27

2

1/21/82

NTIS

ornl

I-924.

ORNL/TM-8018

OAK
RIDGE
NATIONAL
LABORATORY

UNION
CARBIDE

Large Climate-Moderating Envelopes for Enclosed Structures

A Preliminary Evaluation of Energy Conservation Potential

R. L. Wendt
G. E. Giles
J. E. Park

ORNL/TM--8018

DE82 007132

OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A06 Microfiche A01

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ORNL/TM-8018

Contract No. W-7405-eng-26

ENERGY DIVISION

LARGE CLIMATE-MODERATING ENVELOPES FOR ENCLOSED STRUCTURES

A Preliminary Evaluation of Energy Conservation Potential

R. L. Wendt
G. E. Giles*
J. E. Park*

Part of the National Program for
Building Thermal Envelope Systems and
Insulating Materials

MASTER

Prepared for
The Department of Energy
Conservation and Renewable Energy
Office of Buildings and Energy Research and Development
Buildings Systems Division

Date Published: December 1981

*Technical Applications, Computer Sciences

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

Table of Contents

	Page
LIST OF TABLES	v
LIST OF FIGURES	vii
ACKNOWLEDGMENTS	xi
SUMMARY	xiii
1 Introduction	1
2 Breakthroughs in Construction Technology	3
3 Potential Applications of LCMEs	14
4 Some Major Issues Affecting the Potential Utilization of an LCME	17
5 Potential Energy Conservation	20
6 Hypothetical LCME for Modeling Climate Moderation	22
7 Calculation of Fluid Circulation Within a Hypothetical LCME	25
8 Adapting a Conventional (Rectangular Region) Hydrodynamics Code to Simulate a Flow in a Triangular Region	26
9 LCME Heat Transfer Boundary Condition Code	33
10 Discussion of Results	49
11 Discussion of the Effects of Phenomena not Included in the LCME Models	89
12 Conclusions	93
13 Recommendations	94

REFERENCES	95
APPENDICES	99
Appendix A. Literature Survey	101
Appendix B. SALE Implementation	103

LIST OF TABLES

Table		Page
8.1	Relevant Physical and Numerical Parameters for Flack's Experiments and the LCME	30
9.1	LCME Boundary Conditions - Normal Daily Values	34
9.2	Solar Radiation Intensity and Related Data	39
9.3	Thermophysical and Optical Properties	41
9.4	Parameters for Heat Transfer Correlations.	43
10.1	Energy Budget for San Antonio	64
10.2	San Antonio - Estimated Yearly Degree-Day	66
10.3	Madison Wisconsin - Estimated Yearly Degree-Day	82
10.4	Heating Energy Required	83
10.5	Comparison of Normal Weather Data	85
10.6	Estimates of DD Savings at Additional Sites	87

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

LIST OF FIGURES

Figure		Page
2.1	Layout of a Proposed 300 Meter-Dia. Geodesic Dome Enclosing a Community in Western Canada	4
2.2	Section Through the Terradome One Enclosed Community	4
2.3	Exterior View of Geodesic Dome Envisioned to Envelope Most of the Existing Community of Winooski, VT	5
2.4	Interior View of the Dome Enclosing Winooski, VT	5
2.5	Exterior View of the First Permanent Fabric Building, Which Was Built in 1972 and Is Located at La Verne College in California	6
2.6	The 210,000-m ² Haj Airport Terminal Under Construction in Saudi Arabia. This Structure Utilizes a Series of Peaked Fabric Roof Sections to Cover The Terminal. The Sides are not Enclosed	8
2.7	A Model of a Department Store in San Mateo, California; Under Construction in 1981. More Than 7,000-m ² of the Store's Shopping Area Will Be Covered With a Permanent Fabric Roof	8
2.8	The Permanent Fabric Florida Festival Facility is Located in Orlando, Florida. It Houses a Series of Small Art, Craft, and Food Shops as Well as Plants Native to the Area	9
2.9	Interior View of a Fabric-Covered Department Store in San Jose, California	10
2.10	Air-Supported Recreation Facility at Riyadh University in Saudi Arabia	10
2.11	Exterior View of a 50,000-m ² Air-Supported Office Structure Study Done for GSA in 1976	11
2.12	Interior View of GSA's "Megastructure" Showing Multiple Work Levels Under an Air-Supported Fabric Roof	11
2.13	A Hypothetical LCME Enclosing A Small City Was Developed For Presentation To a Conference at Winooski, VT in 1980 . . .	12

	Page
6.1 This Hypothetical LCME Was Developed to Allow Modeling With Existing Computer Codes	23
6.2 Probable Cross-Sectional Geometry of an LCME	23
8.1 Idealized LCME for Preliminary Calculations	27
8.2 Comparison of Calculated and Measured Velocities Within a Triangular Enclosure	31
8.3 Comparison of Calculated and Measured Isotherms Within a Triangular Enclosure	32
9.1 Diurnal Temperature Cycle Used in the LCME and ORSMAC/LCME Compared With Statistic Data in Reference 10.1	35
9.2 Definition of Parameters for Insolation Model	37
9.3 Energy Balance of a Sheerfill Fabric Roof Element	44
10.1 LCME Model.	50
10.2 Diurnal Temperature Variations Calculated by the ORSMAC/LCME Code for Steady Periodic Conditions	51
10.3 ORSMAC/LCME Results Compared With LCME Results Using an Interior Velocity Maximum of 0.02 m/s	52
10.4 Temperature Variations for Successive 24-hour Cycles During the Simulation to Achieve Steady Periodic Conditions	53
10.5 Temperature Variations for Successive 24-hour Cycles During the Simulation to Achieve Steady Periodic Conditions With the LCME Code	54
10.6 Fluid Velocities Within an LCME From the ORSMAC/LCME and LCME Computer Codes	55
10.7 Comparison of Interior Air Temperatures Calculated by the ORSMAC/LCME Code With Those Calculated by the LCME Code Using Three Interior Velocities	57
10.8. Comparison of Ground Temperatures Calculated by the LCME Code Using Different Interior Velocities With ORSMAC/LCME Results	58

	Page
10.9 Diurnal Temperature Variations Calculated by the ORSMAC/LCME Code for Steady Periodic Conditions	59
10.10 ORSMAC/LCME Results Compared With LCME Results Using an Interior Velocity Maximum of 0.02 m/s	60
10.11 Temperature Variations for Successive 24-hour Cycles During the ORSMAC/LCME Simulation to Achieve Steady Periodic Conditions	61
10.12 Temperature Variations for Successive 24-hour Cycles During The LCME Simulation to Achieve Steady Periodic Conditions . .	62
10.13 Interior Fluid Velocities Within A San Antonio LCME	63
10.14 Comparison of LCME Design Options (San Antonio, Jan. 21) . . .	67
10.15 Comparison of LCME Design Options (San Antonio, July 21) . . .	68
10.16 Seasonal Diurnal Temperature Variations for San Antonio, Texas LCME. LCME Computer Code Results	69
10.17 Seasonal Diurnal Temperature Variations for San Antonio, Texas Vented LCME. LCME Computer Code Results	70
10.18 Seasonal Diurnal Temperature Variations for San Antonio, Texas Vented LCME With Reduced Transmissibility. LCME Computer Code Results	71
10.19 Yearly Variation of Daily Mean Temperature for San Antonio LCME as Calculated by the LCME code	72
10.20 Graphical Representation of Energy Savings as Calculated From Estimated DD	73
10.21 Surface Temperatures for Uncovered and LCME Covered Ground. .	75
10.22 Comparison of Surface Temperatures for Uncovered and LCME Covered Ground. Horizontal Lines Indicate Comfort Zone . . .	77
10.23 Seasonal Modification of Ground Daily Mean Temperatures by an LCME	78
10.24 Seasonal Diurnal Temperature Variation for Madison, Wisconsin, LCME. LCME Computer Code Results	79

	Page
10.25 Seasonal Diurnal Temperature Variations for Madison, Wisconsin Vented LCME. LCME Computer Code Results	80
10.26 Yearly Variation of Daily Mean Temperatures for Madison, Wisconsin LCMEs as Calculated by the LCME Code . . .	81
10.27 Graphic Presentation of the Relative Energy Savings for Winter- and Summer-Dominated Climates	86
11.1 Spectral Characteristics of Fabric (Sheerfill)	90

ACKNOWLEDGMENTS

We would like to express our appreciation to Dr. John E. Effenburger and his staff at Chemical Fabrics, Inc., and Birdair, Inc., for sharing with us their knowledge of fabric structures and the energy consumption aspects of such buildings.

We would also like to thank Ken W. Childs, Computer Sciences, UCC-ND, for his helpful discussions about this project.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

SUMMARY

Three factors which influence the energy consumption of buildings are the interior climate (comfort zone), the building envelope and the exterior climate. Manipulating the comfort zone and changing the characteristics of the building envelope are traditional means of reducing a building's energy consumption. The concept of moderating the exterior climate to reduce a structure's energy consumption has been investigated using several differing approaches. Some of these approaches are the intelligent use of vegetation, site selection, and landscape design to create moderated micro (house) and mezo (community) climates. Another concept, and the subject of this report, is to isolate the structures from the exterior environment by enclosure within a large envelope. The membrane which forms the envelope skin may or may not have a significant thermal insulating value. The inhabited structures are surrounded by a mass of air that does not freely mix or exchange energy with the atmosphere. This mass of air becomes an intermediate climate or a buffer between the conditioned inhabited space and the exterior environment.

This study is a preliminary estimate of the energy conservation benefits of a large climate moderating envelope (LCME). A hypothetical LCME design was chosen and a coupled fluid dynamic and energy transport analysis was performed to estimate the energy conservation potential of this design. The heat transfer models included insolation, outside air temperature and wind, thermal radiation exchange with the sky and between the fabric and ground and thermal storage in the earth mass beneath the LCME. The energy transported within the fluid by the buoyancy driven circulation was modeled as an incompressible fluid utilizing the Boussinesq approximation. The climatic conditions were assumed to vary in smooth repeating daily cycles. The numerical simulation of climatic variation was continued until the results within the LCME achieved a repeating daily cycle. The results for selected seasonally characteristic days were utilized to estimate the annual energy consumption of structures within an LCME relative to similar structures exposed to the exterior environment.

The relative annual energy savings for summer-dominated climates was estimated to be ~ 70%. The energy savings for a winter-dominated climate LCME were estimated to be somewhat smaller but the LCME concept could offer significant benefits for agricultural applications for this type of climate.

1. INTRODUCTION

The energy consumed in our cities and buildings is greatly affected by the climatic conditions in which they are placed. Most of the attention in building energy conservation to date has focused on the building as the sole variable in this relationship. Another approach to energy conservation is to look at the potential of moderating or manipulating the climatic condition around our cities and buildings in order to make them more closely approximate the human comfort zone. There are several ways in which the climate surrounding cities or buildings can be moderated at the local level. This study investigates some of the basic impacts of putting a large secondary enclosure around a number of functions and thereby creating a Large Climate Moderating Envelope (LCME).

An LCME is an enclosure of thousands or hundreds of thousands of square meters. It may be an air-supported, tension, or dome structure. The enclosed functions may be as diverse as a greenhouse, an office complex, a shopping center, a college campus, or an entire small community. An LCME is not a building per se. It is the creator of a new and more moderate climate in which to place various functions. As such, the LCME, like the buildings it encloses, works to fulfill the basic functions of a shelter.

The most important function of a shelter is to maintain an environment in which the temperature gradient inside allows our body temperature to remain near 98.6F. Clothes are our first shelter, and we add or remove them in response to the temperature of our surrounding environment. A building or an LCME can be viewed as a secondary shelter which moves the ambient climate toward the zone of human comfort.

Another function is to protect the body against the extremes and discomforts of weather. Again, clothes form our initial shelter against rain, snow, strong winds, and excessive sun. However, they do not effectively protect against the extremes of these conditions. A building or LCME provides the secondary shelter that eliminates the extremes.

Protection against predators and the provision of privacy are other functions of shelters.

An LCME is then a potential part of the system of shelters used by man to create a habitable environment in which to live. It differs markedly from the clothes and buildings approach to sheltering. It adds a third layer of sheltering, and, because of the magnitude of its size, the LCME creates an outdoor environment within the shelter. Not only does protection occur "within the inhabited spaces," it occurs "outside" this space but within the envelope as well.

The scale of these envelopes is such that microclimatic manipulation could occur. Temperature and humidity changes could be made and wind or airflow and precipitation induced. The full extent of the microclimatic manipulation potential is not now known. However, a number of very large traditional structures have shown a clear tendency to develop a microclimate within their envelope.

The dream of changing an existing climate to one more habitable without having to relocate to where it naturally occurs is becoming technologically feasible, at least on the microclimatic scale through the use of LCMEs. Enclosed communities are no longer only a Buck Rogers' fantasy or the dream of the futurist. This movement of LCMEs to the verge of reality is the result of important developments. Perhaps most important has been the development in recent years of the ability to economically enclose extremely large volumes with inflated, tension, or dome structures. Teflon-coated fiberglass fabric was developed as the enclosing membrane in air-supported and tension structures and has enabled these membranes to be considered permanent (lasting 30 years or more). A discussion of advances in construction technology follows in the next section.

Another facilitating development has been the current trend to higher density development. This trend has resulted from the impact of higher land, construction, and transportation costs. The density of development necessary to make an LCME economically feasible closely resembles the density now occurring in many urban areas.

The rapid rise in the cost of traditional materials and methods has enhanced the consideration of innovative approaches which have the potential of reducing costs. The inflated roofs of domed stadiums have consistently shown this approach to be less costly than a traditional roof. To some degree, these same economic benefits apply to an LCME.

The ability to privately finance very large projects such as the Sears Tower and John Hancock Building in Chicago indicate that the capital formation required to develop at least the smaller LCME is realistically possible. New approaches to property ownership such as the condominium pave the way for the kind of ownership required for a multi-occupancy LCME used to house a neighborhood or small town.

Another factor leading to the consideration of LCMEs is the rapid rise in energy costs. This economic factor is inducing serious reconsideration of how we create our built environment. Not only will the energy performance of our buildings and their equipment be reconsidered, but so will the energy embodied within that structure (energy utilized in manufacturing materials and in erection which is reflected in construction costs) as well as the energy used in transportation and energy distribution systems. This subject is more fully discussed later in the report.

