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BUILDING TECHNOLOGY PROJECT SUMMARIES 1990

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U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
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FOREWORD

Construction is one of the Nation's largest industries. In 1989, new construction put in place amounted to $418 billion, about nine percent of the U.S. Gross National Product. The quality of constructed facilities directly affects the productivity of the U.S. building industry and affects the safety and quality of life of all building users. 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 building technology measurement laboratory. CBT increases the usefulness, safety, and economy of buildings, and enhances the international competitiveness of U.S. building services and products, through the advancement of building technology. CBT produces performance prediction and measurement technologies that are relied upon by private industry, state and local governments, and those Federal agencies with building-related programs to provide them technical bases for cost-effective construction decisions. CBT conducts laboratory, field, and analytical research to develop technologies for predicting, measuring, and testing the performance of building materials, components, systems, and practices. CBT's 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, such as the Ashland Oil Storage Tank collapse near Pittsburgh, PA, in 1988, and to promptly and publicly report their causes to help preclude recurrences.

CBT is assigned the role, under the National Earthquake Hazards Reduction Program, to provide research and technical support for developing seismic design and construction practices. For example, CBT's post disaster investigation of the California Loma Prieta earthquake of 17 October 1989, provided the basis for recommendations to improve design and construction practices for building and lifeline structures and to mitigate damage to existing structures in future earthquakes.

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's staff totals about 120; 80 are professionals, 40 hold doctorates, and 30 are registered engineers. About 60 research associates from U.S. industry, guest researchers from foreign laboratories, visiting scholars from universities, and students complemented CBT's staff during 1989.

CBT's facilities are located in Gaithersburg, MD, about 40 km (25 mi) northwest of Washington, DC. Its unique and comprehensive laboratories include: a computer controlled six-degree-of-freedom structural testing facility, a 54 MN (12 M lb) capacity universal structural testing machine and a 14 m (45 ft) high reaction buttress equipped with a horizontal ram of 4.5 MN (1 M lb) capacity, seven environmental chambers including a $15 \times 13 \times 9.5$ meter ($48 \times 40 \times 30$ ft) high chamber for evaluating the thermal performance of full-scale buildings, a 1-meter guarded hot-plate for measuring thermal conductivity, a calibrated hot-box with open test section of 3×4.6 meter (10×14 ft), 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 1990 is about $10 million. Approximately 40 percent comes from direct appropriations from Congress; the remainder from other Federal agencies.

This report summarizes CBT's research for 1990; it is arranged by research programs. Each summary lists the project title, its activities, the CBT point of contact, and sponsor.

Contents

STRUCTURAL PERFORMANCE

NONLINEAR/CHAOTIC BEHAVIOR OF DYNAMIC STRUCTURAL SYSTEMS

Principal Investigator: Emil Simiu
Structures Division
301.975.6076

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop a computational and experimental basis for the study of nonlinear and chaotic phenomena in structural engineering.

PROBLEM Engineering systems exhibiting nonlinear behavior and subjected to active controls 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.

APPROACH CBT is constructing nonlinear structural device (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 and experimental study of dynamic behavior of forced and autonomous aeroelastic oscillators will be performed.

RESULTS Results of past year's efforts include:

Burnes, T. J., Cook, Graham R., and Simiu, Emil, "Chaotic Behavior of Galloping Oscillators," *Recent Advances in Wind Engineering*, T. F. Sun (ed.), Vol. I, pp. 348–355, International Academic Publishers/Pergamon Press, 1989.

Cook, Graham R. and Simiu, Emil, "Chaotic Motion of Forced and Coupled Galloping Oscillators," *Proceedings of Sixth U.S. National Conference on Wind Engineering*, Vol. II, March 8–10, 1989, University of Houston, A. Kareem (ed.), pp. C7.1–11, 1989.

Simiu, Emil and Cook, Graham R., "Periodic Quasiperiodic and Chaotic Rotation of Forced Autonomous Galloping Oscillators," *Proceedings of Eighth Colloquium on Industrial Aerodynamics*, Aachen, Sept. 4–7, 1989, Part 1, Fachbochschule, Aachen, FRG, 1989.

Cook, Graham R. and Simiu, Emil, *Periodic and Chaotic Motions of a Modified Stoker Column—Experimental and Numerical Results*, NIST Bldg. Sci. Ser. 168, February 1990.

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

OBJECTIVE To study various aspects of the dynamic behavior of compliant structures identify and reduce uncertainties and risks associated with dynamic behavior.

PROBLEM 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.

APPROACH CBT is investigating fundamental aspects of chaotic behavior of compliant structural assemblies subjected to fluctuating excitations of a mechanical and/or hydroelastic nature. Findings will be used by MMS to establish research needs for the reliability of compliant offshore structures and to verify reliability approaches implicit in the design of these structures. The research also will assist MMS with a technical basis to ensure acceptable risks for safe operation of compliant offshore structures.

RESULTS Results of past year's efforts include:

Burnes, T. J., Cook, Graham R., and Simiu, Emil, "Chaotic Behavior of Galloping Oscillators," *Recent Advances in Wind Engineering*, T. F. Sun (ed.), Vol. I, pp. 348–355, International Academic Publishers/Pergamon Press, 1989.

Cook, Graham R. and Simiu, Emil, "Chaotic Motion of Forced and Coupled Galloping Oscillators," *Proceedings of Sixth U.S. National Conference on Wind Engineering*, Vol. II, March 8–10, 1989, University of Houston, A. Kareem (ed.), pp. C7.1–11, 1989.

Simiu, Emil and Cook, Graham R., "Periodic Quasiperiodic and Chaotic Rotation of Forced Autonomous Galloping Oscillators," *Proceedings of Eighth Colloquium on Industrial Aerodynamics*, Aachen, Sept. 4–7, 1989, Part 1, Fachbochschule, Aachen, FRG, 1989.

Cook, Graham R. and Simiu, Emil, *Periodic and Chaotic Motions of a Modified Stoker Column—Experimental and Numerical Results*, NIST Bldg. Sci. Ser. 168, February 1990.

DYNAMIC CHARACTERIZATION OF STRUCTURAL NETWORKS

Principal Investigator: William C. Stone
Structures Division
301.975.6075

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop a computer-controlled high-speed "intelligent" loading system which can be fired in a manner to reproduce the requisite pulses (applied force-time histories) to within the accuracy needed.

PROBLEM Structural systems are being developed for which the dynamic response must be determined with high accuracy. 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 has shown, it is advantageous to characterize these systems dynamically by the matrix of their dynamic Green's functions (i.e., the response of the various coordinates to unit impulse excitations). In practice, especially for purposes of control 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 other than impulsive are mathematically ill-posed.

Prior CBT work was successful in developing computational capabilities which, if the physical structure could be pulsed with a force-time history replicating that of an analytical defined inverse Gaussian pulse, would permit highly accurate identification of dynamic response characteristics for structures of the type described above. This work is aimed at developing a such an experimental loading system.

APPROACH Because of the need for autonomous force application (without the benefit of a reaction surface) and substantial force magnitude, load will be produced by means of mass expulsion. CBT will address technological problems including developing: 1) onboard microcontroller subsystem, and its associated programming; 2) a high-speed valve system driven by electrostrictive stacks; and 3) a high-speed pulse-power subsystem to drive the electrostrictive elements.

Initial tests will be performed with one-dimensional excitation forces being applied to a candidate test structure with resultant three-dimensional accelerations being recorded.

This research will be useful to Federal and private agencies concerned with accurate identification of dynamic properties of special structural systems. Potential practical applications include, control of flexible robots and the identification of flutter characteristics for experimental aircraft. Potential spinoffs include the development of nondestructive testing methods for such members as, e.g., the tethers of deep water compliant offshore platforms, and for active control and damping of dynamic structural vibrations, as e.g., docking loads on orbiting structures and seismic loads on buildings.

CBT will publish a report describing the development of the high-speed single-channel valve for ASCE Journal of Aerospace Engineering and publish a paper

for AIAA Conference on Structures and Dynamics on the results of the parametric experiments. An application for a U.S. patent for the loading system will be submitted and a laboratory prototype hardware unit will be constructed during 1990.

RESULTS Results of past year's efforts include:

Created computer program THRUSTER for CBT's interactive graphics program resulting in a disk file of the required analog output voltages from the microcontroller subsystem needed to produce the "intelligent" load profile. The results of the analysis led to the solution (hardware components) to amplify the displacements from the piezoelectric actuator to achieve the desired levels of thrust. The components are being detailed for fabrication.

STRENGTHENING METHODOLOGIES FOR STRUCTURAL SYSTEMS AND MEMBERS

Principal Investigator: Mark Johnson
Structures Division
301.975.6067

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop design guidelines to predict the performance of structural systems and elements after strengthening.

PROBLEM Many existing structures are considered deficient when evaluated by the current building codes and standards. This deficiency applies to a) structures which were designed and constructed in compliance with older building codes which are no longer applicable, or b) structures in which deterioration occurred during its service life. Various strengthening techniques have been used to improve lateral strength and ductility of structures in high-risk seismic regions. However, there are no established criteria or design guidelines to assess the overall capacity of strengthened reinforced concrete structures. This research will develop the technical information needed to establish design guidelines which can be used as criteria for predicting the performance of reinforced concrete structures after strengthening.

APPROACH The problem will be approached in two tasks:

1. Study the strength and deformation behavior of single mechanical anchors subjected to combined shear and tension loading in uncracked concrete.

2. Evaluate the effectiveness of anchors for attaching infilled walls and/or steel bracing to strengthen reinforced concrete frames. The evaluation of anchor needs and the knowledge of the behavior of anchors will be used to establish criteria to predict the strength and behavior of strengthened reinforced concrete frames.

A report on the behavior of anchors under combined shear and tension loading will be published in 1990.

RESULTS Results of past year's efforts include:

Johnson, Mark K. and Lew, H. S., *Experimental Study of Post-Installed Anchors Under Combined Shear and Tension Loading*, manuscript in press.

NDT METHODS FOR CONCRETE

Principal Investigator: Nicholas J. Carino
Structures Division
301.975.6063

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop a draft standard on the use of the impact-echo method and investigate the use of neural networks for interpretation of impact-echo results.

PROBLEM In 1983 this project was initiated to develop the basis for a test method, based on stress-wave propagation, to locate internal defects in concrete structures and other heterogeneous construction materials. The impact-echo method has been developed, and experimental and analytical studies have demonstrated the applicability of the technique for detecting a variety of defects in concrete. At this point in time a method can be put into practical application provided a standard test procedure is adopted.

One of the difficulties in any test method based on wave propagation is the interpretation of the test results. It would be desirable to automate the signal interpretation procedure. Recently, software has been made available that uses the principle of neural networks for pattern recognition. It should be determined whether this approach is suitable for the analysis of impact-echo test results.

APPROACH Based on the knowledge and experience gained from past research, a practical guide on the use of the impact-echo method is being prepared. The guide will be the source document for preparing a draft ASTM standard for this method.

The neural-network approach attempts to simulate pattern recognition as learned by humans. A neural-network program gains the "intelligence" to recognize patterns by a training process analogous to human learning. In applying this technique to impact-echo testing one must "train" the program to distinguish between flawed and unflawed concrete.

This research will examine the possible approaches for training a neural-network program so that it will be able to make reliable decisions about the presence of flaws in the test object. Available software will be used for this work.

Reports on Impact-Echo, Maturity Methods, and Statistical Analysis of In-Place Tests for RILEM Workshop on Testing During Construction, The Application of the Impact-Echo Method and Draft Standard Test Method for ASTM and on Feasibility of Neural Networks for Interpretation of Impact-Echo Test Results will be published during 1990.

