Developing an Energy Design Tool — Phase I Report

**J. A. Heidell
J. D. Deringer**

February 1987

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute**

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PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

DEVELOPING AN ENERGY DESIGN
TOOL--PHASE I REPORT

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February 1987

Prepared for the
Office of Buildings and Community Systems
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

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(a) The Deringer Group, Riva, Maryland.

ABSTRACT

Existing energy expertise for the design of commercial buildings could go largely unused because it is not available in a manageable form to building designers and owners. This report proposes making this expertise available to designers of commercial buildings as an energy component of the design tools that will be available in the 1990s. The energy component would be developed with Department of Energy funding and would be integrated with commercial design tools. The energy component would make it simpler to consider energy alternatives as the building is being designed. The report surveys this subject area, analyses potential applications for such tools, describes and analyses concepts and models of the energy component, and provides a phased feasibility plan for research and development work on the energy design component.

PREFACE

This report discusses background and planning information for developing energy components of design tools to help building designers consider energy use at any stage of the design process. If the objectives of this work are achieved, the results would be a tool such as the fictional architect uses in the following scenario.

In May, 1992, George McMoore sits at his workstation and adjusts his reading glasses. George's firm is designing a 60,000 square foot regional office and research facility in Sacramento for Western Software Products, a Fortune 500 firm. George's computer is equipped with Designer ECADD, the latest in computer-aided design and drafting software.

George completed the facility programming last week and is beginning the conceptual design for the building. Western wants a building with a progressive image, yet is conservative about using new technologies, including several strategies that George is fond of. The construction budget is tight. Because a separate division within Western will operate the building, George is not optimistic about trading off operating savings against increases in the construction budget.

Nevertheless, he sets to work. Pressing an icon on the computer screen, he selects the ECADD system (expert computer-aided design and drafting) and initializes the space planning mode. He generates a basic set of floorplans that meet the specifications already developed by the facilities program. When satisfied with the floorplans, he sketches the building on the screen, specifying standard envelope features including substantial amounts of glazing (40%), as a starting place for investigating energy concerns.

He next selects the energy characterization mode, which can supply information on energy patterns for a typical office building of this configuration in the Sacramento region. The program automatically calculates expected energy and demand costs based on the local utility rates. It then describes the energy flows within the building in charts that depict lighting and HVAC system

energy consumption and cost, as well as typical heating and cooling schedules. The screen shows that lighting and cooling are the two major targets for improving the energy (and cost) performance of the building.

George then selects the icon for identifying energy-efficient strategies. At first, the program supplies a summary of the most important strategy areas, with details available in submenus. The energy design tool processes the request and produces a set of priorities as follows:

- reducing solar gain through the windows
- reducing energy used for lighting
- selecting customized lighting systems
- selecting customized Heating/Ventilating/Air Conditioning (HVAC) systems.

He requests further detail on the solar gain strategies and obtains a list of the top ten strategies along with relative estimates of cost, energy consumption and other design impacts for his building configuration. Since lighting glare is a real concern for the firm (most of the research is done on computer terminals), he decides against using daylighting. He reduces window size for the research offices, and specifies high performance glazing with interior blinds as the option set that best meets his client's glare concerns yet remains within construction and energy cost bounds. He also specifies trees on the the east, south and west elevations, both for shading and for developing the building's image.

He then requests appropriate lighting options and opts for high-efficiency lamps and ballasts throughout the building, with a high degree of task lighting in the research offices. Parabolic fixtures are selected for the conference rooms, executive suites, and public lobbies.

Next, he requests HVAC system selection options, and the program supplies him with recommendations for six different systems, complete with energy and comfort information on each--information that reflects both his specific floor plans, and the glazing, window management, and lighting strategies already selected. Based upon cost and comfort/amenity requirements from Western, he

selects a split HVAC system (constant volume interior, variable air volume perimeter system with economizers) with cooling provided by conventional chillers.

At this point, he has a conference call with his electrical and mechanical engineers. As a results of feedback from this teleconference, George replaces the chillers and strip heaters with electrically driven heat pumps.

George then switches to the ECADD design mode, adds a structural system, and generates specific wall, fenestration, roof, ceiling and internal partition assemblies by modifying manufacturers' assemblies retrieved from videodisk. A request for a total cost estimate using up-to-date cost data indicates that construction cost is within Western's budget.

The system has been providing ball park energy and cost estimates of decisions, but now George wants to see details of the energy cost consequences of his design decisions to date. He calls up Energy-2, the latest energy design program. As it runs, it graphically provides energy and cost results. George is able to change building components on the fly and watch the consequences of these decisions. His earlier decisions stand, with minor modifications.

Satisfied with the basic building design, George now starts working on a more innovative design concept that he will present to the client as an option. He is a good designer, and in CADD sketch mode, quickly comes up with a promising concept. The building shape is more interesting, the internal spaces are more varied, and almost all building occupants will have some direct view outside to the wooded site. The construction cost of the alternative is only 2% higher than the standard building with a 15% reduction in estimated energy cost.

George uses the CADD 3D modeling capabilities to produce internal and external color perspectives of the base building and the alternative. He is hopeful that the client will accept the alternative, since both the image and the internal spaces of the second design are much more interesting than the base building, even though the alternative has a slightly higher first cost than the standard design.

As it turns out, the client is elated with the improved amenities and image of the alternative design and approves it. As the project proceeds, both George and his engineering consultants use further elements of the decision and design tool to assist in the detailed design of the building's lighting, HVAC, and envelope subsystems and components. Detailed drawings are developed on the ECADD system, and printed out for use during construction.

The effective use of the ECADD system continues beyond the design stage. During the construction phase, the energy analysis modes are used to evaluate glazing substitutions that resulted from a shortage of the specified prefabricated windows. George also uses the system to develop a users' guide to the building, containing information on how to operate and maintain the various building components and systems. The guide profiles the expected energy consumption by end use, HVAC system, time of day and season, so that the building operator will have some basis for identifying potential equipment malfunctions and areas for performance improvement.

Once the building is constructed and tested (against performance expectations developed by the ECADD system), George files away the building files so that they will be available to assist in any future retrofits or expansions of the building.

SUMMARY

This report documents the planning phase of a proposed four-phase project for creating computer software to provide energy expertise in a manageable form to architects and engineers--thereby decreasing energy use in new buildings. The government sponsored software would be integrated with commercially developed software for use in the design of buildings. The result would be an integrated software package to aid the designer in the building design process and to provide expert insight into the energy related implications of a proposed design. The preface presents a scenario showing how the proposed software tool could work. Without such an effort, available energy expertise, which could presently result in significant long-term savings nationwide, will go largely unused by designers and owners who have shorter-term goals to meet and little time or incentive to become energy experts.

The project is one element of the Building Systems Integration Program (BSIP), a multiyear research program being conducted by the Pacific Northwest Laboratory (PNL) for the U.S. Department of Energy (DOE). This planning report is the joint effort of PNL staff and Mr. Joseph Deringer of The Deringer Group.

Parts of the design tool described in the Preface already exist. A few computer-aided design and drafting (CADD) systems now have very limited design capabilities as well as limited analysis capabilities (site design work, engineering analysis, cost estimation, construction document preparation, facilities management, etc.). These capabilities will be dramatically extended within the next 5 to 10 years. Anticipated enhancements include the following:

- advanced engineering analysis tools
- expert systems to aid in the design and integration of building components
- video catalogs of manufacturers' products (with performance data)
- building code compliance checking programs.

This research would develop an energy component available for inclusion by commercial developers of advanced design software, as that design software is being developed. Coordination with software designers and the building design

community would be critical to the success of the research. The overall system that could result from this coordinated effort is expected to contain the elements pictured in Figure S.1.

Currently available energy analysis tools do not provide the two kinds of help most needed by designers: help in identifying good energy strategies when generating design concepts and help in properly designing a strategy once one is selected. The potential merits of a good strategy can be entirely lost if it is not properly employed.

The benefits of an effective energy design decision tool are potentially significant. The payback comes from the significant value to the nation of the energy saved as a result of good energy design decisions. Improving energy-related decision making alone will result in a 15% reduction in energy use by new commercial buildings with no increase in first cost. If such improvements were widely used, a national energy savings of over \$350 million could be expected from the new commercial buildings constructed each year. The estimated one-time cost for developing the tools would be \$515 million. Despite the advantages of the integrated system shown in Figure S.1, an energy component of CADD tools cannot be expected to be developed by the private sector.

This report proposes a long-range effort to develop an energy design tool suitable for integration into larger commercially developed advanced computer-aided design programs. The development effort is comprised of four phases:

1. Survey and initially investigate of the research area to determine the feasibility of providing an energy design tool for integration into commercially developed and integrated computer-aided design tools.
2. Develop the initial methods and tools including:
 - a whole-building model to integrate subsystems
 - selected subsystem models
3. Expand of the methods and tools to more
 - design stages
 - building types

FIGURE S.1. Energy Component as it Relates to a Comprehensive Building Design Tool

- building subsystems
- energy factors

4. Integrate the energy components with design software.

The present report documents the Phase 1 feasibility assessment and planning phase of this work. This first phase has included:

- identification of research objectives
- completion of background surveys of relevant disciplines and technologies
- completion of preparatory research necessary to structure the research plan
- development of the research plan itself.

The objectives of the proposed research will be to provide an easily integrated energy design decision component to various commercially developed integrated computer-aided design tools which would:

- contribute significantly to the design of energy efficient buildings
- contribute significantly to the design professional's understanding of energy efficient design practices
- benefit (learn) from the innovative and successful decisions made by the design professional as he or she uses the system
- eventually provide the building operator with helpful insight to the most efficient use of the building
- assist in assessing options, as needed, for retrofit, modification, or expansion of the existing building or its use patterns.

The following five background surveys were completed to provide support to the feasibility assessment of the proposed research.

1. Survey of Knowledge-Based Systems (Expert Systems) Development: This survey examined the rapidly developing area of knowledge based engineering and potential applications to the building design process.

2. Survey of Current Work on Building Design Process Models and Tools: Research efforts were identified by universities, by government laboratories and by HVAC controls and equipment manufacturers, mostly in the early stages of development.
3. Survey of Computer-Aided Design and Drafting (CADD) Development: Several systems were identified as having desirable 3-dimensional, object-oriented data base structures, most useful for the proposed research purposes. Possibilities of cooperative R&D efforts have been explored with several vendors.
4. Survey of Energy Research Programs and Results: Because the research will use existing energy information this summary of recent and ongoing energy research efforts is useful.
5. Survey of Related Data Bases: Economic, energy and thermal data are important inputs to energy decisions. A survey of available data bases was made to determine potentials for using them as resources for the research effort.

Preliminary research was completed in the following four areas necessary to structure a comprehensive research plan:

1. Define Application Areas: This analysis helped to define potential applications for the research plan. Three major application areas were defined: new building design and construction, retrofit design and construction, and building operations and maintenance.
2. Development of Energy Decision Models: Two models were developed--a whole-building model and a building-subsystem model. Research efforts for building subsystems will be integrated via the whole building model.
3. Timing and Sequence of Energy Design Decisions: A seven step sequence for making design decisions was adapted from several recent sources.

4. Computer-Based Prototype: In addition to the preliminary research described above, the Phase 1 Feasibility and Planning effort also developed a prototype computer-based system using the microcomputer-based EXSYS 2.2 expert system package.

The remaining three phases are described in Chapter 10. A proposed schedule is included here as Figure S.2.

FIGURE S.2. Research Program Schedule

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PART I. INTRODUCTION, CONCLUSIONS AND COSTS

This report is divided into four parts. The first part tells why the time is right for developing an energy component of commercially developed computer software tools for the design of commercial buildings. The first part also presents the overall conclusions and the estimated research and development costs.

Considerable knowledge now exists about energy use and conservation in buildings. This knowledge is of greatest value in designing new buildings, where significant savings are possible simply by applying the existing energy expertise. Transferring this expertise from lengthy technical reports to building designers and owners is not easy. Part I introduces the problem and an approach to a solution. The approach seeks to incorporate existing knowledge into an energy component of building design tools. The design tools themselves are being developed by commercial software vendors, but without the energy component. With a program to develop and add an energy component to such design tools, energy performance objectives for buildings can more easily be achieved, and significant energy savings for new buildings can be realized.

DEVELOPING AN ENERGY DESIGN TOOL--PHASE 1 REPORT

1.0 INTRODUCTION

The goal of this multi-year research effort is to develop energy components of commercially developed design tools to improve the ability of building designers to apply existing energy knowledge in their work. The research proposes to integrate existing energy knowledge into the design process, to make it readily available to designers at the time when it will be most useful: when they are doing the design work using computer-aided design software (CADD). The proposed energy design tools will assist designers and owners to make better energy decisions before they build. The first focus of the research is the early stages of design. Further research efforts will focus on later stages such as decisions during and after construction.

This research will focus on:

- understanding the design process as it relates to energy decisions
- developing detailed structures for describing energy decisions, including their sequence and timing
- developing symbolic logic techniques and hierarchical structures for describing the decision relationships
- applying this knowledge to energy design tools.

The research program is divided into four phases as shown in Figure 1.1. This report presents the results of the Phase 1 feasibility planning. In Phase 2, whole-building and component models will be developed. These are the basic parts of an energy design tool. In Phase 3, these parts will be expanded to consider additional building types, components, and design stages. In Phase 4, the expanded tools will be integrated with advanced building design software.

This project will rely on existing energy research results and upon new information as it becomes available (e.g., algorithms, energy use data, and information on components and energy transfer). It will not generate new energy information, but find ways to use that information more effectively.

FIGURE 1.1. Research Program

Figure 1.2 shows the domain of the proposed research program, and how it draws on existing energy knowledge, energy analysis tools and energy data bases as inputs and resources.

1.1 POTENTIAL ENERGY CONSERVATION BENEFITS

Significant potential benefits flow from improved energy decision making by building designers and owners. The payback comes from the value to the nation of energy saved as a result of good energy design decisions.

One example is the energy savings potential for new commercial buildings. Energy use can be reduced by about 15% from design decisions alone,

FIGURE 1.2. Domain of Research

without any increase in first cost.^(a) The research that produced the recent recent Small Office Building Handbook (Burt et al. 1985) provides a number of examples of no-cost energy reductions of this magnitude.^(b)

The key savings came from transferring existing knowledge to designers who otherwise would not have ready access to it. Given the current construction

-
- (a) Refer to the level of energy conservation produced [in the Small Office Building Handbook (Burt et al. 1985)] with no increase in first cost of the strategies used, relative to the base case.
 - (b) This may represent a very slight increase of 0% to 10% in design efforts and costs. However, such costs rarely exceed 5% or 6% of total construction costs. Often, such design cost increases can be offset by decreases in first cost from improved decision making. One objective of this research is to improve decision making to lower both first cost and energy costs at the same time.

volume of new commercial buildings, the resultant savings of 15% represents a potential national energy savings from improved design decisions of over \$350 million for each year's construction. After 10 years of accumulated savings, this represents a potential savings of \$3.5 billion, simply from making existing energy expertise widely available. Much of the methodology to be developed by this research would be applicable to energy decisions for building retrofit and major rehabilitation, leading to potential benefits greater than the levels indicated above.

1.2 DIFFICULTIES IN ACHIEVING ENERGY BENEFITS

Over the past decade, considerable knowledge has been accumulated about how buildings use energy and about techniques for conserving energy in buildings. However, the use of energy knowledge is not widespread. Outside of a small energy research community and a small group of energy experts who together have generated most of the knowledge, the understanding and application of this energy knowledge are meager. The thousands of architects, engineers and owners who design or retrofit some 200,000 commercial buildings each year are making little use of the large body of energy knowledge that exists, and many energy conservation opportunities are missed.

One problem with the existing energy knowledge is that it must be obtained from many lengthy technical reports in different energy subject areas and from numerous building energy case studies. Most designers simply do not have either the time or the resources to internalize the vast amounts of information required to become energy experts, or even to become reasonably energy competent. For example, a book containing excellent energy knowledge may cost only \$40, but if the designer must take 40 hours to absorb that information, the cost of lost revenues may be \$2500 to \$4000.^(a)

It is easier for design engineers to take advantage of many quantitative research results because they have been incorporated into the American Society

(a) The Small Office Building Handbook (Burt et al. 1985), mentioned earlier, is an example of an excellent resource that can take some time to absorb. If anything, the time estimate given above to absorb good energy reference materials is probably underestimated.

of Heating, Refrigeration and Air-Conditioning Engineers Handbook of Fundamentals or into the algorithms of numerous analysis models. This will continue. However, the existing research and knowledge are not readily accessible to architects nor readily available in the important early stages of design.

Also, existing energy analysis tools do not provide the several kinds of help most needed by most designers, especially in the early design stages:

- help in identifying the energy performance objective for a building
- help in identifying good energy strategies to achieve the performance objective
- help in properly designing a strategy that has been selected.

The designer must make all of these decisions for one or more energy strategies before he is able to specify the data inputs for energy analysis tools like DOE2. Also, energy analysis tools almost exclusively emphasize quantitative analysis, and thus ignore a number of important qualitative factors that more advanced tools will be able to manipulate.

1.3 BACKGROUND DISCUSSION

Modern commercial buildings are complex, and the days when one person could competently design in detail all aspects of an entire structure are gone. Today, a team of people is needed, each specializing in some aspect of the building, who collaborate on designing and constructing buildings, even small ones.

Also, the amount of building design calculations, analyses, and tests has increased. Since the 1960s such analyses and calculations have been gradually embedded in computer programs to increase accuracy, to speed design decisions, to improve the quality of design services, and to lower costs.

Designing a building involves decisions in many subject areas, and each subject area usually requires detailed knowledge of one or more disciplines. A striking aspect of building design is the large number of different subject areas involved, and the depth of knowledge required in each subject area to

produce good design solutions. This can include consideration of materials, equipment, construction procedures and sequences, as well as evaluation of alternative solutions.

This situation is exacerbated because buildings are not mass productions of a single design. Building design and construction still are essentially a combination art and craft. There are about 4 million commercial buildings in the country. Each year, about 120,000 new buildings are designed and built, and about 80,000 buildings are retrofit (about 3% and 2% of existing stock, respectively). The design and construction of most of these buildings are unique, even though they often use mass-produced components.

Because there is not enough time, resources, or knowledge available to each designer of each building to examine each decision area in detail, typical building design today involves standardized design assumptions and solutions. Most building designers, especially those involved with the numerous smaller buildings, are generalists who know only a little about each of the subject areas involved. Typically, these generalists make decisions based on handbook references, general rules of thumb, conservative assumptions, and substantial overdesign. Unfortunately, such approaches frequently produce designs that are not very energy efficient and are far from optimum in either economic terms or in the quality of the environment produced.

Given the difficulties in using existing energy knowledge and the limitations of current energy analysis tools, there is a gap in transferring the sizable body of existing energy knowledge to the many designers and owners who determine the energy use of this country's building stock. This gap is unlikely to be filled by the private sector for several compelling reasons.

Energy efficient design is typically a low priority in the design process. The rising energy prices in the second half of the 1970s helped to emphasize energy efficiency. However, in the current market, energy expenses represent only about 30% of total annual operating and maintenance costs. These costs are often not perceived as significant in relationship to builders' concerns about financing, construction costs, physical appearance, zoning, codes, contract management, etc. Due to the resulting relatively low priority

placed on energy efficiency, there is not much of a market for privately developed energy software unless it can be sold at a low cost. This has been the case for energy analysis software, and will be the case for energy design decision software. Since energy design process software will be expensive to develop, it will be difficult for a private software firm to recover its investment, let alone make a profit, due to the small market size.

2.0 CONCLUSIONS AND COST ESTIMATE

The research program will result in a significantly greater understanding of how to incorporate existing energy knowledge into the design decision process. The energy component of design tools that will result from the research can have a significant impact on the design of cost-effective, energy-efficient buildings, without requiring designers to become energy experts.

2.1 DEVELOPMENT COSTS FOR THE ENERGY DESIGN TOOLS

The development of energy design tools is viewed as a collaborative effort among many national research laboratories and private sector companies. This collaboration should extend to the sharing of development costs.

2.2 COST SHARING WITH NON-DOE ORGANIZATIONS

Cooperative agreements with CADD manufacturers can provide CADD software and assistance in developing the interface between the energy components and CADD tools. Artificial Intelligence (AI) computers and expert systems software are available at PNL and other national laboratories to support the research. Also, contacts with universities are being investigated to provide support in developing design strategies and software. Additional sources of non-government funds will also be investigated.

Cooperative research agreements with other federal agencies are also being pursued. For example, the Army Corps of Engineers Construction Engineering Research Laboratory is conducting research on comprehensive design tools for military buildings.

2.3 DOE RESEARCH COSTS

The program to research the design process and develop the entire comprehensive research program is estimated to cost 15 million dollars over 9 years.

PART II. BACKGROUND SURVEYS FOR PHASE 1 FEASIBILITY PLANNING

In planning the energy design process research program several background surveys of the relevant subject areas were needed. This part begins with those surveys (Sections 3.0 through 7.0). The surveys of R&D areas discussed here include:

- knowledge-based systems development (Section 3.0)
- current work on building design process models and tools (Section 4.0)
- computer-aided design and drafting (CADD) development (Section 5.0)
- energy research programs (Section 6.0)
- related data base development (Section 7.0)

These surveys are only intended to determine general status and trends as a guide for developing the research plan and later, for carrying out the research activity itself.