2. BREAKTHROUGHS IN CONSTRUCTION TECHNOLOGY

The ability to construct a permanent LCME has existed for only a relatively few years. In the traditional approach to construction, the size and weight of structural members increase as the size of the building increases. Because of this, there are physical and economic limits to the size of traditional buildings. Geodesic dome structures, tension structures, and air-supported structures can be increased in size to much greater limits without a proportional increase in weight.

Geodesic Dome Structures

Of the three structural systems currently envisioned for use as LCMEs, the geodesic dome is perhaps the oldest and best known. A number of moderate- to large-sized clear span structures have been built throughout the world utilizing this concept. Typified by numerous high-strength tension struts and multi-axial nodes, the geodesic dome has relied on relatively small rigid panels between the struts to form its skin. Another mark of the geodesic dome is its round floor plan.

Advances in computer technology have allowed the extremely complex structural calculations of the geodesic dome to be made. Even more complex structures are envisioned utilizing double or triple levels of interconnected structural members. These systems increase the thickness of the dome and permit proposals for very large (300-m-diameter) domes to be made.

The use of high-strength material normally associated with airframes for planes has helped satisfy the materials requirements for such large structures. Although more expensive than traditional materials, these aircraft materials offer excellent weight-to-area-enclosed ratios which keep very large structures economically feasible.

A proposal to utilize a 300-m-diameter by 60-m-high dome as an LCME has been made by Space Structures of Plainview, New York (Figures 2.1 and 2.2). The study was commissioned by a Canadian investment group looking at housing in western Canada. The proposal envisions the south-facing portion to be enclosed with transparent material while the remainder would be enclosed with heavily insulated opaque panels. The enclosed functions would include residential, commercial, and small garden plots. An even larger dome was proposed by Winooski, Vermont, to enclose their entire existing community (Figures 2.3 and 2.4).

While the geodesic dome provides a system for enclosing large spaces, the system itself appears to have limitations for very large applications. The multi-panel approach to creating the skin provides many opportunities for leaks. This can be overcome through careful construction and maintenance. However, it is unlikely that adequate maintenance could be accomplished on the larger domes because of the number of joints to be maintained as well as the difficulty in reaching them, resulting from the size and geometry of the dome.

ORNL-Photo 5909-81

Figure 2.1
LAYOUT OF A PROPOSED 300 METER-DIA. GEODESIC DOME
ENCLOSING A COMMUNITY IN WESTERN CANADA

ORNL-Photo 5910-81

Figure 2.2
SECTION THROUGH THE TERRADOME ONE[®] ENCLOSED COMMUNITY

ORNL-Photo 5911-81

Figure 2.3
EXTERIOR VIEW OF GEODESIC DOME ENVISIONED TO ENVELOPE
MOST OF THE EXISTING COMMUNITY OF WINOOSKI, VT.

ORNL-DWG 5912-81

Figure 2.4
INTERIOR VIEW OF THE DOME ENCLOSING WINOOSKI, VT.

The geometry of domes (round or oval) may limit their applicability to certain functions and topographic features. In addition, these geometric forms are difficult to extend or increase in size in order to permit future growth. For these reasons, domes, as LCMEs, will probably be limited to smaller, more clearly defined functions where growth or other major change is unlikely to occur. Functions which can utilize multiple interconnected small enclosures could also be housed in a series of domes.

Permanent Fabric Tension Structures

The concept of fabric tension structures is not new. The tents of nomadic peoples throughout the ages provide numerous early examples. However, permanent fabric tension structures of the size that might become an LCME have only recently been developed. The reasons for this development can be traced to improvements in materials engineering, structural engineering analysis, and field erection that resulted from intensive experience gained since the first permanent fabric building was built in 1972 (Figure 2.5).

ORNL-Photo 5913-81

Figure 2.5

EXTERIOR VIEW OF THE FIRST PERMANENT FABRIC BUILDING, WHICH
WAS BUILT IN 1972 AND IS LOCATED AT LA VERNE COLLEGE IN
CALIFORNIA.

Prior to the development of Teflon-coated fiberglass fabric, the life expectancy of fabrics used in tension structures was about 8 years. The life expectancy of the Teflon-coated fiberglass is about 30 years or more. Thus, materials development, coupled with computer-aided structural engineering analysis, has allowed this construction technique to be pushed toward its limits. Individual structures as large as 210,000 m² have been built (Figure 2.6). In addition, a wide variety of functions has been enclosed, including various college buildings, athletic facilities, an airport terminal, and several shopping centers (Figures 2.7, 2.8, and 2.9).

Permanent fabric tension structures have been effective in reducing overall building energy consumption in areas of relatively mild climate and for functions in which cooling loads dominate. This reduction occurs as a result of the high reflectivity of the fabric markedly reducing the solar gain. In addition, the transmissivity is such that more than ample lighting of the interior can be accomplished by sunlight. The typical high soaring spaces may produce temperature stratification with the cooler comfort zone being maintained only in the lower inhabited portion of the structure.

The typically repetitive nature of the structural system in a tension structure permits subsequent additions to handle growth. This characteristic, as well as the typically smaller module, can be more easily adapted to diverse functions and to conform to irregular terrain. It would appear that the potential size and applicability limits on fabric tension structures as LCMEs would be those of cost and impact on the environment rather than, as with domes and air-supported structures, a limit that is inherent in the structural systems themselves.

Air-Supported Permanent Fabric Structures

Air-supported structures are a fairly recent development. Many small-scale structures are utilized for swimming pool and tennis court enclosures, temporary warehouses, reservoir covers, and other similar functions. The large-scale versions have been used as exposition pavilions, stadium covers, and athletic buildings (Figure 2.10). The advent of a "permanent" fabric material has enabled air-supported fabric structures to be considered for a much broader range of functions (Figures 2.11, 2.12, and 2.13).

As in tension structures where the fabric is stretched over cables, the air-supported structure also gains its strength from the stretching of fabric over cables. This time, however, the tensioning occurs as the structure is inflated and the fabric balloons out against restraining cables. Efficient shapes for air-supported structures tend toward being superellipse in plan. In general, they have a much lower profile (0.2 or less rise-to-span ratio) to avoid being damaged by wind.

ORNL-Photo 5914-81

Figure 2.6

THE 210,000-m² HAJ AIRPORT TERMINAL UNDER CONSTRUCTION IN SAUDI ARABIA. THIS STRUCTURE UTILIZES A SERIES OF PEAKED FABRIC ROOF SECTIONS TO COVER THE TERMINAL. THE SIDES ARE NOT ENCLOSED

ORNL-Photo 5915-81

Figure 2.7

A MODEL OF A DEPARTMENT STORE IN SAN MATEO, CALIFORNIA; UNDER CONSTRUCTION IN 1981. MORE THAN 7,000-m² OF THE STORE'S SHOPPING AREA WILL BE COVERED WITH A PERMANENT FABRIC ROOF.

Figure 2.8

THE PERMANENT FABRIC FLORIDA FESTIVAL FACILITY IS LOCATED IN ORLANDO, FLORIDA. IT HOUSES A SERIES OF SMALL ART, CRAFT, AND FOOD SHOPS AS WELL AS PLANTS NATIVE TO THE AREA.

ORNL-Photo 5917-81

Figure 2.9

INTERIOR VIEW OF A FABRIC-COVERED DEPARTMENT STORE
IN SAN JOSE, CALIFORNIA

ORNL-Photo 5918-81

Figure 2.10

AIR-SUPPORTED RECREATION FACILITY AT RIYADH UNIVERSITY IN
SAUDI ARABIA.

Figure 2.11
EXTERIOR VIEW OF A 50,000-m² AIR-SUPPORTED OFFICE STRUCTURE
STUDY DONE FOR GSA IN 1976.

Figure 2.12
INTERIOR VIEW OF GSA's "MEGASTRUCTURE" SHOWING MULTIPLE
WORK LEVELS UNDER AN AIR-SUPPORTED FABRIC ROOF.

SCHEMATIC SITE PLAN

SECTION

Figure 2.13

A HYPOTHETICAL LCME ENCLOSING A SMALL CITY WAS DEVELOPED FOR PRESENTATION TO A CONFERENCE AT WINOOSKI, VT. IN 1980.

While air-supported structures use minimal materials to enclose incredible amounts of space without interior supports (34,000 m² at Pontiac, Michigan, stadium), they are not without inherent limitations. The height and shape are limited. The overall size is constrained by the economics of construction, the required compression ring, and the power necessary to keep it inflated. It is a difficult structure to increase in size. Growth would be by replication rather than by addition. Specific consideration must be given to continually maintaining inflation since this is the source of the envelope's support.

For LCMEs of limited size and growth potential, the air-supported structure may provide an ideal enclosure. It lacks the structural supports within the envelope of a tension structure, while at the same time, it retains many of the positive energy aspects of the fabric tension structures.

3. POTENTIAL APPLICATIONS OF LCMEs

The use of LCMEs to change the microclimate around an aggregation of structures has a number of potential applications. On the small end of the spectrum is a variety of large single-use structures, while on the large end are diverse multifunctional spaces including an entire enclosed community.

The problems and potential for development appear to be directly related to the size and complexity of the functions enclosed. Some "change of lifestyle," as addressed in Section 4, is inherent in any LCME. However, the changes associated with enclosing an entire community are clearly massive. For this reason, the smaller, more functionally focused LCMEs would appear to be a more realistic first application.

Greenhouses

This is perhaps the simplest application of an LCME in that its interior development replicates the simple unbuilt exterior environment utilized in food production. It requires minimal human habitation and, thus, allows a somewhat broader swing in the interior temperature. In addition, potentially higher interior humidity may constitute an asset as opposed to a liability in a human environment.

The primary justification for the use of LCMEs as greenhouses would be to allow the major production of food in close proximity to a high concentration of population where adverse climatic conditions preclude growing produce outdoors. The massive size of an LCME, coupled with a significantly extended growing season, could allow many crops to be produced more economically locally than those which have been grown in another part of the country and shipped to market. Year-round growing seasons are possible with existing envelope materials in many parts of the country. Minimal heating energy would be required to overcome severe cold periods.

Another application of the LCME greenhouse could be in the arid portions of the sunbelt where irrigation water is expensive and in short supply. The LCME can be designed to trap the moisture transpired from plants during the day and condense it at night, utilizing the inside surface of the envelope which has been cooled by night sky radiation. Much work needs to be done in order to effectively utilize this potential. However, in theory, it would be possible to reduce water consumption to that utilized in the plant growth process and that small amount leaked through the skin. This would approach a closed water cycle.

Shopping Centers and Large Office Complexes

This application of the LCME is significantly more complex than the uninhabited greenhouse, but less complex than the multifunctional 24-hour uses described later. The currently available Teflon-coated fiberglass fabric favors LCMEs which have comfort-conditioning requirements dominated by the need to cool the structure. Both shopping centers and office complexes typically require cooling through most of the year in many climates. This is due to the heat created by people and artificial lighting within the structure. The Teflon-coated fiberglass envelope of an LCME reduces the artificial lighting requirements by providing daylighting throughout most of the inhabited day for the shopping center or office complex. In addition, much of the heat and humidity generated by the occupants may tend to rise to the high points of the large interior volumes created by these structures. This may help to create a stratified comfort zone at the level of the inhabitants. In the relatively mild climatic zones, the impact of an LCME could be dramatic on the design and construction of enclosed space. Weathering, including freeze/thaw, wet/dry, ultraviolet deterioration, dust abrasion, etc., would be virtually eliminated. Extremes of temperature would be dampened so that small, efficient, comfort-conditioning systems would be adequate. The demarcation line between inhabited space and the enclosed "outside" space could become less distinct. There could be a greater intermixing of "indoor" and "outdoor" activities. Walking as a means of personal transport could increase due to the reduced distances and more moderate climate inherent in an LCME.

University Campuses, Military Bases, and Neighborhoods

These functions are markedly different from the above in that each is more functionally diverse and they all are inhabited all day. Daylighting and moderated temperature are significant benefits, but excess humidity control, ventilation, and pollution control also become major factors. The psychological aspects of being in a totally enclosed and controlled environment begin to become a key factor. Much additional work needs to be accomplished in order to adequately evaluate an LCME for these functions.

The interior of an LCME utilized for these functions would resemble the out of doors with open space, trees, plants, and other natural elements. This could help mitigate the isolation from nature that one might otherwise experience. Interior construction might more closely follow traditional outdoor construction since privacy, sound isolation, security, and other similar factors would be the key to the acceptance of an LCME for 24-hour multifunctional use.

Small Towns

By far the most complex application of an LCME would be to enclose a small but complete community. The diversity and incompatibility of many functions found in complete communities would, in all likelihood, preclude putting all functions within the same envelope. This situation suggests the use of separate but closely spaced and interconnected envelopes, each of which would house groups of compatible functions.

Such applications of LCMEs are probably most appropriate where the exterior climate is extremely hostile and where being "outdoors" is rarely very pleasant. Communities such as this would need overwhelming reasons to exist in their locations. Examples might be scientific research reasons, such as in Arctic regions; proximity reasons, such as in support of the maintenance and operation of pipelines, railroads, and other communication links; strategic reasons, such as supporting military bases; and finally resource harvesting reasons, such as in support of mining and lumbering.

4. SOME MAJOR ISSUES AFFECTING THE POTENTIAL UTILIZATION OF AN LCME

Environmental Issues

An LCME will create numerous environmental issues. The magnitude and importance of these issues is proportional to the size and complexity of the LCME's function. Because of the "newness" of the concept, there are many questions and few answers. Some of the important environmental issues are discussed in the following.

Climate - What kind of microclimate will the envelope create? Can it be manipulated to approximate the comfort zone without massive use of energy? These two questions are addressed in a preliminary way later in the report. Can humidity be controlled without loss of thermal benefits? Will precipitation occur inside the envelope? Can it be controlled to satisfy the irrigation needs created by the elimination of natural rain within the LCME, or will an artificial system be needed? What will be the impact of the climatic change on the native insects, birds, animals, and plants that might inhabit the envelope. Many natural ecosystems could be affected by enclosure in an LCME. These impacts should be understood before proceeding to build such a structure.

Disease Control - Questions regarding health and sanitation pose a major set of issues. An LCME could become a warm, moist environment with relatively stagnant air and, therefore, a potential breeding ground for parasites and fungi. Whether or not this would occur is not known at this point. Will animals and pets create major health problems if they coexist with humans in the dome? The open outside environment has a great diluting effect and takes care of a "multitude of sins" by dispersing them over a wide area. With dilution greatly limited within an LCME, the effect might not be tolerable.

