The Technical and Economic Feasibility of Establishing a Building System Integration Laboratory

September 1989

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THE TECHNICAL AND ECONOMIC FEASIBILITY
OF ESTABLISHING A BUILDING SYSTEM
INTEGRATION LABORATORY

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FOREWORD

This report is one in a series describing research activities in support of the U.S. Department of Energy (DOE) Building System Integration Research Program. The goal of the program is to develop the scientific and technical basis for improving integrated decision-making during design and construction. Improved decision-making could significantly reduce buildings' energy use by the year 2010.

The objectives of the Building System Integration Research Program are

- to identify and quantify the most significant energy-related interactions among building subsystems [for example, walls; roofs; windows; heating, ventilation, and air conditioning (HVAC) subsystems and equipment; lighting; power]
- to develop the scientific and technical basis for improving energy-related interactions in building subsystems
- to provide guidance to designers, owners, and builders for improving the integration of building subsystems for energy efficiency.

The lead laboratory for this program is the Pacific Northwest Laboratory. A wide variety of expertise and resources from industry, academia, other government entities, and other DOE laboratories

are used in planning, reviewing, and conducting research activities. Cooperative and complementary research, development, and technology transfer activities with other interested organizations are actively pursued. The research reports prepared for the program are listed in a bibliography at the back of this report.

In this report, the feasibility study of an experimental building system integration laboratory is summarized. Comments about the work described in this report will be appreciated by the authors or program managers.

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SUMMARY

On December 22, 1987, the U.S. Congress provided funding to the U.S. Department of Energy (DOE) "to study the feasibility and conceptual design of a whole building system integration laboratory" (*Title II of Pub. L. 100-202*). A whole-building system integration laboratory would be a full-scale experimental facility in which the energy performance interactions of two or more building components, e.g., walls, windows, lighting, could be tested under actual operating conditions. At DOE's request, the Pacific Northwest Laboratory (PNL) conducted the study with the assistance of a technical review panel representing other federal agencies and the academic and private sectors, including professional societies, building component manufacturers, and building research organizations. The results of the feasibility study are presented in this report.

BACKGROUND

Until FY 1984, DOE buildings research had concentrated on improving the energy efficiency of individual materials, components, or subsystems such as insulation, windows, heating and air conditioning equipment, and lighting. However, since FY 1984, DOE has received funding to explore whether increased attention to the integration of components and subsystems during the design and construction phases of buildings could lead to greater energy savings.

Building system integration research is based on the theory that a building functions most efficiently when it is designed, constructed, operated, and maintained to take maximum advantage of the energy performance interactions of its parts. Retrofitting and advanced components cannot make up for a poor design. This research analyzes the combined effects of the building envelope (walls, roofs, and foundations), heating, ventilating, and air-conditioning (HVAC) equipment, service hot water equipment, lighting, occupants, and climate on the amount of energy that a building uses. The objective is to improve the energy efficiency of buildings by developing new and better ways to select, combine, and integrate major building components so

that together they operate as a more energy-efficient whole. The whole building, then, is designed and constructed as a better and more efficient operating system.

The Building System Integration Research Program was established because it was believed that substantial energy savings improvements were possible in buildings designed to optimize energy efficiency. This belief was based on the results of computer simulations of buildings redesigned for optimal energy savings. These results indicated that significant energy savings were possible in commercial buildings if the operation of the subsystems within those buildings were correctly integrated. For example, a properly designed and constructed commercial building can minimize use of nonrenewable energy for heating and cooling and be 50% to 70% more efficient by storing excess energy generated by people, lighting, and equipment for heating and cooling.

Energy conservation standards recently developed by DOE, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE), and the Illuminating Engineering Society of North America (IESNA) are based on the concept of building system integration. Together these organizations have established standards that no longer simply prescribe (e.g., require specific amounts of insulation), but rather evaluate performance in terms of the interaction of components and climate for any proposed design. Figure 1 illustrates the differences between system integration research and component and subsystem research.

The Building System Integration Research Program has relied primarily on computer analysis tools to study building interactions. However, the results of this approach are limited by the modeling capability and limitations of available computer programs. Even though these computer programs have become increasingly sophisticated, a large margin of error still exists between theoretical and actual application of system integration design strategies. Experimental studies are needed in conjunction with modeling analyses to make future simulation more accurate.

Figure S.1. Building System Integration Research

Recent experimental research projects have examined research hypotheses developed using both computer simulation and laboratory testing. One example is the examination of the interactions between lighting and HVAC subsystems. In many buildings, such as large office buildings, the dominant energy use is due to the lighting and cooling loads. Because lights release heat into the space, a reduction in the lighting load causes a corresponding reduction in the cooling load. However, the issue is more complex. Both lighting power consumption and light output are strong functions of lamp temperature. Lamp temperature, in turn, is dependent on the overall room thermal environment, especially air flow conditions and air temperatures near the light fixtures. The room thermal environment is

determined by many factors in addition to the heat from the lights; these factors include the operation of fans and heating and cooling equipment, thermostat setpoints, and temperature conditions on exterior surfaces. Current computer codes just cannot handle this complexity. The National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards) is conducting parametric tests of a number of lighting fixture types and HVAC subsystems in a controlled test chamber sized to simulate an office environment, to develop accurate correlations between the two subsystems. Only then can a computer model and simplified design procedures be developed. The large size of the components being studied in this type of experimental research requires a facility that can more

adequately handle many component combinations and simulate other actual building conditions, such as weather and occupancy, than is possible in experimental facilities now available to government or private sector researchers. For this reason, the feasibility study was funded to examine whether such a facility is warranted.

A building system integration experimental facility would provide the additional information needed to accurately gauge building energy performance and provide the symbiotic link between simulation and experimentation. A research program based solely on simulation and theory can provide calculations that are drastically wrong and not strong enough to provide a sound foundation to warrant major industry changes. Further, a program based entirely on experimentation would be prohibitively expensive, time-consuming, and unnecessary. The building system integration research program requires both. An experimental facility would allow researchers to interchange building subsystems such as HVAC, lighting, or wall components in a climate-controlled test facility to examine the optimal combinations for a given climate location. Adding an experimental test facility to the current system integration research program could 1) provide a test bed to enhance innovation; 2) provide product manufacturers and building designers with the tools necessary to design improved component interfaces, new components with improved and integrated functions, and buildings with optimized components that perform more efficiently; 3) increase industry acceptance of new ideas while minimizing expensive demonstration in new buildings with real tenants and productivity requirements; and 4) provide information needed to upgrade computer simulation tools.

As part of this feasibility study, Pacific Northwest Laboratory examined four experimental facility options or approaches to filling the gap in the DOE experimental program. The first option is to use an existing research facility, such as an environmental chamber where different component combinations can be subjected to weather changes. A good example is the test facility at NIST that is being used in the lighting and HVAC study described earlier. The second option is to use existing occupied buildings having the appropriate characteristics to suit the experiments. The third option is to lease or purchase

unoccupied buildings having the appropriate characteristics necessary to do the experiments. The fourth option would be to construct a new facility completely outfitted as an experimental facility. In this study, PNL explored the technical, experimental, and economic feasibility of each option. After the preferred alternative was identified, a conceptual design and cost estimate were prepared for that alternative.

The feasibility study findings led to the key conclusions and recommendations presented in the following paragraphs.

Building system integration research has the potential to effect significant savings and improve the overall energy efficiency of commercial buildings. These savings come from increased knowledge of the fundamental operation of building components and subsystems and their interactions. Research results can be transferred to architects, engineers, product and component manufacturers, and building owners through new building standards, upgraded computer simulation tools, new product technology, and publications and information databases.

The addition of a building system integration experimental facility would greatly benefit the current research program. The facility would markedly improve the capacity of the building system integration research program and complement existing research methods. It would enable researchers to test a variety of hypotheses in "real-world" applications. Theoretical and actual energy consumption differ widely, even in buildings that are designed with the most sophisticated design methods. It is vital, therefore, that researchers be able to test theories and promising technologies rather than depend on theoretical computer analysis. The information gained from such an experimental facility will help the commercial building industry properly utilize energy conservation technologies and ensure that buildings will function according to design.

Certain characteristics were deemed important for a building system integration experimental facility. The facility should be

- flexible and capable of serving as a test bed for fundamentally new concepts

- capable of close control, i.e., a facility in which the materials and methods of construction are well understood and all of the significant boundary conditions are known and can be controlled and quantified - Only under these conditions, when all variables are known and measured, can observed test results be correlated with test conditions with confidence.
- able to accommodate large components, multiple temperature-control zones, and other energy use characteristics typical of moderate and large commercial buildings.

The private sector and other government research organizations have expressed an interest in using, and could benefit from, a DOE building system integration experimental facility if it were available as a "user facility." Facilities currently available to buildings researchers consist mainly of scale-model test laboratories and small environmental chambers for testing individual components and subsystems. No research facility on the scale of that examined in this study exists in the United States. Such a facility could be useful to product manufacturers, utility and academic research organizations, national standards groups such as ASHRAE and American Society for Testing and Materials (ASTM), and other government research organizations such as the U.S. Army Construction Engineering Research Laboratory.

A building system integration experimental facility is not needed for residential-scale building system integration research. The study confirmed that there were adequate existing facilities and

available test-homes to perform residential building system integration research. The experimental facility would be used to study commercial building system applications.

The construction of a new experimental facility was determined to be the preferred alternative. The study indicated that, although several options exist for developing new building technologies, the most promising is the construction of a new test facility, called a Building System Integration Laboratory (BSIL). This alternative was chosen because of its superior technical, experimental, and economic feasibility.

Phased construction is feasible. If budget constraints rule out rapid construction of the complete facility, phased construction could be pursued because a substantial amount of research can be conducted in a first-phase structure. The study concluded that the preferred alternative could be constructed in three phases:

- **Phase 1** - Construct a three-story test building with a basement (Figure 2), each floor measuring 54 ft by 54 ft, at an estimated cost of \$2.7 million.
- **Phase 2** - Expand the test building to 54 ft by 108 ft, with the north- and south-facing walls measuring 108 ft, for an additional \$2.7 million.
- **Phase 3** - Further expand the test building to its complete dimensions of 108 ft by 108 ft (Figure 3), and add an engineered storage building, for a final increment of \$5.4 million.

Figure S.2. Phase 1 Test Building Architectural Perspective

Figure S.3. Phase 3 Test Building Architectural Perspective

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1.0 INTRODUCTION

More than 36% (26.9 quads) of the nation's primary energy was consumed in providing services to residential and commercial buildings in 1985 (Office of Buildings and Community Systems 1988). This is equivalent to 12 million barrels of oil per day or the power output from nine hundred 500-megawatt coal-fired power plants. Although conservation is helping to reduce energy consumption in buildings, the consumption of primary energy is still expected to rise an additional 41% between 1985 and 2010 (Office of Policy, Planning and Analysis 1985). Obviously, buildings offer a substantial potential for improved energy efficiency with all of the attendant benefits such as improved energy security, improved balance-of-trade, and reduced impact on climatic change.

Past research on building components and subsystems has produced incremental improvements in building energy efficiency. For example, buildings constructed in 1986 will use an average of 5% to 10% less energy than comparable buildings built in 1976 (Pacific Northwest Laboratory 1986). However, additional energy efficiency depends on more fundamental improvements. Building system integration research offers the potential for fundamental change. Studies have shown that well-designed buildings using integrated systems can reduce energy consumption by between 30% and 50% (Stoops et al. 1984).

In recognition of the importance of system integration research, the U.S. Department of Energy (DOE) Office of Buildings and Community Systems (OBCS) established a program to research building system integration. Substantial progress has been made, but additional improvements in building energy efficiency depend on a better understanding of building subsystems interactions. The requirement for experimental investigations of complete integrated subsystems operating with multizone space demonstrated the need for a facility capable of simultaneously testing multiple, full-sized building subsystems.

In fiscal year 1988, the United States Congress mandated a study of the feasibility of establishing a laboratory dedicated to research on building system integration issues. In response to that mandate,

DOE requested the Pacific Northwest Laboratory (PNL)^(a) to conduct the feasibility study of a Building System Integration Laboratory (BSIL). This report documents the PNL study.

1.1 FEASIBILITY STUDY GOALS AND OBJECTIVES

The goal of the study was to determine the technical and economic feasibility of establishing a building system integration experimental facility and to develop a conceptual design of a whole-building system integration laboratory. This was accomplished by achieving three primary objectives:

- **Determine the need for an experimental facility.** The feasibility study explored whether a need exists for such a facility. Answers were sought for two related questions: Is building system integration research required? If so, would an experimental facility significantly contribute to advancing research goals?
- **Explore several alternatives.** Four alternatives were investigated to determine which was most viable in terms of the relevant economic and technical criteria established by the determination of need.
- **Develop a conceptual design and cost estimate for a preferred alternative.** If a research laboratory is needed, what should it look like? How much would it cost? Would that cost be reasonable in light of the benefits the experimental facility would yield?

1.2 METHODOLOGY

The feasibility study consisted of two activities: review of system integration research needs and development of a conceptual design and cost estimate for the BSIL. A technical review panel assembled by DOE assisted in the completion of both activities.

(a) Operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

Valid assessment of a multidiscipline facility such as the BSIL depends on having a wide range of technical advice on building system integration research needs and techniques. The technical review panel was assembled by DOE to ensure that the feasibility study considered the most complete and accurate information on these subjects. The panel comprised representatives from professional societies, universities, equipment manufacturers, and laboratories involved in buildings research.

Building system integration research needs were evaluated by reviewing the status of research in this area and determining where additional research is required. The assessment of research needs included a review of current research activities and advice from the panel.

The conceptual design and cost estimate were produced by an architectural/engineering company, Kaiser Engineers, based on a set of functional criteria developed by PNL in conjunction with the technical review panel. These functional criteria, presenting the design requirements for the BSIL, were developed from the capabilities required to

meet the building system integration research needs identified by the review of current research activities.

13 REPORT ORGANIZATION

The needs for building system integration research and an experimental facility are discussed in Section 2. In Section 3, four options for conducting building system integration research in an experimental facility are presented and analyzed. Design and cost estimates for the preferred alternative are described in Section 4. The long-term effects and benefits of an experimental facility are discussed in Section 5. Conclusions and recommendations of the study are noted in Section 6.

Detailed supporting information is contained in three appendixes. The technical review panel members and their affiliations are listed in Appendix A. The results of a design workshop in which concepts were developed for the preferred alternative are presented in Appendix B. The architect/engineer's report on the conceptual design and cost estimate is presented in its entirety in Appendix C.

2.0 BACKGROUND AND RATIONALE

The energy consumed by buildings is a very large part of the total energy consumption in the U.S. economy. In 1987, residential and commercial buildings consumed over 36% of all energy consumed in the United States. This is equivalent to 12 million barrels of oil per day or the power output from nine hundred 500-megawatt coal-fired power plants.

Between 1975 and 1987, energy use per square foot dropped by 25% in new residential buildings and by 13% in new commercial buildings (Energy Information Administration 1989, p. 39, Table 13). However, because of the predicted large increase in residences and commercial building square footage between now and the year 2010, building energy use is predicted to increase by 41%. Therefore, something must be done to curb energy use and still allow for the predicted growth of the sector.

This section provides important background for the need to take such action. In addition, it describes a DOE research thrust designed to help meet that need.

