NISTIR 89-4068

Building Technology Project Summaries 1989

Noel J. Raufaste

U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
National Engineering Laboratory
Center for Building Technology
Gaithersburg, MD 20899

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U.S. DEPARTMENT OF COMMERCE, Robert A. Mosbacher, *Secretary*
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Raymond G. Kammer, *Acting Director*

Foreword

Construction is one of the Nation's largest industries. In 1987, new construction put in place amounted to $399 billion, 8.9 percent of the U.S. Gross National Product. The quality of constructed facilities directly affects the productivity of all U.S. industry and the safety and quality of life of every citizen. Their quality governs the wealth of the Nation; over two-thirds of the Nation's fixed reproducible wealth is invested in the constructed facilities.

The Center for Building Technology (CBT) of the National Institute of Standards and Technology (NIST), formerly the National Bureau of Standards, is the Nation's central engineering measurement laboratory. CBT produces performance prediction and measurement technologies that are relied upon by private industry, State and local governments, and Federal agencies with building-related programs to provide technical bases for responsible and cost-effective construction decisions. CBT conducts laboratory, field and analytical research. The work focuses on removal of critical technical barriers leading to increased usefulness, safety, and economy of buildings and other constructed facilities. Its findings enhance the international competitiveness of U.S. building services and products. CBT's basic and applied research includes programs in structural engineering, materials, mechanical and environmental systems, and computer-integrated construction.

CBT's building research program is the major nonproprietary source of technical information for developing voluntary standards for buildings by organizations such as the ASTM; American Concrete Institute; American Society of Heating, Refrigerating and Air-Conditioning Engineers; American Society of Civil Engineers; and model building code organizations. The resulting standards are widely used in building codes.

CBT is the Federal laboratory authorized by legislation to investigate the physical causes of major building and construction failures and to assist in creating and maintaining data bases on structural failures.

CBT provides a quality assurance program for over 1000 public and private construction materials testing laboratories nationwide that is relied upon by owners, designers, builders, and State and local governments responsible for buildings and transportation facilities.

CBT works closely with its international peer organizations to assure cognizance of foreign research developments, that research efforts are complementary, and that U.S. interests are represented in preparation of recommendations for international standards and practices.

CBT staff totals about 120; 80 are professionals, 40 hold doctorates, and 30 are registered engineers. Seventy-five research associates from U.S. industry, guest researchers from foreign laboratories, visiting faculty members from universities, and students complemented CBT's staff during 1988.

CBT's facilities are located in Gaithersburg, Maryland, about 25 miles northwest of Washington, D.C. Its unique and comprehensive laboratories include: a computer controlled six-degree-of-freedom structural testing facility, a 12-million-pound universal structural testing machine and a 45-foot-high reaction wall, seven environmental chambers including a $30 \times 40 \times 50$ foot chamber for evaluating the thermal performance of full-scale buildings, a 1-meter guarded hot-plate for measuring thermal conductivity, a calibrated hot-box, a five-story plumbing tower, passive solar test facilities, a network of outdoor exposure sites, and other specialized laboratories for research in materials characterization and quality assurance.

CBT's budget for 1989 is about $10 million. Approximately one-third comes from direct appropriations from Congress; the remainder from other Federal agencies.

This report summarizes CBT's research for 1989; it is arranged by research programs. Each summary lists the project title, its activities, the CBT point of contact, and the sponsor.

Contents

STRUCTURAL PERFORMANCE

DYNAMIC CHARACTERIZATION OF STRUCTURAL NETWORKS

Principal Investigator: William C. Stone
Structures Division
301.975.6075

Sponsor: National Institute of Standards and Technology

The purpose of this research is to develop computational and experimental capabilities for highly accurate identification of dynamic response characteristics of structures.

Structural systems are being developed for which the dynamic response must be determined with high accuracy up to frequency components of thousands of Hertz. These systems, which include orbiting space structures and components of automated manufacturing facilities, typically consist of networks with relatively simple topologies and with elements that are relatively long compared with typical wavelengths of traveling disturbances.

Recent data shows that it is advantageous to characterize these systems dynamically by the matrix of their dynamic Green's functions (the responses of the various coordinates to unit impulse excitations). In practice, especially for purposes of controlling of orbiting structures subjected to transient dynamic loads, it is necessary to evaluate the Green's function experimentally for the actual structure, rather than analytically for an idealized model. However, there are considerable difficulties in achieving this because impulsive loads are not physically realizable. Moreover, the inverse problem of inferring the Green's functions from the response to loads rather than impulsive is mathematically ill-posed.

CBT's work focuses on recent mathematical research resulting in development of pulses of the inverse Gaussian type and generalizations which allow the systematic and accurate solution of the inverse problem associated with the project's objective. Numerical experiments are being conducted to assess the accuracy of recovering the exact Green's functions by deconvolution of response contaminated by noise.

A parallel effort is aimed at developing a testing capability consisting of computer-controlled high speed actuators which can be activated in a manner to reproduce the requisite pulses (applied force time histories) to within the accuracy needed. Because there is a need for autonomous force application (without the benefit of a reaction surface) and substantial force magnitude, the load will be produced by mass expulsion. Significant technological problems to be addressed include the development of the onboard microcontroller subsystem, and its associated programming, the development of a high speed, multi-channel valve system, driven by electrostrictive stacks, and the development of a high speed pulse power subsystem to drive the electrostrictive elements. Potential practical applications include, in addition to orbital structures, the identification and control of non-collocated robots and robotic handlers (such as flexible robot arms to be used in construction and materials handling), and dynamic identification of flutter characteristics for experimental aircraft. Initial tests will be carried out with one-dimensional excitation forces being applied to a candidate test structure with resultant 3D accelerations being recorded.

These findings will be useful to Federal and private agencies requiring accurate identification of the dynamic properties of special structural systems, including large orbiting structures. These findings will result in applications to structural engineering technology of new results for mathematics, structural dynamics, and measurement since research thereby contributing to improved reliability of structural systems for defense, communications, and industrial purposes. Potential spinoffs include the development of nondestructive testing methods for the tethers of deep water compliant offshore platforms, and for active control and damping of dynamic structural vibrations, e.g., docking loads on orbiting structures and seismic loads on buildings.

NONLINEAR/CHAOTIC BEHAVIOR OF DYNAMIC STRUCTURAL SYSTEMS

Principal Investigator: Emil Simiu
Structures Division
301.975.6076

Sponsor: National Institute of Standards and Technology

The object of this research is to develop a computational and experimental basis for the study of nonlinear and chaotic phenomena in structural engineering.

Engineering systems exhibiting nonlinear behavior and subjected to active control may undergo chaotic motions. An understanding of the basic aspects of such motions is needed to develop the theoretical basis of design and evaluation methods appropriate for these systems.

CBT is constructing a nonlinear structural device (a modified Stoker column) with periodic forcing to characterize its chaotic behavior by means of Lyapunov exponents and other descriptors based on measured data. Exploratory numerical study of dynamic behavior of forced and autonomous fluid-elastic oscillators also will be performed.

PERFORMANCE EVALUATION OF STRUCTURAL INTEGRITY

Principal Investigator: John Gross
Structures Division
301.975.6068

Sponsor: National Institute of Standards and Technology

The objective of the project is to develop guidelines for assuring structural integrity of structures under construction.

Many instances of structures collapsing during construction are recorded each year. During construction, a structure is particularly susceptible to collapse due to 1) the vulnerability of the complete structural system, 2) low material strength or incomplete connections, 3) construction overloads, or 4) improper construction techniques such as premature removal of formwork. More than any time in its service life, a structure under construction lacks general structural integrity "the quality of being able to sustain local damage with the structure as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage."

During FY 1989, CBT is developing adaptive techniques for selective removal of members under load, addition of new members and/or material, and temporary loads such as jacking forces. Also, methods are being developed to facilitate and control the adaptive analysis. CBT's research consists of four parts:

1. Develop a method to account for the addition or removal of structural elements for a building during construction.

2. Develop specific analytical models or elements to represent selected construction conditions or procedures (e.g., an element which models incomplete connection slip).

3. Develop interactive computer graphics techniques to assist in the description of the construction sequence and interpretation of the analytical results.

4. Develop parametric studies to identify stages of construction and construction operations and/or conditions which render a structure particularly susceptible to collapse.

Guidelines for assuring structural integrity of structures under construction will be developed using the results from these four activities.

The first year of this research focuses on the theoretical bases for addition or removal of structural elements for a structure under load. A literature search will be conducted to identify adaptive analysis techniques and a pilot computer program will be initiated. This effort will involve the adaptation of an existing structural analysis computer code to test appropriate strategies. This work will be coordinated with ASCE's Standards Committee on Design Loads for Structures Under Construction.

STRENGTHENING METHODOLOGIES FOR STRUCTURAL SYSTEMS AND MEMBERS

Principal Investigator: Long T. Phan
Structures Division
301.975.6077

Sponsor: National Institute of Standards and Technology

The objective of this research is to develop design guidelines to predict the performance of structural systems and elements after strengthening.

Many existing structures are considered deficient when evaluated by current building codes and standards. This determination is based on a) the structures were designed and constructed in compliance with older building codes which are no longer applicable or b) deterioration occurred during the service life of these structures. Various strengthening techniques have been used to improve lateral strength and ductility of structures in high risk seismic regions. Many of these techniques have been field-applied; however, there is no established criteria to assess the overall capacity of strengthened concrete structures. This research program will develop the technical information needed to establish guidelines to predict the performance of concrete structures after strengthening.

The problem will be approached in two phases:

1. Strength and deformation behavior of single and groups of mechanical anchors in cracked and uncracked concrete will be studied.

2. The effectiveness of anchors in installing precast and cast-in-place concrete infilled walls will be evaluated.

The assessment of anchor needs in infilled walls, coupled with the knowledge on the behavior of anchors, will be used to establish criteria for predicting the strength and behavior of strengthened concrete frames.

MEASUREMENTS FOR ASSESSING STRUCTURAL STIFFNESS

Principal Investigator: Richard D. Marshall
Structures Division
301.975.6071

Sponsor: National Institute of Standards and Technology

The project's objective is to develop instrumentation systems and techniques to measure the effective stiffness of building structures and structural assemblies.

Reliable estimates of structural stiffness and damping can have a significant impact on construction costs and are essential for predicting the serviceability and structural safety of building systems. It is essential that the stiffness of retrofit schemes, used to increase seismic safety, be compatible with the stiffness of the existing structure. While the stiffness of isolated structural components usually can be predicted with sufficient accuracy, this generally is not the case for combinations of components and assemblies. Examples include various types of floor slabs interacting with columns or bearing walls, the interaction of cladding panels with the structural frame, and the ability of nonloadbearing partitions to impart stiffness to building frames. Analytical models for predicting system stiffness and damping usually involve gross simplifications of the actual systems and, for various reasons, physical models often prove to be impractical.

CBT's effort consists of four phases:

1. Assess the state-of-the-art of smart sensors and microprocessor based data acquisition and processing systems capable of extended operation in environments associated with full-scale measurements of structural response.

2. Conduct a workshop in instrumentation and measurement techniques to obtain measurements of the type(s) needed to assess structural stiffness and damping, and establish measurement accuracy.

3. Design and construct a prototype measurement system for unattended, long-term measurements of parameters required for estimating structural stiffness and damping, by pilot study of a building structure, and demonstrate the utility and reliability of the measurement system.

4. Develop improved instrumentation and measurement methods for structural engineering applications in the laboratory.

FULL-SCALE MEASUREMENTS OF WIND EFFECTS ON 300M TV TOWER AT SHENYANG, PRC

Principal Investigator: Richard D. Marshall
Structures Division
301.975.6071

Sponsors: National Science Foundation
Johns Hopkins University

The objectives of this project are to 1) provide technical support and instrumentation for measuring wind forces on the 300m Shenyang TV Tower and the resulting structural response and 2) participate in analyzing and interpreting the recorded field data from the TV Tower and disseminating the test results.

Wind tunnel tests are not capable of providing information on along-span correlations of wind loads on structures with circular cross-section. Such correlations, which are important for determining design loads, will be obtained from full-scale measurements on the Shenyang tower. This tower is one of the largest slender structures with circular cross-section in the world and can therefore yield the large Reynolds-number data needed to obtain reliable information.

A CBT researcher will instrument the tower with wind speed measurement devices, pressure transducers, strain gages, and accelerometers to obtain the data needed. This work will be performed in collaboration with Johns Hopkins University and the Chinese Ministry for Radio and TV.

The data will be analyzed for information on along-wind and across-wind loading and response. Information on structural characteristics will be obtained from technical drawings and from in-situ tests.

STATIC IMPACT LIMITER TESTING

Principal Investigator: H.S. Lew
Structures Division
301.975.6061

Sponsors: Transnuclear Inc. and
E G & G, Inc.

The objectives of this project are to determine static load-deformation characteristics of impact limiters (cushions) and to determine the adequacy of impact limiter attachments.

Impact limiters are used to protect nuclear spent-fuel containers from impact during transit. Currently, drop tests of limiters are being carried out at the Sandia National Laboratories to make general observation of limiters' deformability. Measurements are not taken during the drop tests to document the deformation characteristics.

CBT will perform specified tests using its 12M-pound universal testing machine to measure deformation. This will be performed by means of LVDTs and strains using electrical resistance strain gages. NIST's tests will carefully document deformations of limiters under various angles of load applications and strains of attachment fixtures. These data will be used by the sponsoring organization to establish the adequacy of the limiter device. All measuring devices and the acquisition system will be calibrated using reference standards traceable to fundamental constants maintained by NIST.

STRUCTURAL AND MECHANICAL DESIGN CRITERIA FOR LOW IMPACT RESISTANT STRUCTURES (LIRS)

Principal Investigator: Richard D. Marshall
Structures Division
301.975.6071

Sponsor: Federal Aviation Administration

The objective of this project is to provide FAA with test data, design criteria, and analytical models to predict the response of low impact resistant structures to aircraft impact.

The potential hazard of an aircraft colliding with navigational aids during landing or take off operations has led FAA to investigate use of structural systems with low impact resistance. The

goal of designing low impact resistant structures (LIRS) is to impart minimum damage to an aircraft in the event of an accidental collision. "Break-away" mechanisms implemented in structural systems were considered by FAA to fulfill the goal. To ensure the effectiveness of such a system 1) the investigation of impact characteristics of structural systems, including mechanical components such as the electrical conductors is required and 2) the development of analytical models for simulating impact phenomena is needed.

CBT's research consists of four activities:

1. Develop computer-based analytical models to predict the response of LIRS systems subjected to aircraft impact.

2. Test selected LIRS systems under conditions simulating an aircraft collision. Data resulting from this testing activity will provide the basis to validate the analytical model(s) developed in 1 above.

3. Assess and improve the analytical models to bring their predictions into acceptable agreement with the response observed in full-scale tests carried out under activity 2.

4. Perform static load testing of a prototype LIRS and develop improved load criteria to design LIRS for offshore exposures.

ASSESSMENT OF THE UNCERTAINTIES AND RISKS ASSOCIATED WITH THE DYNAMIC BEHAVIOR OF COMPLIANT OFFSHORE STRUCTURES

Principal Investigator: Emil Simiu
Structures Division
301.975.6076

Sponsor: Minerals Management Service

The purpose of this project is to study various behaviors of compliant structures to identify and reduce uncertainties and risks associated with dynamic behavior.

Compliant offshore structures are increasingly being used in various applications, particularly in deep waters. Their hydrodynamic, dynamic, and structural behavior is complex; little experience is available to draw upon to evaluate their safety performance.

During FY 1989 CBT is investigating the fundamental aspects of chaotic behavior of compliant structural assemblies subjected to fluctuating excitations of a mechanical and/or hydroelastic nature. Findings from this research will aid MMS establish research needs about the reliability of compliant offshore structures and to verify reliability approaches implicit in the design of these structures. The work will also contribute to providing MMS with the technical bases to ensure acceptable risks for the safe operation of certain types of compliant offshore structures.

NDT METHODS FOR CONCRETE

Principal Investigator: Nicholas J. Carino
Structures Division
301.975.6063

Sponsor: National Institute of Standards and Technology

The objective of this project is to investigate the application of previous CBT research in the impact-echo method to massive concrete structures and to layered systems.

There are no standard methods for locating internal defects in concrete structures and other heterogenous construction materials. The impact-echo method, based on the interaction of stress waves with internal discontinuities, shows potential to fill this need. It was demonstrated, analytically and experimentally, that the impact-echo method can be used successfully to detect a wide variety of flaws in relatively thin concrete structures. The thickness of the largest specimen tested has been 1 m. There is a need to verify the applicability of this technique to thicker structures and to investigate the applicability of the impact-echo method to assess layered systems. Layered systems include slabs on grade, overlayed concrete slabs, steel-lined reactor vessels.

During FY 1989 CBT will perform impact-echo tests on thick concrete members. These members will include large concrete test specimens at CBT such as the 2-m-thick reaction floor of its Structures Laboratory. Finite element studies of wave propagation in layered systems will be performed to gain an understanding of the impact-echo responses for various combinations of materials. Experimental studies will be performed to verify the analytical results. A variety of test specimens will be investigated: slabs on grade with and without cavities at the interface; steel-lined slab with and without interfacial voids; asphalt concrete overlayed slabs with controlled interfacial conditions as well as voids in the concrete.

The applicability of making measurements on concrete pile-like structures also will be investigated. In these investigations, the goal is to develop the experimental techniques for successful impact-echo testing of thick structures. Suitable impact sources and a suitable low frequency transducer will be identified.

SPREAD FOOTINGS FOR HIGHWAY BRIDGES

Principal Investigator: Felix Y. Yokel
Structures Division
301.975.6065

Sponsor: Federal Highway Administration and
National Institute of Standards and Technology

The objective of this research is to develop a design procedure and a design guide document for shallow bridge foundations.

The type of foundation selected for a highway bridge is a major factor in the construction and maintenance cost of the structure. A key decision in selecting a foundation system is whether to use a shallow or deep foundation to support the structure. Although shallow foundations (spread footings or mats) normally are less expensive to construct than deep foundations (piles or drilled shafts), the majority of highway agencies rely mostly on deep foundations to support bridges.

CBT's research under the first phase of this project indicates that most types of highway bridges can accommodate the differential settlements associated with traditional spread footing design practice without a modification in their design. Thus, in many instances where pile foundations are presently used spread footings would be adequate.