Inside Air Quality - It is assumed that major sources of air pollution such as industrial and power plant exhausts and automotive exhausts have been excluded from the LCME. Other potential pollution sources such as those associated with burning natural gas for domestic use, outgassing of paints and other building products, and radon emissions from the earth and building materials need to be carefully analyzed before developing a detailed design. Unlike a super-sealed super-insulated house, an LCME will have a tremendous volume in which some dilution can occur. In addition, it can be assumed that the LCME would be vented during optimal weather conditions and would be relatively "leaky" at other times.

The use of ample plant material within the LCME would help compensate for the CO₂ given off by the inhabitants. This factor could significantly reduce the need for "outside" air within the LCME and improve its overall energy performance.

Dust control in an LCME is another issue about which little is known. Ionized air is an issue being studied in large buildings. Although it has not been proven, there appears to be an interrelationship between whether or not (and how) air particles are charged and people's attitudes or outlook.

Odors - Most sewage systems currently vent to the atmosphere through nonpressurized gravity flow systems. Offensive odors created by sewage are normally taken care of by dilution and dispersion, but this means may not be available in an LCME. Pressurized sewers as found in large buildings might solve this problem. There is also the question of residential ventilation. If someone is cooking lasagna and his neighbor hates lasagna, what does he do with the odors? One solution would be a fume sewer. Another approach to the problem of odor is forced ventilation of the LCME to get rid of it by dilution the way the atmosphere does. However, the benefit of having the LCME now becomes little more than a way to keep the rain and snow off the inhabitants if a large heating, ventilating and air conditioning system is needed. Vents opened to control the interior temperatures could reduce odor concentrations. However, venting to control odors could be detrimental to climate control.

Noise - A domed or an arched structure such as an LCME, unless adequately treated, reflects, telescopes, and enhances noise. For example, if a water line had to be repaired, the usual approach would be to bring out the jackhammer. However, trapped within a domed structure, the noise of that jackhammer could reverberate around and around the structure. Outside, the noise would be sent up into the atmosphere where it would attenuate. On the other hand, one of the advantages of the envelope might be that the inside would be quiet in an otherwise noisy surrounding environment.

Psychological - The psychological impact of the LCME needs to be assessed. For example, what would be the impact on why people live in a given community? Would the LCME change or eliminate these reasons? When evaluating whether an LCME makes sense, a determination will have to be made as to what it is about the community that keeps the people here and whether the LCME will enhance or destroy it. Perhaps the challenge of the elements, if not too severe, is something of a positive asset. Protection from the elements is something that can be considered as positive, but this might not be considered adequate justification in some cases.

Transportation and Materials Handling - It does not appear that the exhaust from automotive internal combustion engines can be permitted in the interior of the LCME. While trying to improve an environment, trying to envelope it, insulate it, isolate it from the external world, it is not appropriate to introduce troublesome sources of pollution that can be avoided. Electric cars, bicycles, walking, moving walkways, and other modes of transportation can be substituted for the automobile.

Solid waste collection is now handled by trucks that drive up and down the street to pick up trash. This is probably not the way it should be done in the LCME. The LCME needs to be thought of as one building. It is more than just an aggregation of small buildings under something like an umbrella; it is a real building. Therefore, materials handling systems may more closely resemble those of large buildings now in existence.

Regional Impacts - What is the impact of an LCME on the region around it? Storm runoff is one factor that can have a regional impact. In some locations, many cubic meters of water will be draining at one period of time. What impact will this runoff have on the areas into which it drains?

The visual and aesthetic impact of the LCME will also be tremendous. Some LCMEs may be 100-m high, the height of a 28 to 32 story building. The size of such a structure would have quite a visual impact on the region.

Economic, Ownership, and Governmental Issues - Because of their size and complexity, many potential LCMEs would be materially affected by economic, ownership, and governmental issues. This report identifies only some of the more basic questions and does not attempt to develop and analyze all the potential scenarios.

How is the LCME to be paid for? Depending on its size, we are talking of a cost of up to hundreds of millions of dollars. If the LCME is created all at once, all the costs have to be addressed at once. That is one of its real liabilities.

What does it do to the property values inside? Moreover, who owns the land? Who is responsible for maintenance of the interior space? Who owns the envelope? Is it a private structure, a municipal structure, a state structure, or a federal structure? Anytime something that big is created, significant responsibilities and liabilities must be addressed.

Further, putting a city in one "building" will create many municipal problems. One example is population restriction. What do you do with growth (increasing demand)? How do you utilize vacant space that occurs from a migration out of the envelope (decreasing demand)? What is the process for determining who is to be inside and who is to be outside of the LCME?

When utilized as a neighborhood or small community, there are social issues as well. For example, how much of the LCME is to be used for low-income housing, minority housing, ethnic housing? Instead of a normal marketplace that helps determine where people live, there is an artificial marketplace in the envelope. The sociologist will have to become involved with these issues to determine whether it works or whether it will be creating social strain that will ultimately cause the project to be a failure.

5. POTENTIAL ENERGY CONSERVATION

An LCME has the potential to affect the energy consumption of its enclosed functions in several ways. First, by moderating the climate surrounding the enclosed structures, there can be a reduction in the energy required for comfort-conditioning. The magnitude of this moderation depends on whether the envelope's energy exchange characteristics remain constant (the case with current state-of-the-art technology) or whether the envelope can change its characteristics in response to the exterior climate. This study investigates only a "passive" or unchanging approach.

Another important reduction in energy consumption accrues from the reduction in transportation- and distribution-related energy consumption associated with the high-density development that is expected to be found in LCMEs. The costs of erecting the envelope will tend to cause a closer aggregation of functions within the envelope which will markedly reduce travel and distribution distances. This effect also occurs in traditional developments where high land value increases density. Shorter travel lengths coupled with a moderated climate will tend to encourage walking and bicycling as a primary means of transport. In addition, the unacceptability of the internal combustion engine's exhausts within the envelope will affect the choice of energy source used to support motorized transit.

The short distribution distances found in all high-density developments could facilitate the economic utilization of otherwise "waste" energy sources. These shorter distances could also reduce line losses in power distribution and potential district heating and cooling systems.

The potential energy reductions in transport and distribution are extremely hard to quantify without a detailed analysis of how the functions relate to each other and how people will utilize them. This analysis is beyond the scope of this study.

The embodied energy (i.e., energy contained in materials and used in the construction of the LCME and interior structures) of an LCME is expected to differ greatly from that of similar nonenveloped functions. This stems from the fact that the moderated climate within the envelope and the absence of normal weathering (ultraviolet degradation, expansion/contraction, freeze/thaw, wet/dry, wind and dust degradation, etc.) can change the whole approach to building within the enclosure. Materials normally utilized only on interiors may form the "exterior" surfaces of the enclosed structures. A high-embodied-energy material such as face brick, which is prized for its appearance and durability, would no longer be necessary within the enclosure. A substitute with similar appearance and durability within the envelope might be composed of a 1/2 in. thick veneer of vitrified tiles (i.e., brick) bonded to gypsum board and cellular paper stress skin panel. Another area of important materials trade-off would be in the area of roofing. Materials not now used because of excessive expansion/contraction or ultraviolet degradation could be considered. Snow loads which cause heavier roof construction in some parts

of the country would be eliminated. However, due to the significantly higher population density, roofs may be converted to usable "outdoor" open space. The structure supporting such roofs may, in fact, be heavier than that required for normal roofs; however, the waterproofing requirements would be much less demanding.

Specific examples need to be developed in detail in order to quantify the change in embodied energy. This, too, is beyond the scope of this project.

6. HYPOTHETICAL LCME FOR MODELING CLIMATE MODERATION

Potential structural systems that could be utilized in creating LCMEs include geodesic domes, inflated structures, and various tension structures utilizing a fabric membrane to form the envelope.

In order to inexpensively model the climate-moderating potential of an LCME, an envelope had to be developed that would both reasonably resemble a potential prototype and lend itself to modeling with existing computer codes. Most of the computational fluid dynamics tools available at Oak Ridge National Laboratory were developed for rectangular two-dimensional geometries. However, circulation within an isosceles right triangle cross section can be estimated using a slight modification of the computer code ORSMAC (reference 6.1). An isosceles right triangle cross section reasonably approximates the cross section of a tension structure. With this in mind, a 450-m by 750-m envelope was developed (Figure 6.1). The basic module was 75-m by 150-m by 85-m high in the form of a right angle prism. This right angle prism shape was chosen to allow the envelope to be modeled with the existing but slightly modified ORSMAC computer code. The structure was to consist of 85-m-high pylons interlaced with cables over which a Teflon-coated fiberglass fabric would be stretched. The overall size of the envelope was made big enough to house most potentially viable functions. In addition, this size was chosen to minimize the possibility of three-dimensional flow patterns in our study module which cannot be modeled with ORSMAC.

In reality, a large fabric-covered tension structure would look somewhat different (Figure 6.2). A major change would be a significantly reduced height-to-width ratio. The lower structure would enclose more space with less material and reduce the sail effect of a tall structure in the wind. The studies, to date, indicate that this change may not materially affect the heat transfer phenomena observed in the model.

Another change would be the general shape of the envelope. The support cables would form a catenary between pylons providing broad sweeping curves to the structure. The fabric cover also requires two-directional stretching in order to maintain its structural integrity. This stretching is most easily accomplished in a curved format. In short, an actual LCME would have a very complex geometry by comparison to the hypothetical one investigated.

ORNL-Photo 5921-81

Figure 6.1

THIS HYPOTHETICAL LCME WAS DEVELOPED TO ALLOW
MODELING WITH EXISTING COMPUTER CODES.

ORNL-Photo 5922-81

Figure 6.2

PROBABLE CROSS-SECTIONAL GEOMETRY OF AN LCME.

An existing computer code, SALE (Simplified Arbitrary Lagrangian-Eulerian, reference 6.2), developed at Los Alamos National Laboratory (LANL), has the potential of modeling these complex geometric forms. As a part of this project, SALE was implemented on Oak Ridge computers. More experience with the code and some modifications to allow LCME calculations are required before modeling of the complex geometries inherent in LCMEs can be done with confidence. Thus, it was felt that a somewhat less costly, more basic analysis should be done to determine what level of climate moderation could be expected from an LCME before proceeding with a detailed analysis of complex geometries. These basic analyses have also served to identify the energy transfer mechanisms which will prove invaluable when further work is done in this area.

7. CALCULATION OF FLUID CIRCULATION WITHIN A HYPOTHETICAL LCME

The energy budget for an LCME depends on energy exchange with the atmosphere and the earth and on the storage of energy within the enclosure. Energy exchange takes place due to radiation through the translucent structure and radiation between the fabric, enclosed buildings and the ground and on internal heat generation. The solar loading and losses to the night sky are major elements in the energy budget for an LCME. The heating of the LCME interior fluid by people, lighting, and appliances is not included in this preliminary analysis. This component of the energy budget could be significant in some circumstances. The term "energy budget" is used in this report to mean a detailed accounting for the heat losses and gains from various phenomena internal and external to the LCME envelope. Finally the fluid enclosed by an LCME is not a stagnant insulator. Buoyancy-induced circulation may act to promote or destroy stratification even in a "sealed" LCME. Strategies which allow selective venting using buoyancy forces may contribute to savings in maintaining a benign climate within the LCME.

Thus, the energy exchange mechanisms must be analyzed as a part of any evaluation of LCMEs. In this report, we have divided the analysis into two areas, which will be described separately. First, the energy exchange at the boundaries of the enclosure is analyzed, including radiation and convection at the ground and at fabric surfaces and including estimates of effects of sun, night sky and wind. This heat transfer model (hereafter called the LCME model) depends on meteorological data, interior fluid temperatures and velocities and physical properties of fabric and earth. The model is "driven" by solar cycles. The fluid dynamics model depends on the geometry of the LCME and is "driven" through the buoyancy of fluid heated by the heat transfer model at the boundaries of the LCME. The heat transfer model and the fluid dynamics therefore are mutually dependent; an analysis of the energy budget for an LCME requires the simultaneous solution of both models. The models, the technique for obtaining a solution, and some typical solutions are described in the following sections.

8. ADAPTING A CONVENTIONAL (RECTANGULAR REGION) HYDRODYNAMICS CODE TO SIMULATE A FLOW IN A TRIANGULAR REGION

Most computer codes which solve some versions of the Navier-Stokes equation have been designed to obtain a solution within a rectangular region. Thus, the choice of programs to be used in a first evaluation of the energy budget for an LCME was limited. A "general quadrilateral mesh" code applicable to an LCME of arbitrary cross section could be obtained; time and budget targets would require its application without local experience. Alternatively, a code already in use locally might be adapted to simulate a simplified LCME. The latter approach has been used.

The code ORSMAC, an Oak Ridge extension of the simplified Marker and Cell technique (SMAC, reference 8.2) developed at the Los Alamos National Laboratory, was selected. The advantage, as mentioned above, was a base of familiarity and experience with the code. As a disadvantage, a number of compromises with the physics and probable geometry of an LCME were required. ORSMAC is a two-dimensional (Cartesian) code developed to analyze the interaction between the hot water discharged from a power plant and a flowing cool river. Thus, a basically incompressible fluid is treated, with fluid buoyancy modeled using the Boussinesq approximation. Further, portions of the energy equation (the "work" terms) were omitted as being negligible for an incompressible fluid. Neglect of these terms is questionable for air when large (several tens of meters) elevation changes are involved.

In the following sections, the adaptation of the ORSMAC code to calculate the fluid circulation in an isosceles right triangle is described, and results from the code are compared to experimental data for flow in a small chamber having a triangular cross-section.

Adapting ORSMAC for a Triangular Region

The ORSMAC incompressible hydrodynamics code was designed to handle rectangular or square problem regions. A square region showing portions of the computational mesh is sketched in Figure 8.1. The triangular problem region is also shown. Basically the scheme is to create two identical circulation patterns, one on each side of the diagonal (symmetry plane) shown on the sketch. In a sense, this is wasteful, with the necessary calculations being done twice. The payoff is in avoiding the expense of developing a special code or implementing a "general quadrilateral" code.

