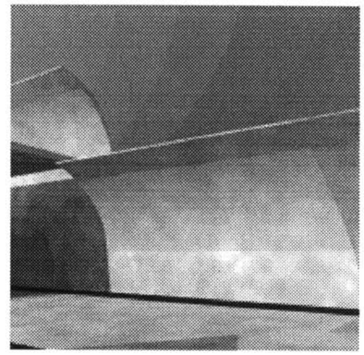

Thermal Design through Space and Time

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June 1991

SUBMITTED TO THE DEPARTMENT OF ARCHITECTURE IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ARCHITECTURE AT THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY FEBRUARY 1997

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ABSTRACT

One of the primary roles of architecture is to control the environment at the service of a building's inhabitants. Thermal qualities are a significant factor in the overall experience one has inside and outside a building. However, thermal issues are not often considered within the context of the architectural design process, resulting in buildings that are not responsive to thermal concerns. Heat has the potential to influence the form of architectural space. The methods by which architects can use thermal energy as a formative element in design is open to further exploration. In this thesis, I explore new methods for architects to describe thermal intentions and visualize thermal qualities of design proposals.

Beyond the economic issue of energy conservation, the thermal qualities of building spaces affect the quality of human inhabitation. The capability to describe and visualize heat would allow architects to adjust the building's thermal characteristics to modify a person's experience of the place. With a more complete understanding of thermal qualities of their building proposals, architects would be able to design for the complete gamut of thermal sensations that humans can experience. What is needed is a working vocabulary that describes the range of thermal conditions possible in buildings.

In this work, I describe a vocabulary for a building's thermal qualities using four sets of measurable, opposing terms: open versus protected, bright versus dim, warm versus cool, and active versus still. Next, I then articulate the thermal qualities of a co-housing project to create a thermal experience that enhances the community aspects of co-housing. Using a variety of visualization techniques, I verify that the design proposal is achieving the intended thermal goals. Using the knowledge gained from this and future thermal design exercises, we can begin to reflect on the general relationships between thermal phenomena and physical building forms, learning about the thermal qualities of architecture.

Thesis Supervisor: Julie Dorsey

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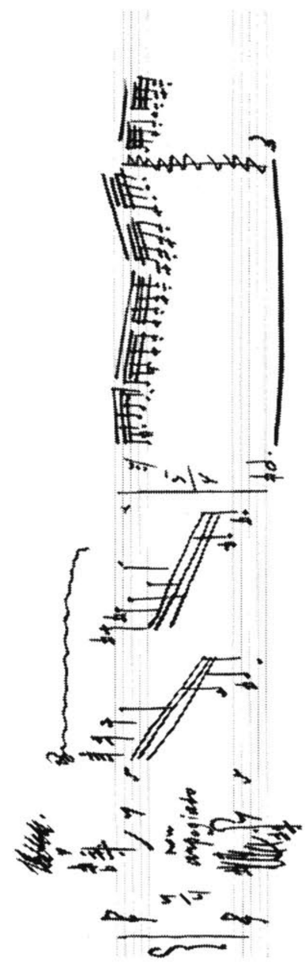
Contents

1. INTRODUCTION

One of the primary roles of architecture is to control the environment at the service of a building's inhabitants. Thermal qualities are a significant factor in the overall experience one has inside and outside a building. However, thermal issues are not often considered within the context of the architectural design process, resulting in buildings that are not responsive to thermal concerns. Heat (or lack thereof) has the potential to influence the form of architectural space. Much like one designs to control light and its associated experiential qualities, one can also use heat to inform design decisions. Unlike light, thermal energy and its formal associations are not readily visible and are poorly understood within the design community. The methods by which architects can use thermal energy as a formative element in design is open to further exploration.



Beyond the economic issue of energy conservation, the thermal qualities of building spaces affect the quality of human inhabitation. The capability to visualize heat would allow architects to adjust the building's thermal characteristics to modify a person's experience of the place. Today, architects are able to consider the "coolness" of north light, or the "warmth" of a southern exposure. However, these thermal descriptors do not precisely describe the physical behavior of heat. With a more complete understanding of thermal qualities of their building proposals, architects would be able to design for the complete gamut of thermal sensations that humans can experience.

The key to successful use of thermal qualities as elements in architectural design is finding ways to allow for the qualitative expression of numerical thermal information. The chasm between the qualitative and the precise numeric is bridged when one looks to music as a precedent. The physics of sound are scientifically definable. Professional musicians are capable of producing sound with precise control over its physical character (frequency, volume, tone, etc.) Musical compositions are written in an equally controlled, formal musical language that prescribes the quality of the sound to be played.[1] Yet, even with all of the precise numerical structure of music, great poetic movements of sound are still possible.

[1] Tufte, E. *Envisioning Information.* Graphic Press: 1990. p. 59.

To bring the same type of liberating structure to thermal design, a working vocabulary must be defined, bounding the range of thermal conditions possible in buildings. In this work, I describe a building's thermal qualities with four sets of measurable, opposing terms: open versus protected, bright versus dim, warm versus cool, and active versus still. These thermal qualities in buildings are experienced by its inhabitants over time and through space. Because the sun changes position during the day and throughout the different seasons, thermal conditions will vary greatly with time. In addition, the way in which a person inhabits and/or moves through a building will change the thermal sensation that the person experiences.

In this thesis, I articulate the thermal qualities of a co-housing project to create a thermal experience that enhances the community aspects of co-housing. The geometry and material qualities of building forms are chosen to develop particular thermal experiences. Elements in the-design develop thermal stability in exterior spaces that are traditionally inhospitable much of the year. Interior movement of people towards community centers is reinforced with coincident flows of thermal energy. The central space in the design is a thermally dynamic place that piques the senses.

Using a variety of visualization techniques, I verify that the design proposal is achieving the intended thermal goals. Space and time are compressed onto images that articulate the human thermal experience. From this and future thermal design exercises, we will begin to reflect on the general relationships between thermal phenomena and physical building forms. Understandings these relationships can stand as a starting point for learning about thermal qualities of architecture.

2. THERMAL VOCABULARY

Thermal design in architecture has been hampered by the singular goal of achieving thermal comfort, resulting in even thermal quality everywhere. Until today, the ideal goal for designers has been to achieve "thermal comfort" in all habitable spaces. Not only is thermal comfort difficult to define, using it as the end-goal creates thermally homogenous building spaces. Designing for "thermal comfort" is akin to lighting a building so that all spaces are evenly lit. Creating an evenly lit building would result in some spaces being too dim and some spaces being too bright, because certain building spaces house tasks that require different degrees of lighting than spaces that are for other functions. Enforcing an even lighting everywhere would also eliminate the ability of an architect or lighting designer to use the varied experiential qualities of light to help define the architectural qualities of the building spaces.

Just as there exists a range of comfortable lighting levels in buildings, there also exists a range of thermal levels in buildings that go beyond the generic description of "thermal comfort". However, because of a fixation on achieving "thermal comfort", we have not thought much about how we would describe this range of thermal conditions. Today, architects may consider the "coolness" of north light, or the "warmth" of a southern exposure. These thermal descriptors do not precisely describe the physical behavior of heat nor the qualities of the thermal experience. Also lacking is any consideration of how the thermal experience might change over time. With a more complete vocabulary for describing thermal qualities of their building proposals, architects would be able to design for all of the thermal sensations that humans can experience.

Previous descriptive analyses of thermal conditions falls into two general categories: engineering analysis that formulates thermal comfort and descriptive prose of thermal experiences. There has been considerable scientific research done to analytically describe the concept of "thermal comfort". This type of research is focused on mathematical representations of thermal situations when people are "not dissatisfied". Due to its focus on only thermal comfort as a thermal descriptor, the usefulness of this previous work is necessarily limited. Nonetheless, it provides insight into the physical factors that make people comfortable.

Thermal comfort is described by Gan,[2] Fanger[3] and ISO 7330[4] in terms of the two thermal comfort indices, predicted mean vote (PMV), and predicted percentage of dissatisfied (PPD). These indices take into account the following environmental factors: air velocity, air temperature, mean radiant temperature, partial water vapor pressure or the air, and the occupant's activity level and clothing.[5]

At the other end of the thermal descriptive spectrum, one finds work by Heschong[6] and fictional literature such as Jack London's Call of the Wild,[7] that give emotive depictions of thermal experiences that the reader can almost feel through the power of the words. However, there is little or no effort to the characterize the type or quantities of physical forces that are causing the sensation, and without this information the described thermal experiences would be difficult to incorporate into a new building design.

To better describe thermal qualities, one needs to formalize a thermal vocabulary that can adequately describe the full range one might find in architecture. I will define four basic thermal qualities in my thermal vocabulary: exposure, air temperature, air movement, and stability. Together, these terms combine to accurately depict the thermal conditions one might find in a particular place. This thermal vocabulary is only one of a multitude of ways of giving formal structure to the description of heat in buildings. I have selected this vocabulary because it is conveniently concise, while still giving a more complete thermal description than is typically found in architectural discourse.

A place's exposure refers to the visibility of it's surfaces to external surfaces with different radiant temperatures. This thermal measure is useful for determining the radiant thermal gains or losses one might expect to find. Building spaces whose material surfaces have a view to the sun, with it's high radiant temperature, will have a high thermal exposure. A direct view of large areas of high temperature surfaces, such as radiators, will also give a space a high thermal exposure. Rooms which only have visibility to surfaces with similar radiant temperatures, such as a windowless space, will have a moderate exposure. Spaces with views to cool surfaces or the night sky will have a low exposure and can expect to have large radiant losses.

Air temperature is the dry bulb temperature found in a space. Dry bulb temperature measures the average energy in the room's air. While dry bulb temperature is only one of the factors that determine the human thermal experience, this measure has his-

2 G. Gan and H. Awbi. "Numerical Simulation of the Indoor Environment." *Building and Environment*. 29 (1994). pp. 449-459.

3 P.O. Fanger. "Numerical Simulation of the Indoor Environment." *Thermal Comfort-Analysis and Applications in Environmental Engineering*. Robert E. Krieger Publishing Company, Florida (1982).

4 ISO 7330. "Moderate thermal environments-determination of PMV and PPD indices and specification of the conditions for thermal comfort." *International Standards Organization*, Geneva (1984).

5 $PMV = f(V_r, T, T_{mrt}, P_v, I_{cl}, M, W)$

$$PPD = 100 - 95\exp(-(0.03353PMV^4 + 0.2179PMV^2))$$

V_r	function of air velocity
T	air temperature
T_{mrt}	mean radiant temperature
P_v	vapor pressure
I_{cl}	clothing thermal resistance
M	occupant's metabolic rate
W	external work

6 Heschong, Lisa. *Thermal Delight in Architecture*. MIT Press: 1979.

7 London, Jack. *The Call of the Wild.* MacMillan: 1963.

torically been the only feedback used for control of the typical residential HVAC system. One typically sees the predominance of this thermal measure over all other measures because it is easily sampled with an inexpensive thermometer.

Air movement is defined as a measure of the mass and velocity of air moving through a space. In addition to transferring heat from one place to another, moving air greatly affects human sensation of heat. Because of evaporative cooling, the human sensory system reacts to even slight movements of air.

Stability describes the likelihood of a place's thermal character to change over time with the external environment or other external factors such as adjacent spaces. In general, this term will show how thermally dependent or isolated a space is on adjacent places. A place with high thermal stability will not see much thermal change even when there are dramatic changes outside or in adjacent spaces. This could be due to limited exposure to the environment, low air flow to or from nearby rooms, or highly stable material properties. On the contrary, a place with low thermal stability will change rapidly with the external changes. Often, places with low thermal stability will have a strong physical connection with the exterior of a building or other interior spaces. In contrast with the independence of the other three thermal variables, thermal stability is often dependent on the place's exposure and air movement.

The use of the above-described thermal vocabulary in thermally-aware design opens up a range of possibilities not available when only designing for thermal comfort. While it is true that most of the physical characteristics of this thermal vocabulary are used in current formulations of thermal comfort, the algebraic definition of thermal comfort sets as a goal only a small subset of all the possible thermal combinations. Comfort is nebulous and perhaps not a reasonable goal at all for certain places. In addition, the use of thermal comfort as a measure hides the distinct qualities that one gets from the different thermal components. A room with high air temperature plus a low radiant temperature and a room with a low air temperature plus a high radiant temperature might give equivalent levels with the thermal comfort formulation, while in fact they produce very different thermal experiences.

To aid in the definition of the bounds for the thermal vocabulary, I associate terms that represent the minimum and maximum values one might expect to find in a building. These terms are useful as descriptive tools, and they can be readily associated with a numeric scale to aid in the translation from this descriptive vocabulary to a computable value. Exposure can use “bright” as the maximum and “dim” as the minimum. Air temperature can use the typical “warm” and “cool” as its bounds. For air movement, “active” can be the maximum and “still” can be the minimum. Stability can range from “protected” to “open”. Used together, this terminology forms a thermal descriptive system.

When using this thermal descriptive system in architectural programming, one can describe the individual thermal qualities. For example, in this thesis, I wish to design a communal dining and meeting space. I would like for the thermal qualities of the space to change with the environment, so I will say that it is an “open” space. I would also like for there to be a strong visual connection to the outside, and desire a “brightly exposed” space. To reinforce the sense of changeability in the space, as well as to induce high thermal flow, I will describe it as moderately “active”. Finally, I will say that this space is fairly “cool” because this will be a space in which people stay for measured amounts of time, bringing their own energy into the space.

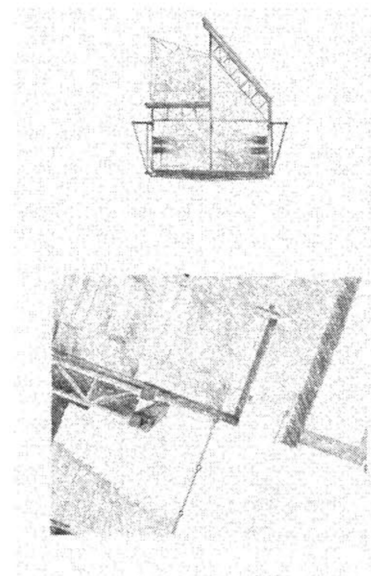
If we associate each of the thermal qualities with a linear scale from 0 to 10, we could use a more precise, concise and computable description. The above example could translate to the following:

stability	2
exposure	9
air temperature	3
air movement	8

With this computable thermal vocabulary, we can now explicitly state our thermal design intentions so that we can later use computational tools to aid us in verifying or analyzing that the design solution is satisfying the stated thermal intentions.

3. THERMAL VISUALIZATION

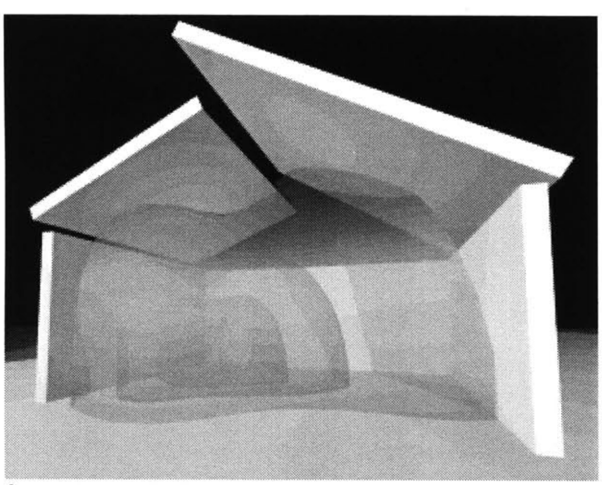
Methods for visual representation of thermal intentions and thermal analysis are not yet well-developed. Thermal descriptors are inherently difficult to represent using traditional design media due to the high dimensionality of the information compared with the 2-dimensional nature of the printed image. Shaun Roth[8] has developed a system of rendering architectural plans and sections by combining a limited palette of primary colors to denote a zone's thermal temperature and thermal flux. He has chosen colors so that they combine when overlaid to represent the color that corresponds to the thermal condition that would result from the combination of the two primary conditions. This clever color-encoding system could be used as the basis for a visualization system. In addition to Roth's system, one might add complementary visualization techniques to represent other thermal qualities such as air movement or radiant exposure.



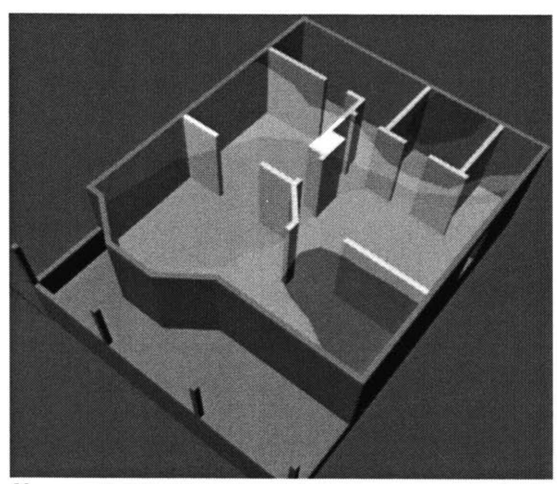
[8] *A pseudo-color hand rendering of temperature and thermal flux.*

Roth, Shaun. "Representation of Thermal Energy in the Design Process". MIT M.Arch. Thesis. 1995.

Designing a visualization that will ultimately be presented in printed form, is quite different than designing for an interactive presentation on the computer screen. To capture as much thermal information as possible in a single static image, we can use a combination of visualization techniques. We would likely use pseudo-coloring to represent a scalar thermal value (such as solar exposure) on the building surfaces. It becomes difficult to use pseudo-colors to represent scalar values within the building space,[9] as this can begin to occlude the rest of the visualization. A solution to the occlusion problem is to only pseudo-color a sectional slice within the space. Although this results in a reduction in the quantity of visualized information, the clarity is greatly enhanced.[10]



[9] *visualization of too much data is difficult to read*



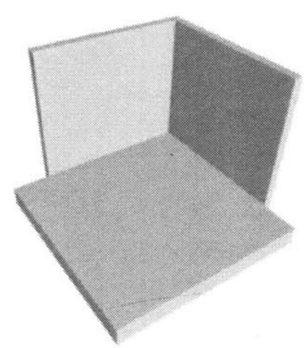
[10] *Sectional slices of data show less data but are clearer*

For a static visualization to clearly convey large amounts of information, it is useful to look at icon representations. By associating an icon with a particular data type, it is possible to include a large number of different data types within a small amount of physical space. For example, I have designed a simple system for visualizing design intentions using icons to represent four thermal variables - solar exposure,[11] air temperature,[12] air movement,[13] and stability.[14] These icons have been chosen so that they can coexist within a small footprint without distracting from or distorting each other's information.[15]

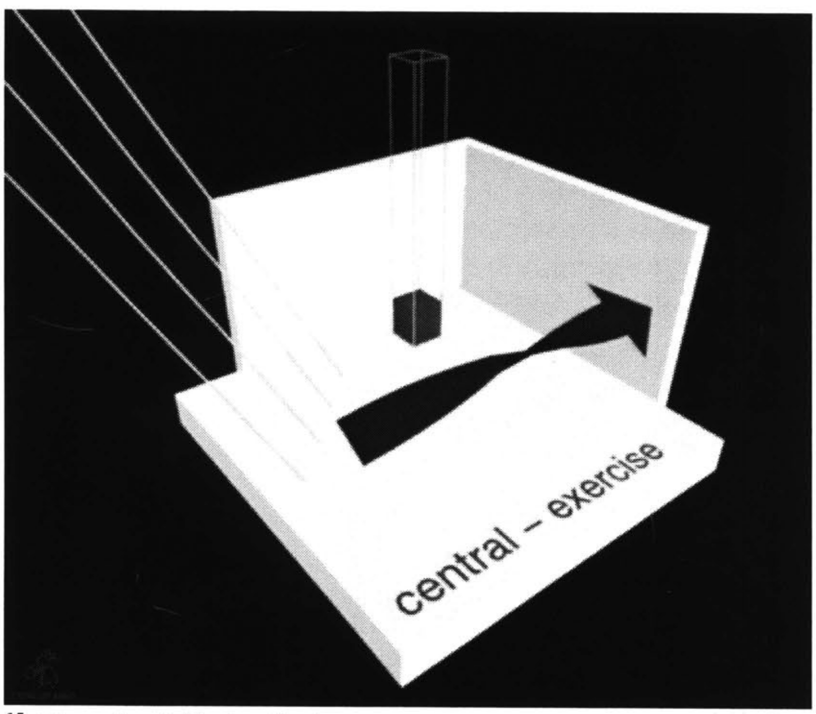
11 solar exposure - number of rays

12 air temperature - height of bar

13 air movement - width of arrow

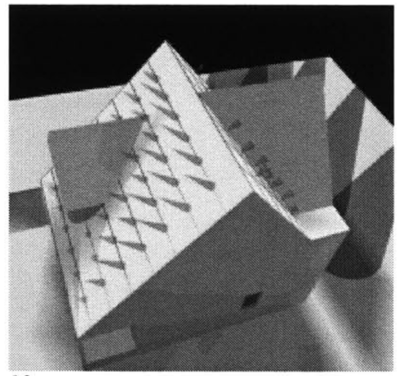


14 stability - height of wall



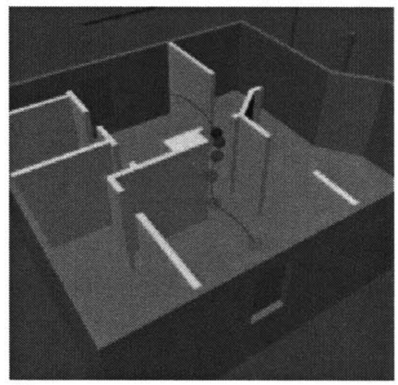
15 Thermal variable visualization

Thus far, we have discussed visualizations of static, scalar data. Thermal information also contains vector data that often changes over time. To represent these additional dimensions in a static image is truly a difficult design problem. Vector data can be visualized as a directional icon. Typically, engineering visualizations will use arrows, whose lengths represent the points' magnitudes. However, it is easy to imagine how confusing this might become if the directional icons are within 3-d space. When viewing the icon, one can't determine the true size of the icon because of the perspective foreshortening.[16] Using an isometric view can help alleviate this problem, but it is not always a desirable projection to use.



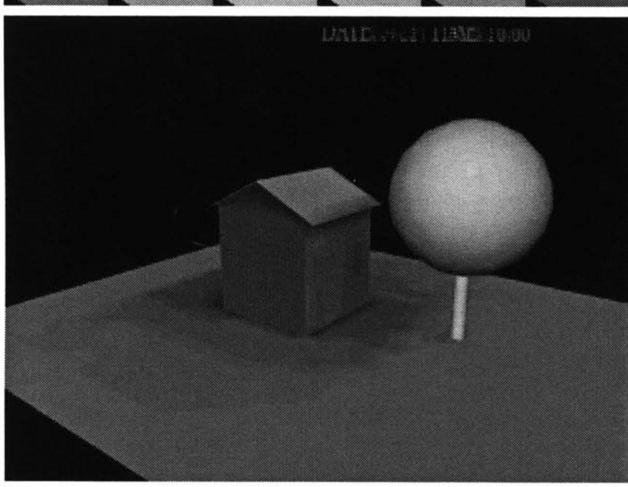
16 Perspective foreshortening changes the apparent cone size.

Representing time in a static image is also a significant challenge. Since it is not possible to show in a static image how all the thermal information is changing over time, it is necessary to compress the data in one of many possible ways. In the some cases, it is better to use less data types and simply show the data at each point in time. If we were to visualize air movement over time, we could trace out the full path of a small number of air particles.[17] Another data compression method is show all the data, but to filter the data to reduce its complexity. If we were to take the averages of each pixel in a series of static images[18] that show solar exposure, we would have a single image that describes the average amount of solar exposure over that particular range of time.[19] We could just as easily have the image show the maximum or minimum solar exposures.[20]

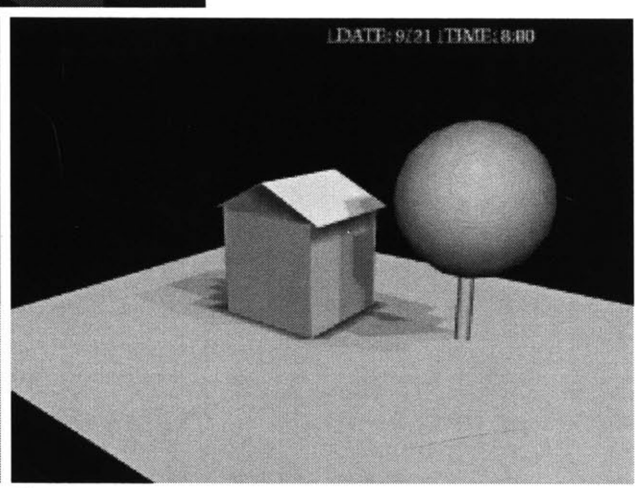


17 Air particles

18 Series of static images taken over time

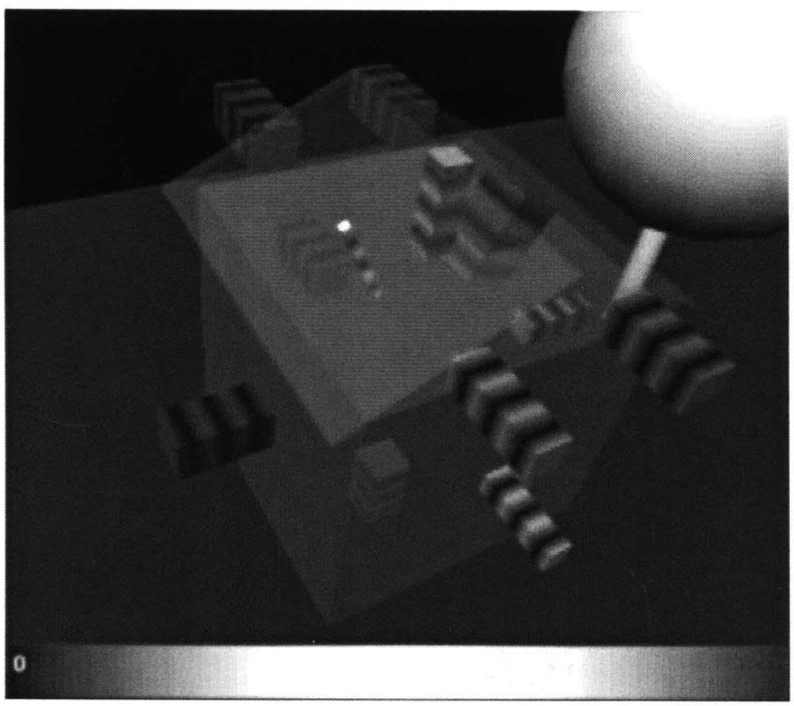


19 Image average



20 Image maximum

When we are using the computer screen as the ultimate destination for the visualization, we then open the possibility of developing an interactive visualization in which the user helps define which data are shown. It is possible to design a system that would let the user move an icon through the space, displaying the data at that point by pseudo-coloring the icon. If we let the icon represent a human figure, then we can map any type of thermal information onto this icon. This type of data mining is especially useful for displaying volumetric data. With an interactive visualization, it is also possible to show how thermal data change over time. Vector data can be animated to show their movement, as in the following frame from an animated visualization of heat flow.[21]

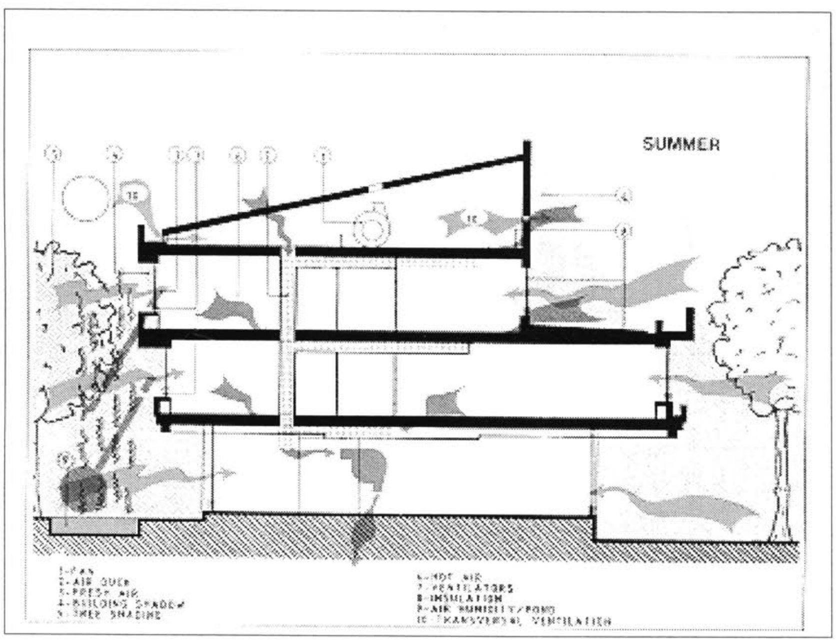


[21] *Heat flow animation*

4. EXISTING ANALYSIS TOOLS AND METHODS

Along with better ways to express thermal intentions, we need to find methods for thermal analysis of building designs that will give feedback as to success or failure in meeting the thermal intentions. There exist many tools to aid the building designer in this capacity. I will examine these tools and critique their strengths and weaknesses.

