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THERMALLY-INDUCED VENTILATION IN ATRIA:

AN ATRIUM CLASSIFICATION SCHEME AND PROMISING TEST SITES

Prepared for:

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EXPERIMENTAL INVESTIGATION OF THERMALLY INDUCED VENTILATION IN ATRIA (TIVIA)

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DISCLAIMER

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ABSTRACT

This report is an element of an overall investigation into thermally-induced ventilation in atria. The overall project will include:

1. Establishing and reporting the current state-of-the-art;
2. Selecting existing sites for atria testing;
3. Testing the sites for development of design algorithms.

The principal area of interest is thermally-induced cooling in commercial use buildings. However, heating and heat transfer plus non-commercial applications will be considered as well. The specific topics of this report are: 1) the development and presentation of an atrium classification scheme, and 2) the identification of promising test sites.

In establishing the atrium classification scheme, specific attention was given to:

1. Climate--hot-arid, warm-humid, and temperate,
2. Atrium configuration--open, closed, and adjustable tops,
3. Thermal mechanism--natural convection, radiative cooling, shading, and others.

Application of the resulting three-dimensional (three-coordinate) matrix was considered and tested. Although the testing was for purposes of checking scheme application, the procedure indicated that most of the atria examined were of the adjustable-top configuration with daylighting the principal functional mode. However, it was noted that thermally-induced air flow was present in many of the atria classified.

In the identification of promising test sites it was noted that there appears to be a shortage of buildings which meet the atrium definition. Consequently, prospective test sites were categorized as follows based upon anticipated value to the study:

1. Commercial atria--already constructed,
2. Commercial atria--planned or under construction,
3. Residential atria--already constructed.

It is anticipated that the selection of actual test sites will be based on recommendations from Eureka Laboratories, LBL, and DOE, using material and criteria presented here. It is projected that the selection will be made in August 1981.

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1.0 INTRODUCTION

1.1 Background

Thermally-induced ventilation is among the identified topics for investigation in the commercial passive cooling program for the U.S. Department of Energy (DOE). Thermally-induced air flow includes thermal chimneys as well as convective air flow within the shell of a structure. However, thermal chinmeys have not been included in this investigation. Further, while the central topic--atria performance--is of world-wide interest, test site identification has been limited to the continental United States for practical reasons.

The major emphasis of this investigation is cooling of commercial use facilities through thermally-induced ventilation in atria. In addition, heating, heat transfer, and non-commercial applications are of secondary concern--particularly as regards concept transferability. While thermally-induced ventilation for cooling purposes is central to this study, it is recognized that numerous other factors enter into atrium design. Among the additional elements to be integrated are: daylighting, heating, physical circulation, landscaping, human comfort, air quality, and aesthetics.

For purposes of this project, an atrium is defined as a space which:

1. is surrounded on <u>all</u> sides by building(s) or glazing;
2. is capable of inducing ventilation by buoyancy (from internal heat gain or solar gain);
3. has the purposes of cooling, ventilation to maintain air quality in the atrium or adjacent spaces, day-lighting <u>or</u> heating;
4. has a top that may be open or roofed (glazed or opaque);
5. excludes thermal chimneys and parking lots.

Some courtyards as well as greenhouses will meet the definition.

1.2 Project Overview and Scope

There are two major phases in this project: the literature review and planning phase, and the field testing phase. This report is one of three elements for the first phase. The specific emphases in this project include:

1. Search literature for design concepts and operating principles for atria, identify atria thermal functions in buildings, obtain existing experimental data (convective and gross ventilation rate emphasis), identify experimental techniques and equipment for experimental work, locate computational techniques applicable to atria, and review environmental data useable for correlative analysis in assessing atrium benefits.

2. Inventory existing atria for state-of-the-art report, list promising test sites, and classify atria types.

3. Develop experimental plan including preliminary correlative analytical model, select test sites, identify critical measurements, specify instrumentation and data acquisition equipment, and determine testing sequence and schedule.

4. Conduct experiments including collection and reduction of testing data after acquisition and debugging of instrumentation.

5. Identify atria correlations including comparisons of measurements with correlative model and modification of the model.

6. Assess potential of atria for inducing ventilation.

7. Develop guidelines and rules-of-thumb for atria design.

Two topics are covered in this report:

1. The development and presentation of an atrium classification scheme which uses a three dimensional (three coordinate) format.

2. The identification of promising test sites which includes individual detailed descriptions.

This report serves as an important link between the state-of-the-art examination (Report No. 81-EN-17) and the eventual testing of selected sites. The classification scheme provides for actual site selection within the integrated context of climate differences, atrium configuration possibilities, and alternative thermal mechanisms. The detailed descriptions of promising test sites are expected to facilitate ultimate selection from a comprehensive perspective.

2.0 CLASSIFICATION SCHEME DEVELOPMENT

2.1 Introduction

A well differentiated classification scheme such as that developed by Doug Balcomb at Los Alamos Scientific Laboratory for passive heating is notably absent for passive cooling systems. One of the tasks in project TIVIA is to develop a classification scheme for one specific building element, the atrium, which can provide passive cooling by inducing ventilation. When combined with the work of other passive cooling researchers under contract to DOE, it is believed that a comprehensive passive cooling classification scheme encompassing all systems will result.

The primary consideration in developing this atrium classification scheme is to provide a design-oriented correlative tool which is usable by building designers. The approach taken emphasized application over theory by presenting the known or assumed relationships between atrium configurations, thermal operating modes, and climate in graphic conceptual form rather than in complex analytical form. The most direct method is to simply matrix each of these variables against one another such that any correlations which may exist between them will become evident at a glance. The matrix dimensions encompass the three variables that most influence atrium performance--site climate, atrium configuration and the thermal mechanisms operating which determine atrium operating modes.

Once the basic design parameters for the building are established from the matrix, the various rules-of-thumb developed at project end can be applied to the design. This classification matrix is presented in Figure 2-1. The Z-axis describes the climate dimension of the atrium site as a function of ambient temperature and humidity. The X-axis describes the physical configuration and siting of the atrium. The Y-axis describes the known and assumed thermal functions of the atrium. These are explained in detail below.

2.2 Climate

The climate variables of solar radiation, temperature, atmospheric humidity, and wind combine in complex ways to establish environmental conditions at the building site. Attempts to provide some sort of reasonable ordering, i.e., a "climate classification scheme," to identify the expected range within which the building system will have to provide human thermal comfort, have resulted in a number of descriptive schemes. There are complex, esoteric single-parameter descriptors [1] such as mean radiant temperature (MRT), sol-air temperature, or effective temperature (ET) that are based on several parameters describing complex human physiological responses to heat and cold. There are also indices that are oversimplified, such as heating and cooling degree-days, that consider only ambient dry-bulb temperature. This does not adequately address human comfort. The climate classification developed in this report is based solely upon the climate parameters of air temperature and relative humidity, the two most familiar determinants of human thermal comfort. Additionally, these climatic parameters were selected because the historical data base for temperature and relative humidity is quite extensive for the United States and is readily available to designers in tabular form for a large number of locations. No such tabular data exists for ET or MRT; they must be calculated for each location.

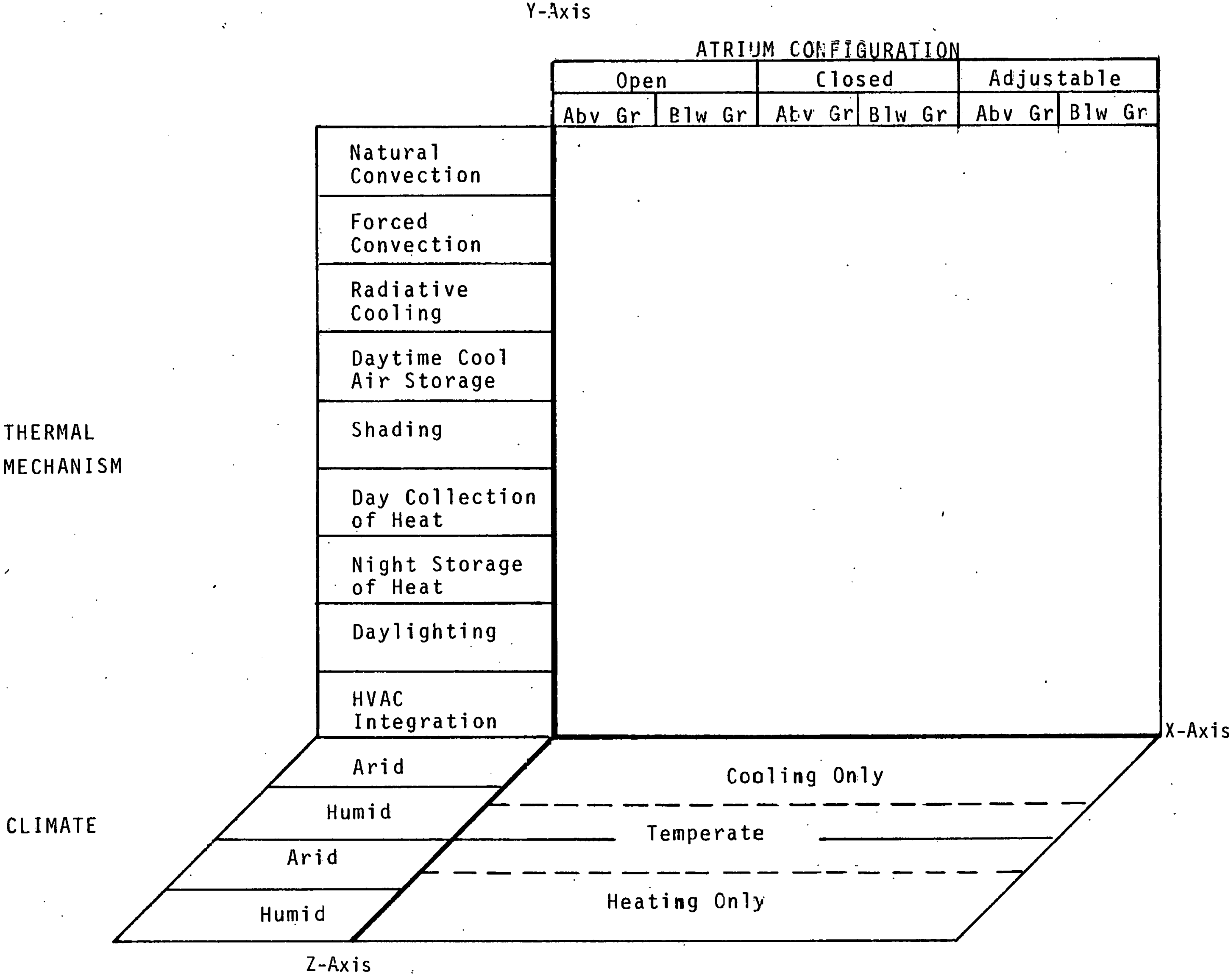

Figure 2-1 Atrium Classification Matrix

Work done by Bowen [2] has suggested that the United States can be divided into three broad climatic zones having varying temperature and relative humidity regimes. This agrees closely with the historical work done by Koppen and others [3,4] in classification of world climates. Most of the United States is classified as having a temperate climate with varying seasonal heating and cooling requirements. The other two climatic types, hot-arid and warm-humid, are distinguished by having a year-around cooling requirement but distinct temperature and humidity differences.

The Climatic Atlas of the United States [5] is the source of most of the climatic data used in this report.