During FY 1989, CBT will evaluate the settlement data collected by FHwA to determine the accuracy and the degree of reliability with which foundation displacements can be quantified. Methods for settlement prediction will be recommended and incorporated into a guide manual for shallow foundation design. The design manual will be based on the principle of limit state design and will contain quantitative criteria for required load capacity and allowable displacements in terms of the characteristics of the superstructure, and analytical approaches to settlement prediction tied to present methods of insitu and laboratory soil exploration.

The manual will be used by bridge designers throughout the United States. It is expected to lead to more extensive use of shallow bridge foundation and to a reduction in the cost of highway construction.

SITE CLASSIFICATION FOR RADON RESISTANT CONSTRUCTION

Principal Investigator: Felix Y. Yokel
Structures Division
301.975.6065

Sponsor: Department of Housing and Urban Development

The objective of this research is to develop a site classification method which can be used to assess the radon potential of sites prior to construction.

Radon emission has been recognized by EPA as a major health hazard in single family dwellings and a problem for the ground floor of multifamily dwelling units. Indoor radon abatement has been mandated by Congress in Title III of the Toxic Substances Control Act (dated January 25, 1988). There are several independent studies underway aimed at identifying high-risk areas, modeling radon entry mechanisms into buildings, developing in-situ radon measurement methods and developing various radon abatement methods which include radon-resistant construction and abatement methods in existing buildings.

There is a need for in-situ measurement methods which can be used to asses the radon risk associated with building sites. Present methods consist of extraction of soil-gas samples to measure their radon concentration and in-situ soil permeability measurements by the injection of pressurized air. These measurement methods are sensitive to transient conditions such as temperature, barometric pressure, and soil moisture concentration gradients.

CBT's research will be performed in four phases. Phase 1 will be completed in FY 1989. The phases are:

1. Assessing the feasibility of the approach through a study of available literature and data.

2. Developing a site classification method to link the radon potential of the site with recommended remedial measures.

3. Developing a testing protocol linked to the site classification.

4. Verifying the test methods and performing a demonstration.

EARTHQUAKE ENGINEERING

SEISMIC MONITORING OF GSA BUILDINGS

Principal Investigator: Long T. Phan
Structures Division
301.975.6077

Sponsor: General Services Administration

The objective of this research is to develop procedures and criteria for locating strong motion instrumentation in new and existing Federal buildings.

Current design criteria based on economic considerations permit controlled damage to take place in buildings during anticipated earthquake conditions. This requirement necessitates an ability to predict the resisting forces developed under large deformation cyclic loading and likely failure mechanisms to provide safety to the building occupants. Although considerable advances have been made in mathematical modeling and dynamic analysis to predict structural performance, the accuracy of the prediction is highly dependent upon the ability to characterize the dynamic properties of the structure (mode shapes, damping) and the seismic excitation. The dynamic properties of the building can be obtained from either ambient vibration tests or low-level forced vibration tests, while site dependent earthquake ground motions can be obtained from strong-motion instrumentation.

Two GSA buildings will be included in this study: a Federal office building in Portland, OR and a Federal detention center in Los Angeles, CA. The building in Portland (UBC Zone 2) is a prestressed concrete building with shearwalls providing lateral load resistance. The Los Angeles building (UBC Zone 4) is a steel moment resisting frame structure.

CBT will perform the following:

1. Review the structural plans and specifications of the two buildings; from site visits obtain as-built building data and document structural and nonstructural data.

2. Develop mathematical models of the buildings for computer analysis.

3. Make measurements of the buildings' structural response characteristics to determine their dynamic properties by conducting ambient vibration tests. These tests will establish base-line response characteristics of the building which will be used to determine changes in structural performance due to structural damage and to verify the validity of mathematical models.

4. Perform a dynamic analysis of the buildings to determine their structural performance under credible earthquake excitations. The analysis will identify the locations where severe damage is likely to occur and the most desirable locations for installing strong-motion instruments.

5. Install strong motion instrumentation in either the Portland or Los Angeles building based on the results from 4. This work includes procedures for determining how many instruments are required for a particular building, the optimum location of the instruments, the operating requirements for the instruments, procedures for their installation and maintenance and utilization of the data obtained following strong ground motion.

SEISMIC PERFORMANCE OF PRECAST CONCRETE CONNECTIONS

Principal Investigator: Geraldine Cheok
Structures Division
301.975.6061

Sponsor: National Institute of Standards and Technology

The objective of this project is to develop technical data to formulate rational and consistent seismic design provisions for precast concrete frame structures.

At present there is limited guidance about the design and detailing of precast concrete structures for seismic resistance. The UBC currently permits the use of precast concrete elements to resist seismic forces provided the design and detailing used satisfy the Code requirements for cast-in-place concrete structures. What is known indicates that precast structures tend to be less ductile and tend to have a less stable inelastic response than do cast-in-place monolithic structures. This is primarily because the inelastic strains are concentrated in the connections, which are small and weak in comparison to the precast elements themselves. Thus, the connections are often unavoidable weak links.

During FY 1989 CBT will:

1. Form a task group and discuss multi-year research plan about precast concrete connections. The proposed research plan is composed of four phases. Phase 1 involves testing post-tensioned precast connections. Based on results from phase 1, phase 2 will involve further testing of post-tensioned precast connections and a limited number of welded connections. The use of light weight aggregate in the precast elements will be studied in phase 3. Development of design guidelines and practice will occur in the final phase of this study.

2. Develop a comprehensive research plan.

3. Complete a design of connection.

4. Test two monolithic beam-column connections designed to UBC seismic zone 4 requirements. This will establish an upper bound for the precast connections.

A task group of peers from academia, the Prestressed Concrete Institute, the Portland Cement Association, and practicing engineers will provide technical support to the project staff. It is expected this group will guide the design of specific joint details for CBT's consideration for study.

SEISMIC RESISTANCE OF MASONRY WALLS

Principal Investigator: Charles Yancey
Structures Division
301.975.6073

Sponsor: National Institute of Standards and Technology

The objective of this project is to develop a rational procedure to determine the ultimate shear strength and behavior characteristics of reinforced masonry building shear walls for use in structural design.

The process of developing tentative seismic design provisions for unreinforced and reinforced masonry building components reveals a scarcity of information for behavior of masonry components under repeated reversed inelastic lateral loading as might be experienced by building components

during an earthquake. Existing codes are based on past experience and crude knowledge of the behavior of masonry components.

CBT's investigation will involve experimental testing and analytical studies. Experimental tests will provide needed information, not presently available, to serve as the basis for development of mathematical models. Various failure modes will be examined to identify the characteristics of each and the significant parameters affecting the different failure modes. Analytical expressions for design as a function of the key parameters will be developed such as amount and configuration of reinforcement, affects of axial load, effects of aspect ratio, and effect of material properties.

TECHNICAL ASSISTANCE AND ENGINEERING EXPERTISE FOR SEISMIC CONSTRUCTION ACTIVITIES

Principal Investigator: H.S. Lew
Structures Division
301.975.6061

Sponsor: Federal Emergency Management Agency

The U.S. Congress passed the Earthquake Hazards Reduction Act of 1977 (P.L. 95-124) and the President established the National Earthquake Hazards Reduction Program (NEHRP) the following year. The NEHRP established the Interagency Committee on Seismic Safety in Construction (ICSSC). The program also assigned to NIST responsibilities to work in both the Federal and private sector to improve seismic design.

CBT provides the Technical Secretariat to the Interagency Committee on Seismic Safety in Construction (ICSSC). The purpose of this Committee is to assist the Federal departments and agencies involved in their ongoing programs. This will be based on existing consensus standards when feasible and will be consist with OMB guidelines. CBT's work includes development of reports for improved practices for design of new and existing buildings and response of Federal agencies to major earthquakes.

In the private sector CBT is working with the Building Seismic Safety Council (BSSC), an organization consisting of professional organizations, trade associations, and code groups. With CBT's assistance the BSSC issued a set of seismic design provisions for new buildings (NEHRP Provisions). BSSC is working on updating these provisions to incorporate the results of recent research and is working in the area of existing buildings.

This project continues past efforts of working with the private sector through the BSSC and the Federal Government in development of improved seismic design criteria. CBT is working with FEMA contractors to develop reports on existing hazardous buildings. CBT also provides the Secretariat to the ICSSC.

Results of this work includes preparation of possible "code" provisions for seismic design. These will be available for consideration by standards developing organizations. Improved seismic design provisions that are acceptable on a national level, should lead to a uniform safety and economy for all types of building construction.

SECRETARIAT FOR U.S. SIDE UJNR PANEL ON WIND AND SEISMIC EFFECTS

Principal Investigator: Noel J. Raufaste
Structures Division
301.975.5905

Sponsors: Several Federal Agencies and
National Institute of Standards and Technology

The objective of this project is to provide the U.S. Secretariat of the United States-Japan Panel on Wind and Seismic Effects.

The U.S. Panel on Wind and Seismic Effects was created in 1969. Annual meetings alternate between Japan and the United States (odd numbered years in Japan; even numbered years in the United States). The Panel is composed of 16 Federal agencies participating in nine task committees. The task committees focus on specific national issues, e.g., earthquake hazards reduction, buried pipelines and telecommunication systems. The results of task committee workshops and conferences are shared at the annual joint meeting and often published as proceedings.

During FY 1989, the Panel will continue to:

1) exchange wind and seismic technology (including data, information, measurement and test facilities and equipment, and researchers) between appropriate U.S. and Japanese organizations;

2) develop strong technical links between scientific and engineering researchers of the government, industrial and academic organizations from the two countries, and encourage exchanges of guest researchers;

3) conduct joint research in areas of strong winds, earthquakes, storm surge and tsunamis;

4) publish findings from joint research efforts and distribute proceedings of annual joint meetings;

5) conduct cooperative programs to improve engineering design and construction practices and other wind and earthquake hazards mitigation practices.

CONCRETE AND STONE

EXPERT SYSTEM FOR IDENTIFYING CAUSES OF CRACKING IN CONCRETE

Principal Investigator: James R. Clifton
Building Materials Division
301.975.6707

Sponsor: Construction Engineering Research Laboratory

The objectives of this project are to: develop a knowledge base for an expert system that identifies causes of cracking in concrete; demonstrate the representation of knowledge in images by integrating images of cracks into the expert system; and determine the feasibility of driving the expert system by voice.

An important part of the inspection of concrete structures and components is the detection of visible indicators of degradation; cracking is one of the major indicators. Cracks in concrete are caused by numerous processes. Information is needed to identify these processes for determining the risks associated with the observed cracking. The availability of an expert system to aid inspectors in identifying the causes of concrete cracking would be of significant assistance in condition assessments.

The causes of cracks in concrete often are identified based on the environmental conditions, type of concrete, and the crack characteristics, such as shape, density, and location. Information on crack characteristics can be effectively transferred by images, which are a form of knowledge representation. Therefore, images of cracks whose cause is known will be integrated into the expert system. The images will be linked with production rules so examples of cracks will be shown. A database of cracks will be developed, including the means to interface the image database with the expert system.

During FY 1989, CBT will focus efforts on assessing the feasibility of developing a voice-driven expert system for diagnosing causes of concrete cracking. This research will be performed in collaboration with the Construction Engineering Research Laboratory (CERL). CERL will develop the hardware needed for the voice-driven computerized system. CBT will help CERL evaluate and procure voice recognition equipment. It will take at least 2 years to fully develop the system. CERL has developed a voice recognition system for use by inspectors to record inspection observations, rather than make on-site written records. Inspector's comments are transferred to a remote computer. By linking the voice recognition system with the expert system for cracking, the inspector could ask questions about crack characteristics and be given advice about the identification of the causes and severity of the cracks. It is anticipated that the system with image comparisons and voice recognition capabilities will be located at a central site and be wirelessly connected to small field computers.

PERFORMANCE CRITERIA FOR LONG LIVED CONCRETE FOR RADIOACTIVE WASTE STORAGE

Principal Investigator: James R. Clifton
Building Materials Division
301.975.6706

Sponsor: Nuclear Regulatory Commission

The objective of this research is to develop performance criteria for selecting concretes to be used in constructing structures requiring a 500-year safe life for storing low-level radioactive wastes.

The Nuclear Regulatory Commission (NRC) is responsible for developing a strategy to store low-level radioactive wastes. In one approach, the radioactive wastes would be stored in concrete vaults, either buried or constructed above ground and covered with earth. A service life of 500 years is required for the storage vaults.

During FY 1988, likely deterioration processes were identified. They included sulfate attack, corrosion of reinforcing steel, alkali-aggregate reactions, leaching by groundwater, and acid attack. The likely deterioration processes were analyzed for existing knowledge on their mechanisms, rates, and characteristics of their deterioration curves. Also, an experimental approach to obtain data needed to make service life predictions was developed, candidate concretes were identified, materials for them obtained, and modeling of moisture transfer processes in concretes was initiated.

During FY 1989, modeling of relationships between the pore structure of concrete and the rate of moisture, chloride ion, and sulfate ion intrusion by convection, diffusion, and capillary action in concrete will continue. The models will form a basis for predicting the time required for the initiation of degradation processes. Experimental studies in FY 1989 and FY 1990 will be aimed at obtaining the data needed to validate and to use the models to predict service lives.

CEMENT SOLIDIFIED WASTE FORM TESTING

Principal Investigator: James R. Clifton
Building Materials Division
301.975.6707

Sponsor: Nuclear Regulatory Commission

The objective of this project is to analyze the appropriateness and adequacy of the Nuclear Regulatory Commission's (NRC) test program for predicting long-term (300-year) performance and stability of cement solidified low-level radioactive wastes.

NRC's requirements for land disposal of low-level radioactive wastes (LLW), disposal containers are required to have a structural stability life of 300 years. One method being considered for providing structural stability to LLW is by solidification with inorganic and organic cements (solidification agents), where the mixture of the wastes and the solidification agent results in a waste form that is intended to be structurally stable.

NRC published a report on Waste Form which provides technical criteria for acceptable waste forms and guidance to LLW generators to demonstrate their ability to meet NRC's stability requirements for solidified waste. Yet, results of recent NRC sponsored studies raised questions about the structural stability of cement solidified waste forms. These questions concern the appropriateness of hydraulic and asphaltic cements as solidification agents for certain LLW and the adequacy of NRC's testing program for assessing long-term performance of cement solidified waste forms. Hence, NRC requested CBT to develop performance criteria to predicts, with reasonable assurance, the long-term stability of certain types of cement solidified wastes.

CBT's research consist of three tasks:

1. Analyze the appropriateness and adequacy of NRC's test program to demonstrate the long-term (300-year) performance of cement solidified waste. Cements being used to solidify LLW include hydraulic cements and asphaltic cements. This task involves the review of pertinent NRC documents and sponsored research on this subject. Topical reports submitted by vendors applying for qualification acceptance by NRC of solidified LLW forms will be reviewed. Based on the findings and conclusions, recommendations for improvements in the test program will be developed.

2. Analyze proposed additional waste form testing on cement solidification systems and formulations. The analysis includes a review to determine if data gaps identified in Task 1 are addressed by planned future research.

3. Evaluate the findings from Tasks 1 and 2 for conclusions about the adequacy of NRC's testing program to predict the service lives of cement solidified waste forms. Based on the results of the analysis, conclusions on the usefulness of the test program and recommendations for the development of additional performance criteria will be provided to NRC.

MODELS FOR DEGRADATION PROCESSES IN CONCRETE

Principal Investigator: James R. Clifton
Building Materials Division
301.975.6707

Sponsor: National Institute of Standards and Technology

The objective of this project is to develop and validate mathematical models that describe the mechanistic paths and kinetics of the processes leading to concrete degradation.

Degradation of concrete is a national problem, as evidenced by the Strategic Highway Research Program, by ACI establishing a new committee on service-life design of concrete, and by the service life requirements adopted for concrete used to store radioactive waste. The recent National Materials Advisory Board's publication, *Concrete Durability—Multibillion-Dollar Opportunity* emphasized the need for long-term research programs on concrete durability, listing the most important concrete durability problems as physical and chemical processes: i) freezing and thawing, ii) sulfate attack, iii) alkali-aggregate reactions, iv) corrosion of reinforcing steel, and v) thermal cracking.

CBT is developing mathematical models of the thermodynamics mechanisms, and kinetics of the degradation processes. The thermodynamic aspects of concrete deterioration have not been well studied. They will be addressed to define the conditions under which deterioration is thermodynamically possible and to aid development of accelerated tests for kinetic studies. The effect of microstructure on degradation processes will be studied to understand how the transfer and distribution of moisture in the pore-and-air-void structure, and the distribution of phases in the concrete, affect reaction mechanisms and kinetics.

The first degradation process being studied is freezing and thawing. Investigations are being performed on the movement of moisture through the pore-and-air-void structure, the capacity of the concrete for freezable water, and thermodynamics of the process. Characterization of pore-air-void structures will be performed using scanning electron micrographs of closely spaced sections from specimens of hardened cement paste. The feasibility of superimposing and making three-dimensional composites of the images using our imaging system will be determined. Analytical and experimental methods will be identified and developed to fill gaps in the knowledge of the freeze-thaw mechanisms of concrete. It is anticipated that the recommended analytical and experimental investigations will require 2 years to complete. This project will contribute to an improved understanding of degradation processes and will provide the bases for improved standards.

CHEMISTRY AND PHYSICS OF CEMENT PARTICLE INTERACTIONS

Principal Investigator: Leslie Struble
Building Materials Division
301.975.6715

Sponsor: National Institute of Standards and Technology

The objectives of this research are to a) advance understanding of the time-dependent interactions between cement particles and how these interactions are modified by chemical admixtures and b) contribute to this understanding through development and validation of mathematical models based on physical and chemical mechanisms.

One of the most important properties of fresh concrete is its ability to flow and to remain plastic during placement. The rheological behavior of concrete is an indirect measure of its initial microstructure—for example, the density with which particles pack and the extent to which they flocculate. This initial microstructure not only controls the flow properties prior to set, but also provides the framework on which microstructure develops as cement hydrates and hardens, so the final performance of concrete is a result of its initial microstructure.

The research will emphasize the development and testing of mathematical models based on conceptual models. The models will address the relationships between interparticle forces, flocculation, and rheological properties, and the effects of these factors on microstructure of hardened cement pastes. Experimental studies will be designed and carried out to fill gaps in knowledge identified during the formulation of the conceptual and mathematical models, and to provide data needed to validate the models.

