NATIONAL BUREAU OF STANDARDS REPORT

9589

Full-Scale Climatic Exposure Building Facility

by

Frank J. Powell
Environmental Engineering Section
Building Research Division
Institute for Applied Technology

Interim Report
to

Office of the Chief of Engineers
Naval Facilities Engineering Command
Department of the Air Force
Washington, D. C.

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

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[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D. C., 20234.

[2] Located at Boulder, Colorado, 80302.

[3] Located at 5285 Port Royal Road, Springfield, Virginia 22151.

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NBS PROJECT		NBS REPORT
42103-40-4212532	August 2, 1967	9589

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Table of Contents

Summary

This interim report gives the present status of the plans to conduct engineering experiments on a full-scale building exposed to natural weather conditions. Covered are the background that led to this planning effort, the needs for building research of this type and the objectives for the enterprise as a whole. The objectives and designs of each of the twelve major experiments to be incorporated into the building are given. Construction and operational requirements are set forth to provide guidance for detailed architectural and engineering design and specification necessary for a firm estimate of construction and operational costs.

In summary, it is proposed to plan, design, and erect a full-scale climatic-exposure building facility on the NBS grounds at Gaithersburg, consisting of a two story high building about 50 x 100 feet in plan, special in that several of its parts or sub-systems are to be themselves the prime subject of building research investigations involving their performance under natural climatic exposure conditions not duplicable in laboratory testing. Twelve or more separate, highly interrelated engineering investigations are proposed, covering a period of about 5 years, involving weather, roofings, insulated roof constructions, walls and partitions, flooring, building moisture content, air conditioning loads and systems, and acoustic measurements. A relatively new construction technique is proposed that involves winter-time erection of the building beneath a continuously air-pressurized plastic hemi-spherically shaped balloon with measurement of the environment between the balloon and building under construction and collection and analysis of scheduling times and costs. To achieve economy and avoid redundancy in recording data and evaluating results, a central automatic instrumentation system feeding into the NBS Computer Facility is proposed. In all investigations, the opportunity

to acquire well-characterized long-term performance data on the building fabric and interior environment in response to actual outdoor weather exposures is of major importance and of much technical interest to the government, industry and professional architects and engineers. Considerable savings in operating cost are expected by use of a central data recording system and the NBS Computer Facility, as compared with the cost of data acquisition and reduction by each of the twelve investigations separately. With the data acquistion system proposed, there will be opportunity of a pioneering kind to develop statistically-meaningful data on conditions to which buildings and materials are subjected in use, and on their response.

For some of the investigations, estimates can be made as to prospective benefits. Investigations on roofings, and on self-drying insulated roofs, can each be seen to have potential savings possibilities on the order of several millions of dollars per year to the government alone, simply by increasing service-life. Major benefits not immediately translatable in dollars include developing criteria, tests, and information suitable for defining and improving the performance of a building and its components. Performance findings should be immediately applicable for use in actual buildings without major questions arising of the sort usually encountered when findings developed in laboratory tests must be extrapolated to cover actual use applications.

The estimated total cost for an enterprise of this magnitude spread over possibl 7.5 years is on the order of 1.8 million dollars including planning, design, erection of the facility, conducting at least twelve major investigations, and analyzing and publishing results.

The above estimate in terms of the cost of each investigation averages to approximately $20,000 per year or about 4/5 of a man-year effort; which is very reasonable for conducting major experimental research.

There is a long history of use of climatic exposures to develop data on durability or performance of building exterior materials and sub-systems among many countries. These have been achieved by exposure to climate of samples of materials, wallettes, panels or cubicles of various kinds, often with controlled heat transmission. Heating load measurements have been made for both unoccupied and occupied houses of various types. The aim and impact of the proposed facility is not to replace any or all of such useful measurements, but to provide and advance knowledge as to the inter-relatedness and performance of the sub-systems of a building, to develop improved weather-response data, and methods of analysis and criteria of performance in-situ and under the transient temperature conditions resulting from climatic changes.

Full-Scale Climatic Exposure Building Facility

by

Frank J. Powell

1. INTRODUCTION

This report gives the present status of the plans to conduct engineering experiments on a full-scale building exposed to natural weather conditions.

a. Background

The idea for this facility grew out of a meeting between Tri-Services and NBS representatives held in September of 1963. The purpose of the meeting was to discuss NBS Report 8052, Proposed Specification of Requirements for Insulations and Self-Drying Flat-Roof Constructions at Normal Occupancy. The proposed specification was based on a long-term laboratory study of insulated flat-roofs conducted at NBS and jointly sponsored by the Tri-Services and NBS. It was felt that full-scale trials, on an actual building, under actual weather conditions, of the self-drying and thermal insulating performance of several insulated flat-roof constructions, for comparison with findings developed in laboratory tests of small 2-ft square specimens subjected to simulated weather conditions, would be necessary before the Tri-Services could implement completely the proposed specification on a broad scale.

Accordingly, a proposal to Tri-Services for field evaluation of insulated flat-roof constructions was prepared for Fiscal Year 1965. The proposal was not accepted; instead, this project was initiated to plan a facility and experiments that would include the several long-standing interests of all Sections in the Building Research Division and those of the Tri-Services that require full-scale tests under natural weather exposure conditions. The planning effort has progressed to date at a part-time manpower pace because of low funding levels. However, it is now at a point that allows preparation of this interim report. Budget requests have been submitted by NBS to acquire funding for continued planning, preparation of blueprints, specifications, and cost estimates by an Architectural-Engineering firm, and funding for construction and operation of the facility.

b. Needs and Justifications

The needs for building research of this type are legion. As one example, moisture in one form or another influences the performance of a building and its elements and markedly affects thermal resistance, structural strength, resistance to fire, resistance to weather etc. In building research it is often not possible, by means of small-scale laboratory measurements, to determine adequately the service performance of the several sub-systems in buildings which, in practice, are full-scale, highly interrelated, and are exposed to a variable and rapidly changing exterior environment. Costs and time required are likely to be prohibitive for a single manufacturer or association to determine long-term performance of several sub-systems in a full-scale building. Of necessity, a large percentage of the industrial research and development effort is spent on product development. Thus, there is a national need for information on the in-situ performance of building systems that will not be satisfied by the building industry alone. This work is a public service because it serves Government, Industry and the Professions.

It is felt that a substantial portion of the billions of dollars expended annually for new construction and the upkeep and improvement of buildings can be saved by the government and public alike from performance information that will permit improved design and operating characteristics of buildings.

c. Objectives

The broad objectives of this enterprise are to provide a means for determining, under controlled conditions, the long-term performance of full-scale elements, and environmental aspects of a building under conditions duplicating those for a building exposed to natural weather conditions, including interactions between components and elements typical in a building. Specific objectives for each of the proposed engineering experiments are given below.

2. PRESENT STATUS OF PLANNING

In order to initiate planning, several basic assumptions were made as follows:

- an existing building or a building that was designed and about to be constructed could not be used because firm control over the design, construction, and specification and testing of materials would be immediately lost.
- the experimental structure must be full-scale and exposed to natural weather conditions. For economy, initially, only one geographic location would be considered although as many as five covering wet, dry, hot, cold and average locations in the United States are desirable.
- real clock time must be used in the conduct of all experiments. Acceleration of time as is expedient in laboratory work would not be considered.

-all measurements would be made in-situ under field conditions. Adjunct calibration and testing work would be done in laboratories.

-that the most probable and economic way to implement this work would be to place the structure on the grounds of the NBS-Gaithersburg facility nearby the laboratories of the Building Research Division thereby eliminating land acquisition costs, personnel travel costs and difficulties arising from inconveniently located back-up laboratory facilities.

-the structure would be designed and constructed to accommodate the engineering experiments to be incorporated in and around the building fabric rather than to design and construct a building on the basis of occupancy requirements. The experiments would be carried out on an unoccupied building and continued, if practicable, while occupied.

The broad concept of a fixed controlled indoor environment against which the performance of the building fabric would be measured in response to changing natural out-door weather conditions, would be the starting point common to all engineering investigations and their relationships to each other.

The present status of the design for each of the 12 engineering investigations follows. Each of the engineering investigations is considered to be of normal project level effort in size and difficulty.

a. Structural Engineering Experiments
R. G. Mathey, In-Charge
Structural Engineering Section, 421.01

The objectives of the structural engineering experiments are to investigate the time-depedent structural behavior in-situ of a precast, prestressed, steel-reinforced structural frame and foundation system that contains several types of joints and connections and to study the correlation of weather with phenomena involving cracking, creep, deflections, building settlement, loss of prestress, etc. The behavior of interfaces of foundation to floor and wall, walls to floors, walls to roof, including possible correlation with out-door weather, is of particular interest.

Many of the designs for structural engineering systems are based on theoretical considerations verified by laboratory tests. Design problems that cannot be readily handled theoretically are usually solved by empiric means. A large body of experience is available but little information is available concerning the actual in-situ performance of structural systems that in practice are dynamic. There is a need to compare performance as predicted at the time of design with the actual performance. Such comparisons become especially important with the trend toward industrialization of building construction and larger scale prefabrication of major building elements.