2.2.1 Hot-Arid Climates

In the climate dimension of the matrix, hot-arid climates fall into the region that indicates year-around cooling is necessary. This primarily describes the true desert climates that are typically found in the southwestern United States. Included are portions of California, Nevada, Arizona, New Mexico, and Texas below about 30°N latitude. The cooling requirement is exacerbated primarily by the extreme high temperatures found in this climatic type. Mean daily maximum temperatures typically exceed 100°F for at least 90 days out of the year. Diurnal temperature swings of 50°F are not unusual.

Relative humidity also undergoes a relatively large diurnal swing ranging from lows of 10-20% during the day to well over 50% at night. Table 2-1 presents suggested ranges of values for diurnal and seasonal mean temperature maxima and minima ($\overline{T}_{max}$, $\overline{T}_{min}$) and relative humidity ($\overline{RH}_{max}$, $\overline{RH}_{min}$) for hot-arid climates. Examples of locations in hot-arid climates are Las Vegas, Nevada and Yuma, Arizona.

2.2.2 Warm-Humid Climates

Warm-humid climates also fall entirely into the region of the matrix that indicates year-around cooling is needed. The cooling load in this case is a result of high temperatures combined with high humidity. These climates are found mainly in Florida and portions of other states that are adjacent to the Gulf of Mexico. Outside of the continental U.S., the state of Hawaii exemplifies this climatic type. Daily mean maximum temperatures are typically over 85°F. The diurnal and seasonal temperature swing is small, typically 20°F. Average temperatures do not fall below 65°F. Daily mean maximum relative humidity is typically over 80%. The suggested range of values for temperature and relative humidity for warm-humid climates is presented in Table 2-1. Examples of warm-humid locations in the continental U.S. are Miami, Florida; New Orleans, Louisiana; and Brownsville, Texas.

2.2.3 Temperate Climates

Temperate climates overlap the climates where the predominant year-around requirement is either heating or cooling only. Temperate regions seasonally experience similar temperature and humidity patterns, although not to the same extremes as those found in cooling-only or heating-only climates. The "arid" or "humid" designation implies the relative humidity conditions during the summer cooling season. Temperate-arid climates are generally found in the western United States, a relatively short distance inland from the Pacific Ocean, but still under the influence of air masses originating in the Pacific. Diurnal and seasonal swings of temperature and relative humidity are moderately

Table 2-1 Typical Diurnal Temperature and Relative Humidity Ranges Defining Climatic Types.

	TEMPERATURE °F				RELATIVE HUMIDITY %			
	Summer		Winter		Summer		Winter	
	Avg. Max.	Avg.Min.	Avg. Max.	Avg.Min.	Avg.Max.	Avg.Min.	Avg. Max.	Avg.Min.
HOT-ARID	105	75	60	32	30	10	60	25
WARM-HUMID	90	75	75	60	85	65	85	50
TEMPERATE-ARID	95	60	60	32	60	20	70	50
TEMPERATE-HUMID	95	70	60	35	85	50	80	70
HEATING ONLY	(All Others Not Falling in Above Ranges)							

large. Typical summer daytime temperature maximums exceed 100°F, with night time lows falling below 70°F. Winters are relatively mild with maximum daytime temperatures averaging 60°F with average minimums usually well below 40°F. Relative humidity varies from a minimum of 20% during the summer months to a high of 90% during the winter. Sacramento, California is a good example of a temperate-arid climate. Some of the high desert areas such as Reno, Nevada may also fall into this category. Temperate-humid climates are found mainly in the Midwestern, South Atlantic and in much of the northeastern states. Summers are warm and humid, with 75%-80% relative humidity and daily maximum temperatures exceeding 85°F. The diurnal temperature range is relatively small, usually less than 15°F. The diurnal and seasonal relative humidity range is also small, usually less than 15% and 10%, respectively. The seasonal temperature range, however, is substantial because of the cold winters. Winter daytime temperature maximums rarely exceed 50°F; average minimum temperatures are usually below freezing. Examples of temperate-humid climates are Chicago, Illinois and New York City, New York. The suggested range of values for temperature and relative humidity for determining if a location falls in the humid-temperate climate is given in Table 2-1.

Heating-only climates will not be addressed since this study emphasizes passive cooling.

2.3 Atrium Configuration

Three basic atrium configurations are recognized: open top, closed top, and adjustable top that are sited with the floor of the atrium either below grade or above grade.

The configurations for the atrium types under investigation are presented schematically in Figure 2-2. Open top atria have direct thermal coupling between the atrium air and ambient air. Closed top atria are indirectly coupled because the atrium opening is closed off to ambient air by opaque, translucent or transparent roofing. One or more of the walls defining the atrium space can also be entirely glazed with translucent or transparent materials. Adjustable top atriums have opaque, translucent or transparent movable panels in the atrium opening that can be opened or closed as needed. The walls defining the atrium space may or may not be opaque.

It can be assumed that there will be some variation between the three different atrium configurations in the thermal mechanisms that drive the atrium operating modes. For example, thermally-induced convective cooling may be more of a factor in adjustable-top atria, whereas radiative cooling may be the dominant thermal mechanism in open-topped atria.

2.4 Atrium Operating Modes

One of the assumed purposes of atria is to provide some or all of the ventilation and/or heating for an adjacent building space through either a coupling provided by natural heat transfer mechanisms (convection, conduction, radiation), or through integration of the atrium space with the building's HVAC system. The other assumed function of atria is to provide daylighting for reducing the electrical energy consumed and internal heat generated by artificial lighting. The vertical axis of the matrix in Figure 2-1 lists the possible thermal mechanisms which support the various operating modes.

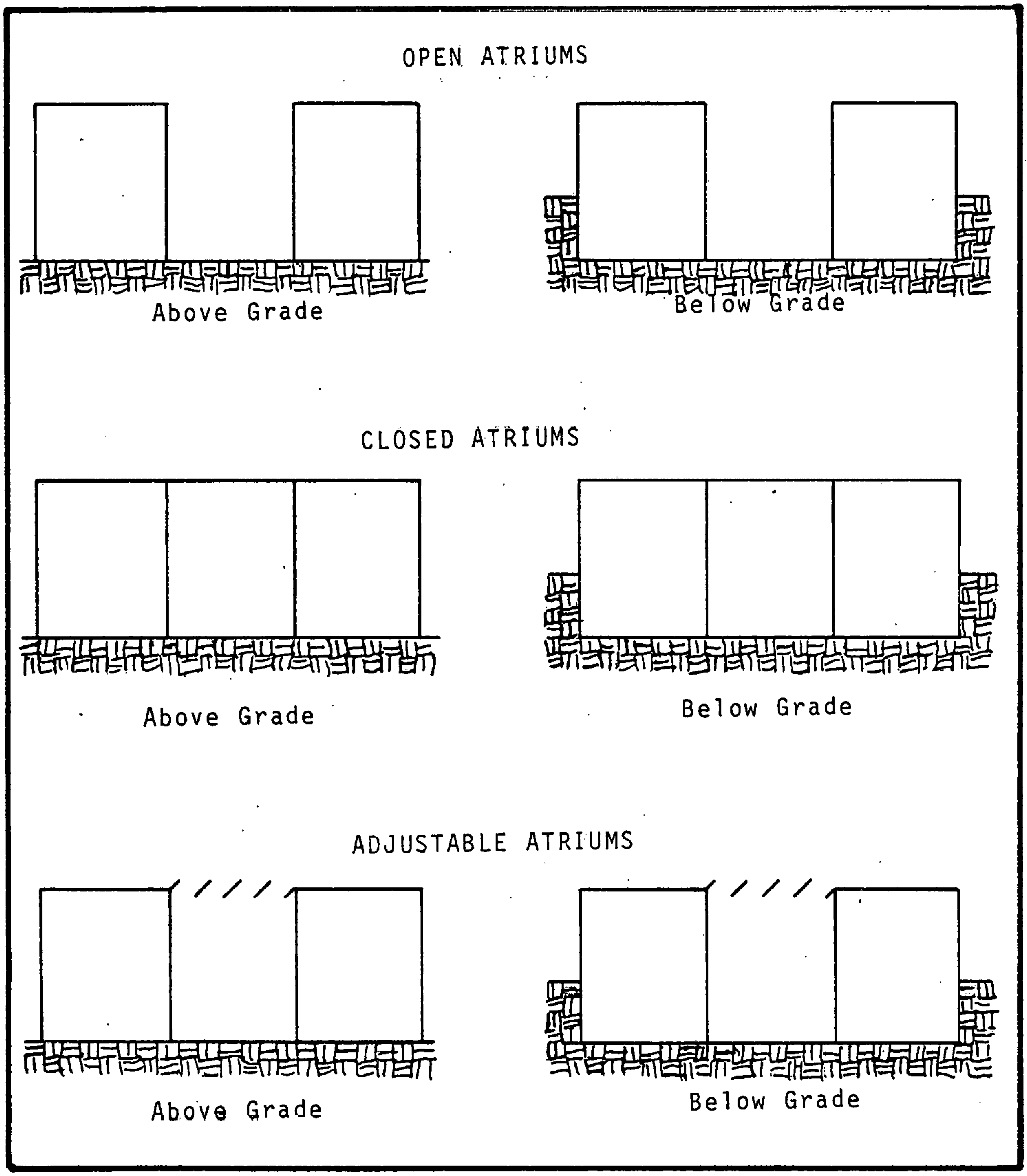

Figure 2-2. Atrium Configurations Considered in the Classification.

The cooling ventilation function is accomplished by natural (thermally-induced) or forced (wind-driven) convection which creates, or assists in creating a flow of fresh cooling air through the adjacent building spaces. Nighttime radiative cooling, when combined with daytime shading can create a significantly cooler microclimate in the atrium space. This is useful especially if the atrium configuration can provide day storage of cool air by earth contact cooling, contact with massive building walls or floor, or by being trapped by a canopy created by tree plantings in the atrium. The cool fresh air can be introduced into the building either mechanically or naturally when the building interior needs cooling or ventilation.

The heating function is accomplished by the ability of the atrium to collect and store heat from incoming solar radiation. This function is quite limited in open-topped atria. Some heat is collected and stored by the walls that are illuminated during the day which tempers the microclimate within the atrium space to reduce heat loss by convection through the building envelope on the atrium side. The atrium also provides a sheltered environment from the wind to reduce building heat loss due to infiltration. Closed and adjustable top atria (closed mode), if an appropriate amount of glazing is incorporated in the atrium cover and walls, provide heating by direct gain. Incoming solar radiation is collected through the glazing and the heat is stored in the atrium air and massive walls and floor. The heat is distributed through the adjacent building spaces by natural heat transfer mechanisms or by integrating it with the building HVAC system.

Perhaps the most widely applied atrium function is daylighting. Sunlight entering the atrium is diffused either by translucent glazing, if used, in closed or adjustable top atria, or by reflection off surfaces in the atrium space. Occupied spaces around the perimeter of the atrium receive this high quality light. The judicious use of daylighting can greatly reduce the need for artificial interior lighting. Approximately 30-40% of a large office building's cooling load is due to heat given off by electric lighting. The use of daylighting reduces the number of lighting fixtures needed. This means less internal heat is generated to add to the building's cooling load.