The identical flows were induced by a careful imposition of symmetries in the boundary conditions and in the gravity. The ORSMAC computer code was modified so the conditions imposed at surface AC were exactly duplicated on surface AB. Similarly, the conditions imposed on CD were exactly duplicated on BD. Due to the modular structure of the code, these changes were easily made. The imposition of symmetry was completed by reversing the direction of gravity on opposite sides of the symmetry plane

SKETCH SHOWING SYMMETRY
PLANE, COMPUTATION MESH, CIRCULATION
(UPPER LEFT) AND IMAGE (LOWER RIGHT)

Figure 8.1

IDEALIZED LCME FOR PRELIMINARY CALCULATIONS

as shown in the sketch. Thus hot buoyant fluid would rise from the ground towards the roof of the LCME in both flows.

In a purely mathematical solution, these symmetries would be sufficient to maintain two identical patterns. Numerically, roundoff within the computer and problems of calculation sequence were found to induce occasional asymmetries (flow across the symmetry plane). These were corrected by forcefully imposing symmetry on the fluid temperature and fluid pressure.

Boundary Layer Modeling

Convective heat exchange between the fabric and interior air contributes to the temperature differences which drive the fluid circulation. In order to simulate the convection in a conventional manner, a very small finite difference mesh would be used near the fabric to resolve the velocity and temperature gradients through the boundary layers. Since ORSMAC uses a constant mesh spacing, an enormous number of computational cells would be required to simulate an entire LCME. This was simply impossible due to the costs. As an alternative, the boundary layer behavior has been modeled, and numerical resolution was replaced by an analytic expression for the heat transfer across the layer. In this application, simple correlations for the heat transfer coefficient for flow along a flat plate have been used. The effect of boundary drag at the fabric-air interface has been neglected. The assumption here is that the core circulation within the LCME dominates the behavior of the boundary layers. That is, buoyancy within the boundary layers is negligible compared to the forcing influence of the interior flow. Put another way, the boundary layers are characteristic of forced convection.

Comparison of ORSMAC Results to Experiment

Since simulation of flow in a triangular enclosure involves extensions to the usual, rectangular region applications of ORSMAC and the boundary layer models used are not normally used for natural convection, an experimental test of these ideas is very desirable. Fortunately Flack and co-workers at the University of Virginia (references 8.3 and 8.4) have obtained measurements of velocity, temperature and heat flux within an enclosure having a right isosceles triangle as a cross-section. In this section, results from ORSMAC are compared to that data.

In Flack's experiments, a prismatic enclosure was used. The prism was oriented such that the hypotenuse of the triangular cross section was horizontal. The base was made of Bakelite and was heavily insulated. Air above the base was trapped by aluminum plates which formed the short sides of the triangle. One plate was maintained at 0°C by a stirred tank of ice water attached to the plate. The second plate was maintained at a (higher) uniform temperature by a tank of heated and stirred water. The ends of the prism were constructed of optical glass. The slant height of the enclosure was 108 mm. The length of the prism (normal to the triangular

cross section) was 254 mm. Velocity data were obtained using a Wollaston prism Schlieren interferometer. For the results of interest for this work, the flow was laminar. The flow was clearly two-dimensional.

Due to limited funding, the computer simulation of Flack's experiment was only qualitative. The most obvious discrepancy was in the boundary layer model used. No shear stress was applied at the boundaries of the system. The circulation driver is the buoyancy, which is proportional to the volume of fluid. The retarding force is the wall shear, which is proportional to the surface area. Thus the model constructed for the LCME neglected the drag, since the volume/surface area ratio was quite large. For Flack's experiment, the ratio was much smaller and the wall shear should be included in the numerical simulation. Similarly, turbulent boundary layers are expected in the LCME; thus the boundary heat transfer coefficient was based on turbulent flow. In Flack's experiment, the conditions were laminar. These conditions could be easily changed in the computer code to resolve the discrepancies between the model and the experiment. Test conditions are summarized in Table 8.1. The LCME flows will be in the turbulent regime (Grashof numbers above 10^7 usually result in turbulent flows) while Flack's flows were observed to be laminar.

In Figure 8.2a, velocity vectors taken from the ORSMAC calculation are shown. In Figure 8.2b, the data obtained by Flack are shown (not to the same scale). Clearly the general structure of the flow, including the direction of circulation and the "dead" region, is the same. The lack of a drag model shows in the shape of the numerical profile, which has its maximum near the boundary.

In Figure 8.3a, isotherms are shown as taken from the ORSMAC calculation. In Figure 8.3b, the isotherms calculated by Flack are shown. The isotherms reported by Flack were generated by a hot-bath temperature of 64C; the velocity data were generated using 49C. Since computer funds were limited, only the conditions appropriate for the velocity-measuring experiment were simulated. The computed isotherms shown in Figure 8.3 are for 49C. Despite this difference the structure of the flow is seen to be qualitatively similar. The flow is stratified, with large temperature drops across the boundary layers and horizontal isotherms in the interior. In the numerical results, the thermal boundary layers are qualitatively correct even though they are not resolved.

Symmetry of the calculated flow field about the ground (diagonal) plane was satisfactory throughout the calculation.

Clearly, the comparison of the computed results with the experimental results shows the potential utility of modeling rather than resolving boundary layers. The qualitative verification of flow direction and structure in the temperature is encouraging.

Table 8.1

Relevant Physical and Numerical Parameters for
Flack's Experiments and the LCME

	<u>Flack's Experiments and Simulation</u>	<u>Simulation LCME</u>
$GR = g \beta \cos \gamma \Delta T L^3 / \nu^2$	6.5, 5.6 x 10 ⁶ *	$\sim 5 \times 10^{14}$
$PR = \rho \nu \bar{c}_p / k$	0.709	0.709
Slant length, L (meters)	0.108	100.0
Range of ΔT (C)	63, 48*	-8 to +7
Computing mesh	20 x 20	10 x 10
γ (rad)	$\pi/4$	$\pi/4$

*Velocities were reported for $\Delta T = 63$
Temperatures were reported for $\Delta T = 48$

g = gravitational constant

β = coefficient of thermal expansion of gas

ν = fluid viscosity

ρ = fluid density

c_p = fluid specific heat

k = fluid conductivity

ORNL-DWG 81-20498

Figure 8.2
COMPARISON OF CALCULATED AND MEASURED VELOCITIES
WITHIN A TRIANGULAR ENCLOSURE

(a) CALCULATED ISOTHERMS

(b) MEASURED ISOTHERMS (REF 8.4)

Figure 8.3

COMPARISON OF CALCULATED AND MEASURED
ISOTHERMS WITHIN A TRIANGULAR ENCLOSURE

9. LCME HEAT TRANSFER BOUNDARY CONDITION CODE

The detailed heat transfer boundary condition routines were designed to supply the necessary boundary conditions to the ORSMAC code for the thermo-hydraulic analysis of an LCME to determine potential energy benefits of the LCME concept. These routines were utilized in two ways. First, selected climatic conditions were analyzed using the coupled ORSMAC/LCME codes to evaluate the movement of energy and fluid within the prototype structure.. Second, an independent analysis was made using the LCME, with simplifying assumptions on the interior fluid velocities and temperatures replacing the ORSMAC code. The simplified model for the interior fluid circulation was devised using knowledge gained from the complete ORSMAC/LCME calculations. With this exception, the heat transfer boundary condition models use the same models and parameters for both types of analyses.

Determination of Representative Sites

The goal of site determination was to provide somewhat representative sites for summer- and winter-dominated climates. All the necessary environmental data must also be available for the chosen sites. The sites chosen were San Antonio, Texas, and Madison, Wisconsin.

External Climate Conditions

Due to excessive computational time requirements, ORSMAC/LCME could not be utilized to analyze a full year with actual or Test Reference Year weather data. Instead, representative days were analyzed using idealized functions for the daily variation of outside air temperature, insolation, and effective thermal radiation temperature of the sky. All seasonal parameters used are reported in Table 9.1. Due to budget limitations, only two days (January 21 and July 21) were analyzed with the ORSMAC/LCME code. Four representative days were analyzed with the LCME code.

The outside air temperature was modeled as sinusoidal with the same daily maximum and minimum temperature as normal for the month and location modeled (reference 9.1). The chosen function closely approximates the statistical hourly variation given in reference 9.2 and is shown in equation 9.1 and Figure 9.1.

$$T_o = T_{om} - T_{do}(1 + \sin((t+a)/c))/2 \quad (9.1)$$

where

T_{om} = normal maximum daily temperature for
month and location modeled

T_{do} = normal daily temperature change

Table 9.1

LCME Boundary Conditions

Normal Daily Values

	<u>Winter</u> <u>January 21</u>	<u>Spring</u> <u>April 21</u>	<u>Summer</u> <u>July 21</u>	<u>Fall</u> <u>October 21</u>
<hr/>				
San Antonio, Texas		Lat: 29.5°	Lon: 99.5°	
AIR: Max	289.4(61.6)	299.8(80.3)	308.3(95.6)	300.7(81.8)
Change	12.1(21.8)	11.9(21.5)	12.1(21.8)	12.6(22.6)
GROUND: 2m	289.1(61)	291.3(65)	300.0(81)	298.0(77)
PERCENT INSOLATION	49	56	76	66
WIND SPEED	6.3 (14)	4.75 (10.5)	3.15 (7)	4.75 (10.5)
Madison, Wisconsin		Lat: 43°	Lon: 89°	
AIR: Max	269.3(25.4)	286.7(56)	300.4(81.4)	279.1(43)
Change	9.6(17.2)	11.9(21.4)	12.6(22.6)	9.2(16.6)
GROUND: 2m	275.8(37)	278.0(41)	289.7(62)	287.4(58)
PERCENT INSOLATION	48	52	69	57
WIND SPEED	6.3 (14)	4.75 (10.5)	3.15 (7)	4.75 (10.5)
NOTE: Temperature - K (F)				
Wind Speed - m/s (MPH)				
<hr/>				

OUTSIDE AIR TEMPERATURE
DIURNAL CYCLE

FIGURE 9.1

DIURNAL TEMPERATURE CYCLE USED IN THE LCME AND ORSMAC/LCME
COMPARED WITH STATISTIC DATA IN REFERENCE 9.1

$$\begin{aligned}
 a &= 10800 \\
 c &= 43200/\pi \\
 t &= \text{time (seconds since midnight)}
 \end{aligned}$$

a and c were chosen to achieve the fit with the statistical data shown in Figure 9.1

The exterior wind speed was assumed to be constant during each day as shown in Table 9.1. The wind speed and air temperature were used to determine an average heat transfer coefficient as shown in equation 9.2 and applied to both exterior sides of the LCME.

$$h_e = .0584 N_{Re} N_{Pr} k_f / L \quad (9.2)$$

where

$$\begin{aligned}
 N_{Re} &= \rho W L / \mu \\
 N_{Pr} &= \mu c_p / k_f \\
 k_f &= \text{thermal conductivity of fluid} \\
 W &= \text{wind speed} \\
 L &= \text{length of fabric side} \\
 \rho &= \text{fluid density} \\
 \mu &= \text{fluid viscosity} \\
 c_p &= \text{fluid specific heat}
 \end{aligned}$$

The insolation was modeled as in reference 9.2 for a normal day including seasonal variations, geographic location and orientation of the surface and is repeated in equation 9.3 with reference to Figure 9.2.

$$I_o = (I_{dn} P_n \cos \theta) + I_d \quad (9.3)$$

where

$$\begin{aligned}
 I_{dn} &= \text{direct normal incident solar radiation, } w/m^2 \\
 I_{dn} &= A e^{-B/\sin \beta}
 \end{aligned}$$

FIGURE 9.2

DEFINITION OF PARAMETERS FOR INSOLATION MODEL

θ = angle of incidence of insolation with surface perpendicular

$$= \cos^{-1} (\cos \beta \cos \gamma \sin \Sigma + \sin \beta \cos \Sigma)$$

I_d = diffuse insolation from the sky = cI_o

P_n = normal percent of maximum insolation observed

A,B = constants in Table 9.2

β = solar azimuth

$$= \sin^{-1} (\cos L \cos H + \sin L \sin S)$$

L = latitude

S = solar declination

H = solar hour = 360 - AST

AST = solar time = TH + EOT + 4(TZL-L)

EOT = equation of time constant from Table 9.2

TZL = local time zone longitude

TH = local standard time

Σ = tilt angle

γ = $\phi + 4$ before noon

= $\phi - 4$ after noon

ϕ = $\sin^{-1} (\cos S \sin H / \cos \beta)$

= surface azimuth angle

These expressions are general and can model an LCME at any orientation and with a very complex geometry. The results presented in this report are restricted to an LCME with an east-west primary axis. Reference 9.2 includes a diffuse radiation model which was assumed to impact both faces of the LCME equally. The component of insolation reflected from the surroundings has been ignored in these analyses. The idealized solar insolation model assumed normal day conditions for the twenty-first day of the month modeled.

Table 9.2

Solar Radiation Intensity and Related Data

	EOT	S	A	B	C
	min	deg	w/m ²	--	-
January	-11.2	-20	390	.142	.058
February	-13.9	-10.8	385	.144	.060
March	- 7.5	0.0	376	.156	.071
April	1.1	11.6	360	.180	.097
May	3.3	20	350	.196	.121
June	- 1.4	23.45	345	.205	.134
July	- 6.2	20.6	344	.207	.136
August	- 2.4	12.3	351	.201	.122
September	7.5	0.0	365	.177	.092
October	15.4	-10.5	378	.160	.073
November	13.8	-19.8	387	.149	.063
December	1.6	-23.45	391	.142	.057

The insolation transmitted through the fabric was assumed to be diffuse with the transmissibility dependent on the angle of incidence as shown in equation 9.4 and indicated by reference 9.3

$$I_t = t I_o \cos \theta \quad (9.4)$$

t = transmissibility of fabric ~ 0.2 .

Since the transmitted insolation should be diffused, the insolation incident on the ground was determined by integrating along the fabric surface and was equally distributed over the ground surface.

