only slight modification of the generating equipment.

The foam plastic used on the case-study dome was Styrofoam[1] FR. This particular formulation is flame retardant and specially formulated to meet the requirements of ASTM test D 1692-59T for self-extinguishing plastics (see engineering data presented in Table 1).

The advantages of this type of expanded polystyrene are its light weight, its resistance to water penetration and moisture vapor transmission, and its low thermal conductivity. It does not support mold growth and is not attractive to rodents. It can be easily handled and fabricated using standard hand and power woodworking tools. However, conventional methods of fastening, e.g., nailing or screwing, are usually inadequate. Heat-sealing methods or adhesives like epoxy prove to be more durable.

For use in the "Spiral Generation" system, the slab foam is cut into rectangular planks whose width depends on the thickness required for the generated structure. Usually the planks are 4 inches wide, 2 inches thick and 10 feet long (see Figure 2).

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[1]Styrofoam is a Dow trademark for polystyrene, expanded approximately forty times into a rigid, closed cell foam having a density range of 1.8 to 4.5 pounds per cubic foot.

Since the Styrofoam density can be varied, the thickness of the generated structure can be made less if higher density foam is used; conversely, it must be increased if a lower density foam is used. These variables are dependent upon the specific use requirements of any particular structure.

The Clubhouse Structure

Webster Golflands presented the research project staff with a tentative list of facility requirements for a temporary type clubhouse. These requirements were studied and summarized as follows:

| FACILITY | EQUIPMENT | AREA (approximate) |
|---|---|---|
| Clubroom | Furniture | 650 sq. ft. |
| Kitchen | Range<br>Dishwasher & sink<br>Hot water heater<br>Cabinet storage<br>Beverage coolers | 160 sq. ft. |
| Toilets | | |
| Men | One WC<br>One urinal<br>One lavatory | 40 sq. ft. |
| Women | Two WC<br>One lavatory | 40 sq. ft. |
| Circulation | | 400 sq. ft. |
| Pro shop | Display cases<br>Counter | 280 sq. ft. |
| Conference & Admin. | Furniture | 300 sq. ft. |
| | Total | 1870 sq. ft. |

Using approximately 1900 sq. ft. as the required floor area, it was determined ($\pi r^2 = A$) that a structural dome would require a radius of 24.59 feet. However, by using part of the space in the upper portion of the dome for the conference and administration area, the radius could be reduced to 22.56 feet. A diameter of 45 feet was therefore established as not only adequate for the required facilities but also being well within the capability of the generating equipment.

Preliminary plans and sketches (see Plates 1 - 5) were developed by the research staff and subsequently discussed with representatives from Dow Chemical

Company. The resulting design proposal showed no unusual technical difficulties and was assumed to be entirely feasible.

Working drawings were then prepared. The required materials were calculated and requested from Dow Chemical.

Clubhouse Construction

On 24 June, three workmen under the supervision of Donald Wright arrived from Dow Chemical Company to begin erection of the case-study dome. All preparatory work such as grading, leveling and trenching had been accomplished by the General Contractor prior to their arrival.

The Dow crew transported all equipment in a single tractor-trailer truck. This equipment was unloaded at the site. First step was assembling the base ring. Pieces of 3" x 3" x 1/4" angle iron, pre-rolled to the diameter of the dome, were bolted together with splice plates to assure continuity. This ring was then placed over the trench and supported on 2" x 4" wood blocks spaced approximately 4 feet apart (see Figure 3).

After the base ring had been positioned, the generating equipment was erected and a starter strip was applied. Generation of the dome required only twelve hours after the equipment had been set up.

Following the generation process, the dome was lowered into the trench by hand. This operation required thirty persons, each supporting a 60-pound load on ropes connected to the base ring (see Figure 4).

After the dome had been lowered and the trench back-filled, all openings were marked, cut, and reinforced with fiberglass and epoxy. Cutting was accomplished with an electric saber saw. Any discernible voids in the vertical joints between the plastic planks were closed by applying a mixture of epoxy resins and ground glass.

Construction of the interior partitions and floor slab were begun while the dome shell was being prepared for exterior painting. Construction of the ventilating monitor was also started.

The dome interior was painted prior to the finish carpentry work. Plumbing and electrical services had been installed before the concrete floor slab was poured.

The completed ventilating monitor was then lifted to the top of the dome and fastened in place with epoxy resin.

Glass for the exterior walls was cut and placed in the mullions. A

flexible polyethylene foam gasket was developed by the project staff for the mullions (see Plate 5).

Preliminary Cost Evaluation

The following calculations are based entirely on data obtained from a single case-study involving the erection of a 45' diameter plastic dome. As in all evaluations, certain variables are present. The most pronounced variable is the current stage of machine development. The amount of hand labor required for the patching of vertical joints has the apparent effect of increasing the unit price when related to the unit price of materials. Another variable present but not of major significance is the possible use of additional coatings.

Table 2 sets forth the number of man-hours required for various operations in the erection of the dome. Finishing involved patching the vertical joints, attaching epoxy strips, and the like.

The hourly rate per worker was computed at $6.40. This rate is based on an hourly rate of $5.00 plus $15.00 per day travel expenses. Applying this rate, a labor cost per operation results as shown in Table 2.

With a projected floor area of 1600 square feet, this yields a total unit labor cost of $1.304 per square foot.

Table 3 provides a cumulative list of materials and their respective prices.

A total materials cost of $2274.50 yields a unit material cost of $1.421 per square foot.

Adding both the unit labor cost and the unit material cost, the total unit cost thus becomes $2.725 a square foot. It should be noted that this figure includes only the dome shell, its coatings and pigmentation, and openings. It does not include the cost of the interior partitions, glass, floor slab or trench.

General Comments

It is apparent that the Dow "Spiral Generation" Process is unique not only in concept but in its versatility. It derives its principal advantages from a well-integrated use of relatively simplified equipment and the economic use of materials. It affords a continuous system of rapid erection and produces a structure which enjoys a high strength to weight ratio.

Its versatility is inherent in the system and the machinery. It is possible to produce structures varying in size with only slight modification of

equipment. The number of workers required would in all probability not be increased when making larger structures, and there would be little if any change required in the basic power supply.

The development of the outside shell, which is highly sophisticated, seems to suffer when conventional building methods are used to complete the interior partitions and enclosing members which are not part of the shell itself. Although this problem does exist, it is not insurmountable. Its solution lies, in part, in re-evaluating the use of conventional materials and their traditional methods of installation.

The actual generation of the shell structure is accomplished in a relatively short time as compared to conventional construction. The large amount of hand labor required in finishing the shell means that the advantage of rapid erection is lost.

There are additional problems which merit further consideration. These problems lie essentially in two categories, one being related to machine development and the other to the complexities inherent in hemispherical shapes.

The systematic problems incurred by the current stage of machine development arise out of the shipment of relatively large volumes of very light-weight materials to the construction site. It would be more advantageous to ship smaller volumes of a more dense material to the site and then expand these supplies at the time of construction. Expansion during generation could be accomplished by modifications which would allow unexpanded material to be introduced directly at the machine head and then be expanded in place. On the other hand, in very large projects where great volumes of foamed material are required, it may become feasible to establish a slab stock plant at the site from which required planks could be obtained and utilized by existing equipment.

Current machine development requires one man to be constantly feeding expanded foam at the machine head while another worker supplies him from a stock pile nearby. These man hours could be substantially reduced by introducing mechanized equipment to do the same tasks. Labor time could also be saved by providing some method as mentioned above; i.e., by feeding the machine with unexpanded foam materials or by supplying a continuous strip of expanded foam.

A continuous system presumably could be achieved by connecting pieces of prefoamed planks prior to introduction at the generating machine.

By referring to Table 2, man-hour requirements related to finishing techniques become evident. Over 80% of the total man hours are utilized for

plugging and sanding vertical joints, painting, and applying interior finishing materials. At present, these operations are accomplished by conventional methods. By using pre-foamed polystyrene in a continuous strip or as a number of strips mechanically sealed, the need to repair vertical joints would virtually be eliminated. Using a plank with twice the present length means that the number of vertical joints could be reduced 50%, thus affording a corresponding reduction in hand labor.

Although the system used for painting is unique, some improvements in distribution would be desirable. Such systems could utilize either an independent spray system or a helical brush rather than the "squeegee" currently being used. These devices may also be incorporated in the generating head which would then provide a continuous process for finish applications. Incorporation of coating equipment would eliminate the need for separate covering and plugging which are the basic causes for the disproportionate amounts of hand labor. Further reductions in sanding and painting could also be achieved by a different choice of coating mediums.

Since completion of the case-study dome, Mr. Wright of Dow Chemical has been experimenting with an asphaltic coating which may be applied by an independent spray and covered with stone chips. It is expected that this new application will be approximately one fourth the cost of the earlier coatings. This coupled with machine refinements reducing hand operations would effectively lower the unit cost to approximately $1.90 per square foot. (This figure is based on elimination of base ring, substitution of asphaltic coating for latex and paint, and 50% of the epoxy used; reduction in labor is assumed to be 50% of the finishing operation in Table 2.)

When such refinements are made the system will be a unique, rapid system for the building of structures of varying magnitude. The system is a revolutionary approach in the building industry.

Table 1. ENGINEERING DATA RELATING TO STYROFOAM FR

| | ASTM Test Method | Styrofoam FR |
|---|---|---|
| **Physical Properties** | | |
| Density (lb./cu.ft.) average | ----- | 1.9 |
| Compressive yield strength (psi) average (at deflection of 5%) | D1621-59T | 30.0 |
| **Water Resistance Properties** | | |
| Water absorption, % by volume | C-272-53 | 0.25 |
| Water absorption (after submersion under 10 ft. head for 48 hours; lbs./sq.ft. of surface area) | ----- | 0.08 |
| Water vapor transmission, per-inch | E96-53T (Procedure E) | 2.0 |
| Capillarity | ----- | none |
| **Thermal Properties** | | |
| Burning characteristics | D1692-59T | SE[1] * |
| Linear thermal coefficient of expansion (in./in./°F.) between 0°F. and 80°F | ----- | 0.00004 |
| Thermal conductivity (BTU-in./sq.ft.-hr.-°F.) | | |
| mean temp. 70°F., average | ----- | 0.26 |
| mean temp. 40°F., average | ----- | 0.24 |
| Heat distortion temperature (maximum for continuous use), °F. | ----- | 170.0 |

* Resistance to accidental ignition: From welding sparks, thrown matches, and other small-scale fire sources. ASTM D1692-59T. Self-extinguishing.

Table 2. LABOR COSTS FOR THE SPIRALLY GENERATED DOW PLASTIC DOME

| | Man-Hours | Percentage | Labor Cost (@ $6.40/hr.) |
|---|---|---|---|
| Preparation | 24 | 7 | $ 153.60 |
| Generation | 36 | 11 | 230.40 |
| Finishing | 266 | 82 | 1702.40 |
| Total | 326 | 100 | $2086.40 |

Table 3. MATERIALS COSTS FOR THE SPIRALLY GENERATED DOW PLASTIC DOME

| Materials | Cost |
|---|---|
| 12,720 Board Feet Styrofoam FR 2" x 4" x 9' - 11.7¢/bd. ft. | $1488.24 |
| 30 Gallons Latex Paint (Red) - $5.00/gallon | 150.00 |
| 20 Gallons Latex Paint (White) - $5.00/gallon | 100.00 |
| 40 Gallons Dow No. 560 Latex - $5.18 | 207.00 |
| 20 Bags No. 4 Vermiculite - $3.00/bag | 60.00 |
| 36 Quarts of Dow DER No. 331 Resin with hardener - $2.66/qt. | 95.76 |
| 50 Yards 3" wide Glasscloth - $8.00/roll | 8.00 |
| 20 Yards 36" wide Glasscloth - $ .40/yd. | 8.00 |
| 125' 3" diameter Ethafoam - $ .06/ft. | 7.50 |
| 3 x 3 x 1/4 angle iron base ring | 150.00 |
| Total Cost | $2274.50 |