2.5 Application of the Classification Scheme

The classification scheme will be used to determine the degree of correlation between the atrium parameters by applying it to existing atria in the United States. Since the classification matrix is three-dimensional, any point in the space bounded by the XY,YZ and XZ planes can be defined by a set of three coordinate values (X,Y,Z). In our case, the "values" are not numerical, but are the atrium parameters--atrium configuration, site climate, and atrium thermal operating mechanism. Neither are they points in space, but are "cells" defined by the atrium parameters. Figure 2-3 illustrates this.

The first step in classifying an atrium involves identifying its physical configuration from the X-axis of the matrix. The atrium configuration is then correlated with its known or assumed thermal operating mechanism given on the Y-axis. This produces F/C, a plot of atrium thermal operating mechanism as a function of atrium configuration that defines the X and Y "coordinates." A dot is placed in the element descriptor square for each F/C in the upper left-hand corner of the matrix. This process is illustrated in Figure 2-4. It is

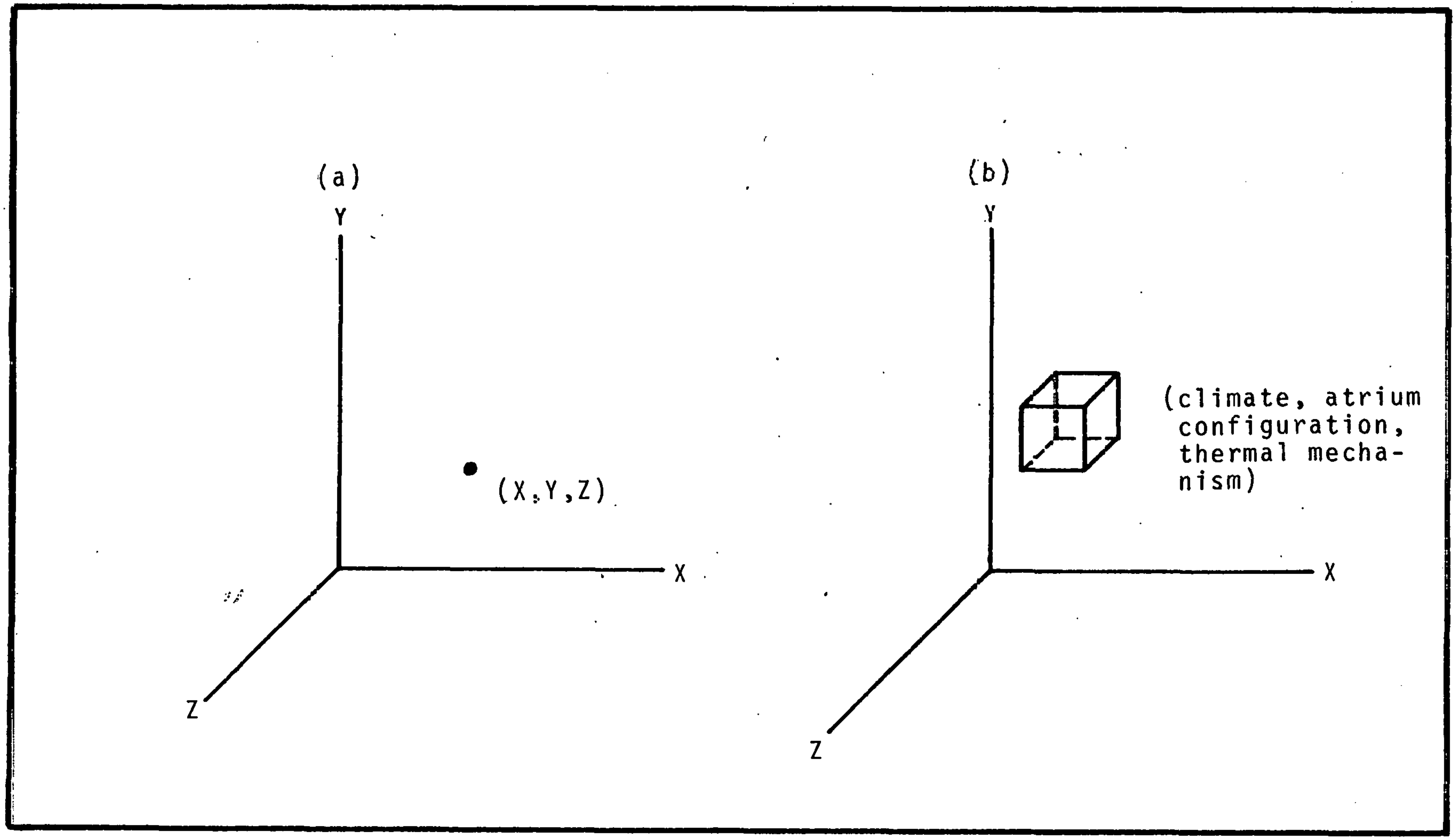

Figure 2-3. (a) standard 3-coordinate notation scheme in mathematics; (b) atrium classification Scheme matrix defining a "cell" of interrelated parameters

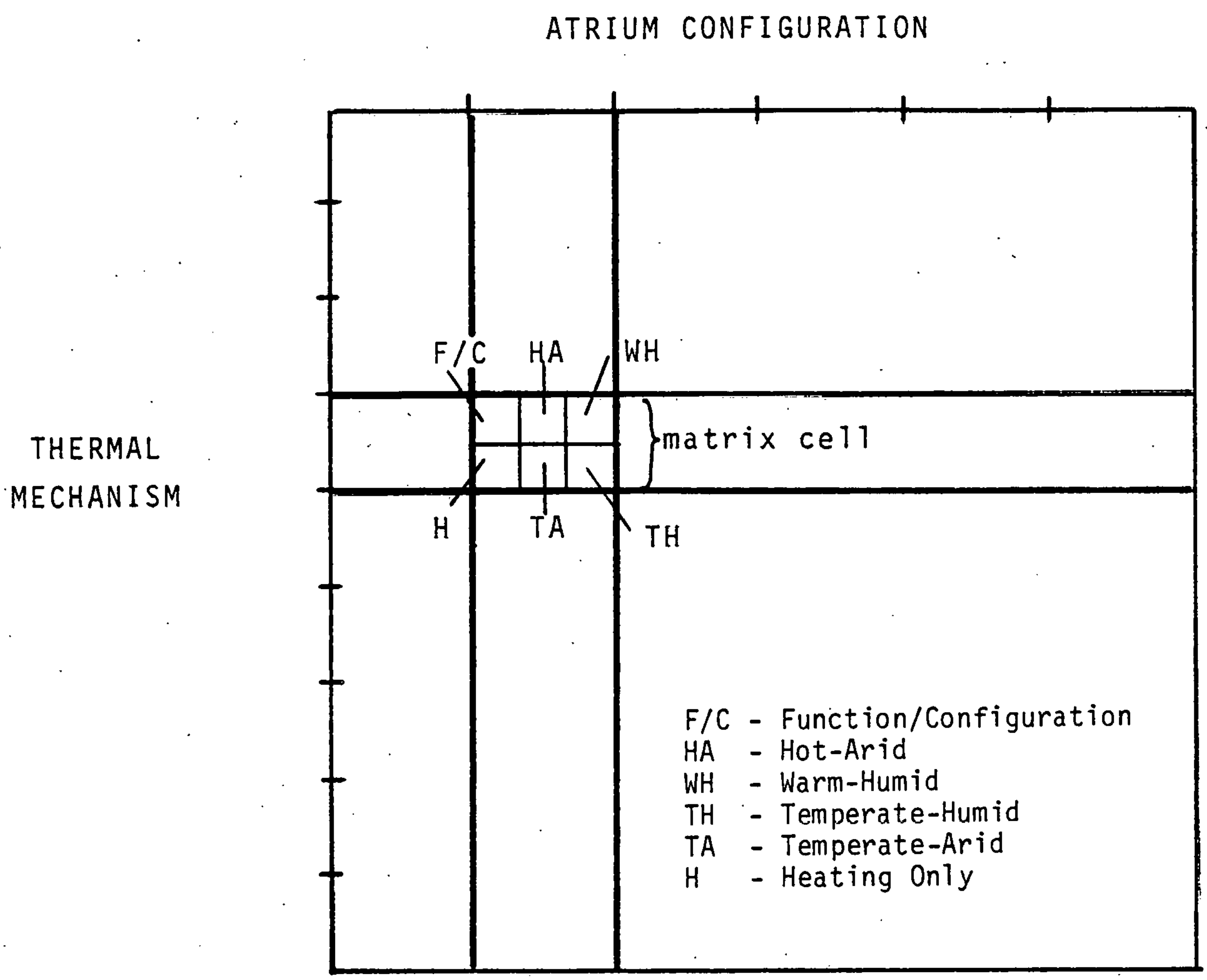

Figure 2-4. Descriptor Element Squares

expected that any single atrium example will probably have more than one F/C combination in evidence. For example, an open-top atrium may have day storage of cool air, shading, and daylighting in evidence simultaneously. In this case, one dot will be placed in each of the element descriptor squares for F/C under the "OPEN TOP" category in Figure 2-5 by each square corresponding to "Day Cool Storage, "Shade," and "Daylighting."

The next step is to identify the site climate by placing a dot in the appropriate element descriptor square for each climatic type in which the particular F/C combination is found. This is illustrated in Figure 2-5. Element descriptor squares are provided for hot-arid (HA), warm-humid (WH), temperate-arid (TA), temperate-humid (TH) and heating only (H) climates. This defines the Z "coordinate" of the classification. For example, the F/C combination of above grade open top atria employing natural convection, five such examples were found; three are located in hot-arid climates and two in temperate-arid climates. The atrium correlative analysis is now complete. This process is repeated for each subject atrium. After enough cases have been analyzed in this way, a pattern will appear. The density distribution of dots is directly proportional to the degree of correlation that exists. The matrix cells with high dot densities are assumed to have high correlation between parameters. Figure 2-5 illustrates an example of the results of this type of analysis. It is recommended that the atria to be tested in Project TIVIA be selected from among those cells that have the densest dot distribution as the correlation between parameters is the highest.

The correlations developed in the classification scheme will be verified by on-site measurement of the parameters and their sensitivities during the Phase II testing part of the project. The classification scheme can then be adjusted as empirical data dictates.

It is recommended that after validation, the classification matrix be refined by using colorful commercial graphics techniques rather than a dot distribution to lend more visual appeal and enhance its ease of use. Perhaps a series of transparent overlays can be used, each individual one having its shading in the appropriate matrix cell to indicate correlation. When laid one on top of another the darkest cells would indicate the type of design strategy to use in a given situation. Having a tool which is easy to use will thus ensure its widespread acceptance.