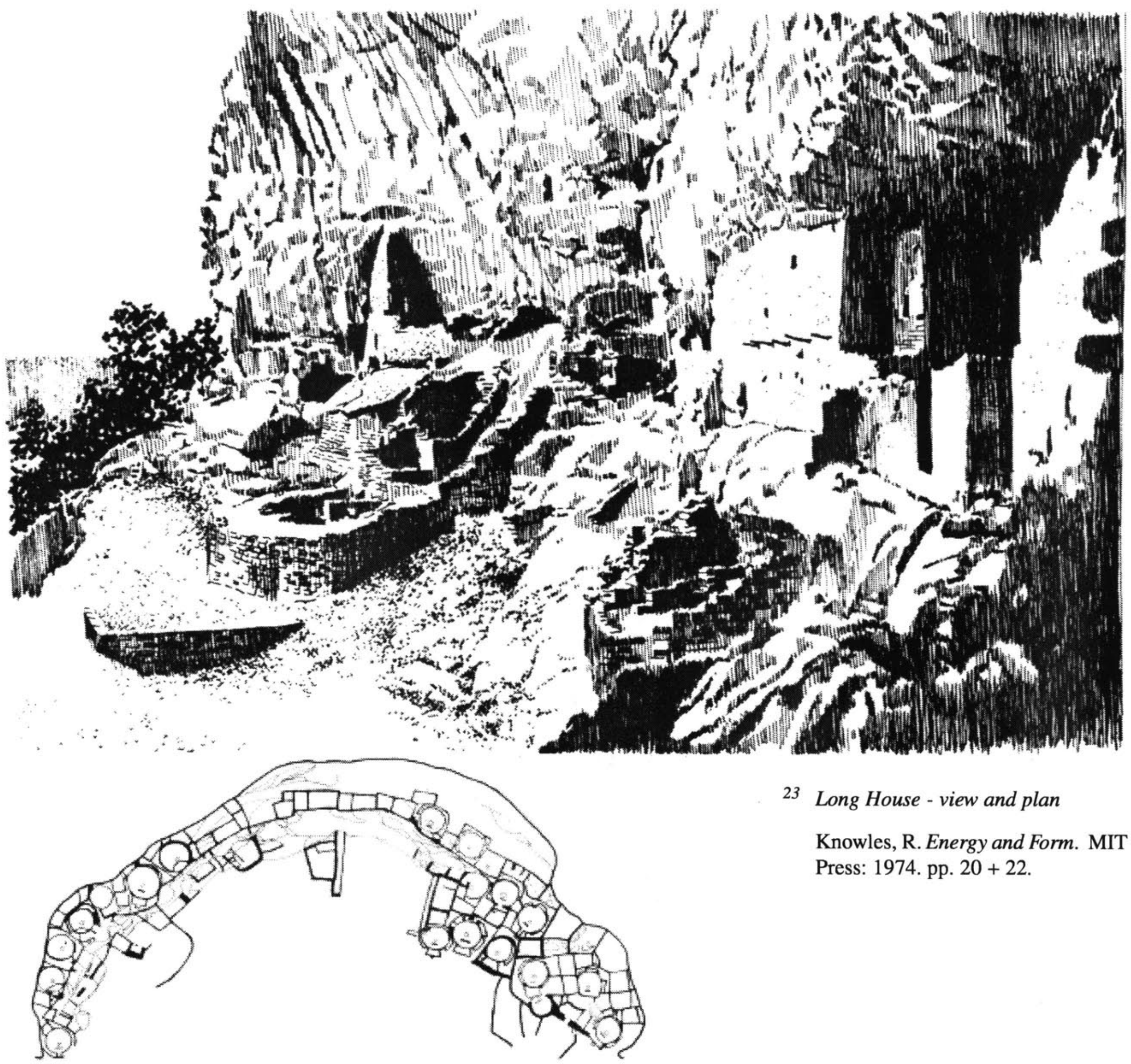
In general, thermal analysis tools fall into two basic categories: tools for architects and tools for engineers. The tools for architects suffer from inaccuracy because of a tendency towards oversimplification. The most basic analysis tool is the architect's soft arrow. This representational icon is often overlaid upon building sections and is used to describe the supposed flow of heat or air through a building proposal.[22] These arrow icons are sometimes cynically termed "smart arrows" because they show the heat flow in the way most beneficial to the design intention, often without any validation. Thus, "smart arrows" are actually less of an analysis tool and more of an expression of design intention.



[22] *Smart arrows*

Ouden, C. *Building 2000.* Kluwer Academic Publishers: 1992. p. 204.

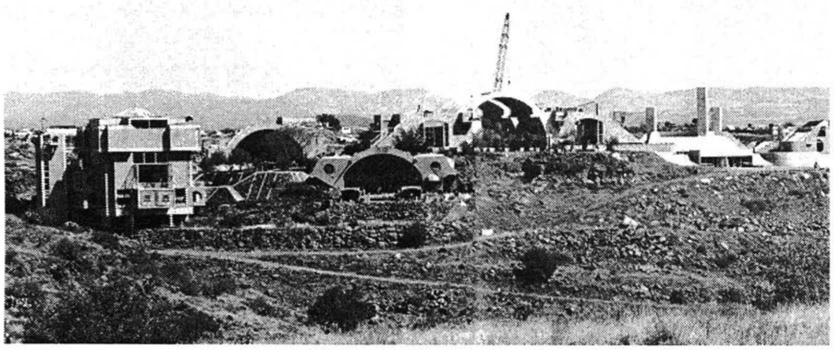
In the most abstract terms, we can describe the evolution of some vernacular architectures towards thermally responsive design as a method of thermal design. Over hundreds of years, various peoples have refined their building design methods through trial-and-error experiences with the real-world thermal conditions. In the American South West, we can see the forms of the Native American pueblos responding to the harsh realities of the solar movements.[23] The Long House building form is optimized to capture much of the winter sun's energy, while protecting itself from the intense summer sun. The obvious disadvantage of using a trial-and-error method to arrive at an ideal vernacular form is the long time such an evolution takes.



[23] *Long House - view and plan*

Knowles, R. *Energy and Form.* MIT Press: 1974. pp. 20 + 22.

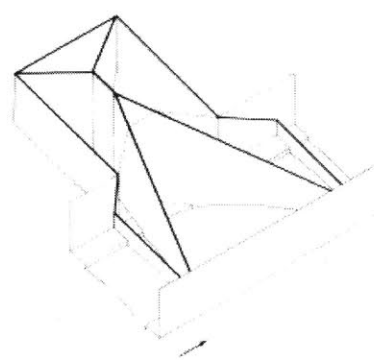
With new materials and design constraints, as a culture, we've departed from these vernacular forms, producing new designs. There has been an attempt by some architects, such as Paolo Soleri, to develop new vernacular forms that can respond to the changing needs of an environmentally conscious society. This approach has been problematic because these propositions are but the early iterations of a process of design and redesign that will long out last the lives of the architects. Thus, projects, such as Soleri's Arcosanti,[24] have cast definitively into concrete a thermal solution that may not produce the desired thermal experience. To study new designs, we need to use predictive methods, rather than wading through the long, iterative, trial-and-error process of building and then rebuilding to fix earlier errors.



[24] *View of Arcosanti in Arizona*

Soleri, Paolo. *Arcosanti*. Avant Books: 1984. p. 8.

Recently, there have been designers who have taken an analytical approach to thermal analysis. In his book, ***Sun Rhythm Form***, Ralph Knowles describes a building's "solar envelope."[25] Using physical models and geometric constructs, he describes ways to create geometric forms that represent the hull within which the building envelope should remain in order not to adversely affect neighboring buildings' thermal conditions. For urban zoning, this method is an intelligent progression from the overly-simplistic height requirements found in many zoning codes. However, at the building-design level this method doesn't address other critical issues such as self shading, material properties, or the amount of solar energy received by the individual building elements.



[25] *Solar envelope drawing*

Knowles, R. *Sun Rhythm Form*. MIT Press: 1981. p. 119.

4.1 TOOLS FOR ARCHITECTS

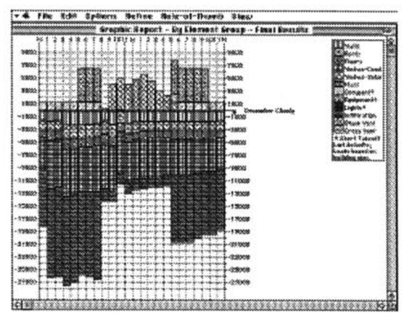
Many energy analysis tools have already been created for architects. Computer software programs, such as Energy Scheming 2.0[26] and Solar 5.4,[27] allow for macroscopic analysis of building designs. Usually based on a 2-d CAD input metaphor, these programs will provide the air temperature for each room (or zone) at several times during the day. The output of the software is typically a 2-d graph plot or a table of numeric data. Three major limitations of this type of software are immediately noticeable. First, the design specification or data input bears little resemblance to how architects work. Some programs, such as the Building Design Advisor,[28] use a 2-d graphical interface to aid with data input. The software is still lacking in one dimension, as architects design using 3-dimensional models and should not be constrained into working with only 2 dimensions.

26 Energy Scheming is commercial software developed by G.Z. Brown. It is marketed to architects.

27 Solar 5.4 was developed by Murray Milne et al. at UCLA. The software is freely available.

28 The Building Design Advisor software was developed at Lawrence Berkeley National Laboratory.

The second problem is that the analysis data output has no physical relationship to the architectural building spaces. The analysis output from Energy Scheming 2.0 is as good or better than most energy analysis software. Output data is displayed in a series of 2-d charts, tables and graphs.[29] The analysis output for a single building is approximately 70 pages long. This voluminous amount of output data is not structured in a way that fosters easy understanding of the thermal data. Often, information is more understandable when it is displayed together with the underlying physical context, and this is particularly important when displaying data for visually-oriented designers.



29 *Output from Energy Scheming*

"Energy Scheming Software Helps Architects Scheme on Energy." Energy Source Builder. (April 1995). fig. 2.

A third, and perhaps less obvious, problem with the above-mentioned architectural analysis tools is the inability of the software to analyze the thermal qualities within a particular space. The software was originally designed for use in energy conservation and to ensure even thermal comfort within a building space. Therefore, it is difficult if not impossible, to get more than a single value for each zone or room in the building. While this level of detail may be reasonable for determining the orientation of a building, designers need more detailed thermal information at the scale of a person or an individual building element, in order to truly design with thermal qualities in mind.

4.2 TOOLS FOR ENGINEERS

Software analysis tools developed for engineers provide more analysis detail and precision at the expense of usability within the design process. Computational algorithms have been developed that accurately model all of the thermal energy transfer that occurs within a building. These solutions are comprised of two general types: macroscopic and microscopic.

4.2.1 Macroscopic Analysis

The first group of algorithms consist of the macroscopic energy models. Macroscopic models consider the temperature of each room or space to be consistent across that space. Programs such as ASHRAE, DOE-2, BLAST, CIBSE, CARRIER, CHEETAH, BSIMAC and QUICK, provide building thermal analyses that are appropriate for overall building energy use and heating/ cooling load prediction.[30] Building performance is dynamically predicted using information including air flow rate (air exchanges), building thermal capacitance (energy storage), convective heat, radiant heat, material thermal resistance's, outdoor dry-bulb temperature, sol-air temperature, and humidity. This climatic and building-model information is entered into an algorithm that can predict how much heat must be added or subtracted from each building space to maintain a comfortable temperature at different times of the day and year. QUICK and others of these programs allow for the dynamic study of heating and cooling cycles. QUICK has been experimentally validated and is very useful for the mechanical engineer who needs to accurately and minimally size HVAC equipment for a building which has already be architecturally designed.

[30] E.H. Mathews, A.G. Shuttleworth and P.G. Rousseau. "Validation and Further Development of a Novel Thermal Analysis Method." *Building and Environment*, 29(1994), pp. 207-215.

However, these macroscopic thermal models are not as useful to an architectural designer as to a mechanical engineer. Programs such as DOE-2[31] primarily predict heating and cooling loads from a complete computer model. An architectural designer needs a program that is designed to predict indoor thermal conditions based on external thermal factors (such as solar heat gain) and assumed mechanical heating or cooling effects. QUICK is better than most other macroscopic programs in this regard, allowing for the simulation of indoor temperatures for passive buildings and for buildings using ventilation, structural cooling or evaporative cooling.

[31] DOE-2 is a public-domain software program for predicting building energy use and energy costs. It was developed by the Simulation Research Group at Lawrence Berkeley National Labs.

The effective thermal analysis program for architectural designers would focus on predicting indoor temperatures based on the information that the designer had provided up to the present point in the design process. For instance, if wall materials are not yet known, then the program would make assumptions about the wall's thermal qualities. Thus, the analysis can immediately proceed and provide the designer with thermal information before the building's design is complete.

The work of the SETIS project[32] incorporates the idea that thermal analysis must begin with an incomplete design. Using an expert system, the program creates the information which is missing from the building model. Although SETIS is tuned for building design rather than only for thermal analysis, the program still suffers from the same inherent shortcoming of all the macroscopic models, the inability to examine thermal qualities in detail.

[32] C. Robin, J. Brau, and J.J. Roux. "Integration of expert knowledge and simulation tools for the thermal design of buildings and energy systems." *Energy and Building,* 20(1993), pp. 167-93.

Building designers must be able to understand the thermal qualities at different points within a building space. While macroscopic models such as SETIS and QUICK are useful for designing buildings that consume less energy, architectural designers must create spaces that satisfy other thermal requirements as well. This necessity requires an analysis of the thermal qualities at many points within a space.

Output from the current macroscopic programs has not been well-suited to design. At best, these models create enough information about a particular room to make a simple line graph of temperature over time. At worst, they produce reams of numerical data that are not easily converted into an imageable format for use by visually-oriented designers.

4.2.2 Microscopic Analysis

Information from a microscopic analysis, on the other hand, can be used to create a volume rendering of a room's thermal energy. This visual representation of energy allows a designer to quickly understand the thermal qualities of the space. There are also tools for engineers that begin to examine these smaller-scale thermal phenomena in buildings. Microscopic energy analysis programs provide the level of detailed information that is missing from the macroscopic programs. While macroscopic models such as QUICK can provide limited information (such as the temperature) about a room over a period of time, the existing microscopic models are best at providing a detailed view of a room's thermal qualities at a specific point in time. Microscopic models are not inherently precluded from producing dynamic analysis. However, the current microscopic algorithms are expensive and time constraints prohibit dynamic analysis from being feasible with present software.

The slow speed of current microscopic analyses is a major hindrance to producing an interactive design system. Even with a fast workstation, such as the SGI Indigo2, to run a thermal analysis of a single room can take from several hours to one week. Analysis times must be reduced to provide an approximate thermal solution within several minutes at most. The accurate microscopic models rely on computational fluid dynamics (CFDs) to solve for airflow (and the heat transfer associated with that movement) in a space. Air flow has a significant effect on heat transfer in most spaces and is factored into the thermal comfort calculations (for evaporative cooling effects), as well. Thus, some calculation of the air flow must be included in a thermal algorithm, or else the solution will most likely be too approximate for many architectural design decisions.

The CFD program VORTEX (Ventilation of Rooms with Turbulence and Energy eXchange) developed by Gan and Awabi[33] produces a direct simulation of the PMV and PPD thermal comfort indices for indoor environments. The program's airflow model uses a combination of the Navier-Stokes (momentum) equation, the thermal energy equation and the concentration of species equation combined with the two equations for kinetic energy and the dissipation rate of the κ–ε turbulence model. Boundary conditions of air velocity and temperature are expected to be given as input values. The equations are solved for a 3-D cartesian coordinate system using the SIMPLE algorithm[34] of discritising by a finite volume technique. To arrive at the PMV and PPD indices, the program then solves for the mean radiant temperature independently from the air flow equations. The mean radiant temperature is calculated for each face of each 3-D grid cell in the model based on the radiosity of the room's wall surfaces.

By calculating the surface radiosity based on given information, this program does not consider that the air flow may influence the initial temperature of the wall surfaces. A more accurate assessment of the initial surface conditions would result if the program had been designed to use a few iterations of the CFD algorithm on a very rough surface grid to modify the initial wall temperatures instead of using given values for surface temperature. An even more accurate solution would be obtained by linking all

33 G. Gan and H. Awbi, "Numerical Simulation of the Indoor Environment." *Building and Environment*, 29(1994). pp. 449-459.

34 S.V. Patanker, *Numerical Heat Transfer and Fluid Flow*, Hemisphere Publishing Co., Washington (1980)

of the air flow and energy equations and solving for a simultaneous solution, such as done by Chen.[35]

While a solution that links the convective, conductive and radiative equations together most closely models the ways that these methods of heat transfer are related in reality, linking is not cost effective. Highly accurate solutions can be achieved with algorithms that do not link the different methods of heat transfer, solving each method of heat transfer individually. Another solution by Chen begins by modeling the conductive transfer of heat to the inside face of the building's exterior wall surface. The wall faces are then subdivided into large patches. Using a few iterations of a computational fluid dynamics algorithm, the temperature of the wall patches is adjusted for convective transfer. These patches can then be used as emitting patches in radiative heat calculations. The computational fluid dynamics is then performed again to give a full description of the thermal qualities of every point in space.

Work by Li and Fuchs[36] also seeks to decouple the radiation exchange calculations from the air energy equation. Their CFD solution studies the effect of radiation on the temperatures in a room with displacement. They concluded that radiation plays non-negligible role in thermal stratification. Work by Tuomaala and Rahola[37] demonstrates yet another method that is somewhat similar to Li and Fuchs's program, except that it places emphasis on studying the dynamic heat transfer. However, currently this model completely ignores the effects of thermal radiation, and it is therefore of limited use.

The microscopic solutions described above rely heavily on computational fluid dynamics to solve for the convective transfer effects. The high cost of CFD algorithms runs counter to the goal of producing an interactive thermal visualization system. The computational model must be designed to provide the designer with an economical thermal computational solution. In order that the designer gets immediate feedback to design decisions, methods of approximation are necessary to reduce the computational expense of the convective flow CFDs. In the visualization of visible energy (light) there exist algorithms for progressive refinement that greatly enhance the usefulness of radiosity-based solutions. A CFD algorithm that similarly progressively refines and is designed to give immediate feedback is a necessary component of an interactive thermal visualization.

35 Q. Chen, X. Peng, and A.H.C. Paassen. "Prediction of room thermal response by CFD technique with conjugate heat transfer and radiation models." *ASHRAE Transactions.* 101:2(1995). pp. 50-60.

36 Y. Li and L. Fuchs. "Numerical prediction of airflow and heat-radiation interaction in a room with displacement ventilation" *Energy and Building.* 20(1993). pp. 27-43.

37 P. Tuomaala and J. Rahola. "Combined Air Flow and Thermal Simulation of Buildings." *Building and Environment.* 30(1995). pp. 255-65.

5. SOLAR EXPOSURE DESIGN TOOL

To begin the exploration for better thermal design tools, I have designed and implemented a simple tool for visualizing the solar energy exposure one might expect to get on the envelope of a building. The solar gains are displayed as a pseudo-colored map on the building geometry. By looking at the color of the building elements, one can see the amount of solar energy the surface is receiving at that particular time and place. It is also possible to introduce the variable of time, animating the solutions over the hours of a day or over days of the year. This tool is the first step towards a full interactive thermal design system that will include solutions to heat transport by radiation, convection, and conduction.

The solar exposure of a building is useful for determining how much passive solar gain one can expect in a building design. Information about the relative shading of the site, neighboring buildings, and the building itself is readily accessible from this tool. Using a time-compressed image, the average solar exposure for a day or for the entire year can be viewed in a single image. The solar exposure information can also be used as the boundary conditions for other, more complex thermal visualizations.

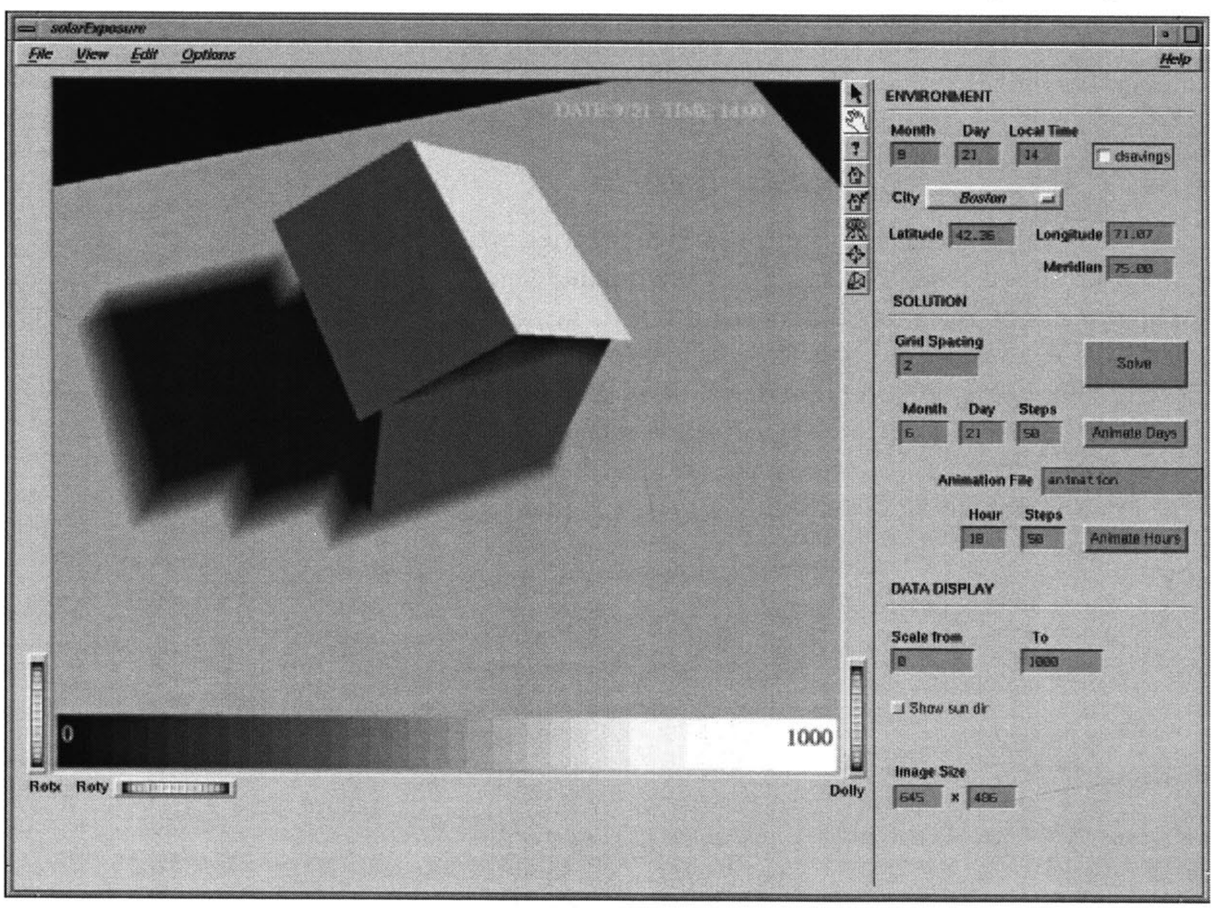
5.1 SOLAR EXPOSURE SOFTWARE

The solar exposure software is designed to give the user maximum control over the quality and speed of the thermal simulation. The process of analyzing a building proposal consists of loading a 3-d polygonal model; selecting the environmental conditions, and choosing a solution resolution. The program then color codes the model to match a scale that represents the amount of incident solar energy. Once solved, the user can freely move the model in real-time to view the solution from any interior or exterior view point.

5.1.1 Software Functionality

The software takes any 3-d polygonal geometric model as input. This type of model is readily output by virtually all CAD modeling software. Therefore, a designer can continue to design with whichever software he or she feels comfortable when using this program. To increase the speed of the thermal solution, it is possible to import geometry that will only be used to occlude other geometry. This type of geometry would typically be the surrounding context or other features that might shade the building site but would not be of immediate interest. After loading in the geometry, the user specifies the geographic location of the site using the menu of cities or by entering in the longitude and latitude. Then, the date and the time of day are selected to aid the software in calculating the solar altitude and azimuth for the solution.[38]

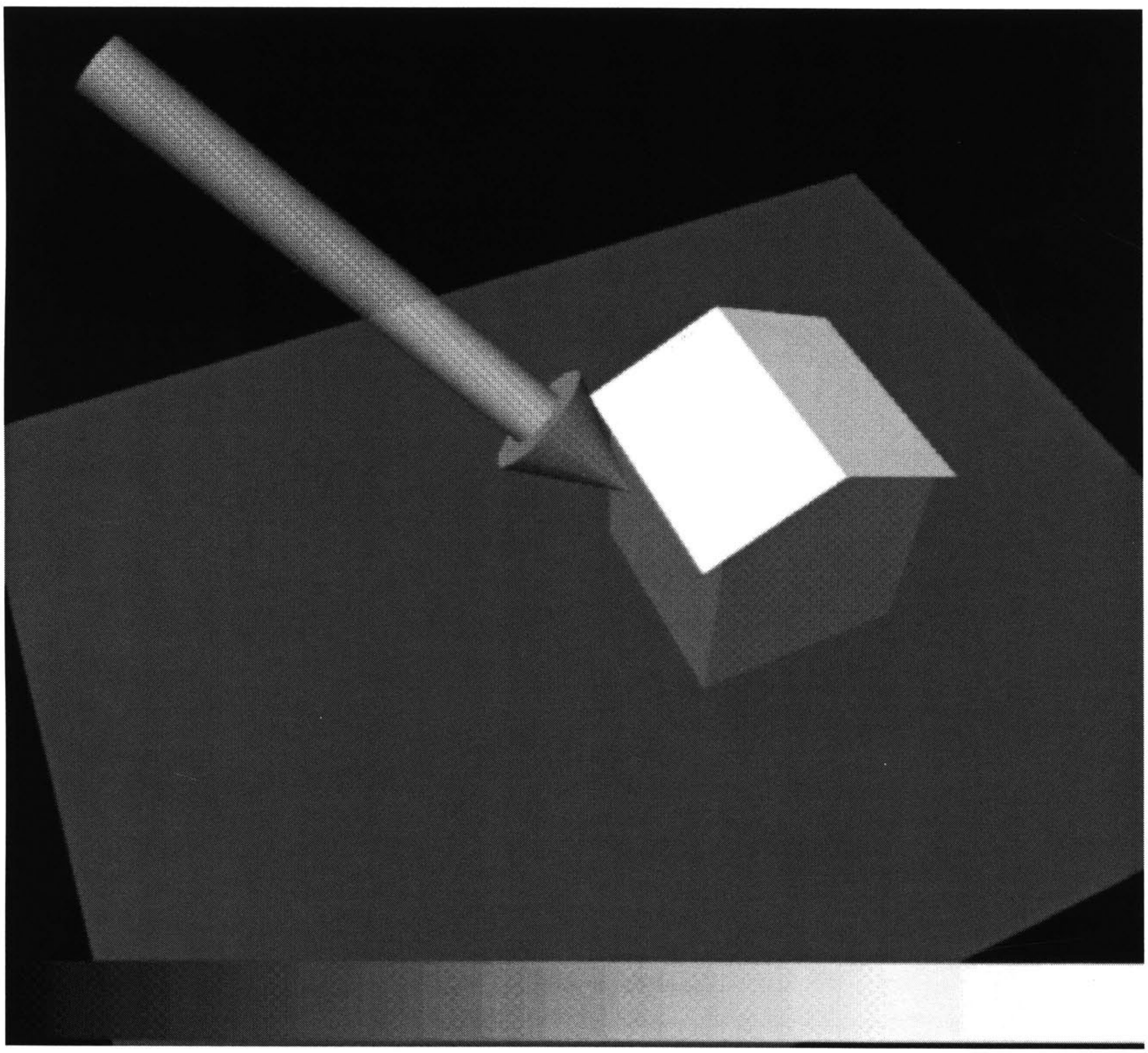
38 Solar exposure interface



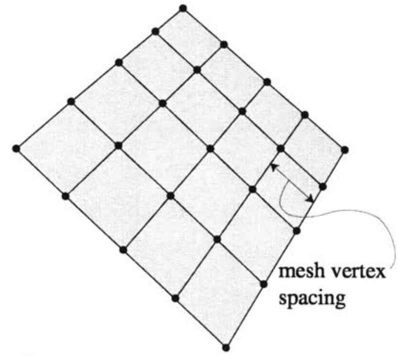
Before (or after) running a solution, it is possible to interactively visualize the sun's direction by turning on the sun vector icon.[39] The arrow corresponds to the solar angle for the chosen place, date and time. The equations to determine the sun's angles based on location, date and time are well-understood and straightforward to implement.[40] The icon direction will change as soon as the user changes any of these three variables, allowing one to visualize the range of motion through which the sun moves.

40 The solar angle equations used in the solar exposure software were based on those found in Greg Ward's Radiance software.

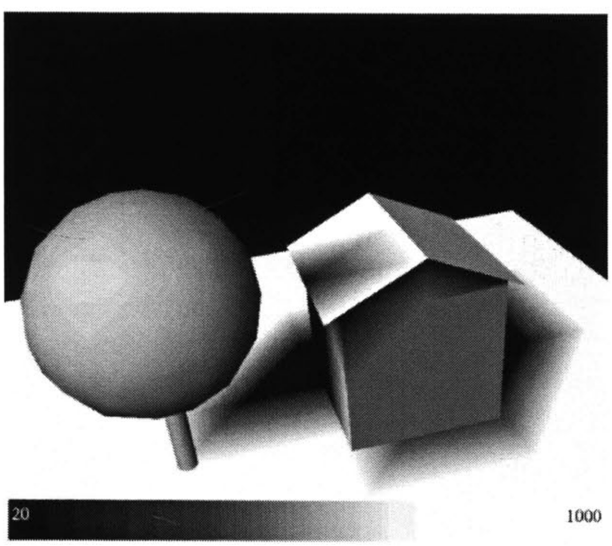
39 *Sun vector visualization*



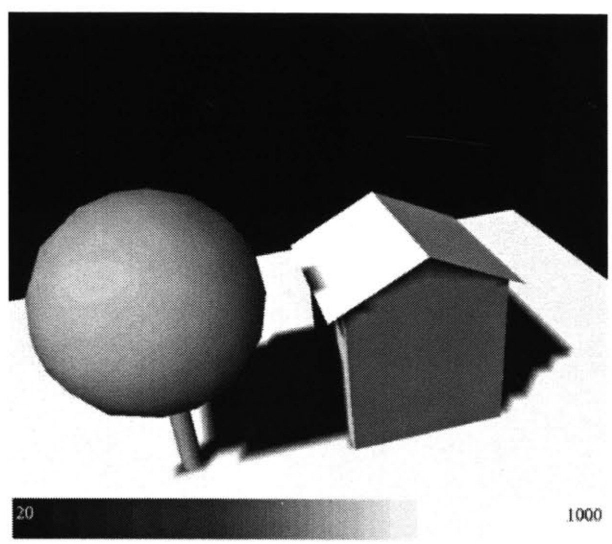
The final preparatory step is to set the mesh vertex spacing for the solution. To solve for the solar exposure, the software divides each of the polygonal surfaces into a 2-d array of mesh elements, whose vertices are separated by a maximum user-specified distance.[41]. The smaller the distance between the mesh vertices, the more mesh elements there will be, and the longer the solution will take to solve. The closer that the mesh vertices are spaced, the more accurate the solution will be. Thus, setting the mesh spacing is essentially deciding the trade-off between solution speed and accuracy. For initial, quick studies, the mesh spacing can be set to a relatively large value.[42] Later in the design process, when the design is more developed, it may be necessary to obtain more accurate results.[43] At that point, it may be worthwhile to invest time in a more detailed solution by using a smaller mesh spacing.



41 *polygon meshing*



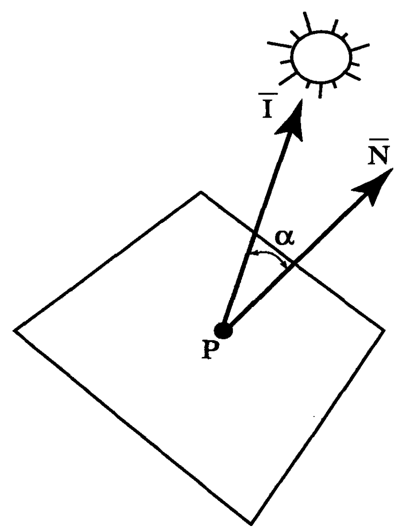
42 *larger mesh spacing*



43 *smaller mesh spacing*

After setting the solution parameters, the user can then run one of three types of solutions. The first choice is to simply solve for the solar exposure at the designated time. After a few minutes, the 3-d model will be colored to match a scale of solar exposure values that is visible in the bottom of the modeling window. In the previous meshing examples, a lighter the color was indicative of higher the solar gain. This seems to be a reasonable scale to use for solar energy, and it also works well when translated into a gray-scale image.