2.1 NEED FOR SYSTEM INTEGRATION RESEARCH

Although the number of residences has increased by 22% in the last 12 years, residential primary energy consumption has risen by only 4%, mainly because of a 25% reduction in heating energy use. Higher prices for energy have also played a role, but a greater interest in saving energy and the use of energy-conserving products, such as insulation, better windows, and more efficient furnaces and heat pumps, have become marketable items for home builders.

A few homes have been constructed to use 50% to 70% less heating energy, but most homes built today do not. Therefore, a significant potential still exists. With the large increase in electrical energy use in southern-tier states, builders are looking for ways to reduce cooling energy use. Studies indicate that a similar 50% to 70% reduction is possible.

Over the same 12-year period, commercial floor space increased by 30% while primary energy consumption grew by 24%. Therefore, newer commercial buildings have not achieved the same efficiency as newer residential buildings. There are many reasons for this: energy costs are passed on to tenants; technological advances are more rapid in residential-size equipment and energy conservation measures; and commercial buildings are much more complex and, hence, harder to design, construct, and operate.

Making advances in building energy conservation is difficult because of the way in which buildings are designed, tested, and constructed. Consider the differences between the typical design and construction of commercial buildings and automobiles. Automobiles go through several cycles of design and are extensively tested and evaluated before they enter the marketplace. In addition, their lifetime is short. Once on the market, cars are independently tested and reported on by consumer magazines. This information is then fed back into the design process. Conversely, commercial buildings are uniquely designed and built; a building's lifespan is 5 to 10 times that of an automobile. There is no testing or evaluation of design and construction beforehand; that would be cost-prohibitive. Nor is there any post-occupancy testing of a building's performance. Any advances in design or construction techniques penetrate the market very slowly when compared to the automobile industry. Therefore, it is important that designers and builders have good advance information to optimally select, integrate, and interface building components. The role of the DOE Building System Integration Research Program has been to develop and transfer such information.

2.2 BUILDING SYSTEM INTEGRATION RESEARCH PROGRAM

Building system integration research studies how the interactions of multiple building subsystems (such as the building envelope, equipment, and lighting), occupants, and climate affect the amount of energy a building uses. The goal of the research

is to maximize the cost-effective use of energy in buildings by understanding and quantifying the energy flows between and among building subsystems so that they may be optimized on a whole-building life-cycle cost basis instead of by analyzing subsystems individually.

The objectives of the DOE building system integration research are

- to provide the experimental means to understand and quantify the energy flows among building subsystems so that they may be optimized on a whole-building basis (instead of on a subsystem-by-subsystem basis)
- to provide the means to develop, test, and document the performance of new building subsystems that synergistically combine to provide more efficient use of energy in buildings
- to provide verification of and improvements to the energy computer simulation programs that model the performance of these interactions and advanced concepts through the detailed and applicable understanding of the physics of energy transport through buildings.

Figure 2.1 illustrates the relationship of building system integration research to other types of building sciences research. At the first level is material and component research that improves the performance of individual building materials and components such as insulation, lamps, and heat pumps. The second level of research considers these elements combined into subsystems, such as the building thermal envelope, lighting, and heating, ventilating, and air conditioning (HVAC) subsystems. The third level of interaction (and complexity) is building system integration research that seeks to optimize the energy efficiency of all building subsystems in an effective whole-building system.

2.3 FEDERAL ROLE IN BUILDING SYSTEM INTEGRATION RESEARCH

Considerable privately-sponsored research is done at the first and second levels shown in Figure 2.1 because it leads to new products, equipment, and materials. For example, the insulation and lighting industries have responded to higher energy

prices by improving and marketing more efficient products. There is also substantial government-sponsored research in these areas. For 15 years, DOE has funded programs that have been directed at technology and product innovation, such as heat pumps, windows, materials testing, and new lamps and ballasts.

At the third level, however, very little private research is under way because there has been no focal point for this type of research. Improvements are likely to require changing more than the product line of a single manufacturer. Companies are more likely to concentrate on their own products and profitability. Consequently, there is less opportunity for a single vendor to benefit from the system integration improvements. However, the potential remains for energy and cost savings from the optimal synthesis of components and materials into an integrated working building. The problem is discovering which changes to building design, construction, and operation make the most energy sense and then working with a cross section of industries that would have to implement the changes to make them work. DOE is the only focal point for this type of broad research.

Preliminary examinations demonstrate that the energy requirements of commercial buildings can be cut by more than half through a better understanding of system integration. These advances would have little or no effect on first cost if properly selected building subsystems are integrated into the design process (Stoops et al. 1984). Figure 2.2 compares the energy consumption of well-designed buildings with integrated subsystems to that of several buildings using current practices. If this level of energy savings were realized in the existing commercial building stock, 3 to 6 quads of energy could be saved each year. In new construction, the energy savings would be 3 to 4 quads per year by the year 2010.

2.4 BENEFITS OF EXPERIMENTAL RESEARCH AND AN EXPERIMENTAL FACILITY

The current Building System Integration Research Program consists of three components: 1) simulating the thermal interactions of innovative integrated building system designs; 2) simulating building performance in the development of "energy

Figure 2.1. Building System Integration Research

use targets"; and 3) developing advanced computer simulation codes and knowledge-based computer systems for building design and operation. All three activities depend on computer simulation, and it is becoming increasingly necessary to complement these activities with experimental investigations. The computer models are based on theoretical assumptions; their output is only as good as the data that creates them.

Building simulation tools have significantly advanced the building design process. However, numerous studies have shown that actual energy use of buildings exceeds the energy use predicted by the simulation tools, frequently by more than 50% (Norford et al. 1986; Piette 1986). The greatest

difference occurs where there is an attempt to model new design approaches. Recent research has shown that simulations do not accurately predict where energy is used in a building (Heidell and Taylor 1985). These findings undermine the confidence of innovative building designers in these tools when they wish to use them for other than conventional design solutions. Experimental building system integration research can improve simulation tools by developing new models for building subsystem interactions and by more accurately characterizing critical variables. The significant energy savings potential discussed in this report represent fundamental changes from current design and construction practice that have not yet become common practice. Common practice will change only when

Figure 2.2. Comparison of Energy Consumed by Current-Practice Buildings and Buildings with Integrated Systems

designers have more confidence in research data and computer design tools.

An example of a design strategy with good but yet unproven energy conservation potential is a water loop heat pump that uses the mass of a structure for thermal energy storage (Marseille et al. 1989). This concept may not meet existing building codes and standards because it varies so much from current practice. Building designers are reluctant to use such innovations as the water loop heat pump based only on the results of computer simulation. Acceptance of fundamental change in design and construction practice by the building community is more likely to occur when data is available from experimental testing that demonstrates the viability and reliability of new products and systems.

A building system integration experimental facility is needed to advance and complement the existing research program in building system integration. This facility would be the nation's primary site for building system integration research.

A building system integration experimental facility is a research facility capable of identifying and characterizing the energy interactions of multiple,

full-scale building subsystems to determine the functional energy relationships between the subsystems. System integration experimental research conducted in a dedicated experimental facility would benefit the energy performance of new buildings in several significant ways:

- The building industry would gain an understanding of building physics and integrative issues through testing conducted under actual conditions. This would help alleviate the industry's skepticism about the DOE research based solely on computer analysis.
- Incremental improvements can result from studies using current computer simulation programs and on what is learned by monitoring existing buildings. However, new breakthroughs will need the capabilities of an experimental facility where controlled conditions can be established and experiments conducted that can apply to many occupancy and climatic patterns.
- An experimental facility would enable researchers to isolate subsystem effects and other subsystem unknowns.

- An experimental facility would provide the capability for testing concepts not currently allowed by building codes and standards.
- An experimental facility would serve as a test bed for new systems, providing a valid way of proving the technology for innovative systems. The information derived from experiments in closely monitored actual applications would help reduce designer reluctance and, thus, could speed the entry into the marketplace for most new building technologies.
- An experimental facility could be used to study and develop intelligent building controls. While many companies offer lighting and HVAC controls that could potentially save a great deal of energy, designers are still reluctant to use the

controls because little information has been published on how to properly design for and place such controls.

- The concepts to develop the so-called "Zero Energy Use" buildings of the future can be studied only on a whole-building level.

Without such an experimental facility, the transfer of technology from conceptual idea to commercial reality would probably not occur for radically new subsystem integration concepts, because they will engender high risk and very likely will not fit within the product line of a particular sector of the building industry. This role within the DOE Building System Integration Research Program is the primary justification for the building system integration research facility.

3.0 BUILDING SYSTEM INTEGRATION EXPERIMENTAL FACILITY ALTERNATIVES

A four-step approach was used to identify and evaluate alternatives for providing an experimental facility for building system integration research:

1) develop the scope of experimental research that needs to be carried out; 2) establish alternative approaches for conducting that research; 3) establish criteria for evaluating the alternatives; and 4) evaluate the alternatives. These four steps are described in this section.

3.1 EXPERIMENTAL RESEARCH SCOPE

A technical review panel was convened; its membership comprised industry representatives, academic and government researchers, and research administrators (see Appendix A). The panel developed a research agenda of candidate building system integration research tasks that would benefit from the establishment of a building-scaled experimental facility, formulated an approach to accomplish the tasks, and developed specific criteria for a building system integration experimental facility. This information was then reorganized in terms of research categories being used in the current Building System Integration Research Program.

Several steps were taken in formulating the research agenda. Before they met, the panel members were sent a questionnaire asking them to list important system integration research issues. A summary was prepared using the questionnaire responses. In a workshop session, the panel refined the list of research issues. Building system integration research needs were evaluated by reviewing the status of current research and determining what additional research is required. The panel then developed a formal research agenda and an assessment of the effects of an experimental facility on such research (Drost, Johnson, and Crawley 1989). The purpose of the research assessment and agenda was to determine if there are sufficient meaningful building system integration research topics to continue the research program and to further explore the need for an experimental facility.

The formal research agenda was composed of seven research activities:

1. **HVAC design and selection for optimized building performance** - This research would produce a methodology for addressing the HVAC subsystems in an optimized building. PNL researchers have estimated that building system integration research in the heating, ventilating, and air conditioning area has the potential to reduce building energy consumption by 0.9 quad per year by the year 2000.^(a) The research requires experiments to determine how the HVAC subsystems interact with other building subsystems, followed by the development of a procedure to optimize the HVAC subsystems in the context of the whole building operation, one in which the output of the HVAC subsystems is constantly varying as the result of the controls imposed upon them. This research product would help the HVAC industry produce energy-efficient designs that are based on a complete understanding of how the HVAC subsystems interact with the building envelope, structure, interior partitions (specifically the air flow patterns throughout the building), and lighting.
2. **ventilation optimization procedure development** - This research would analyze interzone air flows and develop procedures for maximizing air exchange in occupied zones while minimizing the use of ventilation air. Optimization of ventilation systems will become increasingly important because of growing concerns about indoor air quality. Increasing the use of outside air for ventilation will increase energy consumption.
3. **testing integrated system designs** - The goal of this activity would be to solicit and test innovative integrated building systems such as the water-loop heat pump subsystem integrated with thermal storage capability in the structure of the building.
4. **analytical methods for transient effects** - This research would analyze the fundamentals of transient effects, i.e., the rate of change of temperatures throughout the building as the result of

(a) 1987 draft report, Pacific Northwest Laboratory, Richland, Washington.

changes in external temperatures, insolation, wind, HVAC input, and internal gains from equipment usage, and develop methods that describe the phenomena. Transient effects are not simulated well with the energy simulation computer programs currently available because of simplifying assumptions that are made to handle the analysis. Nevertheless, transient effects have a significant effect on system performance. Research on this issue would improve the building industry's capability to account for transient effects.

5. **computer program code verification and algorithm development** - This research would evaluate existing whole-building computer programs and use the experimental capabilities of the facility to develop new algorithms to improve computer program accuracy. Existing computer programs often give conflicting results. Improvements in the predictive capabilities of existing codes would markedly increase their usefulness.
6. **testing of building components** - This research would focus on the full-scale testing of building components in a facility capable of measuring the effect of the components on the whole building and its interacting subsystems. A recurring problem in the building industry has been the difference between predicted and installed performance of building components. The development of more realistic test protocols for component testing would be a significant step toward eliminating this variation.
7. **operation and control strategy development** - The objective of this activity would be to develop and test innovative control strategies for integrated building systems. Specific activities would include improving control logic used in energy management and control systems. Research on control strategies is recognized as having great potential for improving building energy performance (Claridge 1986).

At a second workshop, attended by a subcommittee of the panel, a series of design criteria and concepts for an experimental facility was prepared. This subcommittee identified how the proposed research agenda would influence the design of the experimental facility. The factors include the size, complexity, and frequency of modifications to the

experimental facility; complexity of phenomena being investigated; required isolation from ambient conditions and other internal effects; number of subsystems being simultaneously tested; and limitations imposed by building codes and standards.

The factors were then grouped into three general categories: flexibility, control, and scale. Flexibility refers to the capability to test fundamental new concepts and the ease of making modifications so that a wide variety of experiments can be conducted. Control refers to the capability to ensure carefully managed experiments where both ambient conditions and internal design features can be monitored. Scale indicates that an experimental activity would best be conducted at or near full-scale.

The results of the categorization process are summarized in Table 3.1. Flexibility is required for six of the seven primary research activities. Control is required by all seven activities, while large-scale testing is desirable for five of the seven activities. These results showed that building system integration research will require all three capabilities: flexibility, control, and large scale.

A third workshop, attended by the full panel, was held to review the preferred conceptual design for a facility. This conceptual design was developed from the design criteria previously specified. The panel recommended which items on the research agenda

Table 3.1. Facility Capabilities Required for Building System Integration Research

Research Activity	Required Capability		
	Flexibility	Control	Large Scale
HVAC optimization	X	X	X
Ventilation optimization	X	X	X
Integrated systems testing	X	X	X
Transient effects	X	X	--
Code verification	--	X	X
Component field-testing	X	X	--
Control strategy development	X	X	X

required a facility built especially for experimentation as opposed to items that could be researched in existing laboratory facilities or in occupied or unoccupied leased buildings.

In a subsequent independent effort, a matrix of energy-related building subsystems was prepared to identify significant energy-related interactions (Table 3.2). The matrix identifies the interactions between only two subsystems. It does not consider more complex interactions between or among multiple building subsystems such as the interactions between windows, lighting, heating, ventilating, and cooling subsystems. It was felt that the matrix was sufficiently complete to establish reasonable criteria for an experimental facility. This matrix was first used to reevaluate interactions identified by the technical review panel. The list was used to check the experimental requirements established by the panel. The interactions listed in Table 3.2 can be easily related to the research agenda identified by the technical review panel.

Most of the interactions listed in the matrix address the physics of energy interchange between subsystems. For example, the interaction between the HVAC subsystem and the building envelope subsystem involves the physics of heat transfer between convecting air, both forced and natural convection, and the building envelope and any internal surfaces of different air temperature. Another example, the interactions between internal building partitions and the building envelope, includes radiant heat transfer between two surfaces at different temperatures. The rigorous mathematical treatment of all the energy interchanges between subsystems would make the analysis extremely complex and unwieldy. Thus, one of the principal objectives of the experimental facility is to validate algorithms that are used in energy simulation computer programs as simplifying assumptions of the more rigorous mathematical expressions of the physics involved.

Similarly, there is a continual flux of energy between subsystems; i.e., the building is seldom at thermal equilibrium. However, most building energy computer programs do not analyze the energy situation as a transient but rather as a series of quasi-steady-state situations. This fact may contribute significantly to the poor capability of most of the

computer programs to predict the energy use by individual subsystems.