DOW
"SPIRAL-GENERATED"
PLASTIC DOME

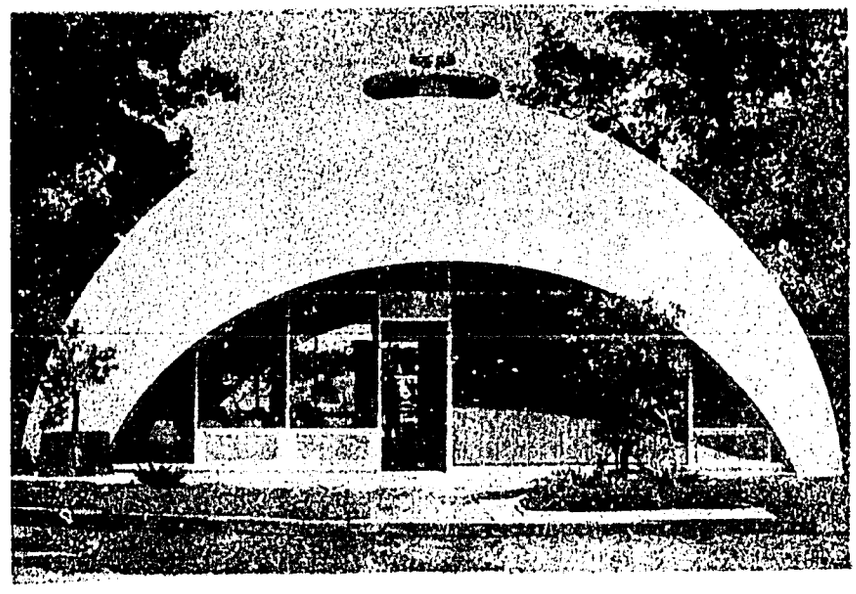


Figure 1

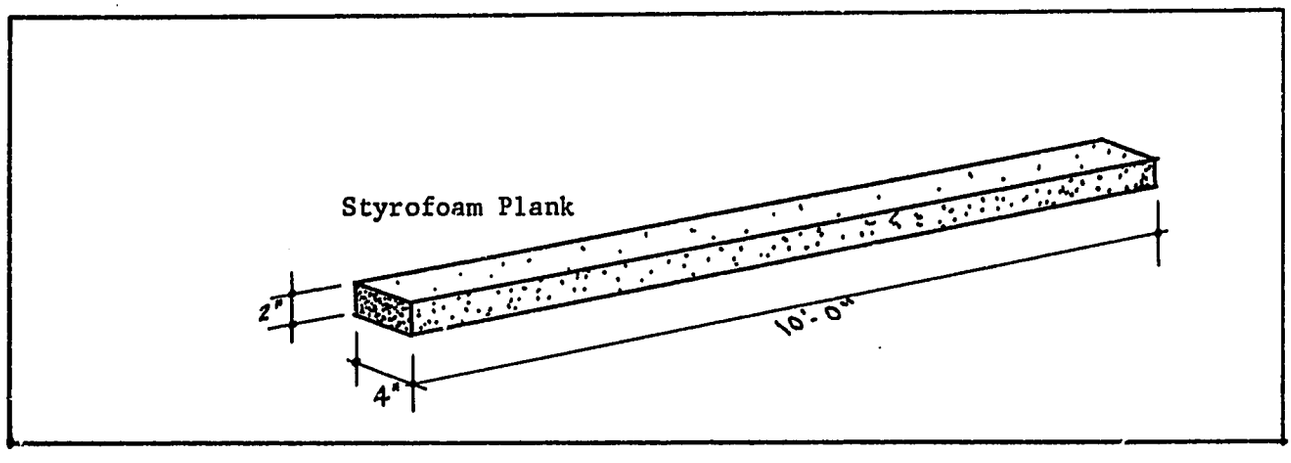



Figure 2

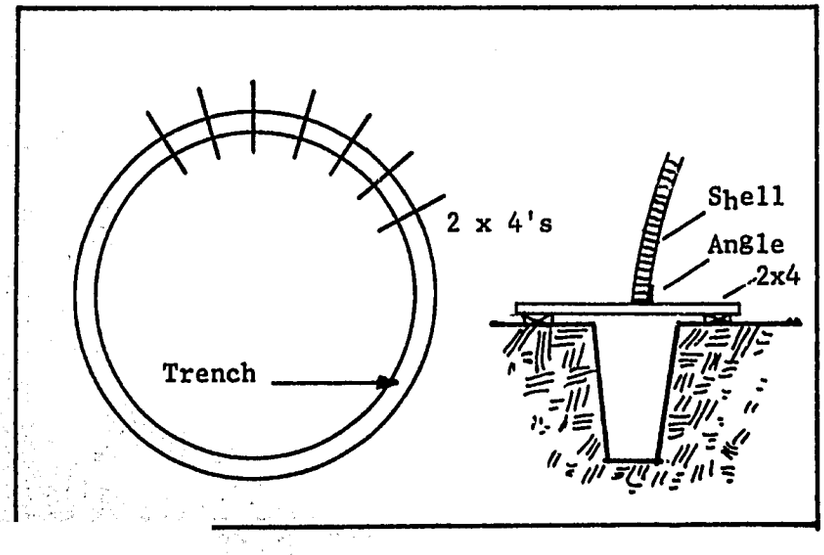



Figure 3

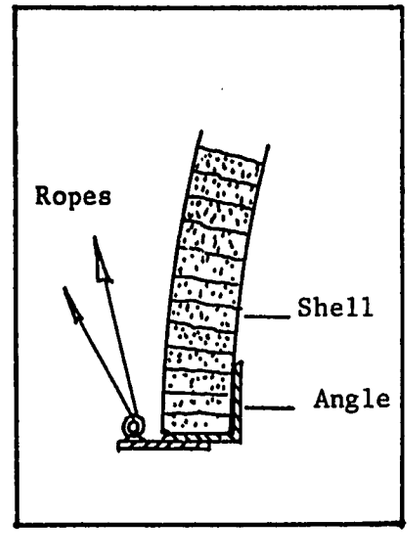



Figure 4

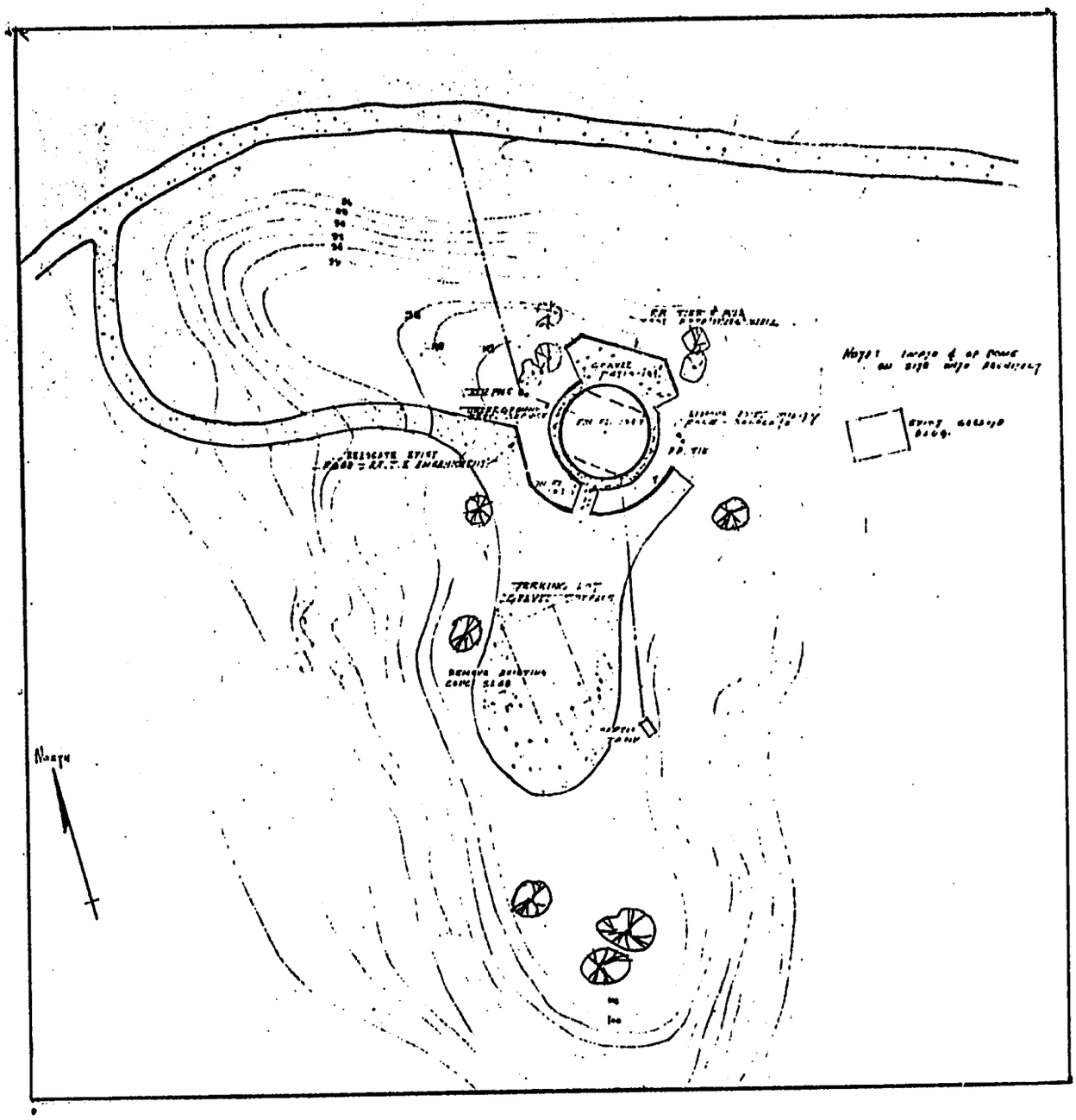



Plate 1

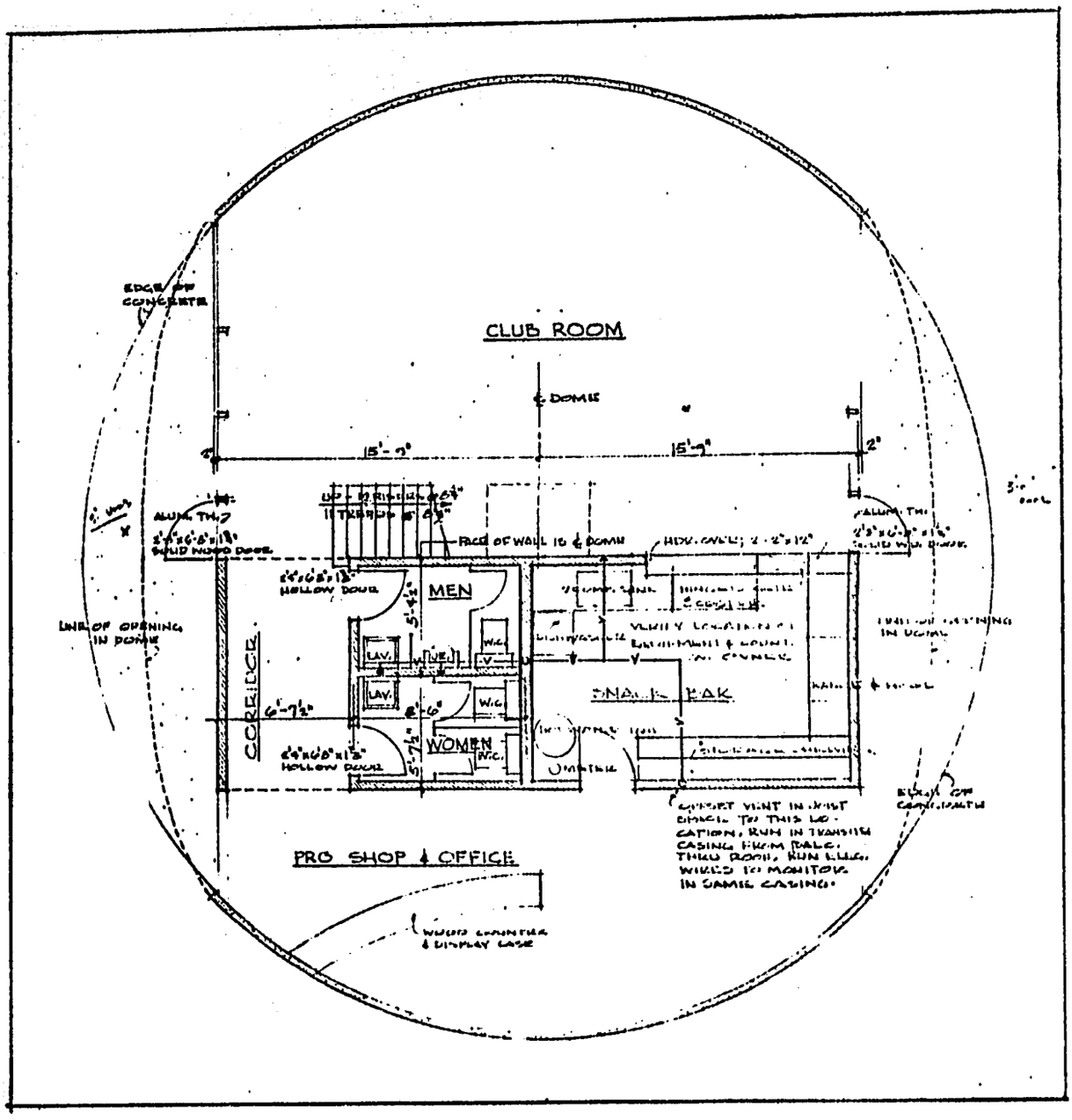
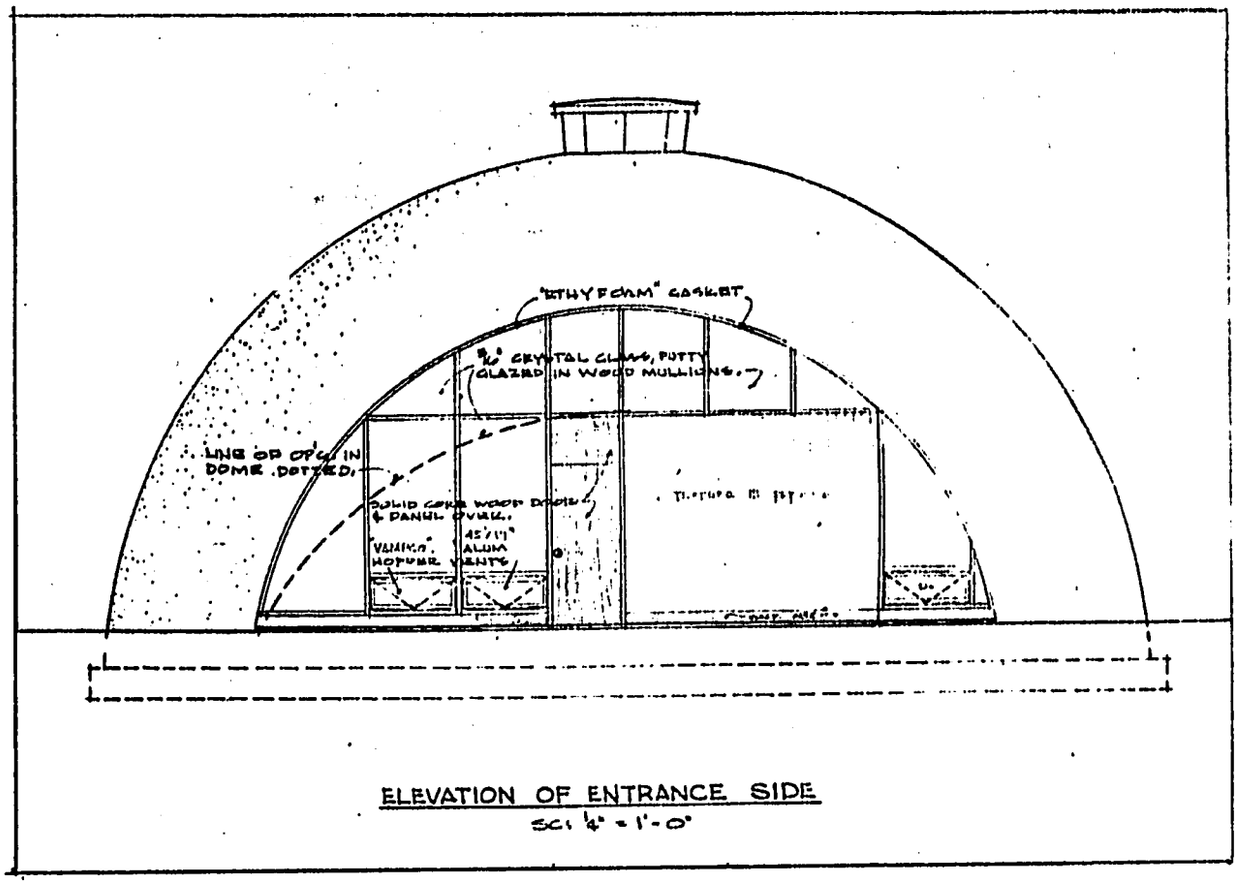
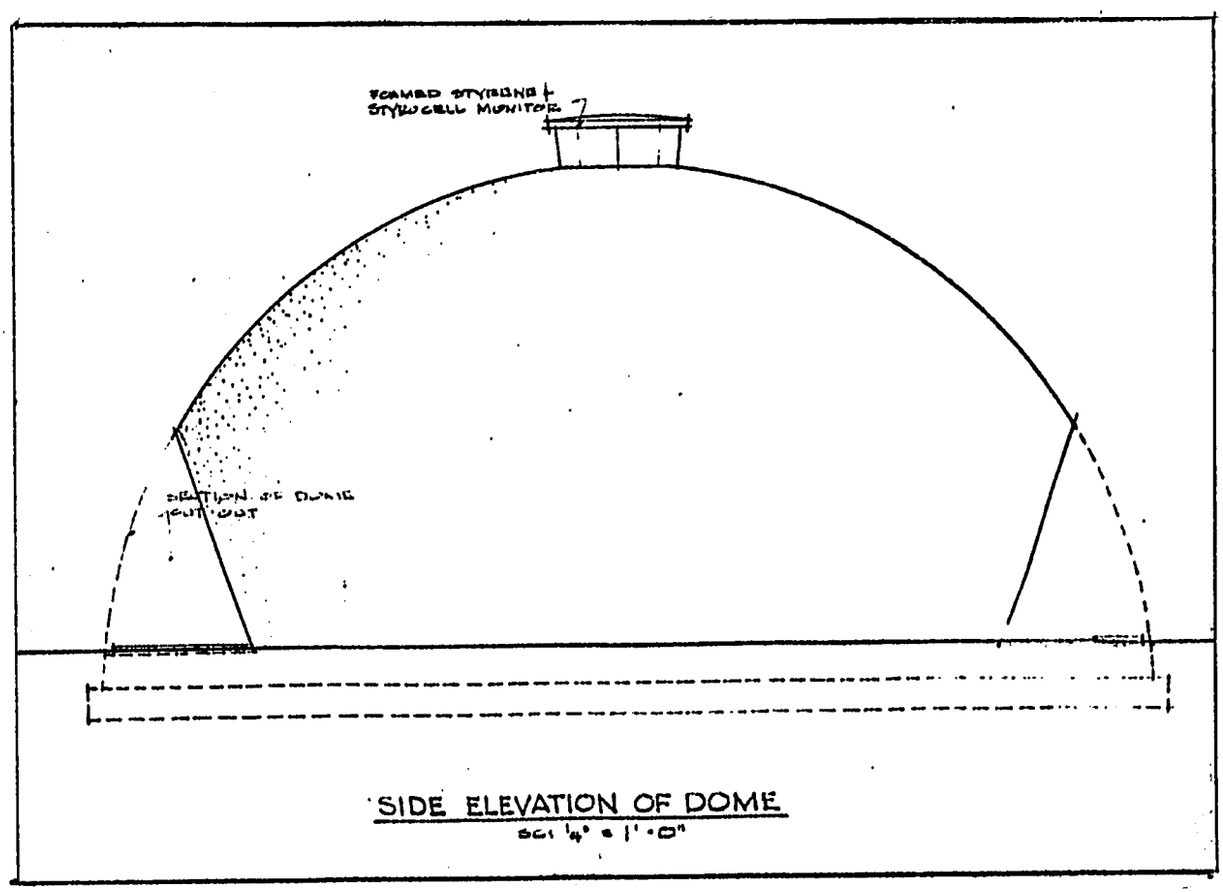