The solar exposure of each mesh vertex is calculated by determining the angular relationship between the sun's direction and the normal to the surface. The incident energy is proportional to the cosine of the angle between the sun's direction and the surface normal.[44] In determining the incident sun energy, it is also necessary to check if the mesh vertex is in shadow, because another object might be occluding the sun light from reaching the mesh vertex.



[44] *solar exposure formulation*

$$E_p = E_s \cdot \cos \alpha$$

E_p	*Incident solar energy at P*
E_s	*Energy of sun*
N	*Surface normal vector*
I	*Sunlight direction vector*

The other two types of solutions are used to solve for a number of points in time. Currently, the software allows for iterating over the hours of a day or over the days of the year. The user selects the start date/time, the ending date/time, and the number of steps in between the start and end. When told to solve, the software will make a solution for each of the time steps, optionally saving the data as a series of pseudo-colored 3-d models or as a series of 2-d images. The output images can then be combined into a movie animation and displayed on the screen or recorded to videotape. Another option is to compress all of the image data into a pair of images using a compression technique. Using the array of images as input, this technique will look pixel by pixel at all the images in a time series to create an average image and a maximum image. Each pixel in the maximum image represents the maximum solar exposure at that pixel over the designated time. And similarly, each pixel in the average image corresponds to the average solar exposure at that pixel.

5.1.2 Successes and Failures

The solar exposure software has proven to be a useful tool in the architectural design process. As this software is a prototype for further development of thermal analysis tools, its failures are noted to guide the development of future thermal analysis tools. The most obvious shortcoming of the software is its inability to progressively refine the mesh resolution. Although the user has some control over the solution progression by selecting a mesh size, there is not a way to continually refine the accuracy of the solution without restarting the solution from the beginning. It would be useful to allow the mesh to automatically refine over time in areas where the solar exposure has a high gradient, similar to how mesh refinement is handled in progressively refining radiosity solutions.[45] Another helpful feature would be to allow the user to select an area of the model that needs higher accuracy. This way, most of the geometry could be solved at a low accuracy, greatly enhancing the speed of the solution.

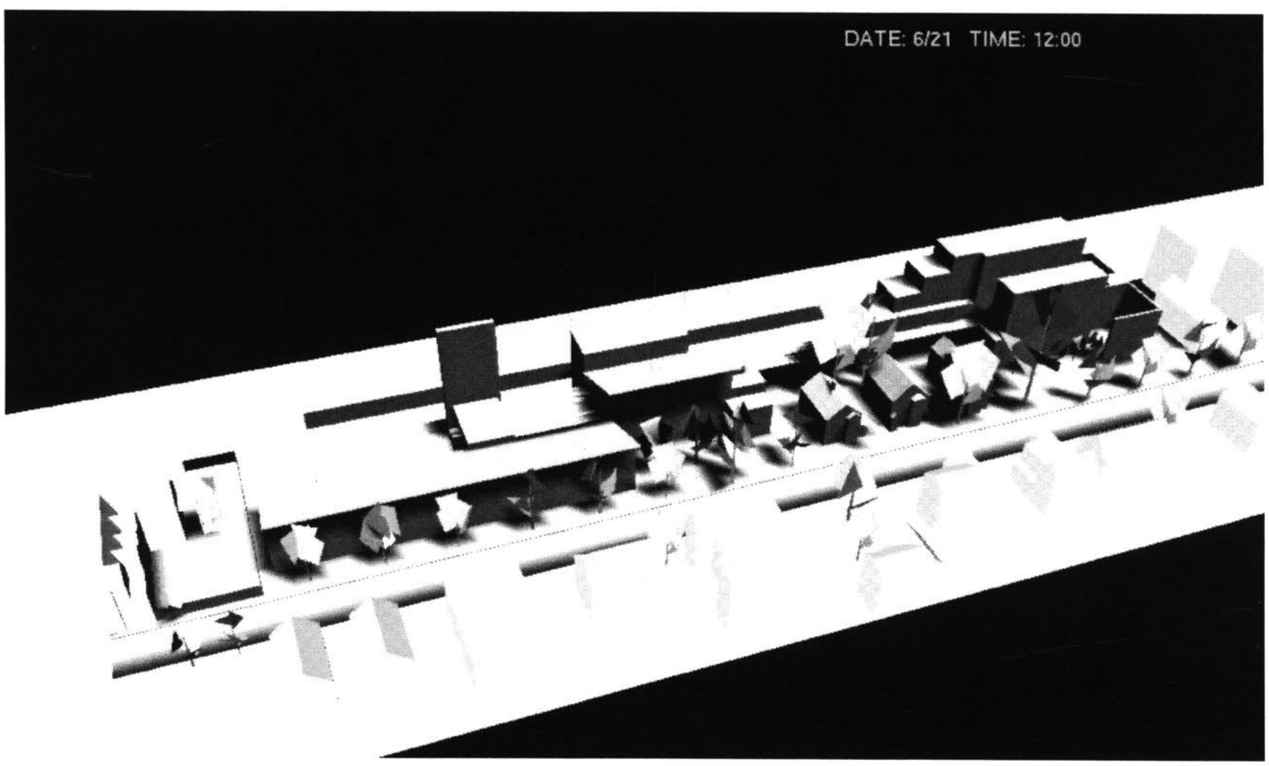
Another area for improvement is the sun vector visualization. The casual user needs a more instructive visualization of the full path that the sun takes over a particular day or over a season. The user should be able to directly manipulate the sun vector icon to change the date or time of the solution.

Any interactive visualization must function quickly in order to be useful, or it will be excluded from the design process. Currently, for a typical building model with moderate accuracy,[46] one can expect to wait approximately 2 minutes for the solution to finish. This speed is not acceptable for architectural design work. With the implementation of optimizations, such as oct-tree subdivision,[47] greater speeds could be obtained.

[45] The Lightscape Visualization System is a commercial software program for radiosity-based lighting simulation. It was developed by Lightscape Technologies, Inc.

[47] Oct-tree subdivision is a method of dividing 3-d space into a hierarchical cell structure that can speed up rendering times.

[46] *The simulation for this model took approximately 2 minutes on an SGI R4400 Indy workstation.*



6. THERMAL DESIGN TOOLS

The solar exposure software is obviously not a complete tool for thermal design. Additional tools are needed to understand complex reflections of solar energy and to understand heat movement within a space.

6.1 EXISTING TOOLS

Radiance[48] is a useful tool for lighting analysis. The software is a physically-based, hybrid ray tracer that is very good at simulating the effects of sunlight in a building. Radiance records its data as true lighting values rather than just using pixel color like many other ray tracers. In particular, the Radiance software is helpful in understanding the quantities of solar energy that one might expect to get from reflections. It is also simple to modify material properties and test combinations of materials in building design.

48 Radiance was developed by Greg Ward at Lawrence Berkeley National Labs.

To study the flow of heat within a building space, a computational fluid dynamics (CFD) program, such as Phoenix,[49] is often used. Using such a program, one can study the flow of heat by conduction, fluid flow, and radiation. The down side to using this software is that it is very difficult to setup and run. Data input is tedious, and all of the thermal boundary conditions in the model must be explicitly specified. For a simulation with solar energy, this is not predetermined and must be pre-calculated. Finally, solution speed can be prohibitively slow for a 3-d model, taking many hours.

49 Phoenix is commercial software that is owned by Concentration, Heat and Momentum.

6.2 FUTURE TOOLS

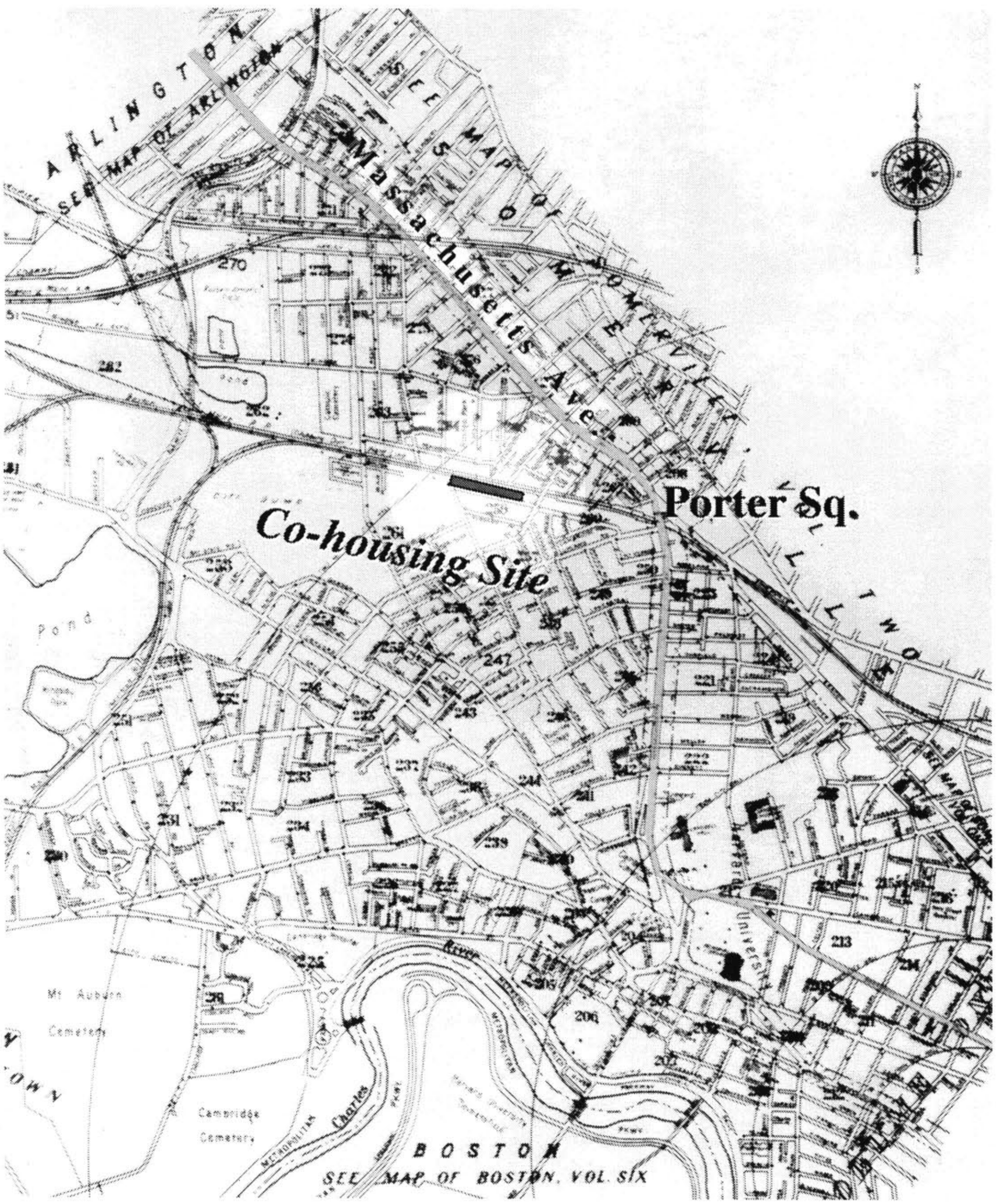
For architectural design, current CFD programs, such as Phoenix, are not practical to use. Although their solutions can be accurate, they lack the ability to be an interactive design tool. To create an interactive design tool, we would start with a program similar to the solar exposure software for determining the energy incident on the exterior of the building envelope. We could then determine the thermal properties of the interior surface of the exterior walls, roofs, etc., and use these values as the boundary conditions for subsequent analysis. Since we would need to calculate the radiant heat transfer, it is probable that we would use a progressively refining radiosity-type algorithm for this method of heat transfer. To simulate the convective flow of heat, a method that is faster and perhaps more approximate than current CFD methods needs to be developed. The simulation tool must also find practicable ways to model the dynamic systems such as one finds with the heating or cooling of massive materials.

It will also be important to develop tools that simulate the human thermal experience over time. Some thermal qualities, such as radiant temperature, are based on a person's position within a space. To visualize a person's thermal condition, it should be possible to script movement through a design that might approximate how one would inhabit the space. The script could also include activity levels and clothing so that a person's true sensations could be determined for various times and activities.

7. THERMAL DESIGN PROJECT

For this thesis, I have designed a co-housing development that uses thermal qualities to further the architectural design goals. On a building site[50] near Porter Square in Cambridge, Massachusetts, I have designed a housing complex that consists of 40 housing units, along with an array of common facilities. This project borrows its site and building program information from an actual project that is being constructed by Cambridge Co-housing Partners[51] in the winter of 1996 and spring of 1997.

51 Cambridge Co-housing is a nonprofit development partnership formed for the purpose of constructing a co-housing development in Cambridge, Massachusetts.



50 *The co-housing project site is located near Porter Square in Cambridge, Massachusetts*

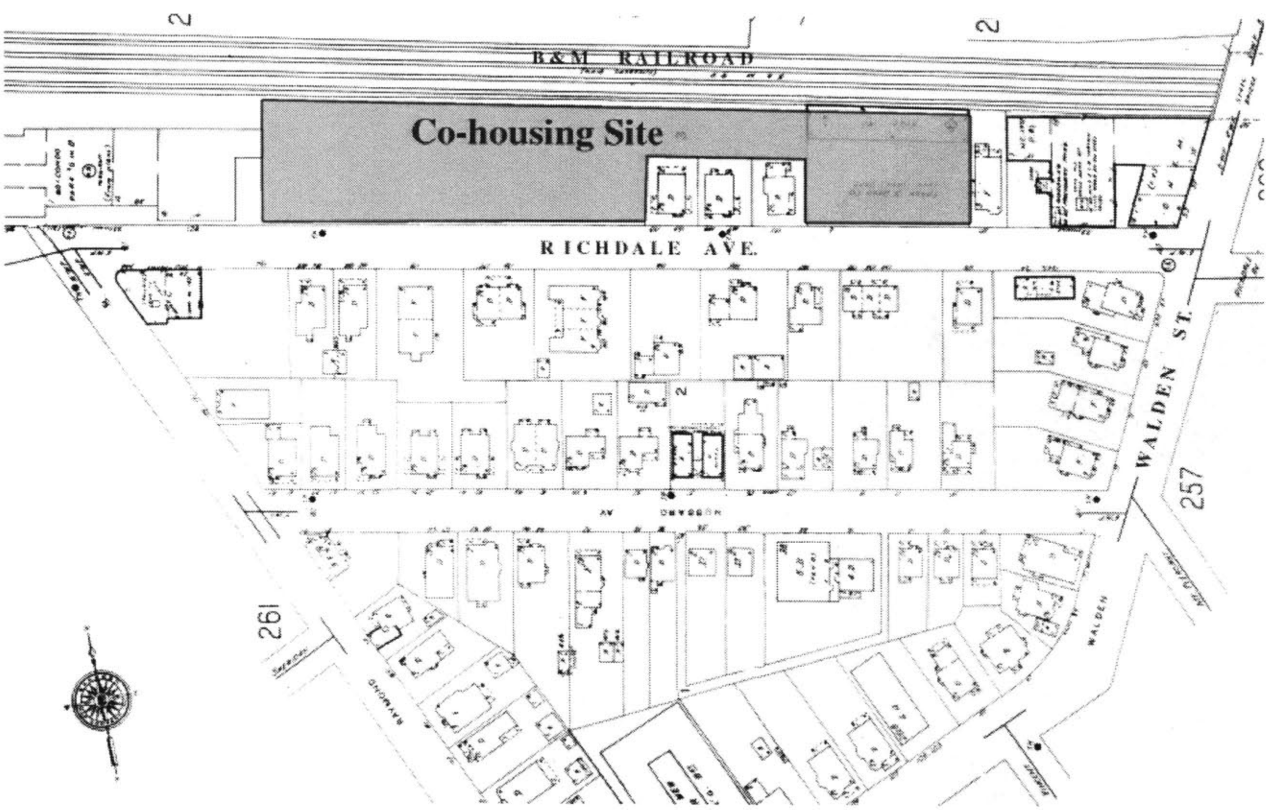
7.1 SITE

The project site is a dumbbell-shaped plot of land approximately 625' by 130'.[52] It is oriented such that the long axis of the site runs nearly due east-west. Parallel and adjacent to the northern property line of the site are train tracks that are in use. The southern edge of the site is bounded by Richdale Avenue, which is a 30' wide residential street with primarily single family homes across from the site. Towards the middle of the site, on the southern edge are 3 single family homes that will remain in place. These houses contribute to the site's dumbbell shape. The neighborhood of the site consists of many 2 to 3-story houses to the south.[53] Immediately to the west is a large, four-story condominium complex. To the east are 4-story brick factory buildings for light industrial use.

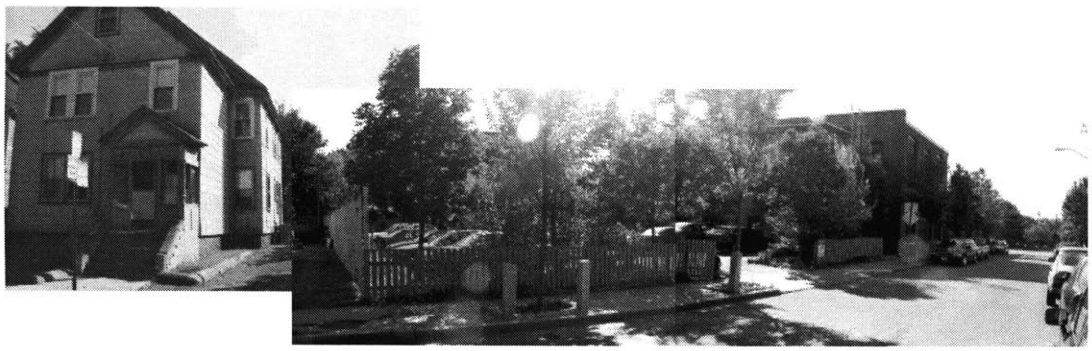
53a *Ariel view of the neighborhood*

52 *The co-housing project site is located on Richdale Ave.*

Sanborn Map Company. 1962.

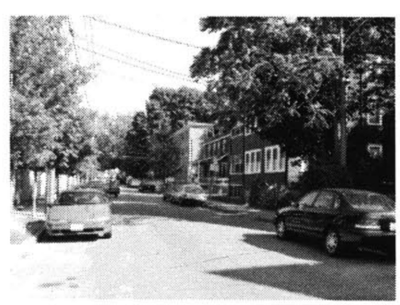


53b *Condominiums immediately west of the project site*

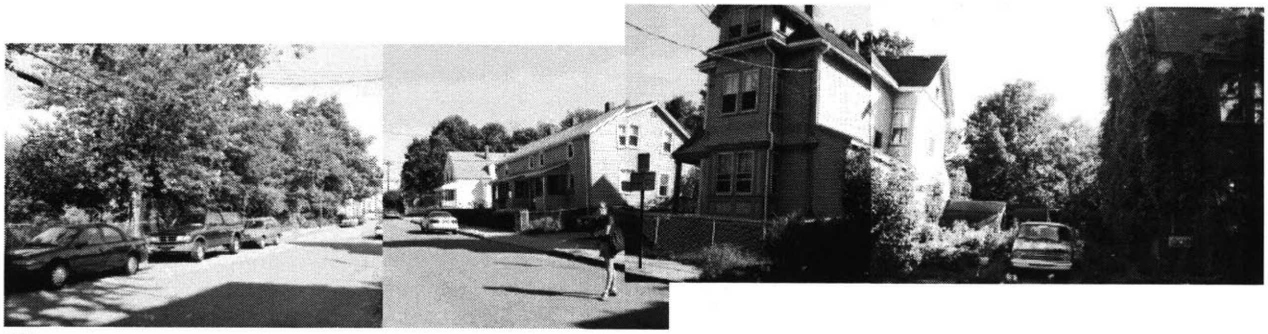


53c *Western end of the southern side of Richdale Ave.*

53d *Southern side of RichdaleAve., opposite the project site.*

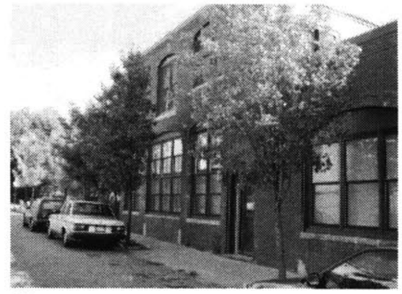


53e *View east down Richdale Ave..*



53f *View east down Richdale Ave..*

53g *Three houses located on the project site.*



53g *View east down Richdale Ave..*

7.2 PROGRAM

The program for this co-housing development is loosely based on the program being used in the actual Cambridge Co-housing development. A majority of the building program is reserved for the housing units. In addition, there is also a fairly sizable amount of space set aside for community spaces such as the common dining/meeting space and the common function rooms. The exterior spaces are considered to be integral to the functionality of this community and are therefore included in the program requirements.

HOUSING	**52200**	**ft. sq.**
40 condominium units		
9 - 4 bedroom units @ 1800	16000	ft. sq.
13 - 3 bedroom units @ 1400	28200	ft. sq.
12 - 2 bedroom units @ 1100	13200	ft. sq.
6 - 1 bedroom units @ 800	4800	ft. sq.
COMMON SPACES	**8000**	**ft. sq.**
dining/meeting	3500	ft. sq.
kitchen	500	ft. sq.
lounge	800	ft. sq.
child care/play	1000	ft. sq.
exercise room	1500	ft. sq.
spa	200	ft. sq.
4 - function rooms @ 200	800	ft. sq.
bathrooms	300	ft. sq.
SUPPORT SPACES	**19000**	**ft. sq.**
Parking garage	15000	ft. sq.
Mechanical	4000	ft. sq.
TOTAL INTERIOR	79200	ft. sq.
EXTERIOR SPACES	**9500**	**ft. sq**
dining patio	2000	ft. sq.
vegetable garden	2000	ft. sq.
lawn	5000	ft. sq.
playground	1500	ft. s.q

7.3 *CO-HOUSING*

Co-housing is a semi-communal way of living in which residents attempt to build a strong sense of community through interdependence. Development of the co-housing project is often done by the community members through a nonprofit development corporation.[54] While the housing units are usually individually purchased and owned, there are community dining, meeting and special-purpose places whose ownership is shared by all members of the community. Typically, residents eat dinner together several evening a week with everyone sharing in the cooking responsibilities occasionally. The communal dining is the most significant community event.

[54] Fromm, D. *Collaborative Communities.* Van Nostrand Reinhold: 1991. p. 197.

Residents also share in a range of special purpose spaces that would not be available in the traditional for-profit development. In this development, we have a large gym, child day-care, an outdoor spa, community-garden space, a large dining room, and a commercial kitchen among other communal spaces. Access to these shared spaces are an important reason why many people choose to live in a co-housing project. Of course, the desire for an increased sense of community is also a strong reason for people to enter into the long and difficult process of co-housing development.

Over time, many co-housing communities change in complexion. The initial members who begin the development often move out, leaving new residents who may not have the same commitment to the original community's values.[55] Eventually, this can lead to a collapse of the community if not enough people are willing to contribute support for the communal activities. To avoid this sort of situation from occurring, it is necessary to reinforce the community aspects of co-housing. Understanding the precarious nature of co-housing, the design architect should consciously work to develop a sense of community. It is possible that the architectural design choices could impact the overall success or failure of a co-housing project.

[55] Fromm, D. *Collaborative Communities.* Van Nostrand Reinhold: 1991. p. 72.

7.4 *THERMAL CONCEPTS*

In this thesis, I am working with thermal qualities to help define architectural spaces and actions. In the way that some designers may use a low wall to guide people through a space, I would use the thermal characteristics to help reinforce this movement. To ensure that the thermal issues are in fact a significant factor in making architectural decisions and forms in this thesis, there may be a stronger emphasis on the role of thermal factors in the design process than one would expect to find in an actual building design.

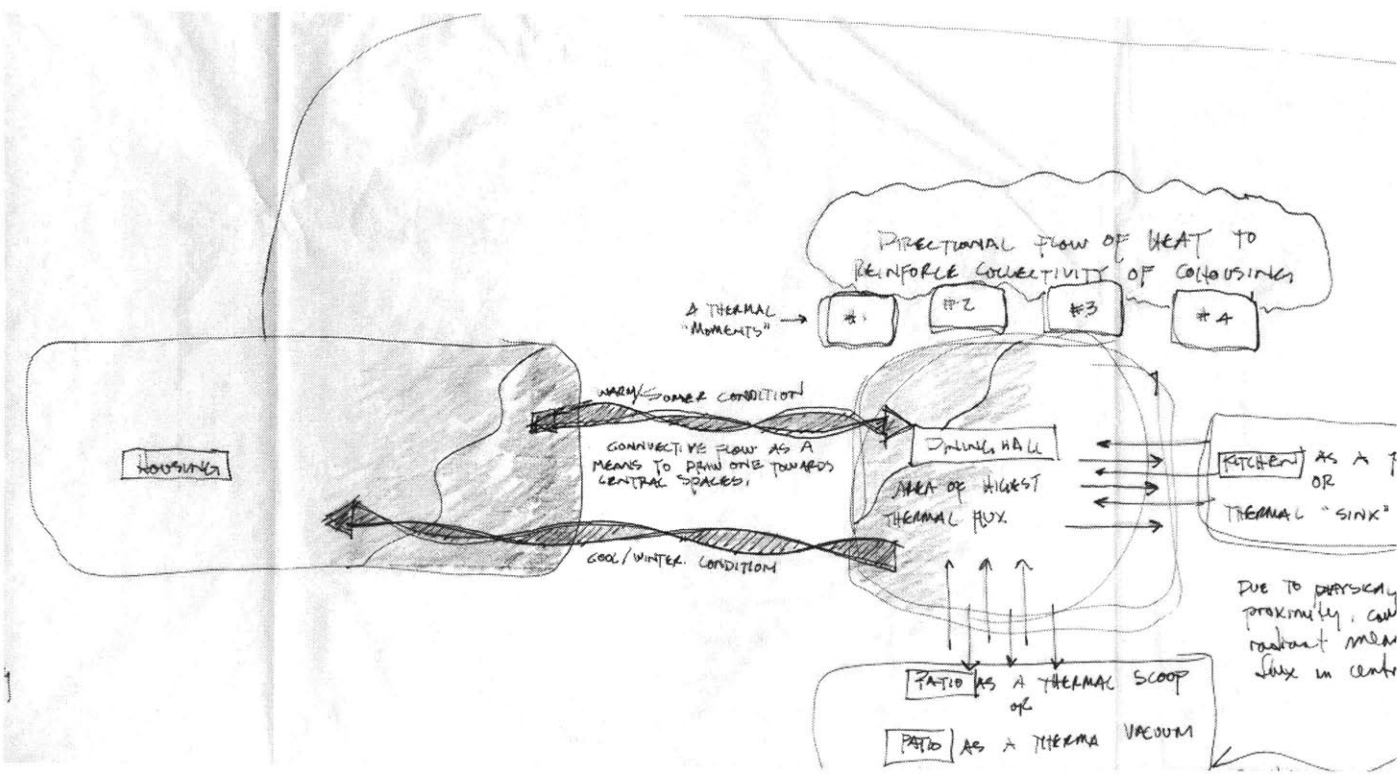
As mentioned before, a co-housing development is a tenuous endeavor that needs architectural reinforcement. In this thesis, I use the thermal qualities of the design to heighten the sense of community. Building geometry and materials seek to develop thermal experiences that support community gatherings. Elements in the building design work to ensure thermal stability in exterior spaces that are often inhospitable for large parts of the year. Interior movement of people towards community centers is defined and supported with flows of thermal energy. The community meeting/dining space is designed to be a thermally vibrant place with a dynamic flow of energy.

7.5 *THERMAL RELATIONSHIPS*

In an effort to begin understanding the thermal relationships in the building program, I diagrammed thermal spatial associations that might help support my design concepts. In this diagram,[56] the dining/meeting space is the area of highest thermal change. It acts as the connection between two thermal sources working in concert, the kitchen, and the main dining patio. These two thermal sources work in a oppositional, push/pull relationship to drive large movements of thermal energy through the dining/meeting space, creating a dynamic thermal environment.

The second major association derived in this diagram was the relationship between the housing units and the central facilities. I saw these two programmatic pieces being distinct physically with strong thermal links or connections that would reinforce movement between these two major pieces of the program.

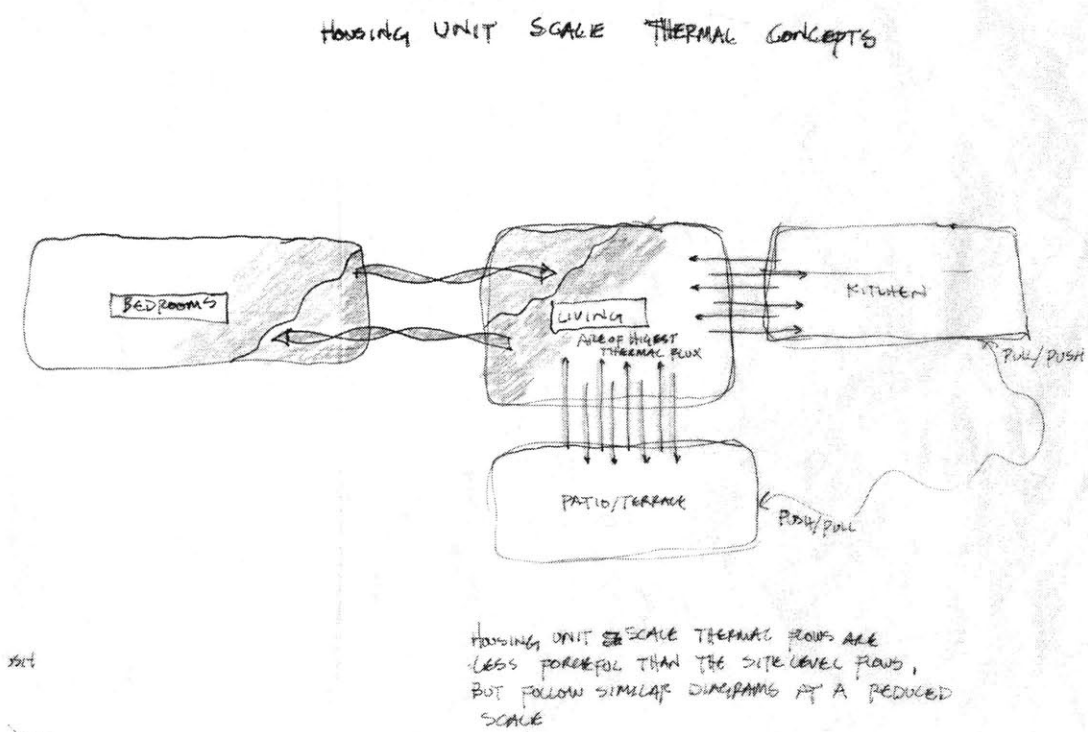
56 *Thermal relationships*



Finally, I imagined that there would be a series of thermally stable spaces directly associated to the main dining/meeting space. These elements would remain thermally distinct and constant, acting as a foil to and perhaps refuge from the thermally dynamic dining/meeting hall. They include a greenhouse space, a gallery, and a dark room.