A second objective of the experimental facility is to provide data to guide the development of improved transient analysis methods. More than half of the interactions noted in Table 3.2 are related to the energy exchange implications of air movement throughout the building. Again, the rigorous mathematical description of open air flow in buildings has received little research attention because of the complexity involved. Instead, algorithms approximating the effects of air movement have been used. The consequence has been an incomplete understanding of the performance of HVAC systems, as contrasted to HVAC components.

A third objective of the experimental facility is to develop the methodology to optimize HVAC subsystems in concert with the other building subsystems. At present, the methodology to evaluate the HVAC subsystem performance within the building environment, much less their optimal design, is not available.

Ventilation optimization is closely related to HVAC optimization because the efficiency of ventilation directly affects the ventilation air flow and the energy required to condition fresh air that is brought into the system. Although ventilation is an integral part of the HVAC subsystem and is not considered a separate optimized independently of the HVAC subsystem. Moreover, ventilation optimization will seemingly require the capability to describe the three-dimensional behavior of open air flow, including the effects of temperature and concentration of various pollutants.

An integral part of optimizing the HVAC subsystem for the transient type of operation required in a large commercial building is the control strategies. Included in the successful operation and control strategy will also be consideration of humidity, indoor air quality, and occupant productivity. The development of innovative control strategies is a fifth objective of an experimental facility.

Because the matrix of two-system interaction in Table 3.2 does not include the interactions of more than two subsystems, it does not identify any

Table 3.2. Matrix of Building Subsystem Interactions

	Envelope ^(a)	Ceilings/Floors	Partitions	Lighting	Windows	Heating
HVAC	Convective air flow-energy transport ^(a) Thermal mass effect ^(c) Occupant behavior-temperature setting ^(d) Thermal comfort ^(e)	Convective air flow-energy transport ^(b) Thermal mass effect ^(c) Thermal comfort ^(e) Air flow patterns ^(f) Temperature stratification ^(g) Thermal energy storage ^(h)	Convective air flow-energy storage ^(b) Thermal mass effect ^(c) Thermal comfort ^(e) Air flow patterns ^(f) Thermal energy storage ^(h)	Increased lighting efficiency ⁽ⁱ⁾ Lighting and energy distribution ^(j)	Energy gain/loss ^(k) Energy distribution from interaction of convective and forced draft air flow ^(l) Moisture formation and control ^(m)	Thermal energy storage and transport ^(b)
Service Water Heating	Thermal energy storage and transport ^(b)	Thermal energy storage and transport ^(b)	Thermal energy storage and transport ^(b)	Thermal energy storage and transport ^(b)	Thermal energy storage and transport ^(b)	
Windows	Energy gain/loss ^(k) Occupant behavior-open/close shades ⁽ⁿ⁾	Solar energy transport and storage ^(o) Convective air flow-energy transport ^(b) Thermal comfort ^(e)	Solar energy transport and storage ^(o) Convective air flow-energy transport ^(b)	Convective air flow-energy transport ^(b) Lighting source - natural versus fixture ^(p)		
Lighting	Lighting and energy distribution ^(j) Occupant behavior-choice of lighting source ^(q)	Lighting and energy distribution ^(j)	Lighting and energy distribution ^(j)			
Partitions	Convective air flow-energy transport ^(b) Thermal comfort ^(e) Radiant heat exchange ^(q)	Convective air flow-energy transport ^(b) Thermal comfort ^(e) Radiant heat exchange ^(q)				
Ceilings/Floors	Thermal comfort ^(e) Thermal bridging ^(r)					

(a) Envelope column includes occupant influence on subsystem interactions, where appropriate.

(b) Convecting air will transfer heat from one region of the building to another, by cooling surfaces in a warmer region and heating surfaces in a cooler region. Windows will generally be at a significantly different temperature from interior walls and, consequently, will promote convective air currents over their surface, thereby influencing the rate and distribution of energy input to the space. Location of windows relative to partitions will influence the air flow patterns within the space.

(c) The thermal mass of the envelope, ceilings/floors, and partitions influences the transient response and distribution of temperatures within the building. This interaction impacts the HVAC system control and response. Large thermal mass introduces lag time in the control performance and dampens temperature variations.

(d) Occupant behavior will dominate HVAC control requirements and total system performance.

(e) Air temperatures requested/set by occupants are influenced by the temperatures of enclosing surfaces (as well as air temperature) due to radiant heat loss/gain to the occupants.

(f) Location of ceilings and interior surfaces relative to inlet and outlet air ducts will influence the patterns of air flow, the extent of mixing within the space, the ventilation effectiveness of the HVAC system, the sensor positions for minimum lag in HVAC controls, and HVAC system performance (as contrasted to HVAC component performance).

(g) Thermal stratification (warm air near the ceiling and cool air near the floor) may occur, reducing ventilation efficiency and affecting energy use unless provisions are made to either achieve complete air mixing (i.e., uniform temperature and composition) in the space or achieve "plug flow" (i.e., total sweep) of the air between inlet and outlet plenums.

(h) Thermal storage may be achieved by either sensible or latent (phase change) heat increase of building structures in one zone accomplished by heat transport via ventilation air. Storage media such as service water may then be used to distribute this energy to other regions as needed.

(i) Placement of inlet air ducts near lighting fixtures can increase lighting efficiency (cooler lighting units) and promote the effective distribution of the heat produced within the lighting fixture.

(j) Lighting distribution to the ceiling and walls will influence the lighting level in the space and, consequently, the lighting energy required. Distribution of energy from lighting to surrounding surfaces by radiant heat exchange will influence the surface temperature, the energy transfer to the region from the lighting unit, and, hence, the HVAC requirements.

(k) Windows generally differ significantly from exterior walls with respect to thermal properties. Insolation through windows will markedly affect energy distribution and utilization within the structure.

(l) The natural convection air flow at the window surface due to the temperature differences between the air and the surface may be either reinforced or opposed by the air flow from the HVAC system. This situation can markedly influence the air flow patterns, the ventilation efficiency, and the sensor position for minimum lag in HVAC controls.

(m) Moisture from condensation on window surfaces may be reduced by evaporation into the air flowing over the surface.

(n) Occupant behavior, e.g., the use of blinds and the opening of windows, will significantly affect the impact of windows on energy use.

(o) Energy from solar insolation will be absorbed/reflected by surfaces, which will increase in temperature and store a portion of the incident energy.

(p) The location of windows relative to lighting will influence energy requirements for adequate work environment and aesthetics. Internal gain of energy from lighting will depend on the extent daylighting is used. Occupant behavior will be important.

(q) Radiant heat exchange between walls and ceiling and floors will result in non-uniform wall temperatures and consequently differing rates of energy transfer to the air at each point on these surfaces. Usually this complex pattern of energy flux to and from the wall is analyzed by making simplifying assumptions of constant wall temperatures and constant ceiling temperatures.

(r) Connections between the ceiling/floors and the envelope may form regions of rapid heat transport because materials may have higher thermal conductivities than surrounding regions, thus creating anomalous heat loss/gains in isolated locations.

fundamentally new approaches for synergistic interactions between subsystems. Nevertheless, a sixth and possibly the most important objective of the experimental facility would be the testing of subsystem arrangements that would involve fundamental changes from current design approaches. As an example, many commercial buildings have opposing heating and cooling demands between internal and perimeter spaces. They also frequently face perimeter demands for heating in the morning and cooling in the afternoon. The efficient storage of excess energy for later use or transfer to an area of demand can save significant energy. Using one subsystem to do multiple tasks, such as a water loop heat pump system integrated with thermal storage in the building's structural components, shows promise in making this possible. Other examples, listed without elaboration, include

- laminar-flow ventilation, from plenums located in the floor and ceiling, to greatly improve ventilation efficiency and greatly reduce fresh air makeup
- heat pipes, perhaps built into the partitions to transport heat from one zone of the building to another with very low temperature difference, to keep the building more nearly isothermal.

A seventh objective of the experimental facility, as identified by the technical review panel, was the development of protocols for the testing of building components. Component testing can best be done in the whole-building environment, but a valuable test facility should not be tied up with testing of components. The more productive use of a whole-building experimental facility would be in developing test protocols that minimize, or account for, subsystem interactions. Actual component testing should be conducted in smaller, existing facilities.

3.2 FOUR ALTERNATIVES FOR ACCOMMODATING EXPERIMENTAL RESEARCH

Four alternative approaches to providing facilities for conducting building system integration experiments were developed as a basis for determining the feasibility of establishing an experimental facility:

1. Use existing laboratory facilities.
2. Use existing occupied buildings.
3. Use existing unoccupied buildings.
4. Build a dedicated experimental facility called a Building System Integration Laboratory (BSIL).

The choice of options for conducting system integration research is controlled by the structural features and capabilities needed to conduct the research. The required capabilities include

- sufficient flexibility to enable testing of fundamentally new concepts, in contrast to concepts that involve only incremental change
- a structural design that ensures complete control of test conditions
- sufficient size to exhibit the thermal characteristics of commercial buildings.

In the following sections, each of the four alternative approaches is described. Included in these descriptions is the extent to which each alternative offers the required capabilities.

3.2.1 Existing Laboratory Facilities

The least expensive and most quickly available site for experimental building system integration research would be an existing research facility. For the testing of residential buildings, many such facilities exist across the country, at several universities, government laboratories, and industrial research facilities. As is explained later in this report, the technical review panel concluded that further study of a building system integration laboratory should be focused upon subsystem integration in commercial buildings. To operate efficiently, the existing facility would have to meet several criteria, including the basic criteria discussed above for a building system integration research facility. It would also require sufficient floor area and ceiling height to typify multizone transient behavior.

The major advantage to using an existing facility is that the capital cost of constructing or renovating a facility would be avoided. Further, experimental

support facilities, such as fabrication shops, instrumentation calibration, and repair, would likely be readily available.

Several such facilities exist, although most can accommodate testing on only a small scale. For example, the Florida Solar Energy Center has a unique whole-house facility that is used to conduct passive solar research. The National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards) has an environmental chamber in which building components can be tested. This facility is being used for a DOE-sponsored study of HVAC and lighting interactions in commercial buildings. The National Aeronautics and Space Administration has several environmental chambers, but they are constantly being used for hostile environment testing in the space program. Other laboratories have even smaller-scale facilities, such as the MoWITT window test chamber at Lawrence Berkeley Laboratory.

With the exception of the Florida facility, existing building science research facilities are dedicated to investigating the interaction of only two subsystems as identified in Table 3.2. A search of university laboratories (American Consulting Engineers Council Research & Management Foundation 1989) and federal laboratories found that no existing facilities satisfy the essential criterion for whole-building system integration research studies of commercial building size, i.e., the criterion of size to typify a representative commercial building's thermal response. Thus, existing laboratory facilities together would be able to carry out only a portion of the whole-building experimental research, and then primarily in residential buildings. The technical review panel considered what portion of the seven high-priority research activities could be carried out in existing facilities. The panel concluded that it would be more efficient and manageable to have a single experimental facility.

3.2.2 Existing Occupied Buildings

This option would incorporate the use of existing buildings having the design characteristics that are desirable for study. Portions of the buildings would be leased for experimentation. Instrumentation would be installed in the building, calibrated, and monitored either from a room(s) onsite or over dedicated or periodically accessed phone lines from

a remote laboratory. Where comparisons between different combinations of building subsystems were of prime interest, multiple buildings would be sought. This could also be done by locating a building in which actual changes could be made to at least some of the building subsystems. For example, several floors might be rented and several different light fixtures types, HVAC terminal outlets, and ceilings might be installed for the series of experiments. In this alternative, it was assumed that building occupants would continue to work in their normal capacity. When the experiments were completed, the building would be returned to its original condition or its condition enhanced, per the provisions of the lease.

Using existing occupied buildings is enticing because the capital expenditure of construction is avoided, the scale of conditions to be studied is appropriate, and actual operating conditions do not have to be simulated. However, this option is less attractive than using existing laboratory facilities or building a new facility, because of 1) the administrative functions of locating and leasing suitable buildings; 2) the limitations on experimental control, experimental reconfiguration, and testing of non-code-approved technologies; and 3) the complexity of conducting experiments in multiple offsite facilities to address the desired range of systems and climatic conditions.

3.2.3 Existing Unoccupied Buildings

This alternative is similar to using existing occupied buildings except that the buildings would be unoccupied. The unoccupied building could be an existing structure or a new building designed to include combinations of building subsystems helpful for the experiments. The monitoring in this alternative would likely be done from within the facility or somewhere onsite. This alternative also presumes some ability to change the characteristics and combinations of building subsystems beyond what might be possible in occupied buildings. The building might be leased or purchased initially and then sold when the experiments were completed. The building could be a new federal building where researchers could provide initial input to the design process and then test the resulting building operation. However, federal buildings are built to support agency missions, and prompt occupancy is usually an overriding factor. The drawbacks of this option are

the same as those for the existing occupied building option: 1) the administrative efforts required to locate and lease suitable buildings; 2) the limitations on experimental control, experimental reconfiguration, and testing of technologies that do not meet current codes and standards; and 3) the complexity of conducting experiments in multiple offsite facilities.

3.2.4 New Experimental Facility

This option is similar to the first except that the facility would be built specifically for the research, or an existing facility would be substantially altered to meet the requirements of experimentation. This option assumes that ancillary support facilities would be included or located nearby. The drawbacks of this option are the initial capital funding required and the implied long-term commitment of operating funds.

3.3 FACILITY CRITERIA

Based on the analysis of the needed experimental research, criteria were developed against which to evaluate each of the four alternatives. The criteria were divided into three categories: technical, experimental, and economic. Technical criteria address such questions as size of facility, number of floors, flexibility of configuration, and type and combinations of subsystems. Experimental criteria address instrumentation, monitoring, and control of experiments. Economic criteria consider the relative costs of each alternative.

3.3.1 Technical Criteria

The four alternatives were compared on the basis of three separate aspects of the technical criteria:

- the existence, availability, and constructability of the type of facility needed to carry out a significant part of the research agenda
- the nature of the barriers or restrictions that are likely to exist with each alternative
- the flexibility to make configuration changes that are possible with each alternative.

The following are typical of the questions considered during the analysis of the four options:

- **Existence, availability, and constructability** - Do facilities or buildings with appropriate characteristics exist, and are they readily available for modification to accommodate building system integration experimental testing? This would include facilities or buildings that have been previously used for experimentation on whole-building thermal effects. For those facilities or buildings identified, questions were asked regarding how they were obtained for experimentation, whether they were appropriate for experimentation, and what technical problems were encountered. In addition, the panel studied whether a new facility could be readily designed and constructed to meet the criteria.
- **Restrictions on building use** - Regulations common to existing buildings or facilities should not pose significant restrictions to the proposed experimental program. Were there restrictions (e.g., code and zoning restrictions) on existing buildings, that would make it difficult to locate or use them for experimental purposes?
- **Flexibility to configuration changes** - Facilities or buildings should have subsystems that can be readily changed or altered to facilitate experimentation. Is it possible or difficult to change or modify building subsystems to obtain comparable results?

3.3.2 Experimental Criteria

The experimental criteria against which the four alternatives were evaluated were

- the ease of obtaining supporting facilities
- the ease of installing and maintaining instrumentation and maintaining the desired test environment
- the ease of setting up and breaking down experiments
- the degree of experimental control that could be achieved.

Support Facilities. It was determined that support facilities should be available to house researchers and to be used to establish experiments, design and construct experimental apparatus, and calibrate and repair instruments and sensors.