Studies of interparticle forces and how they vary will be performed using monosized, spherical silica particles as a model material. Rheological behavior of dispersed or flocculated particles will be measured. The existing mathematical model for simulating microstructure development of cement will be expanded to include the system's response to applied shear, the interparticle forces and resulting flocculation or dispersion, and the effects of cement hydration reactions. The model will ultimately be capable of modelling effects of dispersants and of shear on the microstructure of hardened cement pastes, mortars and concretes.

FIELD TEST METHOD TO MEASURE THE UNIAXIAL TENSILE STRENGTH OF THE BOND BETWEEN REPAIR MATERIALS AND EXISTING CONCRETE

Principal Investigator: Robert G. Mathey
Building Materials Division
301.975.6709

Sponsor: Tri-Services Committee, DOD

The objective of this research is to develop a repeatable field test method that measures the uniaxial tensile strength of the bond between repair materials and existing concrete.

The strength of the bond between repair materials and existing concrete is a major factor for effective repair of existing concrete structures. There is need for a repeatable field test method to measure the tensile strength of this bond.

A small, portable, pneumatic apparatus was recently developed and patented at NIST for repeatedly measuring, in the field, the adhesion of protective coatings. This apparatus, with minor modifications, is expected to be used in the field to measure the uniaxial tensile strength of the bond between a repair material and its existing concrete substrate.

The feasibility of the proposed field test method will be investigated using a controlled laboratory study. Concrete substrate slabs will be cast and cured. After uniformly preparing the concrete substrate surface, repair materials will be applied to the surface. Using a 2-inch diameter core drill, a core will be drilled through the repair material to a depth of about 3/8 inch below the bond plane into the substrate. A disposable metal disk-shaped fixture will be glued to the top of the intact core using a high strength, quick-set epoxy. This metal fixture is used to attach the core to a pneumatic apparatus. The core will be pulled uniaxially by steadily increasing the pressure until failure occurs (through the repair material, bond line, or substrate). Comparisons will be made of the repeatability of test results for the proposed field test method, the current ACI field test method, and uniaxial tests (pipe nipple grips) conducted in a conventional testing machine.

EVALUATION OF SURFACE TREATMENTS TO IMPROVE THE EROSION RESISTANCE OF COQUINA STONE AT CASTILLO DE SAN MARCOS

Principal Investigator: Lawrence I. Knab
Building Materials Division
301.975.6712

Sponsor: National Park Service

The purpose of this work is to perform a laboratory study to evaluate the effectiveness of surface treatments for improving the erosion resistance of coquina stone.

Deterioration of the coquina stone at Castillo de San Marcos in St. Augustine, FL, occurs gradually through erosion. Replacement of severely eroded coquina stones will eventually be required. Probable reasons for erosion include wind and water induced forces (rain and runoff), removal of vegetation, and mechanical abrasion of the stone by people. A potential approach for reducing the rate of erosion from wind, water, and mechanical abrasion is to use surface treatments to "stabilize" and "waterproof" the coquina. The effects of the treatments on the erosion resistance of the coquina need to be evaluated. In addition, the possibility of incompatibilities between the treatment and coquina leading to damage from temperature or moisture cycling, needs to be investigated.

CBT will evaluate one commercially available silane consolidant as requested by the National Park Service. The erosion resistance of treated coquina will be compared with untreated coquina. The erosion resistance will be investigated by measuring the resistance to mechanical abrasion (e.g., wear/weight loss due to abrasion) and the resistance to water erosion (e.g., the depth of erosion caused by continuous dripping of water on the stone). Possible damage of the treated coquina from moisture, temperature, and UV radiation cycling will be investigated by subjecting specimens to two separate tests. In the first test, a cycle will consist of an exposure to about 5 °C, cycled with an exposure to heat lamps. The second test will consist of intermittent moisture and UV radiation. The performance of treated and untreated coquina specimens will be compared after being subjected to moisture/temperature cycling. Visual observation of surface degradation coupled with surface tensile strength measurements will be used to evaluate the performance and possible damage. A method will be developed for surface tensile strength using a bond pull-off test which measures the near-surface tensile strength.

COATINGS

ORGANIC COATINGS

Principal Investigator: Mary McKnight
Building Materials Division
301.975.6714

Sponsor: Tri-Services Committee, DOD

The objectives of this research are to: develop improved procedures for selection, use, and specification of coating systems; transfer the technology to DOD personnel responsible for maintaining coatings on structures; and identify needs for research on coating materials and systems.

The annual cost of organic coatings in the United States exceeds $10 billion; more than half is for protective coatings in buildings and structures. The military uses about $400 million of coatings annually. If more effective criteria for the selection, specification, and use of protective coatings were available, it is estimated that as much as 25 percent of these expenditures could be saved. An essential element in selecting and using a protective coating is knowledge of its service life. However, because a) recent regulations controlling the amount of volatile organic components (VOC) in coatings and b) DOD's requirements to use only those coatings that comply with the most restrictive of VOC rules, the traditional method of estimating service life based on in-service performance is no longer feasible. Currently available methods for predicting service life based on short-term tests do not adequately meet the need for data to aid selection, specification, and use of coating systems.

CBT will continue its work of improving service life of coatings used in the field by maintaining a thorough knowledge of the state-of-technology, interacting with leaders in the field, assessing field problems first-hand, and participating in exchange of information, through the literature and conferences; performing laboratory studies to develop improved test procedures relevant to field problems; providing leadership in standards activities to solve these problems; addressing VOC-related problems by participation in SSPC (including serving as chair of the Coatings Steering Committee); and providing technical support for revising the Tri-Services Painting Guide Specification.

MODELS OF THE DEGRADATION OF ORGANIC PROTECTIVE COATING SYSTEMS

Principal Investigator: Tinh Nguyen
Building Materials Division
301.975.6718

Sponsor: National Institute of Standards and Technology

The objective of this research is to develop and validate models that predict the service life of protective coatings for steel.

U.S. corrosion-related problems are estimated to cost more than $170 billion annually. The use of polymeric coatings is one of the most effective, economical, and widely-used means to prolong the life of corrosion-prone construction materials. However, coatings are frequently susceptible to degradation under in-service environments. Surface analysis data indicate that changes at the substrate/coating interface are often responsible for the failure of coatings. Interfacial changes can lead to the formation and growth of blisters and to the occurrence of corrosion reactions beneath protective coatings. Since blistering and corrosion beneath coatings are important mechanisms of degradation, research is needed to better understand the processes and variables contributing to these mechanisms and to develop models, based on an understanding of the degradation mechanisms, that predict the service life of coating systems. The models are needed to provide the bases of standards for coatings used to protect steel structures.

In FY 1988, our research focused on development of conceptual models of the degradation processes affecting the coating/steel bond. This work included the development of knowledge of degradation mechanisms at the interfaces of high-performance coatings and steel, particularly the development of data on the transport properties of protective coatings using an electrochemical method, and AC impedance.

Research in FY 1989 concentrates on 1) determining the effect of additives, such as fillers and pigments, on the transport properties of high performance coatings, 2) characterizing the chemical changes leading to interfacial degradation of opaque coatings on steel, 3) incorporating new mechanistic and rate data into conceptual models, 4) developing mathematical models, and 5) developing and implementing a plan to transfer our findings into industrial practice.

QUALITY CONTROL TESTS FOR ADHESION OF PAINT

Principal Investigator: Larry W. Masters
Building Materials Division
301.975.6707

Sponsor: U.S. Army (Natick)

The objective of this research is to develop test methods for assessing the quality of adhesion of paint on the exterior surfaces of Army tactical shelters.

The U.S. Army uses a range of tactical shelters for situations requiring highly mobile work, living, or storage facilities. The exteriors of these shelters are painted during their manufacturing. To help ensure the quality of paint adhesion, tests such as the scratch and tape pull-off or the knife lift are performed after the paint has cured. These tests have shortcomings: 1) they are destructive, 2) they provide qualitative and subjective data, and 3) they are not fully responsive to the needs of the Army in assuring bond quality. There is a need to identify or develop an improved test method, or series of test methods, for assessing the quality of paint adhesion.

During FY 1989 and 1990 CBT will be performing the following tasks:

1. Identifying criteria for methods for use in assessing paint adhesion on tactical shelters, methods which may be consistent with the criteria, and methods for evaluation in the laboratory.

2. Performing laboratory evaluations of methods which comply most closely with the essential and/or desirable criteria. The purpose of the evaluations will determine the effectiveness of the methods and the extent to which they comply with the criteria.

3. Presenting the results of tasks 1 and 2 in the form of recommendations on the use of methods for assessing the quality of paint adhesion; criteria and laboratory data will be presented to support the recommendations.

QUANTIFICATION OF EXTERNAL WEATHERING STRESSES FOR INPUT INTO PROBABILITY-BASED SERVICE LIFE PREDICTION MODELS

Principal Investigator: Jonathan W. Martin
Building Materials Division
301.975.6717

Sponsor: National Institute of Technology and Standards

The purpose of this research is to develop probability-based models for quantifying external weathering stresses.

The service life of coatings and other building materials is largely controlled by its physical and chemical properties (resistance) and the environmental stresses (loads) to which it is exposed. For most building materials and exposure environments, the resistance and load factors are best thought of as random variables and hence, best modeled using probabilistic techniques. Of all the variables (material, application, and environmental) affecting the service life of a building material, the variables which are least controlled, most poorly characterized, and probably display the highest temporal and spatial variability are those associated with outdoor environments.

Three environmental stresses typically dominate the degradation of organic building materials; they are temperature, ultraviolet radiation, and moisture. In an earlier part of this study, only temperature was considered. Subsequently, additional factors will be incorporated. In a typical outdoor exposure test, only ambient temperature is measured and is commonly described in terms of minimum, average, or maximum daily or yearly ambient temperature. The actual temperature of the material is of prime importance; not the ambient temperature, since the rate of degradation and the mode of degradation are dependent on this temperature. In FY 1988, an energy balance equation was developed for predicting the temperature of a material as a function of measurable environmental variables and for validating this model against field data.

In FY 1989 CBT is developing distributional models for material temperature which compensate for specimen orientation and color, high and low temperatures, and temperature cycles. CBT also is developing probability models for quantifying external weathering stresses.

CONSTANT WET VERSUS CYCLIC WET-DRY EXPOSURE TESTS FOR UNSCRIBED COATED PANELS

Principal Investigator: Jonathan W. Martin
Building Materials Division
301.975.6717

Sponsor: Naval Civil Engineering Laboratory

The purpose of this research is to quantitatively and systemically determine if a difference exists in the extent, rate, mechanism, and modes of failure between constant and cyclic-wet, unscribed coated panels.

Presently, most accelerated aging tests expose coated panels to either a constant wet (salt fog test) or a cyclic wet-dry environment (KTA cyclic exposure test or the QCT Panel tester). Proponents of cyclic wet exposures have long argued that cyclic exposures are more realistic than constant wet exposure tests because they simulate outdoor exposure conditions better. Conclusions from our previous research on coated panels containing a prominent defect confirmed that the modes of failure for continuous wet and cyclical wet-dry were different, but the underlying mechanisms of failure were identical.

During FY 1989, a set of nominally identical, unscribed, coated panels will be randomly separated into two groups. One group will be continuously immersed in an electrolyte; the other will be subjected to a wet-dry cycle. After specified exposure intervals, all panels will be removed from their respective exposure environments and quantitatively evaluated. Some specimens will be removed from the exposure tests and subjected to microprobe analysis. At the end of the test, the data will be analyzed to determine if the rates, mechanisms, and modes of failure are different for the two exposures. These results will then be compared to those obtained for scribed panels.

METHODS FOR THE DETECTION AND MEASUREMENT OF LEAD-BASED PAINT

Principal Investigator: Mary McKnight
Building Materials Division
301.975.6714

Sponsor: Department of Housing and Urban Development

The objective of this project is to develop recommendations based on the state-of-the-art, laboratory, and field data for methods to detect and measure lead in dry paint films.

An essential step in decisionmaking for abatement of lead-containing paints is determining if lead is present and, if so, how much is present. Methods are required for rapid screening to determine if lead is present and for quantitative measurements of the level of lead in paint.

CBT will a) assess currently available detection and measurement methods to determine compliance with essential or desirable requirements or criteria, and b) develop recommendations to detect and to measure lead in existing paint films. The research follows three steps:

1. Determine from literature or screening tests, information relating to requirements/criteria for detection and measurement methods on the safety, reliability, accuracy, precision, detection sensitivity, specificity, timeliness of measurement, suitability for use in the field and in the laboratory, ease of use, and ability to be used by nontechnical staff members.

2. For the methods appearing to meet the levels of sensitivity, accuracy, reliability, and other criteria that are deemed essential or desireable to HUD, more detailed evaluations will be performed.

3. As required, analysis of materials will be analyzed using more than one laboratory procedure to determine the level of lead present. Methods to be addressed include 1) chemical analyses to be conducted in the laboratory and in-situ and 2) instrumental analyses using portable x-ray fluorescence. Suitable reference materials, such as NIST standard reference materials, will be used to aid in the required calibrations.

At the completion of the laboratory assessment, methods which show promise for field use will be further evaluated, leading to recommendations for:

- an overall measurement protocol for determining the level of lead in existing paint films (including use of screening tests, if feasible, sampling requirements, and procedure for using the recommended quantitative measurement method),

- quantitative measurement method(s), leading to draft standard(s) for consideration by a consensus standards group, such as ASTM's D01, and

- a task group of a voluntary consensus standards committee to cooperate in round-robin testing to determine repeatability and reproducibility of the quantitative measurement method(s) recommended.

ROOFING SYSTEMS

PULSE ECHO ULTRASONIC TESTING OF THE INTEGRITY OF ADHESIVE-BONDED SEAMS OF SINGLE-PLY MEMBRANES

Principal Investigator: Walter J. Rossiter
Building Materials Division
301.975.6719

Sponsor: Naval Civil Engineering Laboratory

The objective of this research is to develop and demonstrate a field test procedure, based on ultrasonic testing, for evaluating the integrity of adhesive-bonded seams in single-ply roofing membranes.

The problem most often registered with the National Roofing Contractors Association (NRCA) about single-ply membranes involves the seam. In practice, the quality of field-fabricated seams is often only assessed by visual inspection at the time of roofing construction. Large bubbles and "fish mouths" can readily be found by visual inspection. This detection method, however, does not detect voids or delaminated areas in the hidden interior portions of seams that may lead to their failures. In preliminary investigations of the feasibility of using nondestructive evaluation (NDE) methods to detect voids and delaminations in adhesive-bonded seams, it was found that the ultrasonic pulse echo method with a wheel transducer was successful, under certain laboratory conditions, in detecting voids intentionally incorporated in seams between EPDM sheets. Although the method offers promise for field inspections of seams, suitable equipment for field use has not been assembled and evaluated for reliability. Further research is needed to develop the equipment and perform the evaluation. The availability of a field test procedure would provide a means for investigating the integrity of new seams at the time of installation and also exposed seams in cases where their durability may be suspect.

This research will be performed in two phases:

1. Pulse echo ultrasonic equipment needed for field testing will be developed.

2. The equipment will be evaluated in the field. Adhesive-bonded seams fabricated under a variety of field conditions will be inspected for voids. Based on the results of the field evaluations, recommendations will be made about the general use of this technique.

QUALITY ASSURANCE OF DOD ROOFING SYSTEMS

Principal Investigator: Walter J. Rossiter
Building Materials Division
301.975.6719

Sponsor: Department of Defense

The objective of this project is to provide technical assistance to the Department of Defense (DOD) for improving the quality assurance of roofing practices.

Unacceptable roofing performance is a major DOD facilities problem. In the late 1970s, the U.S. Air Force estimated that its built-up roofs were lasting, on the average, 12 years instead of the intended design life of 20 years or more.

CBT is providing technical assistance to DOD in the implementation of practices to improve its roofing performance. This work includes the following activities:

1. Attend technical meetings of the Federal Roofing Committee to discuss the in-service performance of roofing, field problems, and research needed to solve the problems experienced; serve as Secretary of the Committee.

2. Provide technical review of roofing documents prepared by DOD or organizations under DOD contract.

3. Perform, as appropriate, inspections of selected DOD roofing materials and systems for purposes of characterizing in-service performance.

CRITERIA FOR MODIFIED BITUMEN ROOFING MEMBRANE MATERIALS

Principal Investigator: Walter J. Rossiter
Building Materials Division
301.975.6719

Sponsor: Department of Defense

The purpose of this research is to develop preliminary criteria and specifications for the Department of Defense (DOD) to use in selecting polymer-modified bituminous roofing membrane materials.

The use of polymer-modified bituminous membranes as the waterproofing component of low-sloped roofing systems is increasing rapidly in the United States. Recent estimates indicate these materials account for 15 percent of the membranes currently installed; this figure will increase to 30 percent or more by 1990. Consensus criteria are needed by DOD and other Federal agencies to aid in the selection and specification of these membranes. Although ASTM task groups have been formed to develop the needed standards, it is anticipated that they will not be available for at least 3 years. In 1988, preliminary criteria for the selection and use of polymer-modified bitumens were suggested. These criteria will provide DOD agencies the basis for guide specifications until voluntary consensus standards are complete.

CBT will continue to provide the database to develop preliminary criteria. Cyclic movement resistance of modified bitumens will be investigated. An apparatus will be assembled to conduct the tests according to a method proposed by the CIB/RILEM Joint Committee on Roofing (the tests are used in Europe). CBT's research will include testing at room temperature and below. Factors to be investigated include the amplitude and frequency of the cycle, and characteristics of polymer-modified bituminous membrane materials such as the type of reinforcement and its location in the sheet, and the bitumen itself. The relationship of the material's performance in the cyclic movement test to its strain energy will also be investigated. This relation is of interest, because strain energy also is important to the membrane's splitting resistance. In addition to laboratory testing, field inspections of selected polymer-modified bitumen roofing systems will be continued to observe performance and identify failure mechanisms.

REPAIR PATCHES ON AGED EPDM ROOFING MEMBRANES

Principal Investigator: Walter J. Rossiter
Building Materials Division
301.975.6719

Sponsor: Construction Engineering Research Laboratory

The purpose of this work is to develop a methodology for assuring the quality of adhesively-bonded seams formed in repairing weathered vulcanized-rubber membranes.