CLUB ROOM
℄ DOME
15'-9"
15'-9"
2"
EDGE OF CONCRETE
ALUM. THLD
SOLID WOOD DOOR
FACE OF WALL TO ℄ DOME
HDW. CABL; 2-2"x12"
2'-6"x6'-8"x1¾"
HOLLOW DOOR
MEN
5'-4½"
LINE OF OPENING IN DOME
CORRIDOR
LAV.
W.C.
6'-7½"
2'-6"
5'-7½"
WOMEN
SNACK BAR
URINAL
PRO SHOP & OFFICE
WOOD COUNTER & DISPLAY CASE

Plate 2




ELEVATION OF ENTRANCE SIDE

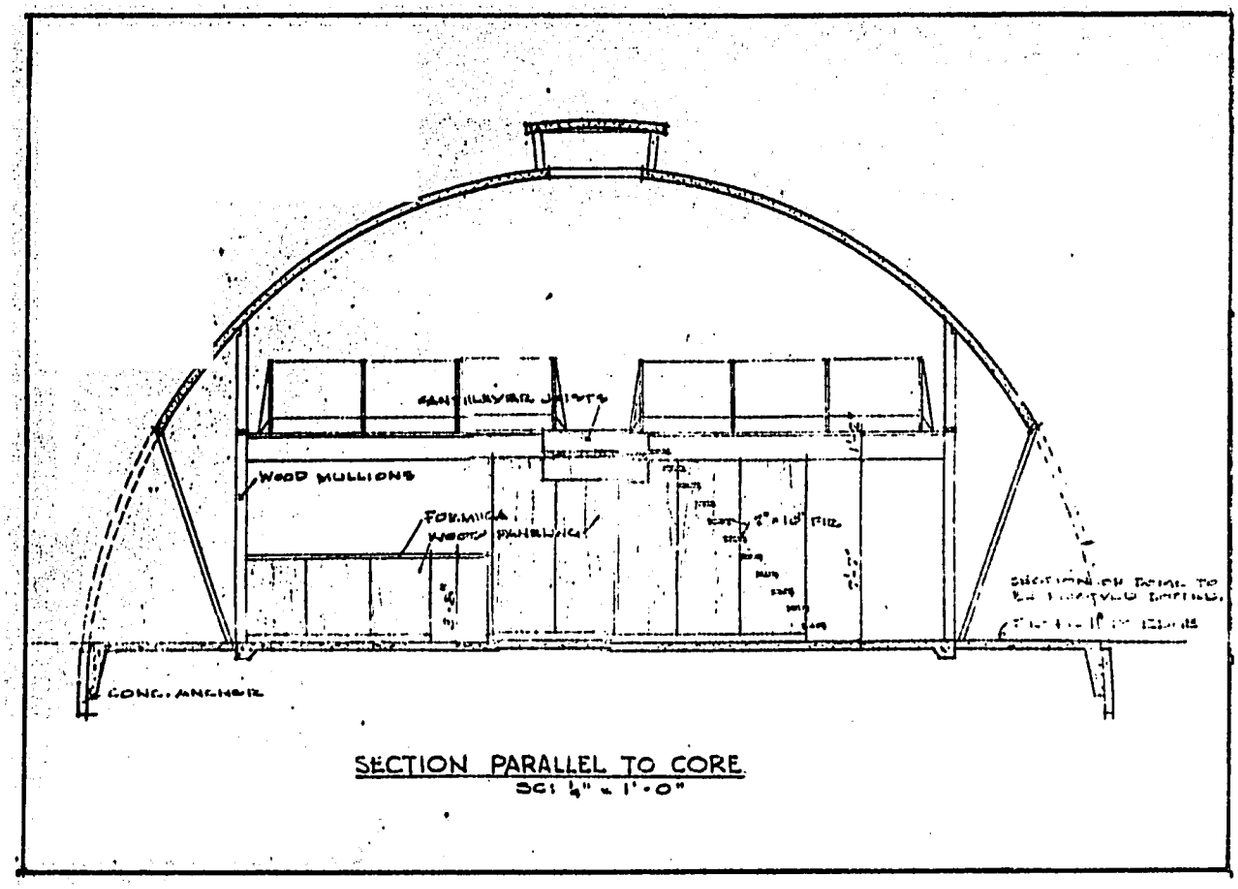
SC: ¼" = 1'-0"




SIDE ELEVATION OF DOME

SC: ¼" = 1'-0"

Plate 3


CANTILEVER JOISTS
WOOD MULLIONS
FORMICA
CONC. ANCHOR
SECTION PARALLEL TO CORE
SCI ¼" = 1'-0"

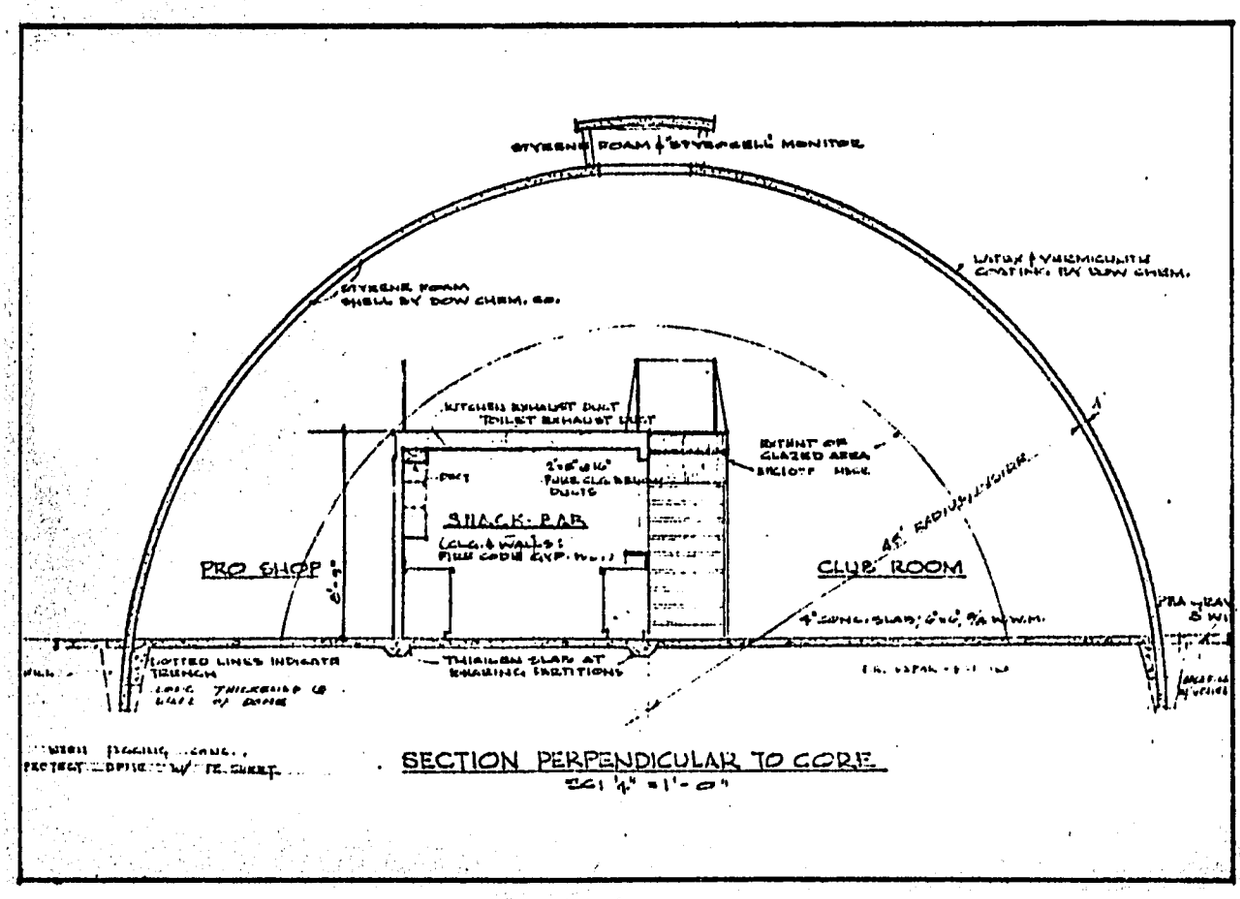
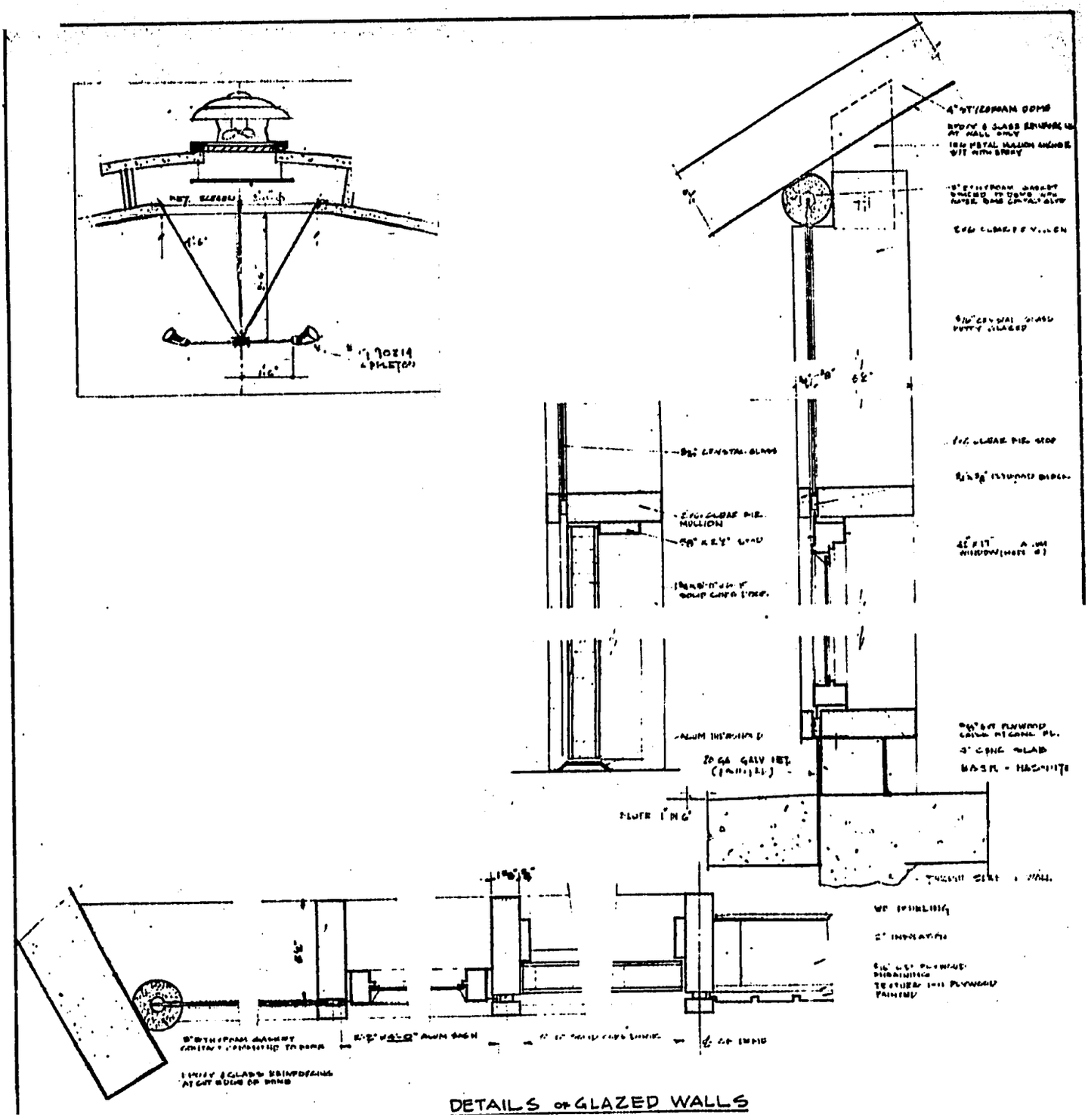

STYRENE FOAM & STYROFELL MONITOR
STYRENE FOAM SHELL BY DOW CHEM. CO.
KITCHEN EXHAUST DUCT
TOILET EXHAUST DUCT
SNACK BAR
PRO SHOP
CLUB ROOM
DOTTED LINES INDICATE TRENCH
THICKENED SLAB AT BEARING PARTITIONS
SECTION PERPENDICULAR TO CORE
SCI ¼" = 1'-0"

Plate 4



DETAILS OF GLAZED WALLS

## Appendix C

# EXAMPLE ON TESTING PROCEDURE AND ANALYSIS

# STRUCTURAL USES OF FOAM PLASTICS FOR HOUSING IN UNDERDEVELOPED AREAS

Sponsor: U. S. Department of State -- Agency for International Development

## Elastic and Plastic Deflection Characteristics of a Polyester Impregnated Paper Skin Urethane Foam Board Spanning Structure

### Introduction:

In the course of investigating the structural applications of foam plastics, staff members of ORA Project 05687 have expressed concern over the present test methods used to establish the performance characteristics of these materials. Concurrently, the development of new production techniques for foams has resulted in composite materials whose properties are radically different from those of simple foams, and for which no standard data or test procedures exist.

One such material, paper skin urethane foam board, has been described in previous reports of Project 05687. The advantages inherent in this material have stimulated the construction of several experimental structures, one of which has been used to develop the data for this report.

### Description of Test Structure:

The structure tested is a membrane beam approximately 5'-0" wide and 12" deep. The section is a triangular closed box made of paper skin urethane foam board 3/8" thick. The paper is impregnated and the panels are joined with polyester resin. The internal bracing membrane is composed of the same materials. The finished beam is 16'-0" long and has been tested for theoretical spans of 14'-6" with simple supported ends and 15'-2" with fixed ends. Only the fixed end data have been used for analysis. The construction of the legs is identical to that of the beams, the ends of which are supported at a height of 2'-8" from the floor to the top surface (see figure 1).

Elastic Behavior:

Because of the limited time and resources available for testing, it was felt that only the most direct, molar measurements were feasible. Consequently, the staff decided to perform a series of load tests on the beam, and to observe the behavior of the deflection curve as the loads were applied and removed. On the basis of these data, theoretical values could be computed for the properties desired.

The actual instrumentation used was simple and quite accurate. Twelve dial gages were mounted on a steel structure below the beam in such a way that vertical movement of the beam could be read within .001". Loads were applied to the top surface. The gages were closely spaced near the ends in an effort to locate by visual inspection the point of contraflexure of the beam. Near the center, where there was less uncertainty regarding the expected mode of behavior, the gages were placed further apart (see figure 2).

Since there was no duplicate structure to serve as a control, a series of tests were run to establish the range for the measurements. The most revealing of these tests was a 24-hour record of the gage readings under constant load with observations made once each hour. Figure 3 represents the average of ten gage readings over this period, and indicates the possibility of an error of from .002" to .003" in any one reading plus a strong cyclic fluctuation of about .010" resulting from hourly changes in temperature, humidity, and the like. The method of averaging gage readings will be described later.

The loading procedure was designed to accomplish three things: first, to establish the capacity of the section within an arbitrary allowable deflection; second, to provide accurate information on the elastic behavior of the structure; third, to establish a pattern of behavior for plastic deflection of foam and polyester-paper composites.

To accomplish the first two objectives, an experiment was designed to minimize the amount of error in recording the deflection and to reduce to a minimum the variability attributable to plastic deflection. A substantial concentrated load (390#) was imposed on the structure at midspan. One of the gages was selected for observation and a small portion of the load was alternately removed and replaced (46.5#). Each time the load changed, the reading of the gage was recorded. The load change was repeated four times for each gage before another gage was selected for observation, thus finally obtaining readings from all ten gages.