3.0 SURVEY OF KNOWLEDGE-BASED SYSTEMS

Knowledge-based systems (or expert systems) are powerful tools for structuring, documenting and distributing energy-related, design process research. "Expert systems" are so named because they permit storage and use of knowledge of one or more experts. The term "knowledge-based systems" is broader and refers to systems that use input from experts, plus knowledge available from manuals, standards, data bases, etc. The term "expert systems" is often loosely applied to both systems. The use of expert systems has been the subject of increased technical and lay attention in the past few years.

By using knowledge-based systems, experts in a particular subject area (e.g., HVAC systems, daylighting, thermal mass, lighting design, lighting controls, etc) can define once in detail the factors involved in energy decisions. Their expertise can then be embedded into computer software, which can help generalists solve similar problems. Today, the use of knowledge-based systems as energy decision support tools has the potential to improve building design decisions just as conventional computer programs have improved building designers' calculation and analysis capabilities.

To use knowledge-based systems, energy decisions are structured as logical relationships (such as rules, hierarchical relationships, and heuristic processes). This structuring has advantages: the logical relationships can be easily modified and refined; one does not need to understand or solve the entire problem area in order to begin; the systems can be made "transparent" to document the decision steps taken; and they can be made to fail "gracefully" when the limits of stored knowledge are approached. In addition, the systems can address the qualitative factors that affect design decisions as well as the quantitative factors that are addressed by traditional, calculation-oriented, software packages.

In the most general sense, expert systems may be thought of as a computerized problem-solving methodology. Expert systems are recognized as a powerful tool to apply to the classes of problems listed in Table 3.1. The two classes of problems most germane to this research program are prediction and design.

TABLE 3.1. Areas of Expert System Applications^(a)

<u>Category</u>	<u>Problem Addressed</u>
Interpretation	Inferring situation descriptions from sensor data
Prediction	Inferring likely consequences of given situations
Diagnosis	Inferring system malfunctions from objectives
Design	Configuring objects under constraints
Planning	Designing actions
Monitoring	Comparing observations to plan vulnerability
Debugging	Prescribing remedies for malfunctions
Repair	Executing a plan to administer a prescribed remedy
Instruction	Diagnosing, debugging, and repairing student behavior
Control	Interpreting, predicting, repairing, and monitoring system behaviors

(a) Lenat 1983, p. 14.

A characteristic of each of these problem domains is that knowledge is required to solve the problem. Solving a problem based on knowledge means using first principles and associated problem-solving skills when information is incomplete or incorrect. Knowledge is defined by Hayes-Roth as composed of facts, beliefs, and heuristics (Lenat 1983). Heuristics are rules of thumb which an expert uses to identify, define, and/or resolve a problem. Heuristic knowledge uses educated guesses based on familiarity with the problem domain rather than a set of algorithms.

Knowledge is just one characteristic of expert systems; other characteristics include expertise, symbolic reasoning, depth, and self-knowledge (Waterman 1986). Expertise is the ability to solve a problem correctly and efficiently in a defined domain. Symbolic reasoning is the ability to abstract from what we already know and apply this to the problem. For example, in most domains, experts do not reduce a problem to a set of mathematical equations. Instead, they use symbolic reasoning to reformulate the problem into a more familiar representation or analogy. Depth implies concentration on a narrow problem

domain that requires considerable skill to resolve. Self-knowledge is knowledge about the system's own reasoning process, and loosely defined this includes the system's ability to explain, or document, what data and inferences were used to make a decision.

3.1 SOFTWARE PACKAGES FOR DEVELOPING KNOWLEDGE-BASED SYSTEMS

The variety of software packages for developing expert systems range from specialized programming languages to complete expert system "shells" to be "filled" with domain-specific knowledge. In general, more features make it easier to develop an expert system. However, additional features can bring along constraints, which make it difficult to describe certain domains. The user must select the best tool for the problem at hand.

In this rapidly developing field, major software is announced almost monthly (Waterman 1986, Harmon and King 1985). There is active research into how experts solve problems, how to embed this knowledge into software, and how to process this knowledge to solve problems. The current research project will monitor developments in this field and take advantage of relevant advances.

3.2 CONSTRUCTING A KNOWLEDGE-BASED SYSTEM

Frederick Hayes-Roth has succinctly described the five major steps for constructing a knowledge-based system (Lenat 1983, p. 24):

1. identifying--determining problem characteristics
2. conceptualizing--finding concepts to represent knowledge
3. formalizing--designing structures to organize knowledge
4. implementing--formulating rules that embody the knowledge
5. testing--validating rules that embody the knowledge.

Identifying is critical to success of an expert system. The problem must be definable and have a reasonable scope, and the people and resources to solve the problem must be determined. Conceptualizing is equally important: here a formal structure is found for representing the knowledge and solving the problem, and an indication is given by a knowledge engineer of whether the problem is best solved by an expert system. In formalizing, the concepts and process conceptualized are restructured into a format that fits the logic of the expert

system shell. Implementing involves restructuring and actually coding of the software shell. During testing, the expert system is evaluated.

Expert systems tend to evolve. When programming with traditional languages, the programmer follows the above sequential steps once. For expert systems, the steps are iterative. Additional expertise can be added as the system develops.

First, a prototype is developed to gain insights into the knowledge area and the problems which will be encountered. This prototype is frequently discarded before the research system is developed by combining many prototypes into a formalized expert system. The last stage is to develop the commercial system. Relatively few expert system development projects become commercial products because most systems are designed for specialized in-house use. Table 3.2 outlines the characteristics of expert systems in each of these stages.

3.3 APPLYING KNOWLEDGE-BASED SYSTEMS TO THE BUILDING DESIGN PROCESS

A computerized approach to designing buildings requires the ability to address prediction and design, good domains for applying expert systems. Predictive systems must be able to identify a number of options and evaluate the consequences. The predictions are typically based upon a model with parametric inputs. Design differs from prediction in that it is more qualitative; the solutions or goals sought are based upon constraints that typically include physical layout and cost.

A conceptual framework for the design process research is outlined in Section 9.0 and uses an expert system as the research progresses. A detailed discussion of the relationship between the design process and expert system tools is provided in Appendix A. The appendix also defines the capabilities of the expert system software that are required to develop the design tool.

TABLE 3.2. Evolution of Expert Systems

<u>Stage of System</u>	<u>Nature of Prototype(s)</u>	<u>Characteristics</u>
Experimental	Demonstration	Small programs with less than 100 rules, taking 1-3 months to develop. Serve as demonstrations of concept or as test approaches. Systems are unusable because they handle only a portion of problem, are inefficiently designed, and are untested.
Research	Research	Medium sized programs with 200-500 rules taking 1-2 years to develop. Work reasonably well on a number of cases but cannot handle the full problem domain.
	Field	Medium to large programs with 500-1000 rules, taking 2-3 years to develop. Tested on real problems and work reasonably well. Include a good user interface.
	Production	Large systems with 500-1500 rules, taking 2-4 years to develop. Extensive field testing and efficient program implementation.
Commercial	Commercial	Accurate advice for range of problems provided in a polished and streamlined format.

4.0 SURVEY OF BUILDING DESIGN PROCESS MODELS AND TODLS

This survey first examined recent publications on design processes and decisions related to energy. Second, the survey identified current work on computer-based models and tools for exploring decision processes during building design work.

4.1 DESCRIPTIONS OF ENERGY DECISION PROCESSES

A number of research efforts that have focused primarily on how buildings use energy have also developed descriptions of the design decision process. The earliest of these was Predesign Energy Analysis (Hart, Kurtz, and Whidden 1980). More recent efforts include the Small Office Building Handbook (Burt et al. 1985) and the similar Cutting Energy Costs in Multifamily Housing: Practical Case Studies for the Builders and Developer.^(a) All of these were developed for DOE. Along similar lines, the Tennessee Valley Authority (TVA) has been developing a series of design manuals entitled Energy Design Guidelines. These manuals discuss specific building types. The first manual, Schools, is available, and several more are in progress. These manuals are intended to assist architects and engineers to incorporate energy efficiency into their standard designs. These publications, although excellent starting points, all had to simplify complex decision processes to fit a written format. An example is the Small Office Building Handbook (Burt et al. 1985), where the simplification is often elegant. However, if the process had been described using an interactive computer, the detail of the decision processes could have been retained along with the simplicity for the user. With this caveat in mind, these efforts make a valuable resource for this proposed research effort, which will examine energy decision processes using the computer to manipulate the complex data.

(a) National Association of Homebuilders, in press.

4.2 CURRENT DESIGN PROCESS RESEARCH USING COMPUTER-BASED MODELS AND TOOLS

The buildings research community has shown widespread interest in developing computer models and tools for design work. Recent hardware and software developments make the prospects of developing such equipment increasingly feasible and cost effective, which has led to considerable research activity. Recent projects range from computer-aided design to expert system development.

Related projects are now under way in universities, government research laboratories, and some private sector firms. The domains of these current efforts range from very narrow models for specific building material components or subsystems to broad university research efforts to develop "generative" design tools for whole-building design. Most current R&D efforts are preliminary and constrained by limited funding. These efforts are summarized below and highlighted in Table 4.1. Further details are contained in Appendix B.

4.2.1 University Research Efforts

Architectural research projects at universities are exploring general design process research, computer-aided design, and knowledge-based systems. University engineering departments are developing expert systems for structural systems of buildings and for some subsystems and components. Few of the university research efforts are related to energy. Rather, the research focuses on general design decisions and computer-aided design. While this research is valuable, much of it tends to be long-range and theoretical.

4.2.2 Government Research Efforts

Government research laboratories are exploring the use of artificial intelligence as a tool for improving building design and construction decisions. Several government organizations are conducting or planning to conduct research or development in expert systems applied to building design. Like the university efforts, only a few of these efforts focus on energy.

4.2.3 Private Sector Efforts

Several private sector firms are developing expert system tools associated with their products, as aids to their sales staff. Two private sector efforts of note are under way. First, CADD systems are being developed or enhanced by

TABLE 4.1. Related Research Activities

Universities	Activities
Carnegie Mellon University	Building Site Location Model HVAC Diagnosis Model Pattern Model for Shadyside community Structural Design Models
University of Victoria, B.C.	Design Pattern Language Model
Massachusetts Institute of Technology	Developed Expert System Shells Component design Cafeteria Planning Project Several structural models Bridge and highway maintenance Land use management Nondestructive testing
State University of New York at Buffalo	Residential Design Planning Model Residential Data Base Model Knowledge Acquisition Model (planned) Roof Aperture Daylight Model (planned, with LBL)
University of Illinois	Long range conceptual design process research
Rensselaer Polytechnic Institute	Energy Graphics computerization
Government Organizations	Activities
National Bureau of Standards, (NBS)	Concrete selection expert system Infiltration expert system (planned) Standards analysis/synthesis model Standards activities related to CADD
Construction Engineering Research Laboratory (CERL)	Energy Conscious Planning Program Activity Based Checking Systems Intelligent Aid for Management of MCA Computer Aided Engineering and Architectural Design System
Lawrence Berkeley Laboratory (LBL)	Envelope/daylighting advanced design tool (planned) Roof aperture daylighting model, with SUNY Buffalo (planned)
Pacific Northwest Laboratory (PNL)	Artificial Intelligence (AI) Laboratory Whole-building energy design model (planned) Building end-use metering data equipment diagnosis (under development)

the dozen or so vendors who dominate this market. Second, several HVAC equipment and controls manufacturers are actively developing expert and knowledge-based systems. For example, both Honeywell and Johnson Controls are developing expert systems for real-time controls, diagnostics, and training tools. Such private sector efforts tend to be closely held until a product is marketed. Some university efforts receive private sector funding (e.g., SUNY at Buffalo), or spinoff from the university into the private sector, as happened with some second generation computer-aided design products.

4.3 RESULTS OF THE SURVEY

Based upon the current general level of activity, several knowledge-based systems for incorporating energy decisions into portions of the building design process will be developed over the next several years. The first systems developed may be for domains with narrow scopes (specific building material components or subsystems) because these are the easiest problems to solve. Without planning and coordination, these first systems will be incompatible with each other, given the diverse tools and methods being used by independent researchers.

Several forums are arising for sharing buildings-related work on design process research, expert systems, and related areas. A forum for sharing university-based architectural research in computer-aided design is the Association for Computer-Aided Design in Architecture (ACADIA). In addition, the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) has a technical committee on Cadd Systems standards. Symposia on government and university research on artificial intelligence applied to buildings have been hosted by the National Bureau of Standards for the past two years. Also, discussions of applications of artificial intelligence and expert systems to buildings are beginning to appear at buildings-related conferences.^(a) ASHRAE formed a group for sharing engineering research issues related to

(a) Examples include the seminar on Energy Design Tools at the AIA Research and Design 85 Conference and the seminar on Emerging Architecture at the "Energy and Integrated Approach" conference in 1986, sponsored by TVA.

knowledge-based systems, the Knowledge-Based Systems subcommittee of Technical Committee 1.5 on Computer Applications, which first met in June 1986. Also, new journals have begun publication for dissemination and exchange of information on expert systems. Two such journals are Expert Systems, published by Learned Information and EXPERT, published by IEEE.

The combination of forums, conferences and journals indicate that there is an ongoing exchange of information in the buildings research community. The traditional areas of coordination between the government laboratories and universities have also started to emerge. A major gap in coordination is among the government laboratories. As national laboratory work in knowledge-based systems increases, active participation in meetings and journals should be pursued.

5.0 SURVEY OF COMPUTER-AIDED DESIGN AND DRAFTING DEVELOPMENT

The building design and construction process is changing rapidly due to the use of CADD equipment. Architects are using computers in the preliminary and detailed design phases to replace traditional drafting, using engineers for structural and thermal analysis of designs, and using builders during the construction phase to manage materials, costs, and schedules. The labor and time savings associated with computers are rapidly making them a necessity, rather than a luxury, for architect/engineers. Computers will soon be integrated into all design phases through links among related data bases for architectural design, engineering analysis, and construction management.

5.1 CADD INTEGRATED DESIGN

CADD is the primary computer tool that will be used for integrated building design. The larger systems are typically bundled as both software and hardware since the hardware plays an important component in the quality, speed, and ease of use of the overall system. The lowest cost systems, designed for microcomputers, are capable of producing quality architectural and engineering drawings. Both large and small systems provide drafting capabilities coordinated with software packages for engineering analysis (see Appendix C for more details).

The current use of CADD systems is similar to that of energy design and analysis tools: both concentrate on providing assistance to the designer once the building design has already been at least partially developed. CADD systems are now used predominantly as sophisticated drafting tools. However, two trends are under way to exploit the design component of CADD.

One trend is the capability of the designer to conduct three-dimensional solid modeling at a graphics terminal. As this trend continues, the nature of the schematic design process will evolve, and concepts for building design will be explored in three dimensional perspective on a computer screen rather than in two dimensions on a piece of paper.

The second trend is the use of integrated CADD systems for building conceptualization, site layout, building design, mechanical analysis, thermal

analysis, and construction specifications. Integrated systems share a common data base so that information entered or modified in one design element is available to all the other elements.

5.2 ROLE OF CADD IN DESIGN PROCESS RESEARCH

This research program can make use of CADD internal data bases and graphics. The data bases contain information on the building's geometry, materials, costs, and thermal characteristics needed to assess conservation strategies. Universal integration with CADD systems will be difficult unless systems are standardized.

CADD system graphics will be used to present the results of energy design decisions. Rather than have the energy design tool output advice to a terminal or printer, the information would enter the CADD data base where appropriate. The graphics of the CADD systems are an effective format for transferring information, and by integrating the energy information with a CADD system the need to develop a separate graphics package is eliminated.

5.3 RESULTS OF THE SURVEY

This project should link into widely used CADD systems, but this is difficult without a set of standards for CADD. Second, a three-dimensional, object-oriented rather than line-oriented structure is preferred because energy decisions tend to be made about objects and sets of objects, not about lines and sets of lines. However, such an approach takes more processing time and data storage. Two systems were identified that currently use three-dimensional object oriented data bases; these are systems by McAuto and GMWC (See Appendix C). Other systems will adopt this structure as computer processing power declines further in cost.

6.0 SURVEY OF ENERGY RESEARCH PROGRAMS

This research will find better ways to use existing data, such as that produced in the government-sponsored research that is surveyed here. Related research was and is being conducted by various utility groups. Federal programs are summarized below.

Component-specific energy research, and the development of energy and economic analysis procedures at the national laboratories are important inputs to this design process research. Component-specific energy research includes lighting, windows, and daylighting systems under investigation at Lawrence Berkeley Laboratory (LBL) and HVAC equipment work at Brookhaven National Laboratory (BNL) and Oak Ridge National Laboratory (ORNL). Inputs to this research may include design manuals under development at the Tennessee Valley Authority (TVA), data presentation research at the Solar Energy Research Institute (SERI), and computer integration work and standards compliance checking programs under development at the National Bureau of Standards. In addition to the component energy research, whole building energy research may also provide input. Appendix D contains further descriptions of such efforts.

6.1 BUILDING SYSTEMS INTEGRATION PROGRAM RESEARCH

The Building Systems Integration Program (BSIP) at PNL is a major resource for design process research. The resources provided by BSIP include the building specific studies (one component of the ongoing design process research element), the whole-building targets project, and the end-use energy consumption data base project. The BSIP structure is shown in Figure 6.1.

The focus of the building specific studies is to develop design guidance for cost-effective design strategies. Individual manuals are prepared for each commercial building type. The design guidance is based upon extensive energy and economic simulations as well as upon the professional judgment and analysis of architects, engineers, and organizations involved in the construction of the specific building type. The design manual for the small office building has

FIGURE 6.1. BSIP Structure

been completed, the mid- and high-rise apartment building manual is almost complete, and research and analysis for the retail store manual will be started this year.

6.1.2 Standards and Targets Research

Development of commercial building standards, along with work on whole-building energy targets, will create extensive energy simulations and cost analyses of energy conservation strategies for commercial buildings. Much of this research base has already been synthesized into effective design strategies. The whole-building targets program will accomplish extensive economic and energy analyses in the course of developing voluntary energy targets for commercial buildings.

6.1.3 Metering of End-Use Data

The end-use energy consumption data base project involves end-use energy metering of commercial buildings and analysis of end-use metered data to derive information on cause and effect relationships for building energy use. Closely

related to this program is the extensive commercial building end-use metering program being conducted by Bonneville Power Administration.

6.2 RESULTS OF THE SURVEY

A number of the existing energy use research results have been flagged, as well as a number of ongoing programs. These efforts will provide valuable input materials to this design process research.

7.0 SURVEY OF RELATED DATA BASES

Many energy decisions, while based on heuristic knowledge, require quantitative calculations and data to accurately assess building systems performance, thermal performance, and design costs. Consequently, data bases on economic, energy, and thermal properties are an important input to the energy design model. Since construction material selection and interior design are important components of the design process, information on other material characteristics (sound characteristics, fire ratings, standard sizes, etc.) and appearance is also desirable. Available data bases are summarized below and more detail is presented in Appendix E.

Economic data bases required include 1) construction materials and labor costs, and 2) energy costs and escalation rates. Commercially available procedures and data bases are available for calculating construction costs at different levels of detail. Two major sources are Means and McGraw-Hill Cost Information Systems. These companies have computerized data bases and cost estimating procedures. Other data bases include ASHRAE's data base of operation and maintenance costs for HVAC systems, and cost estimates completed for DOE research projects.

7.1 SIMULATION DATA BASES

Energy-use data bases include 1) simulation data bases, and 2) empirical measurements. A number of simulation data bases have been created under the BSIP, such as:

- building specific studies for small office and multi-family buildings
- simulations of the PNL/ASHRAE SP41 test buildings
- and simulations for whole building targets (to be created).

The results from the simulations can be used to quickly estimate the impacts of design strategies for a limited set of designs. In addition, LBL has completed parametric analyses using DOE 2.1 to develop regression equations to estimate the impacts of daylighting and lighting design strategies. Increasing use of simulation tools for parametric analyses indicates that additional data bases will be available in the future.

7.2 EMPIRICAL DATA BASES

Data bases of empirical measurements of energy use and building characteristics for commercial buildings include:

- End-Use Load and Conservation Assessment Project (BPA)
- Commercial Buildings End-Use Data Base Development Project (PNL)
- Building Energy-Use Compilation and Analysis (LBL)
- Passive Solar Commercial Buildings Program (DOE).

Analysis of these data will provide insights into the design of commercial buildings based on statistically derived relationships between energy use and physical building characteristics.

7.3 RESULTS OF THE SURVEY

A number of data bases were identified that are potentially useful to this research effort, and the number of data bases is expected to continue to grow, providing a wealth of information to be integrated into the energy design process.

PART III. ANALYSES FOR PHASE 1 FEASIBILITY PLANNING

In Part III we review results of analyses that helped to structure the research into the energy design process. These analyses, together with the background surveys discussed in Part II, form the major background work that led up to the proposed comprehensive plan presented in Part IV. The analyses involved:

- defining application areas for energy-related, design process research and tools (Section 8.0)
- developing conceptual models for structuring the design process research, including a structure for timing and sequence of energy decisions during the design process and a prototype knowledge-based system to test concepts (Section 9.0).

8.0 DEFINING APPLICATION AREAS

The following definition of application areas establishes a framework for research efforts on the energy design process and for setting priorities. The numerous decision areas for building design, construction and operation can be grouped into several major application areas such as:

- new building design and construction
- retrofit and major rehabilitation design and construction
- building operations and maintenance

Figure 8.1 presents a diagram of major application areas. Within each of these application areas, many distinct technical issues must be decided.

Ultimately, one can envision a system to provide complete energy decision assistance for facilities management. Such systems would provide continuity of decision making and tracking of physical changes to a building over its entire life span from concept through its ultimate demolition.