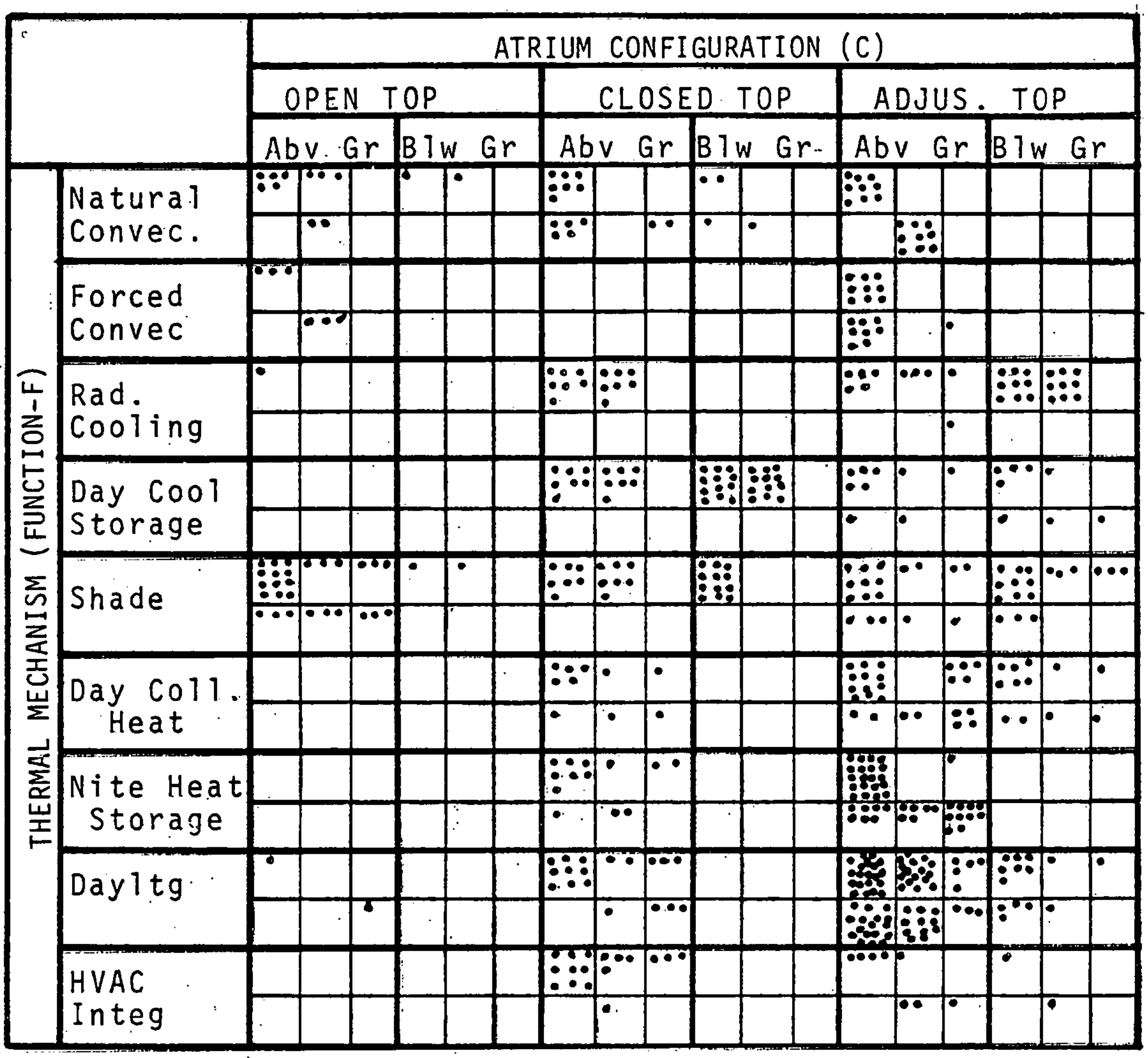

Figure 2-5. Example of Classification Results.

2.6 References

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3.0 PROMISING TEST SITES

3.1 Introduction

The following list of promising sites meets the project definition for atria and provides a range of building types, energy functions, aspect ratios and climates. However, the final selection should consider several other factors including tests of the most "controllable" atrium spaces since the research goal is to validate an analytical model or calculation technique. A qualitative evaluation verifying a site's potential for thermally-induced ventilation may not properly assess the mechanical engineer's success of maintaining isothermal conditions within atrium spaces. Uncoupling the atrium from the HVAC equipment may limit the owners' responsiveness to permit testing. In order to obtain comparative test results, a non-atrium building may be needed for use as an experimental control.

3.2 Deletion of Sites

Eight sites were deleted as promising test sites. These sites were:

1. Energy Showcase Building, Sacramento, Ca.
2. Oakland State Office Building, Oakland, Ca.
3. TVA Headquarters, Chattanooga, Tennessee
4. Illinois State Office Building, Chicago, Illinois
5. Paiute Professional Center, Bishop, Ca.
6. University of Minnesota, Minneapolis, Minn.
7. Twelve Portman-designed Hotels, U.S. wide
8. Arlington Hospital, Arlington, Texas

The first five sites (numbers 1 through 5) will not be included as promising test sites because their completion dates in construction are not within the time frame of this research effort relating to cooling.

The University of Minnesota site was deleted since it is located in a predominantly heating climate (8400 heating degree days) and there are no physical connections to the courtyard.

One of the thirteen John Portman hotel designs was included as a promising site (but others were deleted) to represent this prevalent design within the Hotel category. The Arlington Hospital site was deleted since this atrium receives air supply from exhaust air and heat sources from other areas leaving no possibility for thermally-induced air flow.

All the remaining sites have the potential for cooling ventilation and represent a range of sectional aspect ratios.

3.3 Detailed Information on Promising Sites

This section presents detailed information on eighteen promising sites. It should be noted that three of the sites have more than one atrium which could serve as potential testing candidates. A total of twenty-four atria are available for testing in the eighteen sites. Detailed site descriptions are presented with a summary list in Table 3-1.

Table 3-1. Listing of Promising Sites.

A.	Commercial Atria Constructed.	
1.	Site 1A	Sacramento, California
2.	Crown Center Hotel	Kansas City, Missouri
3.	Hotel Del Coronado	San Diego, California (Two)[a]
4.	Regency Hyatt House	San Francisco, California
5.	Mechanical Engineering Building	University of N. M., Las Cruces, New Mexico
B.	Commercial Atria Planned	
6.	Princeton Professional Park	Princeton, N.J. (Three)[a]
7.	Essex-Dorset Senior Center	Essex, Maryland
8.	Lakeland Wesley Village	Paducah, Kentucky (Four)[a]
9.	Colorado Mountain College	Glenwood Springs, Colorado
10.	Southwest Woodbridge Elementary School	Irvine, California
11.	Simmons Building, Davol Complex	Providence, Rhode Island
C.	Residential Atria Constructed	
12.	Mitchell Residence	Mill Valley, California
13.	Good Residence	Mill Valley, California
14.	Jessee Residence	Pennington Gap Virginia
15.	Solar Atrium Residence	Philadelphia, Pennsylvania
16.	Menlo Demonstration Town Homes	Tucson, Arizona
17.	Melin Residence	Kentfield, California
18.	Forstner Residence	Woodacre, California

a. number of atria available for testing on each site.

3.3.1 Commercial Atria Constructed

SITE 1A, SACRAMENTO, CALIFORNIA

The Office of the State Architect has designed a 4-storied, 288,000 ft.^{2}, office building in downtown Sacramento, which contains an enclosed central atrium. Construction was completed in March 1981, and projected energy consumption is 20% (64,300 Btu's/ft^2/yr) of the energy consumption of existing state office buildings. The passively conditioned atrium space, approximately 120 ft. X 120 ft. X 55-70 ft. houses the vertical and horizontal public circulation, two thermal storage rock beds (at 1.35 million pounds each), public sitting areas, and serves as a pre-conditioner for the building's make-up air. The building is cooled at night by evaporatively cooled night air circulated through the central variable air volume system. The rockbeds are also evaporatively cooled with night air and are sized to meet 60% of the daytime cooling load and provide 75% of the cooling not met by the building's concrete structure.

The design rationale was to: 1) reduce peak heating and cooling loads, 2) reduce annual energy use, and 3) integrate energy systems with architectural and user-related requirements. Figure 3-1 identifies the significant design specifications.

The cooling design is based on the 34°F temperature swing characteristic of Sacramento's cooling season, evening temperatures nearly always dropping below 70°F. Operable exterior louvers covering three double-glass sawtooth bays which are 100 ft. long exclude direct sunlight from the atrium. The mass is cooled by a fan-powered night ventilation system. In modelling the thermal response of the atrium, an additional load was input to simulate the effect of drawing building make-up air from the atrium. An acceptable temperature differential between the atrium space and outdoors was defined as any temperature between the indoor and the average of indoor and outdoor temperatures. Two temperature responses were modelled, one for 4500 ft^2, 60° tilted, south glass and the other for the same south glass with 6000 additional square feet of north shaded glass at a 30° tilt. Since temperature ranges in both cases were acceptable, the north facing glass was included to provide additional daylighting.

Zones within the building were modelled to evaluate heating requirements during Sacramento's cool, short winters (2782 heating degree days). Deep zones, i.e., 30 to 45 feet from the building perimeter, were assumed to receive all heating requirements from stored heat. Shallow zones, i.e., building perimeters, showed insufficient heat to offset skin losses. The sizing of the induction system perimeter heating assumed no self-induced transfer between the interior and perimeter zones. This is the worst case and is not expected to occur in the building open-plan areas.

If no interzone transfer is assumed, large interior economizer loads appear. By sending the economizer airstream through the rockbed, heat is recovered and held for morning perimeter use. The design day heating load is 88 therms and the economizer load on the same day is estimated at 90 therms. Whether the surplus migrates to perimeter zones or is recovered by the rockbed, very small auxiliary heating is expected. Four 5 ft. diameter by 45 ft. long antistratification canvas tubes (fan driven) are used to return upper (warmer) atrium air to lower levels during winter operation.

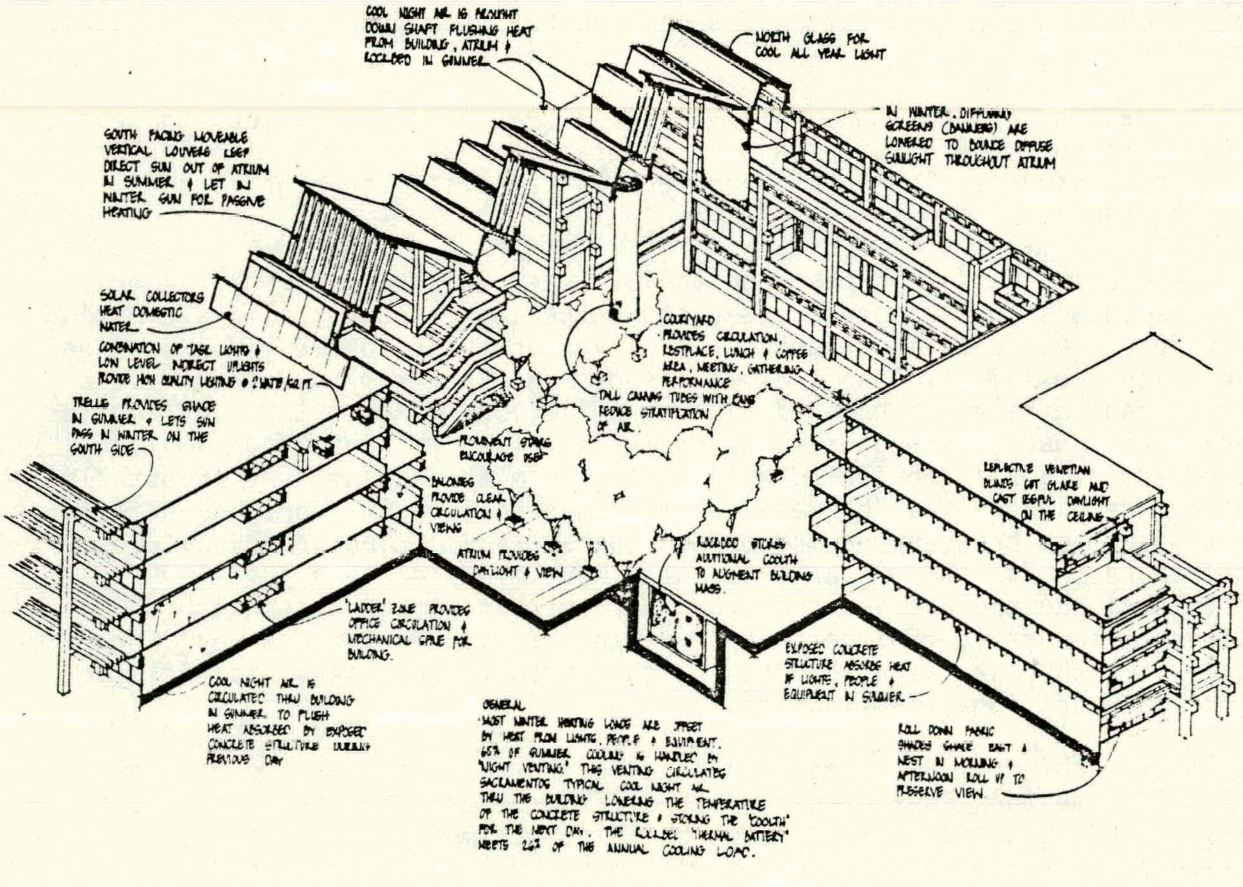

Figure 3-1 Site 1A, Sacramento, California

Based on results of lighting tests made on a mock-up building section, simulations to size, the HVAC system used loads of 1.0 to 2.5 watts/ft^2 in the perimeter and interior zones respectively. In determining annual energy consumption an average lighting value of just under 2 watts/ft^2 was used.