Subsequently, the total concentrated load on the structure was increased to 670#, and the entire procedure repeated at this higher level. The average recorded measurements and net deflections for the 46.5# load are given in figure 4.

Analysis:

The center span load of 390# produced an actual maximum deflection of .431"; a load of 670# produced a maximum deflection of .250"; and 46.5#, a deflection of .023". Assuming a linear relationship between the loads and the observed deflections (figure 5), the equation expressing the relationship between actual loads and observed deflections becomes $P = 1580d$ (1). The deflection can also be expressed as $d = PL^3/48EI$ (2).

Combining equations (1) and (2),

$EI = 32.91L^3 = 1.98 \times 10^8$ (maximum value).

A similar method, assuming 100% end fixity gives for the minimum value,

$EI = 0.5 \times 10^8$.

It is also possible to compute a value for EI from the rotation angle at the support:

Phi (angle of rotation) $= PL^2/16EI$

$EI = (670 \times 182 \times 182)/(16 \times .00786) = 1.77 \times 10^8$.

From measurements made with the load uniformly distributed, values of 1.01 and $1.19 \times 10^8$ have been obtained. On the basis of these preliminary measurements, it seems reasonable to conclude that the EI value for this section falls between 1.20 and $1.70 \times 10^8$, probably close to $1.50 \times 10^8$.

The moment of inertia of the section has been computed to be $2926t^{"4}$ (t represents thickness of stress-carrying material). The elastic modulus of this material may be found in terms of the thickness,

$E = 1.50 \times 10^8/2926t = 5.13 \times 10^4/t$ or, for impregnated paper skin foam board, 3/8" thick, E (per inch width) $= 5.13 \times 10^4$ lbs.

The prediction of elastic capacity on the basis of allowable deflection is relatively simple, using Equation (1). Assuming an allowable deflection of 1/240 of the span;

M (allowable) $= 6.876 \times .75 \times 10^4 = 51{,}570^{"\#}$. This value represents a concentrated load at midspan of 1130#, or a uniformly distributed load of about 25 psf.

The section moduli for the structure have been computed, in terms of the membrane thickness for two layers of polyester impregnated paper,

$Sc = 745^{t''3}$ (compression side)

$St = 347^{t''3}$ (tension side)

Thus, a moment of $51,750^{''\#}$ will result in tension stress levels of

$f = \frac{51,750}{347t} = (149$ lbs/t"psi.

This value can be expressed as 149 lbs. per inch of membrane width, distributed equally between the two paper skins of the membrane.

Tension failures of the paper skin of this board have been produced at a stress level of 180#/inch width on each skin. Thus design of structures of this type on the basis of an allowable deflection not to exceed 1/200 of the span would be expected to yield visually satisfactory results as well as an adequate factor of safety.

Plastic Behavior:

The continuous, gradual deflection of a structure under constant load has been given the generic term, "plastic flow," or "creep". Considerable experimentation has been done with the bahavior of conventional materials in this respect, although the relationships are still far from being precisely defined. New materials, foam plastics in particular, have received practically no similar attention. With this in mind, the experimentation by this project in this area has not attempted to arrive at precise conclusions or relationships which would enable prediction or design. What has been attempted is to determine the most likely form of behavior for structures of this type, to discover any unique characteristics of behavior, and to evaluate its significance in terms of structural performance over time.

Experimental Design:

The same test structure was used for this experiment. After completion of the tests of elastic performance, the structure was loaded as shown in figure 6. This load remained in place for 167 hours and was then removed. During this period, the readings of the ten gages were recorded at varying intervals, several times the first day and only once a day towards the end of the period. The readings were recorded every hour during the last 26 hours of this period before the load was removed, in order to establish

the pattern of daily fluctuation and to gain some indication of experimental error. The results are tabulated in figure 7.

Analysis:

A strong correlation between plastic deflection at each gage and relative stress level at that gage was discovered each time the measurements were recorded. This relationship provided a basis for weighting the deflections at each gage, and permitted a combining of readings from all gages to give a measure of average performance of the entire structure. Weighting of the independent gage readings was accomplished by dividing the net plastic deflection at the gage by the relative stress level at that point, taking the maximum moment value at midspan as one. The averages computed in this manner, adjusted for time of reading, are tabulated in figure 8.

The form of relationship which appears to fit these data best is illustrated in figure 9. The line is a parabola, and the particular equation for this parabola is $d_{(p)} = 1.69t \times 10^{-4}$. This relationship is also shown in figure 10, where the plastic deflection has been plotted against the square root of the elapsed time. Other simple relationship forms (linear, logarithmic, hyperbolic, etc.) have failed to provide as satisfactory fit as the parabola.

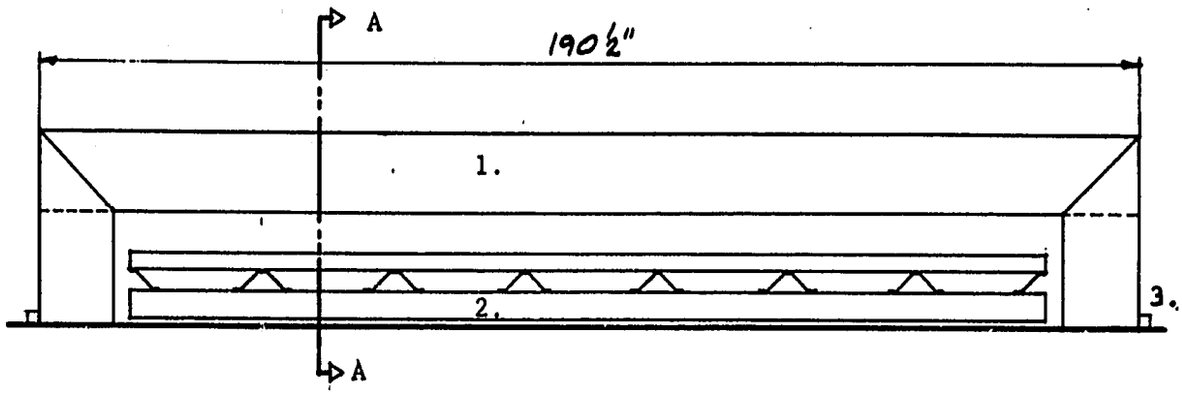
A unique property of this structure was discovered when the loads were removed at the end of 167 hours. Virtually all of the initial elastic deflection was recovered immediately. Following this elastic recovery, the structure continued to recover plastically almost all of the deformation which had accumulated over the study period. The structure was left set up for a period of five days following load removal, and the plastic recovery recorded. The recovery, which follows a logarithmic form, is tabulated in figure II.

This behavior is not typical of conventional materials, and needs further exploration to determine whether it is a property of the particular structure or can be considered characteristic of impregnated paper skin foam boards. An experiment has been set up at the University to explore this question, and is currently in progress.

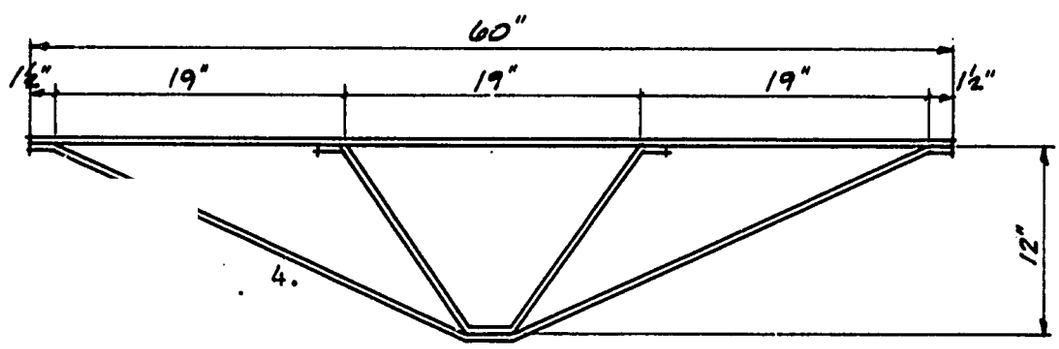
Conclusion:

The results of this study have demonstrated that the design of substantial and durable structures utilizing paper skin urethane foam board is not only feasible but relatively uncomplicated. The performance of the test structure has been highly encouraging, and modifications to the section are being planned for incorporation in the construction of an enclosed structure with floor, walls, and roof made of foam board.

The plastic behavior of the structure has been shown to be of a form which will permit control over the magnitude of the deflection by appropriate structural design. Normal live loads will present no problem at all in this regard. Loads of long duration will cause plastic flow in the structure, but the deflection will approach a plateau. With proper design, the magnitude of this plateau can be kept within reasonable limits during the life span of the structure.



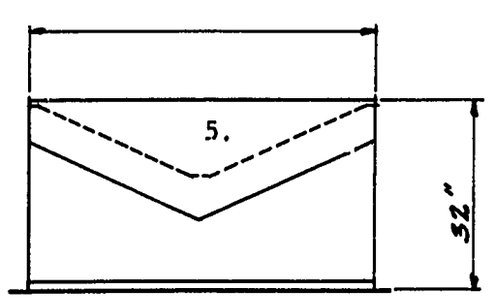

FRONT ELEVATION




SECTION AA

Notes:

1. Paper skin foam board test m structure.
2. Steel mounting for dial gages.
3. Steel thrust anchor.
4. Urethane foam board, 3/8" thick.
5. Top membrane laminated to end for rigidity.




END ELEVATION

Figure 1: Details of Test Structure

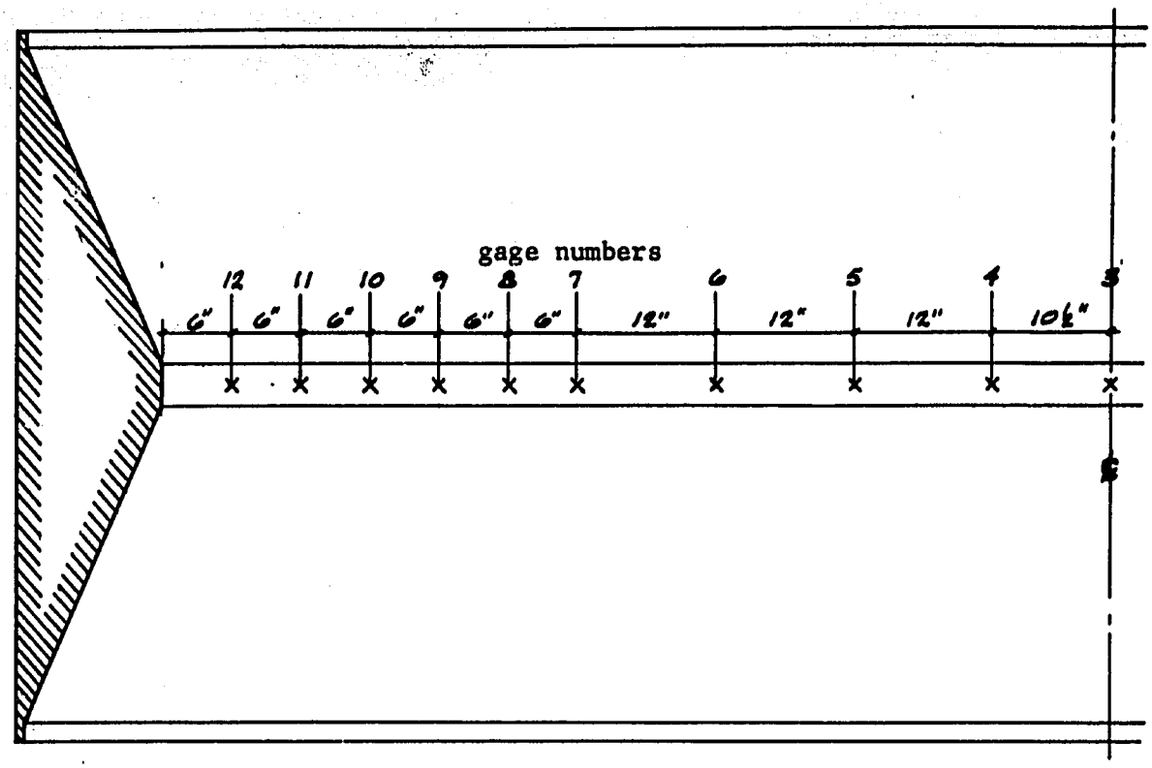



Figure 2: Reflected Plan of Test Structure, Showing Location of Dial Gages.

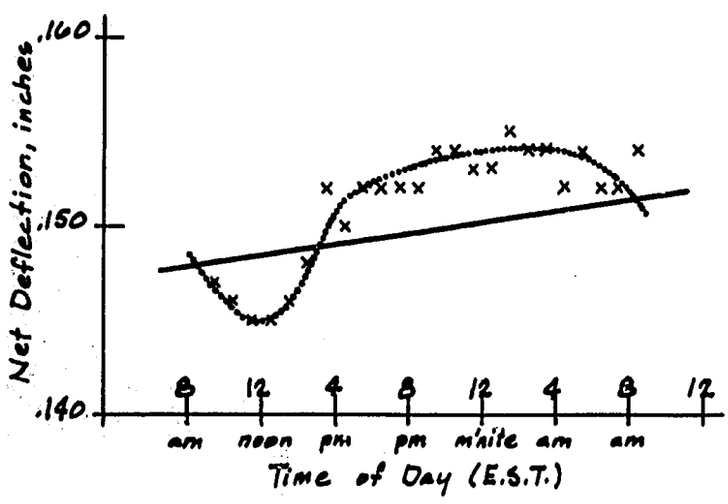



Figure 3: Deflection Cycle over 24 Hour Period from January 6 to January 7, 1964.

Total Load: 390#, Increment: 46.5#

| Gage Nos. | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|
| Unloaded | .624 | .391 | .388 | .285 | .345 | .230 | .328 | .340 | .382 | .722 |
| Loaded | .600 | .414 | .410 | .302 | .361 | .244 | .339 | .350 | .389 | .779 |
| Net d | .024 | .023 | .022 | .017 | .016 | .014 | .011 | .010 | .007 | .007 |

Total Load: 670#, Increment: 46.5#

| Gage Nos. | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|
| Unloaded | .442 | .669 | .552 | .427 | .466 | .341 | .317 | .415 | .443 | .819 |
| Loaded | .419 | .691 | .572 | .444 | .480 | .353 | .328 | .424 | .451 | .825 |
| Net d | .023 | .022 | .020 | .017 | .014 | .012 | .011 | .009 | .008 | .006 |

Figure 4: Average Gage Readings and Net Elastic Deflection for a Load of 46.5 Pounds.