Masonry is one of the most widely used types of building construction for both residential and industrial buildings. Much has been done to control its cracking in the design stage but improvement is still needed. The development of design criteria based on in-situ performance for better control of cracking in masonry is urgent. In-situ observation of the drying shrinkage of masonry units that cause length changes and unsightly cracking is needed under conditions of full-scale, three-dimensional, climatic building exposure.

The design of the structural experiments consists of two types of foundation and footing construction. (See Figure 1) The first is of conventional monolithic concrete and/or concrete block placed on the site; the second is a prefabricated foundation system that is joined only on site. The footings will support a number of precast columns of two story height. Precast beams will be used to join columns at mid-height and top. The roof beams are to be prestressed and of a span of 50 feet. A spacing of 20 feet between main structural columns and roof beams is suggested. No special structural requirements are needed for wall cladding, floors, or roofing, except that the joining techniques should be such that different types of joints, connections, and movements can be studied. If practicable claddings should be capable of being individually removed at will. Comparison of selected areas designed to show masonry cracking and those designed to prevent cracking are desired. Measurements of the settlement of the structure, loss of prestress in roof beams, creep, deflections, and performance of joints and connections, are planned.

The quantities to be measured include expansion and contraction movements, deflection movements, loads on roof, walls, columns, foundations and footings, wind forces and pressures on the exterior faces of the building, temperature, relative humidity of air spaces, moisture content of materials and a complete outdoor weather history. The methods of measurement for these quantities are developed and available. Suitable transducers are available by purchase and will not need to be developed in the laboratory. A final firm count of transducers by type and number must await preparation of design drawings. Data reduction can be handled by computer although supplementary visual and photographic data will be needed for complete analysis. Close supervision of the fabrication of the structural elements will be required and considerable laboratory testing of materials used in construction may be necessary to determine physical properties of the materials used.

b. Roofing Engineering Experiments
W. C. Cullen, In-Charge
Materials and Composites Section, 421.04

The objectives of the roofing engineering experiments are to investigate the durability, deterioration and movement behavior of roofing materials by exposing several full scale designs and arrangements of built-up roofings and roof coverings to natural weather. Also, included is a study of the interaction and interdependenc between components of a flat roof system and to relate available laboratory data to performance in service.

In the past we have determined adequately some of the fundamental properties of materials in the laboratory. However, we have had to rely upon reports from the field or from actual observations of structures in service to relate laboratory data to field performance. We have learned from experience that this is a costly and frequently unreliable means to obtain accurate data and an accurate history of actual field performance of roofing. The performance of the roof system cannot be properly predicted or evaluated solely on the basis of the chemical and physical properties of the individual materials comprising the components of the total system. The interdependence and interaction between and among all materials and components must be taken into account. The roof system may be defined as the covering on the top of the structure including the roofing, insulation, vapor barrier and roof deck. These components function as follows: roofing, the weatherproof covering; insulation, the thermal control element; vapor barrier, the moisture control element; and the roof deck, the structural platform. Premature failures of built-up roof systems, of which about 20 million squares (100 ft^2 = 1 squ were applied in 1966, have been of great concern to architects, engineers, roofing manufacturers, and contractors, and the owners. Field experience has shown movement to be a primary cause of the costly roof failures which have plagued the industry.

In this area much fundamental information is needed to understand the cause and effect of the movements. In some cases, structural movements in the deck are suspect while in others the movement between or within the thermal control element or movements of the membrane itself are listed as contributing factors in many serious failures. A number of factors can cause movement in each or all components as thermal, moisture, structural (creep), etc. The problem becomes extremely complex because of the many varieties of materials available and the almost infinite number of combinations possible. The performance data obtained and design criteria developed would serve as a useful guide in the selection of methods and materials in the design and construction of roof systems which will give continued and satisfactory performance under given exposure conditions.

The design of the roofing engineering experiments consists of five primary areas of the flat roof of the full-scale climatic exposure building facility. The minimum length of run of built-up roofing is 50 feet. Expansion joints will be used to separate areas. The performance of joints and all areas of flashing will be studied. (See Figure 2)

The quantities to be measured in all areas include temperature, linear displacement, stress-strain, pressure, moisture content, and a complete weather history with an indication of whether the outdoor roofing surface is wet or dry. The methods of measurement for these quantities are developed and available. A final firm count of transducers as to type and number must await preparation of design drawings. Data reduction can be handled by computer but supplementary photo-elastic analysis and considerable sampling of materials for laboratory tests will be required.

c. Self-Drying Roof Experiments

F. J. Powell, In-Charge
Environmental Engineering Section, 421.03

The objectives of the self-drying roof experiments are to obtain in-situ performance data of the heat transfer, moisture content, and self-drying properties of several full-scale designs of insulated flat roof constructions and of other types of constructions known not to be self-drying if wetted. The in-situ performance data will be compared with laboratory data previously obtained under simulated temperature conditions on 2-foot square specimens, to demonstrate the feasibility or non-applicability of proposed performance requirements and criteria.

Buildings with flat roof constructions are very common in Government and private use. Roofing applied to flat roofs in 1966 in the U.S.A. aggregated on the order of 2.0 billion square feet; a large, and probably increasing, fraction of the roofs incorporated thermal insulation to improve comfort within and to foster economy in indoor temperature control. Typically, insulated roof constructions perform these functions well when, and so long as, the insulation is substantially dry. Also typically, the construction fails seriously to perform them when the insulation is damp or wetted by water, a condition that can occur as a result of wetting during construction, or of rain penetration through accidental leaks in a new roof, or through leaks almost inevitable as roofing deteriorates.

Conventional designs of insulated flat roofs usually have a vapor barrier membrane under the insulation to prevent entry of water vapor from within the building. In practice, however, wetted insulation confined between the roofing and vapor barrier cannot dry, and restoration of insulating value requires replacement of both insulation and roofing, at a minimal cost of $30 per 100 square feet. Experimental laboratory work conducted here (see NBS Report Nos. 6283, 7347, 7817 and 8052) on small specimens has shown that some insulated roof constructions which do not incorporate a vapor barrier, but instead employ a suitably balanced compromise between vapor permeance and water absorbing capacity, exhibit a substantial ability to dry out, if wetted, by expelling vapor downward when heated by the sun in moderate or warm weather, and thus rapidly recover insulating effect. Thus, a self-drying roof construction offers great promise as a practical solution to the problem of insulated roofs wetted by rain leaks. Its economic value is manifestly great.

Since it is unconventional (the deliberate omission of a vapor barrier under the insulation runs counter to customary ideas) it is understandable that evidence of the merit of self-drying constructions, to be most convincing to practical builders, must be based on tests of full-scale, or adequately large, installations exposed to actual weather conditions on an actual building. Our present data rests on tests of 2-ft. square specimens subjected to laboratory-simulated exposure conditions. There is therefore, a very practical need and reason for a full-scale, roof-in-service, demonstration of the performance of at least some self-drying roof constructions.

It is proposed that the postulated building have its roof consist of twenty or more types of insulated roof designs, each of 100 square feet area or more, and each instrumented with heat flow devices, thermocouples and recording systems, to enable continuous observation of insulating performance, and drying performance when wetted in simulation of a roof leak. A few designs would be of the conventional kind with a vapor barrier, for comparison under the same conditions with the others of selected self-drying design. The interior conditions of the building would be managed to simulate normal air-conditioned occupancy; the exterior would be subject to local weather conditions. To analyse the recorded data, obtained under the transient conditions of weather exposure, use would be made of processing by digital computer. Two chief objectives are sought: an in-service comparison of performance of self-drying versus conventional insulated roof designs and an in-service evaluation of the limiting values of certain criteria for design of self-drying roofs developed in the small-scale laboratory investigations (NBS Report No. 8052) which, if confirmed, provide a basis for performance specifications for such constructions. Some laboratory determinations of thermal and moisture properties of component materials will be necessary. The minimum time for observations is estimated to be at least two winters and three summers with additional time for preparation and instrumentation, and for summarization of results.

The design of the experiments consists of eighteen constructions identifiable by numbers and arrangement in Figure 3. Construction spaces 19 and 20 are reserved for new designs available subsequent to reporting of the laboratory data. The constructions are:

No. 1. Deck - 4 inch thick, monolithic, steel reinforced concrete
- No Vapor Barrier
- Insulation - 6 inch thick perlite aggregate insulating concrete, 30-40 pcf oven-dried
- Built-Up Roll Roofing

No. 2. Deck - Concrete same as No. 1.

- Asphalt Vapor Barrier
- Insulation - 1-1/2 inches thick glass fiber insulation board.
- Built-Up Roll Roofing

No. 3. Deck - 3 inches thick pre-cast perlite aggregate plank; minimum of 3 feet wide, steel mesh reinforced; concrete 30-40 pcf oven-dried.