Sizing the HVAC system proved to be a problem to the designers. Since the building environment depends upon conditions over the previous 1-2 days, conventional ASHRAE sizing methods will not reflect the building's dynamic behavior. Simulations using a modified NBSLD program confirmed this. Assuming that the intent of the ASHRAE 2.5% temperature and corresponding load is to provide the capacity to meet 97.5% of the expected loads, the designers performed an hour-by-hour simulation to determine a similar design load. For site 1, a 1% cooling and .5% heating load were used for system sizing.

The rockbed was sized to meet 60% of the 1300 ton-hr design day cooling load. Distribution of daily cooling loads was based on a three-air-changes-per-hour night ventilation rate. The beds are each connected to vertical air shafts. The bed frontal area is 2000 ft^2 each with a depth of slightly less than 7 ft. The beds are designed for a .3" w.g. static pressure loss at 5 fpm maximum face velocity.

CROWN CENTER HOTEL, KANSAS CITY, MISSOURI

The Crown Center Hotel was designed by Harry Wesse and Associates of Chicago, Illinois and contains a 120 ft. long by 96 ft. wide by 5 story high atrium (see Figure 3-2). The floor of the atrium is a terraced garden using the existing natural hillside. Exposed rocks become the center of a waterfall.

The atrium space is part of the lobby and the foyer. Meeting rooms and a restaurant open into the atrium. The restaurant on the top floor of the hotel is within 10 feet of the atrium roof. Part of the atrium roof, 80 ft. by 18 ft., is enclosed by clear glass in order to provide lighting for the garden plants below.

The atrium is a conditioned space where summer and winter temperatures are maintained by a forced air HVAC system at all five levels. The architects' purpose for the atrium was to provide an aesthetic appearance and integrate building functions over the existing landscape. The architects indicated that the HVAC system was designed to prevent the formation of temperature gradients, i.e., no thermally-induced air flow. No energy contributions by the atrium glazing or waterfall were considered in the heating and cooling load calculations.

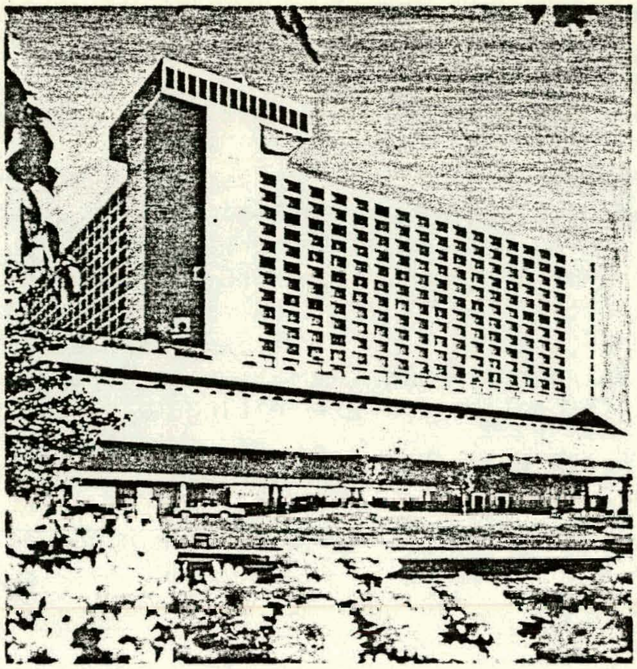

Figure 3-2 Western International's Crown Center Hotel, Kansas City, Missouri.

HOTEL DEL CORONADO, SAN DIEGO, CALIFORNIA

This 3,500,000 ft^2 hotel was designed by James Watsen and Maritt Reid architects. The building, five stories on three sides and three stories on the remaining side, surrounds a rectangular courtyard. The courtyard is 150 ft. by 250 ft. and contains a garden and guest areas. Some breezeway connections are present. Other buildings have been added to the hotel, primarily a seven-story, 200-room addition and a poolside building. The poolside building is three buildings surrounding the pool, one contains a three-story atrium with an enclosed glass top. Deep foliage and trees are present within the atrium and a glass case elevator is located on one atrium wall. Atrium dimensions are 35 ft. wide by 60 ft. long by 3 stories high. It is uncertain as to whether the atrium is part of the conditioned space.

The main 5-story hotel has refrigerated cooling in the central meeting room. The remainder of the building including guest rooms are cooled by wind-induced ventilation. The availability of cool ocean breezes allows air to flow through hallways into rooms and out into the courtyard at balcony points. Depending on wind conditions and direction, air flow may be reversed. The added poolside buildings all utilize cold water refrigerated cooling systems.

The building was constructed in 1888. The architect is not available; therefore, the intended purpose of the courtyard design is unknown. An air-view of the hotel is presented in Figure 3-3.

Figure 3-3 Hotel Del Coronado, San Diego, California

REGENCY HYATT HOUSE, SAN FRANCISCO, CALIFORNIA

John Portman & Associates have designed commercial buildings using atria since the early 1960's. The 20-story, 840-room Regency Hyatt Hotel was constructed in 1968. The atrium is triangular, 300 ft. long, 170 ft. wide and 170 ft. high. According to the consulting engineers for the project, Britt Alderman Associates, the atrium is a completely conditioned space by conventional HVAC equipment (150 tons), six to eight AC units are located under the lobby floor. Controls for the system permit only a 3°F temperature differential between the upper and lower atrium levels to occur. Some atrium air is used for air quality by controlling restaurant and restroom odors through mixing and venting to the outdoors. All the Portman designs contain enclosed top atria.

The Portman atrium designs can be categorized as either supply or relief atria. The supply type are those into which conditioned air is introduced in sufficient quantity to supply other parts of the building. Relief type atria are those which receive return or relief air from adjoining spaces. Both types have normal relief openings or fans and usually both have smoke eject fans at the top which are used only in emergencies. The designers indicated that a supply atrium with large conditioning machinery can reduce the capacity and size of many small units (hotel rooms) when the total outdoor air is conditioned by the large machines.

For the San Francisco Hyatt, the consulting engineers contend that the 300 ft. of atrium glazing will not reduce heating loads and, if any effect, will slightly increase cooling loads because of the closed top design. The designers consider the atrium to be a relief type design.

MECHANICAL ENGINEERING BUILDING, UNIVERSITY OF NEW MEXICO

The Department of Mechanical Engineering of the University of New Mexico will occupy a 60,000 ft^2 building. In the center of this 4-story structure is an open atrium adjacent to all classrooms which utilize natural lighting through skylights. The building was completed in June 1980. (See Figure 3-4)

The building envelope is heavily insulated with roof and wall thermal resistances of 28 Btu's/hr/ft^2°F and 20 Btu's/hr/ft^2°F, respectively. Window area occupies only 8% of the total wall and roof area. Interior concrete columns and floors provide a thermal mass of approximately 160 lbs/ft^2 of floor area.

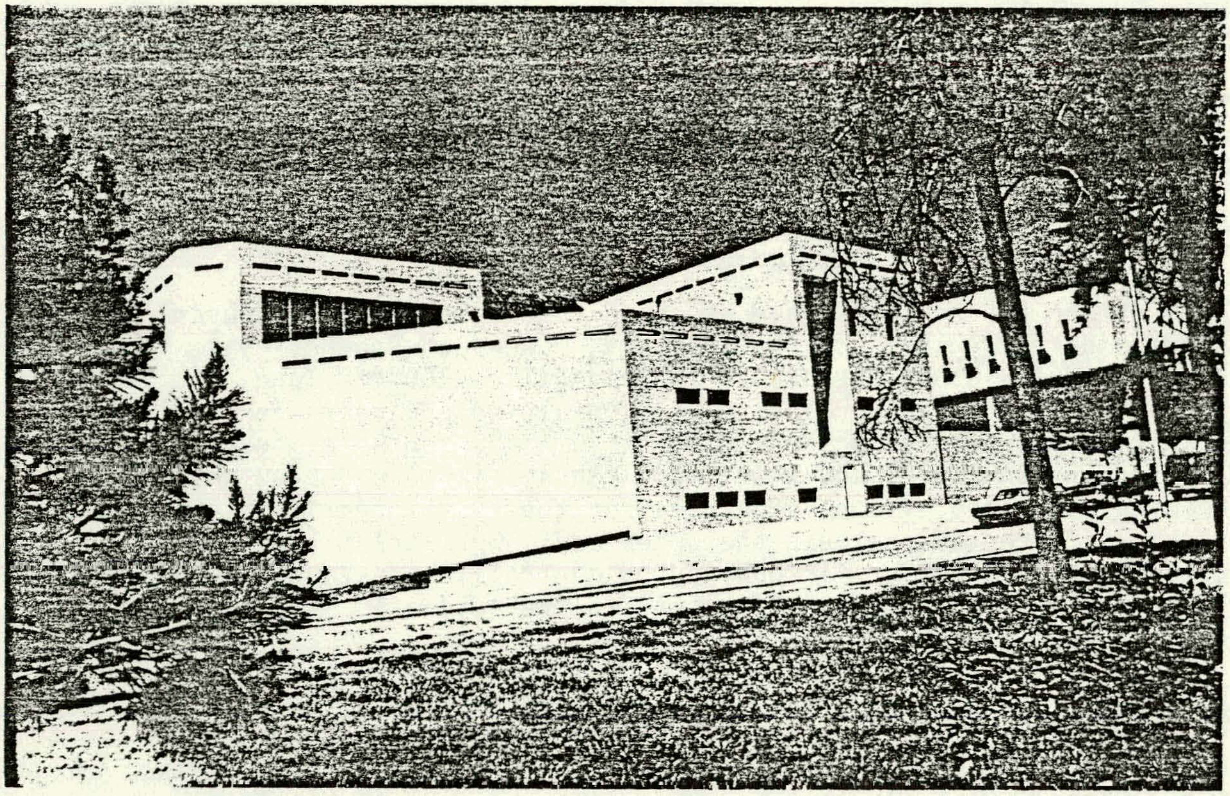

Figure 3-4 Southern Exposure of the Mechanical Engineering Building University of New Mexico, Las Cruces, N. M.