RESULTS Results of past year's efforts include:

Sansalone, Mary and Carino, Nicholas, J., "Laboratory and Field Studies of the Impact-Echo Method for Flaw Detection in Concrete," in *ACI Special Publication* SP 112, Detroit, MI, pp. 1–20, 1988.

Sansalone, Mary and Carino, Nicholas, J., "Detecting Delaminations in Concrete Slabs With and Without Overlays Using the Impact-Echo Method," *ACI Materials Journal*, Volume 86, No. 2, pp. 175–184, March-April 1989.

Carino, Nicholas, J. and Tank, R. C., "Statistical Characteristics of New Pin Penetration Test," *ASTM Journal of Cement, Concrete, and Aggregates*, Winter 1989, Volume 11, No. 2, pp. 100–108.

Sansalone, Mary and Carino, Nicholas, J., "Finite Element Studies of the Impact-Echo Response of Layered Plates Containing Flaws," *International Advances in Nondestructive Testing,* Volume 15, Gordon and Breach.

TECHNICAL REVIEW AND MONITORING OF STRUCTURAL INVESTIGATION OF SILVER SPRING METRO CENTER I

Principal Investigator: Nicholas J. Carino
Structures Division
301.975.6063

Sponsor: National Oceanic and Atmospheric Administration

OBJECTIVE To provide a technical review and monitor the structural investigation performed by GSA at the Silver Spring Metro Center I Office Building occupied by NOAA personnel.

PROBLEM In March 1989, difficulties were encountered while trying to install modular furniture in the new Silver Spring Metro Center I Office Building. Investigations by GSA engineers revealed excessive cracking and deflections in some of the floor slabs. Subsequent reviews of the structural drawings and original design calculations revealed errors in the placement of certain steel reinforcing bars. On April 7, 1989, the Department of Commerce (DOC) Office of the Inspector General requested that CBT personnel inspect the building for normal business occupation. GSA initiated an investigation to assess the condition of the building and develop a method for strengthening the questionable bays. NIST offered its services to DOC to monitor and review the subsequent work to correct structural deficiencies.

APPROACH CBT reviewed the structural investigation and the design of the remedial measures to bring the building to its intended design capacity. CBT reviewed the results of the structural investigation and reviewed and commented on the proposed remedial measures. A final report will be submitted on the structural investigation and the resolutions of questions about the remedial measure.

RESULTS Results of past year's efforts include:

This work helped GSA plan an independent structural investigation performed on behalf of GSA by a private consultant.

SHOCK WAVE ABSORBING STRUCTURES

Principal Investigator: Felix Yokel
Structures Division
301.975.6065

Sponsor: Construction Engineering Research Laboratory

OBJECTIVE To develop criteria for a structural enclosure from which tank artillery can be fired and which will attenuate the noise generated.

PROBLEM Military training exercises generate considerable noise; there is a need for acoustic attenuation to reduce noise on populations in the vicinity of these bases. The noise generated by artillery is of particular concern because its acoustic frequency is in the range of 30 Hz; attenuation by energy absorbing materials tends to be ineffective.

APPROACH CBT is studying information from existing blast studies (Project Eskimo), preparing mathematical modeling, identifying available structural hardware, and investi gating suitable sites available for the project. CBT is performing an analysis to estimate the response of enclosures to absorb the anticipated shock wave and to dissipate energy. The studies involve mathematical modeling linked with small scale physical model tests.

A full-scale test structure will be erected on a military base for data collection and development of construction specifications for construction of shock wave absorbing structures. A report on the project will be published in 1990.

RESULTS New project 1990.

NATIONAL ASSETS PROTECTION STANDARDS

Principal Investigator: Robert Dikkers
Structures Division
301.975.5863

Sponsor: Federal Emergency Management Agency

OBJECTIVE To develop the technical bases for developing national standards for physical security and emergency preparedness measures.

PROBLEM Part 1 of Executive Order 12656 of November 18, 1988, requires FEMA to assist the National Security Council in implementing national security emergency preparedness policy and gives FEMA the lead responsibility for coordinating and supporting the initiation, development, and implementation of national security emergency preparedness programs and plans among the Federal Departments and Agencies.

Proposed Part 335, Title 44 Code of Federal Regulations (Federal Register, Vol. 54, No. 150, p. 32359–32361, August 7, 1989), issued by FEMA, provides for the protection of essential resources and facilities which are part of the national secu-

rity emergency preparedness policy and provides guidance to the Federal departments and agencies in its implementation. Also, the plans and strategies developed will be coordinated with FEMA.

APPROACH

During FY 1990, CBT working with other Federal agencies and private sector organizations will collect existing guidelines, standards, and reports pertinent to this study. Based on information and discussions with officials from Federal agencies and private sector organizations, and consultations with physical security experts and standards development organizations, CBT will develop plans and strategies for needed physical security standards. A report will be published on the development of standards for the protection of national resources and facilities in early 1991.

RESULTS

New project 1990.

EARTHQUAKE ENGINEERING

MEASUREMENT OF STRUCTURAL RESPONSE CHARACTERISTICS OF FULL-SCALE BUILDINGS

Principal Investigator: Richard D. Marshall
Structures Division
301.975.6071

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop a standard test method for measuring structural response characteristics of full-scale buildings.

PROBLEM Reliable estimates of modal frequencies, stiffness and damping of structural systems are essential to predict structural response under loading conditions associated with serviceability and structural safety. In the case of structural renovation or retrofit for hazard reduction, or for accommodating changing service loads, it is necessary that any retrofit scheme be statically and dynamically compatible with the existing structure. Although response characteristics of isolated structural components usually can be predicted with acceptable accuracy from simple models, this is not the case for complete structures where primary and secondary systems can interact in complex ways.

Numerous studies of structural response have been carried out on tall buildings, long-span bridges, and large dams. The most widely used techniques rely on ambient vibrations for excitation or, in certain cases, one or more mechanical shakers to excite specific modes of vibration. Generally, these measurements suggest a strong dependence of response parameters on displacement amplitude, thus raising questions about the validity and proper interpretation of response measurements obtained under low levels of excitation.

The recent occurrence of the Loma Prieta Earthquake offers a unique opportunity to carry out a program of field measurements and analytical modeling to better understand the significance of factors such as displacement amplitude in full-scale response measurements. In particular, it should be possible to interpret measured characteristics under low-level response in light of known high-level response.

APPROACH CBT will select one or more undamaged buildings that were subjected to strong ground shaking and that yielded valid accelerograms during the earthquake. It should be possible from these records to obtain estimates of overall damping, the first two or three modal frequencies and the peak accelerations and displacements.

Initially, ambient and manually excited vibrations will be investigated with the possibility of conducting forced vibration tests using one or more mechanical shakers. This approach will make it possible to obtain higher levels of displacement. However, the main advantages of the approach are that specific modes of vibration can be excited and identified, and estimates of modal damping can be obtained from amplitude decay curves as opposed to less reliable autocorrelation and half-power bandwidth techniques.

Findings from this research effort will have direct application to the improvement of analytical response models, the development of minimum requirements for obtaining full-scale response measurements, and the proper interpretation of such measurements. Structural response measurements based on a standard test method

will form the basis for establishing dynamic properties of structures and will have use in the evaluation of structural damage and/or remaining life.

Two reports will be published during 1990. One report will describe the measurement program and provide details of selected structure(s) and structural response characteristics based on the analysis of strong-motion records. The second report will address the dynamic response measurement of buildings subjected to low-level excitation.

RESULTS New project 1990.

STRENGTHENING METHODOLOGIES FOR BRIDGE STRUCTURES

Principal Investigator: H. S. Lew
Structures Division
301.975.6061

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop design guidelines for strengthening bridge structures for improved seismic performance.

PROBLEM Recent U.S. earthquakes have established that one of the most critical aspects of lifeline security in seismic events is the inadequate performance of bridge structures. Failure of major highway bridges occurred in the 1971 San Fernando earthquake, the 1987 Whittier earthquake, and the 1989 Loma Prieta earthquake. Causes of failure include: inadequate flexural ductility of bent columns; inadequate shear strength of columns; bond failure in plastic hinge regions of flexural reinforcement; and failure of bent cap/column knee joints due to high shear stress. Highway bridges designed and constructed prior to the introduction of modern seismic design requirements in the AASHTO specification (1977) need to be strengthened for improved seismic performance.

APPROACH This purpose of this project is to collect available research based performance data and field-practice information, in the United States and Japan, and prepare design guidelines for strengthening bridge structures for improved seismic performance. This project will be carried out jointly with the University of California at San Diego. Research includes a six-phase approach:

1. Identify problem areas from recent earthquakes.
2. Develop analytical procedures for assessing critical elements and failure mechanisms.
3. Document different techniques for strengthening bridge structures that have been used in the past.
4. Document research results from the United States and Japan on methods for strengthening bridges.
5. Develop guidelines for strengthening bridge substructures for improved seismic performance.

6. Develop recommendations for future areas of research which are not being adequately addressed.

During 1990 a report will be published which identifies failure modes of bridge structures and analytical procedures for assessing failure mechanisms and techniques used to strengthen existing bridge structures.

RESULTS New project 1990.

METHODOLOGY FOR CONDITION ASSESSMENT USING NDT METHODS

Principal Investigator: Nicholas Carino
Structures Division
301.975.6061

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop reliable and practical nondestructive testing procedures for condition assessment of reinforced concrete structures.

PROBLEM An effective plan for seismic strengthening of existing structures requires the development of material and geometric properties of critical structural elements. Nondestructive testing methods offer the potential of performing assessments rapidly compared with destructive methods, such as coring and chipping away concrete. While various techniques and devices have been developed, there are no standards for their use.

APPROACH CBT is developing guidelines for applying existing testing techniques to determine material and geometrical properties of reinforced concrete structural elements and their connections. A methodology will be developed for using electromagnetic-wave propagation, magnetic field, and stress-wave propagation techniques in a coordinated effort to solve problems in condition assessment, including accurate determination of depth, size, and yield strength of reinforcing steel, concrete strength, and dimensions of concrete members, and accurate location of voids.

The project involves four stages:

1. Conduct a literature review of advances in electromagnetic radiation and magnetic field methods.

2. Perform controlled laboratory studies to characterize the precision and accuracy of the various measurement methods.

3. Perform testing of full-scale specimens which simulate typical structural elements and connections. Estimated concrete strengths will be compared with core strengths. This will establish the reliability of the proposed coordinated NDT approach.

4. Produce a draft guide for NDT of reinforced concrete frames.

A report on the literature review of NDT methods for determining depth, size, and yield strength of reinforcing steel will be published in 1990.

RESULTS New project 1990.

SEISMIC PERFORMANCE OF PRECAST CONCRETE CONNECTIONS

Principal Investigator: Geraldine Cheok
Structures Division
301.975.6061

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop technical data and to recommend rational and consistent seismic design provisions for moment resistant precast concrete beam-column connections.

PROBLEM Strength and ductility of joints of precast concrete elements can be achieved by post-tensioning beam and column elements, special reinforcing arrangements, and fiber reinforced grout in the joints. Technical data are needed to establish provisions for codes and standards, thereby promoting precast concrete construction in seismically active areas.

APPROACH There is limited guidance for designing and detailing precast concrete structures for seismically active regions. The 1985 Uniform Building Code (UBC) permits 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. It is presumed 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. Thus, the connections are often unavoidable weak links.