- No Vapor Barrier
- Insulation - 1-1/2 inches thick glass fiber board
- Built-Up Roll Roofing

No. 4. Deck - 1-1/2 inches thick glass fiber formboard between steel bulb-tees

- No Vapor Barrier
- 2 inches thick poured gypsum concrete
- Built-Up Roll Roofing

No. 5. Deck - Kraft-paper steel-mesh

- No Vapor Barrier
- Insulation - 6 inches thick perlite aggregate concrete, 30-40 pcf oven-dried density
- Built-Up Roll Roofing

No. 6. Deck - 2 inches thick wood-fiber formboard insulation between steel bulb-tees

- Built-Up Roll Roofing

No. 7. Deck - 3 inches thick pre-cast perlite aggregate plank; minimum of 3 feet wide, steel mesh reinforced; concrete 30-40 pcf oven-dried

- No Vapor Barrier
- Insulation - 1-1/2 inches thick wood-fiber board
- Built-Up Roll Roofing

No. 8. Deck - 1-1/2 inches thick wood-fiber formboard between steel bulb-tees

- No Vapor Barrier
- 2 inches thick poured gypsum concrete
- Built-Up Roll Roofing

No. 9. Deck - 1-1/2 inches thick glass fiber formboard between steel bulb-tees

- No Vapor Barrier
- 3 inches thick perlite aggregate concrete without reinforcing, 30-40 pcf oven-dried.
- Built-Up Roll Roofing

No.10. Deck - 2 inches thick pre-cast gypsum concrete plank; minimum of 3 feet wide and steel mesh reinforced.

- No Vapor Barrier
- Insulation - 1-1/2 inches thick glass fiber board
- Built-Up Roll Roofing

No.11. Deck - 3 inches thick coarse wood fiber-cementious binder board insulations on a steel frame

- Built-Up Roll Roofing

No.12. Deck - 3 inches thick coarse wood fiber-cementious binder board insulation on a steel frame

- No Vapor Barrier
- 2 inches thick gypsum concrete
- Built-Up Roll Roofing

No.13. Deck - 1-1/2 inches thick wood-fiber insulation board formboard

- No Vapor Barrier
- 3 inches thick perlite aggregate concrete, no reinforcing, 30-40 pcf oven-dried
- Built-Up Roll Roofing

No.14. Deck - Steel deck

- No Vapor Barrier
- 3 inches thick perlite aggregate concrete, no reinforcing, 30-40 pcf oven-dried
- Built-Up Roll Roofing

No.15. Deck - Steel deck

- No Vapor Barrier
- Insulation - 1-1/2 inches thick glass fiber board
- Built-Up Roll Roofing

No.16. Deck - 3 inches thick pre-cast perlite aggregate concrete, 30-40 pcf oven-dried, steel reinforced; minimum 3 feet wide planks

- No Vapor Barrier
- Insulation - 1 inch thick expanded polyurethane plastic
- Built-Up Roll Roofing

No.17. Deck - 2 inches thick gypsum concrete plank, steel mesh reinforced, minimum 3 feet wide
- No Vapor Barrier
- Insulation - 1-1/2 inches thick wood-fiber board
- Built-Up Roll Roofing

No.18. Deck - 2 inches thick gypsum concrete plank, steel mesh reinforced, minimum 3 feet wide
- No Vapor Barrier
- Insulation - 1 inch thick expanded polyurethane plastic
- Built-Up Roll Roofing

No.19. Reserved for new insulated roof systems.

No.20. Reserved for new insulated roof systems.

The periphery of each of the above constructions must be water-tight and incorporate expansion joints. The planned procedure is to measure the performance of each construction as installed for the four seasons of the first year and later deliberately add water to the insulations in simulation of a roofing leak and again measure the performance over the four seasons of the year. The constructions will require a special structural support system suitable to accommodate for the different thicknesses of constructions. The quantities to be measured several times daily, probably hourly, are heat flow, temperature, indoor temperature and relative humidity or dewpoint and outdoor weather. The methods for these measurements are developed. Additionally, a moisture content history is needed for each construction. Methods for continuous automatic measurement of moisture content are not developed. Selected methods will be used to develop in-situ means. A procedure of sampling the constructions over periods of time and drying the samples in an oven to determine the moisture content history is planned. Supplementary photographic and visual data will be obtained. Close supervision of the construction will be required and considerable testing to determine as-installed physical properties will be needed.

d. Flooring Engineering Experiments
T. Boone, In-Charge
Materials and Composites Section, 421.04

The objectives of the flooring engineering experiments are to determine what treatments are effective and necessary for controlling the effects of sub-floor moisture conditions when slab-on-ground construction is used and to compare the performances of various types of floor coverings. In addition, the rate of moisture transmission of various types of concrete slab constructions and the rate of heat transmission through the slabs of various temperature and moisture conditions will be investigated.

A continuing trend both in this country and abroad is to build basementless buildings. There is a need for more complete information on concrete slab-on-ground constructions with respect to heat losses, and floor coverings, with various sub-floor moisture conditions. Satisfactory answers to questions on the construction of gravel beds, the use of vapor barriers, the type of concrete, and the performances of various floor coverings and adhesives are needed. Data obtained experimentally under controlled service conditions are necessary to provide a sound basis for decisions on economical slab-on-ground constructions.

The design of the flooring engineering experiments consists of several concrete slabs on earth or gravel beds with facilities for controlling the slab surface-temperature and temperatures and water levels in the soil under the slabs. Water levels will be adjusted to simulate drained and flooded soil conditions. Means for measuring heat flow through the slabs and procedures for evaluating the performances of various kinds of floor coverings and adhesives would be incorporated. (A sketch of a proposed layout is given in Figure 4.) Suggested slab constructions, each of about 100 square feet in area and 4 inches in thickness, consist of the following: (1) concrete slab over six inches of fine (bank-run) gravel, with paper separator between gravel and slab; (2) same as (1), but with coarse (3/4 inch plus) gravel; (3) same as (1) with about six mil polyethylene membrane vapor barrier in place of paper separator; (4) slab on earth with no paper separator; (5) same as (4), but with six mil polyethylene membrane vapor barrier on earth under slab; (6) same as (4), but using a concrete, made water repellent by an admixture. The above slab construction arrangement will enable direct comparisons between designs over fine (1) and over coarse gravel (2), and between these and a floor directly on earth (4). Further, the effects of a vapor barrier under slabs over gravel (3) and over earth (5) can be compared. Finally, a water repellent slab (6) on earth is included for additional information. Comparisons will be based on findings as to both heat flow and the effects on the floor coverings.

The procedures planned include selection of a soil considered to be typical, and use of currently used design procedures, including an estimate of heat losses on the bases of currently available data for later comparison with in-situ performance. Electrical heating will be incorporated in the slabs to determine heat flow under conditions of flooded and drained soil, for a range of controlled slab and soil temperatures.

A study of floor coverings, adhesives, and methods of application and time of application will be made using square samples of materials about 27 inches or more on a side. Replications of some applications will be used to compare results among the different slab constructions.

The methods of measurement and instrumentation are largely developed. Quantities to be measured include heat and moisture flow rates, temperature moisture content by sampling and over-drying, plus a variety of flooring properties that will be measured on duplicate samples of materials in the laboratory. Supplementary visual and photographic data will be used.

e. Wall Engineering Experiments
T. K. Faison, In-Charge
Environmental Engineering Section, 421.03

The objectives of the wall engineering experiments are to measure simultaneou over a period of time the key performance characteristics of walls of several type each of full-scale dimension and exposed to natural weather conditions outdoors and to normal occupancy indoor environment, and to compare the in-situ performances with performances expected at the time of design.

Much attention has been given to the design and construction of the walls for buildings. One compelling reason is that the total cost of walls for buildings per square foot, including partition walls, is usually greater than costs for the roof or floors. Literally dozens of materials are available for incorporation into the design of a wall. Written specifications of requirements of strength, finish, etc., as determined by specified laboratory test procedures, are readily available for each material. Not so readily available, but much needed, are quantitative and definitive statements of the engineering performance required of the total wall system before a designer begins to select candidate materials. Some progress has been made in these regards and in the development of laboratory methods of test that simultaneously measure more than one property on specimen panels or segments of building walls. However, little information is available to the designer of the total in-situ performance of walls including those that had been subjected to extensive laboratory testing. The need for wall investigat is to determine in-situ, performance of all important engineering aspects that in practice occur simultaneously. For example, properties in regard to strength, water resistance, heat transfer, acoustical performance, wind-pressure resistance etc., may influence each other in important ways and need to be measured multaneously on a full-scale basis. Additionally, the field performance of each uantity can be compared with that obtained from individual tests of that quantity the laboratory.

The designs of the wall experiments consist of those structural aspects as ven under Structural Engineering Experiments, plus a series of heat, air, and oisture transfer studies, corrosion of wall ties in masonry constructions, observa-ons of several types of caulking and sealing materials, observations and compari-ons of the durability of exposed materials, resistance of wall surfaces and joints wind and rain, and acoustical performance. The quantities to be measured nclude expansion and contraction, deflection, loads on walls, wind and rain forces nd pressures, temperature, heat flow, relative humidity, moisture content, air nfiltration, and a complete outdoor weather history including solar radiation.