The use of vulcanized-rubber materials (primarily EPDM) for low-sloped roofing membranes is common in the United States. Current estimates indicate that over a billion square feet are now applied annually. EPDMs are nonpolar, relatively inert rubbers; this makes the adhesive-bonding of sheets, forming membrane seams, a critical parameter associated with long-term performance. This may be even more critical as time passes, and patches and splices are needed. A key concern expressed in the roofing industry is, as these membranes weather, the rubber's surface characteristics may be altered such that successful bonding of the aged material may become more difficult. A technical basis for making repairs to weathered EPDM is lacking and should be developed.

CBT is performing a two-phase study:

1. An assessment of the perform .nce of repair patches on aged EPDM is being performed. The assessment focuses on techniques for cleaning aged rubber surfaces before patching, and ascertaining those which have been successful and those which have been unsatisfactory. Conferences will be held with users of EPDM roofing systems to learn of their experiences with the performance of patches in service. Also, facility engineers at U.S. Army installations will be consulted. On-site inspections of patches made on aged EPDM membranes will be performed. The information obtained from the assessment will be used to develop recommendations for research needed to overcome problems identified during the assessment.

2. Laboratory and field tests will be conducted in Phase 2 to develop a method for preparing seams on aged EPDM rubber. The laboratory research will be designed to provide the technical basis for assuring that the surface of aged rubber in EPDM roofing systems has been properly cleaned before patches are adhered to it.

PERFORMANCE OF U.S. AIR FORCE SINGLE-PLY ROOFING

Principal Investigator: Walter J. Rossiter
Building Materials Division
301.975.6719

Sponsor: U.S. Air Force

The objective of this project is to obtain and analyze information on the in-service performance and failure modes of low-sloped EPDM roofing systems.

The use of single-ply membranes for low-sloped roofs has become common in the United States. Although their performance has, in general, been satisfactory, nevertheless it has not been without problems. In particular, the introduction of single-ply membranes introduced various problems to the roofing. Examples include embrittlement of plasticized membranes, loss of integrity of adhesive-bonded seams, poor uplift resistance of ballasted and mechanically-attached membranes, and difficulty of repairing aged membranes whose surfaces have been altered by weathering. Few studies are available which describe the performance of the new membranes in service. In NBS Special Publication 659, *Low-Sloped Roofing Research Plan*, we noted that a need existed to "obtain and analyze information on the in-service performance and failure modes of low-sloped roofing systems."

Because of the relative newness of the single-ply roofing systems, the Air Force has used them on a limited basis for about 8 years. Although several types of single-ply membranes have been used by the Air Force, the majority are EPDM rubber. Where single-ply systems are in place, the Air Force maintains data on its performance. This data has not been analyzed. A review of the data is needed to help identify failure modes and needs for research.

During FY 1989 CBT is analyzing this performance data. Work includes factors affecting performance as: the type of material, its age, roof size, roof location, method of membrane attachment, overall condition, problems experienced, and needed maintenance. Visits will be made to selected air bases to observe roofs in question. Where possible, samples of the roofing, particularly sections of seams, will be taken to conduct laboratory tests for characterizing the materials.

Based on the results from this research, guidelines for installing and maintaining EPDM roofing systems on Air Force roofs will be prepared.

SERVICE LIFE PREDICTION OF ADHESIVE-BONDED SEAMS OF SINGLE-PLY ROOFING MEMBRANES

Principal Investigator: Walter J. Rossiter
Building Materials Division
301.975.6719

Sponsor: National Institute of Standards and Technology

The purpose of this research is to develop test methods for inclusion in standards which will be used in evaluations of the performance of adhesive-bonded seams in single-ply membranes.

Currently, more than one billion square feet of rubber membranes, primarily EPDM for low-sloped roofing, are applied annually in the United States; this amount accounts for 40 percent of the area of membranes installed. Although the performance of EPDM systems has been acceptable, field performance has not been without problems. The major problem, indicated by the NRCA, and from CBT's field experience, has been the delamination of field-applied seams. Methods for evaluating seam performance are lacking and need to be developed and standardized.

CBT's work focuses on systematically addressing the key barriers to predicting the service life of EPDM single-ply membranes. CBT's research in FY 1986 led to the development of a probabilistic model for predicting the effect of mechanical stress, temperature, and moisture on the time-to-failure in a T-peel test of laboratory-bonded EPDM joints. In FY 1987, research was extended to surface contamination along with extensive field inspections to gain first-hand knowledge of failures. The results of the FY 1987 field studies confirmed that seam failure is the dominant failure mode for EPDM roofing membranes, while the laboratory studies showed that the strength of EPDM seams is sensitive to the presence of residues of anti-bonding materials, specifically talc, introduced during the manufacturing process. FY 1988 research focused on clarifying the effects of talc on T-peel strength.

In FY 1989, laboratory-based research will continue to focus on the effects of inadequate cleaning and cure temperature on strength, and time-to-failure of EPDM roofing seams. Research will model the degradation processes and determine the sensitivity of seam failures to the experimental variables to isolate those which have the greatest effects on the time to failure. This research will draw on the use of computer image processing, probabilistic modeling, and Fourier Transform Infrared spectrophotometric measurements. Work will continue to keep abreast of single-ply systems' field performance, to conduct analyses on failed roofs and to gain a better understanding of the modes and causes of failure.

VAPOR RETARDERS AND AIR BARRIERS FOR BUILDING CONSTRUCTIONS

Principal Investigator: Robert G. Mathey
Building Materials Division
301.975.6709

Sponsor: Department of Energy

The objectives of the project are to: 1) prepare technical assessments of the performance of currently used vapor retarder and air barrier materials and systems for building construction, 2) identify candidate materials and systems from new technologies, 3) define research needs for performance, and 4) conduct laboratory measurements to fill gaps in the characterization and knowledge of the performance of vapor retarder and air barrier materials and systems.

The primary function of a vapor retarder is to reduce the access of water vapor or moist air to cold surfaces for controlling moisture and preventing excessive wetting of materials. However, vapor retarders may perform as air barriers and inhibit air infiltration and indoor moisture dissipation in other parts of the building; therefore, additional ventilation may be required to prevent undesirable buildup of vapor in occupied spaces.

CBT is performing the first phase of a two-phase approach:

1. A study will be conducted to analyze information and building practices about using vapor retarders and air barrier materials and systems in building constructions. The work will focus on: types of materials and systems used; their field performance (e.g., vapor and moisture permeability, degradation, dimensional stability, high temperature resistance, air flow resistance, continuity, compatibility with other materials, local environment); test methods used for evaluating these systems; and installation and fastening techniques used during field application. This work will identify performance characteristics for vapor retarders and air barriers and will consider uses of these materials to the type of building construction (e.g., super-insulated house). Gaps in the technical knowledge about the use and performance of these materials and systems also will be identified.

2. Laboratory and field tests will be performed based on the first phase results, to characterize the properties and performance of vapor retarder materials and systems.

INNOVATIVE MATERIALS

APPLICATION OF ARMY'S BUILDING TECHNOLOGY FORECAST AND EVALUATION SYSTEM (BTFE) TO BUILDING MATERIALS

Principal Investigator: Mary McKnight
Building Materials Division
301.975.6714

Sponsor: U.S. Army Construction Engineering Research Laboratory

The purpose of this work is to assist CERL determine the feasibility of adapting its Building Technology Forecast and Evaluation System (BTFE) methodology to assess building materials.

The Army uses guide specifications in its design of new buildings and other facilities. Guide specifications generally are updated every three or more years; revisions often take more than a year. Hence, there is often a considerable lag between the time building systems and materials are introduced into the market place and the time new systems and materials, acceptable for Army use, are referenced in guide specifications. The Army is developing the BTFE methodology to provide a tool to expedite new technology into practice.

During FY 1989, CBT is reviewing the BTFE methodology. The BTFE procedure involves developing 1) a set of attributes required for a system or material to meet a specific need, 2) a set of questions to be used in obtaining information, 3) statements on impact, cost-benefits and risk assessment, and 4) a numerical rating procedure to prioritize available materials meeting a specific need. CBT is assessing the feasibility of using this system for materials. If it appears feasible, a case study will be performed for a specific materials need.

EVALUATION OF MATERIALS FOR RIGID WALL SHELTERS

Principal Investigator: Robert G. Mathey
Building Materials Division
301.975.6709

Sponsor: U.S. Army Natick RD&E Center

The purpose of this research is to provide technical and scientific support to generate and update ASTM standards on materials and processes used to manufacture Army Standard Rigid Wall Shelters.

All branches of the military use lightweight, air transportable, rigid structures which serve as combination shipping containers and shelters for many types of tactical and life-support services. The use of these shelters has increased rapidly in recent years and life-cycle costs have become a major consideration. The shelters are fabricated from either paper honeycomb or foam plastic core and aluminum skin sandwich panels. While these panels may have advantages, field experience has shown that there are problems with them. Data are needed on the performance of shelters and materials used in shelter panels for adhesion, surface preparation, effects of moisture, and protection from impact, and electromagnetic radiation. Also needed are standards for the materials used in shelter panels and for shelter performance based in part on military requirements.

CBT will provide technical and scientific support in:

1. Evaluating materials for rigid wall shelters in cooperation with the U.S. Army Natick RD&E Center,

2. Providing leadership and advice for development, approval, and promulgation of consensus standards through ASTM Subcommittee E06.53 on Materials and Processes for Durable Rigid Wall Relocatable Shelters, and

3. Revising and updating consensus standards applicable to shelter materials and systems.

IMPROVING THE PROCESS FOR DEVELOPING GUIDE SPECIFICATIONS

Principal Investigator: Robert G. Mathey
Building Materials Division
301.975.6709

Sponsor: Naval Facilities Engineering Command

The project's objective is to develop concise and logically complete guide specifications for specific NAVFAC construction and design contracts.

The Department of Navy uses over 300 guide specifications to develop their design and construction plans and contracts. The guide specifications reference ASTM Standards, Federal and military specifications, ACI guides, and building code manuals. The guide specifications in some cases contain conflicting requirements. NAVFAC officials are concerned that specifications are not complete and consistent and that they contain too much unneeded reference specifications. The uncertainty causes difficulties for NAVFAC and their contractors to demonstrate compliance of the contracted work with the applicable requirements and specifications.

CBT has developed a logical hierarchy for technical provisions in the guide specifications and developed a method to eliminate superfluous information and references to unnecessary and conflicting specifications and documents. Decision rules were developed to determine which of the referenced specifications were not required and which ones needed to be added. The Navy guide specification on cast-in-place concrete (TS-03300), minor building construction (NFGS-03302), and insulating concrete roof deck systems (TS-03501) were analyzed against the decision rules to determine their need for specific referenced data. The analysis provided a bases to develop procedures for applying the decision rules. The application of the decision rules were demonstrated by applying them to a portion of the guide to determine the feasibility of the procedures. Recommendations were made for revising the guide's criteria and provisions to adequately address performance and durability.

QUALITY ASSURANCE LABORATORIES

CEMENT AND CONCRETE REFERENCE LABORATORY (CCRL)

Principal Investigator: James H. Pielert
Building Materials Division
301.975.6704

Sponsors: ASTM and
U.S. Army Corps of Engineers

The purpose of this work is to provide technical assistance, with ASTM Research Associates at NIST, to public and private cement, concrete, aggregate, reinforcing steel, and pozzolan testing laboratories which use ASTM tests.

Roads, bridges, water supply and sewage systems, buildings, airports, railroads, waterway systems, mass transit systems and other structures represent a substantial portion of the Nation's wealth. Construction of such facilities is one of the Nation's largest industries amounting to almost 10 percent of the Gross National Product. Over $4 billion of hydraulic cement is produced in the United States each year with the value of concrete materials in which these cements are used estimated at $20 billion. The testing community's productivity in the cement and concrete fields may be increased by using correct procedures and apparatus which reduce testing errors and provide a sound basis for acceptance of cement on mill certificate.

CBT, through ASTM Research Associates, provides on-site assessment of laboratories and distributes proficiency test samples to public and private cement and concrete tasting laboratories on a voluntary basis. Procedures used in performing conventional quality assurance tests are observed for conformance to applicable national standards. Related test apparatus is checked with inspection equipment and calibrated by CBT personnel. Proficiency test samples of portland cement, pozzolan, concrete, blended cement, and masonry cement are distributed at regular intervals to obtain information on laboratory performance.

The primary benefit of the CCRL programs is improvement in the quality of testing in cement and concrete laboratories in the United States, Canada, and Mexico. Products include: 1) a report for each inspection performed; 2) a comprehensive report on each round of proficiency sample testing; 3) input to standards committees; and 4) reports on results of technical studies.

The CCRL programs benefit the materials testing laboratories and others involved with construction by: 1) improving the quality of laboratory testing; 2) providing data to quantify standard measurement techniques; and 3) providing communications between testing laboratories and standards-writing committees.

AASHTO MATERIALS REFERENCE LABORATORY (AMRL)

Principal Investigator: James H. Pielert
Building Materials Division
301.975.6704

Sponsor: American Association of State Highway and Transportation Officials

The purpose of this work is to provide technical assistance through on-site assessment of construction materials testing laboratories which use AASHTO test methods and distribution of proficiency test samples to public and private laboratories. AMRL is a Research Associate Program at NIST.

The quality of testing in construction materials laboratories is an important national concern as demonstrated by the creation of the Strategic Highway Research Program (SHRP) in 1987 as a 5-year, $150 million national highway and bridge pavement research program. Because of the large amounts of money and critical construction materials involved, standardization of testing to enhance the reliability of quality assurance measurements is of high concern. More efficient use of long-established construction materials and broader use of new materials are facilitated by dependable quality assurance programs.

CBT, through AASHTO Research Associates, provides on-site inspection of laboratories and distribution of proficiency test samples to public and private laboratories. The scope of these services includes testing soils and bituminous materials and measuring frictional properties of highways. Procedures used in performing conventional quality assurance tests are observed for conformance to applicable national standards. Proficiency test samples of asphalt, soils, paint, aggregates and bituminous concretes are distributed at regular intervals to obtain information on laboratory performance. Additionally, technical studies are conducted in areas related to these programs. These are often in conjunction with other CBT units.

The prime benefit of the AMRL programs is improvement in the quality of testing in bituminous and soils laboratories. Specific products include: 1) reports on inspections performed; 2) reports on each round of proficiency sample testing; 3) input to the work of standards committees; and (4) reports on the results of technical studies.

The AMRL program provides benefits to construction materials testing laboratories and others involved with the Nation's transportation systems by: 1) improving the quality of laboratory testing; 2) providing data to quantify standard measurement techniques; and 3) providing direct communications between testing laboratories and standards-writing committees.

REFRIGERANT MIXTURES

SENSITIVITY ANALYSIS OF REQUIRED PRECISION OF REFRIGERANT THERMAL PROPERTIES

Principal Investigator: David A. Didion
Building Environment Division
301.975.5881

Sponsor: National Institute of Standards and Technology

The objective of this research is to determine the needed precision of refrigerant property data for accurate evaluation of the performance of a centrifugal water chiller, by experimental and simulation methods.

An international agreement signed in Montreal in 1987, limits the world production of CFC's 11, 12, 113, 114 and 115 which have been implicated as the ozone layer depleters. The first on the list, CFC-11, is the most popular working fluid in centrifugal water chillers used for air conditioning in large buildings. R12 and R114 are also used to a lesser degree. The Montreal Protocol production reduction has spurred an intensive search for alternative refrigerants.

Many fluids are candidates as alternative refrigerants. Single component fluids and mixtures are being investigated. Their thermodynamic performance is of basic interest. Since there is presently no commitment within the industry to any of the candidates and thermodynamic data on various fluids are of different quality, it is important to know the impact of inaccuracies in the working fluid thermodynamic properties on analysis of performance of the refrigeration system being used. NIST has an extensive thermophysical property measurement and prediction program underway for refrigerants.

Since single component refrigerants and mixtures are under consideration as substitute refrigerants, property data uncertainties for both classes of fluids will be determined. Thermodynamic properties; pressure, temperature, specific volume, specific heats and specific heat ratios will be examined.

Manufacturers design components of the water chilling system and then rate the system performance using a large factory-laboratory test bed. Both of these processes use a series of engineering calculation methods that are heavily dependent on the thermodynamic properties of the working fluid. CBT will determine the precision of the data needed to meet uncertainty requirements of design and test and rating. The laboratory rating process will be a simulation allowing for independent variation of different measured parameters to determine the sensitivity that the thermodynamic properties have on the systems' measured performance rating.

MEASUREMENT AND FORMULATION OF THE THERMODYNAMIC PROPERTIES OF R134a AND R123

Principal Investigator: David A. Didion
Building Environment Division
301.975.5881

Sponsors: Department of Energy and
American Society of Heating, Refrigerating, and Air Conditioning Engineers

The objectives of this project are to: 1) conduct experimental measurements on R134a and R123 to determine the thermodynamic behavior of these fluids; 2) develop comprehensive properties formulation for these fluids by fitting the parameters of an equation of state; and 3) publish the results in tables and charts for the engineering community.

The depletion of the ozone layer in the upper atmosphere has been largely affected by the chlorine atoms in refrigerants. New hydrocarbons of the ethane family will most likely replace fully halogenated ones of the methane series. Identifying new refrigerants is a prime concern of the Federal Government and industry.

CBT is determining the thermodynamic properties (vapor pressure, density, enthalpy, heat capacity, speed of sound) of refrigerants. This work is being performed in four tasks:

1. Experimentally measuring the thermodynamic properties of R134a and R123 as two candidate replacement molecules for R11 and R12. CBT's research performed in FY 1988 identified R134a and R123 as possible candidates because they have few of the ozone destroying chlorine atoms.

2. Formulation of the thermodynamic properties will be performed using the Carnahan-Starling-DeSantis equation of state. This equation of state was developed at NIST during the past 4 years. It provides an accurate measure of the properties of refrigerants.

3. Development of refrigeration tables and charts will be performed using the CSD equation of state. Tables of saturation and superheat properties will be generated for each fluid.

4. Development of recommendations for obtaining additional refrigerant thermophysical and transport property data of new, non-ozone depleting refrigerants will complete the research. This task will be performed in conjunction with producers of refrigerants and refrigeration equipment, manufacturers of insulation, industry associations, and the Federal Government.

NONAZEOTROPIC REFRIGERANT MIXTURE PROPERTY EVALUATION

Principal Investigator: David A. Didion
Building Environment Division
301.975.5881

Sponsor: National Institute of Standards and Technology

The objectives of this project are to: 1) perform thermodynamic evaluation of azeotropes and near-azeotropes (search for CFC alternatives) and 2) evaluate the difference between mixtures and single component refrigerants heat transfer coefficients for high quality evaporative annular flow.