A task group of researchers from academia, the research community, the Prestressed Concrete Institute, the Portland Cement Association, and the private sector, will work with CBT staff to help guide the design of specific joint details for CBT's consideration. An experimental model study will be carried out to characterize joint behavior. A paper, *Seismic Performance of 1/3 Scale Post-Tensioned Precast Beam Column Connections,* will be published in the spring of 1990.

RESULTS Results of past year's efforts include:

Tested two monolithic beam-column connections designed to UBC Seismic Zones 2 and 4 requirements.

SEISMIC RESISTANCE OF MASONRY WALLS

Principal Investigator: Robert Dikkers
Structures Division
301.975.5863

Sponsor: National Institute of Standards and Technology

OBJECTIVE To define the state-of-the-art of seismic performance of masonry shear walls and contribute to developing masonry shear wall design and code provisions.

PROBLEM At the outset of the NBS Masonry Research Program in FY 1983, there was a relatively well-defined need for additional research information on the performance of plain and unreinforced masonry shear walls under earthquake loading

conditions (NBS Building Science Series 106, 1977). There was no unified national standard governing the design of masonry structures and no U.S. building code contained limit state design procedures for masonry construction. In the intervening years, the masonry industry and the design and construction practitioners have made considerable progress toward a national standard for masonry structures (ACI 530-88/ASCE 5-88) and one national model building code (1988 UBC) contains provisions for the limit state strength design of reinforced masonry shear walls. These developments have precipitated the need for a revaluation of the objectives and direction of the 1983 CBT Masonry Research Program.

APPROACH During 1990 CBT will perform two tasks:

1. Review U.S. and foreign technical reports, conference and symposium papers, and technical journals and perform analyses of available test results of the performance of masonry shear walls. Included are plain, partially-reinforced and fully-reinforced walls; clay and concrete masonry; quasi-static and dynamic testing; and shear loading applied in combination with or without vertical loading. The literature search and analyses activities are limited to documents published during the past 15 years. This analysis is being performed to define the state-of-the-art of masonry shear walls, identify knowledge gaps, and determine NIST's objectives for masonry shear wall research.

2. Implement the research program by preparing a detailed work plan, and constructing and testing wall specimens, as appropriate.

A report summarizing the state-of-the-art review and analysis of test data/code provisions for masonry shear walls with recommendations for masonry shear wall research program will be published in 1990.

RESULTS Results of past year's efforts include:

Yancey, Charles W. C., "Influence of Horizontal Reinforcement on the Shear Resistance of Masonry Walls," *Wind and Seismic Effects Proceedings of the 21st Joint Meeting*, NIST Spec. Publ. 776, pp. 286–297, January 1990.

SEISMIC MONITORING OF GSA BUILDINGS

Principal Investigator: Long T. Phan
Structures Division
301.975.6077

Sponsor: General Services Administration

OBJECTIVE To develop procedures and criteria for locating strong motion instrumentation in new and existing Federal buildings.

PROBLEM 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 the 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 perfor-

mance, 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. Results obtained from these ambient vibration tests or low-level vibration tests will establish base-line response characteristics of the building to be used to determine changes in structural performance due to structural damage.

APPROACH Two GSA office buildings were included in this study: one in Portland, OR; the other in Los Angeles, CA. The building in Portland, OR, (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.

The research involves five tasks:

1. Review the structural plans and specifications of two buildings; make site visits to obtain as-built building data and document structural and nonstructural data.
2. Develop mathematical models for the buildings for computer analysis.
3. Perform measurements of the building's structural response characteristics to determine their dynamic properties.
4. Perform dynamic analysis of the buildings to determine their structural performance under credible earthquake excitations. The analysis identified the locations where severe damage will occur and most desirable locations for strong-motion instruments.
5. Install strong-motion instrumentation in either the Portland or Los Angeles building based on the results from task 4.

RESULTS Results of past year's efforts include:

Mathematical models of the two GSA buildings were developed. Dynamic responses of buildings predicted by the models were compared with the experimental results of low-level excitation tests of these two buildings. Within linear elastic range, the predictions of the mathematical models agree well with the measured values.

TECHNICAL ASSISTANCE AND ENGINEERING EXPERTISE FOR SEISMIC CONSTRUCTION ACTIVITIES

Principal Investigator: H. S. Lew
Structures Division
301.975.6061

Sponsor: Federal Emergency Management Agency

OBJECTIVE To assist FEMA develop improved seismic practices for new and existing buildings and lifeline structures.

PROBLEM Congress passed the Earthquake Hazards Reduction Act of 1977 (PL 95-124) which created the National Earthquake Hazards Reduction Program (NEHRP)

in 1978. The NEHRP established the Interagency Committee on Seismic Safety in Construction (ICSSC). The Program also assigned NIST to chair the Committee to develop through cooperative activities, seismic design guidelines for existing and new buildings and lifeline systems.

APPROACH This project is a continuation of work with FEMA to improve seismic design and construction practices for new and existing buildings. CBT provides the Secretariat to the ICSSC.

CBT also works with the Building Seismic Safety Council (BSSC), an organization of trade associations and code groups, to improve seismic design practices. CBT provides technical assistance to the BSSC which issues seismic design provisions for new buildings (NEHRP Provisions).

This work includes development of possible "code" provisions for seismic design. These provisions are reviewed for use by codes developing organizations. Improved seismic design provisions, acceptable on a national level, are expected to lead to uniform safety and economy for all types of building construction.

RESULTS Results of past year's efforts include:

A Handbook for Seismic Evaluation of Existing Buildings, FEMA-178, June 1989.

Techniques to Rehabilitate Existing Buildings for Improved Seismic Resistance, FEMA-172, May 1989.

Lew, H. S., *Guidelines for Identification and Mitigation of Seismically Hazardous Existing Federal Buildings*, NISTIR 89-4062, March 1989.

SEISMIC STRENGTHENING METHODOLOGIES FOR REINFORCED CONCRETE FRAME BUILDINGS

Principal Investigator: Mark Johnson
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301.975.6067

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop guidelines for seismic strengthening for lateral load resisting capacity of lightly reinforced concrete frame buildings.

PROBLEM There is a possibility that a strong motion earthquake will occur in the eastern United States. However, because no destructive earthquakes have occurred in this region in recent history, most reinforced concrete structures are not designed to resist such earthquake motions. Typically, medium- to high-rise reinforced concrete frame structures designed primarily for gravity loads are vulnerable to severe damage or even total collapse. To minimize such vulnerability, these structures need to be strengthened with lateral load resisting elements. Such elements would provide adequate stiffness and strength to resist lateral loads produced by moderate earthquakes and sufficient ductility to absorb imparted energy of a strong earthquake which is expected to occur once during the life of the structure.

It has been observed during past earthquakes that columns of reinforced concrete frame structures lacking adequate lateral load resisting capacity sustain severe damage beyond repair. Significant improvement of building performance can be expected if lateral loads are diverted from columns to lateral load resisting elements.

APPROACH CBT will develop methods to provide lateral load resisting elements such as infilled shear walls and diagonal steel braces to improve seismic performance of reinforced concrete frame structures. Analytical and experimental studies will be performed jointly with Cornell University during this four-phase project:

1. Perform studies of judiciously selected reinforced concrete frame buildings (approximately six) to determine their dynamic response characteristics.

2. Develop methods to improve response characteristics of selected reinforced concrete frame buildings strengthened by the addition of lateral load resisting elements. The results of recent experimental work performed at NIST, NCEER and other academic institutions will be incorporated in modeling the concrete structures with infilled shear walls and steel braces. The analytical studies will identify the amount and types of strengthening elements needed for each type of structure.

3. Perform analytical studies to examine the dynamic response characteristics of a strengthened three-story single-bent 1/3-scale frame.

4. Experimentally test a one three-story single-bent 1/3-scale frame to verify the analytical model and evaluate system performance.

During 1990 a report on analytical modeling of reinforced concrete frame buildings will be published.

RESULTS New project 1990.

MEASUREMENT OF ENERGY DELIVERED TO THE SPT SAMPLER

Principal Investigator: Felix Y. Yokel
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301.975.6065

Sponsor: National Institute of Standards and Technology

OBJECTIVE To simplify current calibration procedure for standard penetration test equipment and provide a reliable basis for correlating tests performed with different equipment.

PROBLEM A troublesome problem is the calibration and comparison of tests performed with different equipment. The calibration device presently used for the standard penetration test is a proprietary calibrator which measures the energy passing through a drill rod below the anvil. The only calibrator presently in existence is in NIST. The calibrator itself is not highly reliable, and the accuracy of its measurements cannot be verified with present technology. In a recent interagency meeting, NIST proposed to switch to hammer velocity measurements with a radar gun to

provide a more reliable, less expensive, and less intrusive test. This procedure will compile generic information on other variables, such as the hammer-anvil system.

A recent analytical study indicates that the energy entering the top of the drill rod is not entirely transferred to the sampler, and that parameters such as the rod and anvil size may have a significant effect on the energy that can be utilized, which is the energy actually delivered to the sampler. To obtain empirical information it is necessary to measure the energy at the point where it is used.

APPROACH

An elasto-plastic energy absorbing device will be built which can be set for different resistance forces. It will consist of a lead block supported by a spring. The lead will be penetrated with rods of different sizes to vary the plastic resistance. The stiffness of the elastic part of the resistance function will be varied by using different springs. The energy required for penetration will be measured by LVDT's combined with a force measurement. With this system a force-displacement-time function can be measured. The energy absorbing device will be tested in the laboratory with an MTS machine, using a range of loading rates.

After completing the laboratory study the system will be installed in the field at the bottom of a tall retaining wall or highway bridge, where it can be accessed by drill rigs. The site will be made available by the Colorado Department of Transportation. Cooperation was secured from the U.S. Bureau of Reclamation, who will make drilling equipment available and from the University of Colorado, who will assign graduate students to the task.

This project will provide generic information on the effect of the important test variables, i.e. hammer/anvil geometry, effect of automatic hammers, rod size, and rod length, on the energy used for penetration. This information will be used in conjunction with a doppler-radar field measurement of hammer impact velocity to correct the blow counts obtained in the field with various types of equipment to a standardized value on which current foundation design criteria are based.

A report on correction factors to be used for Standard Penetration Tests will be published in 1990.

RESULTS

Results of past year's efforts include:

Yokel, F. Y., "Energy Transfer Mechanism in the SPT," *J. ASCE* Geotechnical Engineering Division, Paper 23885, September 1989.

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

Principal Investigator: Noel J. Raufaste
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Sponsors: National Institute of Standards and Technology and Seven Federal Agencies

OBJECTIVE To provide the U.S. Secretariat of the U.S.-JAPAN Panel on Wind and Seismic Effects.

PROBLEM The U.S. Panel on Wind and Seismic Effects was created in 1969. Annual meetings alternate between Japan and the United States. The Panel is composed of seven 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.

APPROACH During 1990, the Panel will continue to:

1. Exchange wind and seismic technology (including data, information, measurement and test facilities and equipment, and researchers) between appropriate United States and Japanese organizations.

2. Develop links between scientific and engineering researchers of the government, industrial, and academic organizations from the two countries, and encourage exchange 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.

A report on the Proceedings of the 22nd Joint Meeting will be published in 1990.

RESULTS Results of past year's efforts include:

Raufaste, Noel J., *Wind and Seismic Effects. Proceedings of the 21st Joint Meeting*, NIST Spec. Publ. 776, January 1990.

CONCRETE

HIGH-PERFORMANCE CONCRETE

Principal Investigator: James R. Clifton
Building Materials Division
301.975.6707

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop guidelines for the formulation and engineering application of high-performance concretes.