Instrumentation, Monitoring, and Test Environment. Sensor installation, wiring, and maintenance should be readily accomplished. Monitoring, early detection of data errors and interruptions, and early correction of problems should also be readily accomplished. The desired test environment should be readily attainable and relatively unaffected by conditions in the rest of the building so that test conditions would be stable.

Sequential Operations. Experiments should be able to be readily set up and broken down. The physical arrangement of the facility should enable researchers to set up the experiments in a minimum amount of time.

Experimental Control. The physical design should enable researchers to isolate the experiments from extraneous factors and to control or isolate the variable factors so that their significance can be quantified.

3.3.3 Economic Criteria

The three economic criteria for comparing the four alternatives were

- initial cost of the facility or building
- setup and decommissioning costs
- operating costs.

Initial Cost. The facility or building acquisition costs are those incurred in the design, construction, and remodeling or other preparation costs. If restoration to existing conditions is anticipated, that cost was also included.

Facility Setup Costs. Cost for setting up and decommissioning the experimental apparatus in each facility or building is included in this category. For facilities that are leased and not dedicated to the experimental program, this cost can be very significant.

Operating Costs. Included are leasing and experimentation costs: preparation, setup, instrumentation, monitoring, maintenance, breakdown, and changeover costs. Travel and per diem costs for staff on travel status for offsite testing are also included here.

3.4 EVALUATION OF ALTERNATIVES

The four alternatives were evaluated against the technical, experimental, and economic criteria described in Section 3.3. The results of that evaluation are summarized in Table 3.3 and discussed in this section.

3.4.1 Existing Research Facility

Technical Criteria

Existence, Availability, and Constructability. A number of building science research facilities are dedicated to investigating the interaction of two building subsystems in combinations as described in Table 3.2. The need for a facility to investigate the integration of the total building system was established by the technical review panel and confirmed by the process outlined in Section 3.1. The ideal accommodation would be an existing research facility that offers sufficient floor area and ceiling height to typify multizone transient behavior. However, a search of university laboratories (American Consulting Engineers Council Research & Management Foundation 1989) and federal laboratories was not successful in locating such a facility.

The following summarizes those portions of the building system integration research agenda that could be done within existing facilities:

- HVAC optimization methodology - in the development and verification of models that allow optimization of HVAC systems in concert with other building subsystems, to investigate HVAC/control and lighting/HVAC interactions, as well as solar gain impacts on HVAC performance
- ventilation optimization - studies of the effects of design alternatives on ventilation efficiency, the developments of an easy-to-use three-

Table 3.3. Summary Analysis of Feasibility Options

Alternative 1 Existing Research Facility	Alternative 2 Existing Occupied Building	Alternative 3 Existing Unoccupied Building	Alternative 4 Dedicated New Facility
TECHNICAL CRITERIA Availability - No existing facilities with full capability. Preliminary studies could be done in number of facilities.	Availability - Principal criteria are sufficient plan area and height to typify multi-zone building energy transient behavior (three floors and about 7000 ft ² plan area minimum). Energy-related characteristics of materials and subsystems must be known. Research would be limited by building codes - hence research limited to incremental changes. Multiple sites required to meet all needed configurations.	Availability - Principal criteria are sufficient plan area and height to typify multi-zone building energy transient behavior. Greater freedom to have features included in initial design. Energy-related characteristics of all materials and subsystems must be known. Research still limited by building codes - hence research limited to incremental changes. Multiple sites required to meet all needed configurations.	Availability/constructability - BSIL design requires innovative features to provide needed flexibility. Could be built in three phases for budgetary reasons. Could be built with code variances to allow testing of radically new concepts. Energy-related characteristics known for the total system.
	Use Restrictions - Potential conflicts with other tenants and maintenance of test environment.	Use Restrictions - Need to maintain habitability of the rest of the building may compromise test environment.	Use Restrictions - Facility fully dedicated to this purpose so no conflicts with other tenants. Can maintain steady-state environment.
	Flexibility to Configuration Change - Probable that retrofitting and the use of multiple sites will be required.	Flexibility to Configuration Change - May design capability for easier retrofits. May require several sites.	Flexibility to Configuration Change - Greatest flexibility - Interior partitions, floors and ceilings, and exterior facade can be reconfigured. Easy access to energy distribution system for convenient changes to HVAC systems.
EXPERIMENTAL CRITERIA Existing facilities could be used where appropriate to conduct the preliminary phases of the building system integration research.	Support Facilities - Satisfactory if leased building is located near a university or research facility, otherwise it will contribute to high operating costs.	Support Facilities - Similar to occupied building. Much enhanced by proximity to a research facility.	Support Facilities - BSIL would be located at a research facility. Would contain needed support facilities.
	Instrumentation, Monitoring, and Testing Environment - Depends on use agreement with other tenants. Proximity to research facilities and extent of telemetering important. Maintaining desired test environment may conflict with normal building operations. Instrumentation difficult.	Instrumentation, Monitoring, and Testing Environment - Better than in occupied building - no contact with other tenants. Proximity to research facilities and extent of telemetering important. Instrumentation difficult but less so than in occupied building.	Instrumentation, Monitoring, and Testing Environment - BSIL would be a dedicated lab and capable of maintaining test environment by using of a guard space controlling the environment on the lab exterior.
	Sequential Operations - Depends on arrangements with other tenants. May require short, intensive testing periods or long unattended tests with remote metering. Low flexibility will limit extent of testing in a single facility.	Sequential Operations - Better than in occupied building because operating schedule would not conflict with commercial users of the building. Low flexibility will limit extent of testing in a single building.	Sequential Operations - Conversion to widely different test configurations can be accommodated within the single facility.
ECONOMIC CRITERIA The use of existing research facilities to conduct the preliminary phases building system integration research would be the most cost-effective alternative for those portions of the program.	Experimental Control - Difficult; may conflict with normal building operation.	Experimental Control - Better than in occupied building.	Experimental Control - BSIL designed to facilitate.
	Initial Cost - Includes costs of locating, determining construction details, contracting, and modifying to testing conditions. Several buildings would be needed over the course of the program.	Initial Cost - Similar to occupied building. Modification may be more extensive but more cost effective. Several buildings would be needed over the course of the program.	Initial Cost - Capital cost of BSIL facility at program start is higher than with use of existing buildings.
	Operating Costs - In addition to normal program costs, must consider costs of building leasing, off-site travel and living, local service support, added staff requirements, more difficult modifications, contact with other tenants, more materials required. Lower productivity. See Table 3.2 for comparison of example scenarios.	Operating Costs - Similar to occupied building. Rental costs may be higher because there may be no other tenant. Provides a potentially larger scale of testing than the occupied building. See Table 3.2 for comparison of example scenarios.	Operating Costs - Significantly lower because no lease costs, lower staff requirement, travel, materials. Higher productivity. See Table 3.2 for comparison of example scenarios.

dimensional model for open flow of air, and the development of appropriate objective functions for ventilation optimization

- field testing of integrated systems - preliminary small-scale testing
- analytical methods for transient effects - preliminary studies of transient load impacts on equipment size and whole-building performance rather than a series of independent steady-state situations
- computer program verification and algorithm development - initial development to handle unusual conditions such as floating temperatures and convective effect in atria
- testing of building components - specific tests on new components to identify potential two-subsystem interactions
- innovative operating and control strategies - limited preliminary studies of feasibility.

In each of the areas, existing facilities would lack the capability to assess the total building system integration and the impact on energy utilization, but could provide initial studies that would provide more information about the problem.

3.4.2 Existing Occupied Building

Technical Criteria

Existence, Availability, and Constructability.

Existing occupied buildings would have to provide adequate size, construction characteristics, and operational flexibility to be considered. Critical features include the following:

- Complete construction details must be available to be able to understand and stipulate all energy-related characteristics of structural materials and assemblies.
- The floor area and ceiling height must be sufficient to typify multizone building energy transient behavior:

- three or more floors
- plan area of roughly 7,000 ft² minimum.

If several buildings with these characteristics could be found and sufficiently dedicated to building system integration research, significant results could be obtained in the following areas:

- HVAC optimization methodology development as applied to conventional building design, e.g., the determination of system coefficient of performance and the effect of operation and control strategies on improving this characteristic
- ventilation optimization procedure development as applied to conventional buildings, i.e., establishing design procedures for achieving the greatest turnover of air in the occupied zone with the minimum use of ventilation air
- computer program verification and algorithm improvement and development for existing whole-building computer codes
- developing the capability to analyze large building performance as a continuous transient system, including all significant interaction between conventional subsystems.

A number of such buildings would be needed in order to confirm the configurational effects in the tasks noted above because of the difficulty of acquiring an occupied building in which the interior configuration can be periodically changed to carry out the experiments. It has been difficult in the past to locate buildings of the appropriate physical characteristics and which are available for relatively nonintrusive experimentation. The DOE Hotel/Motel and Restaurant demonstration projects and the Post-Occupancy Evaluation of Office Lighting projects all experienced difficulties in locating buildings of appropriate characteristics.

The principal drawbacks to the use of an existing occupied building as the experimental facility are 1) the limitation of research to concepts and configurations that are now being built; 2) the need to maintain experimental control; and 3) the degree to

which existing use can be altered or occupants can be disrupted by the experimentation (Gillette and Brown 1986; Hill et al. 1981). These drawbacks are discussed below.

The ability to consider significantly new approaches to improve the energy efficiency of commercial buildings, which may depart from current design convention and building codes, would be lost in this scenario. Thus, results in system integration research would be limited to incremental, **evolutionary** changes in subsystem design; radical new, **revolutionary** approaches would not have a testbed for the evaluation and demonstration phase so essential to effecting technology transfer to the commercial market. The principal incentive for building system integration research would be lost if its implementation is limited to the use of existing buildings designed for commercial occupancy. The technical review panel recommended that all consideration of eventual commercial occupancy be dropped in the development of the concept of a new dedicated experimental facility. The panel felt it would compromise the objectives of the program and add unnecessary capital cost in light of the probability that use of the facility for research would continue indefinitely.

Another difficulty in conducting an experimental task within an existing occupied building is the conflicts that would arise between the use of the building and the maintenance of the required test environment (Hill et al. 1981). Although the results of the experimental tasks must eventually be applied to occupied buildings and account for the impacts of building use on the interactions of the subsystems and the total system optimization, the initial data must avoid this. It must be obtained in a controlled environment, to isolate the effects from subsystem and occupant-behavior interactions. Once the former has been established, the latter can be more easily included into the understanding of total system behavior.

It may be difficult to locate a facility in which the existing use can be altered to the extent necessary to carry out even the studies of an evolutionary nature and achieve those limited objectives of the major building system integration research tasks.

To accomplish a significant portion of the experimental tasks, e.g., to be able to confirm configurational effects in the interaction of building subsystems, the facility should also have

- reconfigurable interior walls and partitions, floors, and ceilings
- a reconfigurable exterior envelope, i.e., variable window types and placement, variable exterior wall construction, variable solar interactions with both building envelope and interior
- accessible energy-distribution service area for HVAC ducts, electrical wiring, and alternative energy sources such as gas or hot water.

Reconfiguration by remodeling and retrofitting of an existing building is an option, but normally an expensive one unless this capability were included in the original building design. It also carries the potential for atypical interfacing with the existing construction. The alternative to having these capabilities in a single existing facility is to conduct the tasks in a number of well-characterized buildings. However, the chances of locating and acquiring several such facilities are considerably less than locating a single adequate building for a selected experiment.

Experimental Criteria

Support Facilities. Support facilities should be available to design and construct experimental apparatus, and to calibrate and repair instrument sensors. If the existing facility is located at a university or other research facility, this criterion would present no obstacle. At any other site, it could be a relatively high operating cost requirement.

Instrumentation, Monitoring, and Test Environment. The installation, wiring, and maintenance of sensors should be easily accomplished to accommodate the conduct of the studies. Again, the proximity to a research establishment would be beneficial for cost-effective operation. Monitoring and early detection and correction of data errors should be easily accomplished, requiring either onsite surveillance or telemetering to a data processing location.

Again, isolation of the test facility from the location of the research staff will add cost.

Sequential Operations. Experiments should be easily set up and broken down. Unless the existing facilities are totally dedicated to experimental tasks, the tasks must be staged in such a way as to utilize either a short period of intense effort or a longer time of unattended operation. High productivity will be more difficult to achieve under these circumstances.

Experimental Control. The facility must permit the isolation of experiments from extraneous factors. However, in the occupied building, maintaining the required isolation will be difficult; attempts to do so may conflict with normal building operation.

Economic Criteria

Initial Cost. The high capital cost of a new facility is avoided by the use of an existing building, but other upfront or peripheral costs for locating and contracting for appropriate buildings, establishing building construction details, remodeling, or other preparation must be considered. Examples include adapting the building to the testing configuration, possibly a significant cost because of the lack of flexibility in configuration control, and decommissioning and restoring of the building.

Operating Costs. Operating costs will be highly dependent on the location and use-permit arrangements. If the facility is remote from an existing research facility, the cost of conducting the research will be significantly higher. In addition to normal project costs of preparation, setup, instrumentation, monitoring, maintenance, breakdown and change-over, the following costs must be considered in evaluating a remote facility:

- real estate rental costs of a leased or purchased building
- multiplier costs for multiple sites where a single building cannot represent the needed conditions or cannot be modified to run other experiments
- higher materials costs (than for a dedicated lab) because reuse of materials and components will be considerably more difficult and costly

- multiple experimental sites because additional research staff will likely be needed to carry on a program at two or more sites
- travel costs to and from an experimental site and per diem
- contract support costs required by remote sites to contract and train local site technicians to maintain support of the experiments and to purchase services for such items as sensor calibration
- transmission of data from experimental sites to a central site for analysis.

3.4.3 Existing Unoccupied Building

Technical Criteria

The significant differences, with respect to technical criteria, between the existing occupied building alternative and the unoccupied building alternative are the greater freedom the program would have to 1) arrange for certain design features to be incorporated into the original design of the building, probably at the incremental cost of these modifications; 2) conduct the test program without being encumbered with interfacing with the commercial occupants; and 3) alter the facility to accommodate the test requirements.

Existence, Availability, and Constructability.

The same criteria would apply as in the previous alternative, except for the possible opportunity to gain access to a wider range of building types and features for testing. The technical review panel suggested that one approach to obtaining the use of new buildings, with specific desirable features, as a temporary experimental facility would be to establish a federal program that would offer favorable construction loan rates to builders who would be willing to incorporate these features and lease back to the government, under favorable conditions, a portion of the building prior to commercial occupancy. Another approach would be to use new federal buildings, as they are constructed and then occupied, as test facilities.

As with existing occupied buildings, the use of an unoccupied new building would limit the research to concepts and configurations that are currently being

built or, at most, are evolutionary extensions of current construction practice. Radical departures from existing building codes and standards would probably not be possible. Consequently, experimentation or innovation would not be possible. The scope of work that could be accomplished would be essentially the same as that achievable with the use of existing occupied buildings.

Restrictions on Building Use. The potential conflict between the occupants of the building and the need to maintain the required test environment would be considerably less in this situation. However, the test program could not embody conditions that would make the rest of the building less habitable, unless the total building were leased during the testing period.

Flexibility to Configuration Changes. The singular difference between the use of an unoccupied, leased building and an occupied building is that the agreements of the former could be completed prior to completion of construction and, consequently, there may be the opportunity to incorporate design features of particular interest to the experimentation program. Both would have similar problems of configurational flexibility, unless the needed features had been considered during the early stage of construction while there were still opportunities to build added flexibility into the building design.