The dominant problem facing the HVAC and refrigeration industry today is to identify ways to lessen the impact of CFC refrigerants on stratospheric ozone. A major, international effort is underway to develop alternative refrigerants. There is a need for a predictive theory for mixture heat exchangers; work needs to be done to replace refrigerants such as R11 and R12 which are harmful to the atmosphere and to optimize the refrigeration cycles. The refrigeration industry is searching for a refrigerant which will not destroy the ozone layer and that has desirable heat transfer properties. Data has revealed, both experimentally and theoretically, that nonazeotropic refrigerant mixtures can be used to enhance cycle performance. The enhancement is due to the design of the heat exchangers of the cycle. An increase in two-phase heat transfer resistance can decrease mixture cycle efficiency. Therefore, a predictive theory for mixture phase change is required to optimize the cycle performance.

CBT is performing two concurrent tasks:

1. Screening the mixtures of ozone-safe refrigerants. This approach involves iterating between cycle simulations and experimental measurements.

2. Developing the theoretical point of boiling heat transfer of mixtures inside horizontal tubes. This work focuses on modeling the heat transfer guided by the knowledge of the governing parameters determined from the experimental results. Once a predictive model has been developed it will be used by the refrigeration industry to design new systems using refrigerant mixtures. The experimental investigation of the boiling heat transfer of mixtures in compact heat exchangers.

MEASUREMENTS OF MODIFIED HEAT PUMP CYCLES USING NONAZEOTROPIC MIXTURES

Principal Investigator: David A. Didion
Building Environment Division
301.975.5881

Sponsor: Department of Energy, Oak Ridge National Laboratory

The objective of this research is to experimentally evaluate in the laboratory the thermodynamic and operational behavior of modified heat pump cycles and systems hardware using nonazeotropic refrigerant mixtures.

In recent years the research interest in the use of nonazeotropic binary mixtures as working fluid for refrigeration systems has increased. It does not appear that new single component refrigerants can be developed because of the limited number of elements available for combination to produce volatile nonflammable, nonpoisonous, chemically stable compounds. Consequently, improvements in refrigerant performance in the future is expected to result from the application of mixtures of known refrigerants. Previous work at CBT and ADL has shown that simple substitution of mixture into a refrigerant system that was designed for single component refrigerants yields only minimal performance increase.

A heat pump model for nonazeotropic mixtures was developed by CBT under EPRI sponsorship which uses a new hard-sphere equation-of-state. The new model will be verified through comparisons with data obtained from hardware tests and also used to supplement the experimental data.

This work is being performed in two tasks:

1. Develop thermodynamic performance evaluation of selected refrigerant mixture. Criteria was developed which establishes methods of rating a refrigerant mixture on the basis of constant heat flux in the heat exchangers and fixes the heat exchange fluid temperature at the condenser and evaporator inlets and outlets. Tests will be conducted for each mixture on the same basis to properly and consistently compare their respective merits for particular representative applications. The compressor will be verified by obtaining the same parity from each of the mixtures (and thereby satisfy the test requirement of constant heat exchanger heat flux). The effect of speed in compressor efficiency will be determined by separate compressor tests. The mixtures R114/R22, known for its improved cycles efficiency and R12/R13, a mixture with increased capacity at lower temperatures, were tested during FY 1988. One or two additional mixtures will be selected for tests during FY 1989. One candidate, R134a/R11 appears particularly advantageous for advanced cycles using solution pumps. A report presenting the various mixtures compositions data and mixture specific analysis will be prepared at the composition of these tests.

2. Evaluation of the performance of counterflow heat exchangers employing two or three fluids. In addition to the empirical characterization and verification of the thermodynamic characteristics of the mixtures in Task 1 it is necessary to determine the heat exchange characteristics that will best explain the mixture. The influence of flow rates, particularly of the sensible heat transfer fluid (probably water or glycol) is important for temperature profile matching. On the refrigerant side the saturation pressure drop tends to enhance the gliding temperature profile in the condenser while it counteracts it in the evaporator. The effect of such pressure drops on the theoretical gliding temperature will be investigated.

EVALUATION OF NONAZEOTROPIC HEAT PUMP CONCEPTS

Principal Investigator: David A. Didion
Building Environment Division
301.975.5881

Sponsor: Electric Power Research Institute

The purpose of this research is to experimentally evaluate new heat pump concepts that use nonazeotropic refrigerant mixtures by designing, constructing, modeling, and testing breadboard heat pump systems.

CBT has studied the use of nonazeotropic refrigerant mixtures in various heat pump cycles since 1985. This work resulted in a considerable amount of quantitative data and has generated several engineering tools for evaluating specific designs of refrigerant systems using mixtures. It is now possible to design and test a breadboard nonazeotropic heat pump system for residential application having superior performance and benefits over existing systems.

During FY 1989 CBT is performing five tasks:

1. Review present and proposed heat pump concepts that use nonazeotropic refrigerant mixtures.

2. Develop a detailed breadboard design of the selected heat pump concept. Design the instrumentation and data acquisition and reduction systems and facility modifications necessary for test and evaluation.

3. Develop a computer simulation of the selected breadboard heat pump system using existing heat pump and refrigeration mixtures models. The model will be designed to allow interpolation and extrapolation of test data and allow predictions of how the system would perform in actual applications.

4. Construct and verify the breadboard, instrumentation, data acquisition and reduction systems, and test facility. Prepare a detailed test plan.

5. Acquire and analyze test data sufficient to characterize the heating and cooling outputs, electrical energy consumption, and efficiency as a function of source and sink temperatures over the full range of ARI (DOE) test points. Establish annual performance for a variety of U.S. climates, characterize defrost operation, and establish oil compatibility with mixture components at extreme high and low temperatures.

HEAT AND MOISTURE TRANSFER

ENVELOPE DESIGN GUIDELINES

Principal Investigator: Andrew K. Persily
Building Environment Division
301.975.6418

Sponsor: General Services Administration

The purpose of this research is to develop an envelope design guide of recommended design and construction practices, for thermal, air leakage, ventilation, and moisture transfer performance for office buildings.

In an effort to reduce energy use and to ensure a comfortable and healthy indoor environment, there has been much field, laboratory, and analytical research performed in the United States during the past decade, to better understand, control, and model thermal performance of building envelopes, infiltration and air leakage in buildings, improvement of building ventilation systems, and control of moisture damage in buildings. This research has increased the knowledge base of building envelope performance, building airtightness, principles governing air infiltration, migration of moisture into and through building envelopes, and interaction of building envelope tightness and performance of ventilation systems. It has revealed that the design of a cost-effective building envelope system having good thermal performance and resistance to moisture penetration and damage, is difficult to achieve. Yet, in spite of all this work there are no guidelines available which have synthesized these studies into a document to design and construct commercial building envelopes.

During FY 1989, CBT is performing a critical technical review of recent research on thermal and airtightness performance of commercial building envelopes. A synopsis document of the findings and guide plans will be produced at the end of this year. During FY 1990, the guide will be developed, reviewed by experts from research and industry, and published. Its review will make use of numerous sources of technical and practical information including ASHRAE, ASTM, the Air Infiltration and Ventilation Centre, local building codes, DOE, GSA, and other agencies. The guide will contain a tutorial on the principles involved in the design of a thermally efficient building envelope that is resistant to air-infiltration and moisture. It will address the importance of the envelope design on performance of the building ventilation system, and the emphasis will be on the practical application of these principles to building design and construction. The information will be presented as case studies of "do's and do not's" with graphic representations. The case studies will focus on architects and engineers to maximize impact on future building practice.

DYNAMIC EVALUATION OF THERMAL BRIDGES

Principal Investigator: Douglas M. Burch
Building Environment Division
301.975.6433

Sponsor: Department of Energy, Oak Ridge National Laboratory

The objectives of this project are to: 1) develop and verify a mathematical procedure to predict the dynamic thermal performance of thermal bridges in building simulation computer models and 2) generate transfer function coefficients of thermal bridges in a commercial building.

Thermal bridges and anomalies significantly affect the steady-state and dynamic heat transfer through building envelopes. Building envelope heat transfer is calculated by computer programs (e.g., TARP, DOE2, BLAST) that use one-dimensional conduction transfer functions (TFCs); they do not include the effect of thermal bridges and anomalies. Using TFCs that account for thermal bridges and anomalies would significantly improve the accuracy of building envelope heat transfer calculations.

During FY 1987, CBT developed a dynamic test method for calibrated hot boxes (CHBs) that characterizes the dynamic thermal performance of wall specimens. This test method obtains TFCs for a wall specimen that accounts for the effect of thermal bridges and anomalies. These empirical TFCs were shown to be successful in predicting the dynamic response of the wall specimen to sol-air diurnal temperature cycles. Based on these research results, CBT prepared a draft ASTM standard dynamic test method.

In this project, the same theoretical approach will be applied to obtain predicted TFCs for thermal bridges of a commercial building. Here a finite-difference model will be used to obtain the dynamic response of the seven thermal bridges to a fast ramp excitation function. Using the analysis procedure of the dynamic test method, the predicted dynamic response for each of the seven thermal bridges will be analyzed to give TFCs.

These TFCs will be used to predict heat transfer rates through the thermal bridges exposed to hourly weather data. By comparing the heat transfer rates predicted by the TFCs to those predicted using the finite-difference model, the TFCs will be verified. Hourly space heating and cooling loads for the commercial building will be predicted for a 1-year period using the building simulation computer model, TARP. Three types of computer simulations will be performed: 1) commercial building without thermal bridges, 2) commercial building with thermal bridges model using steady-state thermal transmittances (U-values), and 3) commercial building with thermal bridges modeled using TFCs. Results for the three types of computer simulations will be graphically compared. Analysis will be carried out for northern, middle, and southern U.S. climates.

EXPERIMENTAL EVALUATION OF DYNAMIC TEST PROCEDURES

Principal Investigator: Douglas M. Burch
Building Environment Division
301.975.6433

Sponsor: Department of Energy, Oak Ridge National Laboratory

The objective of this project is to develop a dynamic test method for a calibrated hot box that characterizes the dynamic thermal performance of complex building walls and includes the effect of thermal bridges and anomalies.

The time-dependent heat transfer rate through building envelopes is calculated by computer programs (e.g., TARP, DOE2, and BLAST, etc.). These computer programs use one-dimensional transfer function coefficients (TFCs) to predict the heat transfer rate through the building envelope. The TFCs do not include the effect of thermal bridges and anomalies which may have a significant effect on the heat transfer rate and cause considerable error in computer calculations.

During FY 1987, CBT prepared a draft ASTM Standard Dynamic Test Method for Calibrated and Guarded Hot Box. Also, during FY 1987, a complex masonry wall having significant thermal bridges was installed in our calibrated hot box. A series of dynamic measurements were conducted on the specimen to verify the dynamic test method.

During FY 1989, the series of dynamic measurements are being analyzed. The analysis will indicate how well the empirical TFCs predict the heat-transfer response of the wall specimen when it is subjected to outdoor excitation functions as: a sol-air diurnal cycle, a 4-harmonic diurnal cycle, and a triangular pulse.

We will continue to participate in the ASTM consensus process to prepare a final ASTM Standard Dynamic Test Method. As part of this effort, we will conduct a computer sensitivity analysis to investigate the measurement accuracy and control requirements for a CHB to obtain TFCs that predict with good agreement the heat transfer response of the wall specimen to different excitation functions.

THERMAL RESISTANCE MEASUREMENTS OF FOAM INSULATION PRODUCTS USING THE GUARDED-HOT-PLATE AND HEAT FLOW METER

Principal Investigator: Robert R. Zarr
Building Environment Division
301.975.6436

Sponsor: Department of Energy, Oak Ridge National Laboratory

The objective of this project is to examine the effect of different thermal conductivity and thickness of materials in calibrating a heat-flow-meter apparatus.

The heat flow meter is the apparatus favored by the foam manufacturers to measure thermal conductivity. The apparatus is calibrated using a specimen measured with a guarded-hot-piate. Thermal measurement laboratories have expressed concern about the accuracy of heat-flow-meter measurement for materials of different conductivity or thickness than the calibrated standard.

During FY 1989, CBT is performing a comparison study using its 1-meter guarded-hot-plate and a commercially available heat flow meter. The samples are fumed-silica board, fibrous-glass board, extruded polystyrene, unfaced polyisocyanurate, and a highly conductivity material (gum or silicon rubber). An advisory panel will advise CBT in selecting materials to investigate the comparison study. It will be composed of ASTM C-16 members and representatives from the foam plastics industries.

Using CBT's guarded-hot-plate, measurements of fumed-silica and fibrous-glass board will be conducted in one-sided mode, heat-flow up, at three mean temperatures of 10, 24, and 38 °C with a temperature difference of 28 °C. Measurements of fumed-silica board will be adjusted to a common pressure of 101.3 kPa using results from previous measurements of the material. Using these results the heat flow meter will be calibrated.

VALIDATION OF MOISTURE-TRANSFER MODEL

Principal Investigator: Douglas M. Burch
Building Materials Division
301.975.6433

Sponsor: National Institute of Standards and Technology

The purpose of this research is to complete a series of laboratory experiments to verify a mathematical model for predicting the combined heat and moisture transfer in multi-layered walls.

During the winter season, the moisture content within buildings is considerably higher than the outdoor moisture content. Water vapor permeates into walls and becomes adsorbed within the outer layers. The accumulation of moisture within building materials was shown to have a profound effect on their thermal insulation properties. Mathematical models currently are not available to predict time-dependent moisture accumulation within building components. As a result, costly experimentation is required because individual measurements cannot readily be extended to different wall geometries and different climates.

During FY 1988, a computer model was developed and verified by comparing it to a single laboratory experiment. During FY 1989, CBT will validate the previously developed moisture transfer model for predicting moisture absorption/desorption rates for building materials. Also we will validate the previously developed moisture transfer model for drying and diurnal cycling conditions. For the drying condition, two multi-layer wall specimens will be pre-conditioned to a high

moisture content, and subsequently dried by exposing its outside surface to a summer elevated temperature condition. For cyclic condition, moisture will be accumulated in the wall specimen by exposing its outside surface to a winter diurnal cyclic condition.

Hysteresis in sorption isotherms will be investigated. Here separate sorption isotherms will be measured for adsorption and desorption processes using equilibrium relative humidities above saturated salt solutions. In addition, permeability measurements of selected materials will be conducted at a low temperature. These low temperature permeability measurements will be compared to previous measurements conducted at typical indoor temperature conditions, to investigate the effect of temperature on permeability.

PREDICTING COMBINED TRANSFER OF HEAT AND MOISTURE

Principal Investigator: Douglas M. Burch
Building Environment Division
301.975.6433

Sponsor: Department of Energy, Oak Ridge National laboratory

The objective of this project is to conduct a series of laboratory experiments to verify a mathematical model for predicting the combined heat and mass transfer in multi-layered walls.

During the winter season, the moisture content within buildings is considerably higher than the outdoor moisture content. As a result, water vapor permeates into walls and becomes adsorbed within the outer layers. The accumulation of moisture within building materials was shown to have a profound effect on their thermal insulation properties. Mathematical models currently are not available to predict time-dependent moisture accumulation within building components.

During FY 1989, we are:

1. Measuring the water-vapor permeability of the wall specimen components using the ASTM cup methods. Saturated salt solutions will be used to provide a range of humidity conditions inside the cups. Sorption isotherms will be determined for the wall specimen components by allowing them to attain different moisture equilibrium using various saturated salt solutions.

2. Conducting a laboratory experiment to condition wall specimens with moisture. Instrumentation will be installed to measure the moisture accumulation in the wood siding, the specimen heat transfer rate, the temperature profile across the wall specimen, and the temperature and relative humidity on both sides of the wall specimen. A data acquisition software program will be prepared to collect the experimental data. The moisture content within the wood siding will be measured as a function of time and compared with that predicted by the mathematical model. The effect of accumulated moisture on the heat transfer through the specimen will be investigated using heat flux transducers. The measured moisture profiles will be compared to those predicted by the mathematical model. The resulting measurements will be made available to building scientists to validate mathematical models for predicting moisture accumulation.

MOISTURE CONTROL IN MANUFACTURED HOUSING WALLS

Principal Investigator: Douglas M. Burch
Building Environment Division
301.975.6433

Sponsor: Department of Housing and Urban Development and
Forest Products Laboratory

The objective of this research is to use a mathematical model to corroborate field measurements of moisture accumulation in eight test walls exposed to outdoor winter conditions in Madison, WI.

Many moisture problems in homes during winter are a result of excessive indoor humidity. Recent damage in walls of manufactured homes in Wisconsin, Minnesota, and other Midwestern States was found to be primarily the result of excessive indoor humidity due to lack of ventilation. Conversely, results from previous research at the Forest Products Laboratory (FPL) indicate that flaws in design and/or workmanship are less likely to lead to moisture damage if indoor humidity is kept at moderate levels. However, too much uncertainty exists in projecting the effects of indoor relative humidity on moisture accumulation in walls for reliable application of current design techniques.

FPL is funded by HUD to carry out a field study to investigate the effects of indoor humidity and wall construction on the moisture-related performance of manufactured housing walls. As part of this study, FPL will field expose eight test walls to outdoor climatic conditions at Madison, WI. Four of the test walls will be of different construction and will be tested with a moderate indoor relative humidity (approximately 35%). The other four walls will be identical to the previous four but will be tested with a high indoor humidity (50–60%). The moisture content of materials within these walls will be measured as a function of time. The effect of moisture on the heat transmission will be investigated.

CBT has previously developed a complex mathematical model that predicts the time-dependent transfer of heat and moisture in multi-layer walls. The model is comprised of two coupled differential equations; namely, a conservation of mass equation and a conservation of energy equation. These equations are solved by the implicit finite-difference method. This model will be extended as necessary to simulate the moisture and thermal performance characteristics of the eight test walls.

During FY 1989 and 1990, CBT will:

1. Provide and calibrate eight heat flux transducers for measuring the effect of moisture on the heat transmission.

2. Measure the permeability and sorption isotherms of wall specimen materials for which transport property data is unavailable in the literature.

3. Predict the moisture performance of the eight walls to assist in designing the experiments, including the determination of where instrumentation should be placed.