One additional application area related to this research is energy and economic analysis activities. Interim products that can be developed are discussed at the end of Section 8.0. However, because this research focuses on the design and construction processes, building operations will not be covered in this report. Of course, buildings are designed with operations in mind, and the effect that considering operations has on a design will be addressed.^(a)

(a) Also, for building operations and control, there is considerable activity in the development of "intelligent" or "smart" buildings and "smart" building subsystems, which operate using a knowledge base to exercise control and which can "learn" from experience in the sense of anticipating desired performance based upon earlier patterns observed. For example, the National Electrical Manufacturers Association (NEMA) has formed a task force to examine smart buildings potentials, and the AIA has held a symposium. It is also likely that building control manufacturers will adopt knowledge-based systems technologies to embed increasing amount of "expertise" into their control devices. As mentioned earlier, several controls manufacturers are active in this area. In some sense this is an expansion of existing control systems both for individual systems and for overall building energy management and control (EMCS) systems.

FIGURE 8.1. Application Areas

8.1 APPLICATIONS TO NEW BUILDINGS

As Figure 8.1 shows, the major applications of this work to new buildings are in programming, design, construction, and commissioning. Each area is discussed below.

8.1.1 Computer Programming Applications (New Buildings)

Energy knowledge on building design, embedded in programming, will form the basis for design decisions (see also Section 9.0 and Appendix F). Thus, building programming is an important application area for research on the design process and energy use of buildings. Although current building programming methodologies do address energy issues, a review of the literature revealed gaps in the information, which in any case is not sufficiently focused and prioritized for making energy decisions. Methods and tools are needed to help building owners, planners and designers develop better and more focused programs relating to energy. Such methods and tools could be incorporated into current programming procedures for building designing to improve the information on which energy-related design decisions are based.

8.1.2 New Building Design Applications

New building design is the major application area for design process research efforts. Much of the proposed research for new buildings would also apply to building retrofit and to major rehabilitation; therefore, the new building applications are discussed in some detail.

For new building design, applications include 1) individual building subsystems or components, and 2) energy interactions among major building subsystems. The relationship of these applications are shown in Figure 8.2 and will be discussed here briefly.

Each building subsystem or component can be considered a distinct research area. For new commercial buildings, the highest priority areas for energy research are:

- HVAC (system selection, design, controls, etc.)
- Lighting (system selection, design, controls, etc.)
- Envelope^(a) (fenestration, opaque elements, mass, etc.)

In addition, for certain commercial buildings the following two application areas are of high priority:

(a) While it is not indicated here, envelope analyses should also be separated into 1) system selection, and 2) detailed system design.

FIGURE 8.2. Conceptual Whole-Building Model¹

- Daylighting^(a) (systems, controls, envelope impacts, etc.)
- Water Heating^(b) (systems, O&M, losses, etc.)

(a) Especially for such building types or functions as offices, schools, and storage.
 (b) Especially for hotels, but also for apartments, hospitals, nursing homes, etc.

Energy decision research can be carried out separately for subsets of these application areas. A detailed list of application areas is presented in Part IV of this report.

Improving decisions in each of these areas can substantially improve the energy performance of these components. For example, providing assistance for decision making about HVAC selection has a high potential impact on energy conservation.^(a) Decision making issues are rarely simply a question of energy or economic optimization; rather, it is the balancing of a number of qualitative and quantitative factors to achieve a solution.

A conceptual framework for energy research on building subsystems is presented in Section 9.0. This includes a list of decision areas and the factors to include in each area. Other detailed frameworks for building subsystems and components are provided by various cost estimating formats (e.g., the Construction Specification Institute (CSI) format).

Because each building subsystem and material component has a narrow decision domain, tackling each part independently represents a good application area for energy decision research, which is supported by knowledge-based tools. Indeed, knowledge-based systems to assist in making energy decisions about specific building parts are being proposed or developed. Two examples are 1) an infiltration analysis system at the National Bureau of Standards, and 2) a system to assist in decision making about roof apertures, including their daylighting contributions, at Lawrence Berkeley Laboratory (also see Appendix B).

A few expert systems for specific building components and subsystems are likely to soon be developed by manufacturers in the same way that manufacturers have in the past developed calculation tools for analysis of specific products. These expert systems will assist with the design of specific building

(a) See, for example, the result of the 10 test buildings used in ASHRAE Special Project (SP) 41, each with multiple alternate systems. The changes in HVAC system often resulted in over 30% change in total building energy use (Reilly et al. 1983).

parts, and they may, or may not, contain information about energy. Costs to generate expert systems must decline substantially before their development by product manufacturers becomes widespread.

8.1.3 Whole-Building Interactions

A broader domain for design process research is at the whole building level where the research applies to energy and cost interactions among major building subsystems, as shown in Figure 8.2. This domain is so broad it is difficult to address, and yet it is the most important application area from the perspective of the return on investment. Such research impacts the early stages of the design process, when tradeoffs among major alternatives and subsystems can still be made. Such tradeoffs must consider the interactions of the systems. For example, decisions about the lighting system will impact both envelope and HVAC systems.

Energy conservation and cost reduction benefits are significant at this level. By considering how building subsystems interact, the designer can take advantage of energy and cost tradeoffs among the major subsystems involved.^(a) The energy and economic impacts of these decisions can be major ones, making a strong case for focusing on building subsystem interactions as a primary domain for this research. The conceptual framework for building subsystem interactions is described in Section 9.0.

8.1.4 Applications to Building Construction

Design process research into the construction process would focus on the energy impacts of change orders and quality control procedures. This research would lead to knowledge-based systems that assess change orders and monitor quality control during construction.

(a) Usually improvements in the energy efficiency of one building system will raise the cost of that building system. However, the improvements often offer the possibility of reducing costs of another major building system, as well as reducing energy use in both systems. The Small Office Building Handbook (Burt et al. 1985) includes a number of examples that demonstrate these principles extremely well.

8.1.5 Applications to Commissioning

Research in this area would lead to knowledge-based systems for checking and diagnosing all of the factors involved in building turnover from contractor to owner.

8.2 APPLICATIONS TO EXISTING BUILDINGS

From a design process perspective, retrofit and rehabilitation are subsets of the new building design process. Available design opportunities and solutions are significantly constrained by the existing building and its installed systems. Changes in a building siting or form are expensive and seldom done. Likewise, major changes to the building thermal zoning and envelope are usually not considered since they are also expensive relative to their benefits. These constraints make the retrofit domain a subset of new building design.

Yet, building retrofit analysis and design procedures differ substantially from new building design. In retrofit analysis a detailed understanding of the existing building is necessary to determine retrofit opportunities. Often, the existing building contains peculiarities or unexpected features or operations. Understanding how an existing building works often requires considerable skill and expertise. These factors make developing generalized procedures for retrofit design difficult.

8.2.1 Retrofit Audit

Two steps unique to retrofitting a building are auditing the building and matching utility bills with audit results. Design decision methods and tools can assist building owners and designers in these steps. In performing an audit, an expert knows which building features and operations an audit should emphasize. Numerous audits have collected data on features with little energy impact and have ignored important energy features. Clearly, a good retrofit design process tool would identify when an audit needs to be done and what building features are important.

Comparing utility bills to analysis tool estimates of energy consumption can be a difficult and demanding exercise even for experts. Surprises exist in building operations, even in professionally managed buildings. If the building

is not operating as it should, the differences in energy use can be substantial. Knowledge of actual conditions can redirect the focus of an audit to the energy problem and possible solutions.

After the above two steps are completed, the design process is similar to that for new buildings: identify energy opportunities, select strategies, design, construct and turnover. However, the energy and economic priorities differ significantly because of the constraints of the existing building.

Building retrofit measures can be grouped according to three objectives: 1) improving operations and maintenance; 2) retrofitting some building features, and 3) doing major rehabilitation of the building. Each objective differs both in the emphasis and in the extent of changes intended to be made to the building.

8.2.2 Retrofit Design Process

A number of good, detailed descriptions for conducting energy audits and retrofits (SMACNA, etc.) already exist. There are also a number of sources of retrofit energy conservation opportunities for most commercial buildings (ASHRAE Standard 100 series). However, none of these sources give sufficient information about which measures to use when. Thus, the development and use of knowledge-based systems can assist in the difficult tasks of:

- diagnosing building characteristics and operation
- correlating actual energy use to analysis tool estimates
- identifying the most cost effective opportunities for retrofit
- selecting strategies
- properly applying the selected strategies
- assessing impacts of implementing the measures
- assessing impacts of turnover procedures and decisions.

Even with the differences in the design process and the constraints imposed by the existing structure, much of the material and procedures that would be developed for energy decisions for the new building design situation is applicable to retrofit situations.

8.2.3 Major Building Rehabilitation

Major rehabilitation, done to an existing building, constitutes such major changes to the existing facility that the design processes are much more like new building design than retrofit. For example, both building operations and physical features can be radically altered. The only changes not likely to be made are in building orientation, siting, and structure. As an application area for design process research, major rehabilitation is a subset of a new building design except for these items.

8.3 APPLICATIONS TO OPERATION AND MAINTENANCE ACTIVITIES

Assessing changes to building operation and maintenance has similarities to the domains of a number of existing knowledge-based systems that perform diagnosis. Potential applications are for monitoring, diagnosis, and control. A major source of detailed knowledge of building operations is likely to come from extensive projects such as the Bonneville Power Administration's End-Use Load and Conservation Assessment Program (ELCAP).

8.4 APPLICATION TO ENERGY AND ECONOMIC ANALYSIS ACTIVITIES

Several design process research applications could significantly improve existing energy and economic analysis activities. For example, specialized energy design decision methods and related knowledge-based systems tools could reduce the expertise required by existing energy and economic analysis tools.^(a) The research plan proposes incorporation of interim research products into existing analysis tools to make such interim results available. Some example applications are listed below:

- Create diagnostics to help develop inputs for energy analysis tools. Some data can be generated directly from CADD data bases, while other input data can be generated from knowledge-based system rules. For example, inputs could be checked for completeness and

(a) For example, knowledgeable DOE-2 users estimate that it takes about two months full time effort to become competent (not expert) in the use of DOE-2, because of its complexity.

inputs from various sources could be checked for consistency and for key input values that can strongly "spike" the energy results in unexpected ways.

- Create diagnostics to analyze the output of energy analysis tools and estimate if the results are "reasonable;" compare output results with typical solutions; examine the output to identify areas for further energy cost reductions; and identify strategies (and input value changes) for achieving such reductions.
- Create diagnostics for economic analysis of buildings to identify actions based on the analysis results.
- Perform real-time interactive energy modeling to simulate a building's energy performance, with a graphical display showing energy operation. The system would examine and make changes in any of the building's systems, and view the change in energy performance interactively. This would require some substantial restructuring of the components of current energy analysis tools and the sequence of calculations.

9.0 DEVELOPMENT OF ENERGY DECISION MODELS

In this section, two major decision models are described: 1) a whole-building energy decision model, and 2) a building-subsystem energy decision model. Note that these energy models will need to be integrated with the commercial tools for building design. The whole-building model focuses on interactions among building subsystems shown in Figure 8.2 in the previous section. The subsystem model provides a series of decision models for selected subsystems. Although the research framework addresses energy decisions throughout all phases of new building design and construction, the first priorities for research are key energy decisions occurring in the early design phases.

9.1 ROLE OF BUILDING PROGRAMMING IN BUILDING DESIGN PROCESSES

The research approach emphasizes that energy decisions are important to each phase of the building design process, from the identification of a need through its realization and use. Figure 9.1 summarizes typical phases of a design project and their relationships to building programming activities. As the figure illustrates, building programming is a goal setting, information gathering, analysis, and communication process that provides the basis for decision making at each stage of the design process. According to the recent AIA publication on building programming (Palmer 1981):

"A program is information the designer can use. It is an organized collection of the specific information about the client's requirements which the architect needs in order to design a particular facility. This encompasses not only the expressed requirements of the client, but all of the human, physical and external factors which will influence the design. Programming is an information-processing process of identifying and defining the design needs of a facility and communicating the requirements of the client to the designer."

Thus, program results enable design decisions to be based upon factual evidence rather than on assumptions, prejudices or stock experience.

Table 9.1 shows the three building programs that are most important for energy decisions: master, facility and component programs. As the table

FIGURE 9.1. The Design Phases

TABLE 9.1. Usefulness of Programming Information to Design Decisions

Selected Design Decisions	Programming		
	Master	Facility	Component
Site Selection	0 ^(a)	x ^(b)	
Feasibility	0	x	
Project Budget/Schedule	0	0	0
Configuration	x	0	x
Orientation	0	x	
Site Plan	0	0	
Envelope Design		0	x
Floor Plan Layout		0	0
Space Layout		0	x
Circulation Design		0	x
Operations Design		0	0
Design Energy Budget	x	0	x
Engineering Systems Selection	x	0	
Engineering Systems Design			0
Nonengineering Systems Selection	x	0	
Nonengineering Systems Design			0
Lighting Systems Selection	x	0	
Lighting Systems Design			0
Structural Design		0	x
Support Service Design		x	0
Fenestration		x	0
Designed Energy Performance		0	x
Landscape Design		0	0
Code Compliance	x	0	0
Economic Analysis	x	0	x
Solar System Sizing		x	0
Construction Materials Selection		0	0
Exterior Finishes		x	0
Interior Finishes		x	0
Equipment Furnishing Selection		0	x

(a) 0 = primary usefulness of information to design decision.

(b) x = secondary usefulness of information to design decision.

indicates, each program provides a basis for different sets of design decisions. There is overlap between the elements handled by each of the program and design phases. Thus, some flexibility is needed in the applying this structure to specific situations. Each program is described briefly below.

9.1.1 Master Program

The master program provides the context for the entire building design project, including overall project design goals, limits, and feasibility. However, for this research a separate decision structure is not proposed for the master program since the key items related to building design energy decisions can be incorporated directly into the facility program.

9.1.2 Facility Program

The facility program will receive the most emphasis in Phase 2 of this research effort. The facility program addresses the key building design decisions and tradeoffs that typically are made during the schematic design phase. While Table 9.1 indicates that energy decisions during the predesign phase are not as important as those made during schematic design, proper pre-design programming cannot be overemphasized as it provides the foundation for the decisions to be made during schematic design.

9.1.3 Component Programs

As indicated in Table 9.1, component programs provide an information basis for making detailed design decisions within each building subsystem, once it is selected. There are multiple component programs involved in a building design, one for each of the subsystems or material components being designed. Phase 2 of this research effort will address only a very limited set of decisions at this level of detail (e.g., HVAC system sizing, etc.). Later phases of the research effort will address building component decisions in detail.

Results from each phase of programming provide a basis (goals, requirements, constraints, etc.) for good decisions for associated design phases. Results of the facility program (predesign) guide energy decisions during schematic design. Likewise, component program results guide energy decisions in the later design phases.

9.1.4 Iterative Design Process

Because the design process is iterative, the building program is often refined during the process (see Figure 9.2). This has implications for developing energy design process models. Building design is both data driven and goal driven. First, building design can be said to be data driven, based upon the analyses and information gathering conducted in programming. However, during design, several (and perhaps many) hypothetical solutions may be generated and evaluated. Some may be discarded, based upon program goals, while others may be developed further. Figure 9.3 shows a typical process. As a result of this process, the goals and information in the building program may change, so the design process can also be said to be goal driven.

Good design decisions depend upon well-defined goals and objectives as well as upon good information about project requirements, constraints and possibilities. At each design phase, programming results provide the basis for design decisions and design integration. This implies that tools used for modeling these design activities need to have inference analysis procedures that are both data driven (forward chaining) and goal driven (backward chaining). (See Appendix A for details and definitions.)

9.1.5 Relationship of Energy Decisions to the Early Design Phases

In general, the earlier that energy decisions can be made, the greater the impact of those decisions on both energy use and cost, and the lower the effort (and cost) of implementing the decisions, as shown in Figure 9.4. The figure shows that energy savings potentials are greater during the schematic design phase than at any other time during building design, and that those savings can be achieved with less effort than later in the process. The schematic design phase is so important because many major decisions that strongly impact energy opportunities are made during this phase. Decisions about siting, orientation, configuration, floor plan layout, envelope design, and the selection of building subsystems (structural, lighting, HVAC, etc) all typically occur during this phase.

Decisions about the selection of each of the building subsystems can profoundly affect the building's ultimate energy performance. For example, recent

FIGURE 9.2. Iterative Nature of Design Process

FIGURE 9.3. Energy Savings

FIGURE 9.4. Effectiveness of Energy Analysis Tools

PNL/ASHRAE SP41 research results (Reilly et al. 1983) indicate that the selection of the HVAC system alone can affect total building energy performance estimates by 30% or more. Also, consideration of energy and cost tradeoffs among the major building systems is a source of significant savings for both energy and first costs. In the proposed research program, the selection of major energy-related subsystems will be included in the Schematic Design phase.

Synthesis is an important characteristic of design activities during schematic design. Ideally, the decisions made are done in a wholistic manner, considering (to the extent that the designer can achieve this) the full range of facility goals, objectives, requirements and constraints. This is a complex

and difficult task, and is often accomplished by developing and evaluating several alternative schemes and then eliminating the less successful solutions.

Unfortunately, virtually no tools are available to assist the designer to make good energy decisions at this time in the design process. Figure 9.5 illustrates why existing energy analysis tools are not easily used during the early design phases. Because existing analysis tools require data that can only be generated after such design decisions are made, there is a limit to how early in the design process they can be used. However, extensive default values permit their use somewhat earlier.

9.1.6 Importance of Building Programming as a Resource for Design Decisions

Three products from building programming are facts (assertions), predictions, and recommendations. Each of these relates to each of the three factors

FIGURE 9.5. Enhanced Programming Products

involved in any energy decision (human, physical, and external factors) as shown in Figure 9.5. An early step in the proposed design process research program will be to use the facts and predictions produced from predesign programming to produce recommendations about energy decisions for schematic design. Normal programming outputs (facts, predictions, and recommendations) in each area are used as inputs to the decision model to identify good energy decisions that are recommendations derived from an enhanced programming process. This same procedure also will be used in the proposed research program to produce recommendations for energy decisions for building subsystems.

9.2 BUILDING DESIGN DECISION MODELS

Two conceptual energy design decision models have been developed in Phase 1 Planning to provide a structure for conducting the Phase 2 research: 1) a whole-building decision model, and 2) a building-subsystem decision model. Each model is structured to use the results of building programming as a major resource in determining energy opportunities and in identifying strategies to attain the opportunities. Also, the energy models must be integrated with the overall whole-building decision model of the commercial software that is being used. Each model is discussed in more detail below.

9.2.1 Whole-Building Decision Model

The whole-building decision model assumes that the owner has already decided that a new building is necessary, that its design is feasible within project constraints, and that a site has been selected. The framework for the whole-building decision model consists of relating the energy decisions to be made during schematic design to the factors to be considered in making those decisions.

The facilities program column in Table 9.1 indicates the breadth of design decisions that can be included in the schematic design phase. Each decision influences the development of a building schematic design, and most of them involve or affect energy use. The decision areas included in the research analyses will be constrained in the early stages of the research, and gradually expanded.

In the model, the basis for the decisions is the information provided from the facility program. The characteristics of these decisions are described in Appendix F. The proposed next phase of research will include developing detailed specification of inputs required for each decision and ranges of possible outputs.

For each of the design decisions addressed above and in Table 9.1, many factors may need to be considered. The decisions made and factors evaluated for each decision form the basic structure for a decision model. Many of the factors influence building design and can impact energy decisions, either directly or indirectly. Table 9.2 lists these factors and places them in three groups: human, physical, and external. The figure indicates, via bullets, the most critical factors for energy decisions.

The factors involved in energy design decisions are both qualitative and quantitative. This is an important aspect of this research effort and of the decision model and is a major departure from historical treatments of energy as primarily quantitative, when qualitative concerns were all but ignored.

The quantitative approach by itself can lead to erroneous design decisions. For example, selecting HVAC systems involves ten major decision criteria: energy use, energy cost, first cost, operation and maintenance costs, flexibility, noise, controllability, thermal comfort levels provided, floor space required for equipment and shafts, and visual impacts. Of these ten factors, only the first three are directly quantitative in traditional energy considerations.

The whole-building decision model is shown in Figure 9.6. This model contains a full set of decision/factor relationships and identifies the specific factors to be considered for each decision. The open circles in the figure indicate that a factor is important but will not be addressed in the Phase 2 research effort for the facility design problem. Solid circles indicate factors to be addressed in Phase 2. Once the basic decision model is developed in Phase 2, using the factors indicated by filled in circles, then the factors indicated by the open circles will be added to the decision model in Phase 3 of the research. The factors are considered in phases to simplify the model development efforts.