When looking at relationships at a smaller scale in the housing units, I saw similarities to the larger site scale.[57] The living room acts as the dynamic pivot with the terrace and kitchen acting as the thermal sources. The bedrooms are linked to the living space in a manner similar to how the housing is linked to the central facilities.

[57] *Housing thermal relationships*



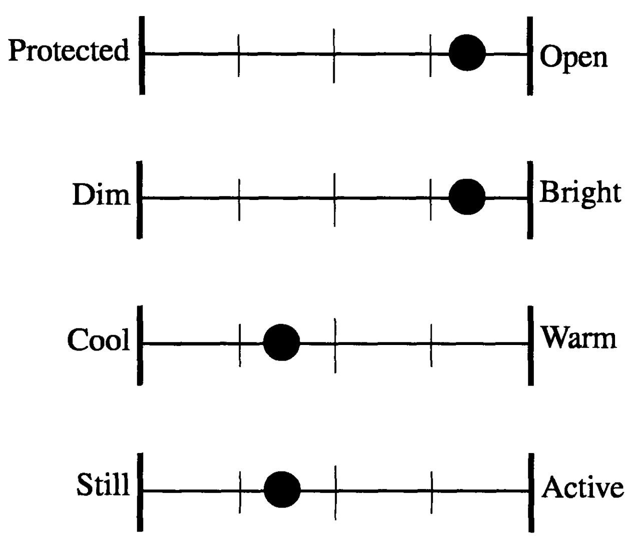
7.6 *THERMAL PROGRAMMING*

[59] (opposite) visual thermal program

At this point, building spaces were beginning to take on some thermal characteristics such as stability and solar exposure. To formalize the thermal intentions for each of the building spaces, I developed a thermal programming data sheet for each space. The thermal data sheet describes on a sliding scale the desired thermal characteristics for each of the four thermal qualities, and also allows for a more qualitative textual description of the thermal conditions. In this example,[58] we can see that the central dining/ meeting space is very bright and open, which is understandable considering that we expect it to be affected by the thermal qualities of the dining patio and the kitchen. See Appendix A for all of the thermal programming data sheets.

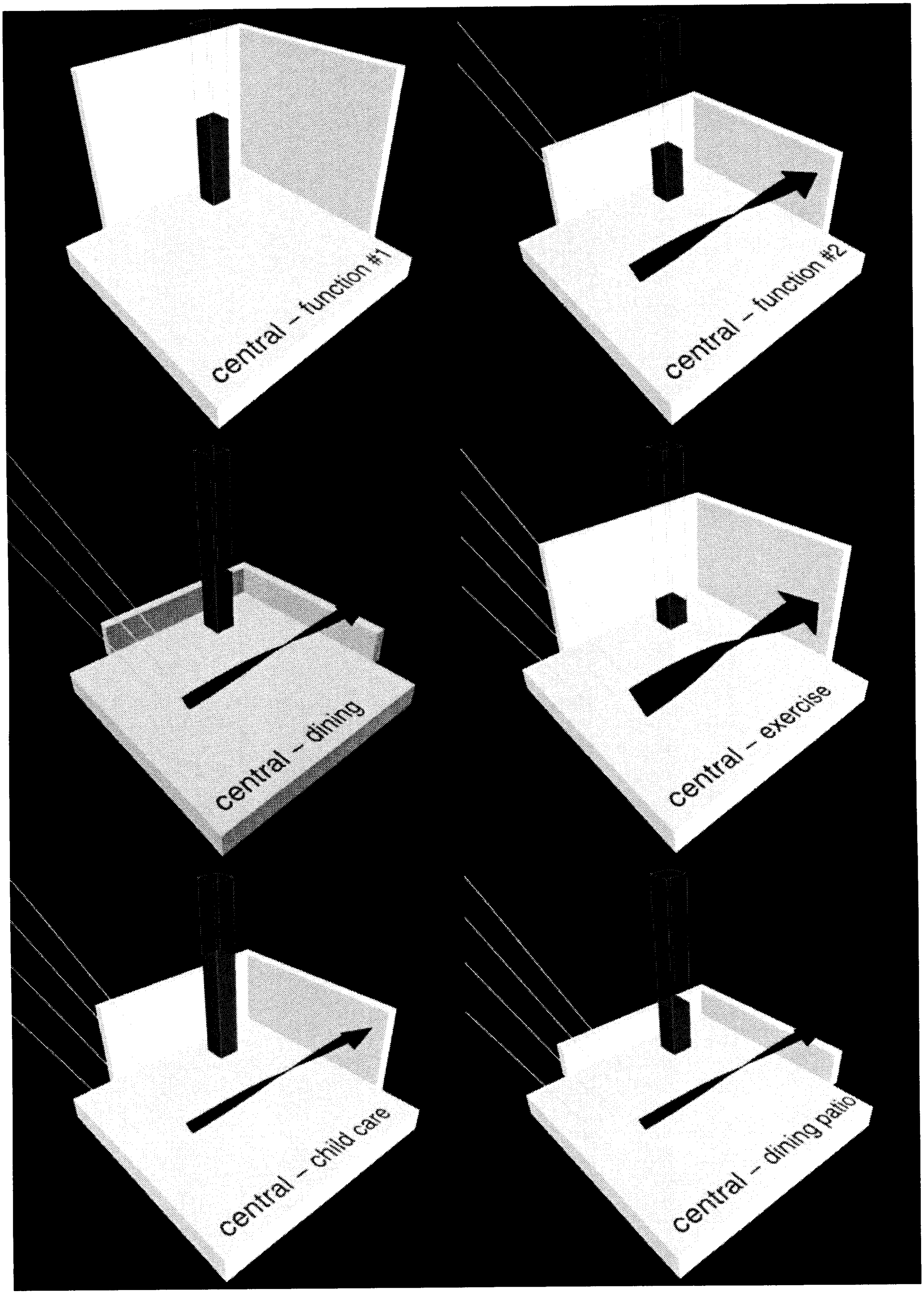
It is also possible to describe the thermal program in a concise visual manner.[59] The height of the wall represents the amount of stability, the vertical block is air temperature, the twisting arrow shows the amount of air movement, and the yellow rays signify exposure. It is also possible to add these thermal icons to design drawings, thereby annotating the design with the thermal intention.

[58] Thermal program data sheet fot the central dining and meeting space.



Central - Dining/Meeting

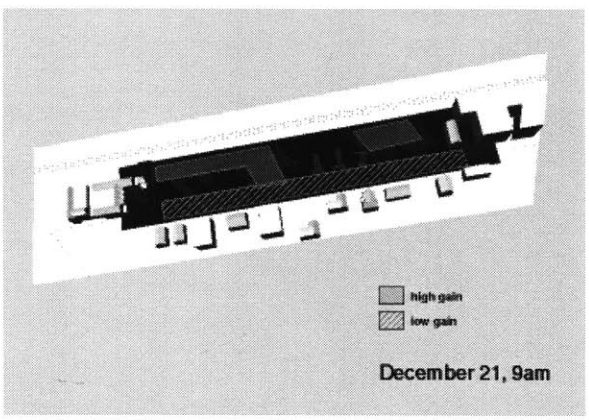
an open, changeable space that is the most public room in the project. brings thermal elements from the environment into the space. Lower air temp and high radiant temp to achieve a bright, active place.


central – function #1
central – function #2
central – dining
central – exercise
central – child care
central – dining patio

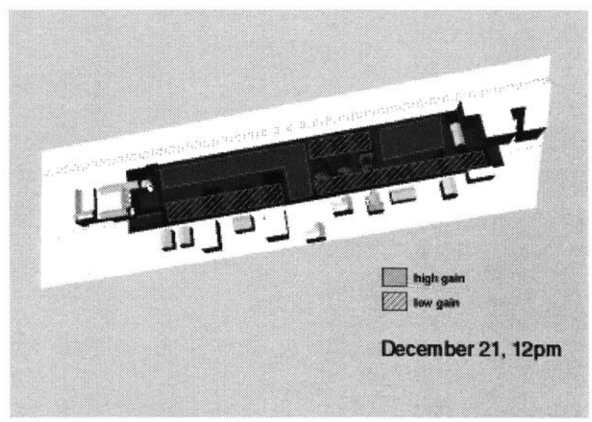
7.7 *SITE DESIGN*

Before beginning to design the co-housing buildings, I studied the thermal characteristics of the bare site. Using the solar exposure software, I was able to determine at which times of the day or year certain areas of the site received high solar gains and when they were in shadow and receiving low solar gain.[60] For the winter months, I looked at the site's solar exposure for the entire day, as this is a critical time to capture solar energy. I used image averaging to create a single average image that represents the average exposure for the entire day. I also produced yearly average images at several times during the day to determine the yearly average exposures for the site.[61] These site analyses helped guide the placement and orientation of my buildings on the site.

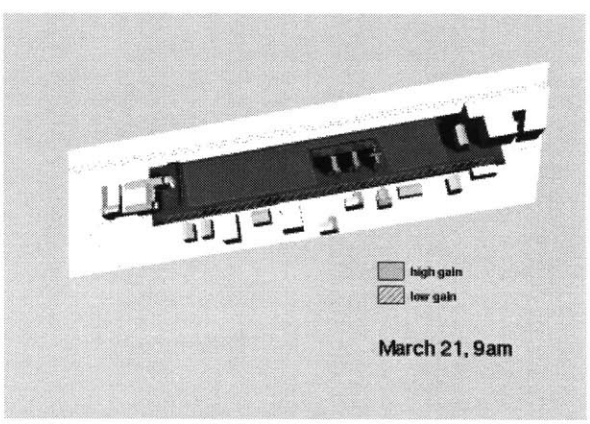
Using crude massing models, I then developed a sense for building forms that would work well with the thermal conditions of the site. Again, I used the solar exposure software for this analytical purpose.



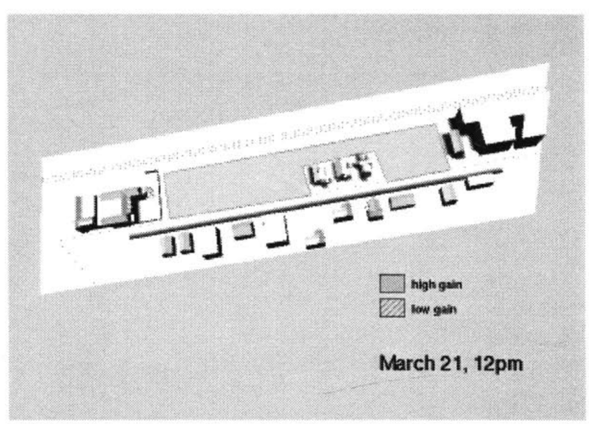
60a Solar exposure - areas of hi /low gain



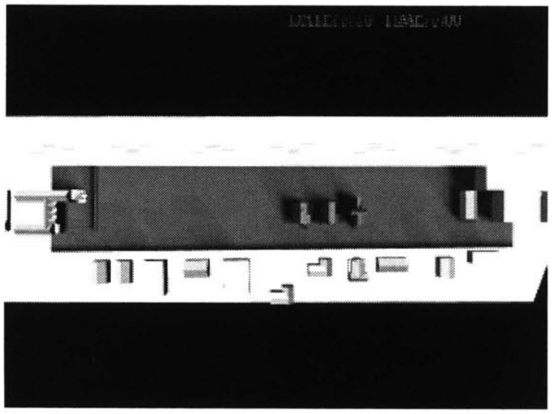
60b Solar exposure - areas of hi /low gain



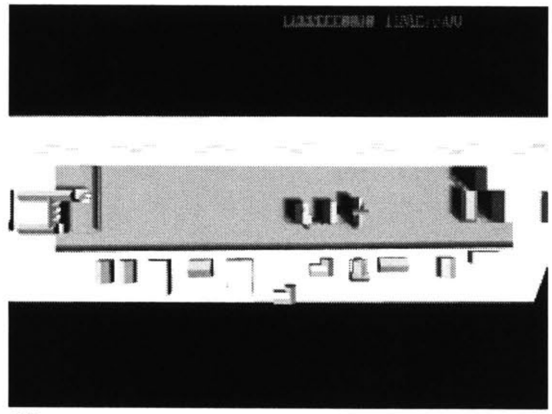
60c Solar exposure - areas of hi /low gain



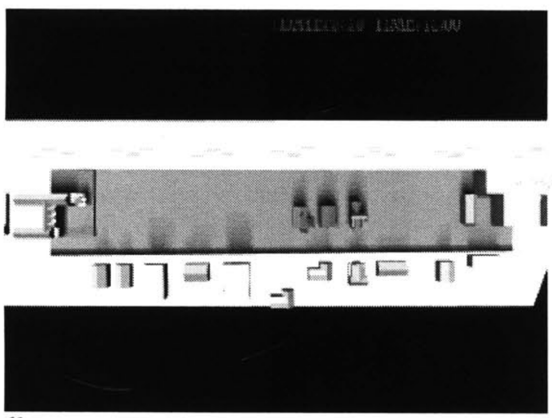
60d Solar exposure - areas of hi /low gain



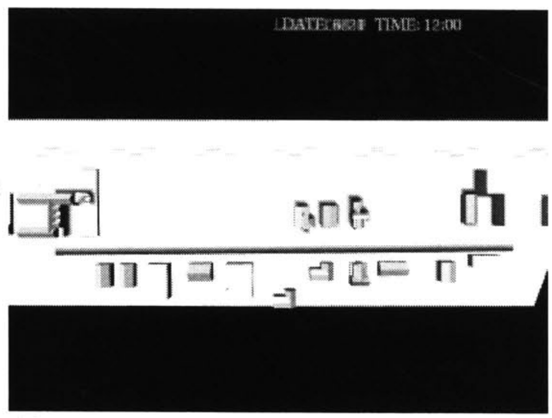
61a Solar exposure - yearly average - 9 a.m.



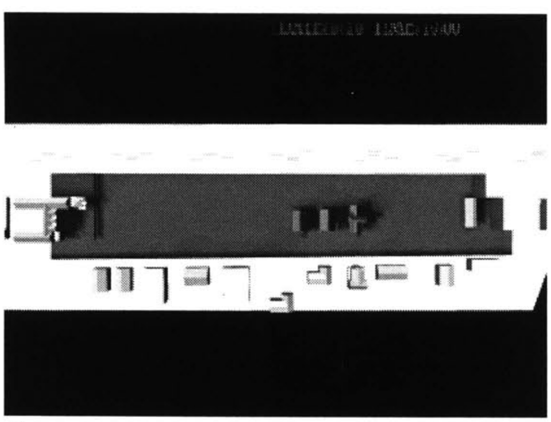
61b Solar exposure - yearly maximum - 9 a.m.



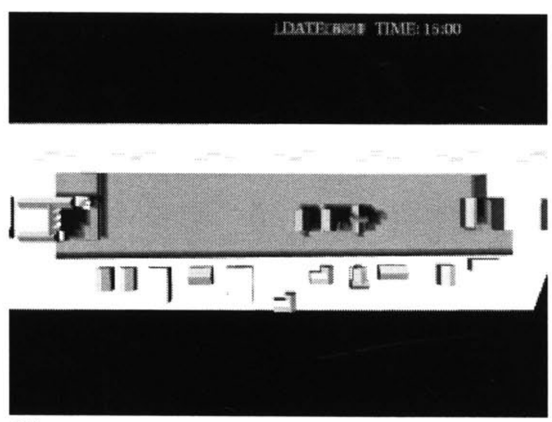
61c Solar exposure - yearly average - 12 p.m.



61d Solar exposure - yearly maximum - 12 p.m.



61e Solar exposure - yearly average - 3 p.m.

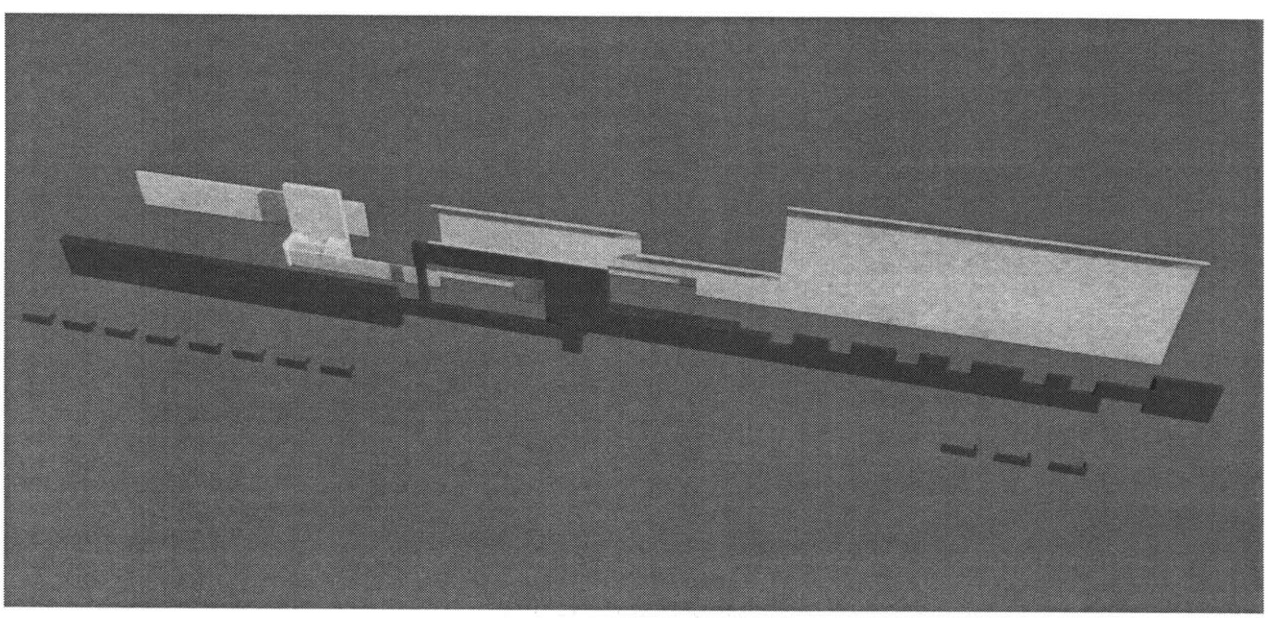


61f Solar exposure - yearly maximum - 3 p.m.

7.8 *THERMAL SYSTEMS*

There are two major wall systems on the site for thermal purposes.[62] Both systems are primarily passive in nature. Because they are substantial and nearly continuous throughout the entire length of the site, they also serve as structural support for the majority of the building, as well as for physically joining the site into a cohesive whole.

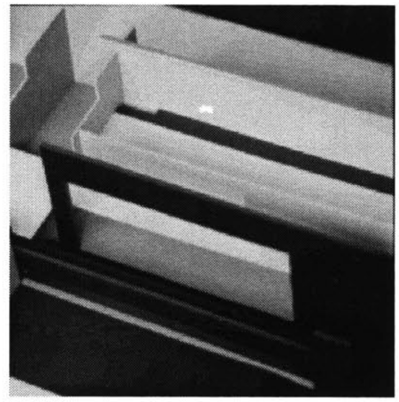
[62] *The two wall systems are shown without any other building structure. The black wall represents the absorptive wall system and the white wall represents the reflective wall system.*



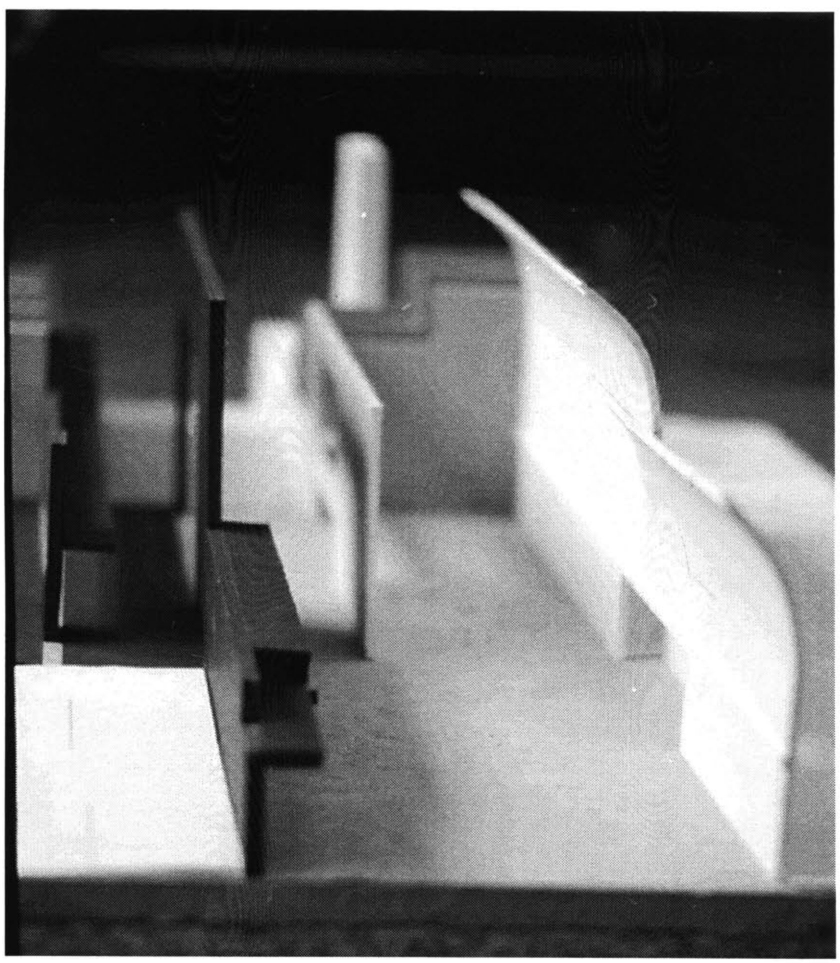
7.8.1 **Absorptive Wall System**

The absorptive system[63] is constructed from a dark-hued concrete. It is massive and capable of absorbing and storing large amounts of thermal energy. The system runs east-west, primarily along the southern side of the site, enabling it to receive large amounts of solar gains when the sun is low in the sky.

The walls act by storing and redistributing the heat. Much of the system forms an inverted concrete channel on its northerly side,[64] that in winter radiates heat and conveys warmed air along its length. People move under this channel in a zone of higher air temperature. In summer, this massive wall and channel system maintain a microclimate that is cooler and less bright than outside its area of influence.



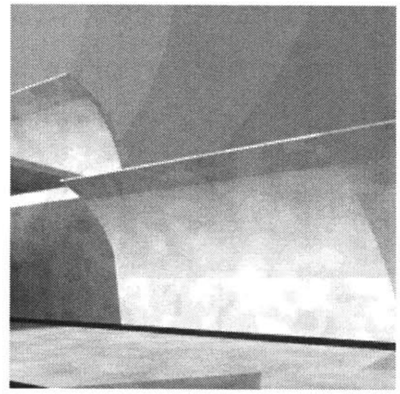
63 The absorptive wall system is shown in black. View of central dining area.



64 The air channel system is located on the right-hand side of the absorptive wall.

7.8.2 **Reflective Wall System**

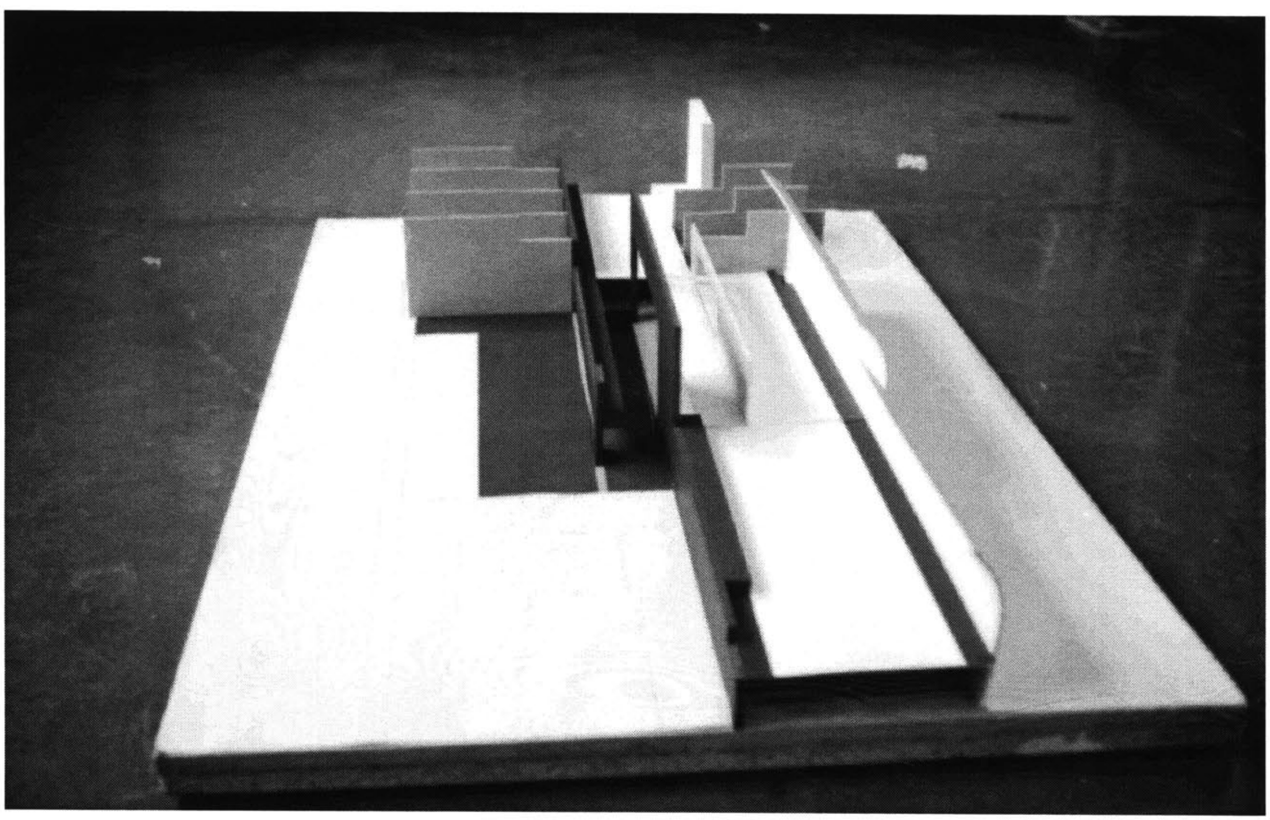
The reflective wall system runs parallel to the absorptive system, along the northerly edge of the site.[65] This system works to collect solar energy through a curved light scoop that is formed by the top edge of the wall.[66] The wall is made from a light-colored, polished concrete that is highly reflective. It is significantly less massive than the absorptive wall system, as its only thermal purpose is to reflect or block sunlight. It is without many openings along its length to insulate from the cool northerly direction and to protect from the adjacent rail lines.



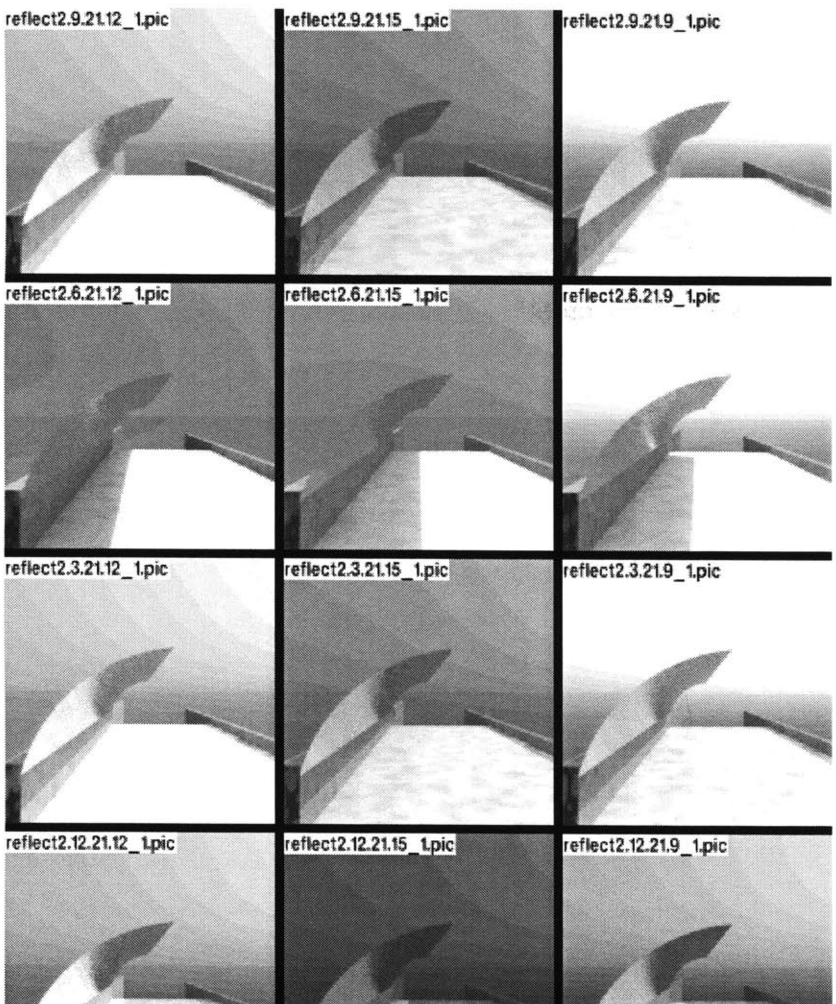
66 The reflective wall scoop.

The light scoop serves a dual thermal purpose. In winter, it acts as a solar collector, doubling the solar gain found in a wide zone at the base of the wall. When the sun is high in the sky during the summer months, the reflector shades the same zone, greatly reducing the solar energy when it is least desired. The 6 to 8 foot wide zone at the base of the reflector zone occurs where lower air temperatures and bright spaces are desirable. The lower air temperatures combine with the high radiant solar gain to make active places for high energy uses, such as the exercise room and the covered courtyard walkway. Without the solar collector, these places would be inhospitable for much of the year.

65 The absorptive wall system is shown in black, and the reflective wall system is shown in white.



The form and orientation of the solar reflector was developed through a series of experiments. Both a flat and cylindrical form were tested at several orientations at key times during the year. The desired performance characteristics included a bright and wide reflection throughout the winter day, a wide shadow throughout the summer day, and neither reflection nor shading during the spring and fall days. The test series for the best-performing test-case that was used in the building design is shown here.[67] All of the test series can be viewed in Appendix C.