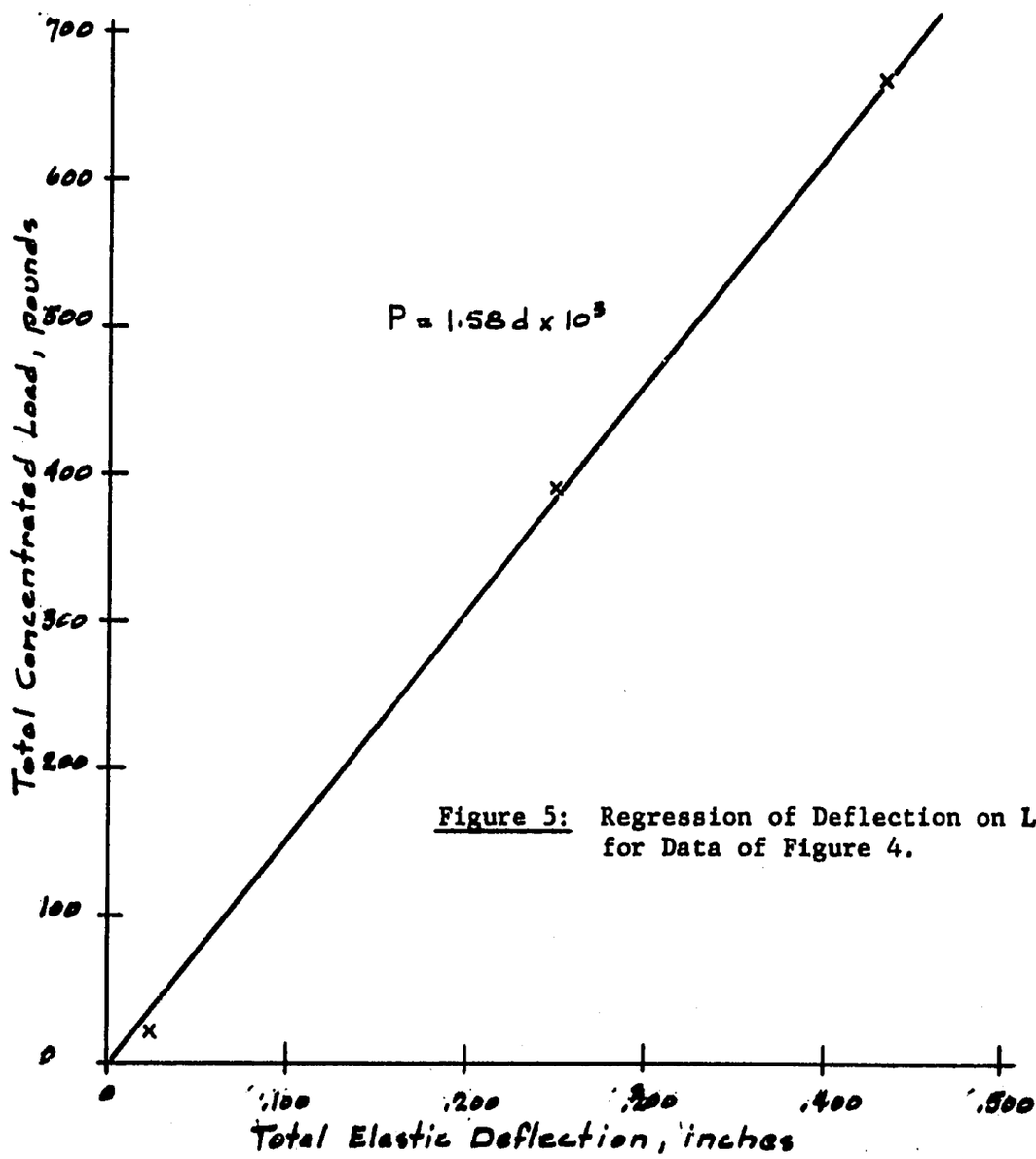



Figure 5: Regression of Deflection on Load for Data of Figure 4.

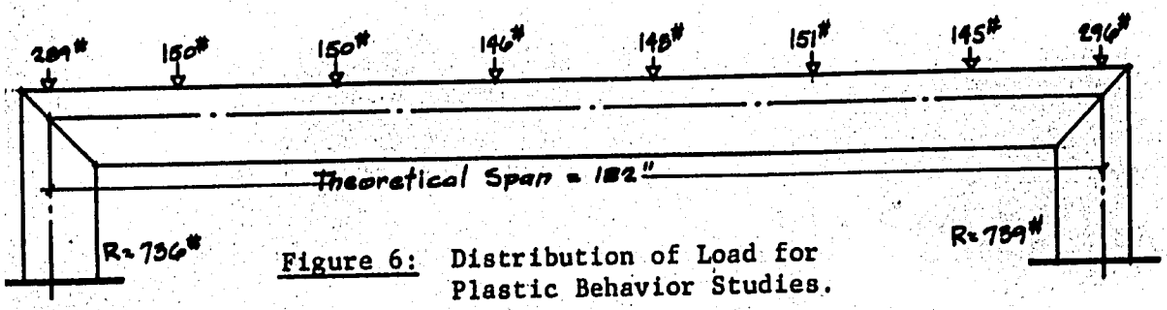



**Figure 6:** Distribution of Load for Plastic Behavior Studies.

Time of Initial Reading: 11:30 AM, December 31, 1963

| Elapsed Time from Initial Reading (Hours) / Gage Number | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|
| Initial Rd'g. | .419 | .596 | .590 | .475 | .520 | .397 | .475 | .472 | .498 | .870 |
| 0.50 | .414 | .601 | .595 | .480 | .524 | .401 | .477 | .475 | .500 | .871 |
| 2.00 | .403 | .612 | .605 | .488 | .531 | .407 | .482 | .478 | .503 | .873 |
| 3.00 | .394 | .621 | .613 | .495 | .537 | .413 | .488 | .482 | .506 | .875 |
| 4.00 | .390 | .625 | .616 | .498 | .539 | .415 | .490 | .484 | .507 | .875 |
| 5.00 | .386 | .628 | .620 | .502 | .542 | .418 | .492 | .485 | .508 | .876 |
| 9.00 | .367 | .647 | .638 | .517 | .556 | .432 | .503 | .495 | .516 | .883 |
| 26.00 | .354 | .661 | .650 | .529 | .566 | .441. | .512 | .503 | .523 | .889 |
| 33.00 | .348 | .666 | .656 | .534 | .570 | .445 | .515 | .505 | .524 | .890 |
| 45.25 | .337 | .677 | .667 | .543 | .579 | .453 | .523 | .512 | .530 | .894 |
| 50.00 | .338 | .676 | .666 | .542 | .578 | .452 | .521 | .510 | .528 | .893 |
| 69.50 | .310 | .704 | .692 | .566 | .598 | .471 | .538 | .525 | .541 | .903 |
| 77.00 | .289 | .723 | .711 | .583 | .612 | .483 | .550 | .534 | .549 | .908 |
| 98.50 | .282 | .731 | .718 | .589 | .618 | .488 | .555 | .538 | .552 | .910 |
| 120.00 | .277 | .736 | .723 | .594 | .622 | .492 | .558 | .541 | .554 | .912 |
| 141.00 | .274 | .739 | .725 | .596 | .625 | .495 | .561 | .544 | .557 | .915 |
| 142.00 | .270 | .743 | .729 | .600 | .628 | .499 | .563 | .546 | .559 | .916 |
| 143.00 | .272 | .742 | .728 | .599 | .627 | .498 | .562 | .546 | .559 | .916 |
| 144.00 | .273 | .741 | .727 | .598 | .626 | .497 | .562 | .545 | .658 | .916 |
| 145.00 | .272 | .742 | .728 | .599 | .627 | .498 | .562 | .545 | .558 | .915 |
| 146.00 | .270 | .743 | .730 | .600 | .628 | .498 | .563 | .545 | .558 | .915 |
| 147.00 | .268 | .746 | .731 | .601 | .629 | .500 | .564 | .546 | .559 | .916 |
| 148.00 | .264 | .749 | .734 | .604 | .632 | .502 | .566 | .548 | .560 | .917 |
| 149.00 | .266 | .747 | .732 | .603 | .630 | .500 | .565 | .547 | .560 | .916 |
| 150.00 | .264 | .749 | .734 | .605 | .631 | .502 | .566 | .548 | .561 | .917 |
| 151.00 | .265 | .748 | .734 | .605 | .631 | .502 | .566 | .548 | .561 | .918 |
| 152.00 | .265 | .748 | .734 | .606 | .631 | .502 | .566 | .548 | .561 | .917 |
| 153.00 | .265 | .748 | .734 | .604 | .631 | .502 | .566 | .548 | .561 | .917 |
| 154.00 | .263 | .749 | .737 | .607 | .633 | .504 | .567 | .549 | .562 | .918 |
| 155.00 | .263 | .750 | .736 | .606 | .633 | .504 | .567 | .549 | .562 | .918 |
| 156.00 | .264 | .749 | .735 | .605 | .632 | .503 | .566 | .548 | .562 | .918 |
| 157.00 | .265 | .749 | .735 | .605 | .632 | .503 | .567 | .549 | .562 | .918 |
| 158.00 | .262 | .751 | .737 | .607 | .634 | .504 | .568 | .549 | .562 | .918 |
| 159.00 | .261 | .752 | .737 | .607 | .634 | .504 | .568 | .549 | .562 | .917 |
| 160.00 | .264 | .750 | .736 | .606 | .633 | .504 | .567 | .549 | .562 | .918 |
| 161.00 | .265 | .748 | .734 | .605 | .632 | .502 | .566 | .548 | .561 | .917 |
| 162.00 | .262 | .751 | .737 | .607 | .634 | .504 | .567 | .549 | .562 | .918 |
| 163.00 | .267 | .747 | .734 | .604 | .631 | .502 | .567 | .548 | .561 | .918 |
| 164.00 | .266 | .747 | .734 | .604 | .632 | .502 | .566 | .548 | .562 | .918 |
| 165.00 | .263 | .750 | .736 | .606 | .633 | .504 | .567 | .549 | .562 | .918 |
| 166.00 | .260 | .754 | .739 | .609 | .636 | .506 | .570 | .551 | .564 | .920 |
| 167.00 | .257 | .756 | .742 | .612 | .638 | .508 | .571 | .553 | .565 | .921 |

**Figure 7:** Measurements of Deflection for 167 Hour Period from December 31, 1963 to January 7, 1964.

| Elapsed Hours | Net Deflection |
|---|---|
| 2.00 | .017 |
| 3.00 | .025 |
| 4.00 | .028 |
| 5.00 | .030 |
| 9.00 | .047 |
| 26.00 | .066 |
| 35.00 | .064 |
| 45.25 | .080 |
| 50.00 | .080 |
| 69.50 | .106 |
| 77.00 | .124 |
| 98.50 | .136 |
| 120.00 | .141 |
| 141.00 | .147 |
| 165.00 | .154 |

**Figure 8:** Corrected Average Net Deflections for Period from December 31, 1968 to January 7, 1964.

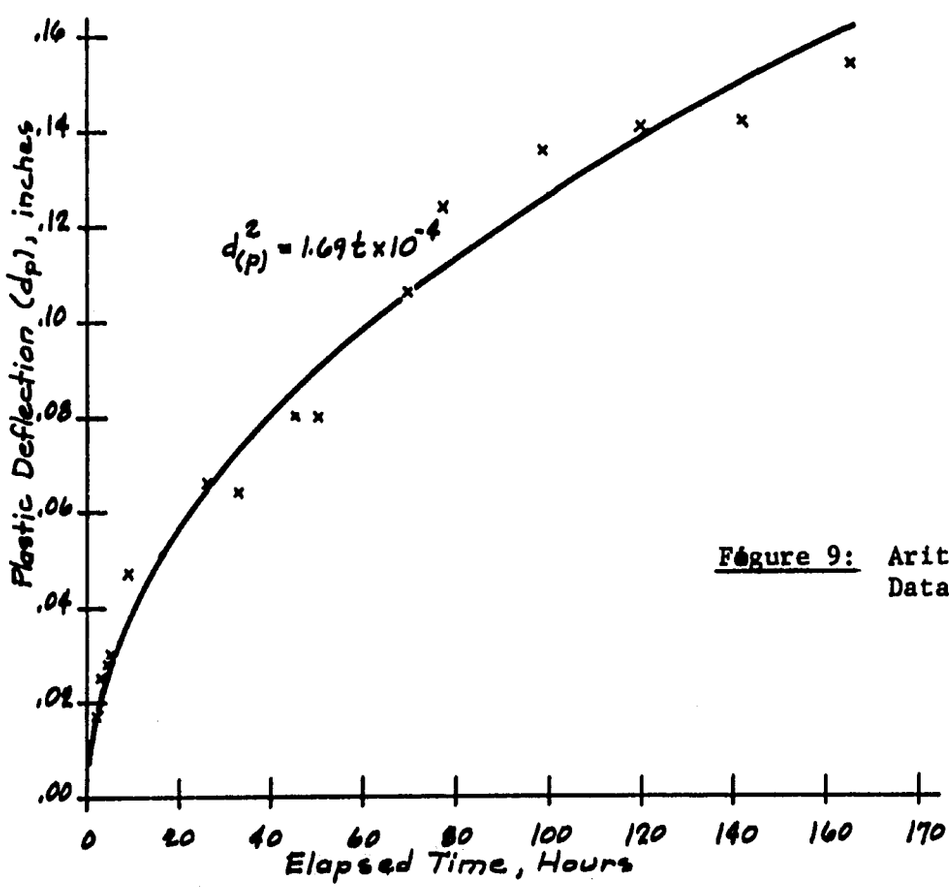



**Figure 9:** Arithmetic Plot of Data of Figure 8:

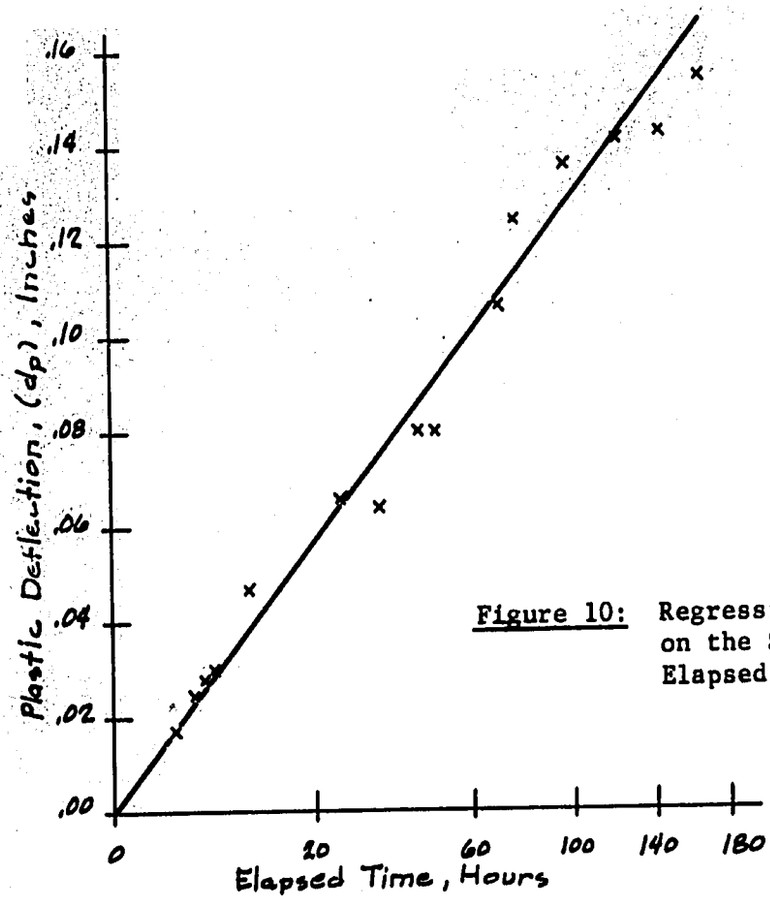



Figure 10: Regression of Plastic Deflectio on the Square Root of the Elapsed Time.