PROBLEM U.S. leadership in developing and applying high-performance concrete technology is necessary for the U.S. construction industry to remain competitive in the face of international competition. High-performance concretes are defined as concretes which achieve desirable combinations of properties outside the range of conventional concretes (e.g., compressive strengths greater than 70 MPa).

APPROACH The initial effort in this multiyear program is development of a national research plan produced in collaboration with leaders from the concrete research and user communities. The plan will give guidance to all the participants in this national effort of ensuring U.S. leadership in high-performance concrete technology. The plan provides direction for advancing fundamental understanding of the properties and long-term performance of high-performance concretes and the development of guidelines which includes a) the design of high-performance concrete mixtures, b) structural design with high-performance concrete, c) quality assurance of high-performance concrete, and d) field construction with high-performance concrete.

During 1990, CBT is organizing a workshop to define the research needs, suggest the elements for a national plan, and propose how the plan should be implemented. The plan will be published at the end of 1990.

RESULTS New project 1990.

CEMENTITIOUS MATERIALS MODELING LABORATORY

Principal Investigator: James R. Clifton
Building Materials Division
301.975.6706

Sponsor: Center for Advanced Cement-Based Materials, Northwestern University

OBJECTIVE To make available, at a single location, models developed by the Center for Advanced Cement-Based Materials and others pertinent to the research of the Center; develop guidelines and protocols for developing and documenting of models which will facilitate their interfacing and use; and coordinate the model interfacing.

PROBLEM The Center for Advanced Cement-Based Materials was established under the sponsorship of the National Science Foundation in February 1988. Modeling is a significant component of each major area of the Center's investigations and a way to coordinate the research of the Center and facilitating its engineering applications. The models are effective tools to transfer knowledge and technology

generated by the Center to other scientific and technical communities and institutions. CBT is performing two other projects funded through the Center ("Computer Simulation of Transport Properties of Cementitious Materials," and "Modeling the Rheology of Dense Flocculated Suspensions") which will be linked with the modeling laboratory. During FY 1989 telecommunications linkages were established between the Center's participants to remotely interface with the models that were archived in the modeling laboratory.

APPROACH During FY 1990, CBT is working with the other member laboratories to interface models and performing the maintenance of an archive of model software and documentation. Laboratory models include:

- microstructural model developed at CBT,
- service life models being developed at CBT,
- "Blind ant" model under development at CBT for predicting the permeability of concrete.

RESULTS Results of past year's efforts include:

Struble, Leslie, Johnson, Steven, Hartmann, Mark, Kaetzel, Lawrence, and Jennings, Hamlin, *Manual for the Cement Hydration Simulation Model*, NIST Tech. Note 1269, September 1989.

Bulletin board—describes models in the laboratory and lists reports on cement and concrete of potential interest to the participants in the Northwestern University Center.

MODELING THE RHEOLOGY OF DENSE FLOCCULATED SUSPENSIONS

Principal Investigator: James R. Clifton
Building Materials Division
301.975.6707

Sponsor: Center for Advanced Cement-Based Materials, Northwestern University

OBJECTIVE To understand the effects of particle interaction potentials and particle packing in determining the microstructure of fresh cement paste and determine the relationships between microstructure and rheological behavior.

PROBLEM Rheology (the study of deformation and flow) of particulate suspensions is important because it governs the behavior of a suspension during processing and it provides an important indirect measure of the microstructure (i.e., the extent of flocculation and the nature of the flocs). The rheological behavior of fresh concrete is important to its flow properties prior to set and its microstructure after set.

APPROACH This 2-year research on the microstructure of fresh cement paste and the relationships between microstructure and rheological behavior involves collaboration between the University of Illinois and CBT. The experimental effort at the University of Illinois establishes relationships between particle interaction potentials and microstructure in a dense, flocculated suspension. The modeling effort at CBT involves the development of mathematical relationships between interaction

potentials, microstructure, and flow properties of the suspensions. The central focus of the modeling effort focuses on adding rheological behavior to CBT's cement simulation model. The work is performed in two Tasks. Task 1 is concerned with establishing relationships between microstructure and rheology based on the distribution of the spacing between particles and the viscosity and yield point of the suspension. Task 2 involves the incorporation of interparticle forces into the simulation model. A final report which relates the estimated distribution of suspended particles (obtained by modeling) to rheological behavior will be published in 1990.

RESULTS Results of last year's efforts include:

The computer code for the cement microstructure model was further developed to include calculations of the distribution of interparticle spacings and incorporated a new particle packing algorithm to extend the application of the model to lower water/cement ratios.

COMPUTER SIMULATION OF TRANSPORT PROPERTIES OF CEMENTITIOUS MATERIALS

Principal Investigator: Edward J. Garboczi
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301.975.6708

Sponsor: Center for Advanced Cement-Based Materials, Northwestern University

OBJECTIVE To develop models for predicting transport properties of cementitious materials.

PROBLEM The microstructural simulation model for cement recently developed by CBT is an important departure from previous models developed by cement researchers. It directly simulates the development of microstructure as cement hydrates. It is a simplified model, but has enough realistic features so its predictions are qualitatively correct, providing crucial insight into the more complex real materials. Similar simple models have proven useful to researchers in the oil-well logging industry for determining the transport properties of porous sedimentary rock. CBT's cement microstructural model (CMM) can perform a similar role for cement, and perhaps may suggest idealized experimental systems to further test theoretical ideas about the transport properties of the pore space of cement and concrete, which are important to material degradation.

APPROACH During FY 1990, CBT will combine the CMM with two new algorithms. These new techniques, the "blind ant" algorithm and the Y-delta algorithm, enable direct, accurate computations of the pore space diffusivity of granular composites to be performed. As the diffusivity of cement and concrete plays an important role in determining their susceptibility to attack by environmental species, there is much to be learned by directly simulating this process on the CMM and studying it as a function of extent of hydration, initial particle-size distribution, and water-to-cement ratio. Directly simulating diffusion on the CMM should enable CBT to identify microscopic causes of macroscopic behavior. Work involves modifying the CMM to include periodic boundary conditions, adapting the "blind ant" and Y-delta algorithms to the CMM, and performing the diffusivity studies on the supercomputer. Putting in periodic boundary conditions will reduce the effect of the relatively small number of cement particles treated in the CMM, thus enabling

better comparisons to be made with real cement systems. This project will determine appropriate boundary conditions at the various cement constituents, requiring detailed knowledge of both cement chemistry and microstructure, and computer simulation techniques. This project is a collaboration with Northwestern University through the NSF Center for Advanced Cement-Based Materials. A report will be published in 1990 that describes the results of diffusion studies.

RESULTS Results of past year's efforts include:

Bentz, Dale, P. and Garboczi, Edward J., "Analytical and Numerical Models of Transport in Porous Cementitious Materials," *Scientific Basis for Nuclear Waste Management*, A Materials Research Society Symposium, in press.

Garboczi, Edward J. and Bentz, Dale P., "Digital Simulation of the Aggregate-Cement Paste Interfacial Zone in Concrete," submitted to *Journal of Materials Research*.

GUIDELINES FOR PREDICTING THE SERVICE LIFE OF CONCRETE

Principal Investigator: James R. Clifton
Building Materials Division
301.975.6707

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop and demonstrate guidelines for predicting the service life of concrete structures.

PROBLEM Until recently, little systematic attention has been given to predicting the service life of concrete. Usually, concretes are designed based on a) empirical relationships between materials, mixture design, and the physicochemical properties of concrete, and b) experience with the performance of concretes in various service environments. Needed are quantitative and reliable life predictions when selecting concrete because of a) applications that require significantly increased service lives, b) increased use of concrete in critical new environments, e.g., offshore, c) the high cost of rebuilding and maintaining the nation's infrastructure, and d) the development of high-performance concretes for which a record of performance is not available.

The increased interest in service life predictions is evidenced by the establishment in ACI of Committee 356 on Service Life Design and by the Strategic Highway Research Program. The recent National Materials Advisory Board publication "Concrete Durability: A Multibillion-Dollar Opportunity," emphasized the need for long-term research on concrete durability.

APPROACH In FY 1990, a generic methodology for predicting the service life of a concrete structure will be developed and testing started. In subsequent years a more comprehensive approach will be developed and demonstrated. Then guidelines will be prepared and submitted to voluntary consensus standard committees for possible inclusion in standard documents. A comprehensive approach for predicting the service life of a concrete structure will be developed including the development of mathematical models, design of experimental investigations to obtain data needed to solve and validate models, creation of a database to provide a resource of experimental data and pertinent published data and, if necessary, development

of new accelerated test methods to data and pertinent published data and, if necessary, development of new accelerated test methods to predict concrete performance. The approach will be developed and demonstrated using a reinforced concrete structure exposed to corrosive levels of chloride ions. The rates of transport or movement, reaction, and absorption of chloride ions and oxygen gas in the pores of concrete at different levels in the structure will be inputs to the models. Also, the effects of carbonation on corrosion will be considered. The experimental design of laboratory studies will be developed based on the important variables identified by the mathematical models. Methods and procedures to obtain and analyze field specimens will be identified and if necessary developed. A database of published data pertinent to the rate and severity of reinforcement corrosion attack will be created along with the data obtained in the experimental studies, used to solve and validate the corrosion models.

Reports on the elements of a generic methodology for making service life predictions of a reinforced concrete structure and development of conceptual model for corrosion of steel in a concrete structure to form the basis for designing the database will be published in 1990.

RESULTS New project 1990.

CEMENT SOLIDIFIED WASTE FORM TESTING

Principal Investigator: James R. Clifton
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Sponsor: Nuclear Regulatory Commission

OBJECTIVE To analyze the appropriateness and adequacy of the NRC test program for predicting the long-term (300-year) performance and stability of cement solidified low-level radioactive wastes.

PROBLEM In the NRC requirements for the land disposal of Class B and Class C, and in certain cases Class A, low-level radioactive wastes (LLW) are required to have structural stability for 300 years. According to 10 CFR Part 61, Licensing Requirements for Land Disposal of Radioactive Waste, structurally stable waste form "... will generally maintain its physical dimensions and its form, under the expected disposal conditions, ..." One of the means 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 structurally stable.

NRC published Technical Position on Waste Form (the TP) that gives technical criteria for acceptable waste forms and guidance to LLW generators on how to demonstrate that solidified waste forms meet the stability requirements. Included in the TP is a program of tests NRC recommends for demonstrating solidified waste forms will be structurally stable for the 300-year period. However, the results of recent NRC sponsored studies raised questions about the structural stability of cement solidified waste forms. The questions concern the appropriateness of hydraulic and asphaltic cements as solidification agents for certain LLW, and the adequacy of the testing program described in the TP for assessing the long-term performance of cement solidified waste forms. NRC requested CBT to

identify performance criteria to predict, with reasonable assurance, the long-term stability of certain types of cement solidified wastes.

APPROACH CBT is performing this research in three tasks. Task 1 analyzes the appropriateness and adequacy of the test program given in the TP to demonstrate the long-term (300-year) performance of cement solidified waste. Cements being used to solidify LLW include hydraulic cements and asphaltic cements. Task 2 involves the analysis of proposed additional waste form testing for cement solidification systems and formulations. This work involves review of documents supplied by NRC and meetings with the NRC staff and researchers. The reviews will focus on determining if data gaps identified in Task 1 are addressed by planned future research. In Task 3, the findings from Tasks 1 and 2 will be evaluated and conclusions identified about the adequacy of this testing program to predict the service lives of cement solidified waste forms. In evaluating the test program for making service life predictions, the methodology developed by CBT for making service life predictions will be applied. This methodology is outlined in ASTM E 632, "Standard Practice for Developing Accelerated Tests to Aid Prediction of the Service Life of Building Components and Materials." Based on the results of the analysis of the test program, conclusions about the usefulness of the test program and recommendations for the development of additional performance criteria will be submitted to the NRC. A report on recommended changes in the evaluation of the long-term performance of solidified LLW relative to asphaltic cements will be published in 1990.