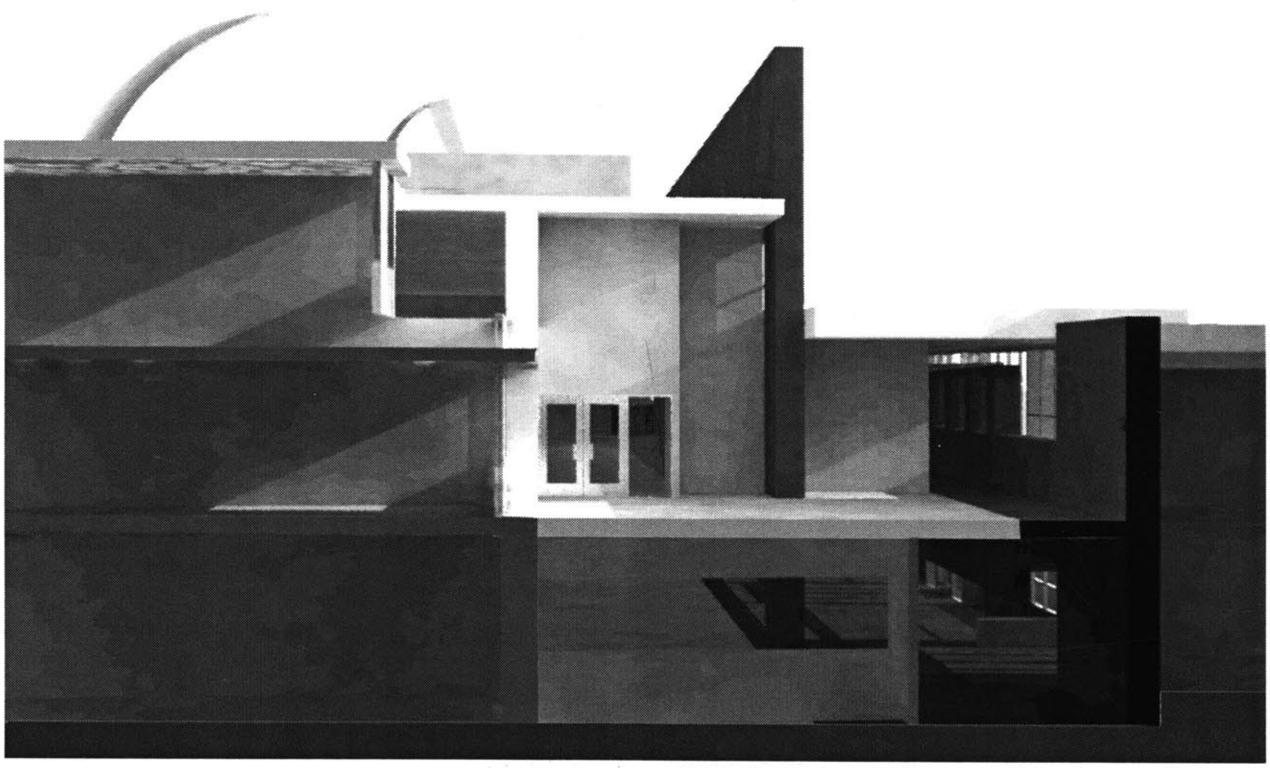


67 *The reflector shows a bright concentration of sunlight in the winter, and shading in the summer. The simulation was done with Radiance.*

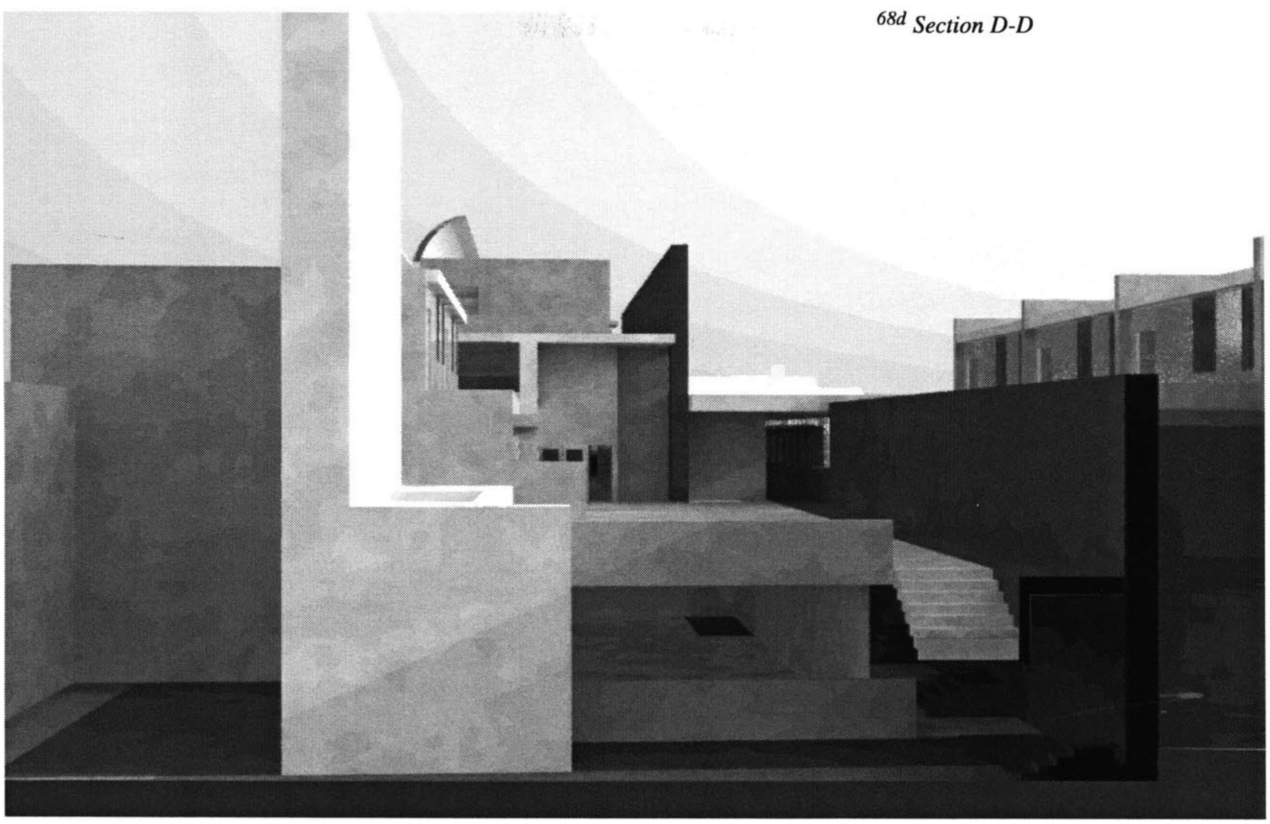
NOTE: The numbers in the title of each image corresponds to design version, month, day, and time in that order.

68a Section A-A. See the plan[76] for section locations.

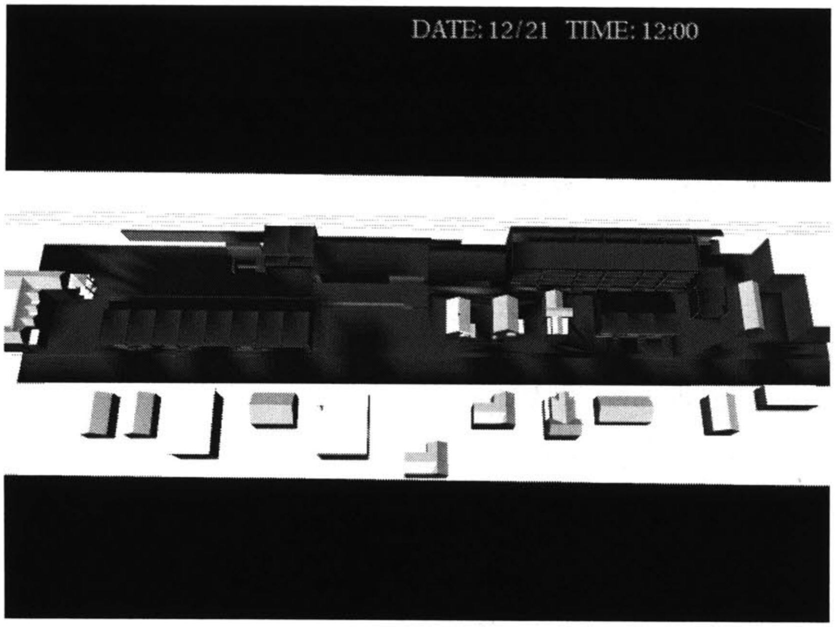
68b Section B-B



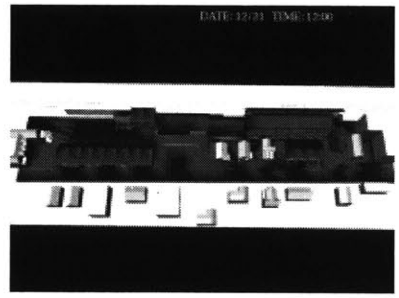
68c Section C-C



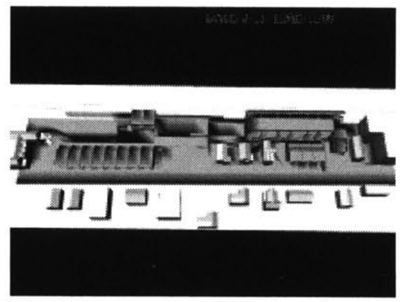
68d Section D-D



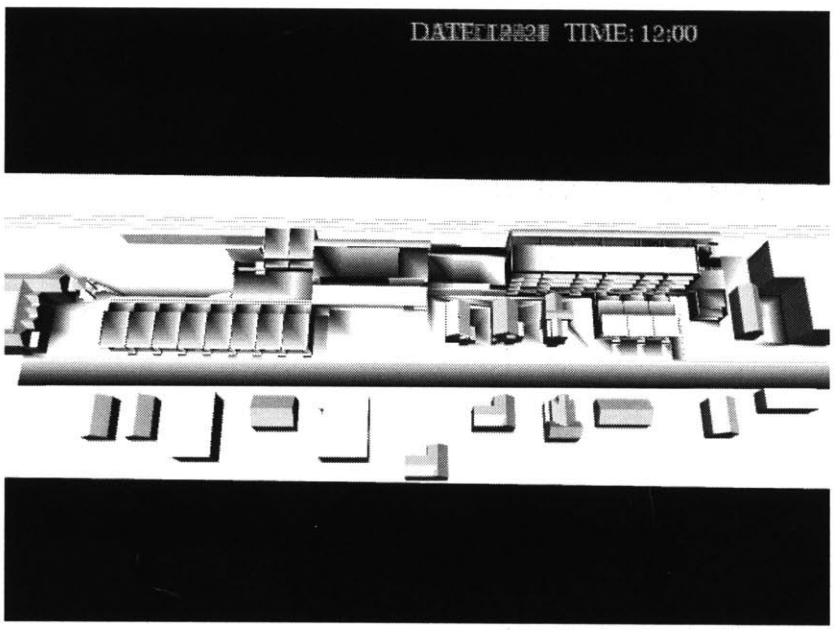
69a Solar exposure - 12 p.m. yearly average



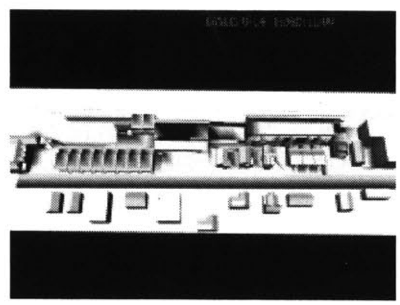
69c Solar exposure - 12 p.m. 12/21



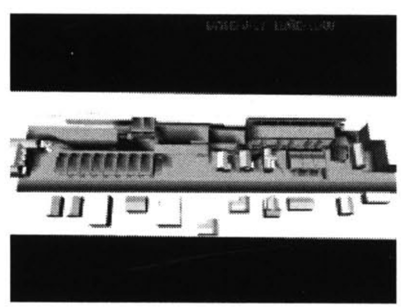
69d Solar exposure - 12 p.m. 3/21



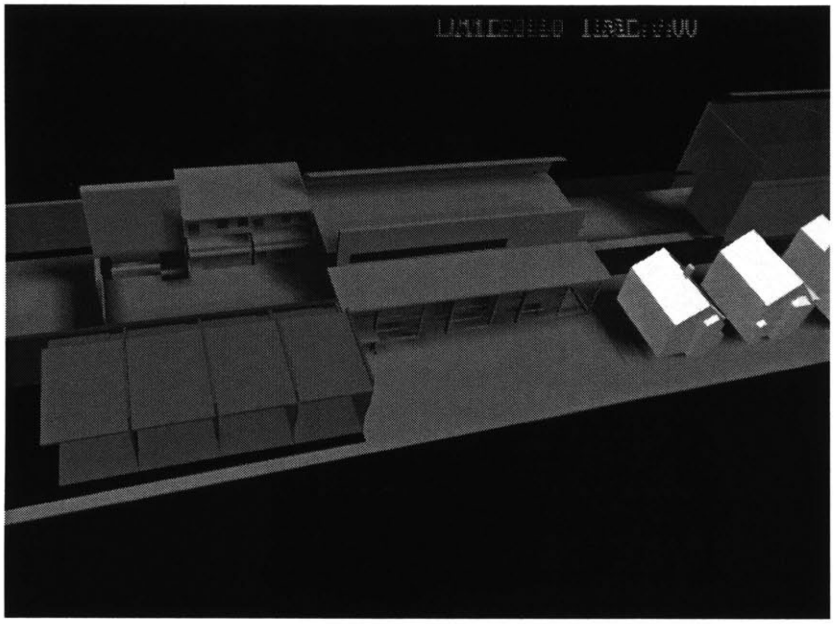
69b Solar exposure - 12 p.m. yearly maximum



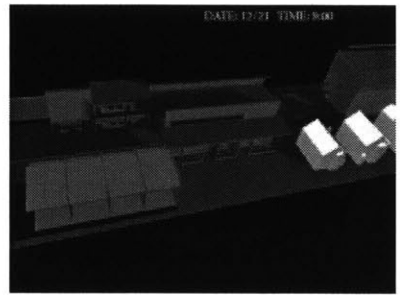
69e Solar exposure - 12 p.m. 6/21



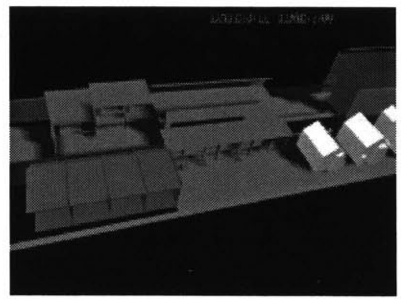
69f Solar exposure - 12 p.m. 9/21



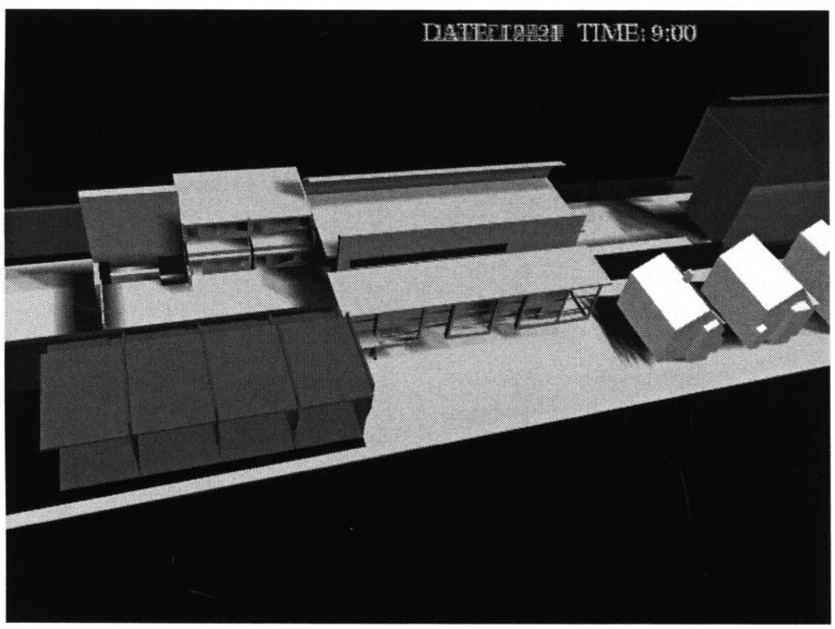
70a Solar exposure - 9 a.m. yearly average



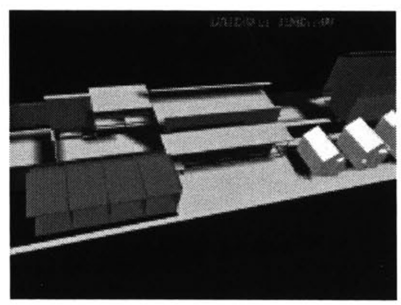
70c Solar exposure -9 a.m. 12/21



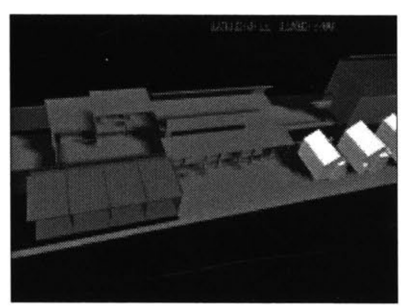
70d Solar exposure - 9 a.m. 3/21



70b Solar exposure - 9 a.m. yearly maximum



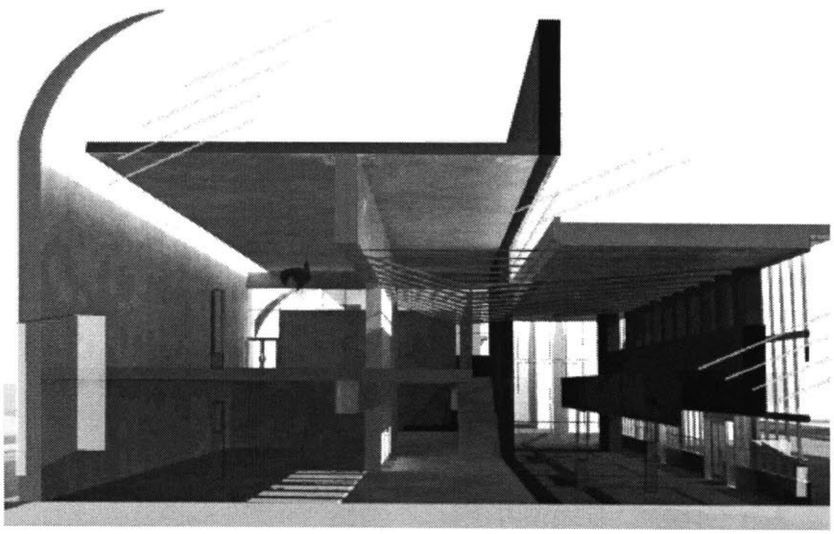
70e Solar exposure - 9 a.m. 6/21



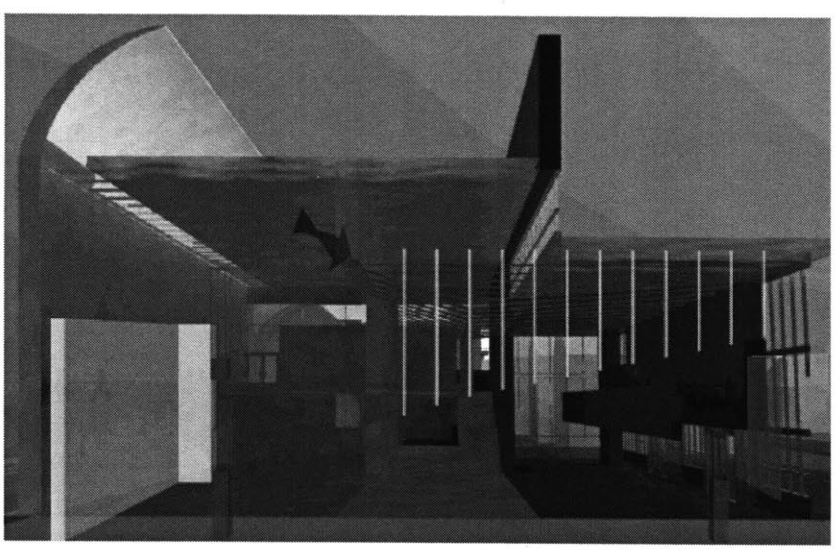
70f Solar exposure - 9 a.m. 9/21

7.8.3 **Active Systems**

In the New England climate, not all thermal conditions can be sustained passively. Especially in the winter evenings, an active thermal system will provide the energy for the dynamic flow that at other times is provided by the sun.[71] The building's central thermal plant is located beneath the tall, slab-like chimney element. The system is integrated with the immediately adjacent kitchen ovens and with the spa located directly above the furnace. From this locus, the heat is pumped through the reflective wall system that is immediately behind the dining space, into the radiative roof trusses, and finally onto the people sitting in the common dining room or on the dining patio. The roof trusses' lower chords are wide metallic plates that offer a high surface area for effective radiation.



[71a] *Annotated section describing thermal conditions at 12p.m. on 12/21.*

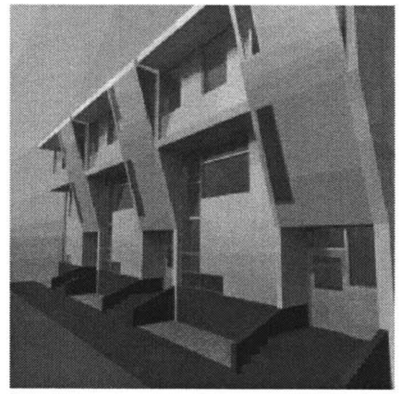


[71b] *Annotated section describing thermal conditions at 4:30 p.m. on 12/21.*

Roof trusses are radiating heat into the dining/living space.

7.8.4 **Row House Systems**

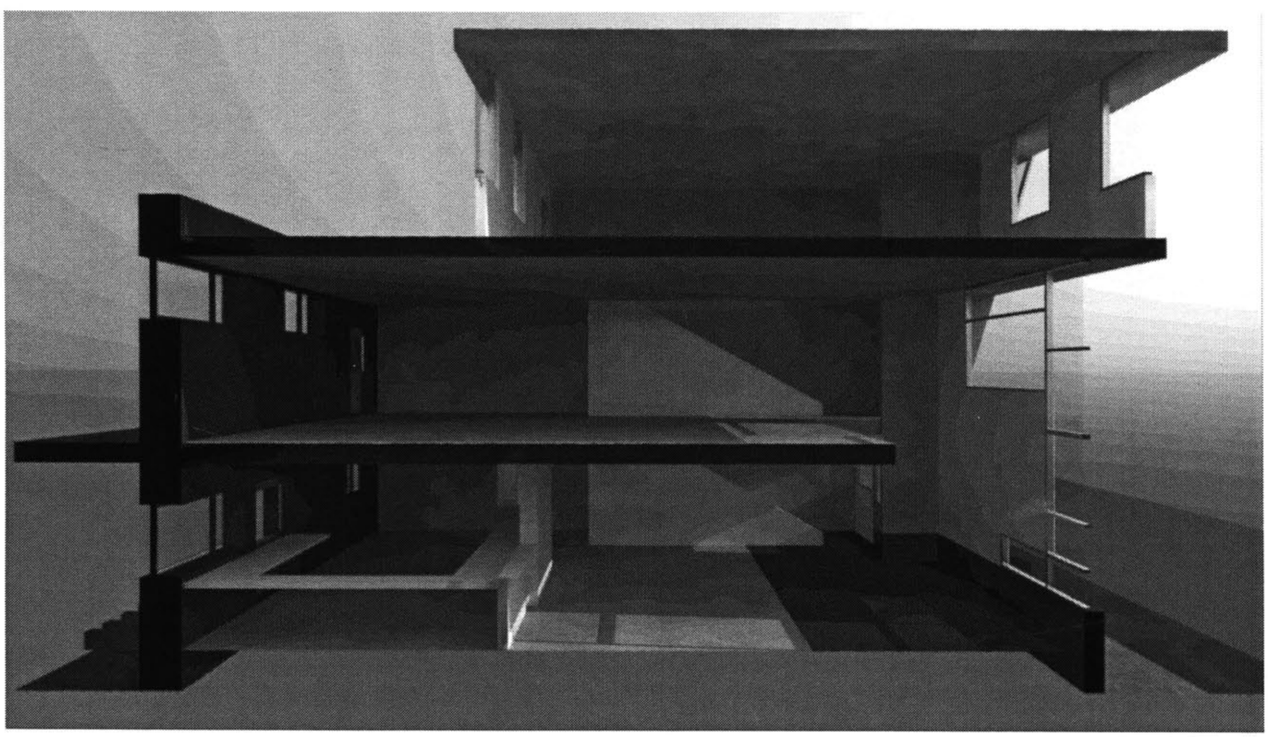
The row houses take the thermal concepts of the central dining spaces and apply them on a smaller scale. Just as the common dining/meeting space is thermally exposed and changeable, so is the same thermal quality evident in the living space in the row houses. Through a highly exposed southern elevation, the row houses get winter solar gains deep into the living spaces.[72] Evening energy is delivered through the living space by an active system that radiates heat from a warmed, deep concrete beam that moves from the kitchen area toward the south, flanking the living space.

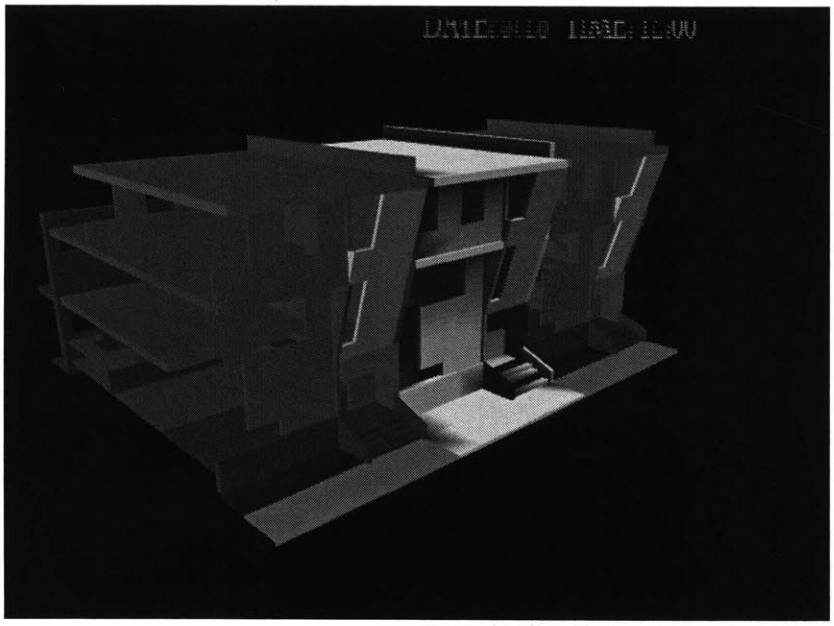


73 View of row houses from the street.

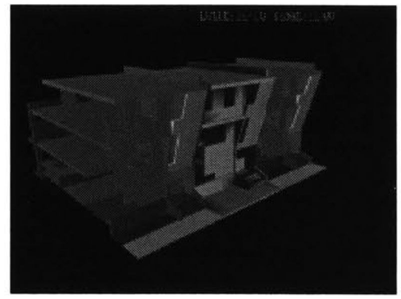
The row houses also modify the outdoor environment. The sloped bay over the entrance serves to reflect energy down onto the front steps.[73] Although a curved element similar to the wall system reflector would have generated more solar gain, the flat slope is simpler to construct.