TABLE 9.2. Factors that Influence Facility Design

Human Factors	Physical Factors	External Factors
Activities ^(a)	Location	Legal Restrictions ^(a) (codes/standards, regulations)
Behavior	- Region	- Building
Objectives/Goals ^(a)	- Locality	- Land Use
Organization ^(a)	- Community	- Systems
- Hierarchy	- Vicinity	- Energy
- Groups	Site Conditions ^(a)	- Environment
- Positions	Building/Facility ^(a)	- Materials
- Classifications	Envelope ^(a)	- Safety
- Leadership	Structure ^(a)	- Solar Access
Characteristics ^(a) (demographic)	Systems ^(a)	Topography
Social Forces	- Engineering	Climate ^(a)
Political Forces	- Communications	Ecology
Interactions ^(a)	- Lighting	Resource Availability
- Communication	- Security	Energy Supplies/ ^(a) Prices
- Relationships	Space ^(a)	- Conventional
- Transfer of Material, Etc.	- Types	- Solar
Policies/Codes ^(a)	- Dimensions	- Alternatives
	- Relationships	Economy
Attitudes/Values	Equipment/Furnishings ^(a)	
Customs/Beliefs	Materials/Finishes ^(a)	
Perceptions	Support Services	Financing
Preferences ^(a)	- Storage	Time ^(a)
Qualities	- Parking	- Schedule
- Comfort ^(a)	- Access	- Deadlines
- Productivity	- Waste Removal	- Operations
- Efficiency	- Utilities (water, sewage, telephone)	Cost/Budget ^(a)
- Security	Uses	- Construction
- Safety	Functions ^(a)	- Materials
- Access	Behavior/Activity Settings	- Services
- Privacy	Operation ^(a)	- Operations
- Territory	Circulation ^(a)	Cost/Benefits ^(a)
- Control	Environment ^(a)	
- Convenience	- Comfort	
	- Visual	
	- Acoustical	
	Energy Use/Conservation ^(a)	
	Durability/Flexibility	

(a) Critical Factors.
Source: Palmer 1981, p.19.

		FACTORS										
		HUMAN		PHYSICAL						EXTERNAL		
		H1. ACTIVITIES H2. GOALS/OBJECTIVES H3. ORGANIZATION H4. CHARACTERISTICS H5. INTERACTIONS H6. PREFERENCES		P1. SITE CONDITIONS P2. BUILDING/FACILITY P3. ENVELOPE P4. STRUCTURE P5. SYSTEMS P6. SPACE P7. FUNCTIONS P8. OPERATIONS P9. CIRCULATION P10. ENERGY USE/CONSERV.						E1. LEGAL RESTRICTIONS E2. CLIMATE E3. ENERGY PRICES/SUPP. E4. TIME E5. COSTS/BUDGET		
DECISIONS		ECONOMICS	1. PROJECT BUDGET 2. DESIGN ENERGY BUDGET 3. DESIGNED ENERGY PERFORMANCE 4. PROJECT COST ESTIMATE 5. CONSTRUCTION COST ESTIMATE 6. OPERATING COST ESTIMATE 7. LIFE CYCLE COST ESTIMATE 8. ECONOMIC ANALYSIS 9. PROJECT SCHEDULE	● ● ○ ○ ● ● ● ○ ○ ●		○ ○ ○ ○ ○ ○ ● ● ○ ○ ○ ○ ● ● ○ ○ ○ ○ ● ● ○ ○ ○ ○ ● ● ○ ○ ○ ○ ● ● ○ ○ ○ ○ ● ● ○ ○ ○ ○ ● ● ○ ○					● ● ○ ●	
		SITE	10. SITE PLAN 11. SITEWORK PLAN 12. LANDSCAPE DESIGN	○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○		○ ○					○ ○	
		GEOMETRY	13. CONFIGURATION 14. ORIENTATION 15. AREA/VOLUME CALCULATIONS 16. SPACE UNIT DESIGN 17. SPACE LAYOUT 18. FLOOR PLAN LAYOUT 19. CIRCULATION DESIGN 20. OPERATIONS DESIGN	● ● ● ● ● ● ● ● ● ● ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ● ● ● ● ● ○		○ ○				○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ● ● ● ● ● ● ● ● ● ● ○		
		SYSTEMS	21. ENVELOPE SYSTEMS SELECTION 22. ENVELOPE DESIGN 23. FENESTRATION DESIGN 24. CONSTRUCTION MATL SELECTION 25. EXTERIOR FINISHES SELECTION 26. INTERIOR FINISHES SELECTION 27. STRUCTURAL SYSTEM SELECTION 28. STRUCTURAL SYSTEM DESIGN	● ● ● ● ● ● ● ● ● ● ● ● ● ● ● ○		○ ○				○ ○		
			29. LIGHTING SYSTEMS SELECTION 30. LIGHTING SYSTEMS DESIGN 31. HVAC SYSTEMS SELECTION 32. HVAC SYSTEMS DESIGN	● ● ● ● ● ● ● ● ● ● ● ● ● ● ● ● ● ● ● ●		○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○				○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○		
			33. SUPPORT SVCE SELECTION 34. SUPPORT SVCS DESIGN 35. EQUIP/FURNISH SELECTION	○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○		○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○				○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○		
CODE	36. CODE COMPLIANCE		●		● ● ● ○ ●			● ● ● ○ ●				

Factors Addressed in:

● Phase 2

○ Phase 3

FIGURE 9.6. Whole-Building Decision Model

The decision factors are grouped into human, physical, and external factors. The relevant programming effort (facility, or component) provides the information about these factors for making decisions. The characteristics of these factors are described in Appendix F.

Human factors are extremely important since they provide a substantial amount of guidance for energy design decisions even before considering physical or external factors. Physical factors include extensive lists about all aspects of the facility and its contents, but the set of physical factors relating to energy decisions is more limited. External factors often act as boundary conditions or constraints imposed from outside the design process. They are generally conditions over which the designer (and often the owner) have little control, or at least substantially less control than they have over the other factors.

Both the human and external factors can strongly influence the design, but the designer often has relatively little control over these factors. Still, they cannot be ignored. The physical factors can be most easily controlled by the designer in developing design decisions based upon programming information.

9.2.2 Building-Subsystem Decision Models

Concurrent with the development of a whole-building decision model that can properly identify energy priorities and strategies from a whole-building perspective, the design of a decision model for building subsystems and components will be addressed. The decision models for building-subsystem design will be developed within the perspective of an integrated building design framework and decision model.

Figure 9.7 describes the decision/factor relationships for building-subsystem decision models. The timing of these building-subsystem decisions during the design process can extend from the schematic design phase through the construction documents phase (see Figure 9.4). There can also be important subsystem and material component considerations to address during building construction and turnover to the client. Similar decision models and logic would apply to change order activities, quality control during building construction,

building turnover checks, and post occupancy evaluations during building operations. Consideration of these post-design activities are long-term research objectives to be considered in Phase 3 of the proposed research program.

Specifics of the building-subsystems decision model will depend upon the detailed development of the whole-building decision model. Also, many similarities between the two models are anticipated. Therefore, the details of the building-subsystem decision model are not addressed in this report.

9.3 TIMING OF ENERGY DESIGN DECISIONS

To complete a structural framework for the proposed research program, the decision processes as defined by the two decision models needed to be integrated into the overall timing of the building design sequence.

The energy design sequence described here has roots in earlier investigations on energy related design process (see Appendix B). The sequence was initially developed as a section on energy related design principles for the recently issued draft revision of ANSI/ASHRAE/IES Standard 90.1P (1986). This process has been well received in both the architecture and engineering communities.

Figure 9.8 is an overview of the seven-step process. Each of the seven steps are graphically described separately, along with supporting textual materials, in Appendix G. This seven-step process will be used as the general procedural framework for incorporating energy decisions into the overall new building design process. This procedural framework will be linked in detail to the factors and decisions shown in the two energy decision models discussed above.

In keeping with a typical iterative design sequence of analysis, synthesis, and evaluation, the last step in the sequence is an evaluation of whether the actions taken have resulted in meeting the energy goal. If the goal has not been attained, the action returns to an earlier step in the process for revision. For example, Step 7 in the energy decision sequence compares the energy result with the energy objective. The comparison includes decision factors defined in the whole-building decision model in Figure 9.8.

FIGURE 9.8. Overview of Design Process

Although the seven-step process is a good general process, more detailed structures will need to be defined within each step and between steps. For example, Figure 9.9 shows basic relationships between loads and energy considerations for a new building design. The material in the figure is sequential in terms of decision dependencies, and indicates many of the data elements to be considered in steps 3 through 6 of the seven-step energy design process. The development of greater detail for the structure of the decision process will occur in the next stages of the research program.

FIGURE 9.9. Opportunities and Problems

9.4 DEVELOPMENT OF PROTOTYPE KNOWLEDGE-BASED SYSTEM TO TEST CONCEPTS

Part of the feasibility assessment included the development of an experimental prototype knowledge-based system. The purpose of the experimental prototype is to test ideas on the structure of the energy design decision model and on how to represent the domain of expertise. The prototype is intended to demonstrate concepts; it is not intended for actual use.

The experimental prototype was developed in EXSYS, a backward chaining production rule expert system shell. The example investigated is the identification of appropriate lighting strategies, daylighting strategies, and HVAC system based upon the designer's budget, the desired image for the building, the owner and designer's goals, climate, fuel prices, and available fuels. Expertise and data bases for the experimental system are based upon the Small Office Building Handbook (Burt et al. 1985) and other research results.

Lessons learned in developing the experimental prototype have been used as input to formalize the decision making models that have been described above for the design process. Closely related, the experience has been used to determine the characteristics of expert system shells that should be used in later stages of the energy design process research.

PART IV. THE DESIGN PROCESS RESEARCH PLAN

Part IV describes the proposed comprehensive research plan. The plan is divided into four phases. Phase 1 planning is essentially completed with the publication of this report. The remaining phases develop, expand and integrate the results of the research into design process models and tools. Without such an effort design tools will be developed, but without considering the energy efficiency of design options. With the comprehensive research effort interim design tools will be developed over the next ten years, culminating in an integrated design tool that does consider energy efficiency in the design of buildings.

PART IV. THE DESIGN PROCESS RESEARCH PLAN

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10.0 COMPREHENSIVE RESEARCH PLAN FOR THE ENERGY DESIGN PROCESS

Section 10.0 describes the proposed comprehensive research plan and its three remaining phases in detail. The proposed plan if implemented can assure that energy use of buildings can be considered by designers using the computer tools that will be available in the 1990s.

10.1 GOALS

The goal of the research is to demonstrate methods to integrate existing energy expertise into the building design process during the 1990s, using an advanced software tool to transfer and apply the expertise. The planned research builds upon existing research in the areas of energy efficient design, the design process, and energy analysis tools. The research will help to incorporate up-to-date knowledge in these areas into routine design processes and advanced design tools.

A summary schedule for the research plan is shown in Table 10.1. The plan calls for focusing the research over the remaining phases on two major elements: the design of the whole building and of subsystems and components. The remaining phases build upon the conceptual framework devised in the Phase 1 planning. In Phase 2, the basic methodologies and tools will be developed, both for the whole-building energy-decision model and multiple, independent,

TABLE 10.1. Summary Schedule for Proposed Comprehensive Research Plan for Design Process Research

	Accomplished Phase 1	Proposed								
		Phase 2 Development			Phase 3 Expansion			Phase 4 Integration		
		FY87	FY88	FY89	FY90	FY91	FY92	FY93	FY94	FY95
Planning	////////									
Whole-Building Energy Design Process Research		////////	////////	////////	////////	////////	////////	////////	////////	////////
Building-Subsystems and Components Energy Process Research		////////	////////	////////	////////	////////	////////	////////	////////	////////
Coordination	/// ///	////////	////////	////////	////////	////////	////////	////////	////////	////////

building-subsystem models. In Phase 3, these methodologies and tools will be expanded to cover more design stages, more building types, and a broader range of energy decisions and decision factors. Useful interim research products will be produced during Phases 2 and 3, and the advanced software tool will come out of the integration during Phase 4.

The cost of the research program would be shared with the private sector by integrating the research results into private sector software. For example, research tools would be incorporated as energy portions of CADD-based design tools developed primarily by the private sector. Also, data bases developed by the private sector will be used as resources.

Although a comprehensive research plan is proposed, it represents a major research effort that requires resources well above current and scheduled funding levels. An alternative limited research plan is summarized in Appendix G. The remainder of this section describes the proposed comprehensive research plan.

10.2 ELEMENTS OF THE COMPREHENSIVE RESEARCH PLAN

Integrating the energy decision models that are developed for the whole building and for subsystems is essential. The key to the integration is the whole-building model. It will become the link with the detailed subsystem models to form an integrated decision model that can assess the energy, cost and quality impacts of decisions made for one building subsystem on the other building subsystems.

The energy design process models and associated tools envisioned capture the energy design rules, experts' knowledge about energy efficient design, and relevant data bases and calculations necessary to identify and prepare energy efficient design options. This wide scope of facts and knowledge will be captured using knowledge-based systems software. One or more knowledge-based systems tools will be used both to structure the research and to present the research results. Links from the knowledge-based system tools to CADD systems, energy analysis simulation tools, economic analysis tools, and related data bases will be investigated and developed.

The research will provide useful tools for both energy research and actual design work. Energy researchers may use the tools to set priorities by examining the effectiveness new research areas, equipment, components and materials. Designers may quickly examine the energy consequences of alternate design approaches through all phases of the design and construction process.

The following subsections describe the major levels of research and how they relate to the development, expansion and integration phases of the research plan. Table 10.2 is a more detailed version of Table 10.1 and shows the major research elements proposed and their proposed timing and sequence. The following material in this section discusses each of these proposed research elements and how each relates to the total research program.

10.3 PHASE 2 RESEARCH AT THE WHOLE-BUILDING LEVEL

This major area of proposed research will produce the methods and tools to integrate the models for building subsystems and components. The primary focus is for new building design. The comprehensive energy decision model developed for new buildings will then be adapted to retrofit applications. In Phase 2, the whole-building research will include developing an energy decision methodology, conducting design process research, and developing a prototype knowledge-based system.

10.3.1 Develop Energy Decision Methodology

Research is needed to support the detailed level of decision making used in commercial building design. This research element will develop a design decision model at the whole-building level that will address energy and cost relationships among building subsystems. Decision structures will be developed that describe the relationships of the energy decision areas and decision factors and that include design timing considerations.

The whole-building design model will be developed in stages. First, independent models will be developed for three building types with different sets of priorities and decision processes: office, retail, and apartment. Second, when the independent models are sufficiently developed, they will be integrated into a single, more generalized decision model.

TABLE 10.2. Detailed Schedule: Proposed Comprehensive Design Process Research Plan

	Phase 2 Development			Phase 3 Expansion			Phase 4 Integration		
	FY87	FY88	FY89	FY90	FY91	FY92	FY93	FY94	FY95
1. Whole-Building Design Process									
A. New Buildings									
- Develop Energy Decision Methodology	////////								
- Conduct Design Process Research	//////////								
- Develop Research Prototype Knowledge-based System (KBS) Design Model	//////////								
- Develop links from KBS to CADD Systems, Data Bases, Simulation Tools, Advanced Imaging and Computers	//	//		//////////					
- Expand Methodology to All Building Types				//////////					
- Expand Methodology to Include Construction Decisions				//////////					
- Expand Methodology to Include Building Commissioning				//////////					
- Integrate with Building Subsystem Models				//	//		//////////		
B. Retrofit									
- Adopt New Building Methodology	////////								
- Conduct Retrofit Specific Design Process Research	//////////								
- Develop Retrofit Research Prototype Knowledge-based Systems Model				//////////					
2. Building Subsystem Design Process Research									
- HVAC	//////////								
- Lighting	//////////								
- Envelope	//////////								
- Daylighting	//////////								
- Service Water Heating	//////////								
3. Integration							//////////		
4. Coordination									
- Public Sector	//////////								
- Private Sector	//////////								
- Links to Systems	//////////								

10.3.2 Design Process Research

Extensive research on details of design processes is required before effective energy design tools can be developed. This element of the research program will produce detailed rules that cover the building types included in the methodology development. The detailed rules will incorporate critical

qualitative and quantitative decision factors related to energy. In this phase, rules will be identified and developed incrementally to address several related sets of design objectives, including:

- identifying the energy performance objectives in a building design in relation to owner objectives
- identifying energy strategies that can achieve the performance objectives
- identifying the appropriate time in the design and construction process in which specific energy strategies are to be applied in order to achieve the objectives
- providing guidance in properly incorporating into the building design the strategies identified.

10.3.3 Develop Prototype Knowledge-Based Systems

Knowledge-based systems will be developed as the primary vehicle for conducting the research. These will be prototype computer models that will develop the concepts from the Phase 1 planning. The capabilities of these computer models permit incremental development of the decision methodology and the design process rules and structures. With the models, complex sets of rules can be developed, permitting the research to include extensive detail about the numerous factors that influence energy decisions.

In Phase 2, separate whole-building prototype models will be developed for three building types. Extensive coordination will occur in their development so that later they can be integrated. Once the independent models are functioning properly, they will be merged into a single whole-building model that will apply to all three building types. Next, the whole-building model will be linked to the building subsystem models being developed in parallel.

The prototype computer models will focus on energy decisions, but the goal is to link these energy models to more generic advanced design tools. This includes investigating and developing interfaces to CADD systems, data bases,

advanced data storage devices, and advanced imaging hardware and software. These research activities will be conducted in parallel with the development of the prototype energy models.

10.4 PHASE 3 RESEARCH AT THE WHOLE-BUILDING LEVEL

In Phase 3 of the comprehensive research program, the methods and tools developed in Phase 2 will be expanded in several ways to extend their domains and to improve their capabilities. They will, for example, be generalized to all building types. Also, they will be expanded to include energy-related decisions during building construction and commissioning and to include the special sets of priorities and processes involved in retrofit building design.

10.4.1 Generalize to All Building Types

Having identified common elements of design during the integration of models in Phase 2, this knowledge will now be applied to expanding the model further. The plan is to include a full range of commercial building types. This expansion should take less effort than developing the first model because of the commonalities of design processes among building types as well as the experience gained in developing the first prototype.

10.4.2 Expand to Construction and Commissioning

Energy decision methodologies and tools will need to consider the impacts of decisions made during building construction (e.g., change orders) on energy use. This is the second major area in which energy-related decisions can have significant impact upon a new building's energy performance. Also, energy decision methodologies and tools will be developed to assist in guiding actions and in identifying impacts of decisions made once the building is constructed and is being turned over to the owner. This expansion in Phase 3 will enable the research products to address the full range of energy design decisions from design inception through building completion and turn over to the building owner.

10.4.3 Retrofit Design Decisions

In many ways retrofit design decisions constitute a subset of those for new buildings because so many building elements are in place and not easily changed (building configuration, structure, envelope, etc.). Thus, modifying the methods and tools that were developed for new building design to retrofit situations requires confining the new building models to the more constrained set of retrofit opportunities. The model must reflect the large shifts in priorities due to cost differences in applying strategies during retrofit compared with new building design.

Also, retrofit design processes have several special problem areas that are not encountered in new building design, including conducting an audit of the existing building, comparing the energy estimates derived from the audit with actual consumption from utility bills, and identifying and selecting energy saving opportunities that match the specific objectives and constraints for the retrofit situation. This element of the research program will develop modifications and enhancements to the new building models and methods to suit retrofits. This effort will include additional research on the specific retrofit processes and energy rules, and the development of a knowledge-based system computer model tailored specifically toward retrofit applications.

10.5 PHASE 2 RESEARCH ON BUILDING SUBSYSTEMS

Specific building subsystems and material components are an important application area for research into energy-related decision processes. Each building subsystem or material component can be considered a separate and distinct area of energy design process research. Improving energy-related design decisions in each of these areas could substantially improve the quality of energy performance for the the specific building parts covered. The energy design research in each of these areas should consider both energy and power (peak demand) impacts of decisions. Both a conceptual framework for the major building energy subsystems and a general list of decision areas and factors to consider for each decision area were presented in Section 9.0.

Given the mix of end uses for commercial buildings, the highest priority areas for energy research are the selection and detailed design of HVAC systems, lighting systems, and envelope systems. Each area can be further broken down into independent research areas, as shown in Table 10.3, and specific design process research can be conducted separately for subsets of each of these application areas.

10.5.1 Developing System Selection Capabilities

In Phase 2 of the research program at the building subsystem level, the concentration will be on developing methods, detailed design rules and knowledge-based system models. The models developed will be used primarily for selecting the appropriate system. For the whole-building research in Phase 2, the building subsystem and component models will focus on the office, retail and apartment building types. Each of the models will be developed separately, but with extensive coordination so that they may be integrated.

10.5.2 Design Process Research Elements for Each Subsystem

Substantial research is needed into the details of energy decision processes within each major building subsystem. Each building subsystem research element will include the same three components as the whole-building element: development of detailed methodology specific to the subject domain, development of specific energy decision rules for the subject domain, and development of a knowledge-based system computer model for structuring and recording the research and for presenting the research results.

10.6 PHASE 3 RESEARCH ON SUBSYSTEMS AND COMPONENTS

The R&D efforts in this phase will expand upon the subsystem results from Phase 2. Methods, decision rules and knowledge-based system models will be expanded to include specific, detailed, system design guidance. Procedures and methods for examining the impacts of subsystem-specific decisions made during construction and commissioning will also be developed during this Phase.

Subsystem results will also be generalized to include a wider range of building types, and the first efforts to link specific subsystem results with

TABLE 10.3. High Priority Areas for Design Process Research on Building Subsystems

<u>Subsystem</u>	<u>Selected Design Process Research Areas</u>	<u>Priority</u>
HVAC	System selection	1
	System design	1
	Component efficiency	2
	Controls	1
	Zoning	1
	Thermal comfort	1
Lighting	System selection	1
	System design	1
	Controls	1
	Illumination criteria and productivity	1
Envelope ^(a)	Fenestration	1
	Opaque elements (roof, wall, etc.)	2
	Conduction, including: thermal breaks moisture impacts solar effects	2
	Thermal mass	2
	Infiltration	1
Daylighting ^(b)	Systems	2
	Controls	2
	Window management	2
	Interface with other subsystems	2
Water Heating ^(c)	Systems	2
	O&M	2
	Losses	2

(a) While it is not indicated here, envelope analyses should also be separated into separate aspects of 1) system selection, and 2) detailed system design.

(b) Especially for such building types or functions as offices, schools, and storage.