The HVAC System includes a heat pump reclaim system, thermal energy storage, solar collectors and air-to-air heat recovery units. The building's mechanical system consists of two heat pump chillers with a combined capacity of 162 tons. Eight concrete water tanks (15,000 gallons each) are used for thermal energy storage. During the winter, four are used to store chilled water. The remaining four are connected in parellel and will store warm water. For the summer, all eight will be used to store chilled water.

Using the air-to-air heat recovery units, exhaust air will pass through heat exchangers to precool or preheat incoming outside air. The shell and tube-type heat exchangers will operate at efficiencies of 65%. A primary emphasis of the building design is to maximize load management potential.

An extensive instrumentation system is being used, including a computer based data acquisition system which will read and record over 200 measurements. It is not knownat this time if the air flow rates within the atrium are being measured.

3.3.2 Commercial Atria Planned

PRINCETON PROFESSIONAL PARK, PRINCETON, NEW JERSEY

Harrison Fraker and Short and Ford architects designed this three building complex containing 68,476 ft^2 (see Figures 3-5 and 3-6). Square footage per building is 28,196 ft^2 and 15,900 ft^2 with each containing an 18 ft wide by 31 ft high atrium. Atrium lengths are 266 ft, 230 ft and 150 ft, respectively. The architects' intent in these atria was to provide important user amenities. In addition, the atria serve to reduce all building energy loads including heating, cooling, and lighting. Movable insulation and ridge vents with the atrium are intended to accomplish a part of these reductions.

Indirect solar energy collection into the atrium is utilized with storage provided by horizontal rockbeds and slabs for night-time loads. Natural ventilation is induced through the atrium by thermal and wind pressure when outside conditions are suitable. Roof spraying provides evaporation during the day to reduce cooling loads. Cool air is stored in the rockbed at night by circulating air under the roof while it is sprayed.

Energy use was modelled in the design process by several in-house microcomputer programs. The "LOAD ANALYSIS" program identified building loads as a function of internally generated heat gains and climate variables.

The "PEG SPROOF" program, a mode thermal network model, simulated the performance of a sprayed roof system coupled to a rockbed. The Solar Load Ratio method was used to estimate annual heating loads for the building. Day lighting performance calculations were aided by the use of "SKYKING," a PEG program which determines the sky factor component of the daylight factor for special geometries, i.e., atria. The energy consumption estimates are:

Heating -	13,700	Btu's/ft^2/year
Cooling -	4,380	"
Ambient Lighting -	2,840	"
HVAC FANS -	9,510	"
Equipment -	17,730	"

Internal heat generation for lighting and people were estimated as follows:

Lighting:

Task	-	.5 Watts/ft^2	
Ambient	-	.2 "	
% Auxiliary	-	20% "	
Net Auxiliary	-	.4 "	
Net Lighting	-	.9 "	
People @ 150	-	.49 "	sensible
ft^2/person	-	.39 "	latent
Total People	-	.88 Watts/ft^2	
Total Gain		1.78 Watts/ft^2	

Construction is now beginning and is scheduled for completion in the Spring of 1982.

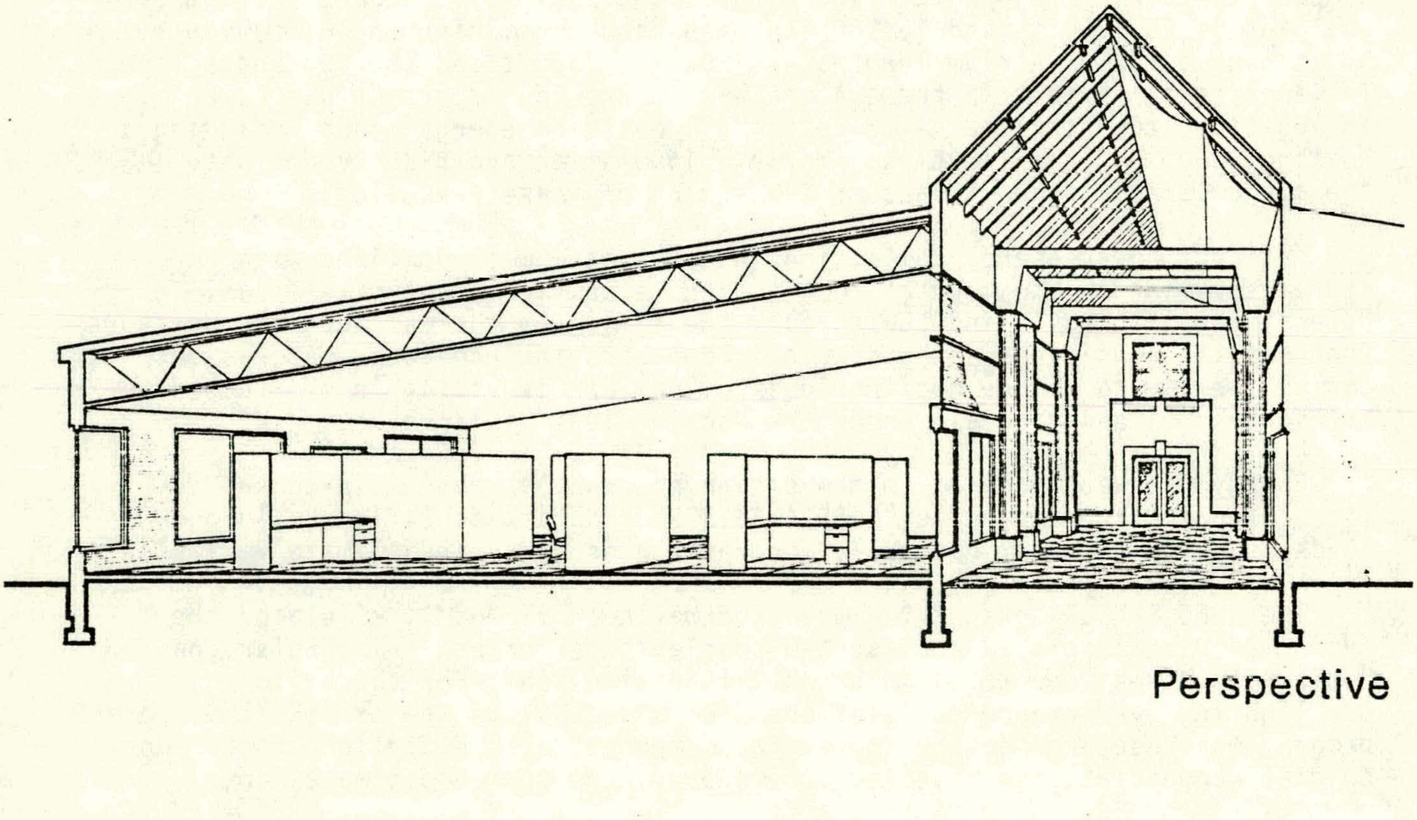

Figure 3-5 Princeton Professional Park, Princeton, New Jersey (Perspective)

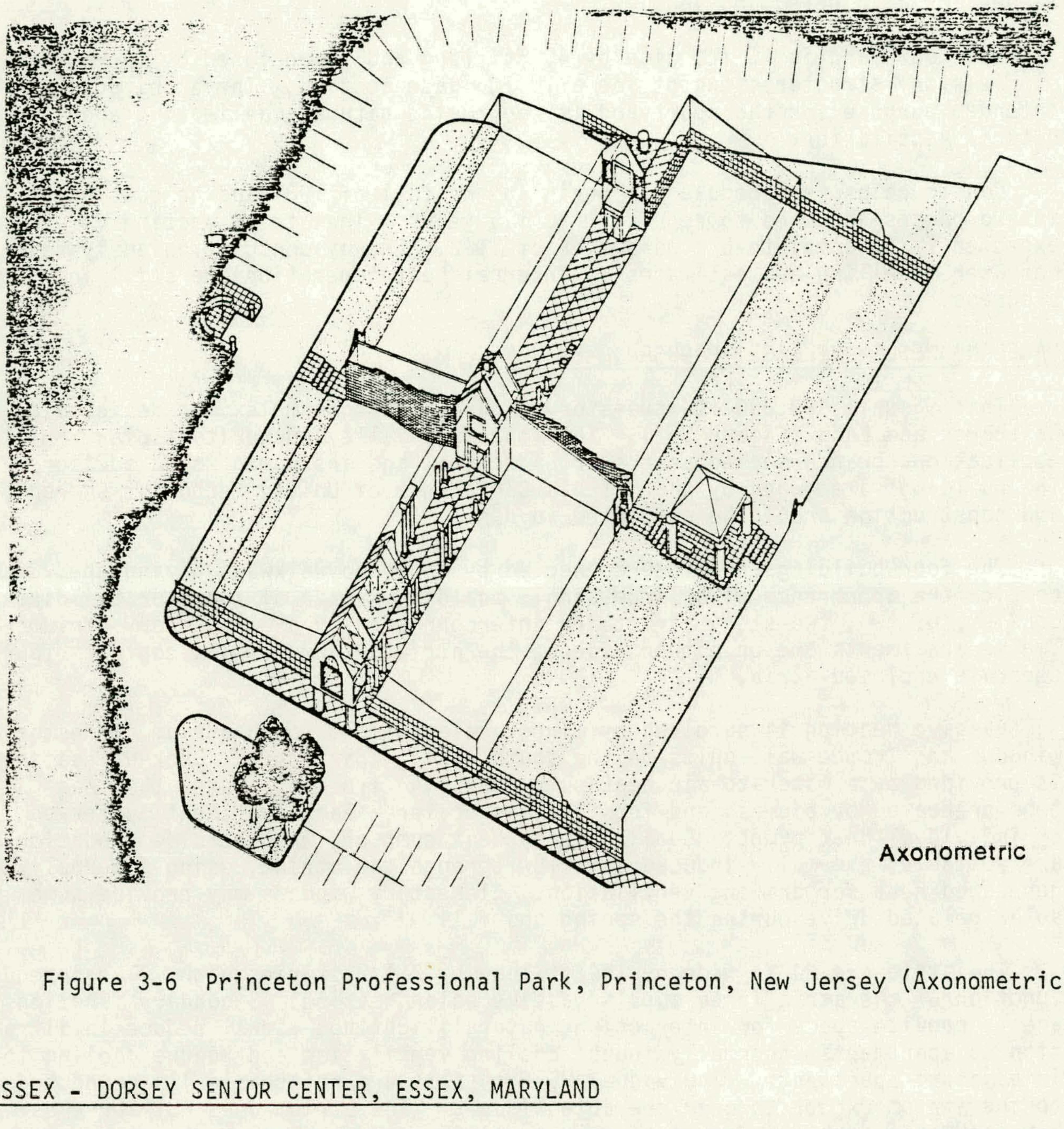

Figure 3-6 Princeton Professional Park, Princeton, New Jersey (Axonometric)

ESSEX - DORSEY SENIOR CENTER, ESSEX, MARYLAND

The Essex Dorsey Senior Center is two, one-story historical school buildings located in Essex, Maryland. The architect, Richard P. Brown & Associates, have combined two 3000 ft^2 buildings with a 7000 ft^2 addition which forms an open courtyard between the buildings. The existing two boilers will be replaced with new boilers and a hot air system. Cooling of office spaces is by refrigerated cooling, but living areas are cooled only by natural cooling. Air scoops on the building are designed to capture wind and vent it through the building to the courtyard. Each living area contains special sliding glass doors which convert indoor verandas to outdoor areas. The verandas, movable walls, floor venting and roof overhangs are principally used from Japanese building concepts dating back to the 14th Century. Concepts from Sweden are also being applied.