72 Section through a row house at 12p.m. on 12/21.

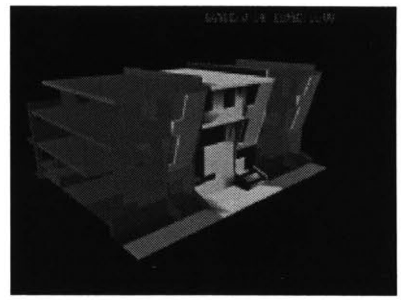




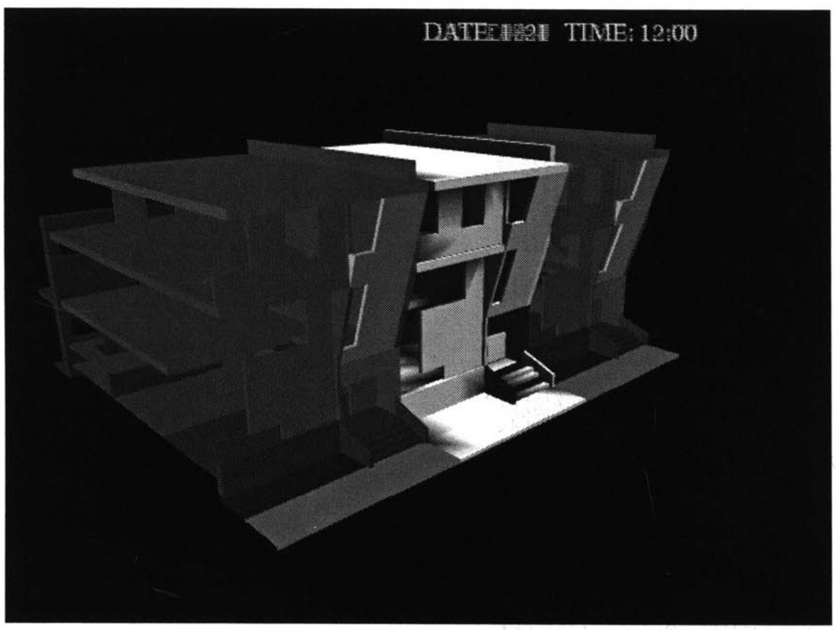
[74a] *Solar exposure - 12 p.m. yearly average*



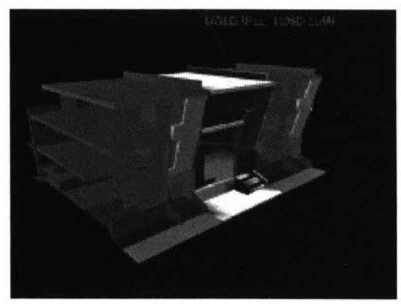
[74c] *Solar exposure - 12 p.m. 12/21*



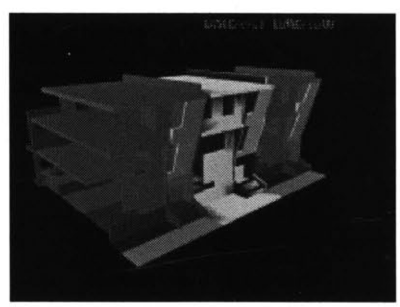
[74d] *Solar exposure - 12 p.m. 3/21*



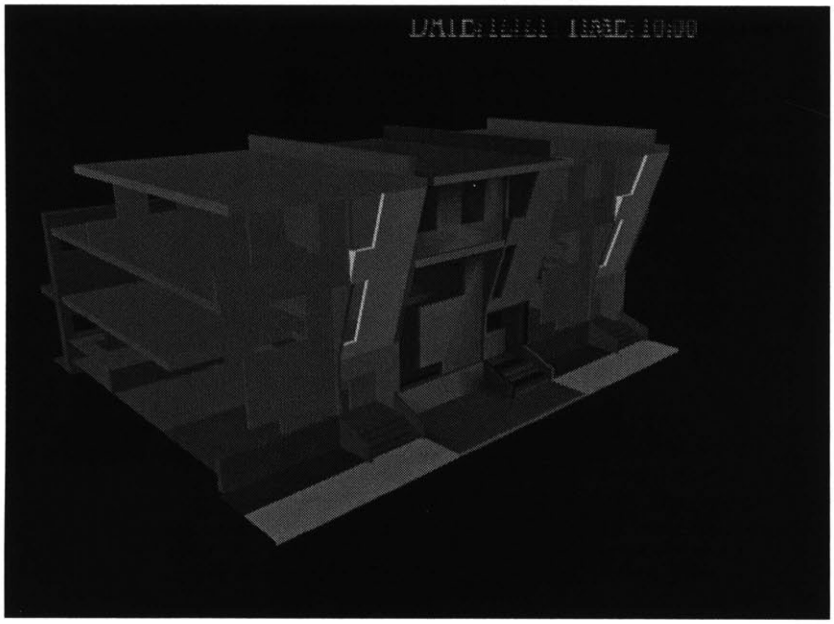
[74b] *Solar exposure - 12 p.m. yearly maximum*



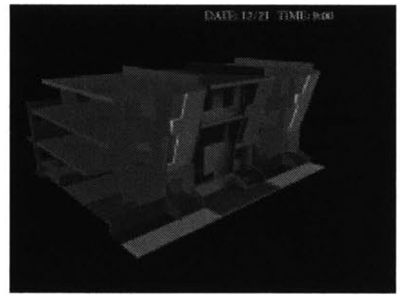
[74e] *Solar exposure - 12 p.m. 6/21*



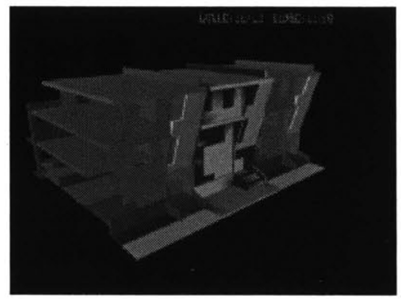
[74f] *Solar exposure - 12 p.m. 9/21*



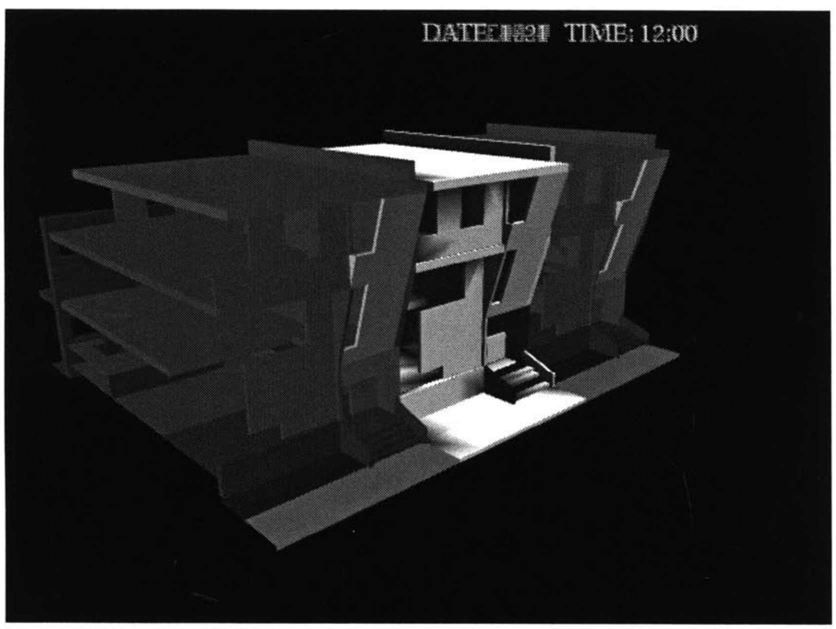
[75a] *Solar exposure - 12/21 - daily average*



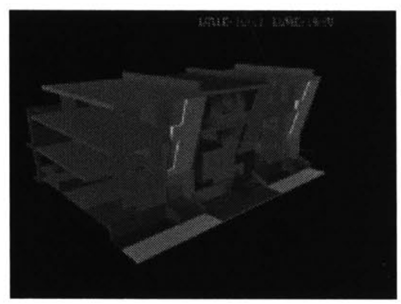
[75c] *Solar exposure -9 a.m. 12/21*



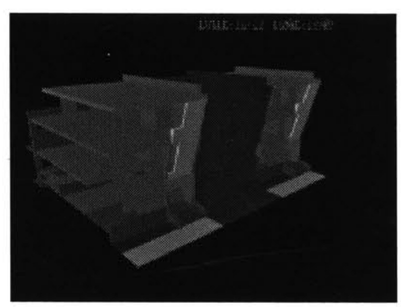
[75d] *Solar exposure - 12 p.m. 12/21*



[75b] *Solar exposure - 12/21 - daily maximum*



[75e] *Solar exposure - 3 p.m. 12/21*



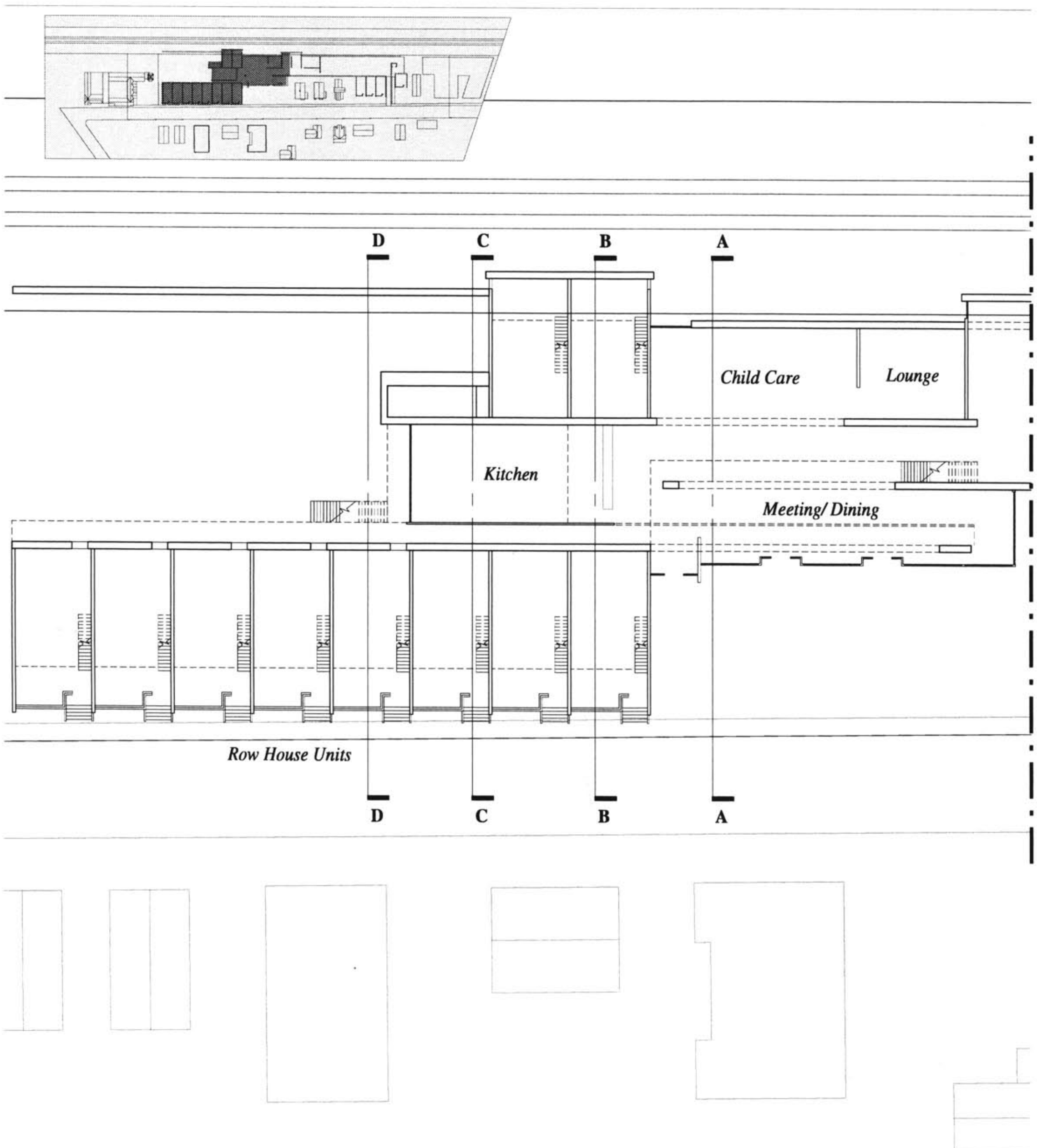
[75f] *Solar exposure - 4:30 p.m. 12/21*

7.9 *THERMAL EXPERIENCE*

The thermal systems in this co-housing project join the building spaces into a singular, functioning organism[76]. As people move through the particular thermal experiences, they can always refer to the larger-scale systems for an understanding of the overall thermal forces at work. To better comprehend the ordering of the thermal experiences, we will follow two illustrative paths through the design. The figures referenced in this tour are keyed into the floor plans with each image.[77]

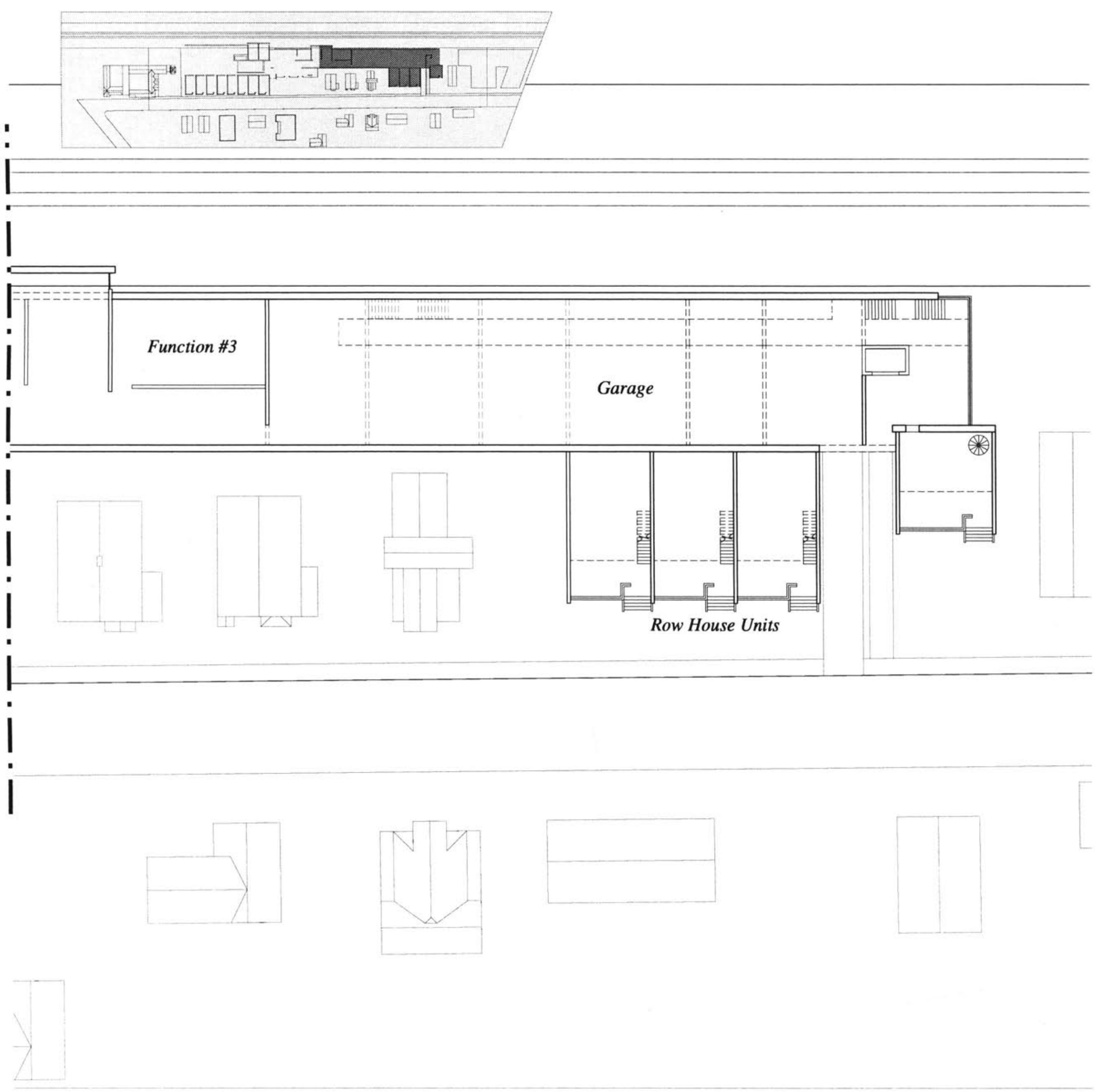
[76a] Ground floor building plan - West

Scale: 1" = 50'-0"

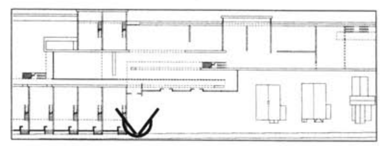


76b Ground floor building plan - Eest

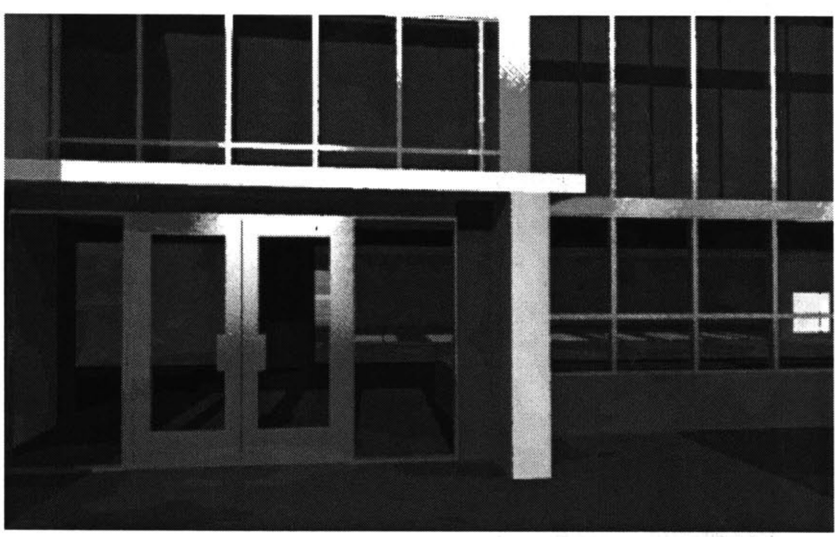
Scale: 1" = 50'-0"

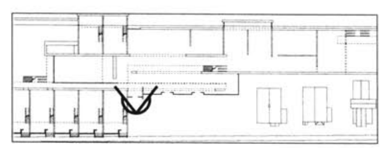


The first path shows how a visitor (or sometimes a resident) might experience the project. We are assuming that it is a sunny November afternoon.

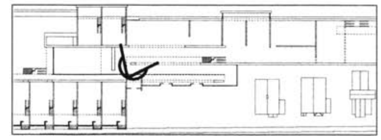


77a We arrive at the co-housing project by car and step down to the curb. The dark absorptive wall is visible behind the highly-glazed southern facade. Several people sit outside on the dining patio.

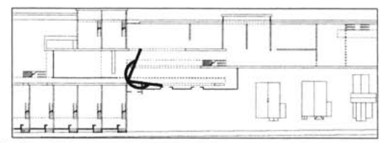




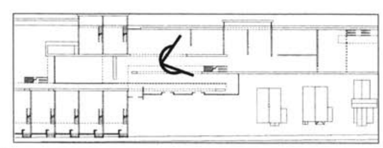
77b Approaching the entrance, we see that we will pass under the absorptive wall.



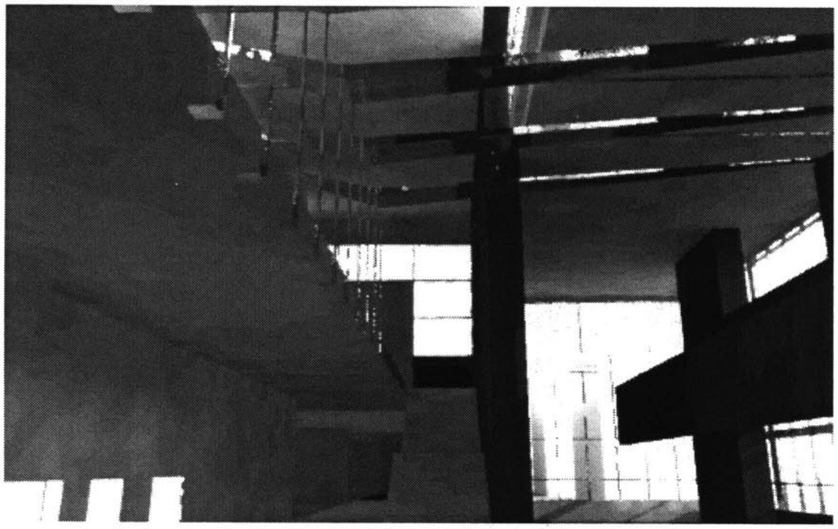
77c We are now standing under the heated channel, which acts as the threshold into the dining space. Warm air is blowing to our left, down towards the row-house units.

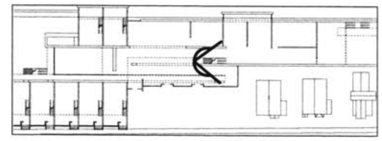


77d Looking to our right, our eye follows the channel to the greenhouse space at the end of the dining room. We also see the main stairs.

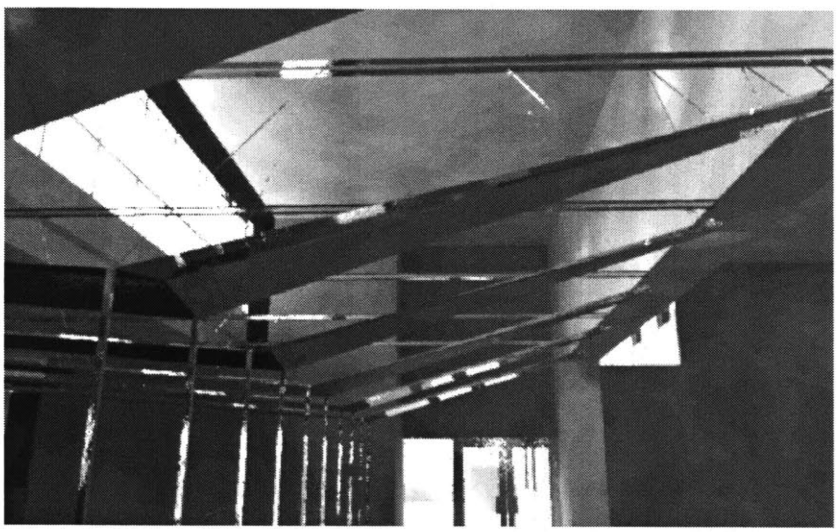


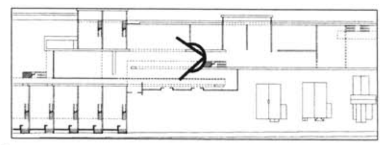
77e Continuing forward, we pass the kitchen to our left and move into the cool bright space between the dining room and the lounge to the rear. We head towards the stairs leading to the second floor.



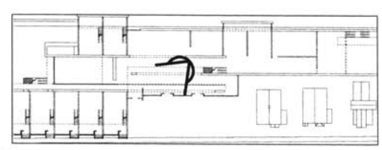


77f As we move up the stairs, we look up to see the roof trusses whose bottom chords serve as radiant heaters for the dining space in the evening.

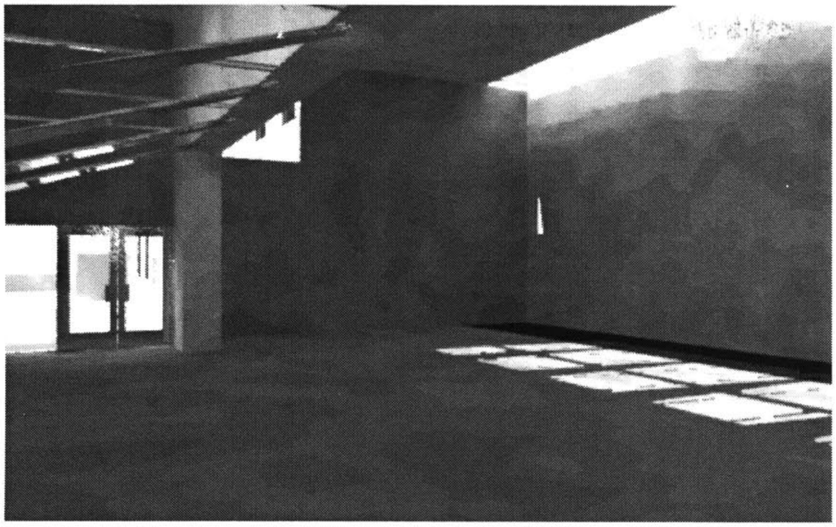


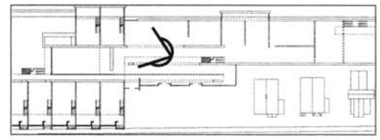


77g We move along the upper balcony under the roof as we head towards the outdoor spa.

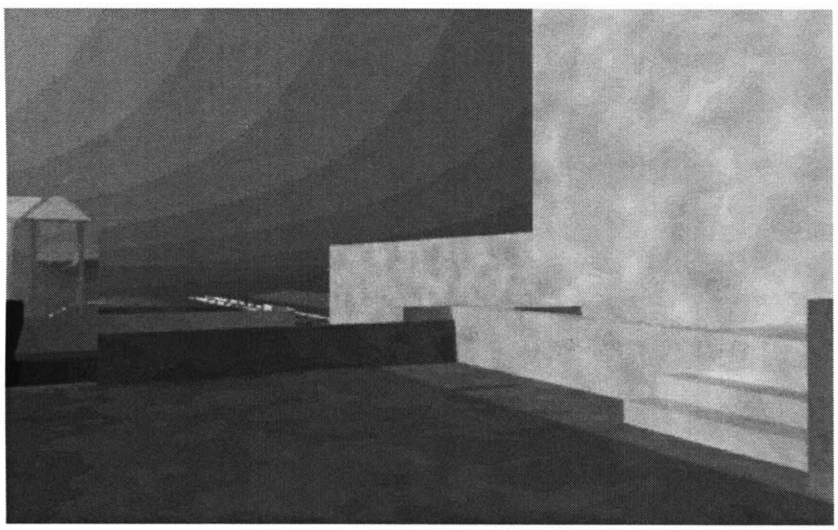


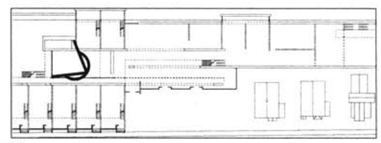
77h We peer back down into the dining room, with its dark-hued materials.





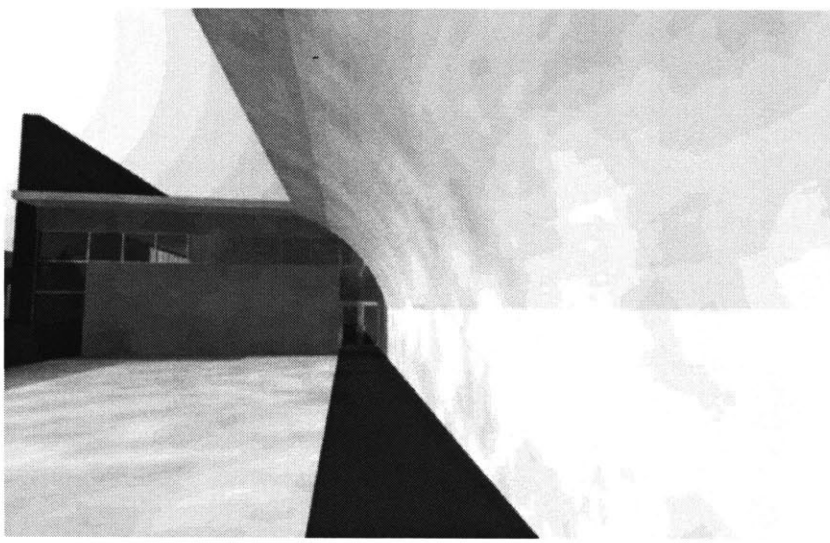
77i As we head outdoors, we pass the exercise room to our right. The room's back wall glows brightly from the reflector wall above.

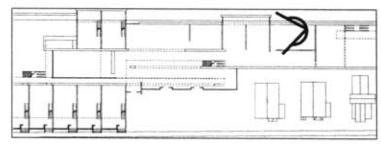




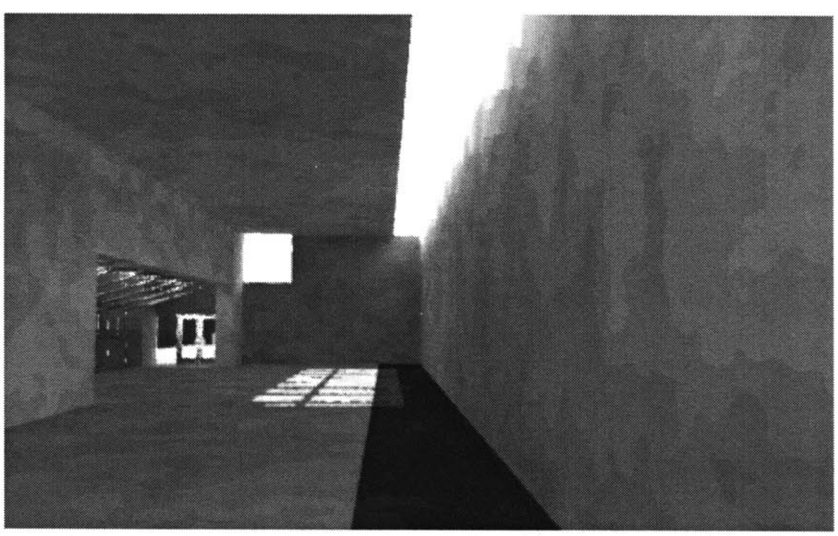
77j Several people bathe in the spa, which draws its heat from the central furnace directly below.

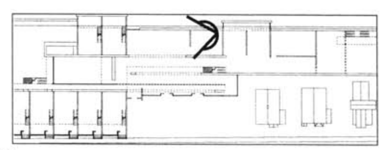
The second path through the co-housing project shows how a resident from the housing units on the eastern side of the complex might experience the project early in the morning.



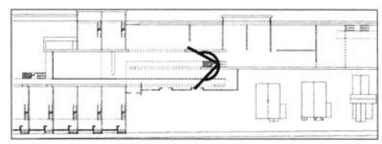


77k With a light sweater for warmth, we exit the building to walk under the reflecting wall. As we move along the wall, we watch children playing on the second story courtyard.

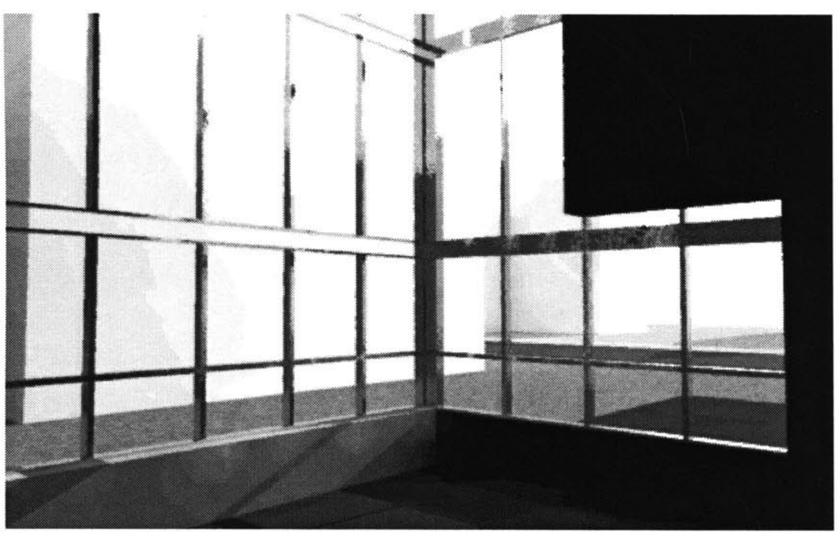


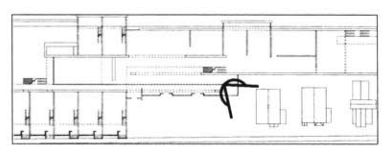


77l We enter into the exercise room, remove our sweater and begin our workout in the bright, active space.



77m After our exercise, we move down the main stairs, cooling down slowly





77n For the next half hour, we read in the warmth of the greenhouse at the end of the dining room.

8. CONCLUSIONS

In this thesis, I have introduced new methods for thermal description and visualization within the architectural design process. Using these methods in the design of a co-housing project, I have tested the feasibility of using thermal concerns to inform design decisions.

The results of this design exploration suggest that further work needs to be done in developing more sophisticated thermal design tools. This thesis does not adequately communicate the thermal consequences of building forms. While a reasonable exploration has been accomplished in describing the geometric relationships of a design's exposure to the sun, there is a lack of understanding of how the design's material properties will modify the solar gains.

There has been an effort in this thesis to describe the thermal conditions over time. Most of these visualizations have described the thermal conditions from the view of a third-party observer. Thermal qualities also need to be described from the point-of-view of the inhabitant of the space. Future work should address this need for a first-person visualization of thermal conditions.