RESULTS Results of past year's efforts include:

Clifton, James (NIST), Tokar, Michael (NRC), Reed, Philip (NRC), and Jagannath, Banad (NRC), *The Use of Cements to Solidify Low-Level Nuclear Waste Materials*, Proceedings of a Joint NRC/NIST Workshop, published as a joint NRC/NIST report, NISTIR 89-4178.

TRANSPORT PROPERTIES OF POROUS MEDIA

Principal Investigator: Edward J. Garboczi
Building Materials Division
301.975.6708

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop and apply analytical and computer simulation models of the transport of fluid and ions in the pore space of porous materials such as cement and concrete.

PROBLEM The degradation of concrete is a major national problem. The basic understanding of the mechanisms of degradation processes is crucial to developing a valid scientific basis for service life prediction. The essential physical mechanism in almost all such processes is the penetration of external species (fluids or ions) into microstructural elements, which allows deleterious chemical reactions to take place. An example is the diffusion of Cl^- ions through water-filled pores to the steel reinforcing bars. When a high enough concentration of ions is achieved, the bars begin to corrode. Also, degradation of concrete under freeze-thaw conditions depends on the movement of water in the pore/void structure of the material.

Significant progress has been made in the last 10 years or so in understanding how transport coefficients like diffusivity and permeability are related to the pore structure of a porous material. This work has been carried out mainly in the United States and France by oil well logging companies (e.g., Schlumberger-Doll) and oil companies (e.g., Exxon), mostly by physicists. The body of knowledge built up in the form of analytical and computer-based models and techniques, though originally formulated for sedimentary rocks, is available to be applied to the problem of transport in porous cementitious materials.

APPROACH

This project will address how rates of transport in cementitious materials are related to pore structure. During FY 1990, CBT researchers will use the theoretical physics techniques and computer-based models developed in the United States and France to develop a sound scientific basis for relating the pore structure of hardened cement paste to its diffusivity and permeability.

Work will include development of the "blind ant" algorithm for use on other processes besides diffusion, and theoretical work on its mathematical foundations to standardize its use. A mercury porosimetry and permeability measurement program will be undertaken in a multi-year program to validate the use of percolation-based permeability theory on cement-based materials. Diffusion studies will be carried out on cement microstructural models using the "blind ant" and Y-delta algorithms.

Further work on the theoretical foundations of the percolation-based permeability theory will be carried out using the mercury porosimetry digital simulation technique. The new technique of AC (frequency-dependent) permeability measurement will be evaluated for its suitability for low-permeability cementitious materials. If applicable, this technique has the potential for greatly accelerating permeability measurements on cement and concrete. Reports will be published on the use mercury porosimetry simulation model in conjunction with "blind ant" diffusion algorithm to analyze and further validate the percolation-based diffusivity theory and on progress achieved during 1990. The knowledge gained from this study will contribute to a better understanding of the mechanisms of degradation processes and thus help establish the scientific basis for service-life predictions.

RESULTS

Results of past year's efforts include:

Garboczi, Edward J., "Comment on Fluid Flow in a Random Porous Medium: A Network Model and Effective Medium Approximation," *Journal of Applied Physics*, to be published in 1 June 1990 issue.

Garboczi, Edward J., "Mercury Porosity and Effective Networks for Transport Calculations in Porous Media," submitted for publication in *Powder Technology*.

Garboczi, Edward J., "Permeability, Diffusivity, and Microstructural Parameters: A critical review," *Cement and Concrete Research*, in press.

Thonar, M. F. and Garboczi, Edward J., "Elastic Properties of Central-Force Networks with Bond-Length Mismatch," submitted for publication in *Physical Review B*.

FIELD APPLICATION OF TEST METHODS TO MEASURE THE TENSILE BOND STRENGTH BETWEEN CONCRETE OVERLAYS AND EXISTING CONCRETE

Principal Investigator: Robert G. Mathey
Building Materials Division
301.975.6709

Sponsor: Department of Defense

OBJECTIVE To validate the feasibility of using pneumatic and hydraulic test apparatuses as field test methods to measure the tensile bond strength between concrete overlays and existing concrete and develop criteria for the tensile bond strength between overlay and existing concrete.

PROBLEM Recent laboratory tests indicated pneumatic and hydraulic test methods provided reproducible tensile bond strength data for measuring the bond of overlay concrete to existing concrete. The pneumatic apparatus was developed at NIST for field measurements of the adhesion of protective coatings. The hydraulic apparatus used in the laboratory study was similar to ACI 503R tensile apparatus with modifications recommended by the Virginia Department of Transportation. The Department evaluates the bond of concrete overlays to existing concrete by using shear tests of concrete cores. The proposed field tests measure the tensile bond strength directly; they need to be validated by field testing.

APPROACH During FY 1990, CBT will validate the field tensile bond strength test methods on pavements and bridge decks in cooperation with the Virginia Department of Transportation. During 1991, the second year of this two year project, preliminary criteria will be developed for the tensile bond strength of overlay concrete. Tensile bond data will be correlated with the extensive shear bond data obtained by the Virginia Department of Transportation over many years. The preliminary criteria for tensile bond strength will be based on field performance of overlay concrete.

A report on the evaluation of field tests and the field test data will be published during 1990.

RESULTS Results of past year's efforts include:

Knab, Larry I., Sprinkel, M. M., and Lane, O. J. Jr., *Preliminary Performance Criteria for the Bond on Portland-Cement and Latex-Modified Concrete Overlays*, NISTIR 89-4156, November 1989.

COATINGS

MODELS OF THE DEGRADATION OF ORGANIC PROTECTIVE COATING SYSTEMS

Principal Investigator: Tinh Nguyen
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Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop and validate models for predicting the service lives of protective coatings for steel and to develop the technical bases for draft standards for adoption by national and international consensus standards organizations.

PROBLEM Corrosion in the United States is estimated to cost more than $200 billion annually. Polymeric coatings help to prolong the life of corrosion-prone construction materials. However, these coatings are 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. Research is needed to better understand the degradation mechanisms and transport phenomena through the coating and along the coating/metal interface, and develop mathematical models for predicting the service life of coating systems.

APPROACH Research in FY 1990 will concentrate on developing methods to perform experiments for testing and improving the conceptual and mathematical models of the transport processes at the coating/steel interface leading to blister formation and corrosion of a coating system. This work consists of 1) developing conceptual models, 2) confirming mechanisms leading to blister formation and corrosion, 3) quantifying the transport properties of environmental elements through the coating and along the coating/metal interface, 4) developing improved methods for characterizing coating characteristics, properties, and reactions that control degradation at the steel/coating interface, 5) developing and validating mathematical models for predicting service life using laboratory and field data, and 6) helping implement new knowledge through standards and other appropriate means. CBT will formulate an implementation plan to ensure that research findings are adequately transferred into practice and are responsive to the needs of the industry. Reports will be published in 1990 on: in-situ measurements of water at the coating/metal interface; diffusion of ions along the coating/metal interface; and mathematical modeling of degradation under coatings on steel.

RESULTS Results of past year's efforts include:

Nguyen, Tinh and Olson, Craig, "Application of Thermal-wave Electron Microscopy to Imaging and Assessment of Corrosion on Rough Steel Surfaces," *Materials and Structures*, Vol. 22, pp. 71–79, 1989.

Nguyen, Tinh and Lin, C., "In-Situ Measurements of Molecular Behavior at the Opaque Coating/Metal Interface," an extended abstract, *Proc. Electrochemical Society*, Vol. 89-1, p. 793, May 1989.

Nguyen, Tinh and Lin, C., *Development of a Technique to Measure Chloride Ions at the Coating/Metal Interface*, NIST Tech. Note 1266, May 1989.

Lin, C. and Nguyen, Tinh, "AC Impedance Measurements of Coated Steel," an extended abstract, *Proc. Electrochemical Society*, Vol. 89-1, p. 71, May 1989.

Nguyen, Tinh and Lin, C., "A Microelectrode Technique for Measuring Chloride Ions in Coating Blisters and Potential at the Coating/Metal Interface," *Proc. Am. Chem. Soc.*, June 1989.

Lin, C. and Nguyen, Tinh, "The In-situ Measurements of Chloride at the Coating/Metal Interface," *Proc. Am. Chem. Soc.*, June 1989.

Bentz, Dale and Nguyen, Tinh, "Simulation of Diffusion in Pigmented Coatings on Metals Using Monte-Carlo Methods," *J. Coatings Technology*, 1989.

Nguyen, Tinh, Hubbard, J., and McFadden, G., "A Mathematical Model for the Cathodic Blistering of Organic Coatings on Steel Immersed in Electrolytes," *J. Coating Technology*, 1990.

Lin, C. and Nguyen, Tinh, "An AC Impedance Spectroscopy Study of the Effects of Surface Roughness and Salt Contamination on the Corrosion Behavior of Epoxy Coated Steel," *Progress in Organic Coatings*, 1990.

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

OBJECTIVE To develop methods to detect and measure lead in dry paint films.

PROBLEM In the 1970's, CBT researchers performed work to assess the performance of a number of commercially-available, portable x-ray fluorescence analyzers. Data were developed in these studies to aid HUD in recommending courses of action for lead-paint analysis. Recent legislation (PL 100-242, the Housing and Community Development Act of 1987, Section 566), requires HUD to update the knowledge about detecting and measuring lead in paint. PL 100-242 requests, among other items an identification of:

- the most reliable technology available for detecting lead in paint;
- safety conditions in testing;
- the overall accuracy and reliability of laboratory testing of physical samples, x-ray fluorescence machines, and other available testing procedures;
- availability of qualified samplers and testers.

APPROACH CBT is a) assessing currently available detection and measurement methods to determine compliance with essential or desirable requirements or criteria, and b) developing recommendations for detecting and measuring lead in paint films. Requirements and criteria identified are: safety, reliability, accuracy, precision, detection sensitivity, specificity, timeliness of measurement, nondestructive, suitability for use in the field and in the laboratory, ease of use and usability by nontechnical staff members. Methods which show promise for field use will be

further evaluated and recommendations for implementation will be made.

A final report will be published in 1990. It will present estimates of the precision and accuracy of commonly used methods and discuss the reliability of commonly used methods, availability of samples and tests, and safety in testing.

RESULTS Results of past year's efforts include:

McKnight, Mary E. and Byrd, W. Eric, *Screening Procedures for Detecting Lead in Existing Paint Films*, NISTIR 89-4049, NIST, Gaithersburg, MD, January 1989.

Byrd, W. Eric and McKnight, Mary E., *Potential Methods for Measuring and Detecting Lead in Existing Paint Films—A Literature Review*, NISTIR 89-4205, NIST, Gaithersburg, MD, 1989.

McKnight, Mary E., Byrd, W. Eric, Roberts, W. E., and Lagergren, Eric S., *Methods for Measuring Lead Concentration in Paint Films*, NISTIR 90-4209, NIST, Gaithersburg, MD, 1989.

ORGANIC COATINGS

Principal Investigator: Mary McKnight
Building Materials Division
301.975.6714

Sponsor: Tri-Services Committee, Department of Defense

OBJECTIVE To develop improved procedures and criteria for selecting, using, and specifying coating systems and transferring the technology to DOD.