(c) Especially for hotels, but also for apartments, hospitals, nursing homes, etc.

the whole-building research results will occur during this phase in preparation for the full scale integration to occur during Phase 4.

10.7 PHASE 4 DEVELOPMENT OF AN INTEGRATED RESEARCH PRODUCT

Phases 2 and 3 of the proposed research program involve the development of a number of separate research products. Although some integration of those separate products will occur during these earlier phases, the final integration will occur in Phase 4. The various elements will be integrated into a comprehensive energy design decision method and tool that can be embedded in advanced CADD-based design tools.

This integration is a major undertaking in itself, and will depend upon having the products of Phases 2 and 3 in working order and producing consistent and valuable guidance within their separate subject domains. Coordination during Phases 2 and 3 will assure that these separate elements are developed with this Phase 4 integration in mind.

10.8 COORDINATION

Coordination throughout the various phases is important to the success of the research effort. The research as planned will be conducted on a cost-shared basis between the public and private sectors. The research products developed separately must be integrated into a single product during the last phase of the research program. Research results are to be incorporated into advanced private sector design tools. Coordination must be carried on with:

- related R&D efforts
- independent developers of design decision models for specific building subsystems
- developers of related computer hardware and software systems that may be linked with the products of this research.

10.8.1 Coordination with the Public Sector

A number of public sector organizations were identified in the Phase 1 planning as being involved in related work, so coordination with their efforts

is important. This subtask involves establishing continued coordination with these organizations, to keep them apprised of developments from this project and to enable their work to be coordinated with the project's activities. This will eliminate redundant work.

10.8.2 Private Sector Organizations

A number of private sector organizations were identified in Phase 1 as important to coordinate with, either because they were involved in related work (CADD systems, cost data base systems, etc.), or because they had specific systems or products with which this research might interface. Coordination should be established with such groups, or in some cases, coordination that was established in Phase 1 should be continued. These groups include university groups, professional or trade organizations, and companies. For example, identified individuals within each organization should be included on distribution lists for interim project products.

10.8.3 Establish Arrangements for Direct Interfacing of Systems

In Phase 1 specific organizations were identified as having products or systems for direct interfacing. Other organizations with such systems or products will be identified in this subtask. This interfacing is considered important, especially with CADD system vendors because the research's ultimate product is seen as being attachable to existing CADD systems as a subsystem that would use the CADD data base as a common information structure. Interface with vendors that have computer-based systems for estimating building costs is also desired. Such interfacing will improve the usefulness of research results and will also reduce research development costs. Arrangements will be sought with selected organizations to enable the direct interfacing of their products or systems to those being developed as part of this Phase 2 effort. The results of this coordination will feed directly into other Phase 2 tasks.

10.8.4 Technical Review

An important part of coordination is assuring that ongoing work is adequately reviewed. Technical reviews of activities are planned, including a

technical review of this report and the proposed research plan. This first technical review will occur in the form of a meeting to discuss the findings and proposals in this report.

10.9 SUMMARY

The comprehensive research plan will result in a greater understanding of how to incorporate existing energy knowledge into the design decision process. The design tools that will result as by-products of the research have the potential for making a significant impact on the ability to design cost-effective, energy efficient buildings without the often prohibitive investment of time to become energy experts. Thus, the development of advanced energy design tools based upon solid energy design process research can have a far greater impact on energy-efficient building design than previous efforts have had.

However, such tools, while needed, will not be developed by the private sector. The market for building energy design software is not large enough to support the substantial investment needed. This fact is borne out historically. Most energy software produced to date was developed either by product manufacturers as part of their general marketing effort, or with government funding.

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APPENDIX A

KNOWLEDGE-BASED SYSTEMS

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KNOWLEDGE-BASED SYSTEMS

This appendix contains supporting detail for the discussion of knowledge-based systems in Section 3.1 of this report. Section A.1 provides a general discussion. Section A.2 defines specific knowledge-based systems requirements for this research effort, and identifies some possible tools and packages that might be used.

A.1 APPLICATION OF KNOWLEDGE-BASED SYSTEMS TO BUILDING DESIGN TOOLS

Knowledge-based systems are typically expensive and time consuming to fully develop, so the benefits should be carefully assessed before their development is started. The main body of this report discusses the value of a knowledge-based design tool for energy efficient design. This section elaborates on those benefits. The design tool is judged to have a high payoff since energy conscious design can reduce energy consumption in new buildings without increasing cost. The practice of energy conscious design can be increased by helping the decision maker to review and select options from more and better choices. In the small office building portion of the Building Specific Studies, it was estimated that energy use can be reduced 20% without increasing costs by making tradeoffs between the building components. While development of the design tool does not ensure that these benefits will be realized, developing a computerized version of this knowledge which can be easily used by the designer and applied to specific buildings could have a substantial market penetration and impact.

With the current drop in real energy prices and the availability of fossil fuels, building energy use is not perceived as much of a problem to developers. Because buildings have a long life-cycle, small savings in a year can be significant over the lifetime, regardless of the long-term outlook for energy costs. Therefore, it is important to maintain and practice the current level

of expertise that permits the design of more energy-efficient buildings that do not increase cost or reduce other amenities.

A large number of building designers and engineers are involved in commercial building design. However, many of these professionals work for small companies which cannot afford to have experts in energy efficient design. Expertise in energy efficient design is scarce due to the complexity of the domain and large body of accumulated research and knowledge developed over the past decade. A fundamental problem is that although information on energy efficient design techniques exists, it is rarely cost effective for designers and engineers to obtain and apply the information. An easy-to-use knowledge-based system would be of value for the typical projects having a small design budget.

Use of knowledge-based systems in the design process research project will help organize the energy design model and result in a system that can be used to create flexible and reproducible design solutions. Expert systems will facilitate the use of facts about building design (such as engineering principals and economics), knowledge gained from previous research efforts, and use of beliefs and heuristics of a selected group of architects and engineers.

A.1.1 Knowledge-Based System Structure For Design Process Research

The building design process is complex since architecture is both an art and a science. Typically, there are many "good" design solutions for a single problem. The building is also a system with complex components and interactions that are difficult to describe. In addition to energy efficiency, numerous competing goals drive the building's design, including cost, marketability, local codes, and timing. As a result, developing a knowledge-based model will be a complex task.

PNL's experience working with architects and engineers in the building specific studies projects indicated that designers do not always follow the same sequential thought process in developing design recommendations. However, it is possible to impose a logical sequence to this process, even though there is no unanimous agreement among design professionals on what the process should

be. The result is that there are a number of ways to formulate a methodology for proceeding through the architectural programming, schematic design, and design development phases of building design.

The conceptualization phase of design tool development will have to define a structure that includes:

- what information is important in each stage of the design process
- which alternatives should be considered
- what the consequences are of those alternatives
- how the alternatives interact.

A structure containing these components is outlined in Parts 3 and 4 of this report.

A.2 SELECTION OF A KNOWLEDGE-BASED SYSTEM FOR DESIGN PROCESS TOOL

This section examines the relationship between expert system development tools and the conceptual energy design process model. The means for translating the conceptual model into a usable tool for building design is the expert system software shell, along with supporting data bases and graphic systems. This translation will not be possible if either expert systems development tools are not appropriate for the job, or (assuming that they are appropriate) the wrong tool is selected. The discussion in Section 3.0 indicates why expert system tools are appropriate, so the focus of this section is on selecting the correct tool.

A.2.1 Introduction To Expert Systems

At the outset, the limitations of knowledge-based systems should be recognized; they cannot solve problems that an expert does not know how to solve. However, knowledge-based systems can be a valuable assistant to the designer and can suggest alternative solutions and analyze alternatives faster than the designer could.

Expert system shells are offered in a variety of structures: editors to assist in developing rules, and interfaces to software and data bases outside of the expert system development environment. The expert system typically

includes four basic problem solving components: a language processor, a knowledge base, an inference engine, and a work space. The language processor is the interface, the information transfer mechanism, between the user and the expert system. This processor frequently takes advantage of graphics or natural language to make it easy for the user to communicate with the computer. The knowledge base contains facts, relationships between facts, and assumptions needed to solve a problem. The knowledge base is distinguished from conventional data bases since it contains symbolic inference and heuristic knowledge. The inference engine is the mechanism to determine what questions to ask the user, to assess whether sufficient information is available for resolving the problem, to develop solutions, and to justify those conclusions. In addition, the inference engine controls what part of the knowledge base is searched and contains procedures for resolving conflicts between rules. The fourth component, the work space, is often referred to as the blackboard. It is where the software, under the direction of the inference engine, assembles and sorts the necessary information from the knowledge base and the user inputs.

The inference engine and knowledge base are typically designed to represent knowledge in one, or a combination, of the following methods: production rules, semantic networks, frames, and pattern matching. Each of these representations of knowledge have associated techniques for using the knowledge of "reasoning." The best representation is dependent upon the problem being addressed. However, none of the systems are likely to capture the actual thought process of the expert. The systems are simply useful paradigms for capturing the knowledge, which can also be programmed into a computer. Often a combination of these paradigms are useful for capturing an expert's knowledge.

Production rules consist of sets of "if . . . then" rules. For example:

If: The climate is temperate
and, the building is a small office building
and, gas is not available,

then: air-to-air electric heat pumps should be considered.

A collection of these rules comprises the knowledge base for the expert system. Rules are not the same as facts. Facts can be information which the user supplies or data from a data base. Rules are the method for using the facts. The process of combining rules with facts in order to draw conclusions is done with the inference engine. The inference engine typically uses forward or backward chaining to solve the problem.

Forward chaining is the process of prompting the user for the facts required by the "if" side, the left hand side (LHS), of the rule to solve the "then", right hand side (RHS), of the rule. The system deduces new facts, from the RHS, and uses those facts to deduce additional facts. In backward chaining, the user starts with a hypothesis about the conclusion (the RHS) and the system looks for facts (the LHS) that will support or solve for that conclusion. Design problems which can be characterized by a large number of solutions starting with a small number of facts are typically programmed as a forward chaining problem. Diagnostic problems, where there are only a few conclusions are typically programmed as a backward chaining problem. Some problems are best characterized with both forward and backward chaining.

A production rule based expert system starts with a few facts provided by the user which encompasses its "world of knowledge." The inference engine is then used to increase the knowledge of its world through deductions using the if - then rules and by asking the user questions.

Frames are another technique used in developing expert systems. Frames are a powerful addition to production rules since they are used to describe the attributes of objects. For example, a frame for a wall might include its length, width, depth, its structural components, interior sheathing, insulation, and exterior sheathing. The power of frames is that attributes and their properties can be defined in advance and are included in the "world of knowledge" of the expert system. In addition, hierarchies between frames can be defined so that one frame can contain the attributes of other frames.

It is difficult to discuss the software capabilities without considering the hardware since the two are closely related. Broadly defined, one of three hardware environments are typically used: microcomputers (IBM PC, Apple MacIntosh, etc.), mini or mainframe computers (MicroVax, VAX, IBM, etc.), or

specialized AI/LISP computers (Symbolics, TI Explorer, etc.). Typically the more sophisticated expert system shells are written for specialized LISP machines. They contain multiple paradigms for representing knowledge (production rules, frames, and pattern matching), sophisticated inference engines including forward and backward chaining, enhanced graphics, and a user-friendly development environment. Shells written for the mini and mainframe computers allow the use of large amounts of memory and typically support access to other programming languages, data bases, and graphics systems. As in the rest of the software industry, the differentiation between the capabilities of the mini- and microcomputer software capabilities is shrinking. However, most microcomputer based systems employ a limited set of paradigms for capturing an expert's knowledge (typically production rules) and usually have backward chaining (less memory intensive) inference engines. The smaller memory use allows the storage of fewer rules and places limitations on overlaying modules written in other programming languages.

Manufacturers of expert systems hardware and software frequently make distinctions between the development environment and the delivery environment. The delivery environment is the hardware which the user of the expert system must have. The knowledge engineer can develop an expert system in a powerful, but expensive, hardware environment to be used in a lower cost computing environment such as a micro- or mini-computer. Since the energy design tool is a long-term research effort, the delivery environment is not a concern. During the course of the research program the development and delivery environments will both change dramatically.

A.2.2 Expert Systems Requirements

The expert system tool should be selected to match the requirements of the problem being addressed. The best tool may not be the one with the most features. Too many features may make the development task more difficult. On the other hand, selection of a tool with the wrong paradigm(s) can make development impossible. This section discusses selection of a tool in the context of the requirements of the energy design process model.

Design process research and the decision making process are both qualitative and quantitative. The knowledge-based system must be able to handle heuristic rules and make decisions based upon data on costs and energy use. Therefore, the tool must have the following capabilities:

- production rules

- the ability to perform mathematical logical relations

- procedures for accessing multiple data bases (energy costs, energy use, and cost of implementing strategies)

- and allow passing data to and from engineering based computational procedures.

In building design there are many cases where the designer assumes a lot by knowing a single fact. For example, if a developer requests a design for a small office building, the designer may automatically assume that the building contains offices (partitioned or unpartitioned), conference rooms, wash rooms, and corridors. Each of these functional space uses also have a set of properties typically associated with them. Prior definition of these properties and their relationship to each other simplifies the development of a knowledge-based system. Of course, the designer needs to have the ability to change these apriori assumptions. In expert systems one convenient way to handle these relationships is frames. In short:

- Frames are viewed as a highly desirable, but not mandatory requirement for the development shell.

Design problems are typically data driven. The building design process begins with a limited amount of data which can lead to a large number of outcomes. As the design evolves, the volume and level of detail of data characterizing the building increase. Throughout this process decisions are made, which help narrow down the set of design options. This structure, where the problem solution is driven by the data inputs, is typically referred to as a forward chaining problem.

Alternatively, the design process problem might be configured to test a limited set of solutions. It is common, for example, in the schematic design

phase for designers to generate a number of alternative design solutions and evaluate them using multiple project objectives and constraints. Also, when considering HVAC systems it is common to identify a few designs and assess those alternatives using cost-benefit performance and an energy simulation tool. Another example is to assume that since an energy efficient building must meet ASHRAE Standard 90, then the expert system could test the hypothesis that the proposed design meets the Standard. The process of searching for facts to test a set of predefined hypotheses is known as backward chaining. In short:

- The expert system shell should have a forward chaining inference engine.
- A backward chaining capability is also desirable.

Since the design process tool is being developed with the goal of assisting, and not replacing building designers, there needs to be a facility to explain why a decision was made. Without a self-explanation ability, the system becomes a black box that is unlikely to be used by anyone but the developers who know the reasoning. Explanations can be limited to illustrating the path taken to obtain a conclusion, or can be more enlightening and contain explanatory text provided by the expert along with references for documentation. While including of explanations and references adds to the coding task, the system becomes more useful since documentation is available at the computer screen, if requested. The alternative is also time consuming: documenting the expertise and the decision making process externally. In short the system should:

- have a facility showing the path taken to reach a conclusion
- provide the user with an explanation for reaching a conclusion.

Experience with developing expert systems indicates that developing the user interface is as expensive as developing the knowledge-based. The user should not have to be knowledgeable about systems work or have much familiarity with computers. Special input screens and graphical representation of both the input and the output are a common approach taken. Most of the high-end expert system development shells contain routines to easily prepare graphic

representations. At the current stage in the design process research effort, the user interface is not considered a high priority. The focus is to demonstrate whether the knowledge required for energy efficient design can be incorporated into a knowledge-based system.

A user-friendly interface with the designer through CADD is planned. However, the integration is anticipated to be a difficult and time consuming task. In order to accomplish this integration and also be able to develop a prototype that makes a good demonstration, the expert system should:

- be able to read and write numeric variables to foreign data files
- have graphic formats for input and output of data.

A.2.3 Identification of Expert System to Use in Research Development

An expert system development environment for the research phase must be selected based upon the identification of the problem and the conceptualization of the design process. This selection must be made within the program's time, money, and institutional constraints. The research effort emphasizes design process research and testing expert systems as a delivery framework for that research. Money has not been allocated for buying costly computers or software. Based upon existing hardware and procurement, three computing environments have been identified:

1. IBM Personal Computer
2. VAX 11/780 or MicroVax II running VMS
3. Symbolics AI computer.

The IBM PC has been used for developing the demonstration prototype. The purpose of the demonstration prototype was to gain some experience in how to formalize design process research into an expert systems environment. The test was used as an aid in developing this planning report and to help lay the groundwork for a research prototype. The demonstration prototype and the rules are described and listed separately from this report.

A number of PC expert system shells were purchased and evaluated by PNL. Based upon these evaluations, the software EXSYS was selected for developing the test prototype. EXSYS is a low-cost production rule-based system with backward chaining. EXSYS has two major strengths. First, trial systems can be

developed quickly because EXSYS has a good language processor and a user-friendly editor for developing consistent rules. The package is easy to use and no programming skills are required to use the editor system. Second, it allows the user to trace the reasoning that led to a conclusion. It also provides the explanation and reference for each rule which the expert typed in during development of the production rules. The program supports calling other programs and passing variables to and from those programs. The primary drawbacks of the system are that it is limited to backward chaining, to using production rules to define problems, and to implying problems because subtasks or subgoals cannot be defined. The result is a limited and rigid paradigm for representing an expert's knowledge. All mathematical operations, except logical operations, must be done outside of the EXSYS program. Conducting these calculations outside the program, although possible, is a relatively slow process.

The use of either OPS5 or OPS83 software with the VAX or MicroVax computers has also been considered. Although it is economically feasible and would allow the knowledge engineers and experts unlimited access to the hardware and software, this option is less desirable than using an AI computer and associated software package. The strengths of the software are that the OPS languages are forward chaining production-rule-based systems, and backward chaining is also feasible. Also, the OPS programming environment allows the knowledge engineer more flexibility to define and control the resolution of the problem with the production rule constraints. However, one of the major weaknesses of the OPS programming languages is that they are not as easy for the knowledge engineer to use as many of the other packages on the market. Implementations in the VAX environment support easy integration with data bases and routines written in other languages. The knowledge can be divided into subtasks and the execution of these subtasks can be controlled. Routines in other languages can also call OPS5 functions. A number of successful expert systems applications have been written in OPS5 and OPS83; however, one must learn the language to program rules. Demonstrated applications have included graphical input and output by calling routines in other languages, such as GKS.

Available computer memory would not be an issue with these implementations. An asset of these languages is that it would be easy to integrate data bases and other programs.

OPS5 was originally developed by Carnegie Mellon University. Digital has a version for the VAX and MicroVax computers. The Digital version is written in the language BLISS and only runs on Digital computers. The OPS83 language, also developed at Carnegie Mellon University, includes the rule based programming structure of OPS5. In addition, it contains a structured sublanguage, like Pascal and C, which the programmer can use to program other functions such as mathematical operations. Like OPS5, OPS83 can call routines written in other languages. Programs written in OPS83 are supposed to be portable across a number of computer systems.

PNL has procured two Symbolics computers that will be available to the design process research and development project. The quickest way to develop a knowledge-based system on these computers is to use one of the powerful expert system development shells. PNL has evaluated shells available for the Symbolics computer and has selected KEE by IntelliCorp as the primary expert system shell for PNL projects. IntelliCorp is currently developing software to run the designed expert systems on the MicroVax. This could be helpful in the development phases for linking the expert system component with VAX based energy and cost data bases and CADD systems.

The KEE expert system package includes several paradigms for coding knowledge, including object-oriented programming, frames, production rules, and the ability to write functions in LISP. KEE also allows the user to trace the path of reasoning and contains a graphical package for display of data. KEE will also support data transfer from external data bases and analysis programs.

APPENDIX B

CURRENT DESIGN PROCESS RESEARCH AND RELATED EFFORTS

APPENDIX B

CURRENT DESIGN PROCESS RESEARCH AND RELATED EFFORTS

This appendix provides additional detail about items discussed in Section 4.1 of this report.

B.1 WRITTEN DESCRIPTIONS OF DECISION PROCESSES FOR ENERGY EFFICIENT DESIGN

A number of research programs have been identified as a base for developing more comprehensive energy design methods and related design tools. Programs that have produced written descriptions of decision processes for energy efficient design are described in this section. All of these written efforts contain excellent information, but are limited in scope and detail because of their hardcopy orientation. Also, these efforts are not related directly to either research on the design process, or to the development of expert systems.

B.1.1 Energy Graphics

Predesign Energy Analysis (Hart, Kurtz and Whidden 1980) was developed for the DDE by Booz Allen and Hamilton Inc. This was one of the earliest energy-related products that focused on decision processes for energy efficient design. Like virtually all procedures developed to date, it is very simplified because it was designed for hardcopy presentation in a manual. It is a tool for assisting architects in testing design strategies in the predesign phase. The program estimates energy use from simple inputs concerning building function characteristics, internal gains, solar gains, envelope heat gains and losses, and ventilation heat gains and losses and then displays the results graphically. The graphs show the thermal performance for an average day in each season. Depending upon the shape of the graph in each season, the manual suggests a number of strategies for reducing energy consumption. The calculations, based on the limited information in the predesign stage, and the graphical techniques are simple, but good examples of techniques for the design methods and tools proposed as part of this current research project.

B.1.2 Building Specific Studies

PNL is developing a set of building specific manuals to aid the private sector in the design of energy efficient buildings. Design teams use professional experience, energy simulations, and economic analysis to recommend sets of conservation strategies. The design manual for the small office is completed (Burt Hill 1985). The manual for apartment buildings is almost complete and the manual for retail stores will be started in mid-1986. An important attribute of these studies is their development and use of energy design decision processes in producing recommendations about good energy strategies for each building type examined. The research conducted to develop these manuals will be an important component of the knowledge component of the design tool proposed.