The designs of the walls must be such as to accommodate the multiplicity experiments to be incorporated and yet represent current design practice. rovisions should be made to include new design ideas. It is suggested that the ront of the building face east and its exterior cladding be of windowless brick asonry to harmonize with surrounding buildings. This masonry wall can be designed include a variety of masonry wall cross-sections including use of different ortars; those with and without air spaces; those whose cavities are filled with pouring ypes of insulations; the use or non-use of vapor barriers; board types of insulation aced near the exterior cladding, at mid-wall, and near the indoor finish; various ypes and thickness of insulation; several indoor finishing plasters, plastics, other indoor finishing materials; a variety of metals and shapes used as wall es for study of corrosion effects; and several types of caulking sealant materials. uring construction the wall would be fitted, by NBS scientists, with a number of ransducers that would be used to record the quantities as given above such as movement, temperature, heat flow, etc.

It is suggested that the longest walls of the building be identical in construction and face north and south. These walls should be made of prefabricated units, some as wide as 20 feet, capable of being removed individually from the outdoor side after construction is completed. These walls should contain windows for a first and second story. Several wall cross-sections should be used in a fashion similar to that of the east wall. For direct comparison it is felt that exterior cladding of the north and south walls should be of a single material such as 1 - 2 inch thick concrete with an exposed aggregate face, or of a combination of curtain-walling and durable cladding split between the first and second story. It is suggested that the west wall be composed of a multitude of constructions, each a minimum of about 100 square feet in area, and include designs that would be used for residential construction such as wood, metal and plastic drop sidings in different colors, etc. North, south and west walls would be fully instrumented similar to that of the east wall.

Most of the methods of measurement have been developed except those for in-situ continuous measurement of moisture content and for air infiltration and exchange. Procedures for the latter are available that will probably be suitable for obtaining quantitative data but possibly not continuously.

From the wall experiments much by way of actual performance results can be expected. For example, by comparison only, one could deduce which methods of joining and fastening work best; the optimum location and resistance of thermal insulation; whether the indoor film thermal resistance can be used as an in-situ heat flow meter to determine the total thermal resistance of a wall without knowing its construction and without destroying any part of the wall other than measuring its surface temperature; the usefulness of vapor barriers; in-situ determination of the thermal diffusivity of a wall; major sources of air leakage and drafts; condensation effects; corrosion and short-term durability of materials; water proofing and closure performance of caulkings; heat gains and losses; illumination levels with and without indoor lighting on a year round basis; natural weather exposure for a variety of materials including concrete, metals, glass and plastics; acoustic performance on an unoccupied basis; and many other results that may be qualitative and based on photographs or other observations over a long period of time.

f. Heating-Cooling Load and Mechanical Systems Experiments
C. W. Phillips - T. Kusuda, In-Charge
Environmental Engineering Section, 421.03

The objectives of the heating-cooling load and mechanical systems experiments are to evaluate one or more existing methods used to estimate the heating and cooling loads of the climatic exposure building. The actual heating and cooling loads of the building will be measured and compared with those estimated before constructio A similar procedure will be followed in respect to the design and specification and in-situ measurement of the mechanical systems that respond to the actual hourly heating and cooling loads in order to maintain a prescribed controlled indoor environment.

Several methodologies for estimating heating and cooling loads and mechanical systems requirements are available in publications of the American Society for Heating, Refrigerating, and Air-Conditioning Engineers and others. Much engineering judgement is required in this design process and little if any valid data are available as to the in-situ performance of such systems after they have been installed in a building. Generally, when air conditioning systems fail to achieve objectives the failure can be classified as one of capacity of a heating or cooling plant, or proper selection of components, which depends upon the heating and cooling load estimate; one of distribution; one of control; or combinations of all three. The special building facility will uniquely provide an opportunity to evaluate presently used design principles and criteria. Existing occupied buildings cannot effectively be used for this purpose because of obvious reasons, such as interference with the intended use of the building, lack of a central instrumentation system, inability to make system modifications as needed, difficulty in using installed proprietary packaged items to provide information relating to principles rather than proprietary item performance, and limitations on ready access of professional personnel directly involved with the investigation.

Mechanical systems for producing and controlling the desired indoor environmental conditions are much affected by the outdoor weather. The non-steady character and extremes of weather may contribute heavily to failures of such systems particularly when they use copious quantities of outdoor air. Experience in large government housing projects has indicated a need for investigation of effects of weather variations for extended periods of time to determine the realistic performance of heating and cooling systems.

Detailed planning of the heating and cooling load and mechanical systems experiments cannot begin until firm definitions of building dimensions, volumes, and constructions of roof, walls, and floors are available. However, the major quantities to be measured can be given as, temperature, pressure, fluid flow, heat flow, time, electric power, voltage, current and frequency, linear displacement and speed, rotative speed, relative humidity, noise, vibration and a complete weather history. The performance of air-cleaning systems incorporated in the mechanical system can be measured. Provision can be made to observe new designs and ideas such as those that combine the heating, ventilating and lighting functions into one unit or process. Methods of measurement are developed and available for these experiments.

g. Moisture Content-Fire Research Experiments

D. Gross, In Charge

Fire Research Section, 421.02

The objectives of the moisture content-fire research experiments are to determine the moisture content history of all major structural elements of the building from the time of construction and to evaluate this information in regard to its general applicability to the intelligent estimation of a buildings' ability to withstand the effects of accidental fires (i.e., its fire endurance period).

The fire behavior of building materials and structures is significantly dependent on the moisture content when the specimen is subjected to test. In spite of this, there is only the most meager quantitative information available on the spatial distribution and seasonal variations in equilibrium moisture content of such materials in service over an extended period of time. A complete moisture history of a building is needed to evaluate the aging periods necessary to approach steady-state conditions as a function of material type, thickness, and location, and to correlate moisture content with mechanical (shrinkage, cracking, etc.), thermal and chemical performance. Also, badly needed is an in-service evaluation of suitable types of moisture-sensing elements and methods.

The design of the moisture content-fire research experiments consists of using small probe-type gages to measure relative humidity in selected structural elements, made from representative building materials, at depths of one, two, four and eight inches below the internally exposed surfaces, as a function of time after placement of the element in position as a part of the building. Such measurements may be used to estimate the approach to moisture content equilibrium as well as the presence and location of local moisture gradients and moisture migration during the drying process. However, such "equilibrium relative humidity" values cannot be considered as substitutes for direct moisture content measurements, primarily because the moisture content-relative humidity relationship for many construction materials is not adequately known. It will therefore be necessary to remove samples at several selected locations of the structure periodically and to determine moisture content and moisture distribution by direct drying and weighing. This will be done by using a diamond core drill of about 1 inch in diameter to remove cylindrical samples of appropriate lengths and filling the hole remaining with an appropriate material to closely match the parent material. The sample removed can be quickly crushed and placed in a small closed jar to reach moisture content equilibrium at a controlled temperature. After measurement of the final equilibrium relative humidity in the jar, the sample can be dried in an oven to determine its moisture content. Where moisture content distribution in an element is desired, the cored sample is divided into an appropriate number of smaller cylinders, each of which is handled separately.

For fire resistance purposes, such measurements are needed in all structural parts of the building that are greater than 2 inches in thickness. Tubes or similar holders for moisture gages should be installed during the casting process, particularly if the structural member is reinforced and pre-tensioned. The number of sensing elements and their locations cannot be stated until the design of the structured members is completed.

The data gathered in this experiment is needed and would be complementary to the evaluations primarily concerned with roofing, self-drying insulated roof decks, floors, walls, acoustics and probably all experiments being conducted on the building.

h. Acoustic Engineering Experiments
H. E. Robinson, In-Charge
Environmental Engineering Section, 421.03

The objectives of the acoustic engineering experiments are to measure the in-situ acoustic performance of the climatic building facility including measurements of structural vibration, e.g. from roof to basement; airborne and impact sound transmission through floors (from basement to 1st and 2nd stories); airborne sound transmission through wall constructions as a function of cracking, installation, etc.; and noise transmission and radiation of exterior walls (especially prefabricated metal panels) as a function of contraction, expansion, popping, sealing, etc., due to changes in weather conditions.

The problem of noise in buildings can be classified generally according to the sources of undesirable sounds; those generated outdoors and transmitted to the indoor environment and those generated indoors from building occupants and building services such as mechanical equipment. Often the problem of design for noise control is considered as two parts; one which treats the architectural and structural aspects of the design, and a second which treats separately the mechanical equipment aspects. In service, architectural, mechanical, and people aspects of the problem occur simultaneously. Little information regarding simultaneous interaction of these aspects is available. However, it is much needed to allow a systems analysis of the total noise environment of a building interior. It is proposed to instrument the climatic building facility to determine the interaction of outdoor and indoor sounds and the effect of the building fabric on this interaction. First-hand knowledge of the details of the building fabric and mechanical systems becomes a necessity for acoustical analysis.

Initially the building should be without occupants to eliminate the variable of noise generated by people. Later, perhaps, additional data for comparison can be gathered on the same building with occupants.

The design of the acoustic experiments consists of installing vibration pick-ups and microphones in strategic locations throughout the building and outdoors. Data concerning temperature, relative humidity, linear movement and weather will be needed but these will be available from other experimental investigations in the building. The precise numbers and locations of acoustic transducers cannot be stated until the size and details of the construction are finalized on architectural construction drawings. It is planned to incorporate an impact or foot-fall experiment at the threshold of buildings. Also, from time to time, known sound sources will be used outdoors and indoors to obtain comparative performance data. It is expected that all transducer signal-data will be recorded automatically and processed for analysis.