The thermal radiation exchange between the fabric and sky, Equation 9.5, is a function of many atmospheric conditions but can be considered to be primarily a function of the outside air temperature (reference 9.4) as shown in equation 9.6.

$$q_{\text{sky}} = \epsilon \bar{\sigma} (T_{\text{sky}}^4 - T_{\text{fab}}^4) \quad (9.5)$$

where

$\bar{\sigma}$ = Stefan-Boltzmann constant = $5.6697 \times 10^{-8} \text{ w/(m}^2\text{K}^4)$

ϵ = emissivity of fabric = .14

T_{fab} = fabric temperature

$$T_{\text{sky}} = .055 T_o^{1.5} \quad (9.6)$$

T_o = air temperature K

Fabric Heat Balance Model

The fabric temperature was calculated from the steady-state heat balance in equation 9.7 with material properties as shown in Table 9.3. The time constant and the stability criterion for a transient explicit calculation of the fabric temperature can be much smaller than the time step to be taken in the ORSMAC/LCME calculations. A steady-state equation was chosen to insure stable calculation of sufficiently accurate fabric temperatures.

$$T_{\text{fab}} = (U_e T_e + U_i T_f + Q_{\text{sa}} + Q_{\text{thn}}) / (U_e + U_i) \quad (9.7)$$

Table 9.3 ,

Thermophysical and Optical Properties

FABRIC:

Specific Heat	(2000)* ws/kgC
Density	$(7.629 \times 10^3)^*$ kg/m ³
Conductivity	(.151)* w/mC
Thickness	$8.1 \times 10^{-4} - 9.7 \times 10^{-4}$ m
Absorptivity	.14 - .2
Transmissibility	.2
Reflectivity	.6 - .7

EARTH:

Specific Heat	962. ws/kgC
Density	2098 kg/m ³
Conductivity	1.3 w/mC
Absorptivity	.9
Reflectivity	.1

AIR:

Specific Heat	1006 ws/kgK
Density	1.41 kg/m ³ at 20C
Conductivity	.0227 w/mC
Viscosity	1.488×10^{-5} kg/ms
Prandtl Number	.73

*Not necessary for fabric analysis.

where

$$U_e = h_e DF$$

$$U_i = h_i DF$$

$$Q_{sa} = I_o a DF$$

$$Q_{thn} = \text{thermal radiation from within enclosure absorbed by fabric}$$

$$DF = \text{length of fabric node}$$

$$a = \text{absorptivity}$$

$$h_i = \max (h_f, h_n, k_f/DR/2)$$

$$h_n = \text{natural convection heat transfer coefficient } w/cm^2K$$

$$= c_1 (N_{Gr} N_{Pr})^{m_1} k_f/DR$$

$$N_{Gr} = g(DR^3 \rho^2)/(-T_f \mu^2)$$

$$N_{Pr} = .72$$

$$C_{1,m_1} = \text{as defined in Table 9.4}$$

$$DR = \text{ORSMAC node spacing}$$

$$k_f = \text{fluid thermal conductivity}$$

$$h_f = \text{forced convection coefficient } w/cm^2K$$

$$= 0.0292 N_{Rex} N_{Pr} k_f/X$$

$$N_{Rex} = \rho V X / \mu$$

$$X = \text{distance from corner along velocity vector } m$$

$$V = \text{velocity along fabric } m/s$$

$$T_f = \text{fluid temperature}$$

Figure 9.3 is a graphic representation of the interaction of the fabric with insolation and is used by the courtesy of Chemical Fabrics, Inc.

Ground Heat Transfer Model

To simulate the heat storage effect of the earth beneath the LCME a two-dimensional transient heat conduction finite difference model of a two-meter thick slab of average soil was used (see Table 9.3). The heat exchanged with the fabric and sky and absorbed from the sun were assumed to

Table 9.4

Parameters for Heat Transfer Correlations

<u>Condition</u>	<u>C_1</u>	<u>m_1</u>
Laminar ($G_r P_r < 2 \times 10^7$)		
Heated from above/cooled from below	0.54	0.25
Heated from below/cooled from above	0.27	0.25
Turbulent ($G_r P_r > 2 \times 10^7$)	0.14	0.333

FIGURE 9.3

ENERGY BALANCE OF A SHEERFILL FABRIC ROOF ELEMENT

be exchanged with the surface cell. The heat exchanged with the interior fluid was assumed to be either forced or natural convection or conduction as in equation 9.8.

$$h_g = \max (h_{fg}, h_{ng}, k_f/DR/3) \quad (9.8)$$

where

$$h_{ng} = C_1 (N_{Gr} N_{Pr})^{m_1} k_f/S_b$$

$$N_{Gr} = g(S_b \rho_{ag})/(T_{FGAV}^2)$$

$$S_b = \text{length of base of LCME}$$

$$\rho_{ag} = \text{average density along base}$$

$$T_{FGAV} = \text{average of fluid temperature along base}$$

$$h_{fg} = .0584 N_{Rel} N_{Pr}^{-.333} k_f/S_b$$

$$N_{Rel} = \rho V S_b/\mu$$

$$V = \text{average of the absolute value of the velocity along the ground}$$

The slab of ground was assumed to be adiabatic at the ends and have a specified temperature at the two-meter depth. This specified temperature is a function of the geographic location and season (Table 9.1) and boundary conditions were chosen to represent normal conditions (e.g., moisture, thermal gradients) for uncovered ground to provide an estimate for the amount of heat stored in the earth mass. These conditions may no longer exist after the LCME has been in place for some time. In fact, considerable heat storage in the ground from one season to the next may be possible. The effect of this storage is difficult to estimate.

The finite difference equations are reproduced in equations 9.9 and 9.10.

For $j=1$

$$T_{g_{i,1}}^{n+1} = T_{g_{i,1}}^n + \frac{dt}{\rho_g c_p D G D I} \left[\begin{aligned} &Q_{ga} + Q_{th} + h_i (T_f - T_{g_{i,1}}^n) \\ &+ k_g D I / D G (T_{g_{i,2}}^n - T_{g_{i,1}}^n) \\ &+ k_g D G / D I \{ (T_{g_{i+1,1}}^n - T_{g_{i,1}}^n) + (T_{g_{i-1,1}}^n - T_{g_{i,1}}^n) \} \end{aligned} \right] \quad (9.9)$$

For $j > 1$

$$T_{g,i,j}^{n+1} = T_{g,i,j}^n + \frac{dt}{\rho_g c_p DG DI} \left[\begin{aligned} & k_g DI/DG \{ (T_{g,i,j+1}^n - T_{g,i,j}^n) + (T_{g,i,j-1}^n - T_{g,i,j}^n) \} \\ & + k_g DG/DI \{ (T_{g,i+1,j}^n - T_{g,i,j}^n) + (T_{g,i-1,j}^n - T_{g,i,j}^n) \} \end{aligned} \right] \quad (9.10)$$

dt = time step size

T_g = ground temperature

k_g = ground thermal conductivity

DG = grid spacing into depth of slab

DI = grid spacing along slab

ρ_g = ground density

C_p = ground heat capacity

Q_{ga} = insolation absorbed by ground

Q_{th} = thermal radiation within enclosure absorbed by ground

Subscript

i = index along base

j = index into depth

Superscript

n = time step number

Radiant Exchange Within the Enclosure

The radiant exchange between the ground and the inside surfaces of the membrane was calculated by an approximation for the network method (reference 9.5). This approximation was developed to reduce the computational costs of the analysis and compared well with the results from a Radiosity (reference 9.6) technique for the same LCME geometry, grid

spacing, time step, exterior environment and radiation properties. The geometric exchange factors were calculated by the Hottel cross string method (reference 9.5) for long gray enclosures (essentially a two-dimensional cavity). The approximate method calculates the net radiant energy flow between surfaces with the same equation as the network method, except that the geometric exchange factors incorporate only the primary radiant energy path between the two surfaces. The alternate paths of reflecting off of other surfaces have been neglected. These reflections may be relatively unimportant due to the high ground absorption ($\epsilon=.85$) and the uncluttered interior of the LCME enclosure.

$$Q_{ij} = \frac{\bar{\sigma} A_i (T_j^4 - T_i^4)}{R_{ij}} \quad (9.11)$$

$$R_{ij} = \left(\frac{\rho_i}{A_i \epsilon_i} + \frac{\rho_j}{A_j \epsilon_j} + \frac{1}{A_i F_{ij}} \right) \quad (9.12)$$

where

ϵ_i = emissivity of surface i

F_{ij} = view factor from surface i to j

ρ_i = reflectivity for surface i

A_i = area of surface i

T_i = temperature of surface, i (either fabric or ground)

Simplified Interior Fluid Model

To enable independent analysis with the LCME code, a set of simplified assumptions about the interior fluid conditions were used. The velocity was assumed to be a function of the time of day and location within the LCME as in the following equations.

$$U_t = V' \sin(t + a)/c \quad (9.13)$$

The velocity along base of the LCME.

$$U = U_t (-\sin(s/S_b) - \cos(s/S_b)) \sqrt{2}/2 \quad (9.14)$$

where

s = distance from $x = 0, y = 0$ corner.

The velocity along the fabric

$$V = U_t \quad (9.15)$$

The maximum velocity, V' , was assumed to be .02m/s, which gives the best agreement with the ORSMAC/LCME calculation of temperature within the enclosure. The interior fluid temperature was calculated assuming instantaneously mixed fluid with heat exchange by convection with the fabric and ground. The assumption of perfect mixing is in agreement with ORSMAC/LCME results.

One design option investigated was a simple venting scheme. During seasons when the LCME interior air temperature was below the comfort zone, the interior air was allowed to mix with the outside air whenever the outside air was warmer. During warmer seasons this scheme was reversed. The vents were assumed to be large enough to allow 0.2 air changes per hour with the exterior air.

Initial Conditions

The transient analysis of LCME usually achieves a near periodically repeating solution within six to ten 24-hour cycles with the following initial conditions. The initial interior fluid temperature is set to the mean outside temperature. The ground temperature is set to the temperature at two meters at depths greater than 0.8m. The surface temperature is as in equation 9.16.

$$T_{\text{sur}} = T_B + (T_{\text{OA}} - T_B)(.8) \quad (9.16)$$

T_B = ground temperature at 2 m

T_{OA} = daily mean outside air temperature = $(T_{\text{O max}} + T_{\text{O min}})/2$

The initial interior velocity for the ORSMAC/LCME analysis was set to zero. The LCME independent analysis set the velocity as in equations 9.13 through 9.15.

10. DISCUSSION OF RESULTS

ORSMAC/LCME Code

Using the ORSMAC/LCME code, daily temperature variations were calculated for an LCME located in San Antonio, Texas, for two seasonally typical days. Model parameters are given in Figure 10.1. Figure 10.2 presents the calculated temperature variation for January 21 (chosen to be characteristic of the winter season). The daily swings in interior air and ground temperature are smaller than the conditions exterior to the LCME and their peaks are slightly later in the day. The Daily Mean Temperature (DMT) for the interior conditions is somewhat greater than for the exterior conditions. The DMT is the average between the daily maximum and minimum temperatures.

The Degree Day (the difference between the DMT and the appropriate comfort temperature target) has been widely used as a simplified method of correlating energy consumption for habitation conditioning with the exterior conditions. The comfort temperature targets (65F and 78F) are shown as horizontal lines on the diurnal temperature plots. The Degree-Day (DD) is an approximate method of determining energy consumption. The more realistic one-year transient using Test Reference Year weather data cannot be analyzed with the present ORSMAC/LCME.

The ORSMAC/LCME diurnal temperature results are compared with the LCME independent analysis results in Figure 10.3. The comparison is especially good for the ground surface average temperatures. The interior air temperature comparison is the best that could be achieved with the present simplified interior air flow models as will be shown below.

Figures 10.4 and 10.5 present the succession of the transient analyses to the steady periodic conditions for January 21. The convergence to the steady periodic conditions of the LCME results (Figure 10.5) is excellent, and this performance can be used to estimate the response of the interior to rapid environmental changes. The response time is chosen to be the time that it takes the interior DMT to reach one-half of its change to the steady-periodic value. The response time is estimated at three days from Figure 10.5.

The convergence of the ORSMAC/LCME simulation for January 21 is not complete. However, based on experience with earlier developmental analyses and the longer run and better converged summer analysis, these results contain most of the features of a converged flow. Additional diurnal cycles could not be calculated due to budget limitations.

Selected diurnal interior velocities for both calculation techniques are presented in Figure 10.6. In general, the ORSMAC/LCME velocities are small and appear to have a smooth behavior only during the day. At night, the normal value is somewhat greater but less repeatable from one 24-hour calculational cycle to the next. This lack of repeatability is due to the very complex nature of the turnover of the interior air that occurs after

FIGURE 10.1

LCME MODEL

DWG. NO. K/G-81-1874
(U)SAN ANTONIO, JAN 21
ORSMAC/LCME TEMPERATURES
STEADY PERIODIC CONDITIONS

FIGURE 10.2

DIURNAL TEMPERATURE VARIATIONS CALCULATED BY
THE ORSMAC/LCME CODE FOR STEADY PERIODIC CONDITIONS

DWG. NO. K/G-81-1889
(U)

FIGURE 10.3

ORSMAC/LCME RESULTS COMPARED WITH LCME RESULTS
USING AN INTERIOR VELOCITY MAXIMUM OF 0.02 m/s

DWG. NO. K/G-81-1888
(U)SAN ANTONIO, JAN 21
ORSMAC/LCME INTERIOR FLUID TEMPERATURE

FIGURE 10.4

TEMPERATURE VARIATIONS FOR SUCCESSIVE 24-HOUR CYCLES
DURING THE SIMULATION TO ACHIEVE STEADY PERIODIC CONDITIONS

SAN ANTONIO JAN 21
LCME INTERIOR TEMPERATURE
SUCCESSIVE 24 HOUR CYCLES

DWG. NO. K/G-81-1887
(U)

FIGURE 10.5

TEMPERATURE VARIATIONS FOR SUCCESSIVE 24-HOUR
CYCLES DURING THE SIMULATION TO ACHIEVE STEADY
PERIODIC CONDITIONS WITH THE LCME CODE

DWG. NO. K/G-81-1886
(U)SAN ANTONIO, JAN 21
VELOCITIES

FIGURE 10.6

FLUID VELOCITIES WITHIN AN LCME
FROM THE ORSMAC/LCME AND LCME COMPUTER CODES

midnight. The LCME velocity function models the reversal of flow direction in a smooth, steady, periodic manner and does not match the nighttime velocities. It is interesting to note that this function, although determined prior to obtaining ORSMAC/LCME results follows the velocity trend during the day very well. A better velocity function should improve the comparison between the two techniques. However, much experience with calculational and experimental flows in large, complex geometry enclosures must be obtained before generalized velocity functions can be determined.

The LCME velocity function was chosen to represent a double circulation pattern. The circulation strength was assumed to vary during the 24-hour cycle with the same function as the outside air temperature. The maximum value of this function was determined by comparison with early ORSMAC/LCME results. Figures 10.7 and 10.8 present the comparison with the current ORSMAC/LCME results. Although the agreement is not perfect, it was the best that could be achieved within the scope of this project and is accurate enough for the goal of determining if the LCME has any potential energy benefit.