Elapsed Time from Initial Reading (Hours)

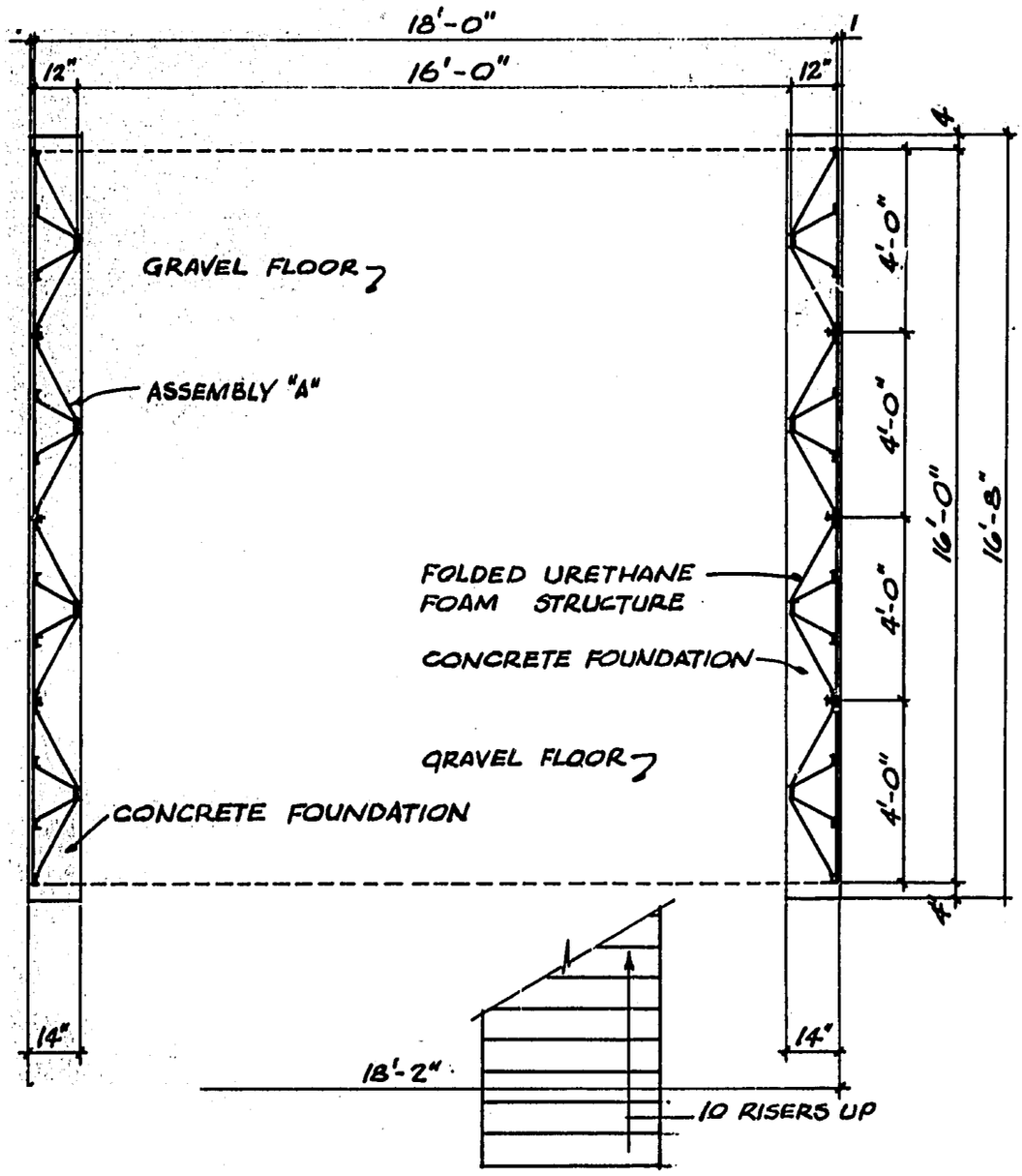
| Gage Number | Initial Reading | 0.5 | 1.0 | 9.0 | 22.0 | 31.5 | 46.0 | 54.5 | 70.0 | 94.5 |
|---|---|---|---|---|---|---|---|---|---|---|
| 6 | .312 | .278 | .271 | .239 | .225 | .226 | .219 | .211 | .216 | .204 |
| 12 | .814 | .802 | .799 | .788 | .783 | .788 | .786 | .783 | .787 | .781 |

Figure 11: Recovery of Test Structure During Period from January 7 to January 12, 1964.

**PROPOSED EXPERIMENTAL FOAM BOARD FOLDED STRUCTURE**

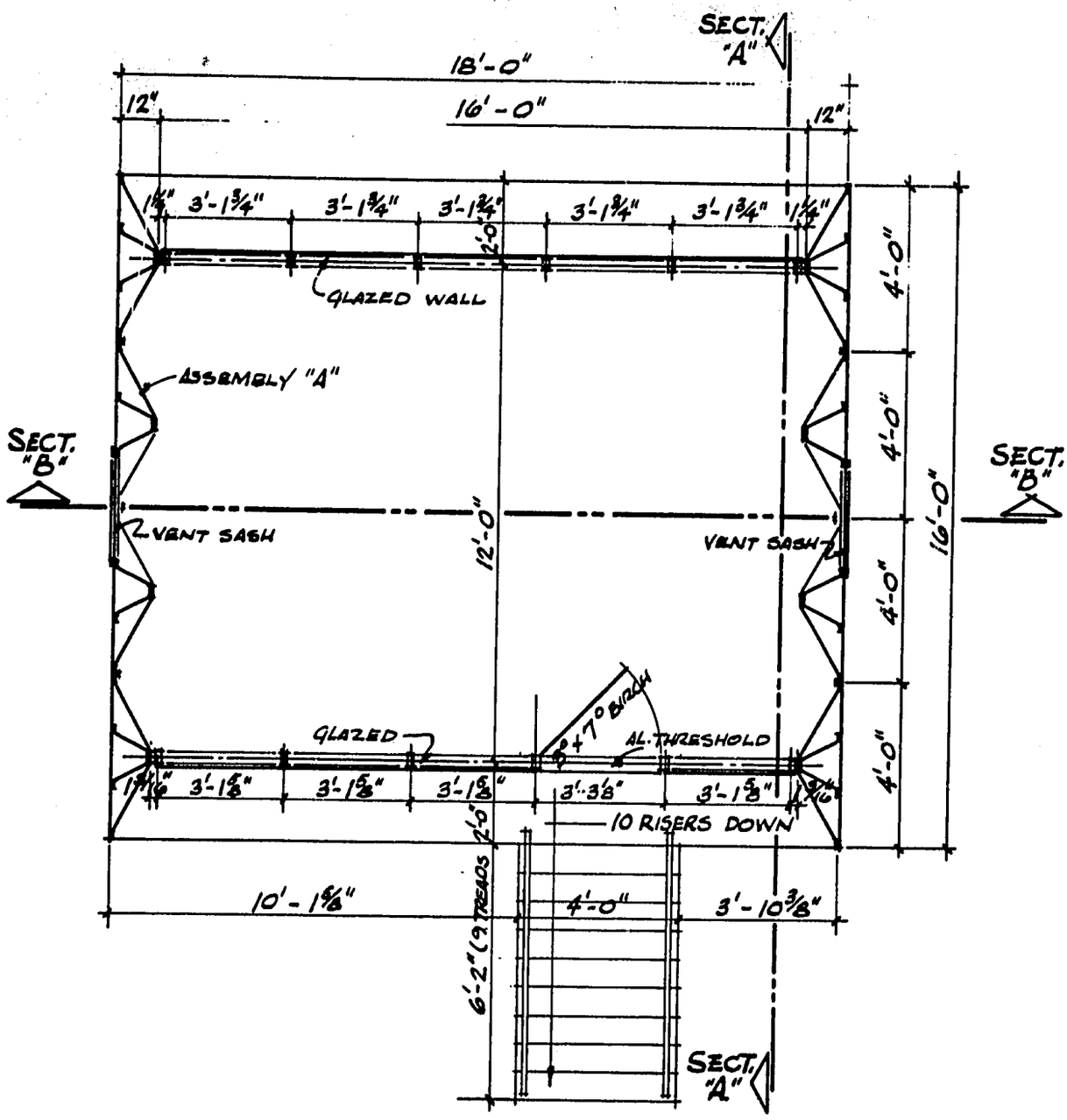
**The University of Michigan, Architectural Research Laboratory collaborating with the Union Carbide Company**

FIRST FLOOR PLAN



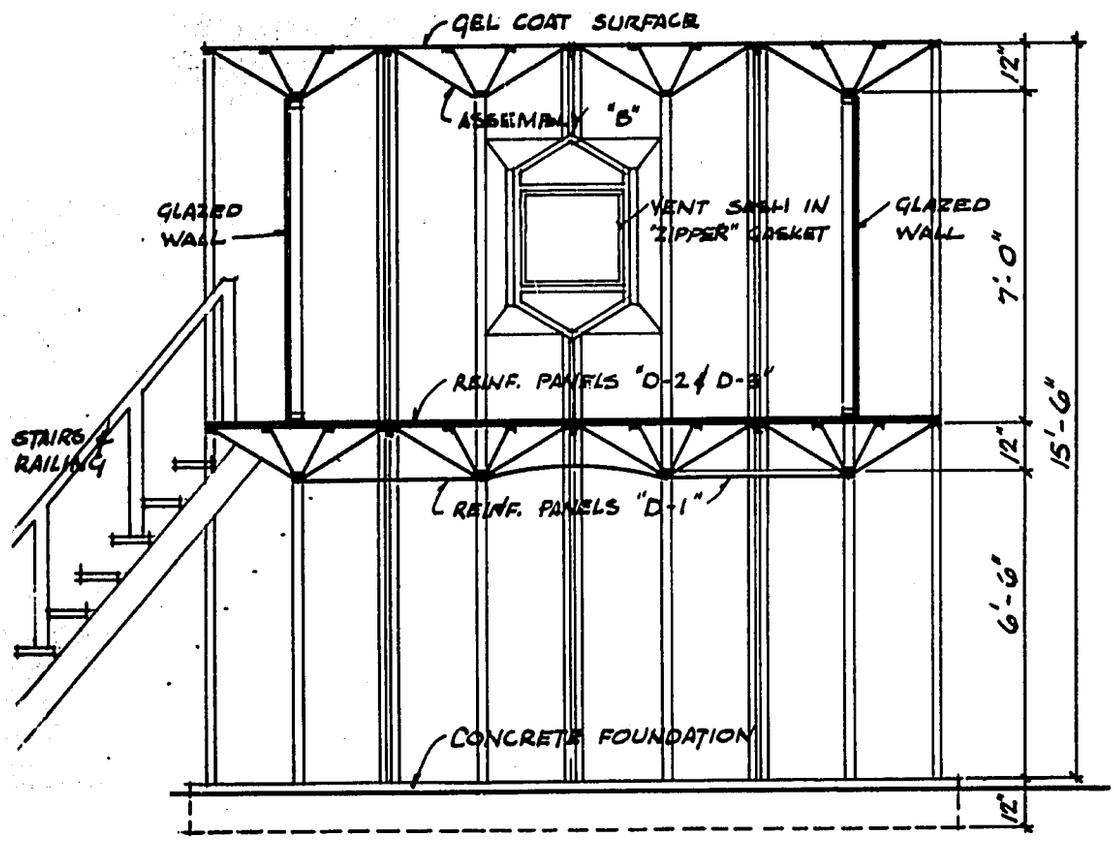

SCALE: 1/4" = 1'-0"

## SECOND FLOOR PLAN



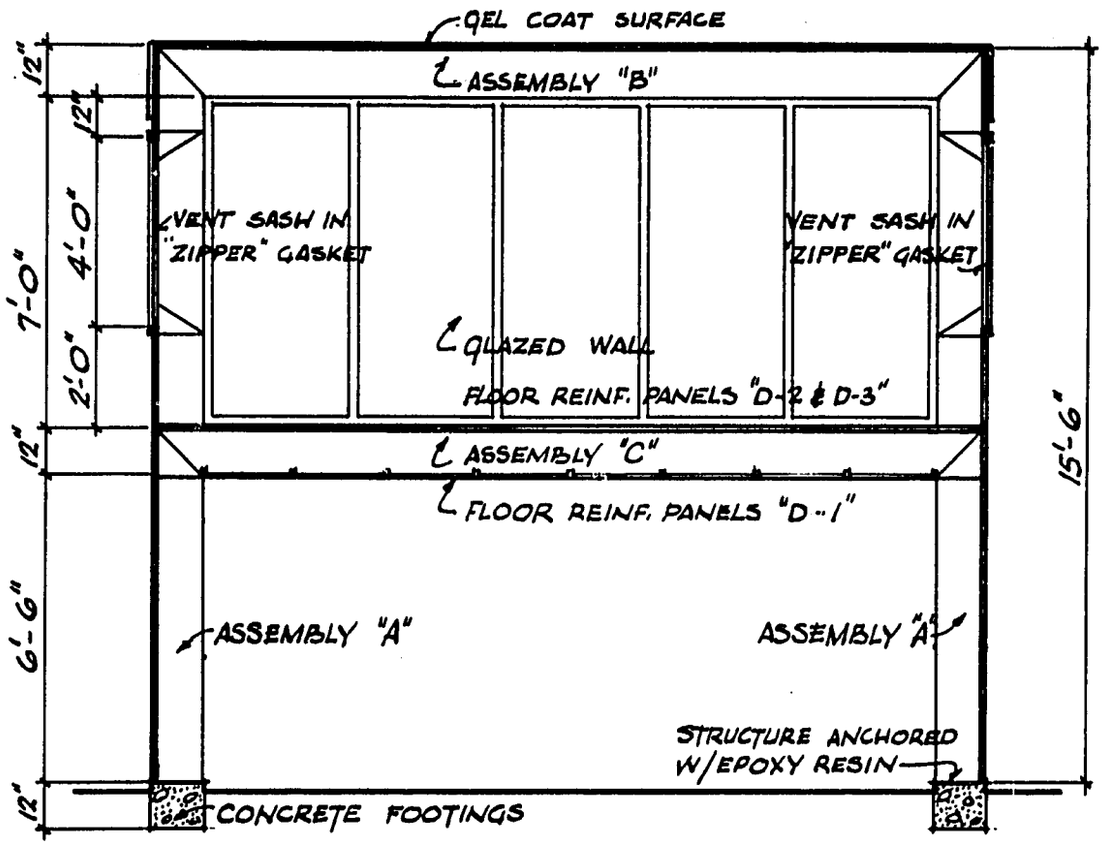

Scale: 1/4" = 1'-0"

## SECTION A

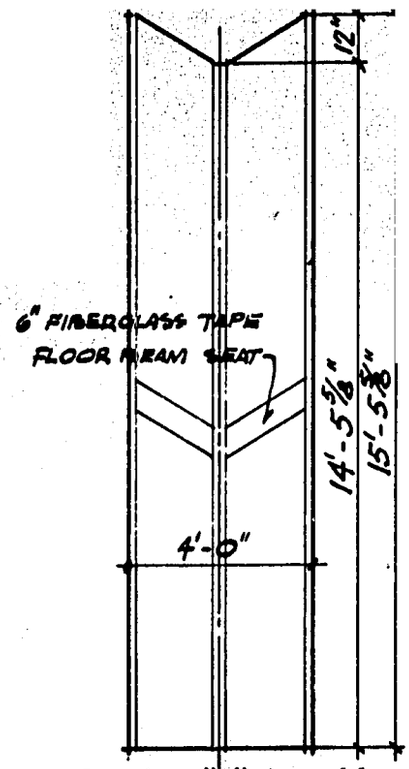



Scale: 1/4" = 1'-0"

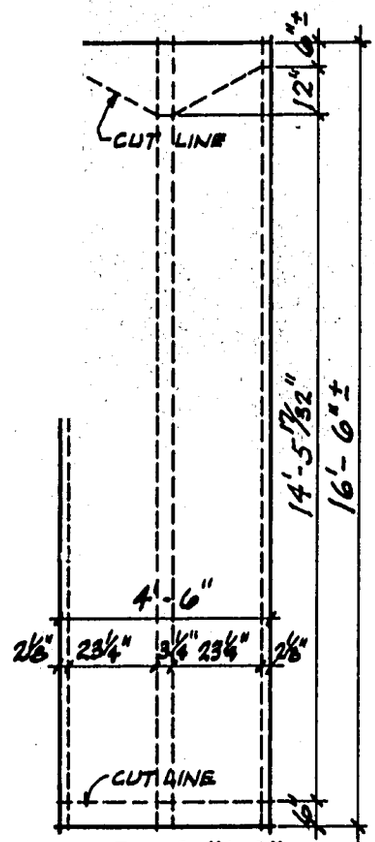
SECTION "B"



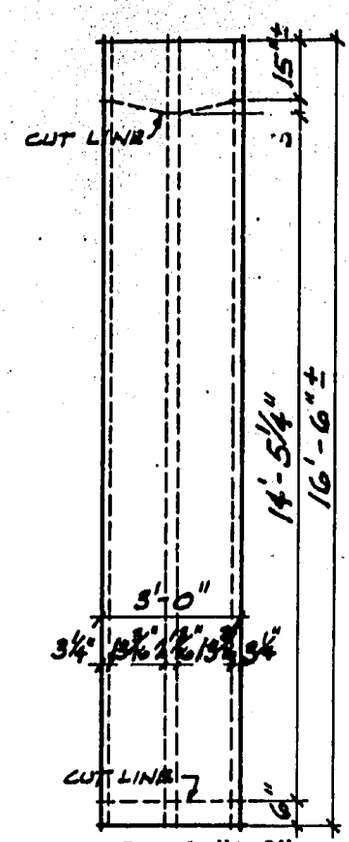

Scale: 1/4' = 1'-0"