4. Predict the measured moisture content of the eight walls using FPL hourly measurements of indoor and outdoor temperature and relative humidity.

5. Perform computer sensitivity analysis to extend the field measurements to account for different indoor humidity and outdoor climatic conditions.

THERMAL ANALYSIS OF DIRECTLY BURIED CONDUIT HEAT DISTRIBUTION SYSTEMS

Principal Investigator: Jin Fang
Building Environment Division
301.975.6417

Sponsor: Tri-Services Committee (DOD)

The objective of this project is to develop computational procedures for evaluating the thermal performance of underground heat distribution systems.

In district heating systems installed in military facilities, hot water or steam are delivered through parallel buried pipes from a central heating plant to the buildings. The transmission heat losses from insulated piping to the surrounding soil account for the major portion of the operating costs. Various experimental techniques as field tests for measuring the heat loss from underground pipes are expensive and time consuming. Mathematical modeling can provide a relatively inexpensive and rapid means for evaluating the performance of the heat distribution system, and assessing the effects of various system variables such as pipe size, insulation thickness, and operating temperatures.

During FY 1988 a computer program developed at CBT based on the finite element analysis to solve a two-dimensional steady-state heat transfer problem was modified and used to predict the heat losses and temperature distributions for sections of two pipes installed with and without pipe supports in a concrete trench. The calculated results indicated that the heat losses through the highly conductive pipe supports are significant.

During FY 1989, CBT will develop mathematical models to predict the thermal performance of buried conduit systems. These computer programs also will calculate the heat losses due to pipe support systems. The daily and seasonal temperature and heat flux variations in underground heat distribution systems at Fort Jackson, SC are monitored by the Army Cold Regions Research and Engineering Laboratory. Verification of theoretical calculations using these finite element computer programs will be compared with the field data. Numerical simulation of heat transfer characteristics and temperature distributions of underground systems will be performed on typical piping support systems.

RADIANT CEILING PANEL SIMULATION COMPUTER PROGRAM

Principal Investigator: George Walton
Building Environment Division
301.975.6421

Sponsor: Department of Veterans Affairs

The objectives of this research are 1) to develop a model and simulation program for predicting the performance of radiant ceiling panel heating and cooling system in buildings and 2) to assist the VA in obtaining in-house capability for analyzing such systems.

The VA requires external expertise to evaluate proposals for HVAC systems. The VA needs to update their "Veterans Administration Energy Program" (VAEP) which is almost 10 years old. For new systems and components, such as radiant panel heating and cooling systems, the VA evaluation system is not able to evaluate new systems.

CBT is performing four tasks:

1. performing a detailed study of the VAEP code. This study will determine how simulation of radiant panels can be added to their VAEP.

2. developing and testing the additions and modifications to VAEP.

3. installing the revised program in the VA computer where it will be used.

4. developing documentation on the revisions to VAEP and the training of VA personnel in its use.

INDOOR AIR QUALITY

DEVELOPMENT OF PREPROCESSOR FOR A GENERAL INDOOR AIR POLLUTION CONCENTRATION MODEL

Principal Investigator: Richard A. Grot
Building Environment Division
301.975.6430

Sponsor: Consumer Product Safety Commission (CPSC)

The objective of this research is to develop a preprocessor and linkage modules for the general indoor air pollution concentration model which will provide a user friendly interface for data input and the ability to interface with air movement and energy simulation models.

CBT is developing a computer program (CONTAM) which will predict indoor air quality. However, the program inputs are not user friendly nor is there a straightforward linkage between this program and others such as AIRMOV (air movement program) and TARP (thermal analysis program) which may be needed for complete analysis. Also, the CONTAM program modules have not been verified or checked.

During FY 1989, CBT will be:

1. developing a user friendly preprocessor program for CONTAM. This work involves developing modules, or preprocessors, needed to make CONTAM user friendly. These modules include, but are not limited to, an input program which constructs the needed CONTAM computer model of the actual structure to be investigated, a source/sink module, and an environmental module.

2. supplying for CPSC use, data to Beta-test CONTAM, including compilers, linkers, etc. CPSC will use these programs to verify the usefulness of the program, perform Beta testing, and make suggestions for possible improvements.

3. identifying and evaluating available models that are of potential use in CONTAM. This identification and evaluation includes source emission models, sorption/desorption models, and chemical reaction models. In the evaluation, CBT will comment on the extent of validation of the model or the adequacy of the data base that the model was built on. This task will identify source/sink models needed to improve IAQ models for CPSC use.

4. performing a preliminary validation of CONTAM and developing modules. CBT and CPSC will select the items to be validated and the method of validation.

DEVELOPMENT OF PROFESSIONAL SERVICES PROGRAM FOR INDOOR AIR QUALITY ANALYSIS

Principal Investigator: Richard A. Grot
Building Environment Division
301.975.6431

Sponsor: Environmental Protection Agency

The objective of this project is to develop a computer program and supporting documentation for contaminant dispersal analysis in buildings, based on CBT's IAQ Model, and directed toward the immediate needs of the professional communities involved in building design, construction, and operation (e.g., architects, building engineers, and health officials).

In previous years, EPA, DOE, and CPSC have sponsored CBT projects to develop computational tools for indoor air quality analysis. CBT's IAQ Model emerged from this research. The model provides state-of-the-art indoor air quality analysis capabilities and establishes the standard against which other IAQ models are being judged. The CONTAM series of programs developed at CBT implements the underlying theory of the CBT IAQ Model. It models building air flow in systems of arbitrary complexity and accounts for arbitrarily mass transport associated with contaminant movement in buildings. These programs are, however, not easy to use and provide capabilities not often needed in present-day practical situations. A parallel family of programs for indoor air quality analysis are being developed; a professional series directed toward the needs of building professionals.

This project will proceed in two phases:

1. a professional version of CONTAM will be developed for the Macintosh™ environment. In this stage, a graphics-oriented program will be developed on the Macintosh™ computer using the advanced development packages presently available only on the Macintosh™ systems.

2. a professional version of CONTAM will be developed for a MS-DOS graphics environment. In this stage, the above graphics-oriented program will be ported to the IBM PC family of computers through automatic translation to the C programing language and use of the state-of-the-art windowing development system, Microsoft™ WINDOWS™. The capabilities of CONTAM in phase 1 will be limited to contaminant dispersal analysis problems for conditions of steady flow driven by user-defined sources and sinks. In phase 2, dynamic analysis under unsteady flows will be included.

CONTAMINANT SOURCE/SINK MODELS FOR THE NIST IAQ MODEL

Principal Investigator: Richard A. Grot
Building Environment Division
301.975.6431

Sponsor: National Institute of Standards and Technology

The objectives of this project are to 1) develop general source and sink models, and laboratory measurement methods to determine model parameters, for indoor air contaminant sources and sinks that are governed by physical and chemical sorption processes and 2) validate these models by comparing predicted and measured contaminant concentration time histories for laboratory and field investigations.

CBT has developed advanced indoor air quality analysis programs to predict the extent, severity, and duration of indoor air pollution problems in buildings. The practical application of these programs depends on using appropriate and accurate contaminant source and sink models. Yet, information for many of the important indoor air contaminants are not available. There is a pressing need to develop these contaminant source and sink models. Given the number and variety of indoor contaminants and the great need for models that can be used for indoor air quality analysis this research focuses on one class of contaminant sources and sinks (i.e., those governed by sorption phenomena). This work focus on developing a single or group of related general computer programs to model the behavior of contaminants in this class.

We will build on the experience gained in earlier studies involving a) the sorption mass transport of formaldehyde gas in and out of building materials and b) the sorption mass transport of organic gases in and out of gas filtration media. Existing gypsum wallboard formaldehyde sorption models will be applied to the indoor air quality analysis of whole buildings to validate the predictive capability of these models. The development of models (and laboratory measurement methods for determining model parameters) for other building construction materials and their application to

whole-building indoor air quality analysis will be considered. Organic gas filtration model development, planned as part of a separate project sponsored by CPSC, will be coordinated with this study to develop models that may be used in whole-building simulations and to apply these models to practical indoor air quality analysis.

METHODS FOR MEASURING THE EFFECTIVENESS OF DEVICES FOR REMOVING THE GASEOUS CONTAMINANTS FROM AIR STREAMS

Principal Investigator: Bal M. Mahajan
Building Environment Division
301.975.5856

Sponsor: National Institute of Standards and Technology

The objective of this project is to develop methods for measuring the efficiency of filters to remove gaseous contaminants from air.

Filtering devices using granular materials called sorbers, such as activated carbons and chemically treated alumina and other organic substances, are being used to remove or chemically change gaseous pollutants found in buildings. These devices can be incorporated into the heating, ventilating and air conditioning (HVAC) systems of buildings, similar to filters used for the removal of particulates. Particulate filters can be evaluated by using ASHRAE Standard 52. Over the years, attempts were made to evaluate gaseous removal filters for some specific applications; however, no general procedures are available for evaluating the effectiveness of these devices. Hence, methods are needed to provide acceptable means to evaluate these devices so effective and economical control methods may be promoted for improved indoor air quality.

Test methods were developed to evaluate the effectiveness of filter media for removing gaseous contaminants from air. The test methods employ a test loop system where a sample filter media is challenged with known gaseous contaminants introduced into the intake air at desired concentrations. The contaminant concentration, upstream and downstream of the filter media, are measured using gas chromatography.

During FY 1989 CBT is collecting data on contaminant penetration (efficiency) through the filter media as a function of elapsed time and other variables. Other variables include: temperature, relative humidity, and speed of the carrier air; physical and chemical properties of the filter media; granule size, packing density, and bed depth of sorber media; and properties and concentration of contaminant gases. These data are used to determine the breakthrough conditions and capacity of the filter media.

The data collected during FY 1988 will be analyzed to develop a theoretical basis for predicting actual filter performance using the results of laboratory tests and theoretical sound basis for the performance of gaseous filters will be developed using the framework of interactive contaminant developed in CONTAM.

INFILTRATION/VENTILATION—LARGE BUILDINGS

Principal Investigator: Andrew K. Persily
Building Environment Division
301.975.6418

Sponsor: Department of Energy

The purposes of this research are to 1) develop test methods for evaluating the movement of air into and within large commercial buildings and to 2) determine the efficiency of the ventilation systems of commercial buildings for removing contaminants at a minimum energy cost.

In comparison to residential buildings, little data exists on air leakage and air movement in large commercial structures. Limited data indicates there is a wide range of air leakage rates in large buildings. Previous DOE/CBT research demonstrated that large buildings experience under- and over-ventilation during their annual operation. Even buildings which have a total air exchange rate sufficient to remove contaminants may have zones which require little heating or cooling and therefore receive small amounts of ventilation. Also, the design of the air distribution system and the placement of internal partitions may result in uneven distribution of an otherwise adequate amount of ventilation air.

Test methods for evaluating ventilation and indoor air quality will be applied to the Madison Building of the Library of Congress. These will include measurements of air exchange rates, ventilation effectiveness and internal airflow rates. Measurements of contaminant levels and their spatial distribution also will be made. The contaminants which will be measured include CO_2, CO, respirable particles in five ranges spanning 0.3 to 10 microns, formaldehyde, and radon. These measurements will produce a data set of contaminant concentrations in office buildings and an assessment of the usefulness of these ventilation efficiency measurement techniques for characterizing the ability of building ventilation systems to remove contaminants.

The work in the Madison Building will be conducted in conjunction with the J. B. Pierce Foundation of Yale University. The Pierce effort will concern occupant reaction to the indoor environment in relation to thermal comfort and ventilation, and the development of surrogate measures for indoor air quality.

THERMAL AND ENVIRONMENTAL EVALUATION OF ADVANCED TECHNOLOGY OFFICE BUILDINGS—PHASE IV

Principal Investigator: Richard A. Grot
Building Environment Division
301.975.6431

Sponsor: General Services Administration

The objective of this research is to conduct a measurement program to evaluate the thermal and environmental performance of advanced-technology office buildings.

The design and construction of modern, advanced-technology buildings places more requirements on the building's thermal and environmental performance. A better understanding of the thermal, environmental, and operational characteristics of advanced-technology buildings is essential to avoid design, construction, and operation errors that may result in a building unsuited to its tenants. The inability to meet thermal comfort criteria and air quality standards in buildings is due to 1) improper selection of building materials, 2) poor building design, 3) poor construction quality, and 4) improper operation of the building systems.

Under previous GSA research agreements, CBT developed design specifications for installing a diagnostic center, and performance criteria and programming directives for the installation of a diagnostic center in advanced technology buildings. The diagnostic center concept has been applied to programming requirements for three Federal buildings: Portland, OR; Overland, MO; and Long Beach, CA. The evaluations of these advanced technology buildings include thermographic inspection of the building envelope, thermal resistance measurements of the envelope, pressurization tests of envelope airtightness, tracer gas analysis of air exchange, and monitoring of indoor levels of contaminants. CBT is conducting a multi-phase research effort to conduct these evaluations in the new, advanced-technology Federal office buildings.

During FY 1986 (Phase I) CBT performed a design review of the new Portland East Federal Building in Portland, OR and installed a diagnostic center within the building.

Phase II (FY 1987) involved the installation of a diagnostic center in the Portland building and a design review of the new Overland building. During Phase III (FY 1988), the Portland building testing began before occupancy and is continuing for 1 year after occupancy. Phase III also included design review for the installation of a diagnostic center in the Long Beach building. The experience in Portland has served to fine-tune the approach for use in this future facility.

During FY 1989 CBT is performing Phase IV of the research. This involves the installation of a diagnostic center in the Overland building and continued operation of the diagnostic center in the Portland building until the end of the 1988-1989 winter season. CBT is installing and using the diagnostic center in the Overland building to perform move-in and early occupancy testing of the Federal building in Overland. We will analyze the data in the Overland building to determine if the building meets its original design and anticipated performance.

Based on pre-occupancy and move-in period testing in the three buildings, we will develop guidelines for building operating procedures and servicing during building commissioning and move-in. This program will validate diagnostic techniques for evaluating performance issues as envelope thermal integrity, ventilation and indoor air quality, and establish cause and effect relationships between these performance issues and building features and operation.

DEVELOPMENT OF SORPTION SOURCE/SINK MODELS FOR GASEOUS INDOOR AIR POLLUTANTS

Principal Investigator: Richard A. Grot
Building Environment Division
301.975.6431

Sponsor: Department of Energy

The objectives of this project are to 1) develop general macroscopic source and sink models that may be used for practical, whole-building indoor air quality analysis for indoor air contaminants that are governed by sorption processes and 2) validate these models via comparisons with predicted and measured contaminant concentration time histories.

CBT has developed advanced indoor air quality analysis programs to predict the extent, severity, and duration of indoor air pollution problems in buildings. The practical application of these programs depends critically upon appropriate and accurate contaminant source and sink models which, for many important indoor air contaminants, are not available. There is, therefore, a pressing need to develop these contaminant source and sink models. The character of a small number of indoor contaminant sources and sinks were studied in the past, but few of these studies produced models that may readily be used for indoor air quality analysis in real building situations.

Indoor air contaminants are classified in several broad classes: formaldehyde (HCHO) and nitrogen dioxide (NO_2) represent complimentary extremes of this class of contaminants and, as such, will be the focus of this CBT modeling effort. Both are affected by sorption phenomena, but the dispersal of NO_2 is significantly modified by irreversible conversion while that of HCHO is not. A single or group of related general models will be developed to model the macroscopic whole-building behavior of contaminants that fall within this class.

This research will build on the experience gained in earlier CBT work involving the sorption mass transport of HCHO in and out of building materials. Existing gypsum wallboard HCHO sorption models, developed to characterize test chamber behavior, will be adapted so that they may be applied to whole-building indoor air quality analysis. These same models will then be applied to the problem of modeling NO_2 source/sink behavior. This will involve the dete.mination of model parameters, using small-chamber test data, and the validation of whole-building models through comparison with measured data from large-chamber tests and field tests.

AIR QUALITY STUDY OF RADIATION ONCOLOGY FACILITY

Principal Investigator: Andrew Persily
Building Environment Division
301.975.6418

Sponsor: National Institutes of Health

The objectives of this research are to: 1) investigate the application of recently developed ventilation and air quality evaluation techniques in a medical treatment and laboratory research facility, and 2) study indoor air quality problems in the Radiation Oncology Facility at the National Institutes of Health and to recommend modifications to the HVAC systems to meet current standards for indoor air quality.

Maintaining acceptable indoor air quality is a matter of great concern in building design, construction and operation. The sources of indoor air quality problems and their manifestations are varied. Most indoor air quality research in nonresidential buildings has concentrated on the office environment and its unique set of problems and concerns. Scientific research and medical treatment facilities are characterized by different problems and concerns due to the unique activities that occur in these spaces, the substances associated with these activities, the design of the mechanical ventilation systems, and the sometimes sensitive populations that occupy these spaces. Research is needed to develop the tools to investigate indoor air quality in this unique building type to develop guidelines for the design and operation of these buildings, and standard protocols for the investigation of indoor air quality problems in these buildings.

The Radiation Oncology Branch at the National Institutes of Health is an example of a space combining scientific research and medical treatment activities. It is also experiencing indoor air quality problems, and therefore is an appropriate candidate for indoor air quality research in this building type.

The indoor air quality problems in this facility will be studied to understand the air quality issues in this building type, modifying the tools that are currently used for investigating ventilation and air quality, applying and refining some recently developed measurement and analysis techniques, and developing new techniques specific to this building type.

CBT and others have developed several techniques for studying ventilation and air quality in buildings, including the tracer gas techniques for office buildings. The appropriateness of these techniques to this building type will be studied, and these techniques will be modified for application in these buildings. The integral tracer pulse technique, recently developed at CBT, also will be used in this work to refine the application of this new and promising technique for determining airflows in buildings.

CBT will make a detailed review of the design of the HVAC systems to determine if the original design was adequate for providing acceptable indoor air quality. CBT then will complete a detailed on-site inspection of the existing systems to determine if field modifications, poor workmanship, duct collapse, have caused the systems to function in an unacceptable manner. Extensive tracer gas measurements will be made to determine air flow rates throughout the facility. A wide variety of nonbiological contaminants will be measured to determine if they exceed recognized National standards. These included CO_2, CO, formaldehyde, nitrogen oxides, radon, and volatile organic compounds. Finally, recommendations for improving the indoor air quality in the facility will be made.