All instrumentation is currently obtainable commercially.

i. Weather Engineering Experiments
W. C. Cullen and J. C. Davis, In-Charge
Materials and Composites Section, 421.04 and
Environmental Engineering Section, 421.03

The objectives of the weather engineering experiments are to specify an instrumentation system and measure the micro-climate surrounding the building continuously 24 hours a day for a minimum period of 5 years.

Detailed definition of the weather surrounding the building is a key need in this project. The broad objective of determining the response of the building fabric to varying weather conditions against the fixed indoor environment requires a detailed knowledge of the weather in-situ. Information is available from the Weather Bureau-but this information applies, strictly, to the weather as measured at a given location in or near large cities (usually at local airports). It is expected that the information obtained can be utilized in other geographic locations whose weather history patterns are similar to those obtained in this project. As mentioned earlier, it would be desirable to conduct these same experiments at locations whose weather patterns are different from those of the Washington, D. C. area such as hot climates (Florida or Arizona) and cold climates (Minnesota or Maine), but the cost would probably be prohibitive.

The design of the weather experiments consists of using those weather measuring instruments and systems that are commissioned by the Weather Bureau. These are very well defined and specified (volumes of information are available) and instruments are obtainable by purchase. In addition, other instruments and measurement systems that are not formally commissioned will be used and some may require laboratory check or development. For example, a method or transducer that will monitor a surface to indicate and record what time periods the surface is wet, dry, or snow or ice-covered, is desired especially for roof areas. All recorded data will be computer processed and a daily weather history provided for use in the analysis and evaluation work of all other experiments in this project.

j. Instrumentation and Data-Handling
J. C. Davis, In-Charge
Environmental Engineering Section, 421.03

The objectives of the instrumentation and data-handling experiments are to investigate the suitability of the several commercially available instrumentation systems for use in a central data gathering and control function for the climatic building facility, to prepare specifications for the purchase of such equipment, to acquire the equipment and perform suitable operational tests in the laboratory before it is installed in the building, to operate the equipment during the service life of the project, and to supply computer processed data to all experiments in a form suitable for analysis and evaluation.

The need for a rapid automatic data gathering and processing system is technically as well as economically based. To satisfy the need for data that would indicate the instantaneous performance of the total building and its environments, each individual experiment must be read out rapidly and accurately. It is estimated that the instrumentation system should be capable of recording signals, both a.c. and d.c. types, from about 2000 transducers in as little as six minutes. Flexibility and versatility in operation are important to accommodate changes as they need to be made. Literally, millions of bits of information will be gathered over the five-year life-span of the project. To accommodate separation and reducti of these data into meaningful and understandable performance, computer processing is indispensable. To do this it is obviously more economical to operate a data gathering system that will accommodate perhaps a dozen major experiments as compared to each experiment operating its own individual data recording system.

Selection of the design of the instrumentation and data handling experiment consists of study of the state-of-the art of commercially available equipment for use in this project, including meetings with engineers from instrumentation compani and visits to field sites where various kinds of systems are in service. This phase of the experiment is essentially completed. Present thinking for the overall system considers favorably the use of a "real-time" or "on-line" computer. A real-time computer has the advantage of being able to make calibration corrections and corrections due to non-linearity to the information logged by the acquisition system, and to look up table values. It also serves as a control mechanism for the system. It can feed back signals that order priority, sort data into experimental categories, and allow signals to be used only when needed. One of the difficult choices involves sampling techniques. For any reasonably large experimental operation there will be many situations where signals will be sampled about once every second, but there will be others where the sampling rate is once every half hour or even once every day. Two alternatives are available from manufacturers. One suggests that the on-line computer does the scanning, that there be no electrical scanners in the system whose scanning rates, once set, faithfully log information at a preset rate for a large number of transducers. For this method soft-ware programming can instruct the computer to sample each transducer at a different rate from other transducers. The other alternative suggests that all transducers be scanned by electrical scanners at fast preset rates: one large block, for example, at once every second, and another large block at once every minute. Under this plan many of the unneeded signals must be discarded and there will be large redundancy, but it may, upon analysis, be found to be less expensive as compared with the costs of programming the computer. Preliminary studies for these alternatives are underway and the final choice necessarily must fit the budget available for instrumentation. A final number of transducers awaits detailed specification of number, type, and location, on design drawings of the building. A tentative sketch of an instrumentation plan is shown in Figure 5.

This sketch shows electrical scanners. It shows also with each scanner a block representing a conditioner. The conditioner will include such devices as an automatic reference junction for thermocouples being scanned, a constant-current device for supplying excitation voltages for transducers such as strain gages, and a zone-box which usually consists of an insulated metal block to keep connection in thermocouple circuits at constant temperature so that no extraneous voltage is generated. Conditioner costs can be large and a way needs to be devised for each conditioner to share a large number of transducer lines. The memory of the computer will store the data and periodically "dump" to magnetic tape, but the out-put of an on-line computer will not be in a final reduced and collated form. The data on the magnetic tape will be manually transported to the NBS computer center for reduction. Rental of the total acquisition system may offer economic advantages.

The next phase of the instrumentation experiment is to prepare specifications for the type of system selected. Much information for this phase is at hand but awaits implementation after policy and budget decisions are made. Proper preparation of specifications for a system will require considerable effort. Other phases of the data acquisition, laboratory checking, installation, operation, computer programming, and coordination of these efforts, are planned but can be implemented only as budgetary and man-power situations permit. Service contracts on instrumentation are mandatory.

At the present stage in planning firm costs are difficult to estimate. It is certain, though, that the soft-ware will cost at least as much as the hardware, and possibly more. Manufacturers indicate about $100,000 for hardware, not including transducers, and from $100 - 200 K for soft-ware.

k. In-Situ Methods of Measurement Experiments
F. J. Powell, In-Charge
Environmental Engineering Section, 421.03

The objectives of the in-situ methods of measurement experiments are to identify and develop techniques of measurement not presently available for in-situ use.

Presently available are many methods of measurement from NBS, ASTM, USASI, etc., that are primarily useful in the laboratory. Some of these techniques are suitable for field use while others need refinement. The need for measuring various quantities in the field under dynamic conditions is well known. For example, the determination of moisture content within concrete in the field requires insertion of a transducer into wet concrete before it sets during construction. Contact between liquid water and transducers often destroys the usefulness of the transducer or radically changes its calibration. Similarly, in heat flow much of the measurement is done under static conditions of constant temperatures but, in-situ, dynamic conditions prevail.

The plans for in-situ experiments are to utilize those methods of measurement known to be suitable for field use and at the same time incorporate into the experiments new and hopefully simpler, less costly, means for obtaining reasonably precise in-situ data. Several variables and methods have been mentioned in descriptions for all experiments in this project and as details develop others will become identifiable. A considerable amount of preliminary laboratory evaluation of a measurement idea or system may be required before it is actually installed in the building.

1. Inflatable Balloon Construction Technique Experiment

F. J. Powell, In-Charge
Environmental Engineering Section, 421.03

The objective of the inflatable balloon construction technique experiment is to utilize the technology of inflatable buildings as a demonstration for a construction technique for permanent buildings of relatively large areas.

One of the needs of this project is to avoid the effects of weather on the components of the building during its construction to assure that materials installed are in a condition as is normal in use, i.e. not excessively wetted or exposed to prolonged effects of freezing and thawing. Further, it is well-known that architects, engineers, contractors, and construction workers are hampered by winter-time weather conditions which ultimately increase the costs of buildings. If a construction technique were available that would be truely independent of the weather it may be possible to effect savings from more efficient scheduling and from the effects of down time and loss of momentum of construction crews. Further, a guarantee of year-round work for construction crews could become technically feasible. The military uses inflatable buildings for various purposes, such as assembly areas for helicopters, portable hospitals, etc. The technology is such that these buildings can be made to cover reasonably large areas and can be fitted with air-curtain doors or openings that would permit passage of trucks or materials. There are questions concerning the use of inflatable buildings for construction. These deal primarily with the safety of the environment between the plastic bubble and the building under construction since the construction process generates noxious gases, dust and dirt, noise, etc., from a variety of activities.

The design of this experiment is to erect an inflatable building of a size sufficient in volume to generously cover the permanent building to be constructed within-during a winter season. The environment within the bubble would be measured to determine its nature and it would be continuously monitored for safety. Records would be kept of construction time and cost for comparison with normal construction procedures, to determine if savings are possible. Upon completion of the construction of the permanent building, the inflatable building would be removed and measurements on the permanent building and its environments would begin. The planning for this experiment is in its early stages and cannot be implemented greatly until firm definition of the permanent building is obtained.