PROBLEM Organic coatings used in the United States exceed $10 billion annually; more than half are used for buildings and structures. The real property value of military facilities is about $300 billion. The annual cost of coating maintenance is about $400 million. It's estimated that 25 percent of these expenditures could be saved when more effective criteria for selecting, specifying, and using protective coatings become available. Research is needed to: provide the technical bases for criteria which are responsive to technological and regulatory changes controlling coatings systems, develop improved testing procedures, determine "weak links" in the systems, and transfer the knowledge to the base engineers responsible for coating system design.

APPROACH During 1990, CBT continues to: visit military installations and attend coatings meetings to learn about coating problems; broaden the base of the Tri-Services Committee meetings to include other Federal agencies for improving technology transfer among government agencies; perform laboratory studies to develop improved coating test procedures; provide leadership in standards activities to focus attention on DOD problems; and implement the results of the work by authoring manuals, presenting talks, preparing draft standards, and publishing reports.

CBT will continue to chair ASTM D01.07 Committee on Government Relations and direct the committee's attention towards a review of DOD test-method needs and recommend appropriate actions; serve as chairman of the SSPC Coatings Steering Committee and support development of SSPC specifications for low-VOC (volatile organic components) coatings; provide organizational and

technical support for development of a Tri-Services guide specification for painting of facilities; and investigate feasibility of using a multiple award schedule with job-related performance requirements to meet the short-term need for low-VOC coatings for use on DOD facilities. Reports will be published in 1990 on lead-in-paint regulations and activities and on feasibility of using multiple award schedule for coatings for DOD.

RESULTS Results of past year's efforts include:

McKnight, Mary E., Bentz, Dale P., and Roberts, W., *Measuring the Extent of Rust on Steel After Abrasive Blasting—A Feasibility Study*, NISTIR 90-4257, NIST, Gaithersburg, MD, 1990.

QUALITY CONTROL TESTS FOR ADHESION OF PAINT

Principal Investigator: Larry W. Masters
Building Materials Division
301.975.6707

Sponsor: U.S. Army, Natick Laboratory

OBJECTIVE To develop test methods for assessing the quality of adhesion of paint on tactical rigid wall shelters.

PROBLEM The U.S. Army uses tactical shelters in situations requiring highly mobile work and as living and storage facilities. The exterior and interior surfaces of the shelters are painted during the manufacturing process. To help ensure the quality of paint adhesion, scratch, tape pull-off, or knife lift tests 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.

APPROACH CBT is conducting the research in three tasks:

1. Assess the Current State of Technology. This task consists of identifying criteria for methods to use in assessing paint adhesion on tactical shelters, identifying methods which may be consistent with the criteria, and identifying methods for evaluation in the laboratory.

2. Perform Laboratory Evaluations. This task consists of laboratory evaluation of the effectiveness of the methods and the extent to which they comply with the criteria. Examples of methods which may be included are the NIST button adhesion test, and methods based on ultrasonics and infrared thermography.

3. Develop Recommendations on Methods. This task consists of presenting the results from tasks 1 and 2 as recommendations for using these methods to assess the quality of paint adhesion. Criteria and laboratory data also will be presented to support the recommendations.

A final report on the criteria, results of laboratory evaluations, and recommendations on the use of methods for assessing the quality of paint adhesion will be published in late 1990.

RESULTS

Results of past year's efforts include:

Watanabe, Hiroshi, Masters, Larry W., and Seiler, James F., *Quality Assurance Tests for Adhesion of Paint on Tactical Shelters*, manuscript in press.

ROOFING SYSTEMS

PERFORMANCE CRITERIA FOR SINGLE-PLY ROOFING MEMBRANES

Principal Investigator: Walter J. Rossiter
Building Materials Division
301.975.6719

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop performance criteria for seams of single-ply membrane materials.

PROBLEM Single-ply roofing membrane materials account for about two-thirds of the low-sloped membrane systems installed in the United States. Many factors including durability, performance, cost, and architectural considerations have influenced its rapid acceptance. The performance of these materials has not been problem-free. Survey information from the National Roofing Contractors Association (NRCA) show performance problems are more prevalent for the single-ply systems than for the built-up systems. Defective laps and seams are the most frequent problems described in the NRCA surveys. They account for about 25 percent of reported failures. As revealed by participants at the 1987 NIST/NRCA Round Table on Roofing Research, "the factors affecting roofing performance must be more fully understood to assure success with new materials and systems." The participants also stated that performance tests and criteria for single-ply systems need to be developed.

APPROACH During 1990, CBT will develop criteria for the performance of seams in single-ply systems. Work will address proper adhesion, water permeability, puncture resistance, and durability. Criteria and test methods associated with these requirements will be developed. Preliminary criteria and test methods will be based on observations of failures in the field, calculations of stresses using mathematical models, laboratory tests results, and U.S. and foreign information on roof membrane performance. Mathematical models developed by CSTB and MIT will be reviewed for use in CBT's roof membrane modeling activities. Improved models will be developed to estimate in-service stresses, and to validate the models with in-service data. The results from the models will be used to plan and conduct laboratory and field research to fill the technical gaps in the preliminary draft criteria. Investigations of the effects of peel stresses in the membrane seam and creep rupture of seam joints stressed in tension while exposed to moisture will be conducted. A search for improved methods for obtaining reliable information on in-service performance and failure modes will continue. This activity will be conducted with the assistance of industry associations such as the NRCA and the Roof Consultants Institute.

During 1990 two reports will be published. One will be on Thermal Analysis Techniques for Characterization of Rubber Membrane Materials. The second will address an approach to development of performance criteria for single-ply roofing membranes.

RESULTS Results of past year's efforts include:

Martin, Jonathan W., Embree, Edward, Stutzman, Paul E., and Lechner, James A., *Effects of Inadequate Cleaning Level on the Time to-Failure of EPDM T-peel Specimens*, NIST Bldg. Sci. Ser., in publication, expected publication spring 1990.

Martin, Jonathan W. and Embree, Edward, "The Effect of Contamination," *Journal of Materials in Civil Engineering*, Vol. I, No. 3, August 1989.

Rossiter, Walter J., Seiler, James F., Jr., and Stutzman, Paul E., "Field Testing of Adhesive-Bonded Seams of Rubber Roofing Membranes," *Proceedings of the 9th Conference on Roofing Technology*, Gaithersburg, MD, May 1989.

Martin, Jonathan W., Embree, Edward, and Rossiter, Walter J., "Effect of Contamination Level on the Strength of Butyl-Adhered EPDM Joints in EPDM Single-Ply Roofing Membranes," *Proceedings of the 9th Conference on Roofing Technology*, Gaithersburg, MD, May 1989.

Frohnsdorff, Geoffrey, "Integrated Knowledge Systems for Roofing Technology," *International Journal of Roofing Technology*, Vol. 1, 1989.

PERFORMANCE OF USAF SINGLE-PLY ROOFING

Principal Investigator: Walter J. Rossiter
Building Materials Division
301.975.6719

Sponsor: U.S. Air Force

OBJECTIVE The obtain and analyze information on the in-service performance and failure modes of low-sloped EPDM roofing systems.

PROBLEM 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 brought to the roofing industry a number of problems that were specific to the new systems. 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. Little information is available on the performance of new membranes in service. In NBS Special Publication 659, *Low-Sloped Roofing Research Plan*, the report cited a need exists 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 USAF has used this material on a limited basis for about 9 years. Although several types of single-ply membranes were used by USAF, the majority are EPDM rubber. Where single-ply systems are in place, the base engineer is required to report annually to USAF Engineering Headquarters on their condition using a standardized form. The performance data obtained to date have not been analyzed. The USAF has considered that such an analysis is needed before its use of the systems can proceed on a broader basis.

APPROACH Performance data available in the USAF files on single-ply roofing will be reviewed. The review will focus on 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. In many cases (based on the information in the data file), the base roofing engineer will be contacted

by telephone to discuss the performance of the roofs in follow-up to the written reports. Visits will be made to selected bases to observe the roofs in question. Where possible, samples of the roofing, particularly sections of seams, will be taken to conduct laboratory tests for characterizing the materials. The site visits will be selected based on reported membrane performance.

Based on the results of the study, guidelines for the installation and maintenance of EPDM roofing systems on Air Force roofs will be prepared. A final report will be published describing the conduct and results of the study. During FY 1990, CBT will produce inspections of USAF single-ply roofing systems and author a final report which includes the findings of the study and guidelines for the installation and maintenance of EPDM systems for USAF roofing.

RESULTS New project 1990.

ASSESSMENT OF SINGLE-PLY ROOFING MATERIALS

Principal Investigator: Walter J. Rossiter
Building Materials Division
301.975.6719

Sponsor: U.S. Army Corps of Engineers

OBJECTIVE To prepare a research plan for thermal analysis procedures for characterizing roof membrane materials and develop laboratory data for characterizing field expanded polymer-modified bituminous membrane materials.

PROBLEM One of the subjects discussed at great length by the participants of the 1987 Round Table on Roofing Research was the characterization of new roofing membranes before and after aging. It was recommended at the Round Table that a need exists to develop methods to characterize membrane materials and to develop criteria for judging whether the changes in service are within acceptable limits.

The CIB/RILEM Roofing Committee recently recommended that thermal analysis techniques be applied to membrane characterization. Although the Committee presented preliminary data on some typical properties of new or laboratory exposed specimens, no data were available for materials that had aged in-service. The technical bases for using thermal analysis techniques for roofing membrane characterization need be fully developed to incorporate these methods in consensus standards and guide specifications.

Of the newer single-ply membrane materials, polymer-modified bitumens are currently experiencing a rapid increase in use. They account for 10–12 percent of the membranes installed annually. Estimates suggest its annual use will increase to 25 percent or more in the next 5 years. Data on the field performance of these systems have not been developed. Consensus standards and criteria to aid in their evaluation, selection, and specification also are not available.

APPROACH This research consists of two tasks for characterizing the newer membrane materials: identifying applications of thermal analysis methods for membrane characterization, and measuring a range of performance-related properties of polymer-modified bitumens. In the first task, the work will consist of holding a

workshop on the use of thermal analysis methods for characterizing membrane materials and the changes that they undergo in service. The workshop will include: assembling a working group of 6 to 10 individuals having experience with thermal analysis methods, holding the workshop, and publishing the proceedings including a research plan.

In the second task, samples of selected polymer-modified bitumen membranes will be taken from Army roofs. Properties of the samples will be measured including strain energy, tear resistance, low temperature flexibility, and moisture absorption. In addition, thermal analytical measurements, such as those recommended by the joint CIB/RILEM Committee on elastomeric, thermoplastic, and modified bitumen roofing, will be conducted.

A report on the thermal analysis workshop will be published in 1990.

RESULTS Results of past year's efforts include:

Rossiter, Walter J. and Seiler, James F., *Interim Criteria for Polymer–Modified Bituminous Roofing Membrane Materials*, NIST Bldg. Sci. Ser. 167, February 1989.

Performance Testing of Roofing Membrane Materials, Recommendations of RILEM 75-SLR/CIB W.83 Joint Committee on Elastomeric, Thermoplastic, and Modified Bitumen Roofing. November 1988. (Publication is available from Walter Rossiter, Committee Secretary, NIST.)

PERFORMANCE SPECIFICATION FOR PVC MEMBRANES

Principal Investigator: Walter J. Rossiter
Building Materials Division
301.975.6719

Sponsor: Department of Defense

OBJECTIVE To provide the technical basis for a performance-oriented standard specification for poly(vinyl chloride) (PVC) sheet membrane materials.