The second ORSMAC/LCME analysis was for a summer representative day, July 21. These results are summarized in Figure 10.9. The unvented LCME does not appear to offer any energy benefits since the DMT for both ground and air is greater than the exterior conditions, thus actually requiring more air conditioning. Although this configuration increases energy consumption, this analysis was vital to validate the LCME analysis to which it is compared in Figure 10.10. The venting of the LCME was a very obvious design option suggested by this overheating. The ORSMAC/LCME could not easily model the vented condition but with the simplified assumptions for the interior air temperature the LCME code could model such a condition. This analysis is discussed below.

The progression of the transient analyses demonstrate the convergence to steady periodic conditions (Figures 10.11, 10.12). The estimated response time of two to three 24-hour cycles is somewhat shorter than for the winter analysis.

The summer ORSMAC/LCME velocities, Figure 10.13, are virtually identical to the winter analysis during the period from the ninth to the eighteenth hour and have nearly the same positive values during the night hours. The summer analysis has a more violent reversal of flow and achieves greater negative velocities. The velocities are still low compared to the mean exterior wind of 4.08 m/s. The assumed constant wind velocity for this analysis as shown in the Weather Data Table (Table 9.1) was 4.75 m/s. The maximum interior velocity observed during the whole ORSMAC/LCME transient was 0.225 m/s.

Table 10.1 contains a comparison of the energy budget for the ORSMAC/LCME and LCME analyses for a 24-hour cycle under steady periodic conditions.

DWG. NO. K/G-81-1884
(U)COMPARISON OF INTERIOR AIR TEMPERATURE
SAN ANTONIO, JAN 21
LCME RESULTS

FIGURE 10.7

COMPARISON OF INTERIOR AIR TEMPERATURES CALCULATED
BY THE ORSMAC/LCME CODE WITH THOSE CALCULATED
BY THE LCME CODE USING THREE INTERIOR VELOCITIES

DWG. NO. K/G-81-1885
(U)COMPARISON OF GROUND TEMPERATURES
SAN ANTONIO, JAN 21
LCME RESULTS

FIGURE 10.8

COMPARISON OF GROUND TEMPERATURES
CALCULATED BY THE LCME CODE USING DIFFERENT
INTERIOR VELOCITIES WITH ORSMAC/LCME RESULTS

**ORMSAC/LCME TEMPERATURES
SAN ANTONIO, JULY 21
STEADY PERIODIC CONDITIONS**

FIGURE 10.9

DIURNAL TEMPERATURE VARIATIONS CALCULATED BY THE
ORMSAC/LCME CODE FOR STEADY PERIODIC CONDITIONS

DWG. NO. K/G-81-1875
(U)COMPARISON OF LCME WITH ORSMAC/LCME RESULTS
SAN ANTONIO, TEXAS
JULY 21

FIGURE 10.10

ORSMAC/LCME RESULTS COMPARED WITH LCME RESULTS
USING AN INTERIOR VELOCITY MAXIMUM OF 0.02 m/s

SAN ANTONIO, JULY 21
INTERIOR FLUID TEMPERATURE
ORMSAC/LCME RESULTS

FIGURE 10.11

TEMPERATURE VARIATIONS FOR SUCCESSIVE 24-HOUR CYCLES DURING
THE ORSMAC/LCME SIMULATION TO ACHIEVE STEADY PERIODIC CONDITIONS

DWG. NO. K/G-81-1872
(U)

SAN ANTONIO, JULY 21
LCME INTERIOR FLUID TEMPERATURE
SUCCESSIVE 24-HOUR CYCLES

FIGURE 10.12

TEMPERATURE VARIATIONS FOR SUCCESSIVE 24-HOUR CYCLES DURING
THE LCME SIMULATION TO ACHIEVE STEADY PERIODIC CONDITIONS

SAN ANTONIO, TEXAS, JULY 21
ORSMAC/LCME VELOCITIES

FIGURE 10.13

INTERIOR FLUID VELOCITIES WITHIN A SAN ANTONIO LCME

Table 10.1

Energy Budget for San Antonio

Steady Periodic Conditions
Net Energy Gain Over 24-hour Cycle

	January				July			
	ORSMAC LCME	LCME	LCME	LCME	ORSMAC LCME	LCME	LCME	LCME
Vent Condition	NO	NO	YES	YES	NO	NO	YES	YES
Fabric Transmissibility	.2	.2	.2	.1	.2	.2	.2	.1
<u>GROUND (w)</u>								
Absorbed Insolation	2.51×10^8	2.51×10^8	1.254×10^8	1.25×10^8	3.18×10^8	3.18×10^8	3.18×10^8	1.59×10^8
Radiation Loss to Sky	-1.548×10^8	-1.948×10^8	-9.58×10^8	-9.58×10^8	-1.635×10^8	-1.634×10^8	-1.63×10^8	-7.45×10^7
Convection	-3.79×10^5	-8.73×10^5	1.406×10^8	1.406×10^8	-3.16×10^6	-6.96×10^5	-3.808×10^6	-3.2×10^6
Radiation to Fabric	-3.17×10^7	-8.17×10^7	-5.86×10^7	-6.86×10^7	-5.9×10^7	6.29×10^7	-6.17×10^7	-1.48×10^7
<u>FABRIC (w)</u>								
Absorbed Insolation	2.04×10^8	2.04×10^8	2.04×10^8	2.04×10^8	3.23×10^8	3.23×10^8	3.23×10^8	3.23×10^8
Radiation Loss to Sky	-2.19×10^8	-2.13×10^8	-2.19×10^8	-2.18×10^8	-1.85×10^8	-1.857×10^8	-1.854×10^8	-1.8×10^8
External Convection	-6.8×10^7	-6.8×10^7	-	-5.95×10^7	-2.01×10^8	-2.09×10^8	-1.94×10^8	-1.5×10^8
Internal Convection	6.31×10^5	6.31×10^5	-	4.96×10^5	6.06×10^4	2.93×10^5	-6.14×10^6	-6.2×10^6

LCME Code Results

The LCME code requires approximately 2% of the computational time of the ORSMAC/LCME code to achieve steady periodic conditions and therefore can be used for many more analyses with much less cost. The code was used to investigate the effects of venting, reducing the fabric transmissibility, LCME orientation and location.

LCME Design Options Investigated

Figures 10.14 and 10.15 present the investigation of modifying the fabric transmissibility and the simple venting scheme described in Section 9. Venting the LCME produced significant modification of the interior air temperature and the Daily Mean Temperatures. Significant energy savings could be accomplished utilizing this design option. Venting was effective since even during the winter the exterior temperature rises above the interior air temperature.

The effect of reducing the fabric transmissibility was not as pronounced since the insolation and thermal radiation to the sky temperature were both reduced by half. Thus, steady periodic conditions for a transmissibility of 10% were not significantly different from the calculations with a transmissibility of 20%.

The LCME with primary axis north-south produced steady periodic conditions that were very similar to those for an east-west orientation.

Summer-Dominated Climate

The steady periodic temperatures for four seasons at San Antonio, Texas, are presented in Figures 10.16 through 10.18. The DMT for these analyses are compared in Figure 10.19 with the exterior DMT. To summarize, the unvented LCME is only slightly beneficial during the heating season, beneficial in the transition seasons (spring and fall) only by reducing the diurnal temperature changes and detrimental during the cooling season. Venting the LCME can achieve a great deal of climate moderation during most of the year as measured by DMT.

This DMT information was used to estimate the energy consumed in conditioning structures within the LCME in the following manner. First the monthly DMT achievable within an LCME was assumed to be the best of the vented or unvented analyses and presented in Figure 10.20 and Table 10.2. The LCME was assumed to be effective in reducing heating or cooling during a month but not both. If less cooling than heating is required during a month, then the LCME was assumed to only reduce the heating load. This assumption is conservative. Next, the DD for the month was calculated from the ratio of the LCME DMT to the exterior. All months are then summed. The total year energy consumption of enclosed structures calculated in this

Table 10.2
San Antonio
Estimated Yearly Degree-Day

Month	Exterior			Interior to LCME					
	DMT	HEATING	COOLING	LCME DMT	DD HEATING	DD COOLING	DMT-0.6C HEATING	DD HEATING (DMT-0.6C)	HOURLY CALC. COOLING DD
JAN	283.4	251	4.4	287.4	120.9	4.4	286.8	139	4.4
FEB	285.5	172	9.4	288.3	93	9.4	287.7	112	9.4
MAR	289.0	108	35	290.5	25	35	289.9	43	35
APRIL	293.9	17	93.4	291.3	0	93.4	291.3	0	93
MAY	297.4	0	189	291.3	0	0	291.3	0	0
JUNE	300.9	0	287	295.5	0	130	295.0	0	0
JULY	302.3	0	339	298.0	0	208	297.4	0	0
AUG	302.3	0	339	295.5	0	131	295.0	0	0
SEPT	299.3	0	238	291.3	0	0	291.3	0	0
OCT	294.4	18	112	290.4	28	112	289.8	47	112
NOV	288.4	99	11	289.4	59	11	288.8	78	11
DEC	284.8	207	3.9	289.4	90	4	287.8	109	4
Yearly Total		872	1663		415.4	643.8		525.7	269
Percent of Normal					48	39		60	16
Combined Heating and Cooling Savings DD			0			1476		1366	1740
Percent of Combined DD			0			58		54	69

SAN ANTONIO
JAN 21
COMPARISON OF LCME RESULTS

FIGURE 10.14

COMPARISON OF LCME DESIGN OPTIONS

SAN ANTONIO, JULY 21
COMPARISON OF LCME RESULTS

FIGURE 10.15

COMPARISON OF LCME DESIGN OPTIONS

DWG. NO. K/G-81-1940
(U)

FIGURE 10.16

SEASONAL DIURNAL TEMPERATURE VARIATIONS FOR
SAN ANTONIO, TEXAS LCME. LCME COMPUTER CODE RESULTS

FIGURE 10.17

SEASONAL DIURNAL TEMPERATURE VARIATIONS FOR
SAN ANTONIO, TEXAS VENTED LCME. LCME COMPUTER CODE RESULTS

DWG. NO. K/G-81-1788
(U)

FIGURE 10.18

SEASONAL DIURNAL TEMPERATURE VARIATIONS FOR
SAN ANTONIO, TEXAS VENTED LCME WITH REDUCED
TRANSMISSIBILITY. LCME COMPUTER CODE RESULTS

DWG. NO. K/G-81-1880
(U)SAN ANTONIO, TEXAS
DAILY MEAN AIR TEMPERATURE

FIGURE 10.19

YEARLY VARIATION OF DAILY MEAN TEMPERATURE FOR
SAN ANTONIO LCMEs AS CALCULATED BY THE LCME CODE

SAN ANTONIO, TEXAS
DAILY MEAN AIR TEMPERATURE
CDD SAVED

FIGURE 10.20

GRAPHICAL REPRESENTATION OF ENERGY SAVINGS
AS CALCULATED FROM ESTIMATED DD

manner was 42% of the normal San Antonio requirements. Since the more detailed ORSMAC/LCME calculations showed a lower DMT ($\sim 0.6^{\circ}\text{C}$) the seventh and eighth columns in Table 10.2 repeat the calculations reducing the DMT slightly, and still the energy consumption was only 46% normal. The last column of Table 10.2 is a better estimate of the cooling DD required. These numbers were calculated from the hourly temperatures by summing the difference in interior air temperature and the comfort target temperature of 298.7K (78°F) whenever the interior temperature is greater. This technique shows a large difference in the cooling DD required and is a better estimate of cooling requirement than the DMT method. However, the hourly method results for heating DD are nearly identical to the DMT results and thus are not presented.

Both the heating and cooling DD in Table 10.2 are calculated from the same base temperature of 291.3K (65°F). Using this temperature as a base for cooling requirement assumes a normal daily temperature change for the air inside the LCME. For a DMT of 291.3K (65°F) using the same daily temperature change as exterior conditions, the maximum interior air temperature would be 303.4K (87°F). However, from Figure 10.18 the summer maximum interior temperature never exceeds the comfort zone upper limit of 298.7K (78°F). Therefore, very little or no cooling should be required inside the LCME. Thus, the energy consumption for the LCME would be as in the column labeled "hourly calculated DD." The yearly energy consumption would be 31% of that required by the exterior conditions.

A second component to the energy consumption is the energy lost to infiltration. The exact amount of energy consumption due to infiltration depends on the construction of the interior conditioned structures. However, the maximum velocities are reduced from the exterior conditions by factors of 20 (summer) and 70 (winter) which would reduce the infiltration due to velocity to virtually zero. Infiltration is also produced by the buoyancy forces due to the temperature differences between the conditioned space and its immediate environmental air (interior fluid of LCME). In this respect the LCME will reduce the energy loss due to infiltration to roughly the same percentage as the energy consumption calculated by the DMT.

The last component that can be considered with this model is the energy exchange with the ground. Since the LCME codes model the base of the enclosure as uncovered ground, these results are only representative of an LCME containing very few structures (an unrealistic urban environment). Figure 10.21 compares the ground surface temperatures with and without an LCME. The uncovered results were obtained from a one-dimensional version of the LCME code assuming that the total insolation and outside air conditions were applied directly to the surface. All other model parameters were identical. In this winter analysis, the diurnal changes were reduced by the LCME but the DMT was reduced by 1°C which would increase the heat loss to the ground for dwellings within the LCME by $\sim 20\%$. Again the magnitude of this energy loss can only be determined for a specific example so this loss cannot be compared directly to the infiltration or DMT calculations. Typically, the total energy loss through floors is thought to be small, on the order of 10%, while infiltration losses are estimated as 30% of the total energy for conditioning. The diurnal ground

COMPARISON OF GROUND TEMPERATURES
SAN ANTONIO, JAN 21
AVERAGE OF 0.2 m

FIGURE 10.21

SURFACE TEMPERATURES FOR UNCOVERED AND LCME COVERED GROUND

temperatures for the four seasons are presented in Figure 10.22 compared with the outside air temperature and comfort temperature zone. The DMT is summarized in Figure 10.23 and compared with the LCME results. The estimated LCME energy loss to the ground is 60% of normal. Again these analyses ignore the possibly beneficial effects of the LCME storing energy in the ground during one season to moderate the ground temperature in another.