3. DESIGN AND CONSTRUCTION REQUIREMENTS

As given in each of the engineering experiments a number of firm minimum design and construction requirements can be listed as guidelines for the architectural-engineering designers of the building facility. Figure 6 shows a rendering that can be used as a point of departure for architectural and mechanical design.

a. Geographic Location - On the site of the National Bureau of Standards at Gaithersburg, Maryland.

b. Building Orientation - Building front facing due East with enough clear area around the building to prevent distortion of prevailing winds and to prevent sun shadows from adjacent buildings.

c. Building Shape and Size - Preferably rectangular with width dimension a minimum of 50 feet and height sufficient for two stories. See Figure 6. Length optional to satisfy experiments - 100 feet suggested.

d. Footings and Foundations - Some pre-cast and some cast-in-place concrete. See Figure 1.

e. Columns and Spandrels - Reinforced pre-cast concrete with a multiplicity of types of connections. Spaced 20 feet on centers. See Figure 1.

f. Roof Beams - Reinforced, pre-cast, pre-stressed, concrete, 50 feet long (width of building), spaced 20 feet on centers. See Figure 1.

g. Basement and Floors - Part of the floor will be slab-on-grade with the remainder as basement space suitable for housing mechanical equipment, and utilities. The floor between stories may be of several constructions to accommodate acoustic and other experiments. See Figure 1.

h. Walls - The longest walls will be pre-fabricated, some of 20 feet wide units, and shall contain windows. Units should be designed to enable removal from the structural frame. Cross-sections of these walls will vary with experimental requirements but should all have identical exterior cladding. The east wall should be windowless and its exterior made of brick to harmonize with other buildings at NBS. The west wall will consist of a patch-work arrangement of several windowless types of wall, each of a minimum of about 100 square feet in area. (Orientation on Figure 6.)

i. Roof - The roof consists of several types of construction (see Figures 2 and 3) and should be a minimum of 50 feet wide to accommodate that length of run of built-up roofing systems. The proposed self-drying insulated roof constructions require a minimum area of 100 square feet each.

j. Heating, Ventilating, Air Conditioning and Mechanical Systems - The type of heating, ventilating, and air conditioning systems and precise conditions for controlled indoor temperature and relative humidity will be given after the building dimensions are firm.

k. Utilities - Electric power, plumbing, lighting and other services are considered to be standard for normal office use at this time. Depending upon cost and other factors, utilities for later conversion to use the building for other purposes may be requested. Service elevators to the basement, second floor, and roof will be required.

l. Access During Construction - It is imperative that NBS scientists and engineers have free access to all parts of the building during the construction phase in order to install transducers into the building fabric as it is erected.

m. The designer and construction contractor should keep in mind the use of an inflatable structure as a weather-shield during winter-time construction.

n. Innovations should be encouraged.

4. OPERATIONAL REQUIREMENTS

Each of the engineering experiments impose operational requirements for successful conduct of this project. Those presently known are listed below for possible use in the design phase of this enterprise.

a. The indoor temperature and relative humidity of the building will remain fixed within stated limits during the entire service-life of the experiments.

b. The building will not be occupied, except for operating and visiting personnel, but all services for normal occupancy should be operative.

c. Space allocation for operational needs consists only of an instrument room and selected areas of floors for flooring experiments. Therefore, considerable architectural and engineering ingenuity concerning room and facilities layout can and should be done.

d. Convenient access to instrument and transducer circuits should be provided.

e. Service contracts on instrumentation and transducers used are mandatory including the provision that service personnel reside locally.

f. Warning and indicating systems in the event of power or services outages are required.

5. CONCLUSIONS

It is concluded that -

- the need for this enterprise is real and valid and it constitutes a public service.
- the planning effort should be continued.
- sufficient planning has been accomplished to allow an interim report and to provide an architectural-engineering firm with enough detail to allow preparation of construction drawings and specifications, and to estimate firm construction costs.
- additional funds for increasing the planning effort, preparation of plans and specifications, acquisition and checking of an instrumentation system, and construction and operation of the facility, should be allocated.