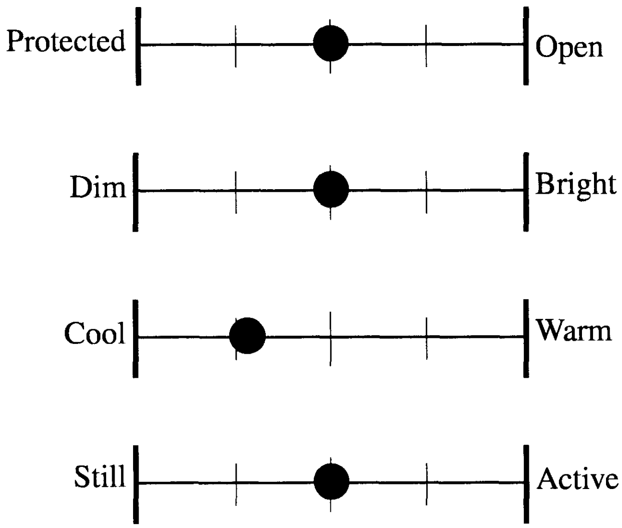
Additionally, one does not yet understand the contribution of air flow, stability, or air temperature to the thermal quality of a space. Still lacking are effective tools for the simulation of radiant transfer and air flow, as well as better methods of visual representation of the thermal data. Development of interactive tools to simulate these types of heat transfer will allow for a more sophisticated understanding of the actual thermal qualities of particular building forms.

While I have not yet developed ways to simulate all of these methods of heat transfer, I have shown a new way to describe the thermal qualities of buildings. This thermal vocabulary is a necessary first step for developing future analytical software tools. With this thermal vocabulary, one gets a formal, computable structure for the description of heat in buildings. This structure also helps define the full range of thermal possibilities.

With the aid of new computational tools created for design, it will be increasingly possible to consider non-visible phenomena, such as heat, in the architectural design process. Empowered with new-found thermal tools and knowledge, architects will create buildings that respond intelligently to human environmental needs.

9. APPENDIX A - THERMAL PROGRAM

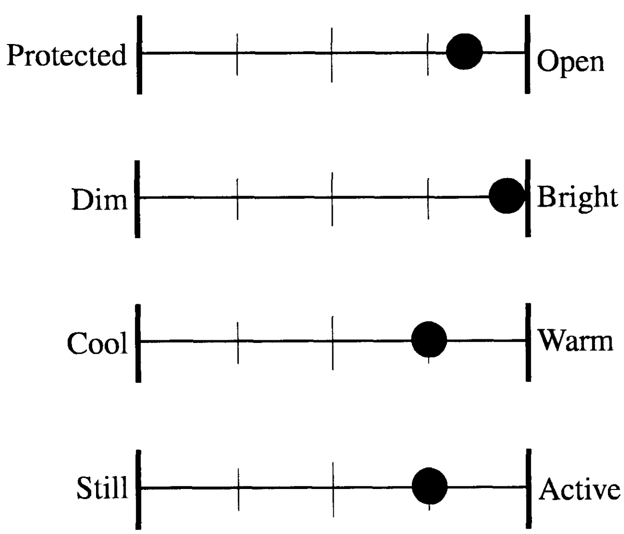
78a Thermal program data sheet



Central - Function 2 & 3

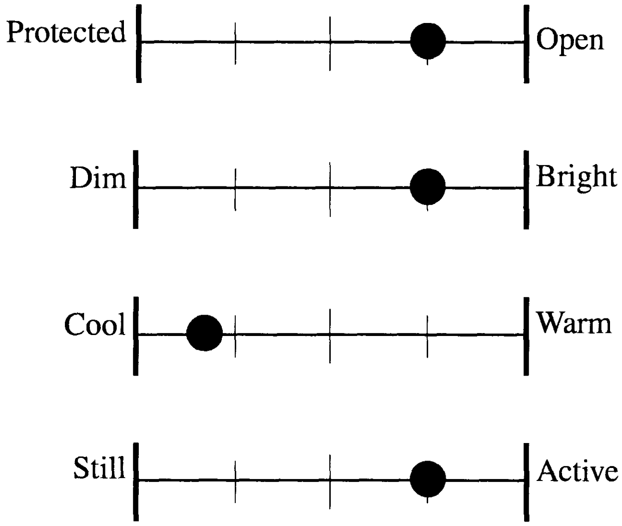
multipurpose rooms that have no windows, but allow in filtered light from above. useful for artwok displays and produciton. Rooms can be combined.

78b Thermal program data sheet



Central - Green house

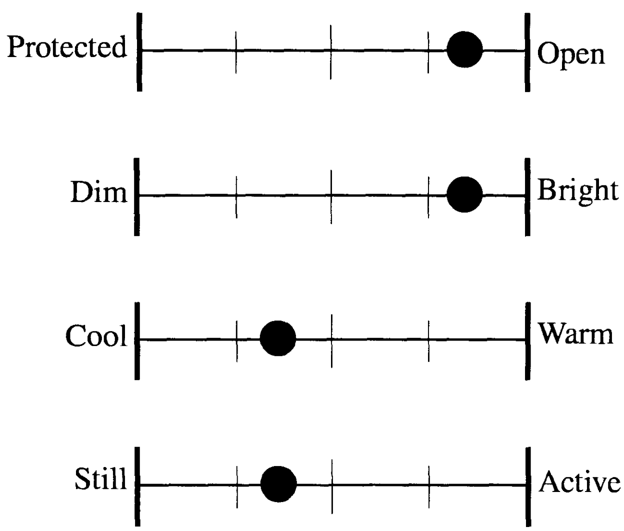
fully glazed to the exterior. is a sun space or green house with an opening to the central meeting/dining space.



Central - Kitchen

kitchen heat flows into the central dining space. similar in thermal quality to the dining space except it has much higher air movement and is less exposed.

78c Thermal program data sheet

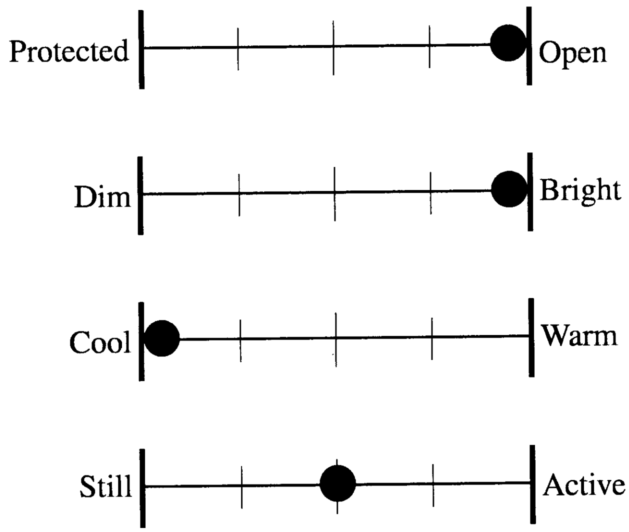


Central - Dining/Meeting

an open, changeable space that is the most public room in the project. brings thermal elements from the environment into the space. Lower air temp and high radiant temp to achieve a bright, active place.

78d Thermal program data sheet

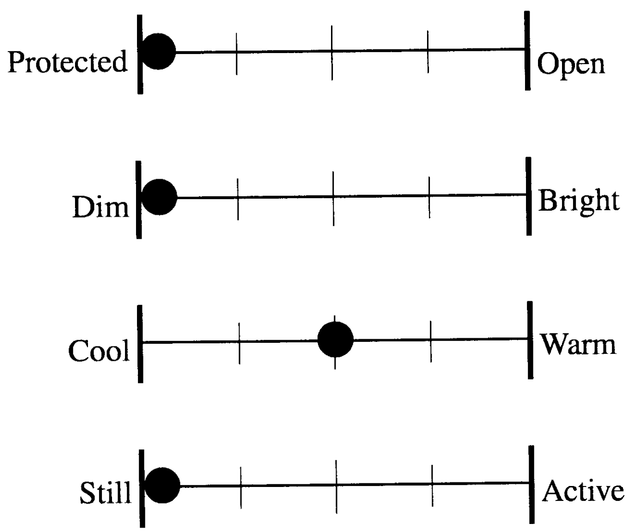
Central - Spa



outdoor hot tub spa with complete exposure to the elements. tub keeps people at 104 while the air is < 50.

78e Thermal program data sheet

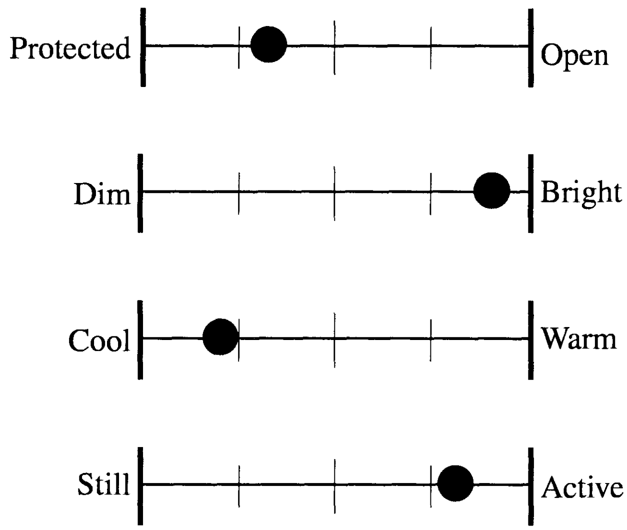
Central - Function 1



isolated and controlled space. could be used for meditation, specialize work, recording, photography, etc.

78f Thermal program data sheet

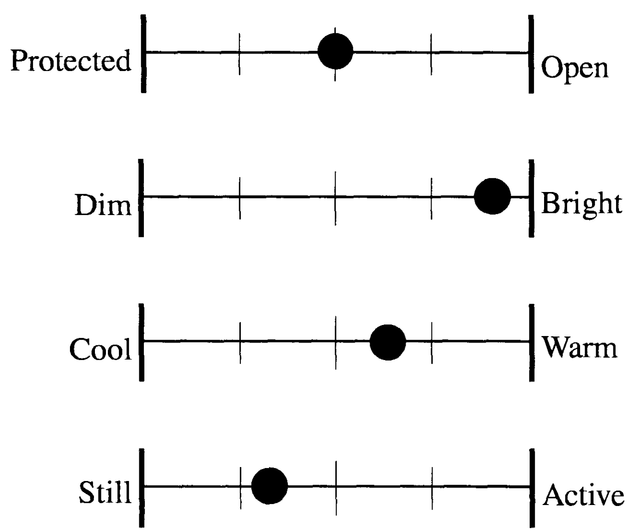
Central - Exercise



windy, dynamically-changes with the sunlight. is still enclosed and somewhat insulated from the other part of the central common house. exposure to the outdoors helps generate high air movement.

78g Thermal program data sheet

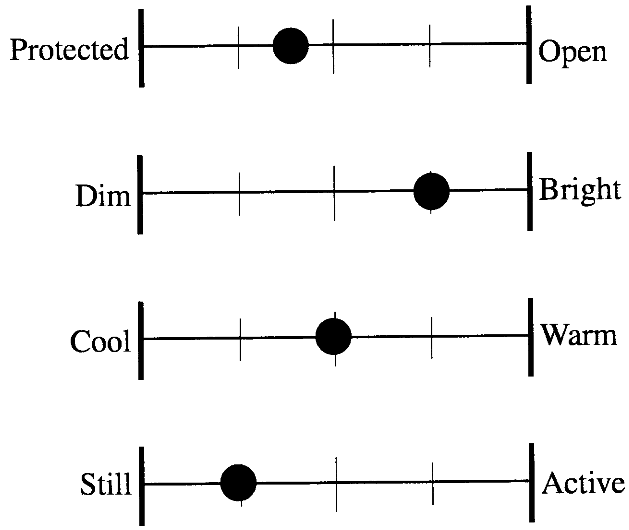
Central - Child Care



moderately protected with a connection to the outside. Similar to the lounge, except more active.

78h Thermal program data sheet

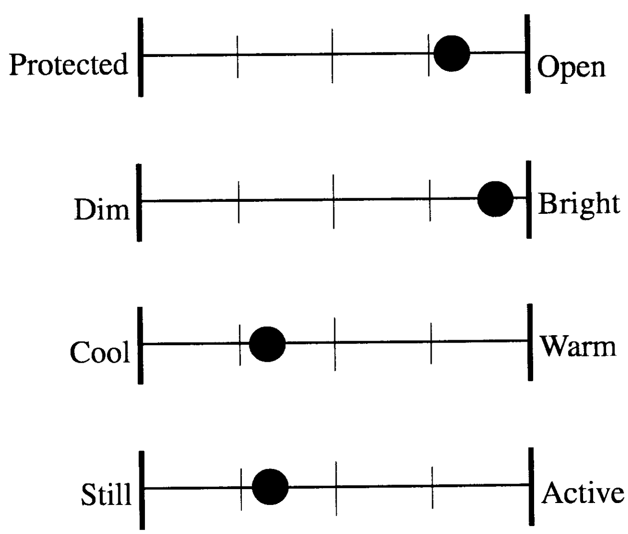
Central - Lounge



more subdued than the dining and kitchen spaces. warmer materials and intimate.

78i Thermal program data sheet

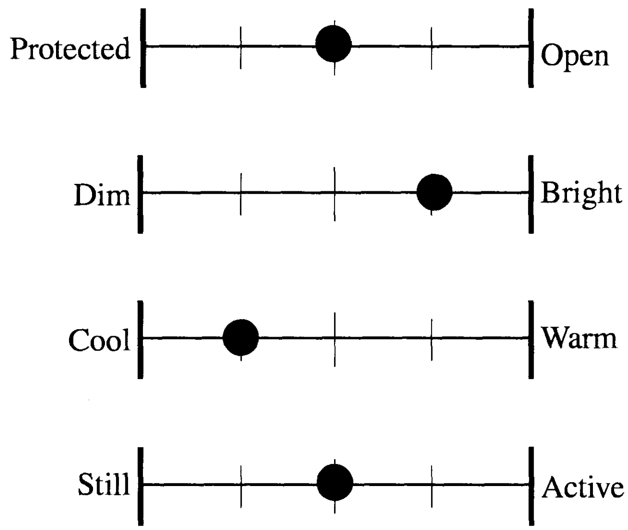
Central - Dining Patio



exterior dining space with similar thermal qualities as the interior dining space, creating a singular thermal experience inside and outside.

78j Thermal program data sheet

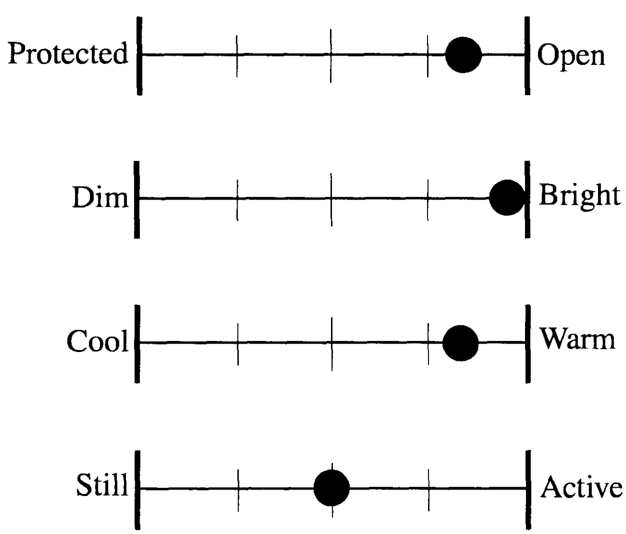
Central - Playground



protected outdoor playspace for younger children.

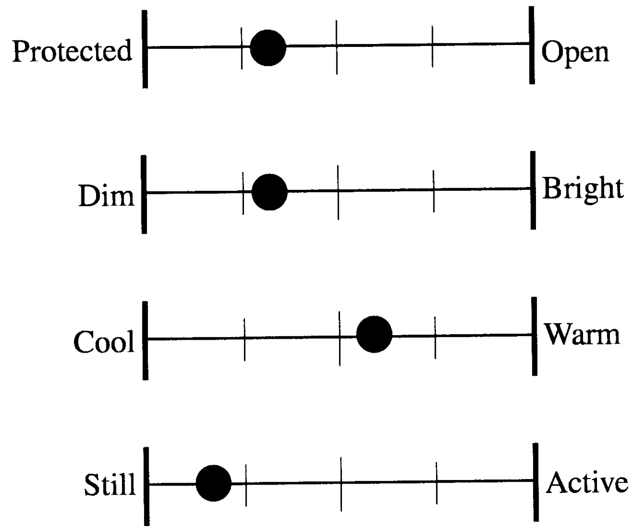
78k Thermal program data sheet

Central - Garden



outdoor garden with the thermal properties of a greenhouse without the glazed enclosure. long exposure to direct and reflected sunlight.

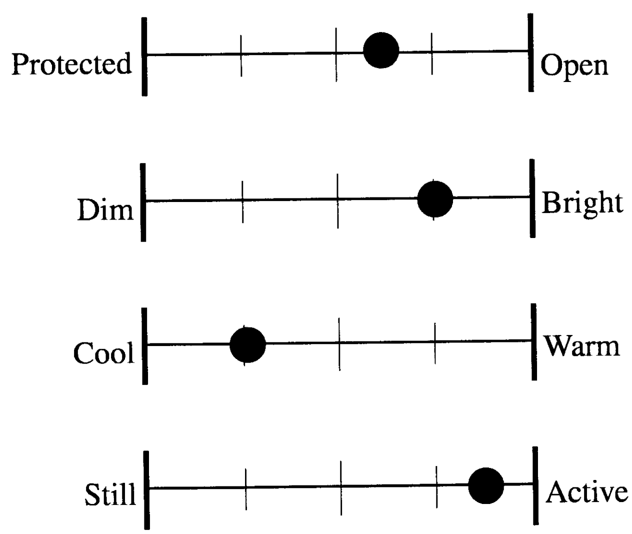
78l Thermal program data sheet



House - Dining

moderately protected with not too much of a view to the sun or sky. still.

78m Thermal program data sheet

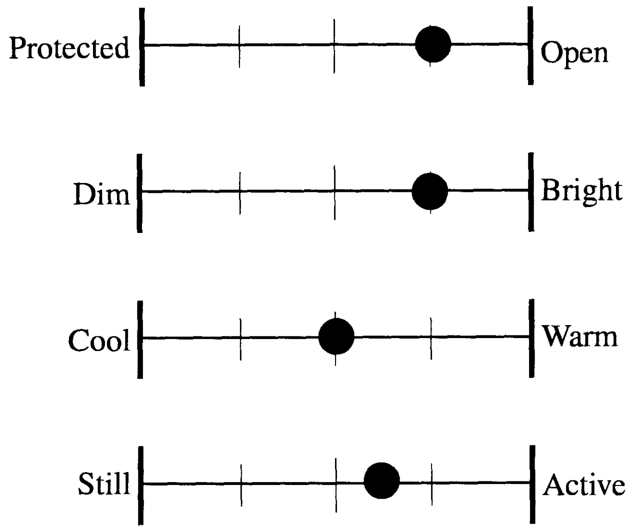


House - Kitchen

above-average exposure with a cool air temp.

78n Thermal program data sheet

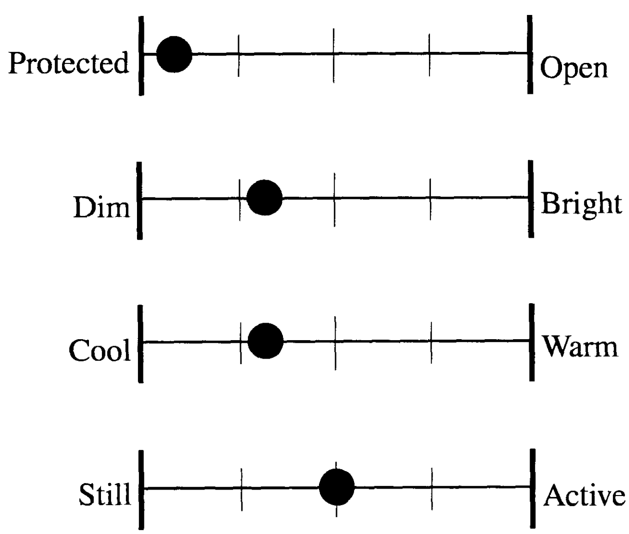
House - Living



bright, dynamic space that is very exposed to both the exterior and the other interior spaces.

78o Thermal program data sheet

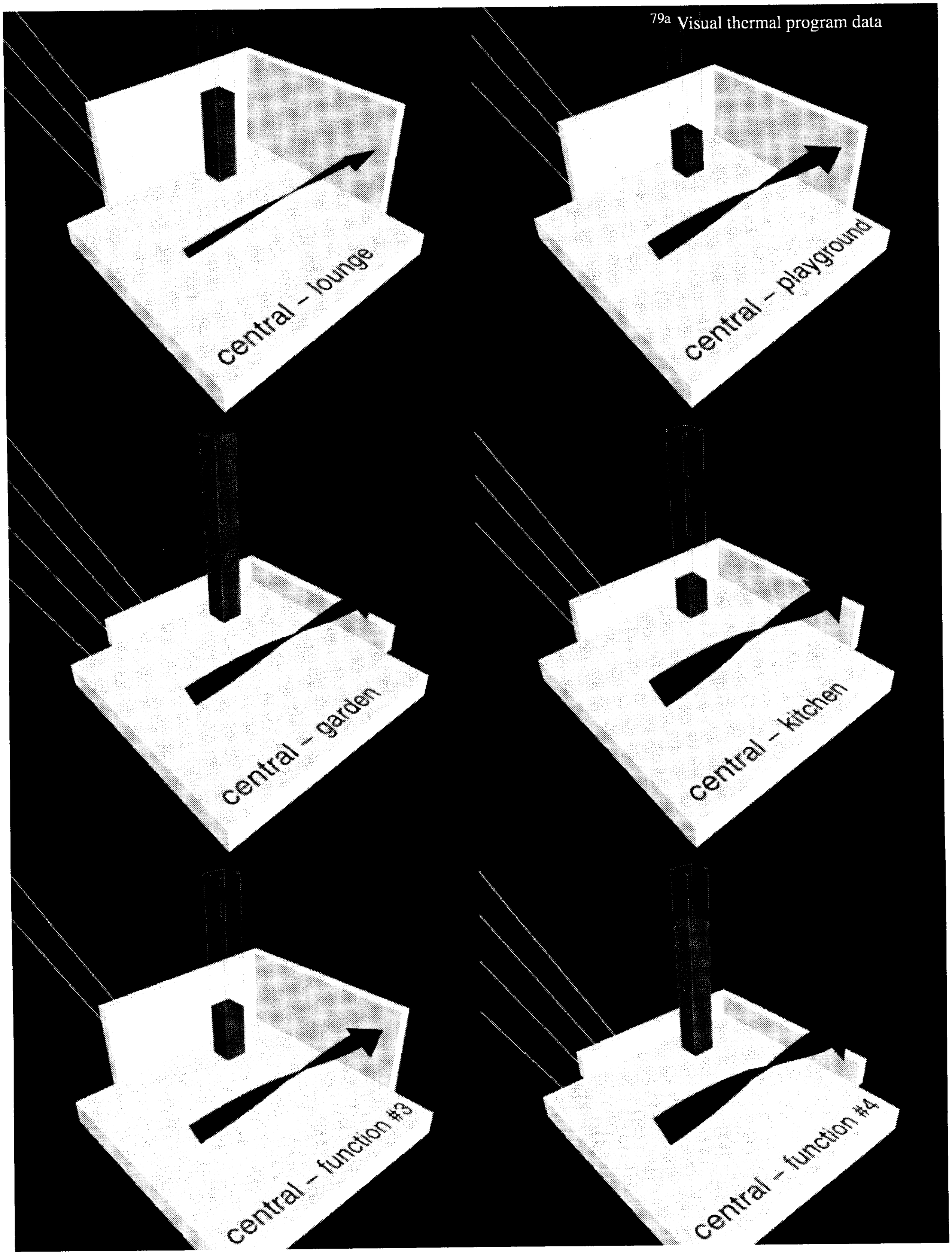
House - Bedroom



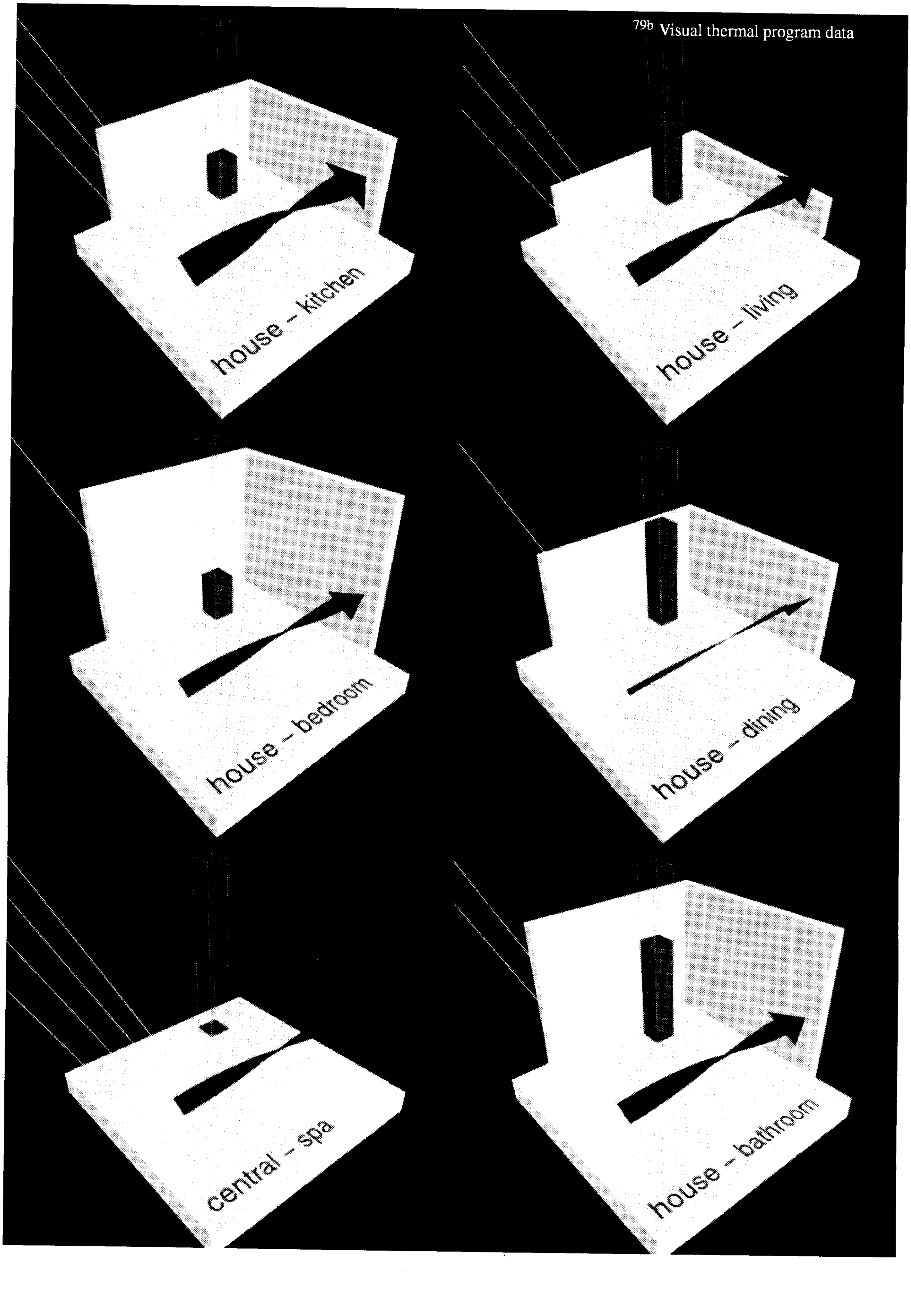
cool, protected environment.