PROBLEM PVC single-ply roofing has been available in the United States for about 15 years. Although many installations performed satisfactorily, significant problems attributed to embrittlement from plasticizer loss during service have occurred over the years. In 1984, an ASTM specification, D 4434, was developed for PVC sheets used as roofing membranes. This is a prescriptive specification; a prime requirement for addressing plasticizer migration is to specify a minimum sheet thickness of 0.045 in (1.1 mm). However, plasticizer loss depends on a number of factors, chief among them the type of plasticizer used. Such factors have not been addressed in the ASTM specification. There are available on today's roofing market, PVC-based materials which do not meet the minimum thickness requirement of D 4434.

APPROACH This research will be performed during 1990 and 1991. CBT is developing puncture tests and thermal analysis methods for characterizing roofing membrane materials, as recommended by CIB/RILEM. These methods will be applied to PVC materials in a laboratory test program. Discussions will be held with members of the ASTM task group on PVC roofing in preparing a study plan. ASTM E632

approach, for assessing the permanence of plasticizers in PVC membrane materials will be undertaken. Recommendations to incorporate such methods in a revised ASTM standard will be made. In addition, the laboratory program will be complemented with selective site visits of PVC roofing to obtain information on in-service performance. An interim report on the progress of the study will be made available.

RESULTS New project 1990.

REPAIR PATCHES ON AGED EPDM MEMBRANES

Principal Investigator: Walter J. Rossiter
Building Materials Division
301.975.6719

Sponsor: U.S.A. Construction Engineering Research Laboratory

OBJECTIVE To develop a method for assuring the quality of bonded seams in weathered vulcanized-rubber membranes.

PROBLEM The use of vulcanized-rubber materials (primarily EPDM) for low-sloped roofing membranes has become common in the United States. 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 by the roofing industry, as these membranes weather, the rubber's surface characteristics may be altered such that successful bonding of the aged material may become difficult. For example, in the CERL study of EPDM roofing at Ft. Benning, GA, it was found that repairs to cut sheets delaminated within months after formation. This may have been due to the use of improper repair materials and patching techniques. A technical basis for making sound repairs to weathered EPDM is lacking and should be developed.

APPROACH This work is being performed as two tasks:

Task 1. Fourier-transform infrared spectroscopy, scanning electron microscopy, and contact angle (wettability) measurements will be used for analytical techniques to assess the effectiveness of cleaning procedures for preparing the surfaces of vulcanized rubbers to receive adhesives.

Task 2. These techniques will be used to assess specific cleaning procedures as solvent action versus mechanical abrasion. The following activities are part of the study:

- Obtain specimens of aged EPDM rubber membrane materials.
- Characterize the uncleaned surfaces of these materials using the experimental procedures developed in Task 1.
- Clean the surfaces of the EPDM specimens using a variety of procedures.
- Re-analyze the surfaces using the surface analysis procedures, thus characterizing the effectiveness of the cleaning procedure for removing surface contaminants.

- Prepare "patch specimens" in the laboratory using aged EPDM that has been cleaned using the cleaning methods under investigation; measure the bond strength and creep rupture resistance of "patches." Relate the results of these tests to the surface cleanness of the aged EPDM as determined by the surface analytical procedures.

A final report on procedures for cleaning the surface of aged EPDM before application of patches will be published in 1990.

RESULTS New project 1990.

QUALITY ASSURANCE OF DOD ROOFING SYSTEMS

Principal Investigator: Walter J. Rossiter
Building Materials Division
301.975.6719

Sponsor: Department of Defense

OBJECTIVE To improve the quality assurance of the DOD's roofing practices.

PROBLEM Unacceptable roofing performance in DOD facilities is a problem. For example, in the late 1970s, the U.S. Air Force estimated its built-up roofs were lasting an average 12 years instead of the intended design life of 20 years or more. DOD is seeking sound design criteria for construction of new and remedial roofing and studying causes of roofing systems failure to implement techniques to avoid future problems.

APPROACH During 1990 CBT is:

1. Serving as Secretary of the Federal Roofing Committee; committee focuses on in-service performance of roofing, field problems, and research needed to solve roofing problems.

2. Providing technical review of roofing documents prepared by DOD and DOD contractors.

3. Inspecting selected DOD roofing materials and systems to characterize in-service performance.

RESULTS Results of past year's efforts included:

As Secretary of the Federal Roofing Committee the following were accomplished: organized meetings, reviewed Committee reports and documents, recorded and distributed minutes, and chaired meetings in the absence of the Chair.

INNOVATIVE MATERIALS

NOISE-MITIGATING CONSTRUCTION MATERIALS

Principal Investigator: Lawrence I. Knab
Building Materials Division
301.975.6712

Sponsor: U.S. Army Construction Engineering Research Laboratory

OBJECTIVE To develop criteria to predict the durability of construction materials that mitigate noise produced during Army training exercises.

PROBLEM The U.S. Army Construction Engineering Research Laboratory is responsible for developing methods to mitigate noise produced by Army training activities, particularly those resulting from firing large caliber weapons. One aspect of this problem is concerned with containing and/or absorbing the sound energy at or near a source. For example, a battle tank or howitzer could be driven into a tunnel-like enclosure, to be fired out through the open end, in the expectation that a substantial part of the acoustic energy of the explosion would be contained within and dissipated by the enclosure. An important concern is what surface materials can be used to absorb and dissipate the sound energy. It is known that most of the sound energy from a large artillery piece is contained within the spectral region of 20–60 Hz. Little development work has been done on absorbing materials for these frequencies and practical absorbing materials are not now available. A structure and its absorbing materials must be functional over a wide ambient temperature range and be able to repeatedly withstand blast impulse over-pressures and high temperatures. Hence, information is needed on the durability of potential noise-mitigating materials.

APPROACH CBT is collecting and analyzing information on potential noise-mitigating materials and facilities to test the materials. Included is an investigation of facilities at NIST and other selected laboratories capable of testing candidate sound absorbing materials under various environmental conditions similar to those occurring in service.

RESULTS New project 1990.

QUANTIFICATION OF EXTERNAL WEATHERING STRESSES—MEASUREMENT AND CHARACTERIZATION OF MOISTURE CONDITIONS IN BUILDING MATERIALS

Principal Investigator: Jonathan W. Martin
Building Materials Division
301.975.6717

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop a reliable method for determining the moisture conditions in a prototype building material under laboratory conditions.

PROBLEM Over the last 10 years, changes have occurred in formulating many building materials. These changes resulted from the need to satisfy legislative restrictions

and the need to respond to higher performance requirements demanded by engineers and designers. Legislation-driven changes include the reformulation of coatings and adhesives to satisfy environmental restrictions; performance-driven changes include the need to reformulate concrete to meet higher strength or sulfate-resistance requirements. Although many materials were formulated which satisfy the initial properties expected of an acceptable material, long-time performance data are unavailable. Building materials tend to degrade at very slow rates when exposed outdoors. Thus, 10- to 20-year exposure times are not uncommon, even in the most severe environments, e.g., coastal Florida. A great need exists for methods to accelerate the degradation of a building material without changing the failure mechanism and yet provide a quantitative prediction of a material's in-service performance. CBT's service life prediction program is designed to help meet this need. This research is an extension of work performed during FY 1989.

APPROACH

Research is being performed in two tasks. Task 1 research is being performed during FY 1990. The research is laboratory-based; it is identifying a suitable device for continuously measuring the moisture conditions on the surface and beneath a coating. The reliability and accuracy of the device will be determined by comparing results obtained with the device against equilibrium moisture absorption isotherm data for the prototype material. Reports will be published during 1990 on gravimetric moisture condition measurements and on electrical moisture condition measurements.

Task 2 will be performed during FY 1991. This work concerns developing a deterministic model to predict the adsorption and desorption of water from the coated panels. The stochastic nature of the moisture condition will be modeled using Fourier analysis to determine the diurnal and seasonal effects of moisture pickup. This stochastic characterization is necessary for establishing cause-and-effect relationships between moisture conditions and rates of degradation and for characterizing different outdoor exposure sites.

RESULTS

Results of past year's efforts include:

Saunders, S. C., Jensen, M. A., and Martin, J. W., *Meteorological Processes Important in the Degradation of Materials Through Surface Temperature*, NIST Tech. Note 1275, 1990.

Saunders, S. C., Jensen, M. A., and Martin, J. W., "Characterization of the Temperature of Coated Panels Exposed Outdoors," *Materials and Structures*, 1990.

Bentz, D. P. and Martin, J. W., "Characterization of Cylindrical Holes in Metallic Substrates Via their Infrared Emission Patterns," *WEAR*, 1990.

TECHNICAL AND SCIENTIFIC SUPPORT IN 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

OBJECTIVE To provide technical and scientific support in developing and updating ASTM standards for materials and processes used to manufacture Army standard rigid wall shelters.

PROBLEM All branches of the military use lightweight, air transportable, rigid structures as 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. Field experience has shown these panels experience performance problems. Data are needed on the performance of 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 on military requirements.

APPROACH During 1990, CBT will provide technical and scientific support to:

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

2. develop, approve, and promulgate consensus standards and serve as Chairman of ASTM Subcommittee E06.53 on Materials and Processes for Durable Rigid Wall Relocatable Shelters;

3. revise and update consensus standards applicable to shelter materials and systems;

4. help prepare technical data for ASTM draft standard for polyurethane foam for use in foam and beam type shelter panels;

5. assist in preparation of ASTM draft standard for adhesives used to repair aluminum skin honeycomb sandwich panels;

6. complete revising and updating ASTM "Glossary of Terms for Rigid Wall Relocatable Shelters"; and

7. assist in revising two ASTM Standards E990 and E1091.

RESULTS Results of past year's efforts include:

The Committee, under CBT Chairmanship, produced;

1. ASTM Standard, E1307-89 "Practice for Surface Preparation and Structural Adhesive Bonding of Precured Non-Metallic Composite Facings to Structural Core for Flat Shelter Panels."

2. "Glossary of Terms for Rigid Wall Relocatable Shelters" which was approved by ASTM and included as a revision to ASTM Standard E874-89 *Standard Practice for Adhesive Bonding of Aluminum Facings to Nonmetallic Honeycomb Core for Shelter Panels*.

QUALITY ASSURANCE LABORATORIES

CEMENT AND CONCRETE REFERENCE LABORATORY

Principal Investigator: James H. Pielert
Building Materials Division
301.975.6704

Sponsors: American Society for Testing and Materials and
U.S. Army Corps of Engineers

OBJECTIVE To provide technical assistance, with ASTM Research Associates at CBT, to public and private cement, concrete, aggregate, reinforcing steel, and pozzolan testing laboratories which use ASTM tests.

PROBLEM 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 these facilities is one of the nation's largest industries—about 10 percent of the Gross National Product. Over $4 billion of hydraulic cement is annually produced in the United States for use in $20 billion of concrete construction. Because of the large amounts of money and construction materials involved, standardization of testing to enhance the reliability of quality assurance measurements is of paramount concern. The productivity of the testing community in the cement and concrete fields can be increased by using correct procedures and apparatus which reduce testing errors and provide a sound basis for accepting cement on mill certificate. More efficient use of long-established construction materials are facilitated by dependable quality assurance programs.