USCOMM-NBS-DC

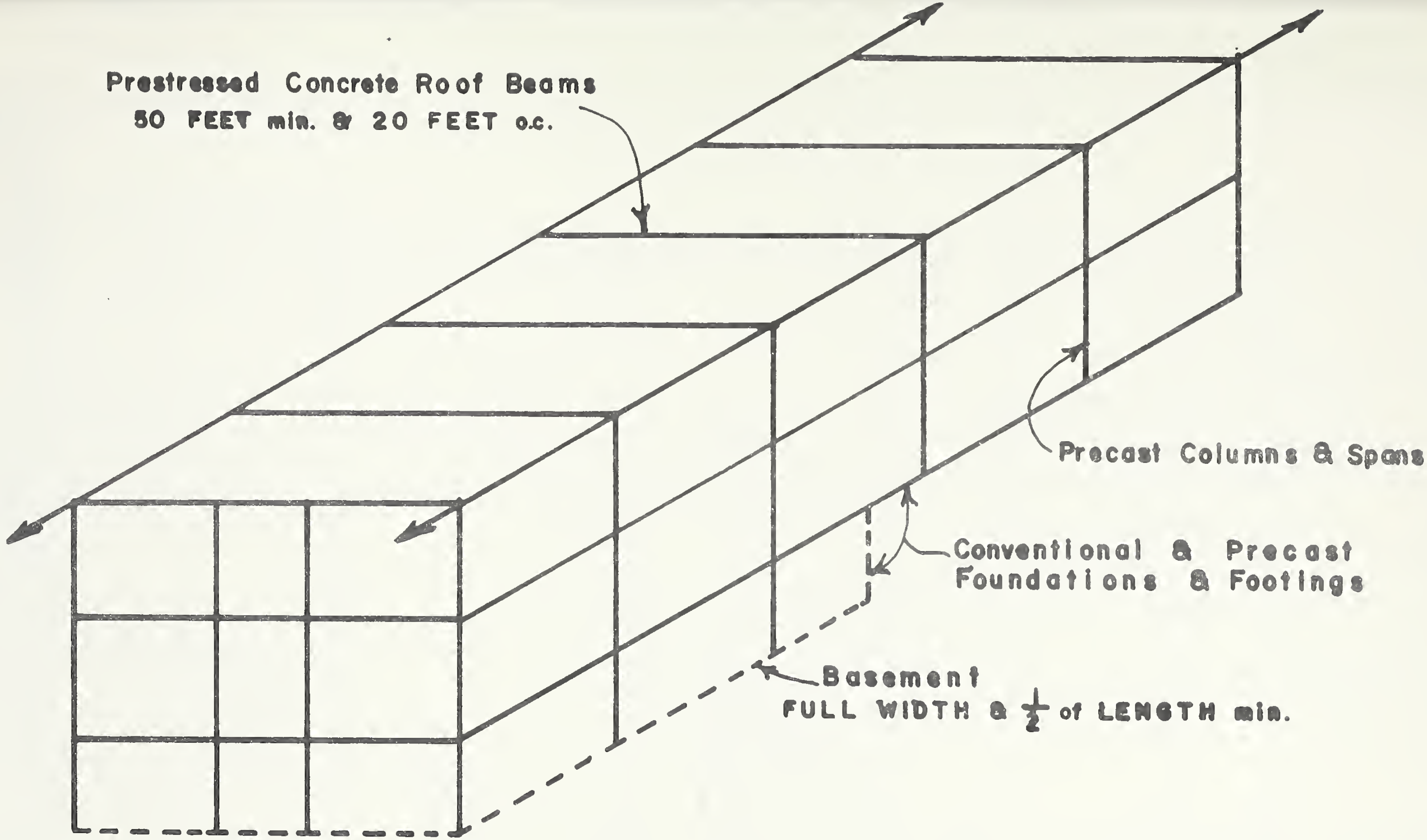


Figure 1. STRUCTURAL FRAME, FOUNDATION, & FOOTING SYSTEM

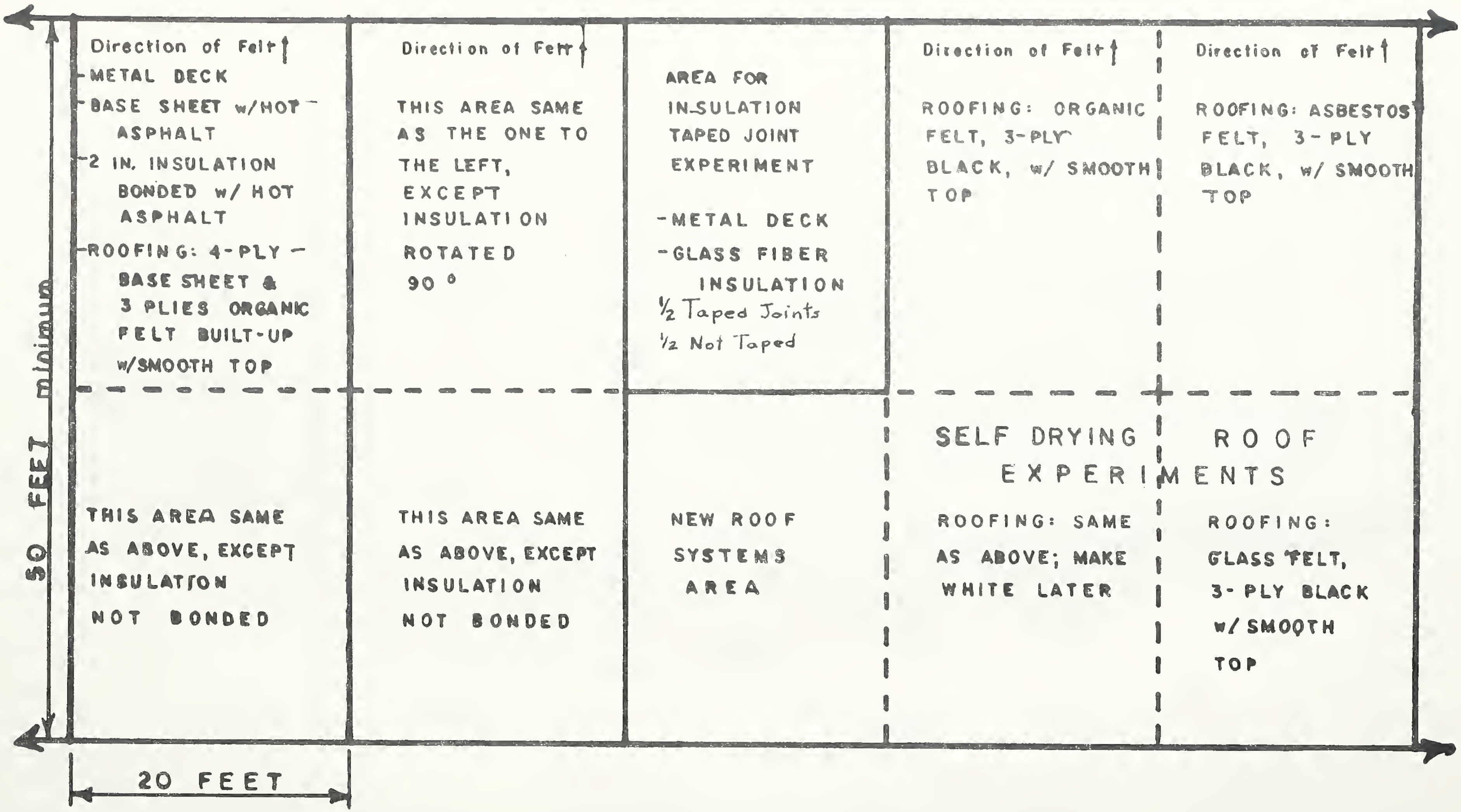


Figure 2. ROOFING SYSTEMS

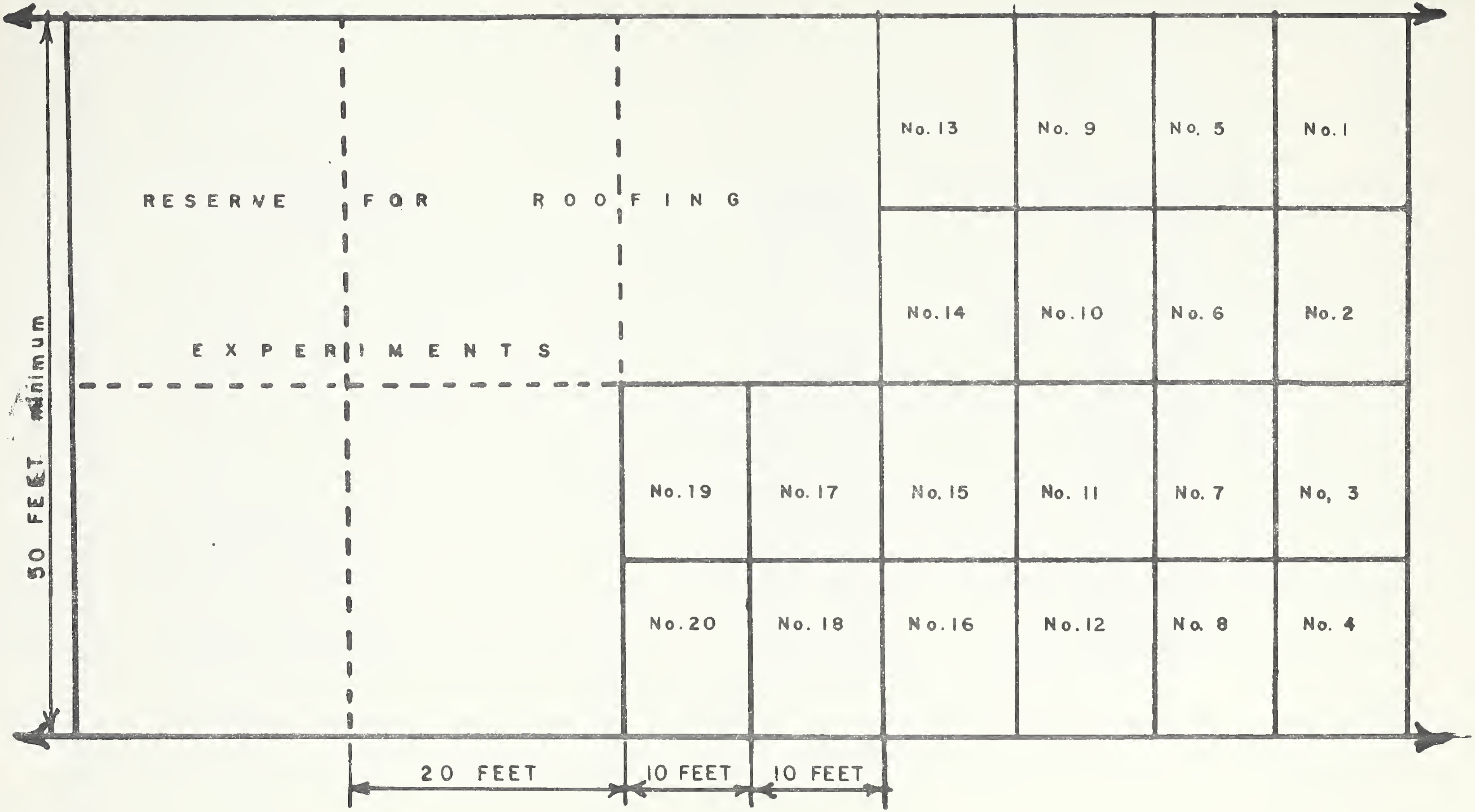


Figure 3. INSULATED FLAT ROOF SYSTEMS

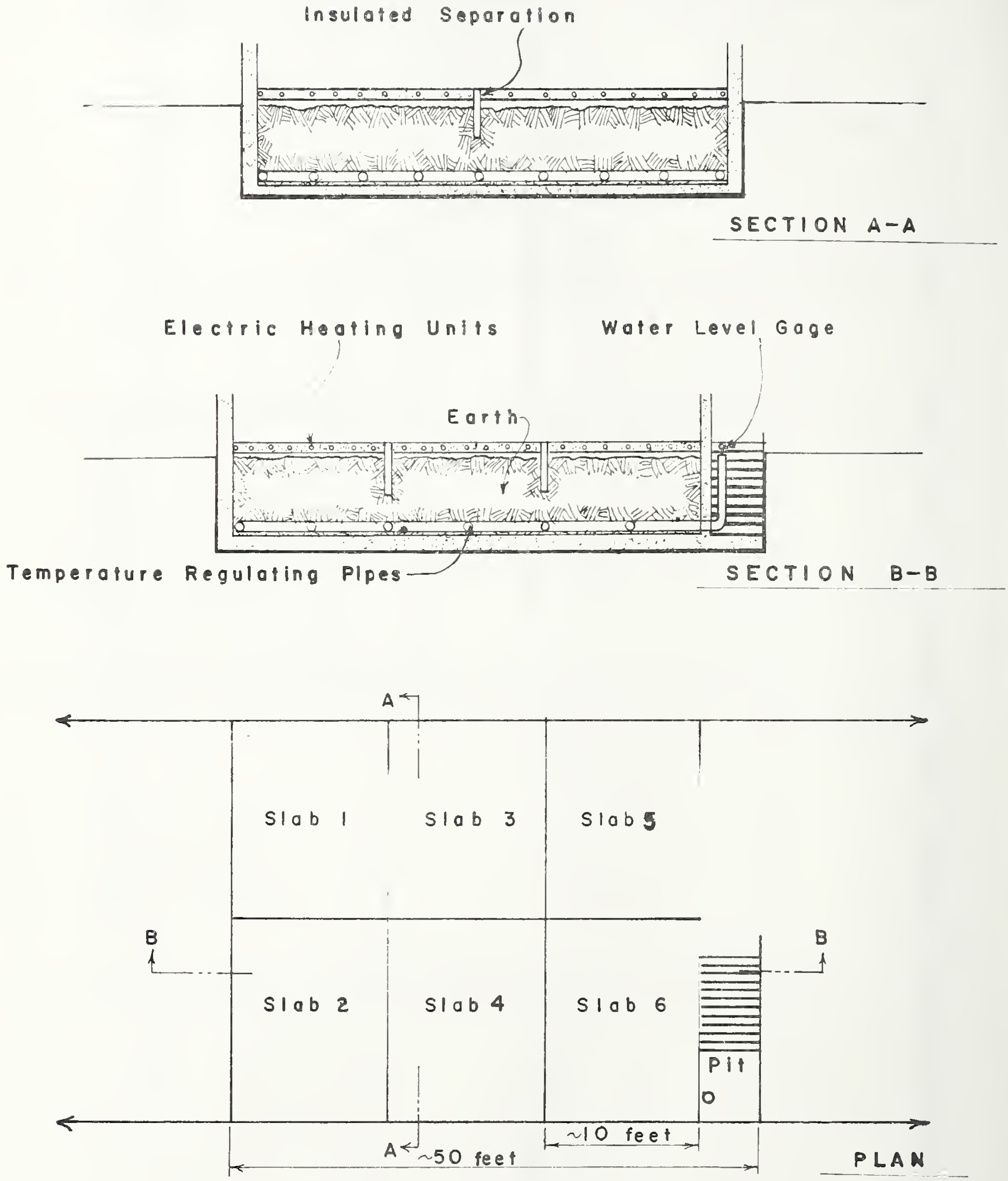


Figure 4. FLOORING ENGINEERING EXPERIMENTS

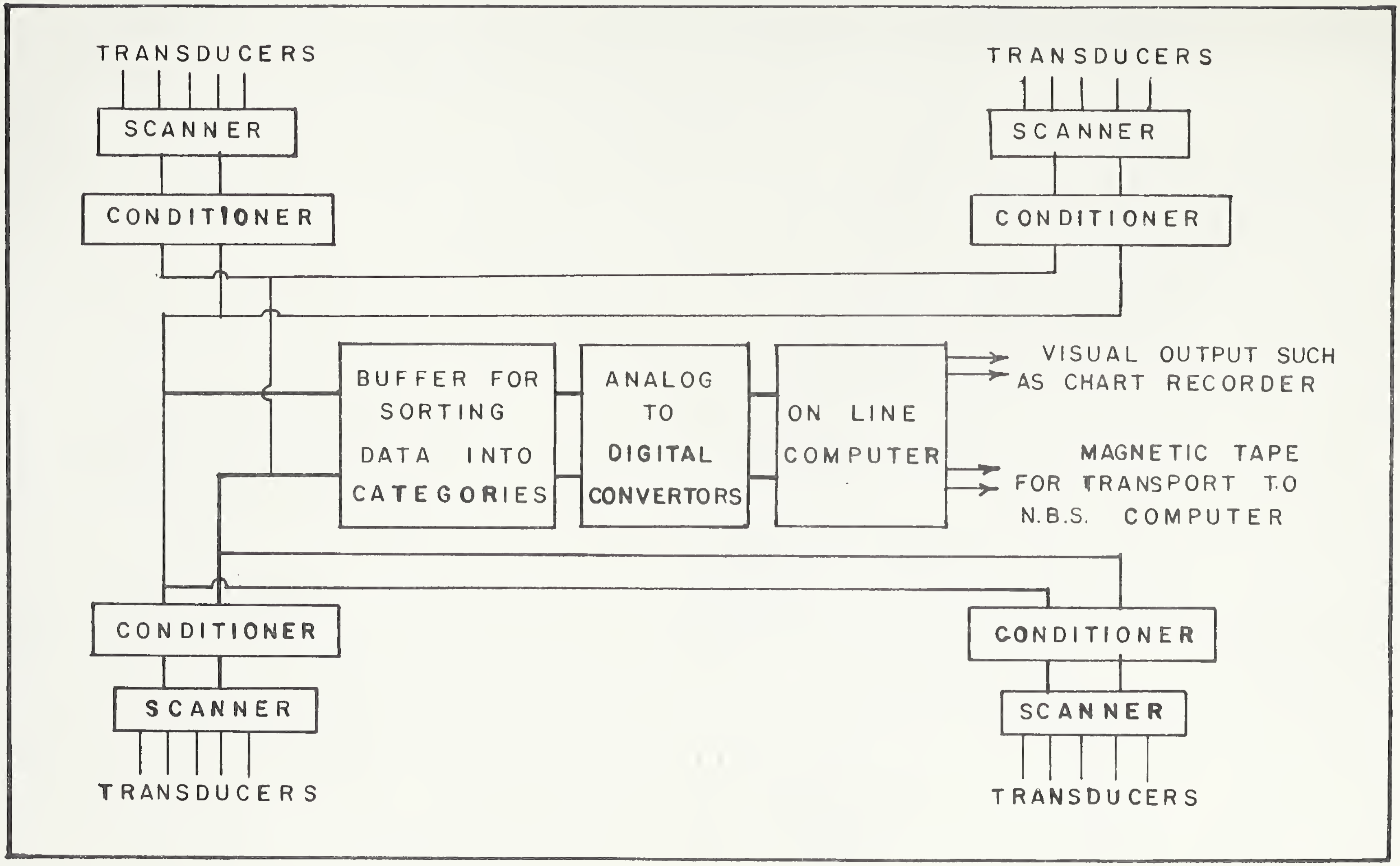
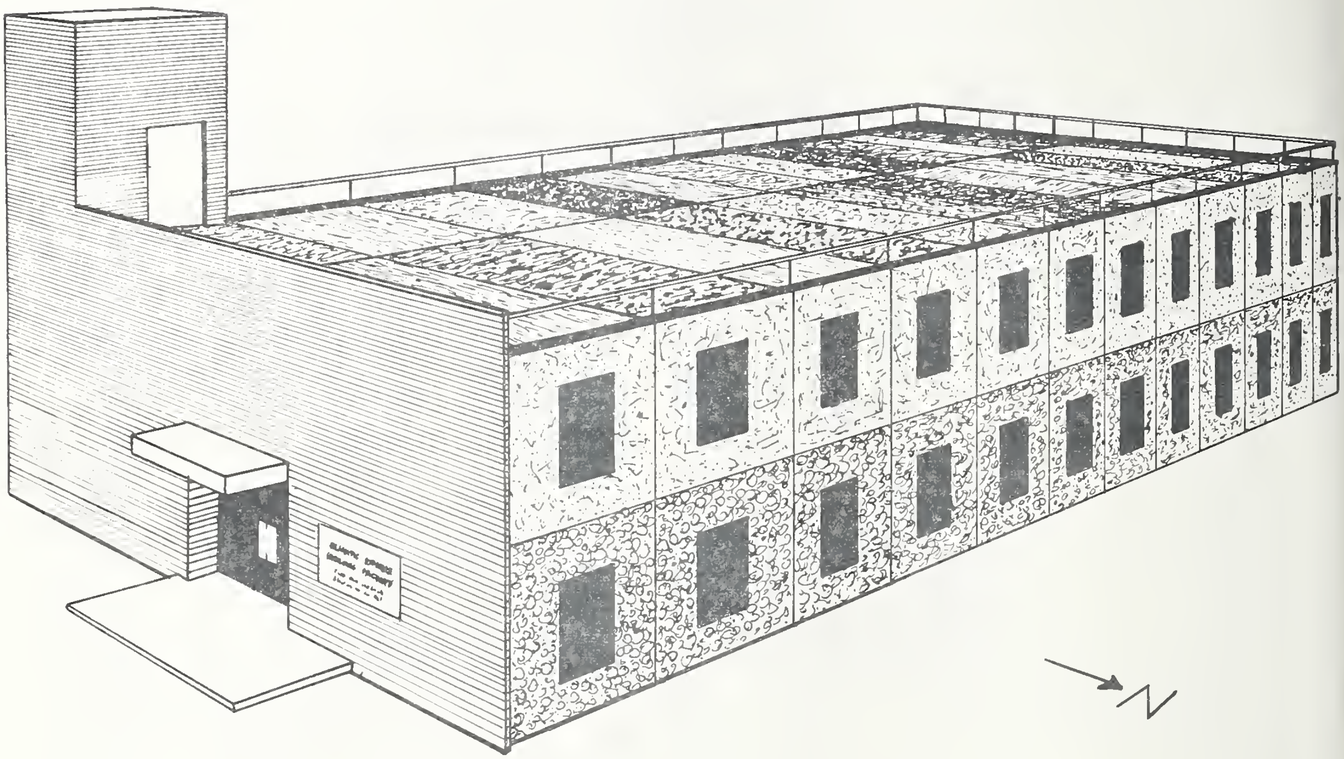


Figure 5. SCHEMATIC OF DATA ACQUISITION SYSTEM FOR CLIMATIC FACILITY



INVESTIGATIONS

1 STRUCTURAL ENGINEERING
2 BUILT-UP ROOFING
3 SELF-DRYING INSULATED FLAT ROOFS
4 FLOORING
5 WALLS AND PARTITIONS
6 HEATING AND COOLING LOADS AND MECHANICAL SYSTEMS
7 MOISTURE CONTENT — FIRE
8 ACOUSTICS
9 WEATHER
10 INSTRUMENTATION AND DATA HANDLING
11 IN-SITU METHODS OF MEASUREMENT
12 INFLATABLE BALLOON CONSTRUCTION TECHNIQUE

Figure 6. PRELIMINARY SKETCH OF PROPOSED FULL-SCALE CLIMATIC EXPOSURE BUILDING FACILITY