Experimental Criteria

To conduct expanded research in leased, unoccupied portions of a building rather than in occupied buildings would reduce the experimental difficulties because the interaction with commercial users would be markedly reduced.

Support Facilities. The response is similar for both the unoccupied and occupied alternatives. Both alternatives would lead to less costly operations if located at a university or other research facility where the need to set up completely self-sufficient support facilities would be minimized.

Instrumentation, Monitoring, and Test Environment. The use of an unoccupied portion (or total) of an existing building would be a much more favorable operating environment because the researchers would not be required to interface with building occupants or deal with "housekeeping" problems.

Nevertheless, the proximity to a research establishment would be beneficial for cost-effective operations, and isolation of the test facility from the location of the staff would add significantly to the cost.

Sequential Operations. Using an unoccupied existing building would be much more convenient than occupied buildings because the operating schedule would not be as constrained by the interface with the occupants of the building. Sequential tests could be staged more conveniently.

Experimental Control. Maintaining the required isolation of experiments from extraneous factors would be easier in an unoccupied existing building. However, the extent of control would be limited by the existing building's design features.

Economic Criteria

Initial Cost. Again, the high capital cost of a new facility would be avoided, but the other upfront costs described in the use of an occupied building must be considered. There may be a tendency to incorporate more custom features, which would increase these costs. However, these costs may be counterbalanced by somewhat lower costs of modification, because it would be done either in conjunction with the building's initial construction or later in the program in the absence of occupants.

Operating Costs. The use-permit arrangement would differ significantly between unoccupied and occupied facilities. The rental charges are likely to be considerably higher in the case of the unoccupied building, because the testing program would be the only tenant for that portion of the building. However, the establishment of a program of enlistment that provided upfront advantages for the builders or building owner could be the important factor in reducing those costs.

Higher program costs are again foreseen if the buildings are some distance from the home base of the research staff.

3.5 FINAL ANALYSIS

The comparisons of the four alternatives resulted in the following final analysis.

- Even if research were limited to incremental improvements in building system integration and conducted in existing buildings (either occupied or unoccupied), the cost of using leased facilities would ultimately exceed that of a dedicated new facility. This stems from the need for many such leased facilities to overcome the limited flexibility of available facilities, the higher cost of offsite operations, and the facility rental costs. A scenario comparing the cost of the three alternatives for using existing leased buildings, as opposed to

a dedicated new facility, is summarized in Table 3.4. The assumptions on which the costs are based are described in the footnotes to Table 3.4.

- A significant portion of building system integration research can be done in existing experimental facilities. This is where most experimental research is carried out now. However, this work involves the interaction of a limited number of subsystems, generally only two. For

Table 3.4. Estimated Cost of Alternative Facility Concepts

Cost Category	Explanation	Alternatives		
		Building System Integration Laboratory, \$ million	Existing Occupied Building, \$ million	Existing Unoccupied Building, \$ million
Initial Costs				
Capital Project	(a)	10.8	—	—
Contracted Space	(b)	—	—	—
Search and Contract		—	0.05/site	0.05/site
Modifications		—	0.50/site	0.50/site
Restoration	—	0.50/site	0.50/site	
Operating Costs				
Rent	(c)	—	0.30	0.50
Staff Labor	(d)	0.65	0.75	0.75
Materials	(e)	0.20	0.30	0.30
Capital Equipment	(f)	0.10	0.10	0.10
Travel	(g)	0.03	0.15	0.15
Contracted Support	(h)	—	0.20	0.20
Telemetry	(i)	—	0.10	0.10
Subtotal Operating Costs		0.98	1.90	2.10
Present Worth Revenue Requirement	(j)	18.20	17.90	19.20

(a) Capital Project - \$10.8 million - The conceptual cost estimate of the BSIL.

(b) Contracted Space - Assumes the cost of locating and contracting space is \$50 thousand, modifications are \$500 thousand, and restoration is \$500 thousand.

(c) Rent - OCCUPIED BLDG is based on 30,000 ft² at \$10/ft²-yr. UNOCCUPIED BLDG is assumed to be 60% higher because no other tenant would be in the building during the testing program.

(d) Staff Labor - BSIL - Assumes 5 full-time employees (FTEs); EXISTING BLDG - A 25% increase in required staff is assumed, to account for the inefficiencies of offsite work.

(e) Materials - BSIL - \$200 thousand/yr. EXISTING BLDG assumes \$300 thousand/yr because of the lack of flexibility to recover material from one site to use on the next site.

(f) Capital Equipment - Assumes a similar amount for each case, approximately \$100 thousand.

(g) Travel - BSIL - Assumes 10 man-weeks of offsite travel and 10 trips across country. EXISTING BLDG - Assumes half-time offsite for 3 staff members.

(h) Contract Support - BSIL - None required. EXISTING BLDG - Assumes contracting and training required for two local technicians plus support services for instrument maintenance and calibration.

(i) Telemetry - BSIL - None required. EXISTING BLDG - \$100 thousand for data loggers, terminals, and dedicated phone lines.

(j) Present Worth Revenue Requirement - Assumes capital costs at front end of a project are equal to their present worth revenue requirement. Phased contracting of leased space is discounted at 8%/yr. Operating costs are similarly discounted at 8%/yr.

BSIL - Assumes one-time construction of the entire project.

EXISTING BLDG - Assumes five sites being contracted in Years 0, 2, 4, 6, 8, with capital and renovation cost discounted at the 8% rate.

total building system integration research, larger facilities capable of typifying multizone building energy transient behavior are required.

- The size criteria can be met through the use of leased facilities, either occupied or unoccupied. However, although these approaches avoid the capital cost of a new dedicated facility, they have several significant drawbacks.
- Of the seven areas of research categorized as the most important for advancing building system integration, five require a dedicated, flexible facility such as the BSIL to achieve the ultimate program objectives. Reliance on leased facilities would limit research, particularly on innovation.
- The use of leased facilities may compromise the validity of results because of uncertainty about the testing environment, construction materials, or methods, and the difficulty of maintaining constant experimental conditions.
- Factors that would influence the selection of either leased space or a dedicated experimental facility in which to conduct a given piece of research include the following:
 - **changeability at large scale** - Research that requires large-scale changeability will favor the use of a dedicated experimental facility. Research that does not require either changeability or a large scale will favor leased buildings.
 - **control of complex conditions** - Research that requires the control of complex external and internal conditions will favor a dedicated experimental facility.
 - **isolation of effects in multi-effect problems** - Research that requires the isolation of specific effects in a multi-effect problem will favor a dedicated experimental facility.
 - **integrative issues** - Research that involves the investigation of issues associated with integration of separate building systems will favor a dedicated experimental facility.
 - **required facade modifications** - Research that requires substantial modification of the building facade will best be done in a dedicated experimental facility.
 - **size and complexity of required modifications** - Research that requires small scale or simple changes can best be done in leased buildings. Research that requires substantial or complex modifications would best be done in a dedicated experimental facility.
 - **isolation** - Research that requires careful isolation from surrounding spaces will favor a dedicated experimental facility, while research that is less sensitive to isolation will favor leased buildings.
 - **incremental and fundamental change** - Leased space will be most appropriate for investigating concepts that result in incremental change. A dedicated experimental facility would be favored for investigating approaches that result in fundamental change and innovation.
 - **very large subsystems** - Research on very large subsystems, systems that exceed the capabilities of a dedicated experimental facility, could not be conducted at an experimental facility and would be best conducted in leased space.
 - **not allowed by existing building codes** - Research that involves modifications not allowed by building codes would favor a dedicated experimental facility.

4.0 CONCEPTUAL DEVELOPMENT OF THE PREFERRED ALTERNATIVE

The functional criteria that were developed for evaluating the four alternatives established the ground rules and design requirements for the overall design of the preferred alternative--called a Building System Integration Laboratory (BSIL). This section describes, in detail, the study used to develop the physical concept of the BSIL. Physical specifications, proposed floor plans, building elevations, and cost estimates are provided.

4.1 THE PREFERRED ALTERNATIVE

The BSIL alternative is a newly-built, dedicated experimental structure designed for large-scale experiments of combinations of full-scale building components under controlled conditions. The exterior walls and roof of the BSIL would be an environmental chamber under which full-scale experiments involving buildings with up to a three-story facade, including opaque walls, windows, and doors, and portion of the roof, skylights and hatches, could be conducted. The BSIL would also be designed to permit the exposure of these experiments to ambient (local climatic) conditions when this is feasible and practical. The BSIL envelope design would permit sequential testing of a number of separate experiments under several seasonal conditions over short periods of time. Thus, experiments would not be limited to summer and winter testing seasonal changes, nor would they depend on the vagaries of year-to-year climatic changes. Thus, the BSIL would have three separate components: 1) an external shell that could simulate desired climate conditions; 2) an internal structure that would allow for several concurrent experiments and a quick change of components; and 3) an onsite support facility to house research staff and support functions.

The internal structure of the BSIL would be designed to support envelope components of experiments and flexibly house experiments involving a wide variety of internal space configurations, exposures, conditions, and occupancies found in commercial buildings. In addition, the BSIL structure would be designed to support easy changeout of various heating, ventilating, air conditioning, lighting,

power, hot water and control components for different experiments. Finally, the BSIL would be designed to provide for flexibility in instrumentation and monitoring of the various combinations of components and spaces involved in the experiments and the rapid changeout of instrumentation for prompt sequencing of experiments.

4.2 CONCEPTUAL DESIGN

The conceptual design of the BSIL, as shown in Figure 4.1, includes an exterior shell that encloses a climate-controlled space (annulus) over the roof and around three sides of a three-story structure that will flexibly support and house the required large-scale experimental testing. Portions of the BSIL exterior shell could be removed to expose an experiment to ambient (local climatic) conditions. The structure to support the experiments is 100 ft by 100 ft in the interior floor plan on each level. Portions of the second-and third-level floors of the structure could be removed to simulate atrium conditions. A basement houses mechanical equipment and immediate support activities. A service core runs vertically the full height of the BSIL, providing access, utilities, and chases for vertical runs for experiment components. There would also be a separate 50-ft by 100-ft one-story storage building for storing experimental components and BSIL shell panels while not in use.

4.2.1 Ground Rules

The scope of the BSIL design study was defined by three ground rules:

- **site** - The conceptual design should not be site-specific; rather, the design should be suitable for a wide range of possible sites and climates. Thus, an outer building shell that can control climate variables should be designed into the structure.
- **support facilities** - It was assumed that support facilities, such as most office space, conference rooms, and computer services, would be located in existing structures and would not be included in the BSIL design.

Figure 4.1. Conceptual Design for the Building System Integration Laboratory

- **instrumentation** - The BSIL design should include provisions for instrumentation, but it was assumed that expenses associated with data collection would be met by individual research projects.

4.2.2 General Design Requirements

The functional criteria for a facility in which to conduct building system integration research included three components: 1) a climate-controlled external shell; 2) a flexible interior structure; and

3) a separate storage building. Based on these criteria, the following general design requirements were established:

- experimental facility height - The external shell of the facility should have three above-ground floors and a basement. Optimal testing requires three above-ground floors. A ground floor is needed to simulate ground coupling and building entrance effects. The middle floor is needed to simulate a typical floor in a commercial building, while the top floor is needed to investigate issues involving interactions with the roof. Support services should be located in the basement.
- experimental facility floor areas - The facility should have floor dimensions to accommodate 100-ft by 100-ft test areas. The minimum floor dimensions are dictated by the need for tests involving experiments with building perimeter external zones (30 ft each) and the requirements for an internal zone measuring 40 ft by 40 ft. This floor area facilitates research on external zones with variable zone depth, as well as interactions between the external and internal zones.
- internal structure - The internal structure of the facility should be designed to accommodate several different types of window and wall configurations.
- external shell - The external shell should be designed to alternate between serving as an environmental chamber and exposing the wall and window facades, which hang on the internal structure, to ambient conditions.

A separate 5000-ft² storage building should be located close to the main facility. This building should be an inexpensive structure in which to store major building and experimental components.

4.2.3 BSIL Design Requirements

The BSIL external shell should be designed to selectively expose or isolate experiment-related walls and roof constructions from ambient conditions. Sections of the BSIL external shell should be removable so that any sections of the wall or roof being tested can be exposed to ambient conditions. The annulus or space between the external shell and the interior structure should be designed to be

conditioned to maintain constant controllable temperature, humidity, and air velocities on the test building exterior.

The configuration of the interior structure, which supports the facade being tested, should be easily altered so that a variety of materials, components, and designs can be tested. Provisions should be included to allow for variable window types, window shading, and facade thermal characteristics.

The BSIL interior structure should include space for three above-ground floors and a basement. The above-ground floors should provide test space while the basement would allow for vehicle access, limited office space, a shop, room for electronic equipment, and test assembly areas. A freight elevator should extend the entire height of the entire structure for transporting large preassembled components to the above-ground test spaces. Some of the above-ground floors should be removable to create a multifloor space, to allow investigations of atria and other large spaces. Provision should be made to vary the ceiling height of the ground floor. The configuration of other internal walls and partitions in the above-ground floors should also be easily alterable.

The interior structure of the BSIL should be designed so that the configuration of lighting, HVAC, electricity, and utilities is easy to modify. It should be designed to also allow an experimental configuration for occupancy similar to that of an operating commercial office building.

The separate 5000-ft² storage building should be constructed onsite, but should be located far enough away from the main structure to prevent interference with the climatic effects on tests.

4.3 PHASED CONSTRUCTION

Immediate construction of a complete facility requires a substantial capital outlay. An alternative approach is to construct a BSIL in phases. Phased construction would reduce the initial capital cost of the facility and allow for future expansion to the final dimensions. Research projects would be grouped and given priority to accommodate phased construction.

The technical review panel investigated this approach and explored a three-phase construction plan was explored. The initial phase would create a structure with a basement and three above-ground floors with interior structure dimensions of approximately 50 ft by 50 ft. The second phase would then expand the facility to an interior structure space approximately 100 ft by 50 ft, permitting tests in the next level of priority and complexity to be run. The third and final construction phase would result in the full-sized BSIL with approximate interior structure dimensions of 100 ft by 100 ft. The completed BSIL could accommodate studies requiring simultaneous multi-oriented facades and exterior zones.

A design was developed that allows for phased construction if funding constraints held back construction of the complete facility. Each phase is briefly described in the following paragraphs. The phased design package is described in more detail in Appendix C.

4.3.1 First Phase

The design for the BSIL first phase consists of three above-ground experimental floors, a basement with an exterior shell on two sides and on the roof, an interior structure of 50 ft by 50 ft, and a vertical service core and penthouse. This results in a 54-ft by 54-ft internal structure test area on each of the three above-ground floors. The service core includes a stairway, elevator, mechanical shaft, and a mechanical and electrical room. A service support area located in the basement includes the main entry, facility control room, a mechanical room, and the service core. The BSIL external shell encloses the south facade and two-thirds of the east and west facades. The external shell is separated from the interior test structure by an 8-ft annular space. A temporary external stairway is included for emergency egress. A perspective of the first phase of the BSIL is shown in Figure 4.2. Plan and elevation views of the first-phase structure are shown in Figure 4.3.

4.3.2 Second Phase

The second phase of construction doubles the available interior structure test area on each above-ground floor to 108 ft by 54 ft. It also adds a material assembly area, shops, and storage in the basement. The service core is expanded to include an

enlarged mechanical and electrical room and a second stairway. The BSIL external shell encloses the south facade and two-thirds of the east and west facades. The external shell on the west facade of the first-phase structure would be relocated to the west facade of the second-phase structure. Plan and elevation views of the second phase are shown in Figure 4.4.