78p Thermal program data sheet

10. APPENDIX B - VISUAL PROGRAM



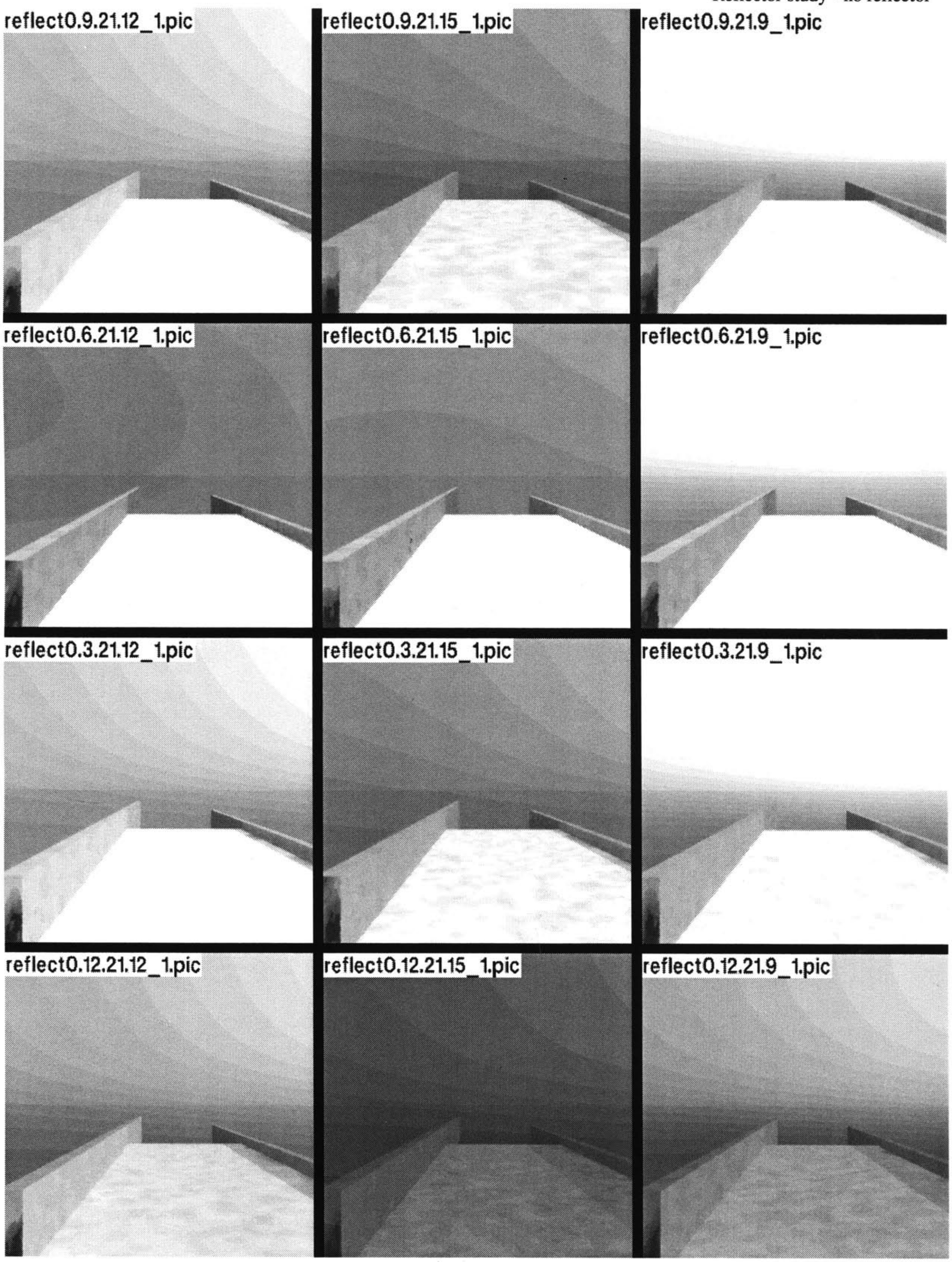
79a Visual thermal program data



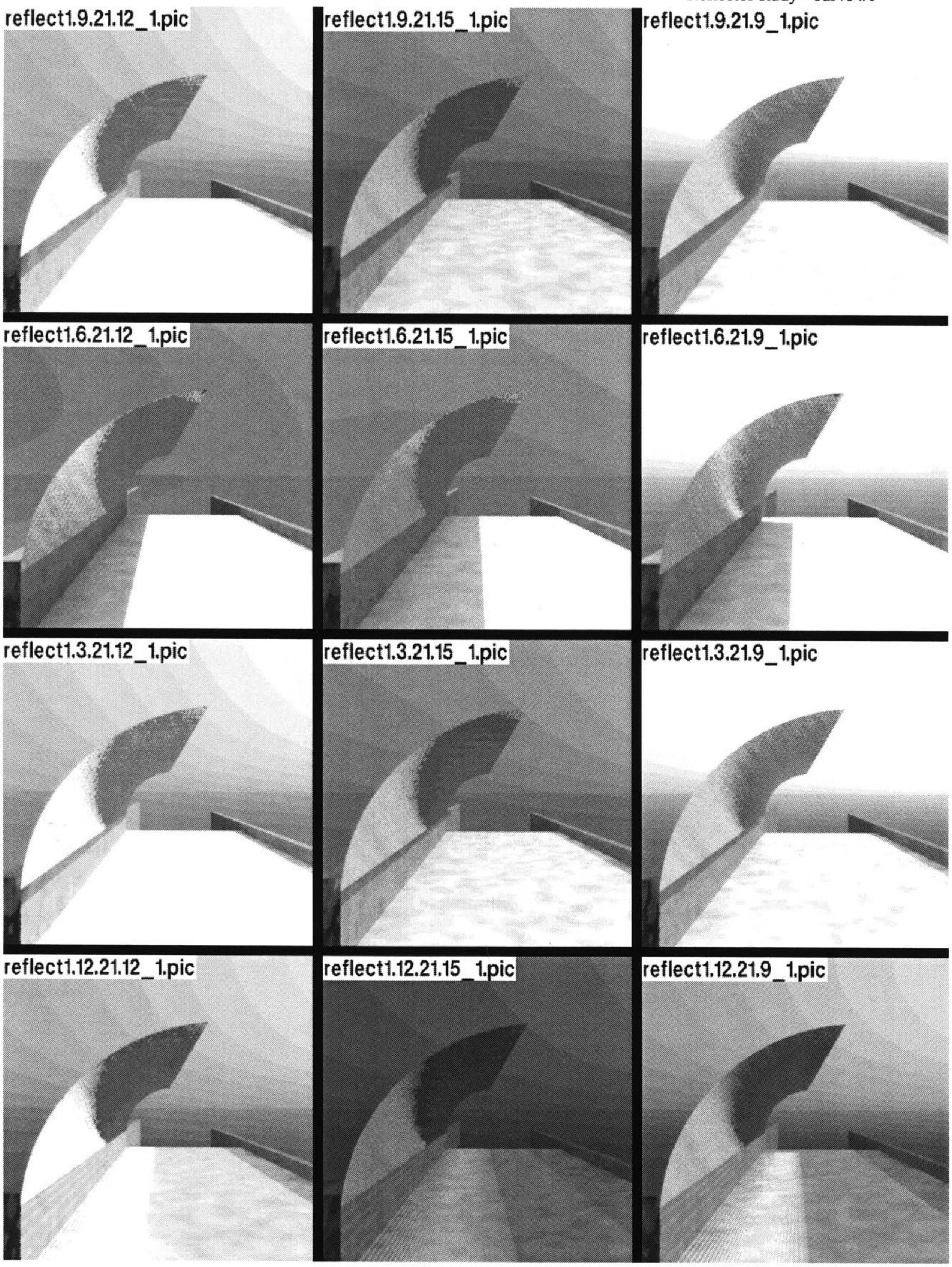
79b Visual thermal program data

11. APPENDIX C - REFLECTOR STUDIES

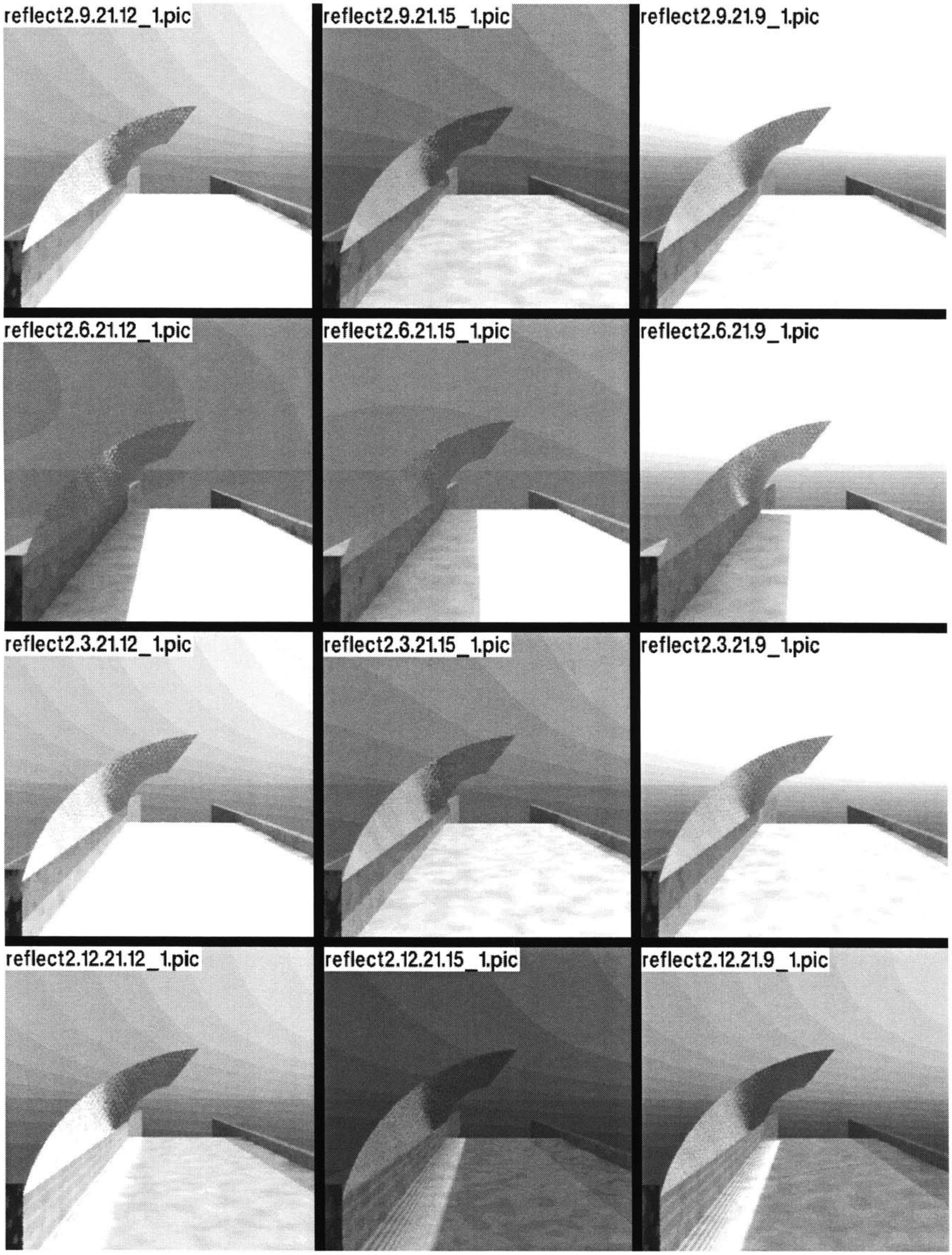
80a Reflector study - no reflector



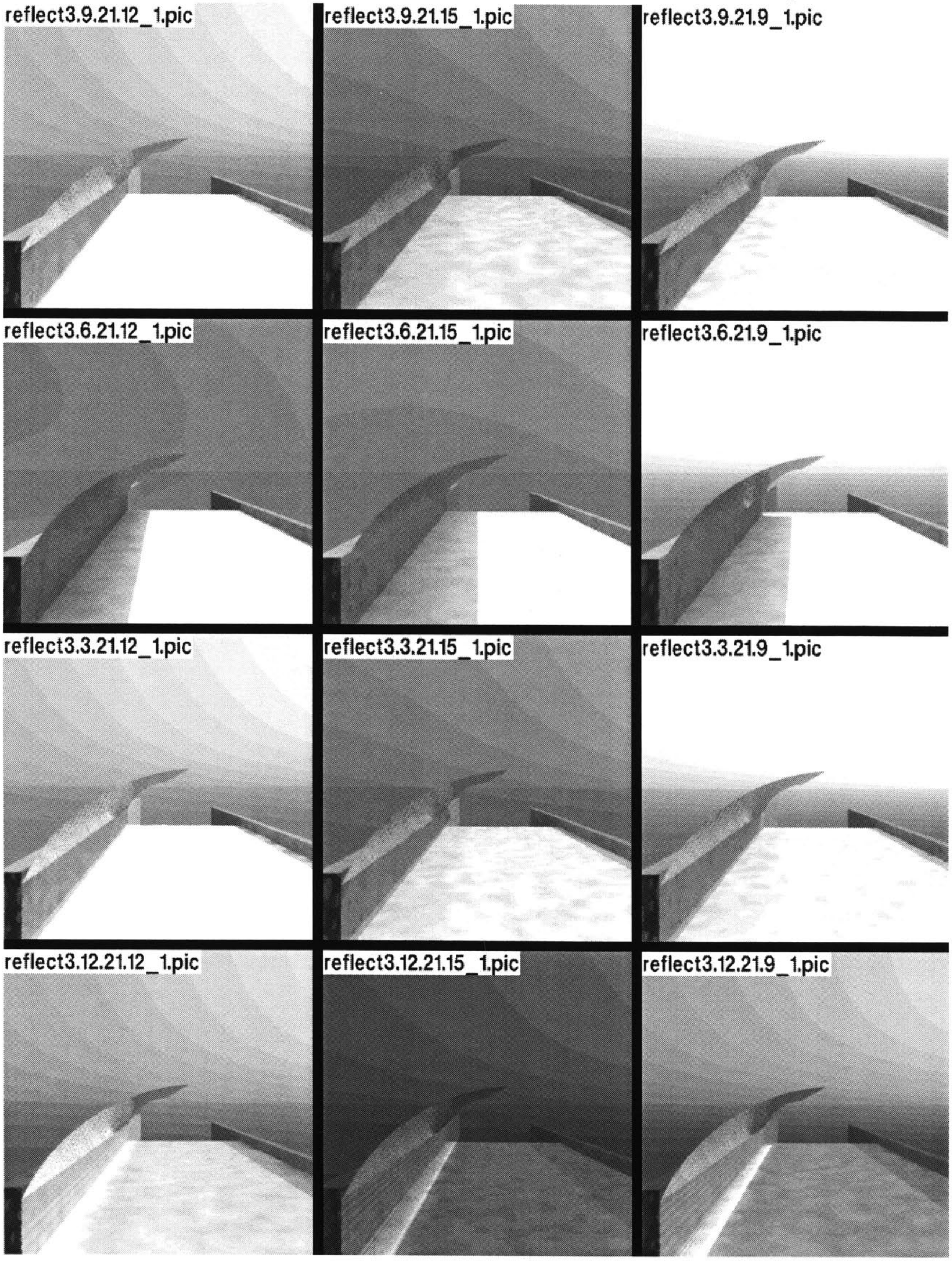
80b Reflector study - curve #1



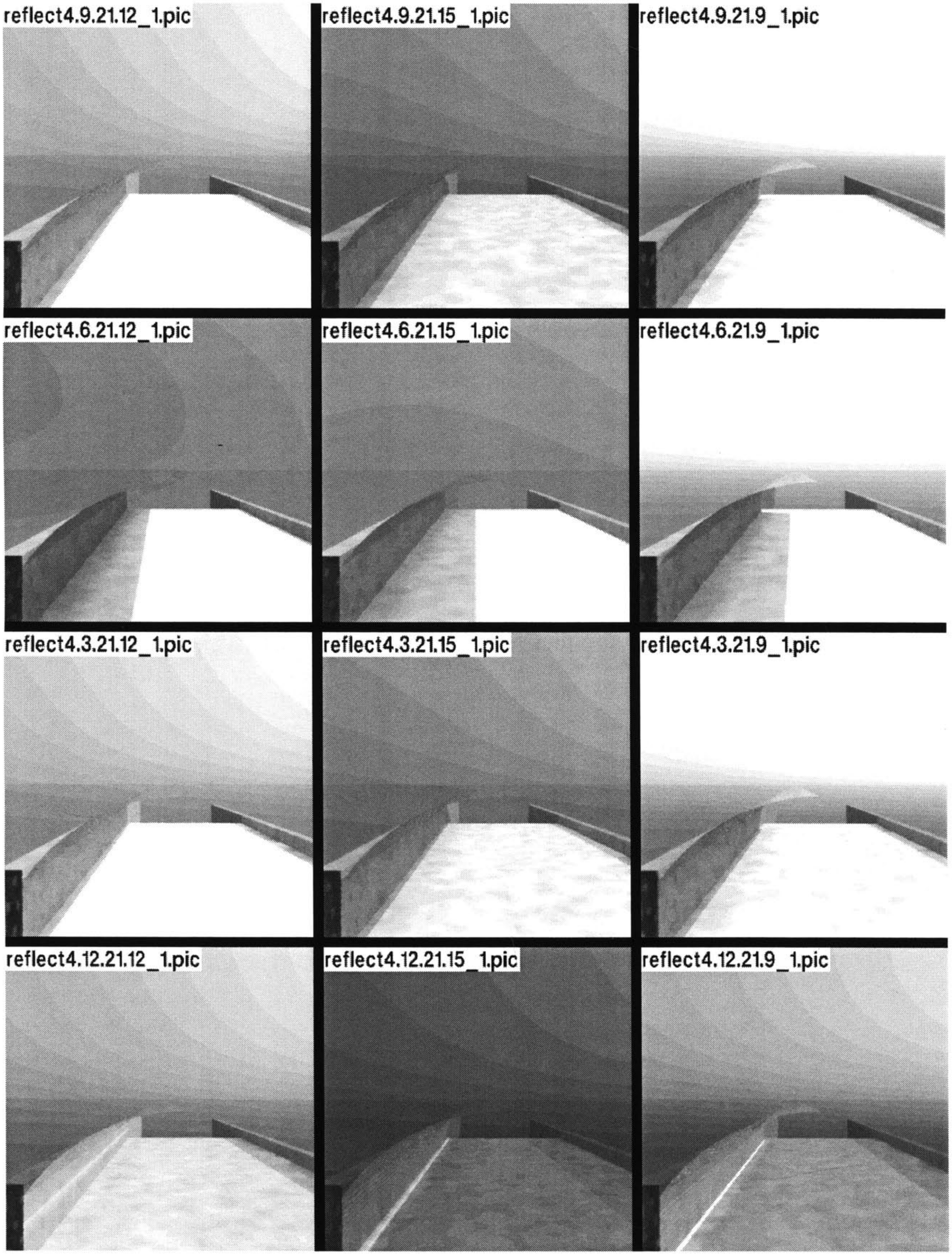
80c Reflector study - curve #2



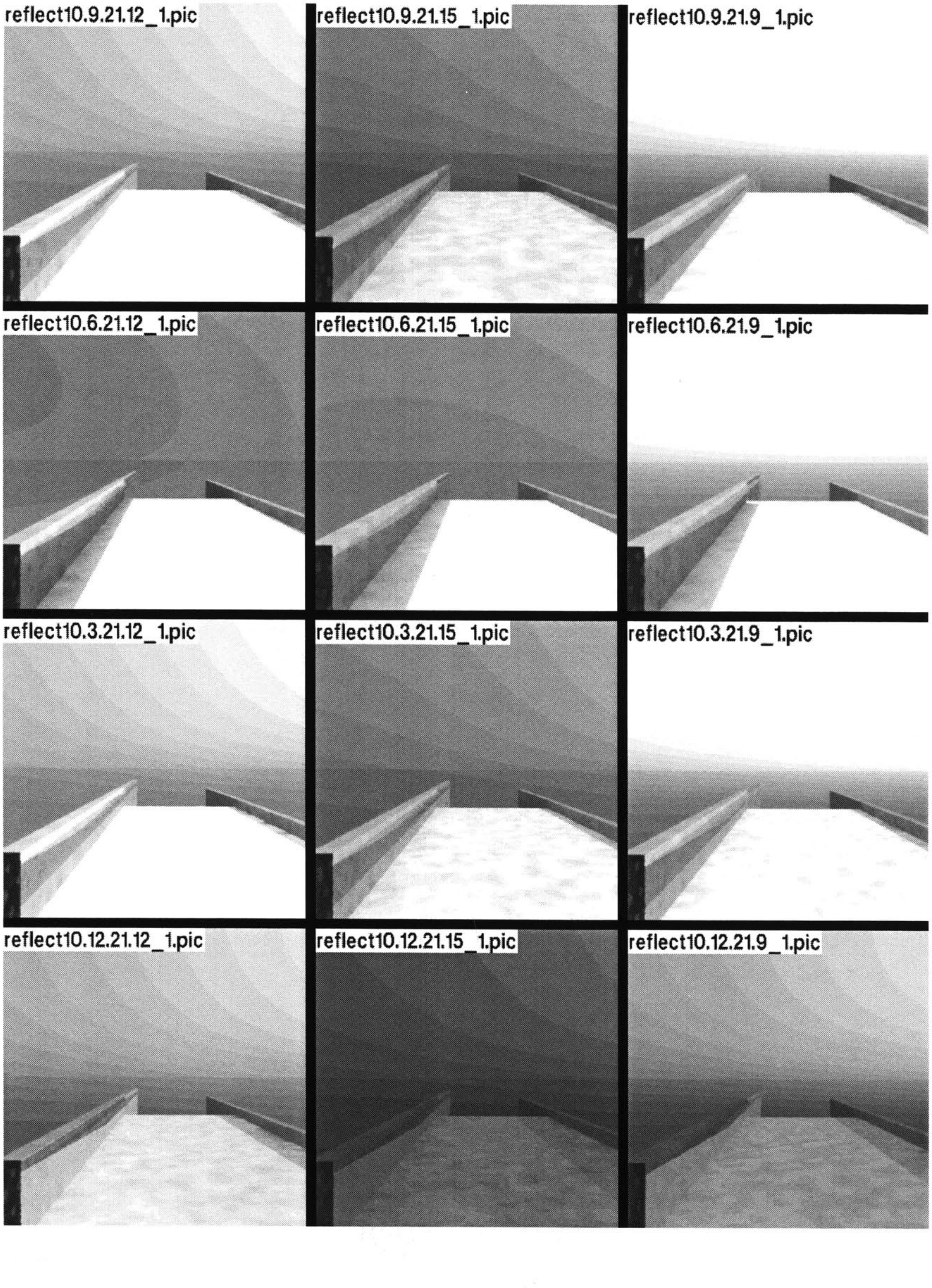
80d Reflector study - curve #3



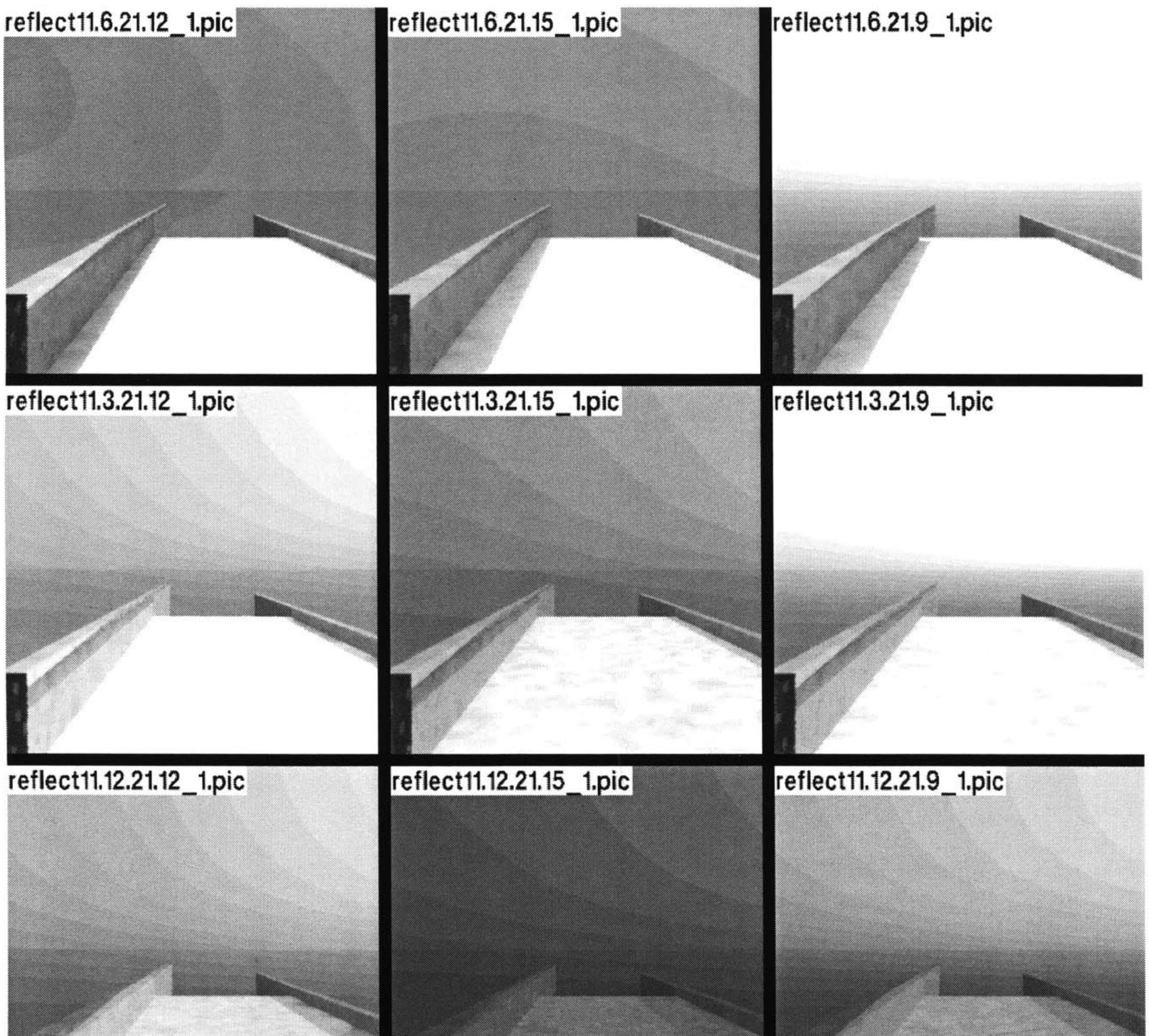
80e Reflector study - curve #4



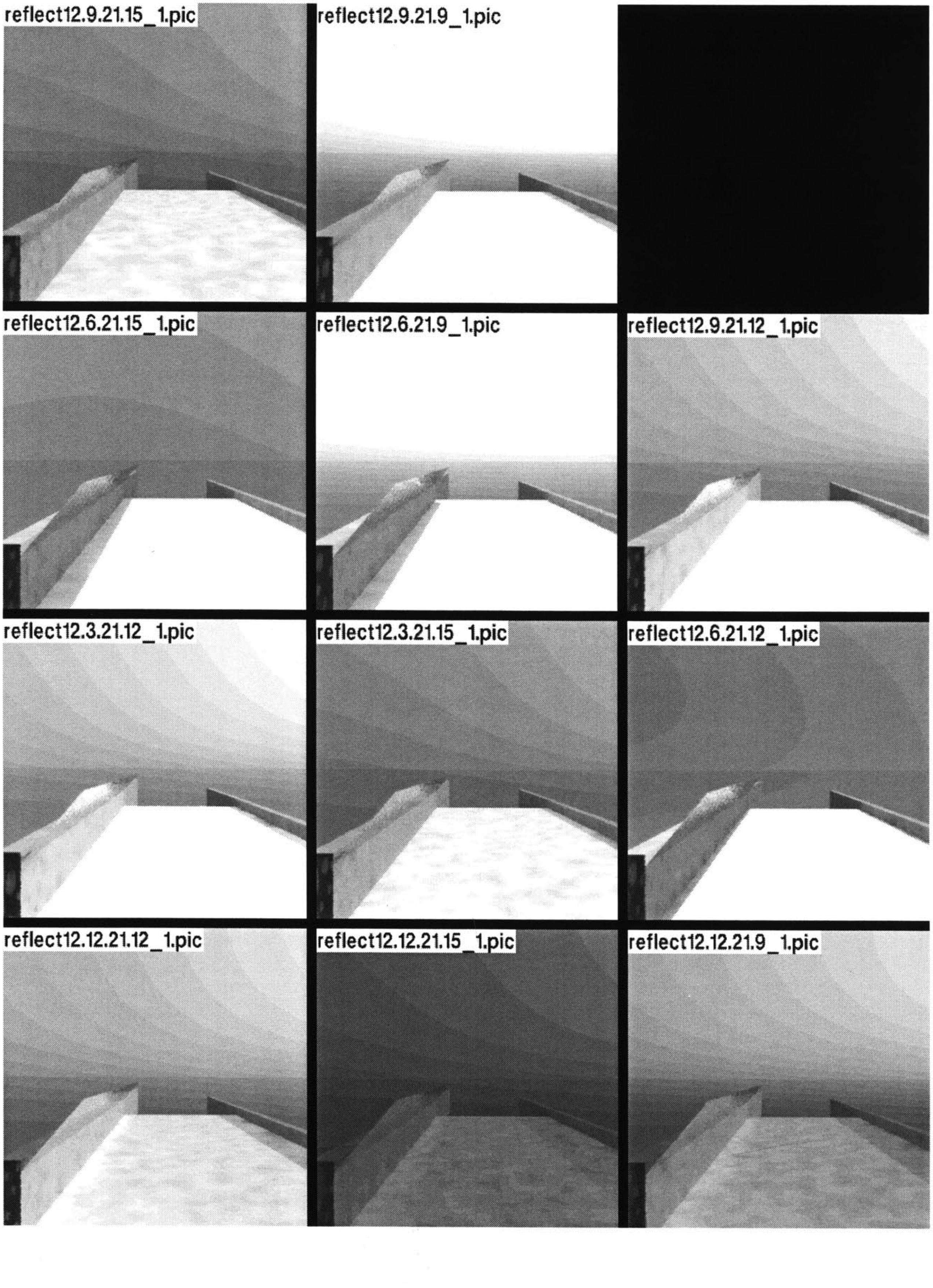
80f Reflector study - flat #1



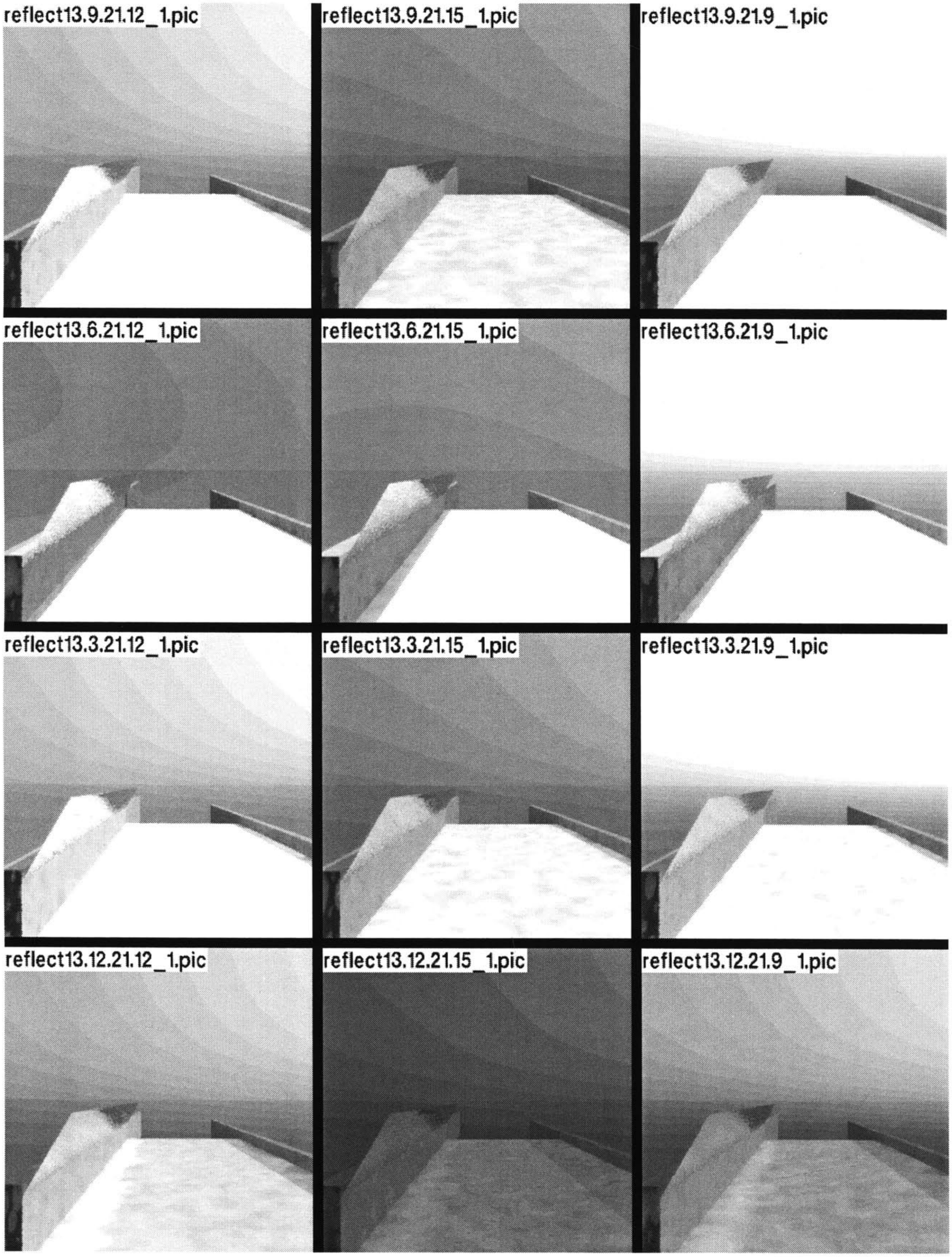
80g Reflector study - flat #2



[80h] Reflector study - flat #3



80i Reflector study - flat #4



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