Winter-Dominated Climate

The analyses were also performed for Madison, Wisconsin, a winter-dominated climate, to provide insight into where an LCME is most beneficial. The steady periodic temperatures for the unvented and vented LCMEs are presented in Figures 10.24 and 10.25. The DMT are compared with exterior conditions in Figure 10.26. The model parameters were the same as those used for the San Antonio analyses including the interior air velocity function. Since the ORSMAC/LCME calculations were not performed, this velocity function may be inappropriate. Table 10.3 presents the calculations which result in an estimated energy consumption that is 70% of normal. The total energy saved as indicated by the DD's is 80% of that saved per year for the summer-dominated climate. Again the infiltration losses will be reduced to about the same percentage. The ground temperature comparisons were not performed.

The venting option for Madison again assisted even in the heating season. This was surprising since the venting was allowed only when the outside air temperature was above the inside and the venting was restricted to a complete air exchange in five hours. The venting in the steady periodic condition is for only five hours per day in the heating season.

Comparison of Energy Benefits Between Locations Modeled

The use of the DD in comparing the energy consumption between the two locations studied is only valid if the internal structures are equivalent in heat transfer performance. It is an obvious economic fact that, in climates where a great amount of heating is required, buildings are constructed to minimize loss. In Table 10.4, from reference 10.1, the heating energy required per DD for dwellings in the summer-dominated climate is more than twice that for the winter-dominated climate. The variable "K" is a measure of differences of climate conditions not incorporated into the DD. Therefore, an average house would require twice as much energy per DD to maintain the desired conditioning in the summer-dominated climate.

The winter-dominated climate LCME would only save ~ 40% of the yearly energy consumption of that saved by a summer-dominated LCME with internal dwellings constructed in the normal manner for each region. The climatic variables incorporated into "K" complicates the approximate method of estimating yearly energy consumption from the DMT. Assuming that "K" is the same for buildings internal and external to the LCME restricts the utilization of some of the exciting design potential of the LCME by

FIGURE 10.22
COMPARISON OF SURFACE TEMPERATURES FOR UNCOVERED AND LCME
COVERED GROUND. HORIZONTAL LINES INDICATE COMFORT ZONE

SAN ANTONIO
GROUND DAILY MEAN TEMPERATURES
LCME RESULTS

FIGURE 10.23

SEASONAL MODIFICATION OF GROUND
DAILY MEAN TEMPERATURES BY AN LCME

DWG. NO. K/G-81-1942
(U)

FIGURE 10.24

SEASONAL DIURNAL TEMPERATURE VARIATION FOR
MADISON, WISCONSIN, LCME. LCME COMPUTER CODE RESULTS

DWG. NO. K/G-81-1787
(U)

FIGURE 10.25

SEASONAL DIURNAL TEMPERATURE VARIATIONS FOR
MADISON, WISCONSIN VENTED LCME. LCME COMPUTER CODE RESULTS

MADISON, WISCONSIN,
DAILY MEAN TEMPERATURE

FIGURE 10.26

YEARLY VARIATION OF DAILY MEAN TEMPERATURES FOR
MADISON, WISCONSIN, LCMEs AS CALCULATED BY THE LCME CODE

Table 10.3

Madison, Wisconsin
Estimated Yearly Degree-Day

<u>Month</u>	<u>EXTERIOR</u>			<u>INTERIOR</u>		
	<u>Degree-Day</u>			<u>Possible</u>		
	<u>DMT</u>	<u>HEATING</u>	<u>COOLING</u>	<u>DMT</u>	<u>HEATING</u>	<u>COOLING</u>
JAN	264.6	830	0	267.9	725.4	0
FEB	266.5	696	0	272.5	582.8	0
MAR	272.0	599	0	278.0	412.3	0
APRIL	280.4	328	0	285.1	192.2	0
MAY	286.3	165	10	289.8	46.5	10
JUNE	291.78	40	53	291.3	0	0
JULY	294.2	7.8	96	291.3	0	0
AUG	293.4	21.7	86	291.3	0	0
SEP	288.4	96	7.8	288.9	74	7.8
OCT	282.9	263	3	287.4	121	3
NOV	274.5	505	0	278.8	388	0
DEC	267.4	<u>742</u>	<u>0</u>	270.8	<u>636</u>	<u>0</u>
		4294	256		3177.1	17.8
					74%	7%
				Total	3195	70%

Total Savings = 1355.1 = 30%

Table 10.4

Heating Energy Required

	HEATING <u>DD</u>	K ENERGY <u>REQUIRED</u>	HEATING <u>DAYS</u>
San Antonio	877	739kJ	145
Madison	4121	352kJ	268
Orlando	361	1642kJ	165

Reference 10.1

assuming that the interior dwellings will be constructed as if they were to be in the exterior environment.

Estimates of Potential Benefits for Other Locations not Modeled

As the preceding analyses are approximate, the extension of these results to other locations without further LCME or ORSMAC/LCME calculations is even more approximate. However, in examining the exterior conditions that would be used in the calculations for other locales, it became apparent that some would be almost identical to the previous calculations. For instance, Orlando, Florida, has weather data that are very similar to San Antonio (Table 10.5). The LCME calculations would not be significantly different for the two locations. As mentioned above, the analyses presented do not consider humidity which is a vital component in determining comfort and air conditioning energy requirements.

The weather data reveals that San Antonio is somewhat less humid than Orlando and this difference would have to be considered in a more accurate analysis. This was not attempted here since we have no information on interior humidity within the LCME.

With this limitation in mind, the DD reduction for an Orlando LCME appears to be about the same as for one in San Antonio. Since the energy consumed per DD is much larger for Orlando (see "K" in Table 10.4), the total energy savings could be even larger. Figure 10.27 presents a very rough method of interpolating estimated energy benefits for the temperature region (neither summer- nor winter-dominated). From this interpolation, it appears that the benefit of the LCME is large as long as the cooling energy required is large. Figure 10.27 also shows that for an LCME the percentage of a normal DD for either heating or cooling is approximately constant from winter- to summer-dominated climates. If this condition were to hold true for other locations, the LCME DD required for various areas of the country might be as in Table 10.6.

LCME as a Moderated Climate for Agriculture

The LCME code (and ORSMAC/LCME code) models the LCME as an empty structure which resembles a giant greenhouse. The LCME code results were utilized to estimate the benefit of LCMEs in winter-dominated climates. From the winter-dominated LCME analyses, (Madison, Wisconsin) the ground under an LCME is estimated to be frozen for 140 days of the year. The interior air is below freezing for an estimated 75 days. The interior air is warmer than the ground because venting brings in warmer outside air.

From the weather data the normal growing season is estimated from May 2nd to October 25th averaging 175 days. The LCME growing season (defined as the period in days the ground temperature is always above freezing) is 225 days, 30% longer than normal. This increased growing season is achieved primarily by the reduced diurnal temperature change

Table 10.5

Comparison of Normal Weather Data

	Winter <u>Jan 21</u>	Spring <u>April 21</u>	Summer <u>July 21</u>	Fall <u>Oct 21</u>	Summer Design Temperature
San Antonio, Texas Lat: 29.5° Lon: 99.5°					
AIR TEMPERATURE: Max	289.4	299.8	308.3	300.7	311(100)
Min	277.3	287.9	296.2	288 .1	301(82)
PERCENT INSOLATION	49	56	76	66	
MAX. REL. HUMIDITY	.81	.83	.87	.84	
Yearly Total Degree-Day: Heating = 872; Cooling = 1663					
Orlando, Florida Lat: 28.05° Lon: 81.03°					
AIR TEMPERATURE: Max	294.4(70.5)	300.5(81.5)	305.1(89.8)	301.1(82.5)	307(94)
Min	283.0(50)	289.2(66.1)	305.1(72.9)	291.9(66)	295(72)
PERCENT INSOLATION	N/A	N/A	N/A	N/A	
MAX. REL. HUMIDITY	.88	.87	.89	.87	
Yearly Total Degree-Day: Heating = 407; Cooling = 1792					

DWG. NO. K/G-81-1877
(U)

FIGURE 10.27

GRAPHIC PRESENTATION OF THE RELATIVE
ENERGY SAVINGS FOR WINTER-, SUMMER-DOMINATED CLIMATES

Table 10.6

Estimates of DD Savings at Additional Sites

<u>Location</u>	<u>Degree Day</u>		<u>LCME</u>		
	<u>Heating</u>	<u>Cooling</u>	<u>Estimated Energy Saving Percent</u>	<u>Percent of Heating</u>	<u>Normal Consumption Cooling</u>
<u>Summer-Dominated Climate</u>					
San Antonio, TX	872	1663	69	60	16
Orlando, FL	407	1792	76	60	16
<u>Moderate Climate</u>					
Atlanta, GA	1719	883	52	67	12
Knoxville, TN	1932	872	50	67	12
<u>Winter-Dominated Climate</u>					
Madison, WI	4294	256	30	74	7
Chicago, IL	3404	514	35	74	7
New York, NY	2693	593	38	74	7
Washington, D.C.	2339	786	43	74	7

which can keep the temperature above freezing at night when the exterior air drops below freezing. The danger of early or late frost is greatly reduced by this same phenomena and by the response to sudden external environmental changes of two or three days. In fact, an LCME should greatly reduce the incidence of frost that damages citrus groves and allow such groves to be established in more northern climates than previously possible.

The LCME may produce some detrimental effects. Irrigation would be required since rain is eliminated. However, condensation on the fabric surface at night might provide sufficient moisture for plant growth. In arid regions this mechanism might be used to retain moisture in the LCME, reference 10.2. The reduction in insolation might prevent the effective utilization of the increased growing season. Since the fabric transmissibility is a function of wave length, more study will be necessary in this area. However, experience with the Florida Festival structure demonstrates adequate ultraviolet insolation to provide growth of exotic tropical plants. Last, the proper balance of carbon dioxide, oxygen and moisture may not be obtainable with the simple venting scheme.

Reduction in Initial Capital Expense for Interior Structures

The moderation of the interior climate would allow the reduction in the size of the physical plant for conditioning the interior structures. The summer design temperatures for San Antonio (Table 10.5) are 3C higher than the normal maximum and 3C higher than the minimum. The LCME calculations with the design exterior conditions can be expected to increase the interior DMT by ~ 6C since the DMT is very close to the minimum temperature (see Figure 10.16). The interior DD would then be 81% of the exterior DD. Thus the size of the of the cooling system could be reduced by 20%.

11. DISCUSSION OF THE EFFECTS OF PHENOMENA NOT INCLUDED IN THE LCME MODELS

Response to Rapid Environmental Changes

The energy benefit of the LCME delaying and reducing sudden environmental changes (e.g., frontal systems; extensive cloud cover) would have to be investigated by a transient analysis using actual hour-by-hour weather data. However, this effect should be significant since the four-to-six-day period necessary to move the interior condition to the steady periodic conditions is a significant length of the period a sudden cold or warm front will displace the DMT from the smooth yearly variation. Since DMT weather data shows significant deviation from the smooth or averaged yearly variation that can account for large energy consumptions, LCME may save energy by reducing these sudden changes.

Variation of Fabric Optical Properties

The transmissibility of the fiberglass/Teflon structural fabric is a function of light wavelength as shown in Figure 11.1 from reference 11.1. More complete information on present fabrics is not available and future fabric materials may have properties quite different from present (e.g., designed to maximize climate moderating or vegetation growth). Since the fabric optical properties control both the insolation absorbed by the ground and the radiant energy lost to the sky, selective transmissibility could be used to select the interior climate desired. Lower transmissibility in the long wave or infrared region will reduce the heat loss to the sky producing higher interior temperatures. Higher transmissibility in the solar frequency spectrum can achieve the same result. The effectiveness of this passive control scheme is suggested by the relative magnitudes of the separate components of the energy budget presented in the section on ORSMAC/LCME results. The insolation and radiant exchange with the sky are of the same order of magnitude while radiant exchange with the fabric is approximately half as significant. The convection component is two to three orders of magnitude smaller. Active control of the structure's optical properties can achieve even greater levels of climate modification. Reference 10.2 speculates, and the approximate analyses therein support, the potential of diurnal active control for maintaining comfortable climates in the extreme cold and hot areas of the world.

Impact of Maximizing Daylighting

The unique design of the LCME allows the option of interior structures to be built without the need for rain protection. This offers the potential for maximum utilization of daylight to minimize the cooling load required by normal artificial lighting. Substantial energy savings have been shown in recent building designs by maximum utilization of

FIGURE 11.1

SPECTRAL CHARACTERISTICS OF FABRIC (SHEERFILL)

daylighting. The Florida Festival building was also designed to maximize daylighting; and due to the high reflectivity of the fabric, night illumination can be provided by a highly efficient central lighting system. The quality of the daylight is quite good due to the diffusion and intensity reduction of the sunlight by the fabric.

Impact of Interior Structures

The heat lost from the interior structures due to heating the habitation space has not been modeled in the LCME code. The heat is not altogether "lost" since the interior air is heated by it and thereby reduces the severity of the interior climate. The heat is lost to the exterior environment through convection to the fabric, which is a slow process, and by radiant exchange with the sky and fabric, which may be somewhat controllable by the design. The magnitude of this effect cannot be easily estimated. A significant modification of the LCME code to model this situation would be necessary to get even a rough estimate since the relative rates of heat transfer by interior structures and the fabric would have to be determined.

Interior structures cooled by a central system exchanging heat with the exterior would have a similar although reduced effect. Vented LCMEs may overshadow this effect.

Impact of Unconditioned Space on Human Comfort Within the Enclosure

A human outside of the interior structures would radiantly exchange heat with the fabric, sky, and ground and convectively with the interior air. During the heating season the personal comfort would be enhanced since all temperatures within the LCME are higher than the exterior conditions and the reduced wind velocity would greatly increase personal comfort. However, the summer conditions produce daytime fabric temperatures that are always higher than outside air temperatures and ground temperatures that can be higher than the interior air temperature (vented condition). This issue could be important to urban use of the LCME concept and should be investigated with an accurate model of the heat transfer to and from a human body within an LCME.

Impact of Precipitation and Ice Formation

Due to the low surface friction and the steep surfaces of the fabric snow, ice and rain were assumed to not adhere to the surface thus reducing insolation. This assumption is supported by the fact that interior air temperatures for the Madison, Wisconsin, LCME are above freezing for an estimated 290 days. If snow or ice were to adhere to the surface, the warmer air below the fabric should melt the ice enough to allow it to slide down the side. Warm air rising from the conditioned structures should also assist in clearing the ice. The fabric should absorb enough insolation to assist in the effect during the early daylight hours. Most of the fabric

surface should be clear to transmit insolation. However, accumulation of ice and snow near the edges of the fabric surface could refreeze and cause structural problems.