4.3.3 Third Phase

The third construction phase would complete the BSIL. The dimensions of each floor are expanded to 108 ft by 108 ft, doubling the area available for experimentation. It adds a second mechanical room, storage, shipping and receiving area, loading dock, and offices to the service support area in the basement. The BSIL external shell would be extended to enclose all four facades and the roof of the test building. The separate storage building would be constructed as part of the third phase. A perspective of the complete facility is shown in Figure 4.5; plan and elevation views are presented in Figure 4.6.

4.3.4 Benefits of Phased Construction

The effect of phased construction on the research agenda is summarized in Table 4.1. As indicated, the structure created by each construction phase will support a significant portion of the total research agenda.

In the first-phase structure, useful research can be conducted in each of the seven areas of the system integration research agenda discussed in Section 3. The relatively small size of the first-phase BSIL will not affect the evaluation of transient effects or the development of protocols for component testing because these efforts can be conducted on a small scale.

The primary benefits of the second-phase structure are its larger size and increased surface area enclosed by the BSIL external shell, which will enable researchers to conduct an increased number of simultaneous tests. The second phase also adds the capabilities to investigate atria and to test moderately-sized internal zones.

The third-phase structure will support the complete research agenda. The floor area available

Figure 4.2. Architectural Perspective, Phase 1

DATE	10/10/73	BY	J. H. H.						
PROJECT	SOUTH BRIDGE								
DESCRIPTION	REPAIRS TO BRIDGE								
LOCATION	SOUTH BRIDGE								
SCALE	1" = 10'								
REVISIONS	<table><tr><th>NO.</th><th>DESCRIPTION</th><th>DATE</th></tr><tr><td>1</td><td>AS SHOWN</td><td>10/10/73</td></tr></table>			NO.	DESCRIPTION	DATE	1	AS SHOWN	10/10/73
NO.	DESCRIPTION	DATE							
1	AS SHOWN	10/10/73							

1. SOUTH BRIDGE

SEE PLAN

LEFT BANK DIRT

RIGHT BANK DIRT

OUTLET SPASTOLE

Figure 4.3. Architectural Plans and Section, Phase 1

Figure 4.3: Mechanical floor and ceiling layout

Figure 4.4. Architectural Plans and Section, Phase 2

Section 19 - 1900 ft. long

NO.	DESCRIPTION	QTY.	UNIT
1	CONCRETE	100	CU YD
2	STEEL	100	LB
3	BRICK	100	1000
4	CEMENT	100	BA
5	SAND	100	CU YD
6	GRAVEL	100	CU YD
7	WATER	100	CU YD
8	WATER	100	CU YD
9	WATER	100	CU YD
10	WATER	100	CU YD

BRIDGE

SECTION 19

SECTION 19

SECTION 19

Figure 3.2: Aerial view of the study area

NO.	NAME	ADDRESS	PHONE	EMAIL
1	...	...	...	...
2	...	...	...	...
3	...	...	...	...
4	...	...	...	...
5	...	...	...	...
6	...	...	...	...
7	...	...	...	...
8	...	...	...	...
9	...	...	...	...
10	...	...	...	...

Figure 3.2: Aerial view of the study area

Figure 4.6. Architectural Plans and Section, Phase 3

CL A

Figure 1: Proposed layout of the 2000sq ft building

Table 4.1. The Impact of Phased Construction on the BSIL Research Agenda

Research Activity	Phase 1	Phase 2	Phase 3
HVAC optimization	2	2	1
Ventilation optimization	2	2	1
Test integrated sub-systems	2	2	1
Transient effects	1	1	1
Code verification	2	2	1
Subsystem-test protocols	1	1	1
Control strategies	2	2	1

NOTES: 1 - All required capabilities are available at this phase.
 2 - Useful research can be conducted at this phase.
 3 - Research of limited usefulness can be conducted at this phase.

for testing will be double that of the second phase, increasing the number of simultaneous tests. The complete interior structure test area would be enclosed by the climate-controlled external shell. This will allow controlled tests on roof and north wall interactions. External and internal zones with maximum dimensions can be investigated.

4.3.5 Unique Features

Although phased construction would initially limit the experimental facility capabilities, several unique features would be available during all three phases. These features are listed below.

- **flexibility**

- **internal flexibility** - The configuration of the ceilings in the test area will be alterable, as will partitions, allowing testing in a wide range of internal configurations.
- **facade flexibility** - The configuration of the wall and window components on the interior structure can be altered or replaced for testing the interactions of various combinations

of opaque wall and window characteristics with other subsystems and their effect on building system performance.

- **equipment flexibility** - The configuration of the test building will include easily altered HVAC, lighting, electrical, and instrumentation subsystems.

- **control**

- **controlled exposure to ambient conditions** - The BSIL shell envelope can be used to selectively expose portions of the test building facade to ambient conditions or to control conditions using a zone-specific HVAC system in the (annular) space between the external shell and the test areas of the internal structure.

- **scale**

- three floors allowing investigations of roof, intermediate floor, and ground interactions
- external and internal zones.

4.4 COST ESTIMATE

The cost of the experimental facility was estimated on the basis of the overall design. The cost estimate assumes that engineering expenses will be 25% of the direct cost and that contingency expenses will be 30% of the total of direct costs and engineering costs. The costs are summarized by construction phase in Table 4.2. The first and second phases each will cost \$2.7 million. The third phase will cost \$5.4 million. The estimated total cost of the completed BSIL is \$10.8 million.

Table 4.2. Estimated Costs of Constructing the BSIL

Cost Component	Costs, \$ thousand			
	Phase 1	Phase 2	Phase 3	Total
Engineering	546	533	1,079	2,158
Site work	173	—	—	173
Test building	1,652	1,636	3,115	6,403
External envelope	377	491	1,055	1,923
Storage building	—	—	187	187
Total	2,748	2,660	5,436	10,844
Total (rounded)	2,700	2,700	5,400	10,800

5.0 BENEFITS OF BSIL RESEARCH

The research performed in a BSIL will have a direct effect on how buildings are designed, built, and operated. The direct benefits from this research include increasing energy savings, improving international competitiveness, and mitigating some of the conditions related to global climate change. This section will show how the research proposed for a BSIL will contribute these benefits.

5.1 ENERGY SAVINGS POTENTIAL

Commercial buildings represent 15.5% (11.6 quads) of the nation's primary energy consumption. This is equivalent to 5.4 million barrels of imported oil per day or the power output of 400 coal-fired power plants of 500 megawatts each.

It has been estimated that properly designed buildings with integrated systems can reduce energy consumption by 30% to 50% (Stoops et al. 1984). If this reduction could be achieved in new construction, the resulting reduction in national energy consumption would be from 3 to 4 quads in 2010. This represents a savings of between \$12 and \$15 billion in 1988 dollars.

All seven research activities discussed in Section 3 will lead to improved building energy efficiency. Developing new HVAC and ventilation procedures, for example, will improve the energy efficiency of the buildings in which these subsystems operate. Testing of integrated subsystems and components under a range of controlled real-world conditions will help commercialize more energy-efficient technologies, resulting in reduced energy consumption. The development of methods for analyzing transient effects will improve building energy efficiency by including transient effects in design and control algorithms. Code verification will increase the usefulness of simulation tools, resulting in improved designs. Finally, new control strategies will assist in integrating subsystems operating building systems more efficiently. The combined effect of these research activities is expected to significantly improve building energy efficiency.

5.2 IMPROVED INTERNATIONAL COMPETITIVENESS

A BSIL will also contribute to improvements in the international competitiveness of the American buildings industry. Research projects involving testing of integrated subsystems and components subsystems, for example, will result in products that will provide American vendors with advanced technologies that can be marketed competitively. A BSIL will provide a test-bed facility to help vendors develop new control and interface strategies. These strategies can provide a competitive advantage in the international marketplace.

The improved methodologies for envelope, lighting, and HVAC optimization will enable the nation's buildings industry to design buildings with both lower initial costs and lower operating costs. The improved optimization will also lead to individual components with more desirable characteristics.

The entire commercial sector in the United States would benefit from a BSIL as well. BSIL research would indirectly improve competitiveness by reducing the cost of owning and operating commercial buildings. In addition, research on worker productivity in a commercial buildings environment has potential for improving productivity.

5.3 MITIGATION OF FACTORS INVOLVED IN GLOBAL CLIMATE CHANGE

By reducing energy consumption, a BSIL would reduce the effluent that contributes to climatic change. This is particularly true because building energy consumption requires electricity, which is often produced by burning coal. The fraction of building energy consumption supplied by electricity is expected to increase from 32% of direct energy consumption in 1984 to 38% in the year 2010.

Coal-fired power plants are projected to provide an increasingly large fraction of electric power generating capacity. Figure 5.1 shows the impact of

Figure 5.1. Building Energy Consumption by Share of Source Fuel, 1984 and 2010

increased coal use on the consumption of primary energy sources. Coal provided 34% of the primary energy consumed in buildings in 1984, but this fraction will increase to 41% in 2010. Coal is a major source of sulfur dioxide and carbon dioxide, both of which are implicated as contributors to the greenhouse effect and global warming. The decreased use of energy potentially realizable from BSIL research will help mitigate these factors.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The feasibility study yielded several major conclusions and recommendations concerning the Building System Integration Laboratory.

6.1 CONCLUSIONS

Regarding the need for a research facility such as a BSIL, the study concluded that

- **Building system integration research is needed.** The results of this study and other investigations of building science research show there is a critical need for building system integration research. It has been estimated that a properly designed building with integrated building subsystems can decrease a building's energy consumption by between 30% and 60%.
- **A BSIL is needed for effective building system integration research.** Although several options are available for conducting system integration research, the study shows that a significant amount of critical research must be conducted in a BSIL for maximum effectiveness. In many cases, a BSIL is the only viable option for conducting the required research.
- **The BSIL could contribute to fundamental improvements in how buildings are designed, built, and operated.** Fundamental changes to design, construction, or operation occur infrequently because both initial change and any failure are very costly. Changes to components occur because they can be tested in a laboratory and localized in field tests first. However, component changes result in only incremental changes to building energy use. A BSIL would provide a testbed and demonstration site for more fundamental building-scale improvements. New approaches to solving the problems facing building designers and operators are more likely to come from a facility specifically dedicated to system integration research.
- **A BSIL should focus on commercial buildings.** In this study, many residential buildings were identified that can serve as experimental and test facilities for residential building system

integration. Similar facilities did not exist for commercial buildings.

- **There will be substantial improvements in building technologies if a BSIL is built that would not occur without such a facility.** Developing a BSIL will realize potential energy savings, increase international competitiveness in the buildings industry, decrease costs for building owners and operators, and provide a showcase for new products. The study results clearly indicate that a BSIL is a vital component of building sciences research. Proceeding with its establishment will positively affect the U.S. buildings industry.

Conclusions regarding the technical and economic feasibility of constructing a BSIL are based on the conceptual design effort. These include the following:

- **A BSIL is technically feasible.** The design work shows that a BSIL is technically feasible. The design process did not identify any technical problems that would preclude or hinder successful construction and operation of a BSIL.
- **A BSIL is cost-effective.** The cost of the initial phase of a BSIL is estimated to be \$2.7 million. The cost of a BSIL is reasonable when compared to the advantages to the international competitiveness of the U.S. buildings industry and the estimated \$12 to \$15 billion that can be saved by cutting 3 to 4 quads of commercial building energy use.
- **Phased construction is feasible.** The design shows that phased construction is technically feasible, despite some limitations to research capability associated with the first two phases of the construction.

6.2 RECOMMENDATIONS

The study resulted in two recommendations:

- **A BSIL focusing on commercial building system integration should be built.** Such a facility is needed, is feasible, and would be cost-effective.

- **The BSIL should be built in three phases.** Given current budget constraints, phased construction should be undertaken. The first

phase should be an extendable, four-story test building approximately 54 feet by 54 feet. Design work should commence as soon as possible.

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APPENDIX B

THE DESIGN WORKSHOP

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THE DESIGN WORKSHOP

The design workshop was held to define the capabilities needed in the BSIL and to generate creative approaches to their design. The workshop participants were a subset of the technical review panel and are identified in Appendix A. The workshop took place on April 25 and 26, 1988, in Washington, D.C.

The design meeting consisted of four activities. First, the results of the first technical review panel workshop were presented and discussed. Second, issues related to the need for the BSIL were discussed. The discussion identified reasons for building and not building a BSIL. These discussions focused attention on the unique features required in a BSIL. Following the general discussion, the group subdivided into four-person design teams that developed independent design approaches to the BSIL. Finally, each design team presented its concept to the other teams for comment and discussion.

The design workshop produced two important results: a list of reasons for building and not building the BSIL and a series of design concepts for the facility.

CONSTRUCTION RATIONALE

The development of conceptual designs depended on having some agreement on the capabilities required in a BSIL. Required capabilities were identified from the results of the first technical review panel workshop and by a general discussion held during the design meeting. The general discussion involved the identification of reasons for building and not building a BSIL.

The participants identified the following reasons for not building a BSIL:

- Tests can be done onsite, in other labs, and on a small scale.

- Too much time will be spent on setting up and taking down tests in a BSIL to produce useful results.
- Technology transfer is already taking place.
- Getting whole-building system data is almost impossible.
- Scarce dollars would be expended without educating the next generation of designers.
- Problems result from poor communication between users and laboratories.

The participants also developed a list of reasons to build the BSIL. These include the following:

- Zero energy use buildings can be studied only on a whole-building level.
- Incremental improvements will result from studies on existing buildings; new breakthroughs will need the capabilities of a BSIL.
- The BSIL will serve as a test bed for new systems.
- A BSIL will provide the capability for testing concepts not allowed by building codes.
- The building industry will gain an understanding of building physics and integrative issues.
- A BSIL will provide the capability for isolating system effects and other system unknowns.
- A BSIL will provide the capability for studying and developing intelligence for building controls.
- A BSIL represents an investment in the future of buildings.

- Test results from a BSIL will be more credible than tests at separate-effects facilities.

DESIGN CONCEPTS

Two design teams independently developed concepts for a BSIL. One of the teams also investigated the integration of a BSIL with field testing in leased or purchased unoccupied commercial buildings.

All the proposed designs included a number of common features that were incorporated into the preliminary design of the BSIL. These features are

- a thermally guarded test building, in which the thermal guard is provided by an external envelope that will allow selective and controlled exposure of the envelope to the environment
- a structure with at least three floors, with minimum dimensions of 100 ft by 100 ft for each floor
- easily reconfigurable internal partitions, operating systems (lighting, electrical, HVAC), and external facade
- ancillary facilities with office space, conference rooms, storage, and computer facilities.

The design workshop participants concluded that a whole-buildings research program should be structured as follows:

- The BSIL should be one part of a whole-building research program. The program should include coordination, technology transfer, and research, and should be conducted at a BSIL, existing facilities, and universities.
- Where appropriate, the BSIL should be supplemented by whole-building research in leased and purchased unoccupied buildings.