B.1.3 Tennessee Valley Authority

The Tennessee Valley Authority (TVA), Division of Conservation and Energy Management, has been developing a series of design manuals entitled Energy Design Guidelines. These manuals are primarily intended to assist architects and other design professionals in incorporating energy efficient design practices into their standard professional services.

The first of the manuals, Schools, has been published, and several more are nearing publication or are under development. The series of manuals specific to selected building types includes schools, offices, and hospitals. The manuals have been organized around a similar design process with example buildings used to illustrate applications of the energy saving design process. The building-specific manuals attempt to describe the broader context that serves to influence or define what is reasonable and achievable in terms of energy for each particular building type. In many cases this involves identifying other issues that often drive major decisions. The building-specific manuals for the various building types share the same energy saving design process, but differ in the detailed treatment of each type. This is partly due to the differences among the building types and partly to the approaches of four different consultants.

Two other manuals oriented towards a generic design process, entitled Evaluation Process and Energy Monographs are under development at TVA. The Evaluation Process manual presents a general process by which energy issues can be understood and addressed through the course of a generic building design process. This process was conceived as a logical shell that would minimize encumbrance of the variable and often idiosyncratic process by which individuals design buildings. The process described pays particular attention to information needs and the sequence and timing of activities, with major emphasis placed on the earliest project stages. The procedures presented help the designer integrate economic and nonquantifiable considerations into the design in a consistent way. This manual has been drafted but is not yet final.

The TVA design process work is viewed as an important input into the development of advanced design tools, including the effort discussed in this report.

B.1.4 American Institute of Architects

The American Institute of Architects (AIA) in their publications (AIA 1981a, b) have provided guidelines on how to integrate energy conservation strategies into the decision making framework of the design process. These materials include the Level 2 Workshop titled "Energy In Architecture: Techniques" and the Level 3 Workshop titled "Energy in Architecture: Applications." The AIA is currently revising these workshop materials. One chapter in the revised material is a generic description of the energy design process. These sources were used extensively in developing the model of the design process described in Section 4.2 of this report.

B.1.5 ASHRAE

During the development of the proposed revision to ASHRAE's standard for energy conservation in new building design, Standard 90.1P, members of the committee developed a conceptual approach to energy decision making as part of the new building design process. The approach is included in the proposed standard issued for public review in July 1985. The approach has been well received in

both the engineering and architectural communities. The AIA revisions to the workshop manuals are an expansion of the process developed by the Standard 90.1P effort.

B.1.6 Commonwealth of Virginia

The State of Virginia has developed a primer for first time owners of smaller buildings. The guide, Owner's Guide to Energy Conservation in Buildings (Deringer et al. 1984), is unusual in that it provides guidance to the owner, rather than the designer. The guide gives guidance to the owner on criteria to use in selecting a building design team in terms of its energy competence. The guide also identifies key energy decisions that the owner needs to make, when those decisions need to be made during the building design and construction process, and the factors to be considered in making the decisions.

B.2 CURRENT DESIGN PROCESS RESEARCH USING COMPUTER-BASED (AND KNOWLEDGE-BASED) MODELS AND TOOLS

The university architectural research community is working on design process research and knowledge-based systems. Engineering departments are working to develop expert systems based on structural engineering. National research organizations are also working to exploit expert systems as a tool for improving building design and construction. Most efforts are in the initial development stages although some published article titles imply more comprehensive approaches or results than their current status suggests.

Ongoing efforts were reviewed to determine the status of related research and identify areas where duplication of effort might occur, or potential areas of coordination. The review was based primarily upon development of a network of contacts through phone conversations and attendance at relevant meetings. These activities are summarized in this section. Only a few of these research efforts are related specifically to energy designs. Usually the research efforts are focused on the general building design process.

B.2.1 University Efforts

The efforts of universities conducting research in the area of automated design process are described in this section. These universities are listed below:

Carnegie Mellon University
University of Victoria, B.C.
State University of New York at Buffalo
Massachusetts Institute of Technology
University of Illinois
Rensselaer Polytechnic Institute.

Carnegie Mellon University

Carnegie Mellon University (CMU) has active building-related research efforts in both architectural and engineering departments. The Architectural Department has been working on several simple models. One such model, the building site location model, is a simple generative model that locates a building within a site, based on information about the site and the building. The model, written in OPS5, is based on rules extracted from the Small Office Building Handbook (Burt Hill 1985) and supplemented by additional rules from available experts (including Fred Dubin).

Another CMU model, the HVAC diagnosis model, is a simple model written in OPS5. It was developed using the same sources as the building site location model. The pattern model for Shadyside is a diagnosis and generative model based upon an onsite study of building characteristics in the Pittsburgh community of Shadyside. The model is written in PROLOG.

The CMU architecture department efforts are using primarily IBM PC AT based systems. An uncompleted project is to link various models via an interactive CADD package for a graphics-oriented user interface. They are exploring either AutoCAD or an alternate graphics package, and have chosen the C language for any special graphics programs to be developed in-house. The efforts appear to be constrained primarily by lack of funds.

The Civil Engineering Department has developed a series of systems for structural design. These systems include HI-RISE (for design of rectangular

high rise buildings), LOW-RISE (for preliminary design of low-rise industrial buildings), ALL-RISE (which is similar to HIGH-RISE but for buildings of any height), and FLODER (for analysis of gravity loads of floor plans generated by HI-RISE). These laboratory systems are not used for actual applications; they are characterized as knowledge-based systems rather than expert systems.

University of Victoria, British Columbia, Canada

Eric Gullichsen and Ernest Chang, in the Department of Computer Science, have entered the patterns of Christopher Alexander's design pattern language into a computer-based format (Gullichsen and Chang 1985). They used the hierarchical structure implicit in Alexander's pattern language in its original form and wrote their system in PROLOG. One problem with this is that the individual rules (the patterns) are significantly more complex than rules in most expert systems. The system is in development, and the article did not discuss how well the model worked.

State University of New York, Buffalo

Professor Kalay in the Department of Architecture is working with a group of about 12 people at the State University of New York (SUNY), Buffalo, on a knowledge-based system for architectural design. They have been working on the system for about 3 years and have some products developed. Funding is from several sources: the National Science Foundation (G. Albright), National Endowment for the Arts (a participatory design grant), and a private corporation, AISA Computer Products.

Their approach is concentrating on developing shells as part of a design tool, rather than on energy. The system, running on a VAX 11/750, is written in Prolog using Pascal for graphics and C for data input/output. Their system has three major parts: the planning model, the data base model, and the knowledge acquisition model.

The planning model, based on a goal hierarchy model, searches for solutions that satisfy alternative goals and also evaluates solutions achieved according to criteria goals. One strength of the system is that goals can be subdivided as far as necessary. The focus for work has been single-family residences. The goal model developed appears to be working and includes

defaults for items that are not known. It is easy to add options to the goals hierarchy in the planning model, but difficult to change the goals' tree itself. The model does not directly examine building quality issues. Such issues are handled indirectly as a multiplication function on costs.

The data base model is an object-oriented data base structure that contains descriptive and procedural/functional frames (e.g., if door must be able to be opened, then check for interferences). The model has consistency maintenance features and integrity constraints. A relational data base is being developed that will underlie the frames. This model is expected to be complete in December 1985.

Work on the third model, the knowledge acquisition model, has not begun. It is postponed indefinitely, and is expected to be difficult to develop.

The SUNY system has a CADD-like, 3-dimensional, object-oriented user interface which is integrated with the previously described models. This package, developed in-house, is implemented and is for sale for \$12 to 50 thousand (depending upon configuration) by AISA Computer Products. The intended market is architects, in the context of developing the next generation of CADD systems.

The group at SUNY Buffalo has agreed to collaborate with the Passive Research and Development Group (Wayne Place) at Lawrence Berkeley Laboratory to work on a model that will incorporate the energy impacts of roof apertures for daylighting.

Massachusetts Institute of Technology

The Massachusetts Institute of Technology (MIT) has been investigating the use of AI in preliminary architectural design. Because of funding and programmatic issues, MIT has been developing their own expert system shells. These shells include IMAC-PC, IMST, and the General Engineering Problem Solving Environment (GEPSE). IMAC-PC is a decision tree processor written in Basic. IMST is an object oriented, forward chaining, and pattern directed shell. It has a data base interface and an explanation facility. GEPSE is a forward chaining, semantic network, rule-based system written in C.

MIT is working on an expert system for component design in CAD systems. They are interfacing with the new version of AutoCAD, which includes a LISP interpreter. Another project is a cafeteria planning project for IBM. The purpose of this system is to aid in the architectural programming phase. IBM typically contracts out the cafeteria planning for its new facilities and has one in-house expert for overseeing the design. They are trying to replicate their in-house expert since he is too busy. Currently, MIT is working on building the knowledge base using the IBM expert system shell named PRISM.

Engineering based applications of expert systems include bridge maintenance (using GEPSE), nondestructive testing, land use management (using IMST), site selection (using IMST), project management, project programming warning system (to track mass transit projects through their life-cycle), highway maintenance planning (written in Prolog), prediction of hidden structural problems in dams and locks, design of structural components, and teaching structural engineering.

University of Illinois

Michael Kim is working on a long range effort called the artificially intelligent design advisory system (AIDAS). AIDAS consists of three components: the design prescriber, the designer, and the design assessor. The system is viewed as an aid to design, not as a replacement. The design prescriber is used to define desirable properties that are derived from several design goals, including personal preferences. A major issue in his research is how to get the designer and the program to communicate since the designer often deals with abstract concepts. The design process is viewed as tracing up and down a teleological hierarchical structure. The goal is to develop all three components to work in unison. This work is in the early conceptual stages.

Rensselaer Polytechnic Institute

The Center for Architectural Research in the School of Architecture has developed an expert system for energy analysis in the schematic design phase (Quadres and Kroner 1984). The program uses the rules contained in the Predesign Energy Analysis Manual developed for DOE (Hart, Kurtz, and Whidden 1980). This approach makes a simple assessment internal heat gains, envelop

heat gains/losses, and ventilation heat gains/losses based upon a limited amount of data. It produces a graphic profile of heat gains and losses for each season. The system analyzes the results in combination with the data inputs and suggests design alternatives based upon selecting appropriate strategies out of a table of options. The tool can be used to examine the impacts of different amounts of glazing, changing the orientation of the building, or changing the envelop UA.

B.2.2 Related Government Efforts

Several government organizations are conducting or planning to conduct research or development projects in expert systems applied to building design: National Bureau of Standards, Construction Engineering Research Laboratory, Lawrence Berkeley Laboratory, and Pacific Northwest Laboratory.

National Bureau of Standards

The Center For Building Technology at the National Bureau of Standards (NBS) is working on a number of expert systems related to engineering and compliance checking with standards. The expert system for durable concrete, written in Pascal, is designed to provide recommendations for selecting the constituents in concrete. The knowledge is based upon the ACI Concrete Guide. Currently, NBS is working with the ACI committed to capture their knowledge and support the knowledge base with heuristics. The prototype, developed by Jim Clifton, consists of production rules with a forward chaining inference engine. The goal for this system is that the ACI committee will maintain and support the expert system.

Andrew Persily, of NBS, is in the planning stages of developing an expert system to be used in conjunction with NBS's thermal analysis program (TARP). TARP is a computer simulation tool designed for analysis and diagnosis of air infiltration rates and air leakage problems. Currently, the model is intended to be applied to residential buildings. The expert system will aid in modeling and interpreting the results of TARP.

NBS supports developing standards rather than creating standards. The work calls for analysis, and a related tool under development is the standards analysis, synthesis and expression software (SASE). The tool, written in

Fortran, is designed to provide a systematic and uniform method for analyzing standards. The program is currently being tested on a typical standard.

NBS has also started a number of research projects to aid in developing standards related to CADD. These efforts include the standards interface for computer-aided design (SICAD). The impetus for this work is to develop a standard between CADD systems for storing data related to compliance with building codes. A standardized approach for storing this data is necessary for efficient use of standards checking programs such as SASE. The approach that NBS is investigating is to have the CADD systems separate the data needed for standards checking from the rest of the CADD routines. In a related effort NBS has been participating in a committee for updating the initial graphics exchange specification (IGES)/ANSI standard for data interchange between CADD systems.

Army Construction Engineering Research Laboratory

The Construction Engineering Research Laboratory (CERL) has a number of efforts under way to apply expert systems to building design and management of the construction process. The energy conscious planning program (EPLAIN) is designed to select cost effective design strategies, given information about climatic conditions and functional use of space. The expert system was written with the KDS shell for the IBM PC. The program asks the user a series of true-false questions about the climate and use of space and uses the answers, coded rules, and a payback analyses to make a decision table.

CERL is also developing a system for checking the habitability conditions of a design space. The program, activity based checking systems (ABCS), is written in Interlisp D. The program is based upon frames and a series of scripts that are a series of pre-programed events. An example of a script is a visitor entering a lobby, checking with a receptionist, and then viewing some exhibits. As each of these events is triggered, the program checks for the functionality of the design. The system is independent of any CADD system so the user needs to input the design data into the ABCS program.

The military uses a system for tracking the design and construction of new buildings. Management data on these phases of building construction are maintained in a data base. The program, an intelligent aid for management of

construction schedules, is used to track the status of projects over a five year cycle. The program consists of a forward chaining, production-rule-based system written in Interlisp and semantic networks to describe the dependencies between tasks. CERL is also working on a natural language interface to the CAPCES database.

Pacific Northwest Laboratory

PNL has an AI laboratory and has been working in a number of AI fields including image recognition, robotics, and expert systems. The laboratory includes a number of AI computers and expert system shells that are either purchased or developed internally. The laboratory staff act as consultants to other PNL department staff developing expert/knowledge-based systems.

PNL is currently developing a number of expert systems. However, the one discussed in this report will be the first in building design. Development of the proposed system is viewed as a cooperative effort with other government laboratories, universities, CADD developers, and other representatives of private industry.

Lawrence Berkeley Laboratory

Steve Selkowitz of Lawrence Berkeley Laboratory (LBL) is developing a plan for an advanced design tool that emphasizes envelope design from the schematic design phase through construction, occupancy, and retrofit measures. The tool is conceived as containing a number of elements, including expert systems for design advice and imaging systems to illustrate the appearance of a space with different lighting and daylighting designs. The tool conceived would be ready in the 1990s and would be the result of a cooperative industry and government effort. LBL is also working with the Architecture Department at the University of California at Berkeley to develop an expert system for daylighting design based upon the a daylighting analysis model. The program is being developed on an Apple computer system using MVP FORTH.

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APPENDIX C

CADD SYSTEMS

APPENDIX C

CADD SYSTEMS

This appendix contains supporting detail for the computer aided design and drafting (CADD) systems discussion in Section 5.0 of this report.

C.1 OVERVIEW OF CADD SOFTWARE AND HARDWARE

CADD systems on the market offer different levels of sophistication in their ease of use, modeling abilities, and integration of ancillary programs for site preparation, engineering analysis, and cost estimation. CADD packages can be divided into three categories based upon hardware requirements and cost: microcomputer-based CADD packages costing less than \$20,000, minicomputer/small mainframe based CADD packages costing \$20,000 to \$80,000, and mainframe computer high-end CADD packages costing over \$80,000. The mid-range systems are often scaled down versions, in terms of capabilities and performance, of the high-end systems.

Current microcomputer systems tend to concentrate on replacing traditional drafting. The systems are typically good for developing two-dimensional drawings and have the ability to extrude lines to make three dimensions (this is often referred to as 2 1/2 D). Some packages offer three-dimensional drawing, but they still do not offer shading in three dimensions. Additional modules to these packages are often available for conducting site work analysis as well as mechanical and electrical design work. Additional packages with differing levels of integration into the CADD software include thermal analysis and cost estimation. In the next few years these packages will be offered with three dimensional modeling as well as better integration of the architecture and engineering design development tools.

Micro-based systems are available for both CPM and MS-DOS computers as well as packaged with modified microcomputer hardware. Most systems are geared for the IBM PC and AT, which reflects IBM's dominance in the personal computer market. In addition to the microcomputer and CADD software, a CADD system requires a digitizing pad or mouse, a high resolution color or monochrome graphics card, a high resolution monitor, and a plotter.

There are many vendors of micro-based CADD systems, but the major software packages are AutoCAD, PCAD, and VersaCAD. Some vendors, including MiCad, offer systems based upon repackaging AutoCAD with enhancements. AutoCAD is clearly the leader in terms of volume of sales. In addition, the company has a relatively open architecture for its software. As a result, a large volume of third-party software is associated with the civil, mechanical, and electrical engineering disciplines that link to AutoCAD. Third-party vendor support includes translators so that AutoCAD will run with larger systems including Intergraph, Cadam, and Computervision. The AutoCAD version 2.1, to be released this year, will incorporate a Lisp processor. Future enhancements will allow integration of other high level languages. Since the program is written in C, a C interface is highly likely.

PCAD, another major microcomputer CADD package, was recently purchased by CalComp so that it now incorporates direct integration with their more powerful minicomputer system. Many of the vendors of minicomputer and mainframe computer systems have developed scaled down and integrated software that runs on microcomputers.

A number of companies are packaging their CADD systems on minicomputers using the Digital (MicroVax II) and Prime hardware. Characteristics of these systems include an ability to support multiple work stations, integration of computer aided engineering packages with the computer aided drafting process, and three dimensional modeling and shading capabilities. These packages are not necessarily more useful than the microcomputer packages when one considers the needs of many architectural firms. The minicomputer systems appear targeted to the integrated architectural and engineering firms. Hardware and

software costs for these systems start in the neighborhood of \$60,000 to \$75,000 for the first work station, with additional work stations costing approximately \$15,000.

Two minicomputer packages extensively reviewed for this research effort are RUCAPS by GMW Computers, Inc., and GDS by McDonnell Douglas. These packages were identified because of their full three-dimensional data base structures and object orientation. Representatives of both these companies are developing enhancements directed towards using CADD systems as part of the conceptualization and design phases. In addition, they are both considering the use of expert systems in their software packages. Other popular packages include the Intergraph system that can run on a modified MicroVax or larger computers and CalComp.

The distinction between the CADD capabilities of the mainframe and minicomputers is not clear, especially as the power of the minicomputer increases and the cost decreases. Many of the vendors that offer software for the mainframe computer offer scaled down packages for the minicomputer. It is not clear how much of this integration strategy is due to short-term marketing strategies, either in starting customers on a small system that can be expanded, or in preparing for the next generation of minicomputers. The distinction between the mainframe and minicomputer systems appears to be the level of integration of a number of users and the speed of the system rather than an expansion of the CADD capabilities of the system. Mainframe CADD vendors include IBM, Prime - MEDUSA, McDonnell Douglas - McAuto, SKOK, and Intergraph.

C.2 ACCESS TO CADD DATA BASES

There are three options for accessing the CADD data bases: use nonproprietary procedures developed by some manufacturers to promote third-party software, use a standardized CADD file transfer protocol, and develop an agreement with a CADD manufacturer to obtain proprietary information on how to access a data base. These options are discussed in further detail below.

Currently, there are two standards for transferring drawings across CADD systems. The standards are the Initial Graphics Exchange Specification (IGES) and Product Design Exchange Standard (PDES). The IGES standard is the older

and more common standard and is currently adopted as ANSI Standard Y14.2. The current IGES standard deals primarily with geometry, not attributes related to the building's components. The IGES standard is constantly under revision and there is now a subcommittee of IGES that deals with CADD for architecture and related engineering. The IGES standard most likely will be extended to cover more building attributes. Currently, most of the major micro, mini, and main-frame CADD packages support the IGES standard. The IGES standard may be the way to link an expert system to the CADD software some time in the future. However, that is not a practical approach now.

At the 1985 A/E Systems Conference, PNL spoke to a number of software manufacturers and software development people about the expert system project for energy conscious building design. Their overall reaction was encouraging for two reasons: first, a number of software companies seemed interested in the project and second, these companies are not planning similar efforts with the same objectives. It also appeared that a cooperative development effort might be feasible. This private sector cooperation could take the form of free software and/or technical assistance with integrating the CADD and expert system software.

C.3 THE FUTURE OF CADD HARDWARE AND SOFTWARE

The current "computer revolution" is causing rapid changes in the field of CADD systems. The impetus for these changes is the increasing sophistication and capabilities and the decreasing costs of software and hardware. Because of these rapid and continuing changes, predicting the future of CADD systems is difficult. Therefore, the research approach must be flexible to take advantages of these changes and follow the markets.

The current generation of minicomputers have tended to relegate mainframe systems to applications with a large number of users. Design work at the computer screen is becoming increasingly affordable with the dramatic reduction in cost of high resolution color graphics monitors and the required hardware to drive the monitors. Software is also becoming cheaper and more powerful. As more firms purchase software, the development costs can be spread over a wider

market, resulting in lower software costs. The features that are now found only on high-end mainframe systems may soon be available for microcomputers at a reasonable price.

APPENDIX D

DATA BASES

APPENDIX D

DATA BASES

This appendix provides additional information on the data bases referenced in Section 6.D and 7.0. These data bases have been identified as potentially useful inputs into either the development of the energy design model or in conjunction with the working of the energy design tool. The data bases have been divided into three groups: economic, energy simulation, and empirical energy-use data bases.

D.1 ECONOMIC DATA BASES

Economics have a significant influence on the set of practical design options. Consequently, it is an important subset of data bases. Two categories of data bases are necessary: descriptions of the material and construction costs of implementing conservation measures, and information about energy costs.