The courtyard is 15 ft. wide by 40 ft. long and is enclosed by surrounding single story structures except for a 10 ft. gate section. The architects intended purpose for the courtyard is to provide natural daylighting and natural ventilation.

Construction is scheduled to begin in the fall of 1981 and be completed in two phases expected to require 1 to 1.5 years. The atrium section is expected to be complete by the summer of 1982. Energy consumption analyses, computer modelling and estimates of internal heat generation are still in progress.

LAKELAND WESLEY VILLAGE, PADUCAH, KENTUCKY

This 96 unit, 93,000 ft^2 two-story, four-building complex was designed by Calthorpe and Ladd (Figure 3-7). The Tennessee Valley Authority, Solar Applications branch served as the architectural and instrumentation advisor. The buildings are owned by the Memphis Conference of United Methodist Church, and construction should be completed in June 1981.

The four buildings are interconnected by enclosed walkways giving the complex the appearance of a large single building. Each of the four buildings consists of two, two-story structures interconnected by a 2 1/2 story atrium. Twelve apartments are on either side of the atrium. The complex contains four separate enclosed atria.

Passive heating is supplied by direct solar gain through atrium clerestory windows and Trombe wall units on the south facing apartments. Back-up heating is provided by a water-to-air heat pump operating from well water that has been preheated by biomass and fossil fuels boiler. Each apartment is served by individual heat pumps. Cooling is by heat pump or, when outside conditions are suitable, thermally-induced air flow through the atrium, using internally generated heat for driving ventilation. Clerestory windows may provide some solar related drive during the spring and fall.

The atria are 24 ft wide by 144 ft long by 2 1/2 stories high. The intended function of the atria is to supply passive solar heating. Secondary functions are to provide space for interaction, natural lighting, views, reduce infiltration to apartments, thermally induce cooling ventilation and reduce cooling loads in adjacent apartments. Individual HVAC systems are not physically connected to the atrium except through operable windows. The atrium does not serve as a heat source or exhaust for heat pump operation.

Energy calculations are being generated at this time. The site is within a 4086 heating degree day region at 37°N lattitude. Average temperatures range 35°F in January to 79°F in July. Solar radiation available in January is 6 to 7 Btu's/ft^2/day and 20-30 Btu's/ft^2/day in July.

There are plans by the TVA Solar Applications Branch to instrument the atrium and Trombe wall operation.

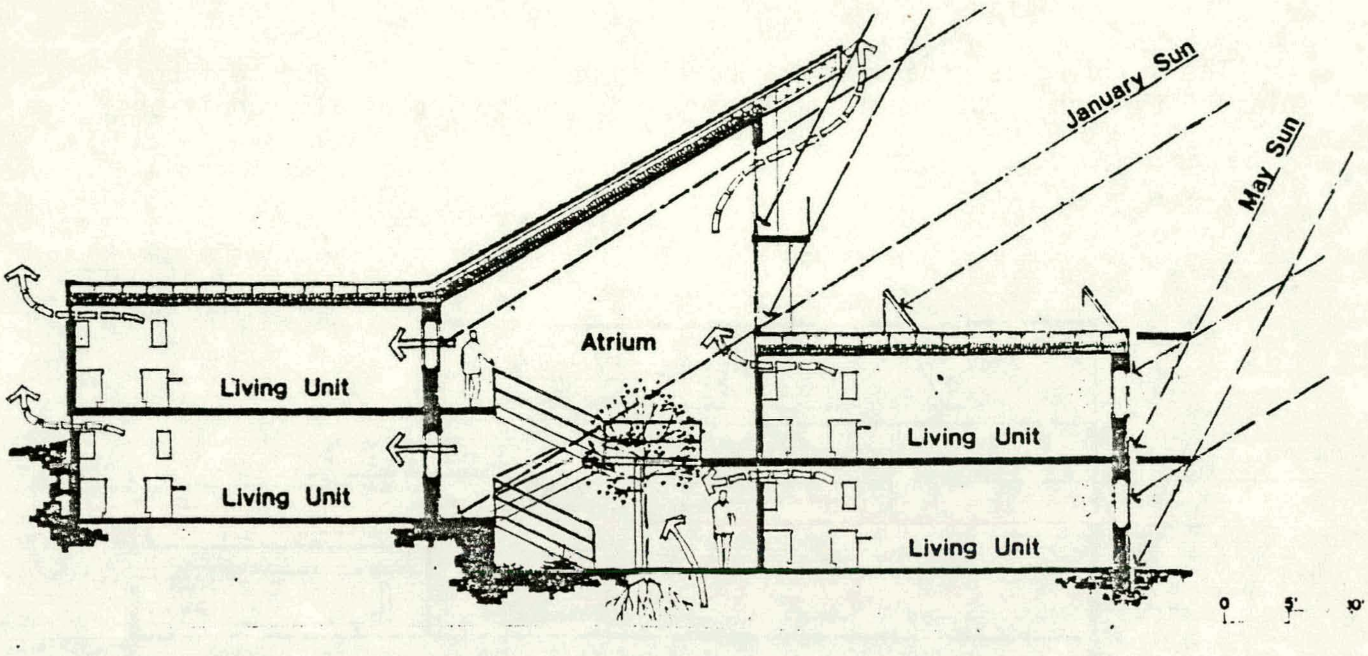

Figure 3-7 Lakland Wesley Village, Paducah, Kentucky.

COLORADO MOUNTAIN COLLEGE, GLENWOOD SPRINGS, COLORADO

Peter Dobrovolny is the designer of the Black Avenue College Center in Glenwood Springs, Colorado (see Figure 3-8). The two-story building comprises 32,000 ft^2 of classrooms. Heating is provided by passive solar heating, i.e., direct gain Trombe Walls and internal gains. Backup heating is provided by electric resistance baseboard heating. In summer, fan forced ventilation with cool night air is intended to cool the structure to 65°F by morning. Unsatisfied cooling needs are met by an evaporative cooling unit coupled to fans. The atrium, 30 ft wide by approximately 130 ft. long functions as a large unheated tempering chamber, a source of natural daylighting and ventilation for class activities around the atrium.

The school is located in an arid region with high diurnal temperature swings. Heating and cooling degree days are 7400 and 300 respectively.

Estimates of energy use were calculated using BLAST AND TEANET computer programs. The breakdown of energy use is:

Heating -	210	$X\ 10^6$ Btu's/year
Lighting -	209	" "
Cooling -	.2	" "
Fans -	.9	" "

The building is scheduled for completion in July 1981, and testing is planned through a DOE grant for one year of monitoring of all conditions.

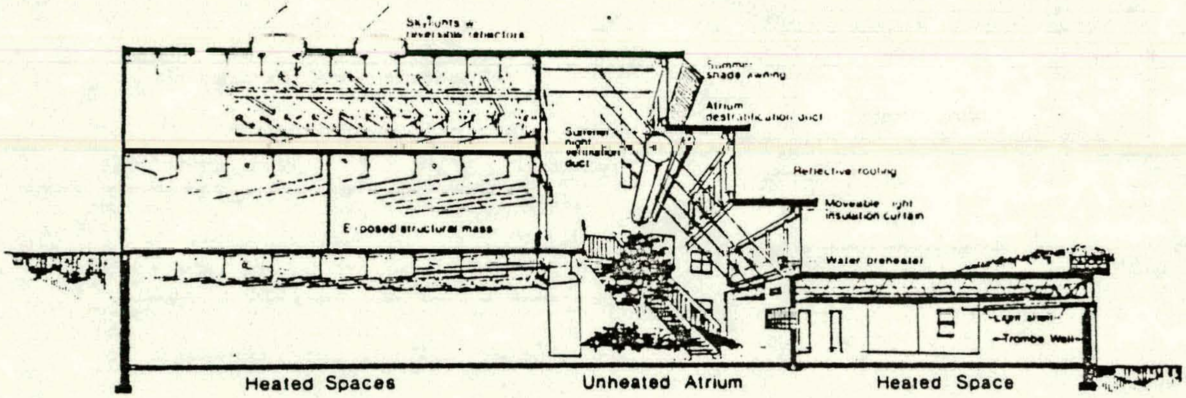

Figure 3-8 Colorado Mountain College, Glenwood Springs, Colorado.

SOUTHWEST WOODBRIDGE ELEMENTARY SCHOOL, IRVINE, CALIFORNIA

This passive/hybrid project is a new elementary school scheduled to begin construction in the fall of this year. The building is a one-story, 43,000 ft^2 structure interspersed with four courtyards or atria. The design rationale was to provide an aesthetic environment for students and staff while simultaneously reducing the cooling and lighting loads which constitute 78% of the energy consumption in typical energy-conserving schools. Clerestories, south-facing light shelves, and the courtyards provide natural illumination to each room. Energy consultants for the design are McCaughey & Smith Energy Associates. Project architects are Porter, Jensen, Hansen and Manzagol.

Artificial lighting will consume 1.6 watts/ft^2 at maximum illumination, a level required by State guidelines. Automatically dimmable artificial lighting will be operated at levels below the maximum with lighting savings expected to reach 75%.

Shading of a shallow pool (8400 ft^2), used to provide passive cooling for the school, is accomplished by using louvers. Up to 300 thermosiphoning water columns are served by the pool. The columns are isolated from the pool during the winter in order to collect heat during the day and release heat at night. Computer simulation of the "cool pool" concept estimates a peak cooling capacity of 1.6×10^5 Btu's/hr and 2.76×10^6 Btu's over a 24 hour period.

The climate of Irvine is relatively mild with summer daily temperature ranges of 61°F to 81°F. Winter design temperatures of 26° were used and annual heating degree days equal 1867.

Additional features of this design include 5-1/2" thick concrete walls and 6" thick concrete floors for thermal mass. Air ducts, embedded in about half of the floor area, will circulate outside air to the rooms at temperatures a few degrees above the daily average. The concrete is then flushed at night with outside cold air to remove the absorbed heat. Estimates have shown this method to reduce peak cooling loads by 25%.

SIMMONS BUILDING, DAVOL COMPLEX, PROVIDENCE, RHODE ISLAND

The Davol Complex consists, in part, of a 100 year building of brick and timber construction. A 28 ft by 260 ft long space between the 150,000 ft^2, four-story building is being added. The atrium roof will consist of "Kalwall" glazing. There are 1,000 ft^2 of vertical south facing glass. The purpose will be to provide ventilation and some heating, however, marketing was cited by the architects, Beckman and Blyderburgh, as the biggest benefit of the conversion. It will provide a covered mall with retail shops opening into the atrium. Natural ventilation is intended as a design function, however, customers may dictate the extent of its use.

Construction will be completed in 10 to 15 weeks. No performance modelling has been performed.