APPENDIX C

**CONCEPTUAL DESIGN AND COST ESTIMATE FOR THE
BUILDING SYSTEM INTEGRATION LABORATORY**

ENGINEERING REPORT
BUILDING SYSTEMS INTEGRATION LABORATORY

Prepared for
PACIFIC NORTHWEST LABORATORY

August 1988

For the U.S. Department of Energy
Contract DE-AC06-87RL10900

Prepared by
KAISER ENGINEERS HANFORD COMPANY
Richland, Washington

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B67329

KAISER ENGINEERS
HANFORD

APPROVAL

KEH-88-46

ENGINEERING REPORT

FOR

BUILDING SYSTEMS INTEGRATION LABORATORY

Prepared by

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APPROVAL

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- Appendix A. Cost Estimate
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ENGINEERING REPORT BUILDING SYSTEMS INTEGRATION LABORATORY

I. INTRODUCTION

A Building Systems Integration Laboratory (BSIL) is being established by the U. S. Department of Energy (DOE) to investigate issues related to complete building systems, their integration and interactions. As compared to other building research facilities, the BSIL will concentrate on problems that can only be addressed by considering a complete building rather than an isolated zone or subsystem. The BSIL will be open to all DOE contractors, other government agencies and laboratories, and to private researchers and vendors.

Kaiser Engineers Hanford Company (KEH) was engaged by Pacific Northwest Laboratory (PNL) to develop this engineering report to describe the facility design and construction of the BSIL.

II. SUMMARY

The objective of the Building Systems Integration Laboratory (BSIL) is to provide a facility capable of investigating whole building systems and their interactions on a complete building scale. These systems include building facade types, roofing types, and mechanical/electrical systems and controls. Also investigated will be their relationship to external environmental elements. The facility will be designed to simulate these various conditions as a typical commercial office building with a modular, interchangeable exterior skin, and a flexible interior test area. To accomplish this, the facility will consist of a multi-level steel-framed test building and a steel-framed outer envelope that encloses the entire test building. The facility will include the following unique features:

- . Removable and changeable facades of the test building.
- . Environmentally controlled annulus around the test building to provide varied environmental conditions.

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- . Removable opaque panels on the outer envelope to provide selective exposure of the test building to the exterior environment.
- . Flexible open test area within the test building allowing varied partition configurations and tempered space volume.
- . Floor to floor heights that will allow varied ceiling heights.
- . Removable floor and roof panels for full building height atrium testing.
- . Interchangeable heating, ventilating, and air conditioning (HVAC) systems in test area.
- . Interchangeable lighting systems in test area.

The BSIL will consist of 53,656 ft² and be divided into three construction phases. Each phase of the facility will be capable of investigating whole building systems independently of the following phase. Phase 1 will consist of 17,224 ft² and include a multi-level test building with service core, facility support area, and outer envelope area. Phase 2 will consist of 15,840 ft² and include additional multi-level test building area, facility support area, outer envelope, and a completed service core. Phase 3 will consist of 20,592 ft² and complete the remainder of the facility. It will include additional multi-level test building area, facility support area, and completion of the outer envelope around and above the test building. Phase 3 will also include a 5,000 ft² storage building.

The BSIL, as described in this report, will have a total estimated cost of approximately \$10,800,000. Approximate estimated cost, in phases, will be \$2,750,000 for phase 1, \$2,660,000 for phase 2, and \$5,430,000 for phase 3. (See appendix A, Cost Estimate, for details.)

III. PURPOSE

The purpose of the report is to evaluate the programmatic requirements for the facility, to develop a preliminary facility design, and approximate facility cost to meet these requirements. It is not the intent of this report to evaluate the need for this facility, or to justify its construction.

IV. DESCRIPTION

A. Site

The BSIL facility has been designed for a generic site. Site development required of any site will include excavation, landscaping, parking, and utility services.

B. Architectural/Structural

Facility Design

The BSIL will consist of a test building, facility support area, outer envelope area, and a storage building. (See appendix B, Sketches.)

The test building will be a multi-level building with structural framework designed to accept modular removable and interchangeable exterior wall panels of varying facade types. A 20-ft main level floor-to-floor height is also included in the design to allow for flexible ceiling heights to accommodate interior space testing. The second and third levels will have a 15-ft floor-to-floor height. This height will allow enough space above the suspended ceiling for heating, ventilating, and air conditioning (HVAC) ducting, test equipment, and controls. The second and third levels and roof will also have an area where the panels will be removable for atrium design testing.

The outer envelope will enclose the test building to provide an environmentally controlled annulus. It will be constructed in a

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modular form to be compatible with the test building facade panel modules. This will allow specific zones at any level of the test building to be selectively exposed to the natural environment while other zones are environmentally controlled. This will be accomplished by removing a portion of the outer envelope panels and adding panels in the annulus to close off the remainder of the annulus from the natural environment.

To remove and interchange the test building exterior facade panels, the outer envelope panels will be removed as required. The outer envelope panels will be of lightweight material and removable by hand from portable scissor-lift platform equipment. The test building facade and floor panels will require heavy-duty, portable equipment for removal. This equipment is not included in the scope of this project.

The BSIL will also include a facility support area within the lower level. This area will provide space for immediate support of experimentation in the test building. However, spaces to support scientists and other personnel; such as additional offices, conference rooms, computer rooms, etc., is not included within the BSIL. These areas will be located within existing adjacent facilities.

A service core will be provided within the center of the test building. This core will provide space for egress stairways, a freight elevator, mechanical/electrical space for experimental equipment, and a service shaft for mechanical/electrical and instrumentation control lines. The core will be designed to provide easy access to experimental equipment and controls.

The BSIL will be constructed in 3 phases. Phase 1 will consist of a 12,220 ft² multi-level test building with a service core and penthouse, a 3,820 ft² facility support area in the lower level and 1,184 ft² of annulus area. (See sketch ES-B67327-A3 in appendix B.) For this phase the support area will include the

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main entry, facility control room, restrooms, janitor closet, mechanical room, and service core. The outer envelope will enclose an 8-ft wide annulus around the south facade and 2/3 of the east and west facades. The steel structure of the outer envelope will extend across the roof for added lateral support. This structure will also provide support for the completed outer envelope in phase 3. For emergency egress, a temporary metal exterior stair will be constructed.

Phase 2 will consist of an additional 11,736 ft² of multi-level test building with corresponding service core and penthouse, 3,672 ft² of facility support area in the lower level, and 432 ft² of annulus area. (See sketch ES-B67329-A4 in appendix B.) The facility support area will include the addition of a material assembly area, shop, instrumentation/electronic shop, and storage. The service core and penthouse will be completed during this phase. The outer envelope will be relocated from the west facade of phase 1 to the west facade of phase 2 and the south facade will be enclosed. The outer envelope will enclose an 8-ft wide annulus around the entire south facade and 2/3 of the east and west facades. Again, the steel structure of the additional outer envelope will extend across the roof for added lateral support and provide support for the completed envelope in phase 3.

Phase 3 will complete the facility and consist of an additional 13,824 ft² of the multi-level test building, 4,608 ft² facility support area in the lower level, and 2,160 ft² of annulus area. (See sketch ES-B67329-A5, appendix B.) The facility support area will include an additional mechanical room for annulus HVAC, storage, a shipping/receiving area, loading dock, and offices. The outer envelope will be completed during this phase and will enclose the entire test building including the roof.

Program Areas

The completed BSIL facility will provide a test building, facility support area, and outer envelope area for investigating issues

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related to whole building systems. The administration and other support offices, conference rooms, and computer facilities will be located in existing buildings adjacent to the BSIL. The following program areas will be provided within the completed phase 3 BSIL design. Phasing of these areas is discussed previously under facility design.

1. Test Building

The test building will house an open test area and service core. The open test area will allow for installation of temporary partitions and suspended ceilings for flexibility of experimental area testing. The open test area will also provide the capability of testing atrium designs. The service core will include a freight elevator, stairs, mechanical/electrical space for experimental equipment, mechanical/electrical shaft, and a penthouse for elevator equipment and a portion of the HVAC equipment required for the annulus area.

2. Facility Support Area

The facility support area, located on the lower level of the BSIL, will provide various support services. This area will include the main entry, shipping/receiving area, material assembly area, general shop, instrumentation/electronics shop, storage, three offices, men's and women's restrooms, janitor closet, facility control room, and two mechanical rooms. These areas will support the functional needs of the facility. The material assembly area will be used to assemble test apparatus and then move it to its testing location. The shop and instrumentation/electronic shop will provide maintenance of test equipment and electronics. The facility control room will provide space for HVAC and other facility controls.

3. Outer Envelope Area

The outer envelope area will provide an environmentally controlled annulus around the entire test building. The

APPROVAL

envelope will maintain specific environmental conditions as required by investigative experiments.

4. Storage Building

The storage building will be used for storing both test building facade panels and the outer envelope panels as they are removed or replaced. This building will not be environmentally controlled.

Facility Structure and Finishes

The BSIL facility test building will be structured to provide ease of installation and removal of various modular test facades. These test facades will be panelized and of all types from precast concrete with varied fenestration to glass curtain walls. Therefore, the test building will be constructed of structural steel columns and beams, with concrete on metal deck floors, metal deck roof, and removable 8-in. thick precast exterior wall panels. Precast concrete panels have been selected as the first test facade because they represent an extreme case for cost and support structure requirements. These panels will include facing studs, R-11 insulation, and interior gypsum board. Also included within the test building will be suspended acoustical tile ceilings and carpeting standard to commercial office buildings. A 36- by 36-ft area of the second and third floors and roof will be provided with removable precast concrete floor and roof panels for atrium testing. The roofing system will consist of R-19 rigid insulation and an elastomeric single-ply membrane.

The service core will include 8-in. concrete block vertical shaft walls and permanent partition walls constructed of metal studs with gypsum board. The ceiling and floor in the lobby area will be provided with suspended acoustical tile and carpeting.

The facility support area will be constructed of cast-in-place concrete columns, beams, walls, floor, and ceiling. The partition walls will be constructed of metal studs with gypsum board and

APPROVAL

will be 1-hr rated at all corridors. Ceilings will be suspended acoustical tile in the corridors, offices, and facility control room and will be suspended gypsum board in the restrooms. Floors will be carpet in the offices and sheet vinyl in the corridors, material assembly area, shop, instrumentation/electronics shop, facility control room, janitor closet, and restrooms. All other floors will be sealed concrete.

The outer envelope will be framed with structural tube steel trusses and steel sections. The envelope will consist of modular 5- by 9-ft removable sandwich panels assembled of foil paper between two panels of clear double-walled, impact resistant polycarbonate material with ultraviolet resistant surfaces, and aluminum framing with attachment flanges. These panels will be lightweight, easily interchangeable by hand, and will provide an approximate U value of $0.4 \text{ Btu/hr/ft}^2 \text{ F}$. The panels can be reassembled so the opaque foil paper can be removed to provide transparent panels when required for experimentation. The roof panels will be of the same construction but will not be removable. The annulus enclosed by the envelope will extend 10-ft belowgrade to allow space for HVAC ductwork and other mechanical services to minimize interference with the test building.

The storage building will be a 50- by 100-ft pre-engineered metal building with 20-ft roof height. The floor will be sealed concrete. The interior will remain unfinished.

C. Mechanical

The BSIL facility HVAC system will be comprised of three systems. These systems will operate separately and consist of the annulus system, facility support area system, and the test building system.

The annulus HVAC system will be designed to provide heating, cooling, humidity control, and normal air filtration for the annulus area enveloping the test building. The system will be designed to maintain a climate around the test building meeting the

APPROVAL

objectives of a specific experiment within the test building. The system will be controlled such that the roof and each facade of the annulus can be zoned separately. The annulus temperature will be controlled between 40 F and 80 F. Conditioned air will be circulated throughout each zone of the annulus by air handling units. Air handling units for this system will be located within the lower level mechanical rooms and the penthouse when phase 3 is completed.

The facility support area HVAC system will provide standard heating, cooling, humidity control and air filtration for the facility support area located within the lower level. The system will maintain a safe and comfortable environment for the operating personnel and equipment. Air handling units for this system will be provided within a lower level mechanical room.

The test building system will consist of air handling equipment located within the lower level. This system will be designed to be interchangeable, allowing testing of a wide range of components and systems. Other experimental HVAC equipment can also be located within mechanical rooms located on each level of the test building. Ductwork within the test building will be double-walled insulated duct with flanged connections, sealed and bolted for ease of duct modifications. This will allow duct reconfiguration/alterations to suit the varying requirements of the test building.

The ductwork routing and supports within the annulus area will be as unobstructive as practical in order to permit the test building to meet its objectives. The ductwork mains will be running in the belowgrade area of the annulus, while duct risers will be running vertically at the corners of the outer envelope, to warrant proper air distribution and ambient temperature control. Ductwork will be reconfigurable and designed similar to that for the test building.

APPROVAL

Air handling units for the different systems will consist of a supply air fan, hot water heating coils, chilled water cooling coil, humidifier, 80% efficiency throwaway air filters, mixing box and a return air fan. Outside air will be introduced by the air handling units in varying amounts to maintain a positive ambient air pressure and make up for the air exhausted from the restrooms. Cooling towers will be located at a location away from the test building on the BSIL site.

Standard potable water and sewerlines and connections will be provided for the restrooms and janitor closet located in the lower level.

D. Electrical

The electrical system will be sized for electrical testing loads and will be flexible for easy access to interchanging instrumentation systems. The system will be instrumented to investigate power quality and power factor.

Space will be provided in the mechanical shaft and above the suspended ceilings for instrumentation as required.