COMPUTER INTEGRATED CONSTRUCTION

INFORMATION EXCHANGE TECHNOLOGIES IN THE BUILDING PROCESS

Principal Investigator: Kent Reed
Building Environment Division
301.975.5852

Sponsor: National Institute of Standards and Technology

The objective of this project is to develop the technical basis for correct and efficient information exchange standards for the building industry.

The use of computers has penetrated the building process including its design, construction, and operation. However, there is little integration of these traditionally separate activities because there exist few effective standards to express and exchange information about buildings. Designers, contractors, and others continue to be plagued by the errors and inefficiencies that occur because information is not available in digital form when needed, is incorrectly transferred out of a sending system, or is incorrectly interpreted by the receiving system. Rational techniques are needed to develop and test information exchange standards if computer integration of the building process is to be achieved.

The existing national standard for data exchange—the Initial Graphics Exchange Specification (IGES)—deals mainly with basic data describing geometric elements and their graphical representation. It lacks the appropriate protocols required to ensure its successful use in specific applications and the supporting methodologies and test cases required to validate specific software implementations.

At the same time, national and international committees are developing the next generation standard, called the Product Data Exchange Specification (PDES) in the USA and the Standard for Product Data Exchange (STEP) in ISO TC/184. Unlike IGES, the new standard is intended to facilitate the exchange of complete product definitions rather than just geometric and graphical data. The interface between PDES/STEP and user applications is being defined by modeling conceptually the users' information needs. The building industry is not well represented in this modeling process and it is developing models *ad hoc*.

During FY 1989 CBT will continue to:

1. Develop the IGES/AEC Translator Forum (IATF) activity, initiated in FY 1987, demonstrating the current state of IGES translators supported by AEC [Architecture, Engineering, and Construction] CAD system vendors. Round-robin transfers of data will be conducted using IGES as the intermediate file format for vendor systems located in CBT laboratory space and in participant's offices. These results will be analyzed and proposed evaluation criteria will be produced for the IGES/PDES Testing Methodology Committee,

2. Develop the IGES Application Protocols (IAAPD) activity initiated in FY 1988.

3. Work with Federal and industrial groups to develop initial conceptual models for two-dimensional drawings, and three-dimensional piping systems. The models will serve as the technical basis for two IGES AEC application protocols.

4. Develop methods for testing application protocols based on work described in 2 and 3 above and evaluate these methods using the IATF.

5. Analyze, extend, and integrate conceptual models being developed for the building industry in the PDES/STEP activity.

6. Develop a core semantic vocabulary for the specification of conceptual models based on work started in FY 1988.

MECHANICAL SYSTEMS AND CONTROLS

EMULATOR/TESTERS AND DIAGNOSTICS FOR BUILDING CONTROLS

Principal Investigator: Cheol Park
Building Environment Division
301.975.5879

Sponsors: National Institute of Standards and Technology and
Department of Energy

The objectives of this research are to develop: 1) real time model estimation algorithms, 2) an Emulator/Tester for evaluating Building Energy Management Systems (BEMS) performance, and 3) diagnostic procedures which will lead to improved operation of buildings and building systems.

The proper operation and control of buildings involves the complex interaction of numerous control loops and many pieces of equipment. It requires development of a new generation of computerized Building Energy Management Systems (BEMS) and test methods for evaluating their performance. These BEMS will be able to react to previous and existing conditions, predict future loads, usage patterns and weather, evaluate alternative control strategies, select the optimal control trajectory hours or days in advance, and provide the operator with real time diagnostic information when problems arise. Research is needed on: 1) how real time models, estimation and optimization procedures, statistical information, if-then rules, and meta-knowledge can be combined, 2) development of test procedures and instrumentation for evaluating the performance of current and future BEMS, and 3) creation of rule-based systems which will provide diagnostic information on BEMS and the building systems which they control.

As a part of a multi-year research effort, the BEMS Laboratory developed by CBT will be used to study how real time models, "tuning" and estimation techniques, optimal control theory, and rule based expert systems can be combined to evaluate control system performance, make control strategy decisions that optimize building performance, and advise the BEMS operator or building manager on building operations, diagnostics and maintenance requirements. A simplified, "on-line" model of a building will be used as the starting point for this research. Data collected from real buildings will be used to identify and develop performance parameters, procedures and algorithms for control system operation, maintenance or repair problems.

FY 1989 research concentrates in two areas:

1. Develop an Emulator/Tester for evaluating BEMS performance.

2. Create a prototype expert system for determining the performance of mechanical HVAC systems and controls and for producing diagnostic information for use by building operators.

The Emulator/Tester work will be performed in support of IEA's Annex 17. The integration of the optimization and diagnostic functions, with statistical information, to create a new generation of "intelligent" BEMS will be carried out in future fiscal years.

ADVANCED BUILDING SYSTEMS SIMULATION

Principal Investigator: George Walton
Building Environment Division
301.975.6421

Sponsor: Department of Energy

The objective of this project is to explore the development of a methodology for incorporating the short term, dynamic effects of local control loops in long term energy calculations in support of the future Energy Kernel System (EKS) being developed by Lawrence Berkeley Laboratory.

Lawrence Berkeley Laboratory has proposed an EKS based on a prototype software system called SPANK (Simulation Problem Analysis Kernel). Studies at CBT during FY 1988 using SPANK, HVACSIM+, ESP and other simulation programs has shown, that one of the biggest obstacles to the development of EKS is the problem of how to properly handle local control loop dynamics in long term energy simulations. These control loops tend to be highly nonlinear and incorporate dynamic effects which do not go away. Attempts to freeze state variables as they reach steady state conditions and remove them from the simulation, such as was employed in the HVACSIM+ program, have generally been unsuccessful. What is needed is some method for incorporating the effect of these short term dynamics in long term, less dynamic variables which can then be used in energy studies.

Various types of local control loops commonly encountered in building systems will be simulated using the HVACSIM+ program, TRNSYS, or other simulation tools capable of handling sets of highly nonlinear differential equation. Studies are being conducted to determine the effect of typical variations in state variables, such as loads, temperatures, flow rates, control parameters, etc., on control loop performance as it effects energy consumption. Simulation experiments will be conducted to try to determine if transfer functions, response factors or some other simplified method can be developed to capture the effect of local loop dynamics on building system energy consumption. If successful, comparison studies will be made between energy simulation incorporating the simplified method and detailed simulations run on a short time step to account for both short and long term dynamics.

COMMUNICATION PROTOCOLS FOR BUILDING CONTROLS

Principal Investigator: Steve Bushby
Building Environment Division
301.975.5873

Sponsor: National Institute of Standards and Technology

The objectives of this project are to: 1) expand CBT's Building Management and Control Systems (BMCS) Laboratory to include a new BMCS Communication Protocols Laboratory and 2) perform research that will assist the building industry in the development, evaluation, and testing of Communication Protocol Standards for the open exchange of information between equipment from different control vendors and between different levels of control in both hierarchical and distributed building management systems.

Over the last 15 years, automatic control systems in buildings have changed from predominately pneumatic control systems to supervisory Energy Management and Control Systems (EMCS) to distributed direct digital control or DDC systems. Recently, the development of local area networks has now made it possible to distribute "intelligence" throughout a building with more of it being placed at both the highest and lowest levels. In the future, integrated building services, combining EMCS, fire detection, security, data processing and communications, are likely to be increasingly in demand due to their potential to reduce first costs, simplify maintenance, and make operator training easier and quicker.

EMCS and DDC systems use proprietary communication protocols which prevent systems supplied by different manufacturers from communicating with each other. This has resulted in "captive customers" who, upon buying a control system, are unable to upgrade or expand it without going back to the same manufacturer. This lack of communication capability between control systems made by different manufacturers also prevents the building owner from obtaining the most capable building service by not allowing him to choose, regardless of the manufacturer, the best EMCS system, the best digital controllers, the best security system, the best fire detection system, or the best telecommunications system.

To help the private sector to develop standard communication protocols for the control of building services, CBT has established a BMCS Communication Protocols Laboratory. This Laboratory will be used in a multi-year research effort to:

1. Assist ASHRAE, IBI, and the building industry develop standard communication protocols for exchanging building service information between different vendor systems and between different levels of intra-system communication.

2. Provide testing and evaluation facilities for use by CBT and industry for studying different protocols and for determining compliance of vendors' equipment to proposed or finalized standards.

3. Develop and verify "reference implementations" of all proposed and finalized protocol standards. Develop procedures for performance and compliance testing.

4. Develop Emulator/Testers to facilitate protocol evaluation at each level of system communication and to serve as diagnostic tools for trouble shooting and assigning responsibility in the case of integrated systems provided by multiple vendors.

5. Develop guide specifications, test methods and diagnostic procedures for evaluating the performance of complex integrated hardware-software systems. This is especially important for systems involving life safety where reliability and response under adverse conditions become critical.

6. Conduct research which will lead to a new generation of tools for designing and evaluating building communication systems encompassing integrated services.

CBT will purchase and assemble communication networks with different types of physical media to interconnect different control systems with actual building equipment and system emulators. Research aimed at achieving the six objectives above will be performed. Private industry will be encouraged to aid in this research and to use CBT's facilities to evaluate the interconnectability of their systems to those of other manufacturers.

During FY 1989, CBT's research will concentrate on providing technical assistance to ASHRAE's SPC 135 committee through the evaluation of existing protocols, the development of an Emulator-Tester, and the analysis of formal techniques for generating reference implementations and conformance tests.

THE DESIGN, CONTROL, AND OPERATION OF VAV SYSTEMS FOR OPTIMIZING PERFORMANCE, AIR QUALITY, AND ENERGY CONSERVATION

Principal Investigator: James Y. Kao
Building Environment Division
301.975.5871

Sponsor: General Services Administration

The objectives of this research are to 1) evaluate and document how various VAV system design and control options affect system operation, building energy performance, and indoor air quality and 2) develop design and operating recommendations, design criteria, and guide specifications leading to improved VAV system performance and improved occupant comfort.

VAV air handling systems are recognized for their ability to conserve energy and to self-balance air distribution. These features coupled with installation cost advantages, have made them popular during the past decade. However, problems have been documented in their performance, e.g., poor air quality, control instability, system noise, inability to meet space loads, inadequate humidity control, poor distribution of ventilation air, and over/under pressurization. Most of these problems may be traced to air flow controls and VAV design issues. Poor system air control not only creates unhealthy and uncomfortable space conditions but is also energy wasteful.

This project is divided into two phases:

1. Perform a preliminary survey of VAV systems in 6 to 10 GSA buildings to determine the general characteristics of these systems and to identify problems associated with different designs and operating practices. This work will result in the selection of 3 to 5 VAV systems. The selection criteria will include VAV system type, supply, and return fan arrangement and control, the configuration of duct distribution system, and building characteristics.

2. Conduct a detailed study on the selected 3 to 5 VAV building systems to document operating problems and their causes and to develop recommendations which will improve the performance of existing and new VAV systems. During this phase, measurements of temperature, humidity, air quality, pressure, and noise data will be made on the selected systems.

COMMISSIONING OF MECHANICAL BUILDING SYSTEMS

Principal Investigator: James Y. Kao
Building Environment Division
301.975.5871

Sponsor: General Services Administration

The objective of this research is to revise GSA heating, ventilating, and air-conditioning (HVAC) guide specifications to incorporate commissioning requirements and to assist GSA on applying these commissioning procedures in actual buildings as pilot projects.

When new buildings are completed, they usually go through some sort of acceptance procedure. Depending upon the owners' desire and competence, the acceptance inspections vary from nonexistence to detailed testing. However, the performance of the building sub-systems and their energy consumption are contingent upon the sub-systems being installed, adjusted, and operated according to the intention of the designers. Some recent research at CBT and at the U.S. Army's Civil Engineering Research Laboratory (CERL) has revealed the poor performance of many HVAC control systems, even when the systems were newly installed.

The testing and balancing standards existing today for HVAC systems are inadequate for the monitoring necessary to assure long-term efficient system operations. Although energy monitoring and control systems (EMCS) can fulfill part of the performance monitoring objective, they are not designed for commissioning purposes and most buildings under GSA management today do not have such systems.

CBT has been developing commissioning procedures for GSA in the field of HVAC equipment and systems during the past two fiscal years. Inspection and testing procedures have been developed for chillers, boilers, air handling units, and other major equipment and systems commonly used in buildings. These procedures are intended to be used in GSA construction projects to alleviate the problems just described. However, two further efforts need to be undertaken in order to successfully apply these procedures in GSA building projects. During the various stages of building constructions, the project specifications and drawings are the main binding documents between the

government and the contractors. Yet, the current GSA guide specifications have very few requirements in field testing and do not reflect the requirements of commissioning procedures being developed by CBT for GSA. Secondly, the commissioning procedures which involve many different pieces of equipment and systems, and which may require the participation of various organizations (e.g. contractor, GSA, other government agencies, commissioning agent etc.) need a period of evaluation and refinement based upon their actual use in the field.

Part 1 is to assist GSA in the development of guide specifications for mechanical systems which will incorporate commissioning procedures. This work will be coordinated with the GSA contractor charged with the development of a new GSA guide specification in the area. NIST will recommend changes, review draft specifications, and revise the contractor's final guide specifications to insure that they reference the commissioning procedures. This will allow specification writers to use GSA official guidelines and their own judgement in deciding the level of commissioning required for individual projects.

Part 2 will be to monitor how the commissioning procedures are actually implemented on two or more GSA construction projects, and to revise the guide specifications and commissioning procedures as needed. NIST personnel will interpret the procedures, observe the commissioning process, provide independent evaluation, refine the commissioning procedures, and improve the guide specifications. Actual inspection and testing of equipment and systems will be carried out by the contractor and the GSA commissioning team, and the cost of the commissioning process will be included in the construction contract. The Specification Option sections will be revised as required to provide direction on what to include or not include for different levels of performance assurance. The construction projects to be monitored by NIST will be selected jointly by NIST and GSA to cover a variety of equipment and systems for commissioning. Since the lead time of construction projects is usually long, it is anticipated that the Part 2 phase of this work will involve a multiyear effort.

DIRECT DIGITAL CONTROL (DDC) BUILDING AUTOMATION SYSTEM (BAS) DESIGN CRITERIA AND GUIDE SPECIFICATION

Principal Investigator: James Y. Kao
Building Environment Division
301.975.5871

Sponsor: General Services Administration

The objective of this research is to develop DDC-based BAS design criteria and a construction guide specification to set a quality standard for GSA's future construction projects.

DDC-based BAS is a relatively new development to energy management and control of HVAC, fire safety, and building security equipment. DDC technology has the promise of offering more reliable, more versatile, and better performance than the conventional control systems. The advances in microelectronics and their declining costs enable DDC-based BAS to favorably compete with conventional systems in most buildings and result in dramatic changes in design concepts and operating practices. The HVAC industry has not yet developed a standard nor have government agencies established specifications which describe function and quality of such systems. Thus, it is important to develop design criteria and guidelines for this new technology.

During FY 1989 CBT is developing guide specifications and design criteria for BAS. Guide specifications will emphasize performance requirements and reflect the state-of-the-art systems. The specification will stress commissioning requirements so the detection and correction of problems after installation may be achieved. The design criteria will be included in the GSA/PBS's Quality Standards for Design and Construction. Following the same format of the Standards, it will have two

parts: GSA policy involving principles of system selection to be included in the main text of the Standard, with detailed information and requirements to be included in appendices as technical aids.

Currently, GSA has several buildings in various construction stages that contain BAS (Boston, Overland, Portland). To deduce possible application scenarios, CBT will investigate the BAS designs for: system selection, component selection, extent of BAS application, specification style and content. The investigations will result in recommended design criteria and specification content.

ASSESSMENT OF ROBOTICS FOR IMPROVED BUILDING OPERATION AND MAINTENANCE

Principal Investigator: James E. Hill
Building Environment Division
301.975.5851

Sponsor: General Services Administration

The objectives of this project are to: 1) complete an assessment of the potential for robotics to be used in the daily operation and maintenance of GSA buildings and 2) develop guidelines and performance criteria for the application of robotic devices to insure safe and reliable operation within a building.

The use of robotics in the factory environment has literally exploded within the past decade with over 16,000 robots in use in the United States and more than 30,000 in use worldwide. The large use is due to the ability of robotics to increase productivity in manufacturing.

The use of robotics outside the factory is now starting to receive attention. One significant area of new interest is in construction and large-scale assembly. The first international conference on construction robots was held in Pittsburgh in 1984. The Japanese are particularly active with more than 20 kinds of construction robots developed or under development.

GSA is currently interested in potential applications of robotics for operation and maintenance functions such as window cleaning, floor cleaning, trash compacting, and miscellaneous materials handling. Some of the robotic devices under development have potential for use in these applications. For example, the Takenaka Komuten Company of Japan has developed a self-climbing inspection machine that climbs a vertical wall checking the quality of tile attachment. At the Mechanical Engineering Laboratory in Tsukuba, a robot is being developed to move on a wall by means of suction legs to paint buildings. Carnegie-Mellon University has developed a spider-like robot to assist in the clean-up at the Three-Mile Island nuclear plant. A major American vacuum cleaner firm is now developing a robot for cleaning supermarket floors.

CBT has been making a comprehensive assessment of the possible application of robotic devices to a variety of building operation and maintenance functions. The assessment includes a state-of-the-art survey of robot technology with potential use in building operation and maintenance. CBT has used the expertise of the NIST's Center for Manufacturing Engineering and a private consultant with significant expertise in robotics in completing this task.

The assessment also includes an analysis of the operation and maintenance functions in a building identifying those that are potentially promising for robotic application. In general, the most promising ones are where the work must be done in dangerous or hazardous conditions (e.g., window cleaning on the exterior of multi-story buildings), where the environment is very structured and the tasks are repetitive, and/or where high quality and high skill levels are required and skilled workers are in short supply.

Potential barriers to the use of robotics within the buildings were determined. Recommendations are being made for changes in GSA practices so that GSA can take advantage of the coming age of robotics. A procedure for implementing robotic use for selected applications are being developed. If appropriate, criteria may also be developed to guide GSA in the application of robotic devices to insure functionality, accessibility, and safety in the operation of buildings.

TEST PROCEDURES FOR EQUIPMENT ENERGY USE

FURNACES, BOILERS AND HOUSEHOLD HEATER TEST PROCEDURES

Principal Investigator: George E. Kelly
Building Environment Division
301.975.5870

Sponsor: Department of Energy

The objective of this research is to provide equitable testing and rating procedures for determining the energy performance of central residential furnaces, boilers, and household heating equipment.