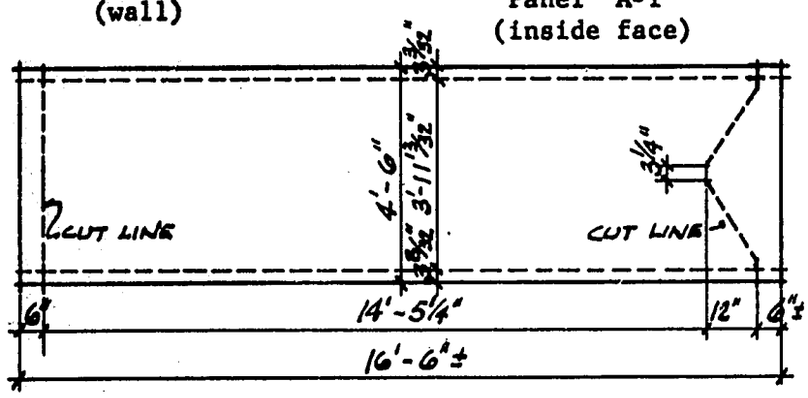

Section "A" Assembly
(wall)




Panel "A-1"
(inside face)




Panel "A-2"
(internal
membrane)

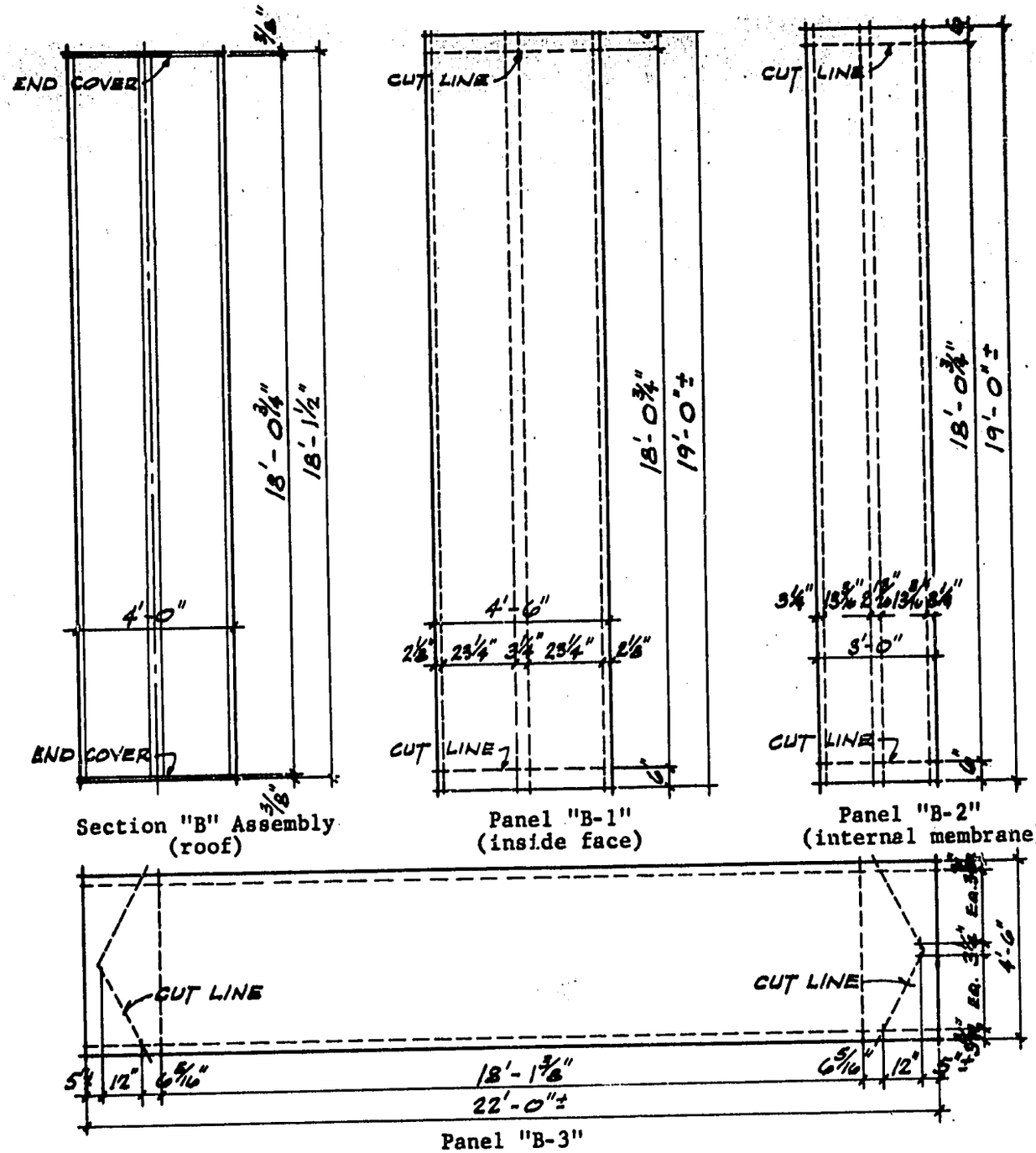



Panel "A-3"
(outside face)

**DETAILS OF WALL ASSEMBLY**: (8 complete assemblies required) Scale: 1/4" = 1'-0"

| Materials List: | Quantity | Size | Remarks |
|---|---|---|---|
| 3/8" foamboard | 8 pcs. | 4'-6"x16'-6" | score for Panel "A-1" |
| 3/8" foamboard | 8 pcs. | 3'-0"x16'-6" | score for Panel "A-2" |
| 3/8" foamboard | 8 pcs. | 4'-6"x16'-6" | score for Panel "A-3" |
| fiberglass tape | 40'lin. | 6" wide | |
| fiberglass tape | 360'lin. | 3" wide | |
| polyester resin | 20 gal. | | |

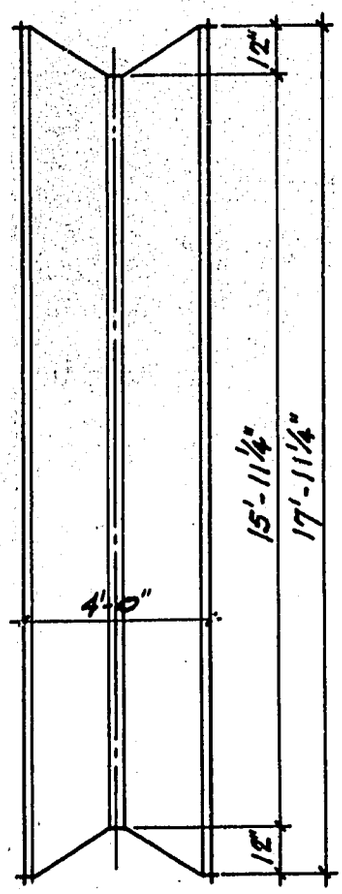
(All scoring: single score from both sides of board, to be folded both ways. Dotted lines indicate lines to be scored, unless specifically marked, 'cut line.')



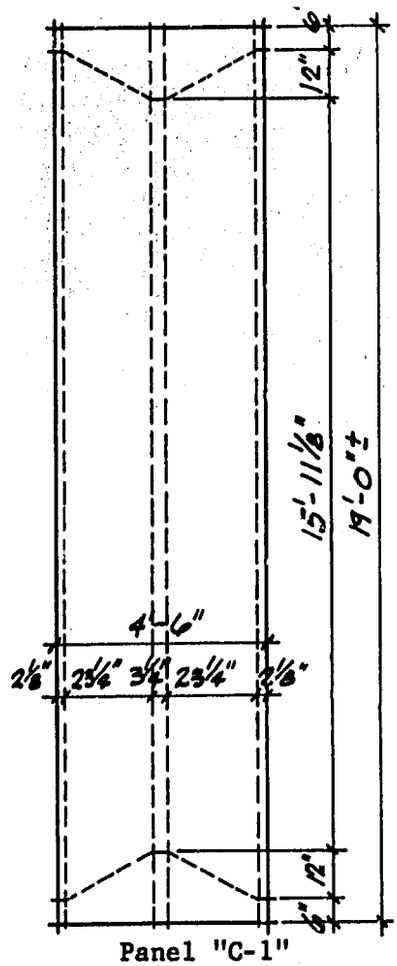

**DETAILS OF ROOF ASSEMBLY**: (4 complete assemblies required) Scale: 1/4" = 1'-0

| Materials List: | Quantity | Size | Remarks |
|---|---|---|---|
| 3/8" foamboard | 4 pcs. | 4'-6"x19'-0" | score for Panel "B-1" |
| 3/8" foamboard | 4 pcs. | 3'-0"x19'-0" | score for Panel "B-2" |
| 3/8" foamboard | 4 pcs. | 4'-6"x22'-0" | score for Panel "B-3" |
| fiberglass tape | 220'lin. | 3" wide | |
| polyester resin | 10 gal. | | |

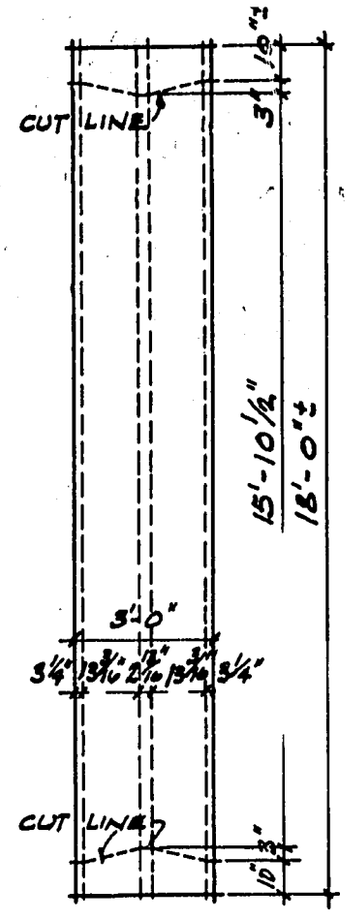
(All scoring: single score from both sides of board, to be folded both ways. Dotted lines indicate lines to be scored, unless specifically marked, 'cut line.')



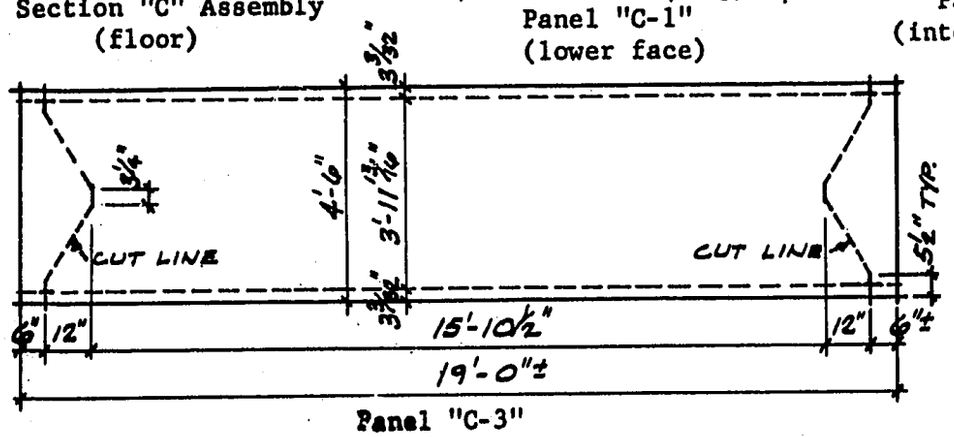

Section "C" Assembly
(floor)




Panel "C-1"
(lower face)




Panel "C-2"
(internal membrane)

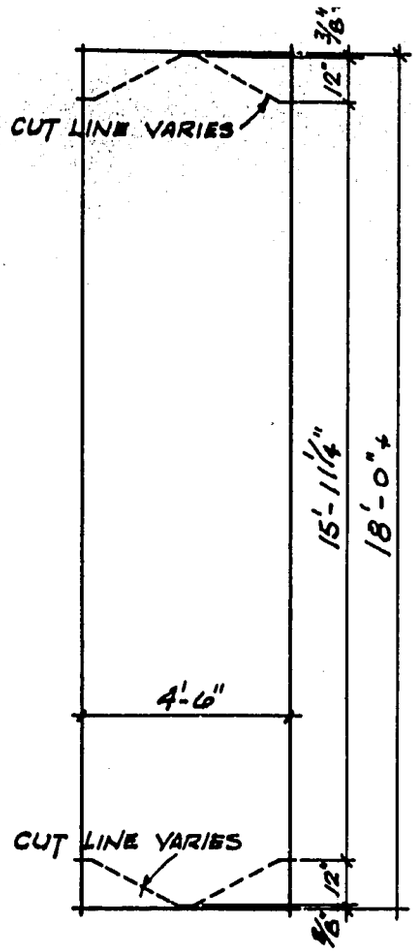



Panel "C-3"
(upper face)

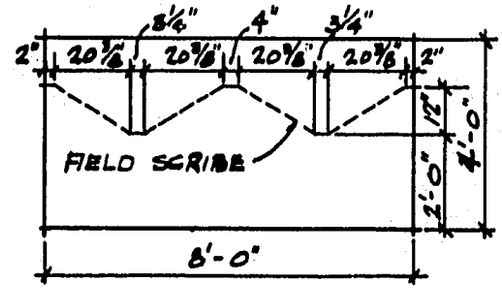
<u>DETAILS OF FLOOR ASSEMBLY</u>: (4 complete assemblies required) Scale: 1/4" = 1'-0"

| Materials List: | Quantity | Size | Remarks |
|---|---|---|---|
| 3/8" foamboard | 4 pcs. | 4'-6"x19'-0" | score for Panel C-1 |
| 3/8" foamboard | 4 pcs. | 3'-0"x18'-0" | score for Panel C-2 |
| 3/8" foamboard | 4 pcs. | 4'-6"x19'-0" | score for Panel C-3 |
| fiberglass tape | 200' lin. | 3" wide | |
| polyester resin | 10 gal. | | |

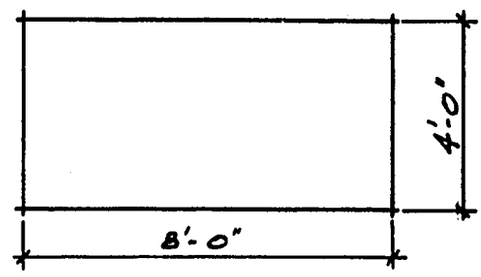
(All scoring: single score from both sides of board, to be folded both ways. Dotted lines indicate lines to be scored, unless specifically marked, 'cut line.')




Panel "D-3" (lower surface)




Panel "D-1" (upper surface)




Panel "D-2" (upper surface)

Note: Each section of D-3 is to be installed in a slightly different manner to determine the optimum method of installation. Ends must be field cut to fit structure.

**DETAILS OF FLOOR STRUCTURE REINFORCING ASSEMBLY:** Scale: 1/4" = 1'-0"

| Materials List: | Quantity | Size | Remarks |
|---|---|---|---|
| 3/8" foamboard | 3 pcs. | 4'-6"x18'-0" | Cut for panel "D-3" |
| 1/4" masonite | 10 pcs. | 4'-0"x8'-0" | Cut 4 pcs. for Panel D-1, balance for Panel D-2. |
| polyester resin | 10 gal. | | |

Appendix D

# STUDY ON THE ECONOMY OF SANDWICH PANELS

# THE THEORETICAL ECONOMIC RELATIONSHIPS BETWEEN THE SKINS AND THE CORE OF A SANDWICH PANEL

Robert M. Darvas*
Associate Professor of Architecture
The University of Michigan

## Introduction

In the design of a sandwich panel, one way to determine suitable strength or stiffness is to make some arbitrary assumptions at the outset. For instance, the final panel thickness can be fixed, or other requirements, such as its minimum structural strength or its maximum permissible deformation, can be established. Economic consideration would not then come into the picture until later.

However, the desirability of using a plastic rather than some other material in such a sandwich panel depends on its price per square foot. The designer must therefore have some means to evaluate the economy of his design.