During the architectural programming and schematic design phases, costs for implementing different conservation measures must be estimated in order to identify viable options. As actual designs are developed in the design development phase, cost estimates based upon material take-offs may be required. Procedures and data bases for calculating systems costs and detailed material take-off cost estimating systems are available from several companies, including Means and McGraw-Hill Cost Information Systems (Dodge Data). This information is available in a number of formats including books, on-line data bases, and microcomputer data bases. The microcomputer Dodge Data, Design Estimator, is a menu-driven data base. R.S. Means also has a computerized cost estimation data base. One version, called Galaxy, is designed to work with a digitizing pad to make material take-offs from building blueprints. In addition, many of the CAOD packages include material cost data bases.

Cost data bases could also be based on bids and actual costs incurred for completed construction projects. For example, the General Accounting Office

maintains a data base of costs for government buildings. Another option is to make a data base from cost estimates developed for other research projects, such as the Small Office Building Handbook (Burt Hill 1985) or ASHRAE Standard 90. One advantage of the latter approach is the ease of integrating the data into the design process tool since the only options considered are predefined.

The interactions among building site selection, shell construction, layout, and HVAC systems is an important consideration in design process research. Specialized data bases, such as the ASHRAE HVAC O&M cost data base, will be a useful input to the research. ASHRAE and the Building Owners and Managers Association (BOMA) collected data on the HVAC maintenance costs for 342 office buildings of various sizes, ages, locations, and equipment types. Multiple linear regressions were used to develop estimates for costs per square foot of building for different building types and HVAC systems. Due to the relatively small sample size, good equations are not available for all system and building types. However, it is the only known data base of this type and will be useful when it is appropriate to consider operations costs.

The second type of economic data base contains information on energy costs, rate schedules, and fuel cost escalation rates. These data are necessary for investigating the economic merit of any energy saving investment which does not also reduce building construction and operation costs. A national data base of actual utility rates does not currently exist. However, a data base could be constructed from average regional fuel costs and escalation rates compiled by the DOE. The data base could then be supplemented through collection of actual utility rate schedules.

D.2 ENERGY SIMULATION DATA BASES

Simulations are useful for assessing the energy impacts of different building orientations, shell configurations, lighting systems, and mechanical systems. The design process research will identify where decisions are made which affect energy consumption. However, a qualitative assessment will be necessary to evaluate the energy use implications of those decisions. The

qualitative assessments can be based upon either rigorous simulations, or to some extent, on heuristic knowledge about the energy use impacts.

A number of data bases of simulations have been created by state energy offices, utilities, government research laboratories, and private consultants. The value of these data bases is difficult to assess since simulation of energy use is not an exact science. The quality and usefulness of each data base depends on the care taken in developing the inputs, the modeler's familiarity with the code, and the internal consistency between simulations. Internal consistency is necessary to ensure that estimates of changes in energy use derived from parametric simulations are comparable.

Existing simulation data bases used in the design process research must have the following characteristics: assumptions about each building type must be internally consistent; the simulations must be well documented; and there must be quality control over the simulation results. Potentially useful data bases are described below.

D.2.1 Building System Integration Program

PNL is conducting many DOE 2.1 simulations for its building specific studies project. The simulations for the small office buildings (less than 50,000 square feet) and apartments have been completed. Work for a design manual for retail stores was started in mid-1986. The simulations for the design manuals include numerous parametric energy analyses to assess the impacts of different energy conservation measures and building configurations. The simulation results will be a valuable input to the design process tool. Use of the data base of simulations for the small office building is already being tested in a trial design process knowledge system at PNL. The data base contains the total energy use, total electric demand, energy use by fuel type, and energy use for the HVAC systems by fuel type on a monthly and annual basis for a limited set of design options.

D.2.2 PNL/ASHRAE SP41 Test Buildings

The DOE 2.1 simulations developed for testing revisions to ASHRAE Standard 90 are based upon ten commercial building types, five representative climate regions, two to four HVAC systems per building type, and a variety of

shell, lighting, and daylighting configurations. The input and output data files and extensive written documentation for these simulations are archived at PNL and could be processed into a data base of simulation results.

D.2.3 Energy Targets

Another potentially large source of internally consistent DOE 2.1 simulations will be the commercial building energy targets work. Simulations will be made to develop energy performance targets. The research, conducted for DOE and ASHRAE SP51, will include parametric runs for a number of commercial building types.

D.2.4 Commercial and Small Apartment Conservation Service

A data base of energy bills, audits, and computer simulations for small commercial and apartment buildings (less than 3000 square feet) has been developed by the Oak Ridge and Argonne National Laboratories. The data are part of the Commercial and Small Apartment Conservation Service (CACS). The DOE 2.1 simulations were made to test the impacts of retrofit measures.

D.2.5 Other Sources

A number of other sources of simulation based data bases on end-use energy use are listed in the report Commercial Building End-Use Energy Metering Inventory. The difficulties and costs involved with obtaining other data bases, learning their idiosyncrasies, evaluating the quality of the simulations, and evaluating the usefulness of the simulations is judged not to be cost effective.

D.3 EMPIRICAL DATA BASES

Use of metered, empirically derived, data to assess the impact of building design strategies is a desirable supplement to simulations. However, it is difficult to obtain suitable data since most sources include a few case studies. It is difficult to know whether the results are valid for any other buildings besides the specific one metered. The Buildings Energy-Use Compilation and Analysis (BECA) and End-Use Load and Conservation Assessment Project (ELCAP) data bases may be useful in the design process research.

D.3.1 Buildings Energy-Use Compilation and Analysis

The BECA data base maintained by Lawrence Berkeley Laboratory (LBL) contains data used to characterize the results of energy savings from energy conserving retrofit measures and new building design features. In addition to building energy use data, the data base contains information on the building's attributes. The data base contains energy use data for before and after the retrofit measures that are related to HVAC systems, building envelope, and lighting systems. LBL's analysis of this data base should prove useful assessing the impact of conservation strategies.

D.3.2 End-Use Load and Conservation Assessment Project

The largest metering effort involving commercial buildings is the ELCAP sponsored by the Bonneville Power Administration. Two components of this research project will directly affect design process research: 1) the metering of buildings before and after conservation retrofit measures and 2) the metering of buildings involved with third-party purchase of energy savings agreements. The overall project includes metering over 300 commercial buildings in the Northwest with a subgroup of new commercial buildings. It will provide a wealth of data on how buildings use energy; analysis of these data will provide new insights into conservation strategies and the energy use patterns of new commercial buildings. The ELCAP data base is currently under development. It will be approximately another year before all the buildings are instrumented.

D.3.3 Other Data bases

The DOE is sponsoring two major end-use metering programs: the Commercial Buildings End-Use Data Base Development Project and the Passive Solar Commercial Buildings Program. The former project emphasizes new commercial buildings employing typical construction techniques, while the latter deals exclusively with passive solar designs. The End-Use Data Base Development Project includes metering of two small and two large office buildings, one retail store, and seven restaurants. Those buildings will be included in the ELCAP data base. DOE also sponsored the metering of six motels. Additional federal projects have included metering of large office buildings, and post offices.

Direct use of the empirical data is not anticipated in the design process research. However, data summaries and analyses of the data are expected to provide additional insights in energy use. The difficulty in using these data stems from the same difficulties inherent to design process research: the combination of building use, climate, and construction tends to make each building a unique case in energy analysis. However, the large data collection projects under way should support the development of statistically valid relationships between building construction and use characteristics and end-use energy consumption.

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APPENDIX E

DESIGN PROCESS MODEL CONCEPTS

APPENDIX E

DESIGN PROCESS MODEL CONCEPTS

Section 9.0 of this report describes the basic structure of a conceptualized model to describe the building design process. This appendix describes the conceptual whole-building decision model further by providing details and definitions of energy-related decision areas and decision factors contained in the model.

E.1 DECISION AREAS

The general decision areas in the design process models are outlined below. The whole-building decision model assumes that the owner has already decided that a new building is necessary, that it is economically and functionally feasible, that its design is feasible within project constraints, and that a site has been selected. Within this context, a number of decisions are made, based upon the information derived from a facility program.

1. Project Budget	This decision area includes the total project budget and its components. Components include design, construction, and operations budget; financing arrangements; and the owner's economic perspective. A determination must be made whether tradeoffs are permitted among budget subelements, and under what circumstances.
	In the first stage of the model's development, the primary decision will be establishing the construction budget. The operations budget will be examined only relative to energy operating costs and will be related to the owner's decision about the design energy budget.
2. Design Energy Budget	This decision includes both the format and amount of the building's energy budget, stated in energy

- units or energy cost units. This is not included as a subelement of the project budget since energy decisions are the focus of this model.
3. Designed Energy Performance
This decision includes calculating or estimating the current energy performance of the building, based upon current information and decisions. This estimate is a quantitative test of the success of energy decisions to date. One subdecision in this area would be determining if the performance is better than the budget and all other conditions are met.
 4. Project Cost Estimate
This decision is the current project cost estimate based upon current information and decisions. Proposed design strategies are based upon whether the estimate is either over or under the project budget. Within the decision model, this estimate might be done at intervals or after each decision.
 5. Construction Cost Estimate
This decision includes the current estimate of the construction cost portion of the project budget. It is compared with the construction cost portion of the project budget.
 6. Operating Cost Estimate
In the first stage of the model's development, this element will focus on energy operating costs and will be linked to the design energy performance estimate. In later stages it will include other operating costs.
 7. Economic Analysis
This is the current calculation or estimate of the overall project economics. It is compared with the initial owner's economic perspective and feasibility estimate. Several potential factors may be included in this analysis, depending upon

- the type of owner, the size, complexity and cost of the project, and the owner's preference for economic analysis. Analysis methods include life-cycle cost and pay-back.
8. Project Schedule A tight project development schedule can adversely affect energy design decisions. This decision area will not be included in the short-range model. It will be considered only in the long term, after the major elements of the model are firmly established.
 9. Site Plan Site planning decisions can constitute a complex set of design decision elements by themselves. In the initial model development, a homogeneous site that will permit optimal siting and orientation of the building relative to energy decisions will be assumed. Since site planning is extremely important, it will be included once the basic model is established.
 10. Sitework Plan This decision area is not included in the short-term decision model but will be included as a long-term research objective.
 11. Landscape Design
Vegetation This decision area includes windbreaks and their use for solar control, etc, and will be a mid-term objective.
 12. Geometric
Proportions Owner requirements or site constraints (tall versus. low buildings, etc.) are extremely important. Decisions in this area include number of stories and surface to volume ratio.
 13. Configuration This area is closely related to the geometric proportions decision area. There are two aspects: 1) Is configuration, or elements of the configuration, dictated by owner requirements?

and 2) Are some building configurations, or configuration elements, more energy effective than others for the set of building goals and requirements? In the initial model development only a small set of predefined alternative configurations will be examined.

14. Orientation

This decision area involves orientation of the building as a whole, spaces within the building, or physical elements of the building. Decisions can require complex spatial analysis and trade-offs. The initial model will be a simple treatment. The building orientation will be constrained to two alternatives: east-west, or north-south (assuming a simple rectangular building configuration).

15. Massing Plan
Considered

This is primarily an aesthetic concern, and is a constraint in the energy decision model. Constraints imposed due to massing considerations include geometric proportions or configuration requirements of the owner.

16. Area and Volume
Calculations

The gross building volume estimate is based upon current information and decisions, and is derived as the aggregate of the volumes of all spaces defined for the building. It includes any building height or volume restrictions.

The gross building floor area estimate, based upon current information and decisions, is the aggregate of the floor areas of all spaces defined for the building. It includes all floors in a multistory building.

The estimate of net area refers to several factors, including net conditioned space (relative

to zoning and HVAC design); net rentable area; net usable area, excluding circulation; and structural and support elements.

Room area calculations are based on the features of the space layout for different activities within the building. Activity area criteria are based upon program requirements.

17. Space Layout	This area includes the sizes of spaces and their relative locations horizontally and vertically.
18. Floor Plan Layout	This decision area includes the synthesis of factors from several other decision areas, including the space layout. From an energy perspective, the decision area includes zoning, orientation of spaces, and whether spaces are open or partitioned.
19. Circulation Design	This area is a subset of space and floorplan layout decision
20. Operations Design	This area includes design decisions based on flow of people, materials and information.
21. Envelope System	The building envelope is a system and it is necessary to investigate system alternatives, and their impacts (energy, cost, appearance, etc). A possible delineation of generic envelope systems could include inert envelope systems (typical systems) and active envelopes. Active envelopes include responsive solar control features, natural ventilation control features, features integrated with HVAC systems (e.g., air flow window systems, etc.), daylighting and integration with interior lighting systems, and active storage or relocation of thermal imbalances.

22. Envelope Design	This area addresses specific decisions related to the design of the envelope system selected or the comparison of designs of alternative systems. This includes all building surface elements (and openings) that are exposed either to the outside air or to subsurface conditions.
23. Fenestration Design	This area includes the type, amount and location of the fenestration. This is one of the most important subelements of the envelope system selection and design.
24. Construction Materials Selection Absorptivity	Energy related aspects of these decisions include material costs, thermal storage properties, and reflectivity to various portions of the spectrum.
25. Exterior Finishes Selection	This area is a subset of the construction materials decision area.
26. Interior Finishes Selection	This area is a second subset of the construction materials selection decision area.
27. Structural Systems Selection	This area influences many energy decision areas.
28. Structural Systems Selection	This area will not be included in the first stages of development of the selection decision model.
29. Lighting Systems Selection	This is an important decision area because of the high proportion of lighting energy use and the impact of lighting heat upon building space thermal loads. A number of factors can be involved: interpretation of lighting criteria and requirements, type of lighting applications, types of lighting system(s), efficiency of the lighting applications and systems, extent and type of

- controls, daylighting, impact on envelope system selection and design, and impact on HVAC system selection and design.
30. Lighting Systems Selection The design decisions for lighting systems will be limited and included in the initial decision model.
31. Support Service Selection This area includes decisions that depend on owner requirements for support services for activities within the building, and on characteristics of the building. This includes vertical transportation, service hot water, services for processes related to functional activities, etc. Energy factors include energy used, systems efficiency, internal heat generation (sensible and latent), and waste heat reclamation opportunities. This area will not be included in the initial decision model development.
32. Support Service Selection This area includes decisions related to design of service systems selected. This area will not be included in the initial decision model development.
33. Equipment/
Furnishing
Generation
Selection These decisions affect both the internal heat of spaces within the building, and the thermal and visual properties of the spaces.
34. HVAC Systems Selection This area is one of the most important decision areas in the decision model, along with envelope and lighting system selections.
35. HVAC Systems Design A limited number of HVAC system design decisions will be addressed in the initial decision model.

36. Code Compliance This area is an assessment of compliance with relevant codes based upon the current design and energy decisions.

E.2 FACTORS TO BE CONSIDERED WHEN MAKING DECISIONS

For each of the design decisions addressed in the design process, a large number of factors may need to be considered. Many of the factors influence building design and can impact energy decisions, either directly or indirectly. The factors are organized into three groups: human, physical, and external. Both the human and external factors can strongly influence the design, but the designer often has less control over them than physical factors. Physical factors are most easily controlled by the designer when design decisions are based upon programming information. The relevant programming effort (facility or component) provides the necessary information about these factors for making the design decisions.

E.2.1 Human Factors

Human factors are extremely important since they provide significant guidance for energy design decisions even before the physical or external factors are considered. Each is discussed briefly below.

Activities

A building is a response to the need to house a set of activities within a controlled environment and to provide services that are either required for those activities or desired by the owner. Descriptions of the activities provide information about the energy-related characteristics of the spaces and buildings that will be designed to house those activities. For example, the following factors are associated with activities:

- occupancy levels
- occupancy pattern (timing and intensity)
- visual requirements (color, contrast, etc.)
- thermal comfort requirements
- services for water, equipment, etc.

- relationship to outdoors (desire for view, etc)
- internal heat levels generated from occupant requirements.

Each characteristic influences the design decisions, and the characteristics of activities can be derived from analysis.

Owner's Goals/Objectives

The owner's goals and objectives strongly influence the building's design. Several goals will be considered in simplified form in the early research analysis, including energy use, investment, construction cost, operating cost, design cost, building image, and building quality. The building quality influences what building materials and systems are acceptable.

Decision Makers

A primary energy research concern is tradeoffs among different building systems. Often multiple decision makers from both designer and owner organizations are involved in a given decision. It is important to identify key decision makers for each decision. For example, if an architect or lighting designer wants to use daylighting in a building design, he may be counting on reductions in cost from downsizing the air conditioning system to pay for increased lighting costs. If the mechanical engineer does not trust that the equipment can be downsized, the cost justification for the entire strategy may disappear.

Characteristics of Designers

The attitude of both the owner and the design team can strongly influence energy decisions. Several attributes of designers will be examined, primarily from a point of view of willingness to accept innovation. Some designers may be very willing to select energy decisions that involve innovation (i.e., risk) whereas others are not. The following categories, derived from diffusion theory, describe an important attribute of designers (and owners) relative to energy conservation technologies.

- **Innovators** designers both willing and motivated to take risks by adopting new high-risk, highly speculative strategies or technologies without a proven track record.

- **Early Adopters** highly respected designers willing to take some risk in trying some innovations already attempted by the innovators. Their risk-taking level is considerably lower than that of the innovators.
- **Adopters** respected designers willing to take less risk by adopting innovations already well developed by the early adopters. This is a limited set of the items tried by the early adopters.
- **Typical** designers with fairly low-risk taking levels. They will try a new technology that has already proven successful on at least five buildings very similar to the one at hand. For example, the fact that automatic daylighting controls have been used successfully on five Federal office buildings is not sufficient evidence for attempting the use of such controls on a speculative office building.
- **Conservative** designers with extremely low-risk taking levels. They will only use already well accepted technology.

Interactions

Often, especially on smaller projects, the full design team is not assembled until the schematic design is complete. Only the architect is involved in developing the schematic design. In these cases, the schematic design product is only a partial solution that typically resolves building size, configuration, floor plan layout, basic envelope system selection and materials. Decisions on lighting and HVAC systems are either assumed by the architect, or are deferred until later.

Unless all the key decision makers are involved at this stage, important tradeoffs among systems cannot be considered and significant opportunities are lost. Even if all players are involved at this stage, the opportunities are lost if they do not communicate with each other about the impacts on other systems of energy-related decisions. (This may well be more the rule than the exception.)

While this lack of timely involvement or lack of communication is a potentially important factor in the design process, a simplifying assumption in the early research effort is that an ideal team exists and is exercising good communication about energy related interactions among different systems. Issues of partial team involvement or of incomplete communications will be addressed later, when other aspects of the research into the energy-related design process are better developed.

Design team communication needs to be emphasized in the long-term because of the importance of the interaction among the multiple decision makers on actual design problems. Thus, tools for conflict resolution or for considering multiple value sets need to be explored as part of the long-term research effort.

Policies/Codes

While this is considered a critical factor in the human factors area within the AIA approach to facility programming, this topic will be addressed in the external factors area.

Preferences

Owner and designer preferences could include potentially effective energy choices from consideration during design. Conversely, they can favor energy choices that might otherwise be ignored. Two examples illustrate this point:

1. **Systems Emphasis:** A design team may place more emphasis on one building system over others as a primary source of energy conservation strategies (often without regard for "objective" energy opportunities or priorities). The system favored might be the envelope, or lighting, or HVAC. If the focus of energy conservation options is first placed primarily on one system, this tends to preclude full consideration of strategies for other systems, due to diminishing returns. Thus, the design team's preferences for focusing on a particular system first can have a large impact both on the total set of strategies that will be considered, and on the sequence and priority of the strategies considered.

2. **Climate Rejecting versus Climate Adapting Design:** A climate-rejecting design approach develops a building design that is isolated from the external climatic conditions. Emphasis is then placed upon energy strategies that make the building systems energy efficient. A climate-adapting design approach first selects strategies that allow the building to take advantage of changes in the external environment as the first avenue. Both approaches, as well as mixtures of them, are valid and produce good results (ref. Ternoey, et al 1982). However, the two extreme approaches tend to produce radically different building solutions (using different sets and sequences of design strategies) applied to the same general problem.

The energy design methodology and tools need to be cognizant of these preferences. Ideally, a design tool should 1) assist the designer in understanding why alternate approaches might be better, and 2) accept the designer's preferences if the designer is tenacious about his/her beliefs.

E.2.2 Physical Factors

Physical factors make up the second major set of information about the facility requirements and constraints that guide decision making. Information about these factors can include extensive lists about all aspects of the facility and its contents. The set of physical factors for energy decisions is more limited and includes the items listed below.

Site Conditions

Site conditions have an significant impact on energy decisions. Once the site is selected, program information about site conditions provides the parameters for site design.

Building/Facility

These factors include owner requirements and criteria for the physical characteristics of the building.

Envelope

These factors include owner requirements and criteria for the envelope of the building.

Structure

These factors include owner requirements and criteria for the building's structural system.

Systems

These include program factors for owner requirements and criteria for the various building systems, including: HVAC, lighting, support services, and controls. Controls are considered a separate system since each building system (including the envelope) can have either manual or automatic controls. The building can also have an integrated controls for all of the systems (e.g., EMCS).

Space

Spaces are the physical counterparts of activities. The spaces contained in a building are direct responses to the activities specified under the human factors category and the physical spatial conditions that must be provided to support those activities. Space decision factors include owner requirements and criteria for types of spaces, spatial dimensions, and spatial relationships. For energy decisions, there are two types of important spatial relationships: 1) those having to do with grouping of spaces into similar thermal zones or lighting zones; and, 2) the relationship of a space or group of spaces to the external environment.

Functions

These factors relate strongly to spaces and to the activities factor within the human factors grouping. The physical functions within a building describe physical consequences of the requirements specified within the activities factor.