The Energy Policy and Conservation Act (P.L. 94-163) (EPCA), as amended, requires the Department of Energy (DOE) to prescribe test and rating procedures and minimum performance standards for various residential appliances. In addition, the 1987 amendments to EPCA require analysis of any test procedure amendments to determine their effect on minimum efficiency standards. DOE has, since 1975, relied on the National Institute of Standards and Technology (then the National Bureau of Standards) to assist in the development of the test and rating procedures.

Combination appliances are becoming increasingly common and new designs, which integrate the functions of space heating, space cooling, domestic hot water heating, and zoning, are likely to appear on the market in the near future. Test procedures for these new products do not exist. Simplified test procedures which are not excessively burdensome to manufacturers are to be developed for these products. While some experimental testing of new equipment and systems will always be necessary, relying solely on this method is impractical. Not only is experimental testing expensive and time consuming, but it does not allow the results to be easily generalized to different designs, operating conditions, or control strategies. What is needed is a comprehensive modeling methodology which can be used along with experimental verification to quickly and easily evaluate different equipment and system designs.

During FY 1989 CBT will use its HVAC Simulation Plus (HVACSIM$^+$) program as the basis for modeling the performance of new space heating and domestic hot water heating equipment appearing on the market, and, in particular, new integrated appliances.

In FY 1988, CBT developed HVACSIM$^+$ compatible component models for boilers, boilers equipped with tankless coils for domestic hot water heating, water storage tanks, water-to-water and water-to-air heat exchangers. Experimental studies were conducted as needed to verify these models and ensure that the results they gave were compatible with the existing DOE appliance test and rating procedures. In addition, the program was used to study 1) the effect of water draw schedule on boiler water heaters using tankless coils, 2) the effect of water and space heating loads on annual residential energy consumption and cost of operation.

In FY 1989 the work on integrated appliances will involve the following subtasks:

1. Complete the study on water/space heating combination appliances, including analysis of water heaters as space heaters and boilers as water heating combination appliances. Laboratory data on an actual water heater will be used to verify and/or refine the boiler model developed in FY 1988. Other topics to be covered include the effect of room temperature on standby losses, water draw patterns on boiler efficiency, combined water and space heating on efficiency, and the length of the heating and non-heating seasons on annual performance.

2. Identify method to determine combined annual efficiency and annual cost of operation of combination space heating/water heating products including identifying any changes needed in ASHRAE Standard 124.

3. Assist DOE in preparation of draft Federal Register Notice of proposed Rulemaking Concerning Furnace Test Procedures including evaluating adoption of the following ASHRAE Standards for inclusion in the DOE Test Procedures.
   - ASHRAE Standard 103 for Furnaces and Boilers
   - ASHRAE Standard 124 for Combination Space Heating Water Heating Boilers.

HEAT PUMP AND AIR CONDITIONER TEST PROCEDURES

Principal Investigator: Piotr Domanski
Building Environment Division
301.975.5877

Sponsor: Department of Energy

The objective of this project is to provide industry, via DOE, with an equitable testing and rating procedure for determining the seasonal energy performance of central residential air conditioners and heat pumps.

The Energy Policy and Conservation Act (P.L. 94-163) (EPCA), requires the Department of Energy (DOE) to prescribe test and rating procedures and minimum performance standards for various residential appliances. During the past 14 years, DOE has relied on CBT to assist them develop test and rating procedures.

During FY 1989 CBT will be performing two tasks.

1. Developing a Rating Procedure for Mixed Systems. CBT is completing a rating procedure for mixed systems operating in the cooling mode. This work will be followed by a rating procedure for mixed systems operating in the heating mode. Impacts of individual components on the heating performance will be evaluated, appropriate correlations will be developed, and methodologies for evaluation of performance of exchanged components will be derived. Laboratory verification of the procedure will be performed.

   CBT is developing methods to predict refrigerant mass flow rate through a short tube restrictor with two-phase refrigerant entering up the tube (most probable condition in the heating mode). Short tube restrictor charts for predicting refrigerant mass flow rate will be generated. These charts will have applications independent of the procedure.

2. ASHRAE Standard Activities in Support of DOE Procedures. For many years CBT has participated in ASHRAE's Standard 116 on evaluation of the seasonal performance of air conditioners and heat pumps. Our technical involvement consists of formulating chapters of the standard which address variable speed systems. This standard, when completed, will be evaluated for possible adoption by DOE.

A RATING METHOD FOR INTEGRATED HEAT PUMP/WATER HEATERS

Principal Investigator: Brian P. Dougherty
Building Environment Division
301.975.6396

Sponsors: Department of Energy and
Electric Power Research Institute

The objective of this project is to provide industry with equitable testing and rating procedures to determine the energy performance of integrated heat pump/water heaters.

The Energy Policy and Conservation Act (P.L. 94-163) (EPCA), requires the Department of Energy (DOE) to prescribe test and rating procedures and minimum performance standards for various residential appliances. In addition, the 1987 amendments to EPCA require analysis of any test procedure amendments to determine their effect on minimum efficiency standards. DOE has, since 1975, relied on CBT to assist in the development of the test and rating procedures.

CBT continues to develop a rating method for integrated heat pump/water heating appliances. The rating method will detail the calculation procedure for predicting seasonal performance. During FY 1989 CBT will be performing four tasks.

In the first task, we are determining the minimum amount of data points required and the interpolation method used, e.g., first or second order, for developing a performance map. Performance maps will be generated for different data sets. The sets will vary in both the number of data points and the location of the points, the latter corresponding to the choice of operating conditions. The generated performance maps will be used within the calculation procedure specified within the rating method. The calculated seasonal performance factors (SEER, HSPF) will be used in choosing a suitable data set and interpolation method.

For the second task, we will be specifying input parameters such as a meteorological data set, a hot water draw schedule, the volume of daily hot water usage, and a water main temperature profile to be used within the testing and rating procedure. Within the existing rating procedures for heat pumps, bin data is specified for calculating SEER and HSPF (for the latter, data corresponding to six major climatic regions are given). Bin data grouped according to intervals of the day, e.g., a set for 7 a.m. to 10 a.m., a set for 5 p.m. to 11 p.m., and a set for all other hours of the day, or possibly hourly data for a full year will be specified for rating purposes. The effects of the meteorological data and the other above water heating related factors on seasonal performance will be evaluated using the heat pump, hourly simulation program.

The third task involves the work to qualify the extent to which the controls of the integrated heat pump/water heating appliance must be known. Information such as the criterion for water heating, i.e., at what water temperatures should heating begin and end and the speed at which the compressor operates while in a water heating only mode, i.e., at maximum or at some "optimal" level, are among the control strategy variables that may have to be determined. If for proprietary reasons, data on a particular facet of the control strategy is not available, laboratory methods for deciphering the needed information will be investigated in another study.

The fourth task is a synthesis of the prior work to yield a preliminary, yet comprehensive testing and rating procedure.

WATER HEATER TEST PROCEDURES

Principal Investigator: A. Hunter Fanney
Building Environment Division
301.975-5864

Sponsor: Department of Energy

The objective of this project is to provide industry with an equitable testing and rating procedure for determining the seasonal energy performance of conventional water heaters.

The Energy Policy and Conservation Act (P.L. 94-163) (EPCA), requires the Department of Energy (DOE) to prescribe test and rating procedures and minimum performance standards for various residential appliances. In addition, the 1987 amendments to EPCA require analysis of any test procedure amendments to determine their effect on minimum efficiency standards. DOE has, since 1975, relied on CBT to assist in the development of the test and rating procedures. CBT's technical assistance includes:

A. Resolving questions which may arise as a result of comments received concerning the proposed test procedure developed by CBT, and changes in the minimum energy efficiency standards for oil, gas, and electric storage-type water heaters.

B. Developing a test procedure for "off-peak" water heaters. The test procedure is based on public comments, the experiences of utilities which have "off-peak" water heaters within their service territory, and experiments conducted at CBT.

During FY 1989 the following improvements will be made:

1. The Cuttler-Hammer Calorimeter will be relocated into our laboratory building. This will eliminate the uncertainty which is associated with the current situation where the measurement of the heating value of natural gas is located several hours away from the laboratory.

2. A menu program will be written to allow the user to easily select the software required for a given test and type of water heater.

3. The ability to test oil storage water heaters and instantaneous gas water heating will be added to the hot water laboratory.

LIGHTING RESEARCH

OFFICE LIGHTING AND ENVIRONMENT EVALUATION

Principal Investigator: Belinda L. Collins
Building Environment Division
301.975.6456

Sponsor: U.S. Army Electronics Materiel Readiness Activity

The purpose of this project is to complete a comprehensive, integrated evaluation of the lighting and other environmental conditions in Army Electronics Materiel Readiness Activity (USAEMRA) facilities.

Most of the military and civilian employees of USAEMRA are required to work in environments characterized by windowless spaces, using highly automated equipment, and performing demanding tasks. These conditions may affect staff productivity and contribute to employee complaints about lighting, thermal conditions, noise, air quality, and lack of view to the outside.

CBT is performing a comprehensive evaluation of lighting conditions such as luminance, illuminance, contrast, color, contrast rendering factors, glare and of other factors such as noise and temperature. Indoor air quality assessments will be made along with a study of the occupants' reaction to the spaces.

The specific tasks are:

1. Consult with architectural and engineering personnel involved in facility design. Review specifications for facility redesign as appropriate.

2. Test and refine data collection methodologies currently being developed for INSCOM for use in EMRA facilities.

3. Conduct environmental studies, including detailed physical measurements of lighting and other environmental conditions at the Vint Hill station.

4. Evaluate results of the environmental studies and provide suggestions for facility design as appropriate.

5. Conduct second assessment of one building after planned changes in facilities are made.

6. Develop design guidelines for future facility design and renovation.

EVALUATION OF COMMERCIAL OFFICE LIGHTING

Principal Investigator: Belinda L. Collins
Building Environment Division
301.975.6455

Sponsor: Department of Energy

The objective of the project is a detailed multivariate analysis of the data obtained in the post-occupancy evaluation (POE) project conducted by the AIA Research Foundation; specifically, exploring detailed relationships between the physical measurement data for the different lighting systems and the occupant assessment.

Current building energy conservation standards include lighting unit power densities that are based solely on professional judgement. Considerable difference of opinion exists about what the proper levels should be, while even further differences exist about the potential effect of those criteria on lighting quality in work spaces. Between 1984 and 1986, DOE funded a project in which extensive data was collected on lighting, unit power density measures, and occupant evaluation of 1217 workstations in commercial office buildings. In 1987, these data were developed into a more comprehensive database allowing initial evaluation of the data and providing a basis for the present detailed evaluation.

CBT is providing technical supervision for the LRI Research Associate, coordination with the University of Michigan, and developing a comprehensive overview of the project results. (Co-funding for these efforts is provided by the New York State Energy Research and Development Authority (NYSERDA), the Electric Power Research Institute (EPRI), and the Lighting Research Institute.) This work includes an analysis of data from the database on user responses to the lighting conditions for the physical measurement data. The emphasis is on integrating the photometric and other data for the seven different lighting systems (in 13 buildings surveyed) with the human response data, and making necessary statistical comparisons to gain insight into the lighting variables that affect human perception of lighting systems. The LPD values are being examined to determine their relation to the lighting system data and the user response data. Analysis of these data will provide information on some of the lighting design factors that affect lighting quality and quantity. A summary report will be prepared which discusses the impact of the physical variations in lighting conditions on the user response and perceptions.

PHOTOMETRIC AND THERMAL PROPERTIES OF LIGHTING SYSTEMS

Principal Investigator: Stephen J. Treado
Building Environment Division
301.975.6444

Sponsor: National Institute of Standards and Technology

The purpose of this research is to develop metrics and procedures for evaluating the performance of lighting systems in building spaces, and assisting in their effective design.

The Illumination Engineering Society has repeatedly indicated the need for sound techniques for measuring and predicting lighting quality. In addition, a recent statement by the Lighting Research Institute indicates that measurement of the near-field effects of lighting fixtures and their interaction with both the thermal and luminous environment is a critical research need in the lighting community. Of particular concern are the luminaires recommended for use with VDT displays. The dramatically different configurations of parabolic and acrylic lens diffusers significantly influence lamp wall temperature and thus both the luminous efficacy and thermal performance of the lamp. These in turn affect the luminous environment—luminance, contrast, spectral composition, glare, etc.—of the visual task. In addition, LRI also recognizes a conflict in recommended criteria for ceiling mounted luminaires for VDT terminals. The new ANSI standard conflicts with the CIE standard both in recommended minimum luminance and minimum shielding angle, and thus light quality. Accurate specification of the luminance and contrast for visual tasks (both paper and VDT) as a function of the luminaire is the initial step in developing effective lighting quality metrics.

During FY 1989 CBT is performing full-scale measurements and detailed computer modeling to assess and predict the luminous environment and thermal performance of various lighting system designs. The effect of lighting system design on illumination quantity and quality, task visibility, and glare conditions are being examined. The detailed luminous environment in office-type spaces are being evaluated through a combination of full-scale measurements in the CBT Light/HVAC test facility, field measurements in real buildings supporting laboratory measurements, and related computer simulations. Procedures for measuring, characterizing, and modeling the detailed photometric

properties of the luminaire and its surround including luminance distribution task visibility and glare conditions will be developed and demonstrated for typical lighting system designs and task types, including paper and VDT tasks.

In FY 1989, near-field photometric measurements will be used to support the development of information needed for micro-modeling of the luminaire, to form the basis of the computational procedure for determining task visibility as a function of lighting system design. The luminaire micro-model is being developed and incorporated into the existing room/lighting model, which treats each luminaire as a point source. This improvement in the model will allow assessment of the effects of luminaire size, and location and type, on task visibility. The model will be validated using measured data. Procedures will be developed for measuring and summarizing the impact of luminance distributions in office-type environments. The research literature on measurement of the impact of variation in luminance, glare, CRF, and veiling reflections will be reviewed to provide guidance in developing a summary metric for evaluating luminance distributions. This metric will be based on the measurement data, insights from the literature, cooperation with NRC—Canada and BRE—UK, and a statistical analysis of field conditions. Both ambient and task lighting systems will be evaluated.

ASSESSMENT OF HIGH TECHNOLOGY OFFICE DESIGN ON PRODUCTIVITY

Principal Investigator: Arthur Rubin
Building Environment Division
301.975.6445

Sponsor: General Services Administration

The purposes of this research are to 1) develop design criteria for automated offices, based on understanding the relationship of environmental conditions (lighting, heating, noise, air quality), systems furniture and building technologies, on productivity and 2) provide input (data, procedures and guidance) to GSA's Handbook, *Quality Standards for Design and Construction*, describing methods of enhancing performance through design.

Automation is introduced into offices to enhance productivity. Yet, it is unclear whether this purpose is being achieved. Advanced systems are placed in settings where lighting and other environmental conditions were designed for paper tasks, resulting in many complaints about office conditions. This has led researchers, designers and using organizations to seek a better understanding of the relationships between office environmental conditions, furnishings, and other design features on office worker productivity, primarily on professionals and managers.

During FY 1989 CBT is developing, testing, and refining tools for use by Federal decisionmakers to make more informed decisions about workplace designs that best accommodate technological advances, thereby improving office worker productivity.

The examination of the design impact on productivity is being performed in new construction projects, such as the Portland Federal Building and the Federal Records Center in Overland, MO. The systems and features of these buildings, including systems furniture, directed toward the development of "high quality work places" are believed to offer enhanced capabilities over conventional design and construction approaches.

Among the issues being explored are:

a. The contribution of particular environmental conditions such as lighting and air quality, to productivity.
b. The interrelationships of features such as lighting, noise, thermal, air quality and ventilation conditions to productivity; i.e. the extent to which contributions are additive.
c. Determining measurement approaches to productivity which are viable; e.g. useful immediately, and those requiring additional work before they can be used.
d. The sensitivity of various measures, or those which can be developed, e.g. time and costs to complete important tasks.
e. The evaluation of "high quality" design and environmental features, such as systems furniture, with respect to enhancing office productivity.
f. The relationships between space utilization and office design effectiveness.

Design, environmental and productivity data are being collected in several different ways:

1. An extensive literature search was completed to determine the "state of the art" of productivity measurement. These data were supplemented by more recent surveys and design documentation; e.g. plans for Federal buildings, Steelcase 1987 office survey.

2. A questionnaire survey was prepared and administered to approximately 200 employees of the Bonneville Power Administration (BPA) prior to move-in to the new Federal building in Portland, OR. A follow-up survey, after occupancy, was administered during the summer of 1988, for initial information after move-in. Pre and post move-in data were analyzed and compared. The data cover design issues, the environment, and their impact on productivity over time.

3. Physical measurements of workspace characteristics such as space and furnishings, lighting, noise, air quality and thermal conditions were made in conjunction with other data collection.

4. In-depth interviews were conducted with selected organizational units and individuals of BPA and other Federal agencies to identify potential activities to measure as "productivity targets"; i.e. those amenable to productivity measures, important, and likely to influenced by design.

5. Records associated with design and productivity were identified and analyzed in conjunction with BPA; e.g. time and costs associated with workstation movement before and after move-in; usage of advanced telecommunications capabilities such as call forwarding. These are expected to contribute to developing indices of productivity.

6. Questionnaire surveys of several Federal buildings with new interior designs featuring "systems" furniture were conducted, to supplement the questionnaire findings in the new Portland Federal Building.

7. Initial measurement techniques were tested in the pre-move and are being refined during subsequent study phases of the Portland Federal Building and in the Federal buildings in Overland, MO and Long Beach, CA. The first productivity measures focused on lighting, furniture systems, "high quality office," and space flexibility issues.

8. To obtain information about the private sectors' design experiences with systems furniture, a survey of the AIA Corporate Architect Committee was conducted. These data are being supplemented by information from BOMA and IFMA (International Facility Management Association), concerned with design and space usage.

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The Center for Building Technology (CBT) of the National Institute of Standards and Technology (NIST) is the national building research laboratory. CBT works cooperatively with other organizations, private and public, to improve building practices. It conducts laboratory, field, and analytical research to predict, measure, and test the performance of building materials, components, systems, and practices. CBT's technologies are widely used in the building industry and adopted by governmental and private organizations that have standards and codes responsibilities. This report summarizes the research underway in the Center during 1989.

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