However, the nighttime fabric temperatures approach the outside air; and due to the possibility of high interior air humidity, frost may form on the inside fabric surfaces. This frost could significantly reduce the effective transmission through the fabric of the radiant energy from the ground to the sky. Insolation through the fabric could also be reduced by frost formation. Again absorbed insolation should clear frost off the inside very early in the morning allowing unhampered transmission of insolation. Frost forming on the outside surface could be more difficult to clear and might significantly reduce the insolation. The modification of the energy budget by frost could improve energy consumption by reducing the loss to the sky but not affect the insolation.

The air-supported LCME with less steep fabric surfaces might allow exterior precipitation to pool or freeze. However, the closer proximity to the ground should allow the underside of the fabric to be warmed, reducing this icing potential as long as the ground temperature or interior structure surface is above freezing.

Rainstorms with cool water flowing off the sides would have a substantial effect on the interior temperatures. However, this water might be trapped for irrigation or drinking while the kinetic energy might be used as a source of mechanical energy for ventilation or other uses.

Precipitation effects on energy consumption can only be modeled using actual or Test Reference Year weather data that includes data on precipitation rate, duration and the effects on insolation and effective radiant sky temperature.

12. CONCLUSIONS

1. The LCME concept can yield large savings in energy consumption for the space conditioning inhabited structures within the enclosure. The climate within the LCME is moderated in its yearly and daily variations producing an estimated energy savings of up to 68% when compared to buildings outside the LCME. The LCME design studied produced the most savings in summer-dominated climates.
2. The LCME can reduce the size of heating and cooling systems required for structures within the enclosure by moderating the extremes of climatic conditions.
3. The buoyancy-induced velocities within the LCME are at least an order of magnitude less than the exterior conditions. This reduces heat loss by interior structures due to forced convection and infiltration and reduces the energy transferred by interior fluid convection to a value much less than thermal reradiation and insolation.
4. The transmissibility of the fabric as a function of wavelength is a very important modeling parameter in determining the LCME interior climate. Accurate knowledge of this property is vital to energy analysis. Proper selection of fabric with respect to the climate will be vital for an energy efficient LCME design.
5. An LCME used as an agricultural enclosure can produce significant lengthening of the growing season for winter-dominated climates even if little benefit is seen in the concept's application to habitation.
6. The preliminary analysis presented demonstrates the potential for large energy savings for the LCME concept. Additional analyses seem to be warranted to more accurately determine the energy conservation potential of the concept.

13. RECOMMENDATIONS

The first step in accurately determining the energy conservation potential should be the comparison of the calculational technique with data from smaller structures (e.g., Florida Festival, Figure 2.8, or other similar structures such as the Pontiac Silver Dome). This comparison will require extension of the models in the LCME code to simulate the geometry and ventilating techniques used in these structures. The models of the LCME code should be improved to allow hour-by-hour calculations for a complete year and to include models for humidity transport, interior heat sources (e.g., humans and lighting) and ground coverings (e.g., vegetation, paving, buildings).

The variation with wavelength of fabric optical properties must be experimentally determined to enable the above comparison and any further speculation of an LCME energy budget. The variation with angle of incidence data would also be necessary before analyzing a complex, curved structure such as the Florida Festival.

Accurate modeling of the geometry of the present fabric structures would also require three-dimensional models. Since very little is known about the buoyancy-induced flow within large complex-shaped enclosures, an improved fluid dynamics calculational technique would also have to be developed or obtained and modified to incorporate the LCME code and other appropriate models.

The active control of optical performance of the LCME and other design concepts should be investigated as even greater benefits may be possible than for the passive LCME.

REFERENCES

- 6.1. Park, James E., Cross, K. E., "Calculation of Fluid Circulation Patterns in the Vicinity of Submerged Jets Using ORSMAC," Union Carbide Corporation - Nuclear Division, Oak Ridge, Tennessee, Report K/CSD-4, January, 1980.
- 6.2. Amsden, A. A., Ruppel, H. M., Hirt, C. W., "SALE: A Simplified Computer Program for Fluid Flow at All Speeds," Los Alamos National Laboratory, New Mexico, Report LA-8095, June, 1980.
- 8.1. Amsden, A. A., Harlow, F. H., "The SMAC Method: A Numerical Technique for Calculating Incompressible Fluid Flows," Los Alamos Scientific Laboratory, New Mexico, Report LA-4370, 1970.
- 8.2. Flack, R. D. Jr., Witt, C. L., "Velocity Measurements in Two Natural Convection Air Flows Using a Laser Velocimeter," J. Heat Transfer, vol. 101, May, 1979, pp. 256-260.
- 8.3. Flack, R. D., Konopnicki, T. T., Rooke, J. H., "The Measurement of Natural Convective Heat Transfer in Triangular Enclosures," J. Heat Transfer, vol. 101, November, 1979, pp. 648-654.
- 9.1. Ruffner, J. A., Bair, F.E., The Weather Almanac, 2nd Edition, 1977, Gale Research Co., Detroit Michigan.
- 9.2. ASHRAE Handbook and Product Directory - 1977 Fundamentals, American Society of Heating Refrigeration and Air Conditioning Engineers, Inc., New York, NY.
- 9.3. Private Communication with J. Effenburger, Chem Fab., Inc., North Bennington, Vermont, 1980.
- 9.4. Duffie, J. A., Beckman, W. A., Solar Energy Thermal Processes, 1974, John Wiley & Sons, New York, NY.
- 9.5. Siegel, R., Howell, J. R., Thermal Radiation Heat Transfer, 1972, McGraw-Hill, New York, NY.
- 9.6. Ozisik, M. N., Radiative Transfer, 1973, John Wiley & Sons, New York, NY.
- 10.1. Strock, C., Koral, L.K., Handbook of Air-Conditioning Heating and Ventilating, 2nd Edition, 1965, Industrial Press, Inc., New York, NY.
- 10.2. Laing, N., "The Use of Solar and Sky Radiation for Air Conditioning of Pneumatic Structures," Proceedings First International Colloquium on Pneumatic Structures, International Association of Shell Structures, Stuttgart, Germany, May, 1967.

- A.1. Catton, I., "Natural Convection in Enclosures," ASME paper, KS-3, Sixth International Heat Transfer Conference, Toronto, Canada, 1978.
- A.2. Elder, J. W., "Turbulent Free Convection in a Vertical Slot," J. Fluid Mech. (1965) vol. 23, part 1, pp. 99-111.
- A.3. Randall, K. R., Mitchell, J. W., El-Wakil, M. M., "Natural Convection Heat Transfer Characteristics of Flat Plate Enclosures," J. Heat Transfer, Transactions of ASME, vol. 101, February 1979.
- A.4. Patterson, J., Imberger, J., "Unsteady Natural Convection in a Rectangular Cavity," J. Fluid Mech. (1980) vol. 100, part 1, pp. 65-86.
- A.5. Taylor, C., Ijam, A. Z., "A Finite Element Numerical Solution of Natural Convection in Enclosed Cavities," Computer Methods in Applied Mechanics and Engineering (1979) vol. 19, pp. 429-446.
- A.6. Küblbeck, K., Merker, G. P., Straub, J., "Advanced Numerical Computation of Two-Dimensional Time-Dependent Free Convection in Cavities," Int. J. Heat Mass Transfer (1980) vol. 23, pp. 203-217.
- A.7. Chan, A. M. C., Banerjee, S., "Three-Dimension Numerical Analysis of Transient Natural Convection in Rectangular Enclosures," J. Heat Transfer, Transactions of ASME (February 1979) vol. 101, pp. 114-119.
- A.8. Oertel, H. H., Jr., "Three-Dimensional Convection Within Rectangular Boxes," Natural Convection in Enclosures, 1980, ASME, HTD-vol. 8, pp. 11-16.
- A.9. Cabelli, A., "Natural Convection in Inclined Hemispherical Cavities," Appl. Sci. Res. (February 1977) vol. 33, pp. 45-73.
- A.10. Powe, R. E., Warrington, R. O., Scanlan, J. A., "Natural Convection Heat Transfer Between Bodies and Their Spherical Enclosure," Natural Convection in Enclosures, 1980, ASME, HTD-vol. 8, pp. 79-88.
- A.11. Schinkel, W. M. M., Linthorst, S. J. M., Hoogenboorn, C. J., "The Stratification in Natural Convection in Vertical Enclosures," Natural Convection in Enclosures, 1980, ASME, HTD-vol. 8, pp. 31-38.
- A.12. Euser, H., Hoogendoorn, C. J., Van Ooijen, H., "Airflow in a Room as Induced by Natural Convection Streams," Energy Conservation in Heat and Mass Transfer, Techniques and Alternatives, Edited by Hoogendoorn, C. J., Afgan, N. H., pp. 259-270, Hemisphere Publishing Corp., Washington, DC, 1978.

- A.13. Laarson, M., "Prediction of Buoyancy Induced Flow in Ventilated Industrial Halls," Energy Conservation in Heat and Mass Transfer, Techniques and Alternatives, Edited by Hoogendoorn, C. J., Afgan, N. H., pp. 271-278, Hemisphere Publishing Corp., Washington, DC, 1978.
- A.14. Bazjanac, V., "Architectural Energy Analysis Report, O'Connell Center, University of Florida, Gainesville, Florida," Center for Planning and Research Development, College of Environmental Design, University of California, Berkeley, June, 1980. (Excerpt published in Progressive Architecture, pp. 28-80, June 1980.)

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDICES

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX A

Literature Survey

Buoyancy Induced Flow in Three-Dimensional Enclosures

Catton (reference A.1) published an excellent review of experimental and numerical studies of natural convection in enclosures. The major emphasis for research in this area has been in understanding solar collectors. These enclosures are generally low aspect ratio rectangular, vertical or inclined cavities with predominately laminar two-dimensional flows. In Catton's review only Elder (reference A.2) presented experimental studies of turbulent flow in enclosures. Most recent research (references A.3 - A.5) in low aspect ratio rectangular inclined enclosures has been primarily interested in laminar flow ($N_{Ra} < 10^7$).

Küblbeck (reference A.6) has reported a numerical technique for two-dimensional natural convection in square cavities and, although results are presented up to $N_{Ra} = 10^8$, claims that it is stable up to $N_{Ra} = 10^{12}$.

Küblbeck claims that most techniques that have been previously reported are unstable at higher Rayleigh numbers.

Three-dimensional flows have received relatively little attention. Chan (reference A.7) and Oertel (reference A.8) present recent numerical studies of three-dimensional laminar natural convection in rectangular enclosures. Complex three-dimensional flow patterns can develop in cavities that would be expected to be two-dimensional.

Some research has been performed for hemispherical enclosures (references A.9 and A.10) which will be of interest in studies of air-supported structures. These three-dimensional flow calculational techniques and experiments were again limited to small cavities or laminar flows. The structure of these flows appears similar to the two-dimensional results presented in this report.

The stratification of temperature in low aspect ratio vertical enclosures is presented by Schinkel (reference A.11) but due to the geometry can not be extended to the LCME geometry. However Schinkel found that stratification began to appear for $N_{Ra} > 2.1 \times 10^5$.

Studies of natural circulation in larger enclosures (rooms) have been reported recently (e.g., see references A.12 and A.13).

Energy Analysis of Large Enclosures

Very few reports of research on energy analysis of large enclosures or the interior climate conditions of such enclosures were found. Bazjanac's estimate of the yearly energy consumption of the University of Florida, Gainesville, Athletic Center (reference A.14) is the closest to analysis of LCME's found. Bazjanac utilized the computer code DOE2.1 which has limited modeling capabilities for flow circulation in large enclosures.

APPENDIX B

SALE Implementation

As mentioned in the body of this report, a practical LCME would probably not have a right-triangular cross-section. That geometry was chosen for preliminary study due to the availability of the ORSMAC computer code.

In order to prepare for the study of more realistic (and complicated) LCME cross-sections, the SALE (Simplified Arbitrary Lagrangian-Eulerian) computer code (reference 6.2) was obtained from the Los Alamos National Laboratory. The code allows the simulation of time-dependent fluid motion in two space dimensions within an arbitrarily-shaped region. The equation of state may be selected by the user. The code is well-documented, and, a three-dimensional (spatial) version is being prepared (at LANL). The code was obtained from A. A. Amsden of the Theoretical Fluid Mechanics Group (T-3) at LANL. It was implemented at Oak Ridge quite easily by C. A. Sady of the Computer Sciences organization.

Three additional tasks must be performed before SALE can be applied to simulate an LCME circulation. First, some additional experience must be gained with the code by running problems for which the answers are known. Second, details of the application of boundary conditions must be modified to increase the generality. Finally, inclusion of humidity effects in the equations appears to be important for agricultural applications or human habitation of LCME's.

To date, SALE is operational on IBM computers in Oak Ridge, and several demonstration problems have been run.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

Internal Distribution

1. R. S. Carlsmith	21-30. J. E. Park
2. H. P. Carter/G. E. Whitesides/
X-10 CSD Library	31. F. S. Patton, Jr.
3. J. S. Crowell	32. H. Postma
4. G. E. Courville	33. M. W. Rosenthal
5. W. Fulkerson	34. W. D. Turner
6-15. G. E. Giles	35-44. R. L. Wendt
16. R. E. Goodsen, Consultant	45. Central Res. Library
17. T. R. LaPorte, Consultant	46. Doc. Ref. Sect. - Y-12
18. T. S. Lundy	47-48. Laboratory Records
19. J. W. Michel	49. Laboratory Records-RC
20. L. I. Moss, Consultant	50. ORNL Patent Section

External Distribution

- 51-75. Jean J. Boulin, CE111.1, FORSTL, U. S. Department of Energy, Washington, DC 20585
76. John A. Effenberger, Chemical Fabrics Corporation, Water St., P. O. Box 476, North Bennington, VT 05257
77. Division of Engineering, Mathematics and Geosciences, DOE, Washington, DC 20545
78. J. N. Rogers, Division 8324, Sandia Laboratories, Livermore, CA 94550
79. Bryan Engen, Owens-Corning Fiberglas Corp., Fiberglas Tower, Toledo, OH 43659
80. Office of Assistant Manager for Energy Research and Development, DOE, Oak Ridge Operations, Oak Ridge, TN 37830
- 81-107. Technical Information Center, DOE, Oak Ridge Operations, P. O. Box 62, Oak Ridge, TN 37830
- 108-181. Building Systems Division Distribution List