Operations

The intended intensity, duration and pattern of operation of the building will have major impact on the identification and selection of appropriate energy decisions. This factor contains owner specifications, requirements, and criteria for operations characteristics.

Circulation

Circulation consideration is important from a general design point of view and can also affect energy decisions. For example, exterior climate will influence whether circulation areas are indoors or outdoors.

Energy Use/Conservation

This factor contains program information about owner objectives, requirements and criteria about energy use aspects of the building and its systems.

E.2.3 External Factors

External factors often act as boundary conditions on the design. They are constraints imposed from outside the design process as conditions to be met. They are generally conditions that the designer (and often the owner) have little control over, or at least substantially less control than either the human factors or physical factors. External factors related to energy decisions are discussed briefly below.

Legal Restrictions (Codes/Standards/Regulations)

Legal restrictions form a set of conditions that must be met. Ultimately, in a design tool, one can envision having machine-readable codes and standards accessible through low-cost storage devices, and processors capable of identifying when specific provisions apply to a given decision. (The National Bureau of Standards is working on this type of system.)

This research will focus on the ASHRAE Standard 90 energy code. For example, one test of a set of energy decisions is whether the results pass the appropriate Standard 90 provisions. Provisions from other types of codes will need to be examined as well because they often constrain or prohibit certain energy decisions. Because of the complexity involved, only selected requirements of building and safety codes will be considered for the early stages of this research.

Climate

This is a fundamental external factor to many energy design decisions. Information about climate is typically derived from an analysis of the macro and micro characteristics of the building site.

Energy Supplies/Prices/Availability

This factor influences the emphasis placed on energy decisions, as well as the choice of fuels considered during the building design.

Time

Project schedules and deadlines influence energy decisions.

Costs/Budget

This factor contains program information (facts, predictions, and recommendations) about project budgets and costs. It may be very general or may involve detailed budgets and cost projections for subelements of the project.

Costs/Benefits

This factor contains owner objectives and criteria pertaining to evaluation of cost versus benefits during design decision making.

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APPENDIX F

OVERVIEW OF THE LIMITED RESEARCH PLAN

APPENDIX F

OVERVIEW OF THE LIMITED RESEARCH PLAN

A limited long-range plan for conducting the research and for developing an energy design process tool for new commercial buildings is presented in Table F.1. The plan presented is designed to fit available funding levels. The table relates the restricted set of activities of the limited research plan to the more comprehensive plan, and shows how the time to accomplish each activity would be longer because of funding constraints.

Like the comprehensive plan, the limited research plan is proposed as a multiyear effort consisting of three Phases, in addition to the Phase 1 feasibility planning already accomplished. The three additional Phases are:

- Phase 2: develop whole-building energy design methodology
- Phase 3: expand methodology
- Phase 4: integrate the research results from Phases 2 and 3

In each Phase of the limited effort three major research activities will be accomplished:

1. conducting design process research
2. developing knowledge-based systems and associated tools to support and to present the research
3. coordinating.

The plan is to develop one portion of the comprehensive plan, the whole-building energy design decision model, and the tools for supporting the development and use of that model. The focus is new commercial buildings. Each of the three phases of the limited research plan are summarized briefly below.

F.1 PHASE 2: DEVELOP METHODOLOGY

Phase 2 research will focus on:

- the whole-building energy design decision model
- the early design stages of new building design

TABLE F.1. Detailed Schedule: Proposed Limited Design Process Research Plan

	Phase 2 Development			Phase 3 Expansion			Phase 4 Integration		
	FY87	FY88	FY89	FY90	FY91	FY92	FY93	FY94	FY95
1. Whole-Building Design Process									
A. New Buildings									
- Develop Energy Decision Methodology	////////								
- Conduct Design Process Research	//////////								
- Develop Research Prototype Knowledge-Based System (KBS) Design Model	//////////								
- Develop links from KBS to CADD Systems, Data Bases, Simulation Tools, Advanced Imaging and Computers	//	//		//////////					
- Expand Methodology to All Building Types				//////////					
- Expand Methodology to Include Construction Decisions				//////////					
- Expand Methodology to Include Building Commissioning				//////////					
- Integrate with Building Subsystem Models				//	//	//////////			
B. Retrofit									
- Adopt New Building Methodology									
- Conduct Retrofit Specific Design Process Research									
- Develop Retrofit Research Prototype Knowledge-Based Systems Model									
2. Building-Subsystem Design Process Research									
- HVAC									
- Lighting									
- Envelope									
- Daylighting									
- Service Water Heating									
3. Integration									
4. Coordination									
- Public Sector	//////////	//////////	//////////	//////////	//////////	//////////	//////////	//////////	//////////
- Private Sector	//////////	//////////	//////////	//////////	//////////	//////////	//////////	//////////	//////////
- Links to Systems	//////////	//////////	//////////	//////////	//////////	//////////	//////////	//////////	//////////

- the small office building type
- the identification of energy opportunities and good design strategies.

Phase 2 will include substantial research on incorporating energy decisions into the building design process, and will build upon the extensive existing

body of energy research results for small office buildings. The Phase 2 research plan addresses the development of a whole-building model that can be used to integrate building energy subsystem decision models that are developed independently. However, ideally, such subsystem decision models should be part of the research plan (as indicated in the comprehensive plan). Their development is not included specifically because of anticipated funding limits.

Phase 2 will consist of four major tasks, each with a number of subtasks:

- Task 1. develop detailed whole-building energy design decision model
- Task 2. conduct design process research on building-subsystem interactions
- Task 3. develop research prototype, knowledge-based system, computer model
- Task 4. coordinate the tasks.

Phase 2 will produce a research prototype, knowledge-based system containing the design process research results.

F.2 PHASE 3: EXPAND METHODOLOGY

Phase 3 will focus on expanding the model to include:

- additional building types
- decisions made during construction
- links to related tools
- good design solutions for energy strategies selected.

The procedures used for the small office building decision model will be used to expand the breadth of the whole-building design model tool. Two additional building types, the retail store and mid-rise and high-rise apartment buildings, will be added to the system.

Phase 3 will produce a more robust research prototype, knowledge-based system incorporating the expanded building-type domain. Data on building materials, material costs, and design options will be integrated into a CADD database. The CADD system will also be used for presenting design options formulated by the designer with the assistance of the design tool.

F.3 PHASE 4: INTEGRATE PHASE 2 and 3 RESEARCH RESULTS

This long-term research phase will involve the integration of the separate research results from Phases 2 and 3. Included will be final integration of the developed methodology and supporting knowledge-based system with one or more comprehensive building design tools with CADD as the focal point. The final product will be a usable energy design component of a building design tool.

F.4 DETAILS OF THE FIRST PART OF THE LIMITED RESEARCH PLAN (PHASE 2)

This section describes a proposed detailed research plan for Phase 2 of the limited overall design process research plan. This detailed Phase 2 plan concentrates upon the development of a whole-building energy design decision model. The primary focus of this decision model is the energy and cost interactions among building subsystems.

Phase 2 will concentrate on research to develop a detailed framework for examining interactions among building subsystems. This research is needed to provide means by which such building subsystem interactions can be addressed and resolved, especially during the early design phases. The research will include the consideration of qualitative factors, aesthetic objectives, and graphical relationships as well as quantitative energy and cost relationships.

Development of building-subsystem energy decision models is not included in this detailed plan for Phase 2 because of limited funding. However, this Phase 2 plan does include assessing the feasibility of linking with one or more independent subsystem energy decision models that may be developed separately from this research effort.

A research prototype knowledge-based system model will be developed as a primary vehicle for both conducting and presenting the research. This research prototype model will expand the concepts developed during Phase 1 in the development of the experimental prototype model.

As discussed earlier, Phase 2 will consist of four major tasks:

1. develop detailed whole-building energy design decision model

2. conduct design process research on building-subsystem interactions
3. development of research prototype knowledge-based system computer model
4. coordinate.

Details of each of the four major tasks are described below.

Task 1: Develop Detailed Whole-Building Energy Design Decision Model

This task will expand the decision model developed in Phase 1 and will increase the level of detail of the model. A general structure for this decision model has been developed during Phase 1 and is described in Section 9.2.1 of this Phase 1 report. The model addresses those energy decisions that pertain to energy and cost interactions among building-subsystems. The current development of the decision model from Phase 1 does not contain any details about how the decision factors relate to each decision area.

Ultimately, the whole-building energy decision model will be developed to be general enough to apply to three important commercial building types. However, to constrain the focus of this task during Phase 2, the main focus for the decision model will be energy decision processes for small office buildings.

Details of this decision model can be developed in parallel with the activities of Tasks 2 and 3 (described below). However, the final form of the model will depend partly upon information to be developed in Tasks 2 and 3. Therefore, this task is separated into subtasks.

Subtask 1.1: Develop Draft Decision Model

This subtask will develop a draft decision model that will contain general decision structures for the major energy-related decisions. The draft model will be used to guide the detailed of Tasks 2 and 3. This subtask will produce a report describing the draft whole-building energy design decision model.

Subtask 1.2: Develop Revised Decision Model

This subtask will expand the detail and refine the content of the draft decision model from Subtask 1.1, based upon the results from Tasks 2 and 3.

The decision structures for the major energy decisions will be developed in further detail, and general decision structures will be developed for the remaining decision areas. This subtask will produce a report describing the final whole-building energy design decision model related to small office buildings.

Task 2: Conduct Whole-Building Design Process Research Examining Building-Subsystem Interactions

The Small Office Building Handbook, the Tennessee Valley Authority design manuals, and the DOE ASHRAE SP41 analyses will form initial resources for developing energy-efficient design strategies for offices. The first step is to determine the relationship of the strategies in the manuals to the energy design process. The next step is to expand upon these strategies because these manuals consider only limited detail for a very limited set of strategies.

The proposed design tool will allow consideration of more strategies since the computer can quickly assess a broader range of options and perform necessary calculations to assess their impacts.

The approach calls for using expertise in each of the following domains: architectural design, lighting design, mechanical system design, experience in design of a large number of small office buildings, and knowledge in energy efficient design.

Design process research conducted for this task will be the basis for a research prototype knowledge-based system. Following review and assessment of the strategies and process employed in the research prototype, the energy design model and associated tool will be refined and extended to cover a broader range of design cases.

Task 3: Develop Research Prototype Knowledge-Based System Computer Models to Structure the Design Process Research

This task will develop one or more research prototype knowledge-based system computer models as vehicles for conducting the research and for presenting the research results. The computer models will incorporate expert system heuristic rules and any appropriate hierarchical (frame) structures to organize the problem domain. Links will also be investigated between the computer

models and one or more energy analysis tools, economic analysis tools, energy data bases, cost data bases, and CADD systems.

The software/hardware system used will most likely be either the KEE software package used on a Symbolics machine, or the OPS83 language on the MicroVAX. The knowledge and facts will be based upon the research described in Task 2 above. Because of the number of subelements involved in this task, it is divided into several subtasks.

Subtask 3.1: Selection of Phase 2 Development Hardware and Software Systems

The planning activities in Phase 1 identified criteria for selecting hardware and software systems for further R&D efforts (see Appendix A), and used these criteria to identify several likely candidates useful for further research development. In this subtask one or more computer hardware and software systems will be selected to be used as part of the Phase 2 design process research effort.

It may be desirable to use two types of systems concurrently for development purposes. Each has advantages. Examples include:

1. The KEE expert system development package on a Symbolics computer system--A sophisticated system such as this will most likely meet the requirements as the development tool for the comprehensive computer model. This system is available at PNL and well satisfies the selection criteria identified in Phase 1 (Appendix A of the Phase 1 report).
2. One or more systems available on microcomputers (IBM PC compatibles) (such as OPS5 or Prolog) for testing and developing selected concepts and research components--This approach can produce incremental products from parts of the research effort that have the potential to be used as isolated packages much earlier than the products from the integrated research prototype system. Some examples are discussed in Subtask 3.7, below. This approach can also be linked, at low cost, to existing energy and economics analysis tools, as well as to cost

and energy data bases. Products of these microcomputer-based systems will be progressively incorporated into the KEE/Symbolics system (or other system selected).

This task will produce a report describing the system(s) selected, the rationale for their selection, and how their uses will be coordinated.

Subtask 3.2: Identify Capabilities of the Knowledge-Based System tool
Selected and Design the Basic Structure of the Energy Decision Model

This task involves understanding in detail the capabilities and limitations of the knowledge-based system tool selected (e.g., the KEE/Symbolics combination) for addressing the problem domain and then designing the basic elements of the energy decision research prototype model. The draft whole-building decision model from Phase 2 Subtask 2.1 will be used as a basis for constructing the elements of the model in terms of the computer system selected.

This model will focus on energy decisions for small office buildings, and will use the substantial research basis for small office buildings identified in Phase 1. This task will produce a short report describing the structure of the proposed energy decision research prototype knowledge-based system model.

Subtask 3.3: Develop Draft Research Prototype Energy Decision Model Using
the Selected Knowledge-Based System

Using the results of Subtask 3.2, a first draft research prototype energy decision model will be developed. The model will focus on identifying appropriate major energy design strategies for a subset of small office building design problems.

This first draft research prototype will address only the major energy decision areas for small office buildings, as identified in the draft whole-building energy decision model developed in Subtask 2.1. Heuristic rules will be extracted from existing research results for small office buildings, including research literature, as well as from individual expertise of the Phase 2 project team members. Further heuristic rules may be adapted from Task 2 as well.

The main product of this subtask will be the knowledge-based system research prototype itself. A report will also be produced that describes the characteristics and behavior of the research prototype. This subtask does not include linking the research prototype to energy analysis computer models, to economic models, or to cost or energy data bases.

The criteria for success for the first draft research prototype to be produced in Phase 2 by this task is that it be able to identify appropriate major energy design opportunities and strategies for the subset of small office buildings considered and that energy experts be able to identify such opportunities and strategies.

Subtask 3.4: Investigate Linking the Research Prototype Knowledge-Based System to CADD System

Integration of the expert system element of the design tool with CADD portion will be investigated in three stages.

The first stage will be accomplished in Phase 2. It is to conduct additional research into a few CADD systems to develop a better understanding of how to develop the interface between a CADD system and the prototype. The most likely CADD systems are RUCAPS, GDS, and AutoCAD.^(a) AutoCAD has been identified because it is the most popular PC-based system and its architecture is relatively open, as evidenced by the number of third-party software products built around it. The other two packages were selected since they were developed with the capability of doing design development work rather than simply drafting. Cooperative development agreements will be further explored with CADD manufacturers in order to ensure private-sector involvement and cost-sharing benefits to both the CADD manufacturer and DOE.

The second stage will be accomplished in Phase 3. It involves developing a basic interface to allow the knowledge system component to read data from the CADD data base. These data include cost of materials, thermal property of

(a) AutoCAD (produced by AutoDesk) is a 2 1/2 dimensional based system that runs on a number of microcomputers including the IBM PC. RUCAPS (GMWC) and GDS (McDonnell Douglas Automation Company) use full 3-dimensional object-oriented data structures.

materials, building dimensions, and any other useful data for developing design options. The link eliminates the need for duplicate data bases.

The third stage will be accomplished in Phase 4. At this point the design tool would be able to update the data base in the CADD system. The update information would include information on how to implement selected design strategies.

Subtask 3.5: Investigate Linking Research Prototype Knowledge-Based System to one or more Energy Analysis Models

This subtask involves investigating the link between the design process research prototype model and an existing energy analysis model. Given the desirability of using a public domain energy analysis model, two options are likely: DOE-2 and ASEAM2. An alternative may be to link the prototype to one or more regression equation models. Based upon project requirements as developed within Phase 2 and upon the decisions made in Subtask 3.1, one or more of these energy models will be selected, and potential links will be investigated. These links would permit on-line checking of the appropriateness of sets of heuristic rules within the model.

This subtask will produce a short report describing the operation of the link and the combined system.

Subtask 3.6: Investigating Linking Research Prototype to an Economic Analysis Model

This subtask involves investigating the link between the design process research prototype model and an existing economic analysis model. A likely candidate for this economic model is a version of the BLCC model developed by The National Bureau of Standards (NBS).

Based upon project requirements as developed within Phase 2 and on decisions on made in Subtask 3.1, an economic analysis model will be selected and potential links will be investigated. This link will permit on-line checking of the economic appropriateness of sets of heuristic rules within the model.

This subtask will produce a short report describing the potential operation of the link and the combined system.

Subtask 3.7: Investigate Linking the Research Prototype to a Computer Based Building Cost Data Base

This subtask involves investigating the link between the design process research prototype model and an existing computer-based building cost data base. Several commercially available data bases exist and are available for computer system capabilities ranging from microcomputers to mainframes.

Based upon project requirements as developed within Phase 2 and decisions made in Subtask 3.1, a data base will be selected and a potential link will be investigated. Because all available cost data bases are proprietary, the selection process will depend partly upon the results of the coordination accomplished with private industry groups in Subtask 4.2.

This potential link would permit more refined on-line analysis of cost impacts of the economic appropriateness of sets of heuristic rules within the model. The link would require an expansion of the sets or rules for building construction impacts of sets of heuristic rules, from that developed in Task 2.

This subtask will produce a short report describing the operation of the link and the combined system.

Subtask 3.8: Identify One or More Building-Subsystem Energy Design Models and Explore Linking These Models to the Whole-Building Research Prototype Being Developed

This subtask will identify one or more energy design decision models being developed independently (for example, the proposed NBS infiltration model, or the fenestration model proposed at LBL). One or more of the identified subsystem models will be examined for its potential to be linked to the whole-building model being developed within this Phase 2, Task 3. If feasible, efforts would be made in Phase 3 to link the two models.

This will enable the whole-building model to take advantage of the more detailed decision processes within the building-subsystem being linked. It will also permit decisions made within the specific building subsystem to have impacts on other building systems. This is an important subtask, for it constitutes the first attempts toward building a comprehensive, integrated energy

decision model that includes both whole-building-subsystem interactions and detailed decision analyses within specific building subsystems.

Subtask 3.9: Develop an Interim Research Product--A Post-Processor for a Public Domain Energy Analysis Tool

This subtask will use one of the knowledge-based system development tools to develop a post-processor for a public domain energy analysis tool. The post-processor will use the results of the design process research from Task 2 above to give guidance to users of the energy analysis tool. The post-processor will examine both the data inputs and the loads and energy outputs from the energy analysis tool. It will identify likely energy design strategies to be considered next in using the energy analysis tool. Possible energy analysis tools to use include DOE-2, ASEAM2, and Controlite.

Task 4: Phase 2 Coordination

During Phase 2, coordination will be established and maintained with both public and private sector groups involved in related development efforts. This coordination has three primary objectives during the Phase 2 research:

1. coordination with related R&D efforts being accomplished by others
2. coordination with energy design decision models for specific building subsystems that are being developed independently from this research effort
3. coordination with related computer hardware and software systems that may be linked to the system being developed during Phase 2.

The task is separated into three subtasks according to the type of groups being contacted and the type of contact.

Subtask 4.1: Coordination with Public Sector

A number of public sector organizations were identified in the Phase 1 planning as being involved in related work, so coordination with their efforts is important. This subtask involves establishing continued coordination with these organizations, to keep them apprised of developments from this project

and to enable their work to be coordinated with the activities of this project. This will ensure that proper coordination occurs and that redundant work does not occur.

The subtask involves establishing a contact list within each of the organizations, telephone communication of activities with those individuals on a routine basis, and distribution of interim reports of project results to those individuals. Also, the subtask involves two meetings with these individuals to jointly review progress. Many of these individuals are anticipated to be ASHRAE members; these meetings may be scheduled to occur during or related to the semiannual ASHRAE conferences.

Subtask 4.2: Coordination with Private Sector Organizations

A number of private sector organizations were identified in Phase 1 as important to coordinate with, either because they were involved in related work (CADD systems, cost data base systems, etc.), or because they had specific systems or products with which this research might interface.

This subtask involves either establishing coordination with such groups, or in some cases, continuing coordination that was established in Phase 1. These include university groups, professional or trade organizations, and companies. Organizations will be identified, as well as specific contact individuals within each organization. These individuals will be included on distribution lists for interim project products.

Subtask 4.3: Establish Arrangements for Direct Interfacing of Systems

Specific organizations were identified in Phase 1 which have products or systems for which direct interfacing is desirable. Other organizations with such systems or products will be identified in this subtask.

This interfacing is considered important, especially with CADD system vendors, because the ultimate product of this research is seen as being attachable to existing CADD systems as a subsystem that would use the CADD data base as a common information structure. A second area is those vendors with computer-based building-cost-estimating systems. Such interfacing will improve the usefulness of research results and will also reduce research development costs.

Arrangements will be sought with selected organizations to enable the direct interfacing of their products or systems with those being developed as part of this Phase 2 effort. The results of this coordination will feed directly into other Phase 2 tasks, as indicated in those tasks.

F.5 TECHNICAL REVIEW OF THE PROPOSED DESIGN PROCESS RESEARCH PLAN

The final step in the Phase 1 effort will be a technical review both of this Phase 1 planning effort and of the proposed long-range research plan presented below. This technical review will consist of the presentation and discussion of this planning report with the research community.

As part of the technical review, a review meeting will be held during the summer of 1986. Individuals and groups active in related areas will be invited to participate.

Additional short-term technical review activities that will be incorporated into the research include:

- present work in progress at appropriate symposiums
- demonstrate research prototypes to the research and design community.

These technical review activities are intended to foster communication among research organizations pursuing projects with similar goals, promote cooperation and integration of research efforts, and insure that the research culminates in a useful product. Review of the design tool development research is scheduled at key stages in the project's development. Technical review ensures that the research yields a useful result.

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