3.3.3 Residential Atria Constructed

MITCHELL RESIDENCE, MILL VALLEY, CALIFORNIA

This owner-builder house consists of a 728 ft^2 addition to 600 ft^2 house and is interconnected by a 160 ft^2 enclosed atrium. The atrium contains 160 ft^2 of roof glazing and 120 ft^2 of wall glazing. The purpose of the atrium is to serve as an air-lock entry, providing heating and ventilation cooling. No experimental tests have been performed to document the effectiveness of these functions.

GOOD RESIDENCE, MILL VALLEY, CALIFORNIA

The Good Residence is a 1300 ft^2 home built in 1938. An enclosed atrium has been added to the south side and forms an air-lock entry. The home is partially buried in the side of a hill with a northern exposure. The architect has indicated the lower level of the home is too cold during any season. The atrium forms part of a forced air double envelope path through the lower level which is heated in the summer. If the atrium heat source can be isolated, it might be useful to instrument the home to determine the cooling mechanism taking place.

JESSEE RESIDENCE, PENNINGTON GAP, VIRGINIA

The Jessee residence is a 2-1/2-story, 4500 ft^2 home with two-thirds of the lower level underground (Figure 3-9). Heating is provided through air collectors, atrium glazing and skylights. Atrium roof venting provides cooling by thermally-induced ventilation. Based on two years of operation, no backup refrigerated air conditioning has been used. No blowers are used in the system. Heating degree days total 4300, but computer modelling of energy use and estimates of internal heat generation are not available.

The atrium skylight is a 4 ft by 16 ft and opens for summer ventilation. Air is drawn through the house to this outlet for cooling. South wall atrium glazing is 16 ft wide by 23 ft high. Twenty cubic yards of rock storage is located under the atrium. No monitoring has been performed.

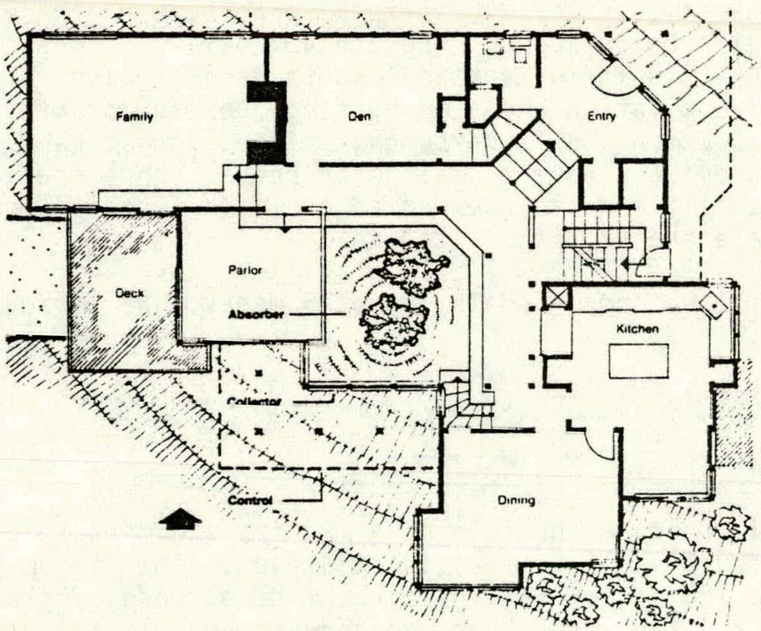

Figure 3.9 Jessee Residence, Pennington Gap, Virginia.

SOLAR ATRIUM RESIDENCE, PHILADELPHIA, PENNSYLVANIA

The solar atrium, designed by Ueland and Junker, is now being monitored in a demonstration two-story model single family home (Figure 3-10).

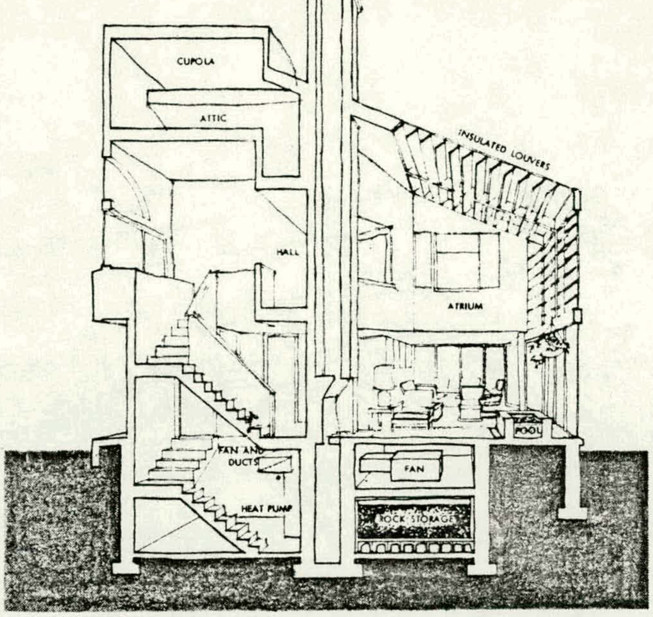

Figure 3-10 Solar Atrium Residence, Philadelphia, Pennsylvania.

The house was completed in September 1979, and monitoring instruments have been installed. All space heating requirements were furnished by solar from 10:00 a.m. to 10:00 p.m. on a typical winter day when outdoor temperatures ranged between 25°F to 30°F. At 6:00 p.m. the system switched from collection to extraction modes using the 250 cubic feet of rock storage for approximately four hours. The use of storage is attributed to the lack of insulating louvers in the atrium. In the cooling mode, night air was drawn into the atrium, across the pool surface, and through rock storage by fan. On the following day with high outdoor temperatures, the house was shut and internal air circulated through rock storage. This system maintained interior temperatures below 80°F when outside temperatures were considerably higher. Instrumentation includes six temperature sensors, two hygro-thermographs, and a data logger. A pyranometer and integrator are planned to be installed. Measurements are taken at half hour intervals, and future experiments are planned for controls, ventilation, window insulation and active water heating. Isolating the heat pump, rock storage, and fan from the atrium may provide useful information on buoyancy driven ventilation.

MENLO DEMONSTRATION TOWNHOMES, TUCSON, ARIZONA

The Menlo townhomes are a series of 10 buildings which include partially shaded outdoor courtyards (Figure 3-11). Construction details indicate 8" masonry exterior walls, 4" concrete slab flooring, and highly insulated walls and ceilings. Evaporative coolers provide the main cooling. No intention of thermally-induced cooling has been determined. These courtyards may produce primarily wind-induced ventilation.

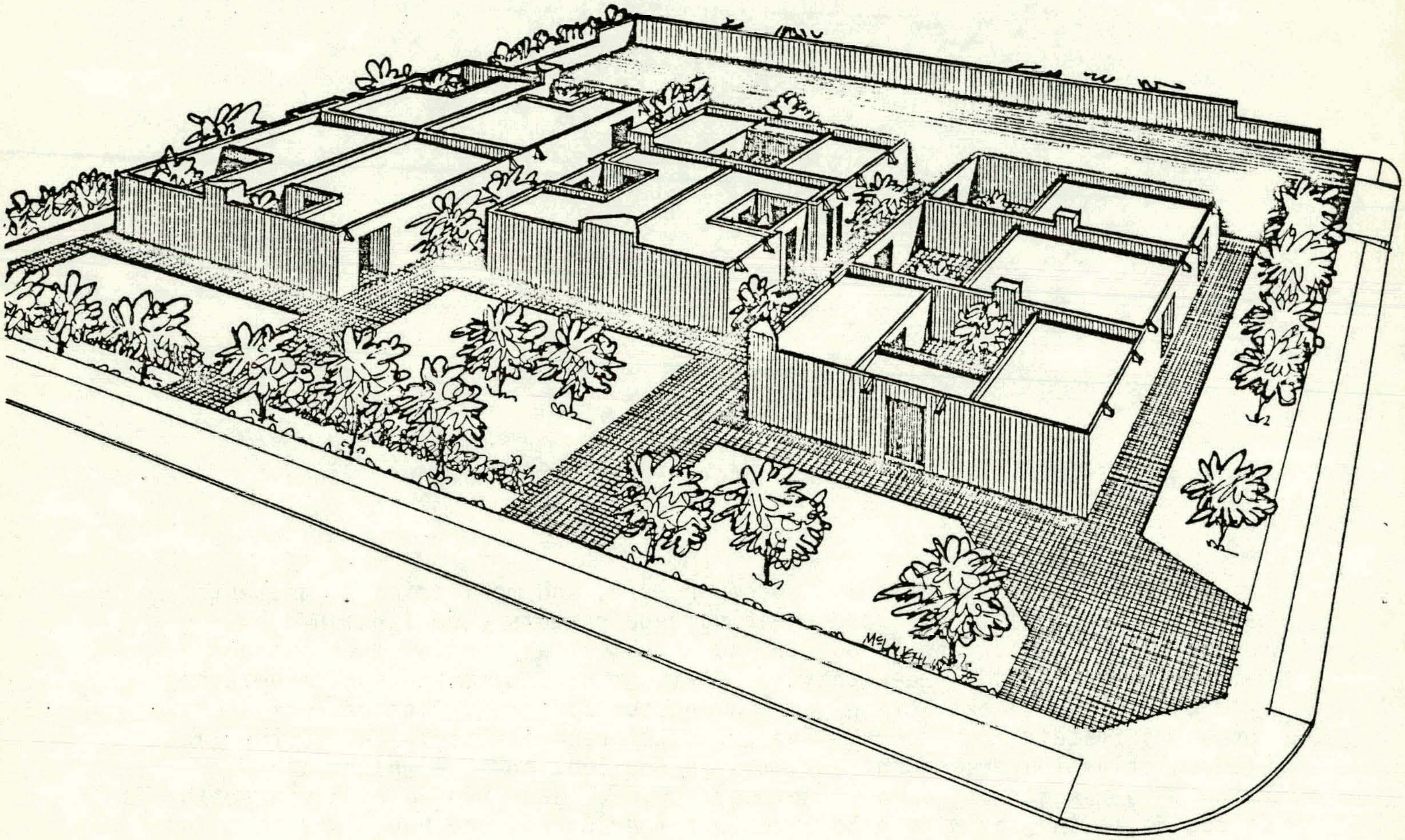

Figure 3-11 Menlo Demonstration Townhomes, Tucson, Arizona.

MELIN RESIDENCE, KENTFIELD, CALIFORNIA

This two-story, 2800 ft^2 home contains 500 ft^2 of unconditioned atrium space.

Passive heating is provided with gas backup through rock storage. The passive design is intended for convective heat flows using no blowers. Cooling is thermally-induced. Convection air flows only by opening windows, doors and skylights to allow flow through the atrium and out upper galley windows to the outside.

The atrium has a 14 ft by 14 ft glass roof. Thermal mass is provided by concrete steps in the entry. The south wall has 260 square feet of glazings with trellise overhangs. The floor of the atrium is irregularly shaped, approximately 20 ft long by 14 ft wide.

Construction is scheduled to be completed in the summer of 1981. No energy consumption estimates, instrumentation or computer modelling has been performed.

FORSTNER RESIDENCE, WOODACRE, CALIFORNIA

This 4500 ft^2 home is located on a 40 acre site. Windows are all thermal pane and the roof is concrete shake. Two atria are located within the insulated space. Two Trombe walls 11 ft wide by 19 ft high and 15 ft wide by 30 ft high are also used. An operable skylight is located over the stair-well for convective air flow. Radiant heat is the backup source; no cooling backup is installed. Construction is scheduled for completion by mid-1981.