The author has found that it has been possible to establish simple formulas to determine the most economical relationship between the skins and the core of a sandwich panel. In other words, it is possible to predict in a theoretical way how the designer can best spend the available money, i.e. how much he should spend on the core and how much on the skin in order to get the most "mileage" (most strength, most stiffness, etc., depending on the goal).

In the following analysis we shall assume that the materials are homogeneous and elastic, following Hooke's Law, and that Young's moduli and the prices per unit volumes are known.

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*This paper has been prepared in connection with a research program conducted by the Architectural Research Laboratory of The University of Michigan on the use of plastic materials in housing. The research program is sponsored by the Agency for International Development (AID) of the U. S. State Department.

## Most Important Notations

$b$ = width of panel

$t$ = thickness of core

$t_1$, $t_2$ = skin thickness

$E$ = modulus of elasticity of core

$E_1$, $E_2$ = moduli of elasticity of skins

$I$ = moment of inertia of sandwich panel

$P_1$ = price of skin per unit volume

$p$ = price of core per unit volume

Other notations will be explained as they occur in the text.

## Development of Formulas

In general, a sandwich panel consists of a core and two skins, one on each side as shown in Figure 1. The skins and the core could be of different thickness and of different materials, whose modulus of elasticity may be designated in order $E_1$, $E$, $E_2$.

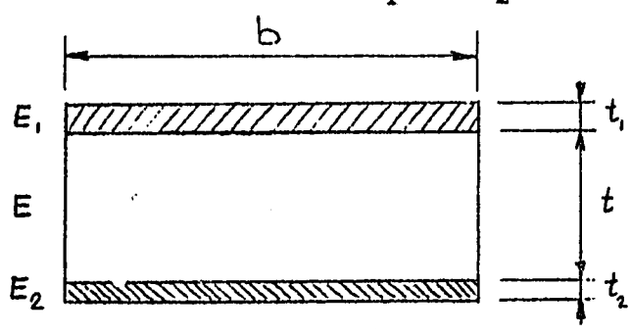


Figure 1

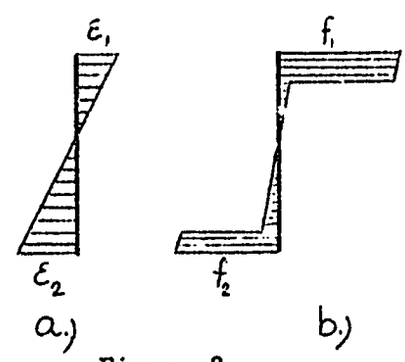


Figure 2

It would be rather cumbersome to work with three different moduli of elasticity while establishing the geometrical properties of the section. Fortunately, the Theory of Elasticity offers us an easier solution. If the Bernoulli-Navier hypothesis holds true, that planes remain planes after deformation, then the distribution of strains will be similar to Figure 2a. Furthermore if

$$f = E\varepsilon \tag{1}$$

at any point of the structure (Hooke's Law), then the stress-distribution will be similar to Fig. 2b, assuming that $E_1$ and $E_2$ are larger than E. This shows that the skins will carry larger stresses, more internal force per unit area than the core and this relationship depends on the ratio of their moduli of elasticity. In other words, a unit area of skin is "worth" more than a unit area of core in the internal force carrying capacity of the section.

Thus if we designate

$$\frac{E_1}{E} = n_1 \; ; \quad \frac{E_2}{E} = n_2 \; ; \quad \frac{E_1}{E_2} = n \tag{2}$$

then the problem can be approached by assuming a transformed section in place of the one shown in Fig. 1, whereby the original skin areas $bt_1$ or $bt_2$ having a modulus of elasticity of $E_1$ or $E_2$ are replaced by skin areas which will be $n_1b$ or $n_2b$ wide and will have a modulus of elasticity of E.

Hence the section replacing the original one is as shown in Fig. 3.

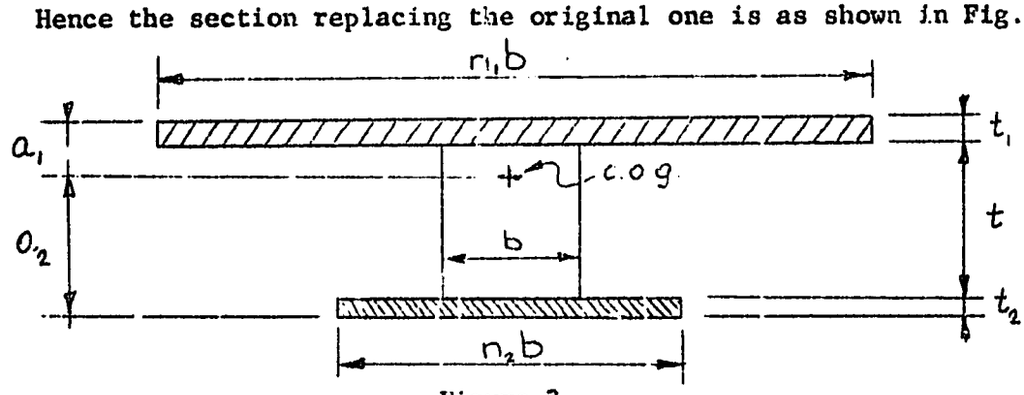


Figure 3

Having transformed the section into one which has the same modulus of elasticity throughout, one may express the distance of the centroid of the section from the top as

$$a_1 = \frac{E_1 t_1^2 + E_2(2t_1t_2 + 2t_2t + t_2^2) + E(2tt_1 + t^2)}{2(E_1t_1 + Et + E_2t_2)} \tag{3}$$

he section in Fig. 3 may be called the "equivalent core" section and the method shown above is very frequently used in structures of dissimilar materials, for example, reinforced concrete, where the reinforcing may be transformed into "equivalent concrete" areas in the elastic investigation.

The Moment of Inertia of the "equivalent core" section (Fig. 3) is expressed as follows:

$$I = b\left[n_1 t_1\left(a_1 - \frac{t_1}{2}\right)^2 + n_2 t_2\left(a_2 - \frac{t_2}{2}\right)^2 + \frac{t^3}{12} + t\left(a_1 - t_1 - \frac{t}{2}\right)^2\right] \quad (4)$$

and the stiffness factor, which is represented by the term EI, and on which the deflection of the loaded panel depends, as follows:

$$EI = b\left[E_1 t_1\left(a_1 - \frac{t_1}{2}\right)^2 + E_2 t_2\left(a_2 - \frac{t_2}{2}\right)^2 + \frac{E t^3}{12} + E t\left(a_1 - t_1 - \frac{t}{2}\right)^2\right] \quad (5)$$

From here on the analysis is restricted to a simpler case, where the skins are of the same material and of the same thickness, thus $t_1 = t_2$ and $E_1 = E_2$. When the skins are of different materials or of different thicknesses, the investigation can be carried out numerically without much difficulty by following the method outlined below:

Thus if $t_1 = t_2$ and $E_1 = E_2$, then

$$a_1 = a_2 = t_1 + \frac{t}{2} \quad (6)$$

and (4) and (5) become

$$I = \frac{b}{12}\left[t^3 + 6 n_1 t_1 (t + t_1)^2\right] \quad (4a)$$

$$EI = \frac{b}{12}\left[E t^3 + 6 E_1 t_1 (t + t_1)^2\right] \quad (5a)$$

respectively.

We now introduce into the investigation the relationship of the core-thickness versus skin-thickness

$$u = \frac{t}{t_1} \tag{7}$$

Hence (4a) can then be written as

$$I = \frac{bt_1^3}{12}\left[u^3 + 6n_1(u+1)^2\right] \tag{8}$$

A. Economy of Stiffness

With equation (8) we may start our investigation of the relative economy of sections. If, for example, we are interested in knowing what u value (what relationship of core-thickness versus skin-thickness) will give us the largest stiffness for the same price per square foot, we proceed as follows:

Since it can be seen in (4a) and (5a) that the Stiffness Factor is different from the Moment of Inertia only by a constant, it is adequate to restrict ourselves to the investigation of the Moment of Inertia and anything established for it will automatically be true for the Stiffness Factor as well.

Let us designate the price of the skin per unit volume as $p_1$ and the price of the core per unit volume as p. Then the price of a section per unit length can be written as

$$\text{Price} = 2bt_1p_1 + btp \tag{9}$$

We now introduce the relationship of core-price per unit volume versus skin-price per unit volume as

$$r = \frac{p}{p_1} \tag{10}$$

Introducing (10) into (9) we obtain

$$\text{Price} = p_1 b\,(2t_1 + rt) \tag{11}$$

and

$$\frac{\text{Price}}{p_1 b} = 2t_1 + rt \tag{12}$$

Careful inspection of (12) shows that if we investigate panels of the same materials and cost, the left side of (12) is constant and will be designated as C.

Hence

$$2t_1 + rt = c \tag{13}$$

Combining (7) with (13) we obtain

$$t_1 = \frac{c}{2 + ur} \tag{14}$$

and

$$t_1^3 = \frac{c^3}{(2 + ur)^3} \tag{15}$$

With the help of (15), Equation (8) can be written as follows:

$$I = \frac{bc^3}{12}\left[\frac{u^3 + 6n_1(u+1)^2}{(2+ur)^3}\right] \tag{16}$$

One can see from this equation that we have succeeded in expressing the Moment of Inertia with the dimensionless u as the only variable in the equation. The next step is to find the specific value of u to make I maximum. We shall obtain the derivative of I with respect to u and equate it with zero.

$$\frac{dI}{du} = \frac{bc^3}{12}\left\{\frac{[3u^2 + 12n_1(u+1)](2+ur)^3 - 3(2+ur)^2 r[u^3 + 6n_1(u+1)^2]}{(2+ur)^6}\right\} = 0 \tag{17}$$

After the necessary simplifications we obtain

$$u^2\left(\frac{1}{n_1} - r\right) + u(4 - 4r) + (4 - 3r) = 0 \tag{18}$$

Equation (18) is a simple equation of the second order and the solution does not offer any difficulties. Hence

$$u = \frac{2(1-r) \pm \sqrt{(2-r)^2 - \frac{1}{n_1}(4-3r)}}{r - \frac{1}{n_1}} \tag{19}$$

or separating the maximums and minimums

$$\boxed{u = \frac{2(1-r) + \sqrt{(2-r)^2 - \frac{1}{n_1}(4-3r)}}{r - \frac{1}{n_1}}} \tag{20}$$

<u>Example 1.</u>

Let us investigate an imaginary sandwich panel built with a 4 PCF urethane foam, and rigid vinyl skins. Assume the following figures:

$n_1 = E_1 / E = 450{,}000/1000 = 450$

$r = p / p_1 = 1.70/17.00 = .10$

then:

$$u = \frac{2 \times (.900) + \sqrt{1.900^2 - \frac{4 - .300}{450}}}{.100 - \frac{1}{450}} = 37.8$$

Thus the maximum stiffness will be obtained for the same price if

$$\frac{t}{t_1} = 37.8$$

For example if $t = 3''$, $t_1$ should be approximately <u>.080"</u>

It will be interesting to point out that if $n_1$ is large, equation (20) can be greatly simplified. That is, when $n_1$ is larger, the second term under the square root and the second term in the denominator can be neglected and equation (20) reduces to the following simple expression:

$$\boxed{u = \frac{4}{r} - 3} \tag{20a}$$

Example 2.

If we assume the same data as under example 1, we obtain

$$u = \frac{4}{.100} - 3 = \underline{\underline{37}}$$

This is so close to the result obtained above, that the use of the accurate formula does not seem to be warranted.

## B. Economy of Simple Bending

Next we are going to investigate economy in bending, or in other words, the proper ratio of core-thickness versus skin-thickness, in order to obtain the maximum bending capacity for the same money spent per square foot.

The average stress in the center of the skin can be expressed with the help of equation (4a) as follows:

$$f_{SKIN} = \frac{M}{I}\left(\frac{t+t_1}{2}\right) n_1 \tag{21}$$

where M is the bending moment acting on the section, the other notations are as explained heretofore.

The maximum stress of the core is

$$f_{CORE} = \frac{f_{SKIN}}{n_1} \times \frac{\frac{t}{2}}{\frac{t}{2}+\frac{t_1}{2}} = \frac{f_{SKIN}}{n_1} \times \frac{t}{t+t_1} = \frac{Mt}{2I} \tag{22}$$

If we assume that the stress in the skin shall govern the design (this is the usual case because of the large compressibility of the core materials generally used), then the allowable moment on the section can be expressed from equation (21) as

$$M = \frac{2I f_{SKIN}}{n_1(t+t_1)} \tag{23}$$

It can be seen from (23) that the allowable moment M depends on the $\frac{2I}{t + t_1}$ term, which is called the section modulus for sandwich panels and will be designated with S.

From equation (4a)

$$S = \frac{2I}{t+t_1} = \frac{b}{6(t+t_1)}\left[t^3 + 6n_1 t_1 (t+t_1)^2\right] =$$

$$\frac{b}{6}\left[t^2 + (6n_1 - 1)tt_1 + (6n_1 + 1)t_1^2 - \frac{t_1^3}{t+t_1}\right] \tag{24}$$

Neglecting the last term in the parentheses (it is very small in typical cases), we obtain

$$S = \frac{b}{6}\left[t^2 + (6n_1 - 1)tt_1 + (6n_1 + 1)t_1^2\right] \tag{24a}$$

We shall introduce now the relationship expressed in (7)

$$S = \frac{bt_1^2}{6}\left[u^2 + (6n_1 - 1)u + (6n_1 + 1)\right] \tag{25}$$

From equation (14)

$$t_1^2 = \frac{c^2}{(2 + ur)^2} \tag{26}$$

Introducing this into equation (25) we obtain an expression for S with the only variable being the dimensionless u. Thus

$$S = \frac{bc^2}{6}\left[\frac{u^2 + (6n_1 - 1)u + (6n_1 + 1)}{(2 + ur)^2}\right] \tag{27}$$

To find the specific value of u which makes S maximum, we have to obtain the derivative of S with respect to u and equate it with zero. Thus:

$$\frac{dS}{du} = \frac{Dc^2}{6}\left\{\frac{[2u+(6n_1-1)](2+ur)^2 - [u^2+(6n_1-1)u+(6n_1+1)]2r(2+ur)}{(2+ur)^4}\right\} = 0$$

After the necessary simplifications we obtain the following expression for u.

$$\boxed{u = \frac{12n_1(1-r) - 2(1+r)}{6n_1 r - (4+r)}} \tag{29}$$

<u>Example 3.</u>

If again we use the same data for $n_1$ and r as in Example 1, we find that the best thickness relationship of the core versus skin for these given core and skin materials is

$$u = \frac{12 \times 450 \times (.900) - 2 \times 1.100}{6 \times 450 \times (.100) - 4.100} = 18.3 = \frac{t}{t_1}$$

For example, if t = 3", $t_1$ should be approximately .164".

Equation (29) can be greatly simplified if $n_1$ is very large.

$$\lim_{n_1 \to \infty} u = \frac{12(1-r)}{6r} \tag{29a}$$

$$\boxed{u = \frac{2}{r} - 2} \tag{29b}$$

If we try to use this formula in place of (29) in example 3 we obtain

$$u = \frac{2}{.100} - 2 = \underline{\underline{18.0}}$$

Which is very close to the result obtained above.

## Observations

It is rather interesting to note that the best economical relationships are greatly different for the two cases; namely stiffness and bending capacity. This points out the necessity of clarification of goals before the design is undertaken.

A third problem, the simple edge compression of sandwich panels does not represent a special case in any economic investigation, since the critical force will depend on the EI transformed stiffness factor for which equation (20) or (20a) may be used.

The investigation becomes more complex when one tries to find the best thickness-relationship for deflection-control. In cases of core materials with low shear moduli, the effect of the deflections due to shear deformations may not be properly neglected. However, because the influence of these shear deformations (in percentages) depend upon the span length of the panel, it is recommended that the necessary study be made numerically for each case as required.

The method presented above should serve as a guide for anyone who may wish to undertake the design of a sandwich panel and wishes to establish some rational relationship between skin and core. The author is aware of the fact, however, that the theoretical values thus obtained may not be the best for production purposes. Other factors like local buckling of skin may also influence the proper design, thus careful and proper engineering judgment is recommended with the use of the above formulas.