APPENDIX A

Cost Estimate

KAISER ENGINEERS HANFORD
PACIFIC NORTHWEST LABORATORY
JOB NO. 247100

** KAISER ENGINEERS INTERACTIVE ESTIMATING **
BUILDING SYSTEMS INTEGRATION LABORATORY

PAGE 1 OF 6
DATE 08/15/88 05:50
BY F.C.DAY

KENR01 - PROJECT COST SUMMARY

WBS	DESCRIPTION	ESCALATED TOTAL COST	CONTINGENCY %	TOTAL	TOTAL DOLLARS
111	ENGINEERING - PHASE I	420,000	30	130,000	550,000
321	CONSTRUCTION - PHASE I	1,690,000	30	510,000	2,200,000
	TOTAL PHASE I	2,110,000	30	640,000	2,750,000
112	ENGINEERING - PHASE II	410,000	30	120,000	530,000
322	CONSTRUCTION - PHASE II	1,640,000	30	490,000	2,130,000
		2,050,000	30	610,000	2,660,000
113	ENGINEERING - PHASE III	830,000	30	250,000	1,080,000
323	CONSTRUCTION - PHASE III	3,350,000	30	1,000,000	4,450,000
	TOTAL PHASE III	4,180,000	30	1,250,000	5,430,000
	(ADJUSTMENT)	-40,000			-40,000
	PROJECT TOTAL	8,300,000	30	2,500,000	10,800,000

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TYPE OF ESTIMATE	STUDY	AUGUST 15, 1988	REMARKS:
ARCHITECT ENGINEER	<i>CR Elliott</i> <i>NUBork</i>		
OPERATING CONTRACTOR			

(ROUNDED/ADJUSTED TO THE NEAREST " 10,000 / 100,000 " - PERCENTAGES NOT RECALCULATED TO REFLECT ROUNDING)

KAISER ENGINEERS HANFORD
PACIFIC NORTHWEST LABORATORY
JOB NO. 247100

** KAISER ENGINEERS INTERACTIVE ESTIMATING **
BUILDING SYSTEMS INTEGRATION LABORATORY
STUDY
KENR02 - WORK BREAKDOWN STRUCTURE SUMMARY

PAGE 2 OF 6
DATE 08/15/88 05:50
BY F.C.DAY

WBS	DESCRIPTION	ESTIMATE DIRECT TOTAL	TOTAL INDIRECTS	SUB TOTAL	ESCALATION % TOTAL	SUB TOTAL	CONTINGENCY % TOTAL	TOTAL DOLLARS
111000	ENGINEERING (PHASE I)	420000	0	420000	0.00	0	30	546000
112000	ENGINEERING (PHASE II)	410000	0	410000	0.00	0	30	533000
113000	ENGINEERING (PHASE III)	830000	0	830000	0.00	0	30	1079000
SUBTOTAL 1 ENGINEERING		1660000	0	1660000	0.00	0	30	2158000
321001	SITEWORK (PHASE I)	132700	0	132700	0.00	0	30	172510
321002	LAB TEST BUILDING (PHASE I)	1270500	0	1270500	0.00	0	30	1651650
321003	ENVELOPE (PHASE I)	290200	0	290200	0.00	0	30	377260
SUBTOTAL 321 PHASE I		1693400	0	1693400	0.00	0	30	2201420
322001	LAB TEST BUILDING (PHASE II)	1258300	0	1258300	0.00	0	30	1635790
322002	ENVELOPE (PHASE II)	377800	0	377800	0.00	0	30	491140
SUBTOTAL 322 PHASE II		1636100	0	1636100	0.00	0	30	2126930
323001	STORAGE BUILDING (PHASE III)	143600	0	143600	0.00	0	30	186680
323002	LAB TEST BUILDING (PHASE III)	2396000	0	2396000	0.00	0	30	3114800
323003	ENVELOPE (PHASE III)	811400	0	811400	0.00	0	30	1054820
SUBTOTAL 323 PHASE III		3351000	0	3351000	0.00	0	30	4356300
SUBTOTAL 3 CONSTRUCTION		6680500	0	6680500	0.00	0	30	8684650
PROJECT TOTAL		8,340,500	0	8,340,500	0.00	0	30	10,842,650

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KAISER ENGINEERS HANFORD
PACIFIC NORTHWEST LABORATORY
JOB NO. 247100

**** KAISER ENGINEERS INTERACTIVE ESTIMATING ****
WHOLE BUILDING SYSTEMS INTEGRATION LABORATORY
STUDY
KEHRO3 - ESTIMATE BASIS SHEET

PAGE 3 OF 6
DATE 08/15/88 12:40
BY F.C.DAY

1. DOCUMENTS AND DRAWINGS

=====

DOCUMENTS: FUNCTIONAL CRITERIA "BUILDING SYSTEMS INTEGRATION LABORATORY" (BSIL) FEASIBILITY STUDY.

DRAWINGS: ES-B67329-A2 ARCH. PLANS & SECTION PHASE I, ES-B67239-A3 ARCH. PLAN & SECTION PHASE II,
ES-B67329-A4 ARCH. PLANS & SECTION PHASE III.

2. ROUNDING - LINE ITEMS:

=====

U.S. DEPARTMENT OF ENERGY - DOE ORDER 5100.4 PAGE J-2 SUBPARAGRAPH (M), REQUIRES ROUNDING OF A COST ESTIMATE TO \$10,000 FOR ITEM COST AND \$100,000 FOR TOTAL COST. REFERENCE: DOE 5100.4, FIGURE I-11, DATED 10-31-84.

3. REMARKS

=====

- A. THIS ESTIMATE WAS PREPARED USING PARAMETRIC TECHNIQUES OF THE FAST-C MODEL OF THE "FREJMAN PARAMETRIC SYSTEM". ADD-
INFORMATION WAS UTILIZED FROM KEH AND FAST'S REFERENCE LIBRARY.
- B. IT WAS ASSUMED AT THIS TIME FOR ESTIMATING PURPOSES THAT THE WBSIL WOULD BE CONSTRUCTED IN "MIDDLETOWN" AS A SITE HAS
YET TO BE DETERMINED.
- C. THE FOLLOWING PERCENTAGE WAS APPLIED AGAINST DIRECT CONSTRUCTION TO CALCULATE ENGINEERING:
- 1. ENGINEERING @ 25%
- D. NO ESCALATION PERCENTAGES WERE APPLIED AT THIS TIME AS A SCHEDULE HAS YET TO BE DETERMINED.
- E. THE FAST-C OUTPUT SHEETS ARE ATTACHED TO SHOW COSTS GENERATED FOR EACH WBS ITEM.
- F. PHASE I ESTIMATE CRITERIA:
- 1. 3 STORY 54' X 54' TEST STRUCTURE.
 - 2. A 54' X 54' BASEMENT AREA FOR MECHANICAL EQUIPMENT ONLY, RESTROOM AREA, LOADING DOCK, AND
FREIGHT ELEVATOR.
 - 3. OUTER ENVELOPE AROUND 2/3 OF BUILDING WITH NO ROOF STRUCTURE.
- G. PHASE II ESTIMATE CRITERIA:
- 1. 3 STORY 54' X 108' TEST STRUCTURE.
 - 2. A 54' X 108' BASEMENT AREA FOR ADDITIONAL MECHANICAL AND STORAGE CAPABILITIES.
 - 3. EXPANDED OUTER ENVELOPE AREA.
- H. PHASE III ESTIMATE CRITERIA:
- 1. 3 STORY 108' X 108' TEST STRUCTURE.
 - 2. A 108' X 108' BASEMENT AREA.
 - 3. A FULL ENVELOPE WITH ROOF AROUND TEST STRUCTURE.

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KAISER ENGINEERS HANFORD
PACIFIC NORTHWEST LABORATORY
JOB NO. 247100

**** KAISER ENGINEERS INTERACTIVE ESTIMATING ****
BUILDING SYSTEMS INTEGRATION LABORATORY
STUDY
KEHR04 - COST CODE ACCOUNT SUMMARY

PAGE 4 OF 6
DATE 08/15/88 05:50
BY F.C.DAY

COST CODE	WBS DESCRIPTION	ESTIMATE DIRECT TOTAL	TOTAL INDIRECTS	SUB TOTAL	ESCALATION % TOTAL	SUB TOTAL	CONTINGENCY % TOTAL	TOTAL DOLLARS
=====								
000	ENGINEERING							
111000	ENGINEERING (PHASE I)	420000	0	420000	0.00	0	126000	546000
112000	ENGINEERING (PHASE II)	410000	0	410000	0.00	0	123000	533000
113000	ENGINEERING (PHASE III)	830000	0	830000	0.00	0	249000	1079000
TOTAL 000	ENGINEERING	1660000	0	1660000	0.00	0	498000	2158000
460	IMPROVEMENTS TO LAND							
321001	SITWORK (PHASE I)	132700	0	132700	0.00	0	39810	172510
TOTAL 460	IMPROVEMENTS TO LAND	132700	0	132700	0.00	0	39810	172510
501	BUILDINGS							
321002	LAB TEST BUILDING (PHASE I)	1270500	0	1270500	0.00	0	381150	1651650
321003	ENVELOPE (PHASE I)	290200	0	290200	0.00	0	87060	377260
322001	LAB TEST BUILDING (PHASE II)	1258300	0	1258300	0.00	0	377490	1635790
322002	ENVELOPE (PHASE II)	377800	0	377800	0.00	0	113340	491140
323001	STORAGE BUILDING (PHASE III)	143600	0	143600	0.00	0	43080	186680
323002	LAB TEST BUILDING (PHASE III)	2396000	0	2396000	0.00	0	718800	3114800
323003	ENVELOPE (PHASE III)	811400	0	811400	0.00	0	243420	1054820
TOTAL 501	BUILDINGS	6547800	0	6547800	0.00	0	1964340	8512140
PROJECT TOTAL		8,340,500	0	8,340,500	0.00	0	2,502,150	10,842,650

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KAISER ENGINEERS HANFORD
PACIFIC NORTHWEST LABORATORY
JOB NO. 247100

** KAISER ENGINEERS INTERACTIVE ESTIMATING **
BUILDING SYSTEMS INTEGRATION LABORATORY
STUDY
KEHROS - ESTIMATE SUMMARY BY CSI DIVISION

PAGE 5 OF 6
DATE 08/15/88 05:50
BY F.C.DAY

CSI DIV	DESCRIPTION	ESTIMATE DIRECT TOTAL	TOTAL INDIRECTS	SUB TOTAL	ESCALATION % TOTAL	SUB TOTAL	CONTINGENCY % TOTAL	TOTAL DOLLARS
ENGINEERING								
	ENGINEERING	1660000	0	1660000	0.00	0	30	2158000
	TOTAL ENGINEERING	1660000	0	1660000	0.00	0	30	2158000
CONSTRUCTION								
	02 SITEWORK	310200	0	310200	0.00	0	30	403260
	05 METALS	3801700	0	3801700	0.00	0	30	4942210
	13 SPECIAL CONSTRUCTION	113700	0	113700	0.00	0	30	147810
	15 MECHANICAL	2425500	0	2425500	0.00	0	30	3153150
	16 ELECTRICAL	29400	0	29400	0.00	0	30	38220
	TOTAL CONSTRUCTION	6680500	0	6680500	0.00	0	30	8684650
=====								
PROJECT TOTAL			0	0	0.00	0	30	10,842,650
		8,340,500		8,340,500				

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KAISER ENGINEERS HANFORD
PACIFIC NORTHWEST LABORATORY
JOB NO. 247100

**** KAISER ENGINEERS INTERACTIVE ESTIMATING ****
BUILDING SYSTEMS INTEGRATION LABORATORY
STUDY

PAGE 6 OF 6
DATE 08/15/88 05:50
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KENR07 - ONSITE INDIRECT COSTS BY WBS

WBS	DESCRIPTION	ESTIMATE DIRECT TOTAL	CONTRACT %	ADMINISTRATION TOTAL	BID PACK PREP.	OTHER INDIRECTS	TOTAL INDIRECTS
=====	=====	=====	=====	=====	=====	=====	=====
111000	ENGINEERING (PHASE I)	420000	0.00	0	0	0	0
112000	ENGINEERING (PHASE II)	410000	0.00	0	0	0	0
113000	ENGINEERING (PHASE III)	830000	0.00	0	0	0	0
321001	SITWORK (PHASE I)	132700	0.00	0	0	0	0
321002	LAB TEST BUILDING (PHASE I)	1270500	0.00	0	0	0	0
321003	ENVELOPE (PHASE I)	290200	0.00	0	0	0	0
322001	LAB TEST BUILDING (PHASE II)	1258300	0.00	0	0	0	0
322002	ENVELOPE (PHASE II)	377800	0.00	0	0	0	0
323001	STORAGE BUILDING (PHASE III)	143600	0.00	0	0	0	0
323002	LAB TEST BUILDING (PHASE III)	2396000	0.00	0	0	0	0
323003	ENVELOPE (PHASE III)	811400	0.00	0	0	0	0
=====							
PROJECT TOTAL		8,340,500		0	0	0	0

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APPENDIX B

Sketches

ES-B67329-A1
ES-B67329-A2
ES-B67329-A3
ES-B67329-A4
ES-B67329-A5

Hand-drawn floor plan of a building layout. The plan includes the following labeled areas and features:

- Top Dimensions:** 72'-0" (total width), 9'-0" (left section), 54'-0" (middle section), 9'-0" (right section).
- Left Dimensions:** 41'-0" (total height), 35'-0" (main section), 6'-0" (bottom section).
- Rooms and Areas:**
 - Future Expansion (Phase 2 & 3):** Indicated by a bracket on the left side.
 - MECH. GARAGE:** Located in the upper right section.
 - Service Core:** Located in the upper right section, adjacent to the Mech. Garage.
 - RESTROOM:** Located in the upper right section, adjacent to the Service Core.
 - LABORATORY:** Located in the upper right section, adjacent to the Restroom.
 - Removable Floor Panels Above, for AT&T Testing:** Located in the central area.
 - OPEN TEST AREA:** Located in the lower central area.
 - MECHANICAL:** Located in the lower central area, below the Open Test Area.
- Structural and Other Features:**
 - Metal Exterior Stair:** Located on the right side.
 - 6" DEEP STEEL TRUSS (TYP):** Located on the right side.
 - TOOT BUILDING - REMOVABLE PRECAST INTERIOR PANELS W/ STEEL STRUCTURE:** Located on the right side.
 - OUTER ENVELOPE - REMOVABLE APPROX. PRECAST/CONCRETE EXTERIOR PANELS W/ STEEL STRUCTURE:** Located on the right side.

Hand-drawn cross-section diagram of a test building. The diagram shows a central vertical section with three 'TEST AREA' levels, a 'MECHANICAL ROOM' at the base, and an 'AIRSPACE CORB' at the top. The building is flanked by 'AIRSPACE CORB' and 'OUTER ENVELOPE' sections. Dimensions are indicated on the left: 15' for the top section, 10' for the middle section, 10' for the bottom section, and 20' for the base section. The total height is 45'.

FNL _____ APPROVAL BY _____		DATE _____		U.S. DEPARTMENT OF ENERGY Richland Operations Office	
PROJ. NO. _____ OR _____		KAISER ENGINEERS HANFORD COMPANY			
APPROVED BY _____ SAFETY _____		ARCHITECTURAL PLANS & SECTION PHASE I			
REV _____ APPROVED/_____ CHECKED _____ DRAWN BY _____ DESIGNED BY _____		PROJECT TITLE BUILDING SYSTEMS INTEGRATION LABORATORY PROJ. _____ WO. BGTB94 JOB _____ SCALE _____ SLOD _____ MOSES _____ DRAWING NUMBER ES-BGTB94A3			
SHEET _____ OF _____		RET _____			

[illegible]

LOWER LEVEL PLAN

MAIN LEVEL PLAN

SECTION

PHASE 2

PWL		APPROVAL	DATE	U.S. DEPARTMENT OF ENERGY Richland Operations Office	
BY				KAISER ENGINEERS HANFORD COMPANY	
PROJECTOR				ARCHITECTURAL PLANS & SECTION PHASE 2	
QA				PROJECT TITLE BUILDING SYSTEMS INTEGRATION LABORATORY	
APPROVED BY				PROJ. NO. B6732	
SAFETY				JOB NO. 0800	
APPROVED BY				SCALE 1/8" = 1'-0"	
CHECKED BY				DRAWING NUMBER ES-B67329-A4	
DESIGNED BY				SHEET 1 OF 1	
DATE				REV	

NUMBER	TITLE	REVISIONS
1	DRAWING TRACEABILITY LIST	
2	REVISIONS	
3	REVISIONS	
4	REVISIONS	
5	REVISIONS	
6	REVISIONS	
7	REVISIONS	
8	REVISIONS

LOWER LEVEL PLAN

MAIN LEVEL PLAN

SECTION

PHASE 3

U.S. DEPARTMENT OF ENERGY Richland Operations Office KAISER ENGINEERS HANFORD COMPANY	
ARCHITECTURAL PLANS & SECTION PHASE 3	
PROJECT TITLE BUILDING SYSTEMS INTEGRATION LABORATORY	
PROJ	WD B67329
SCALE	1/8" = 1'-0"
DRAWING NUMBER	ES-B67329-A5
SHEET	1
OF	1
REV	0

BY	DATE	DESCRIPTION
APPROVED BY	7/24/88	APPROVAL
CHECKED BY	7/24/88	REVIEW
DRAWN BY	7/22/88	DRAWING
DESIGNED BY	7/22/88	DESIGN

NUMBER	TITLE
1	LOWER LEVEL PLAN
2	MAIN LEVEL PLAN
3	SECTION

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