APPROACH With the support of ASTM Research Associates working under CBT supervision, services are provided to public and private cement and concrete testing laboratories on a voluntary basis. These services include on-site inspection of the laboratory and distribution of proficiency test samples. Equipment and procedures used in performing conventional quality assurance tests are evaluated for conformance to applicable national standards. Related test apparatus is checked with inspection equipment 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. Additionally, technical studies are conducted in areas related to these programs. These are often in conjunction with other NIST units.

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) detailed report on each inspection performed; 2) comprehensive report on each round of proficiency sample testing; 3) input to the work of standards committees such as draft standards and data for use in the development or improvement of precision statements; and 4) reports on results of technical studies.

The managers of cement and concrete testing laboratories and the users of the services of such laboratories interact with CBT through the CCRL reports. Summaries of proficiency sample data are provided to ASTM committees C1 and C9 for their use in developing or modifying standards. CCRL staff participate on ASTM standards committees. CBT technical reports, papers in outside journals, and oral presentations are used as appropriate.

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 direct communications between testing laboratories and standards-writing committees.

During 1990 CBT will inspect 230 cement and/or concrete testing laboratories and issue inspection reports; distribute 2600 proficiency test samples and issue test reports; and prepare draft report on a CCRL research activity.

RESULTS

Results of past year's efforts include:

"Evaluation of Test Methods for Measuring the Bond Strength of Portland Cement Based Repair Materials to Concrete," Knab and Spring, *ASTM Cement, Concrete and Aggregates*.

Inspected about 220 cement and concrete testing laboratories and issued inspection reports.

Distributed 2600 proficiency test samples and issued reports of results.

AASHTO MATERIALS REFERENCE LABORATORY

Principal Investigator: James H. Pielert
Building Materials Division
301.975.6704

Sponsor: American Association of State Highway and Transportation Officials

OBJECTIVE

To provide technical assistance, with AASHTO Research Associates at CBT, 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.

PROBLEM

The quality of testing in construction materials laboratories is an important concern when considering the overall question of quality construction. The importance of the testing function is demonstrated by The Strategic Highway Research Program (SHRP) which was initiated 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 important. The productivity of the testing community can be increased by using correct procedures and apparatus which reduce testing errors and provide a sound basis for the acceptance of materials on certificate. More efficient use of long-established construction materials and broader use of new materials are facilitated by dependable quality assurance programs.

APPROACH

With the support of AASHTO Research Associates working under CBT supervision, services are provided to public and private laboratories on a voluntary basis. These services include the on-site inspection of the laboratory and the distribution of proficiency test samples. The scope of the laboratory inspection services includes testing of soils, bituminous materials, and plastic pipe, and measurements of frictional properties of highways. Equipment and procedures used in performing

conventional quality assurance tests are evaluated for conformance to applicable national standards. Proficiency test samples of asphalt, soils, paint, aggregates, and bituminous concrete are distributed at regular intervals to obtain information on laboratory performance.

The primary benefit of the AMRL programs is improvement in the quality of testing laboratories testing materials used in the transportation industry. Products include: 1) detailed report on each inspection performed; 2) comprehensive report on each round of proficiency sample testing; 3) input to the work of standards committees such as draft standards and data which can be used for precision statement development or improvement; and 4) reports on the results of technical studies.

Use of AMRL services is voluntary and provided only as requested by interested laboratories. FHWA through its Federal-Aid-Highway Manual requests that each state subscribing to AMRL services, authorize copies of all inspection reports be forwarded to the appropriate regional and division offices. AMRL staff actively participate on standards committees and are often in leadership positions. Results of proficiency sample testing is routinely made available to ASTM and AASHTO committees. NIST technical reports, papers in outside journals, and oral presentations are used as appropriate.

The AMRL programs benefit construction materials testing laboratories and others involved with the nation's transportation systems: 1) improves the quality of laboratory testing; 2) provides data to quantify standard measurement techniques; and 3) provides direct communications between testing laboratories and standards-writing committees.

During 1990 CBT will 1) inspect 75 bituminous and 50 soil testing laboratories and issue inspection reports; 2) distribute 3500 proficiency test samples and issue test reports; and 3) implement a pilot program for calibration of road roughness measuring devices as approved by CBT and AASHTO.

RESULTS

Results of past year's efforts includes:

Inspected 82 bituminous and 57 soil testing laboratories and issued inspection reports.

Distributed 3600 proficiency test samples and issued reports of results.

REFRIGERANT MIXTURES

ZEOTROPIC REFRIGERANT MIXTURE PROPERTY EVALUATION

Principal Investigator: David A. Didion
Building Environment Division
301.975.5881

Sponsor: National Institute of Standards and Technology

OBJECTIVE To model the heat transfer characteristics of mixtures in the high- and low-quality ranges and to advance the fundamental knowledge of the mechanisms of two-phase boiling heat transfer of refrigerant mixtures.

PROBLEM CBT's research revealed that more surface area may be required for a given heat exchange with a binary mixture than for the same heat exchange with either pure component of the mixture. Scientists have not agreed on the causes of the heat transfer degradation that is associated with mixtures. There is a lack of understanding of key concepts that govern the boiling process of a mixture.

There are two major needs for predicting the capacity of mixture heat exchangers. The first is replacing refrigerants harmful to the atmosphere such as R11 and R12. The refrigeration industry is seeking a refrigerant which will not destroy the ozone layer and which has desirable heat transfer properties. Some azeotropic and near-azeotropic refrigerant mixtures meet both of these criteria. The second need is to develop a predictive theory for mixture heat exchangers to optimize refrigeration cycles. Experimental and theoretical results show zeotropic refrigerant mixtures can be used to enhance cycle performance. The enhancement of a predictive theory for mixture phase change is required to optimize the cycle performance. Past CBT research has determined thermodynamic and transport properties of mixtures essential in the evaluation of the heat transfer for mixtures. The heat transfer phenomena of boiling mixtures inside horizontal tubes was investigated by CBT for the mid-quality range (30–80%). The low- (0–30%) and high-quality (80–100%) ranges are important for predicting the heat load of heat exchangers. Further experimental heat transfer investigations are required in the low- and high-quality ranges.

APPROACH During 1990, research will be performed on the theoretical investigation of the boiling heat transfer of mixtures inside horizontal tubes. Modeling of the heat transfer will be guided by the knowledge of the governing parameters determined from the experimental results. The predictive theory will be used to experimentally investigate boiling heat transfer of mixtures in compact (enhanced) heat exchangers. The experimental and theoretical results of plain tubes will be used to determine new methods of enhancing of the boiling heat transfer of mixtures and also give insights for which existing compact heat exchangers need be tested. The predictive theory also will permit the development of the design and optimization of refrigerant mixture cycles. The cycles can be optimized with either conventional or compact heat exchangers. A technical report describing results of heat transfer experiments will be published in 1990.

RESULTS Results of past year's efforts include:

Jung, D. S., *Horizontal Flow Boiling Heat Transfer Using Refrigerant Mixtures*, EPRI Report ER-6364, May 1989.

Jung, D., McLinden, M., Radermacher, R., and Didion, D. A., "Horizontal Flow Boiling Heat Transfer Experiments with a Mixture of R22/R114," *International Journal of Heat and Mass Transfer*, Vol. 32, No. 1, pp. 131–145, January 1989.

Jung, D., "A Further Study of Horizontal Flow Boiling Heat Transfer Using Refrigerant Mixtures," *International Journal of Heat and Mass Transfer*, submitted for publication, 1989.

Kedzierski, M. A., and Didion, D. A., "Visualization of Nucleate Flow Boiling for a R22/R114 Mixture and Their Components," *Experimental Heat Transfer*, accepted for publication, 1989.

Jung, D. S. and Didion, D. A., "A Mixing Rule for Liquid Viscosities of Refrigerant Mixtures," *International Journal of Refrigeration*, Submitted for publication, 1989.

Jung, D. S., McLinden, M. and Radermacher, R. "Measurement Techniques for Horizontal Flow Boiling Heat Transfer with Pure and Mixed Refrigerants," *International Journal of Experimental Heat Transfer*, submitted for publication, November 1988.

MEASUREMENTS OF MODIFIED HP CYCLES USING TERNARY ZEOTROPIC REFRIGERANT MIXTURES

Principal Investigator: David A. Didion
Building Environment Division
301.975.5881

Sponsor: Department of Energy

OBJECTIVE To experimentally evaluate the thermodynamic and operational behavior of modified heat pump cycles and systems using ternary zeotropic refrigerant mixtures.

PROBLEM In recent years the research interest in use of zeotropic mixtures as working fluids for refrigeration systems has increased greatly. Substantial performance improvements using binary refrigerants have been demonstrated for air conditioning and heat pump operation. At the same time, limitations on the ability to obtain a desired two-phase temperature glide and temperature-enthalpy curve at a given capacity (or operating pressure) level have become apparent. These limitations have kept the observed performance improvements well under those theoretically predicted. As a result of new environmental concerns, this problem was exacerbated by reducing available pure refrigerants used in creating mixtures.

APPROACH The NIST hard-sphere equation-of-state or the NIST SUPERTRAPP molecular simulation program will be used to select the most appropriate mixtures for examination. A set of ternary mixtures will be selected to provide high linearity at a range of temperature glides from about 20 °F to 60 °F while operating at capacity levels and pressures similar to R22. Tests of these mixtures will be conducted on the CBT breadboard heat pump using the vapor compression and single solution circuit cycles. Vapor compression cycle tests will be performed with mixture compositions chosen to give evaporator refrigerant glides over a range of 25° to 55 °F.

RESULTS Results of past year's efforts include:

Buschmeier, M., Mulroy, W., and Didion, D. A., *An Initial Laboratory Evaluation of a Single Solution Circuit Cycle for Use with Nonazeotropic Refrigerants*, manuscript in review, expect publication in spring 1990.

Kauffeld, M., Mulroy, W., McLinden, M., and Didion, D. A., *An Experimental Evaluation of Two Nonazeotropic Refrigerant Mixtures in a Water-to-Water Breadboard Heat Pump*, manuscript in review, expected publication in spring 1990.

CFC REFRIGERANT PROPERTIES

Principal Investigator: David A. Didion
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301.975.5881

Sponsor: National Institute of Standards and Technology

OBJECTIVE To determine the decrease in evaporator capacity of the boiling phenomena of some alternative refrigerants and study the linearity control of the temperature profiles of a ternary zeotropic mixture.

PROBLEM Industry has reported the designated alternative, R123, for the current centrifugal compressor refrigerant R11, has a significant decrease in capacity ($\approx 15\% +$) when retrofitted in the same hardware system. The cause for this decrease is known to be in the evaporator but the fundamental reason from a nucleate boiling heat transfer viewpoint is not understood. Preliminary studies conducted by CBT have shown that the boiling nucleation for each of these refrigerants is different. Whether this is a refrigerant or surface phenomena or both has to be determined if the new R123 evaporators are to be optimized. A cooperative study among NIST, Penn State University, and Wieland Heat Exchanger Company was established to study this problem. NIST's responsibilities will focus on the basic thermodynamics and heat transfer of the nucleation process.

APPROACH This research will determine the quantitative knowledge of the "contact angle" that a nucleate bubble makes with the superheated surface. Ultimately, this property will be needed for both R11 and R123 with and without oil under both static (i.e., nonflow) and dynamic (i.e., flow) conditions for a smooth and a variety of enhanced surfaces. The best estimate of the contact-angle data to conduct the boiling analysis will be determined.

Ternary predictive properties routines will be developed producing binary and ternary zeotropic sets of data to illustrate the "linearizing effect of the third component. CBT will alter its "CYCLE 7" refrigeration system model to quantitatively evaluate the temperature glides and system performance improvements. A tutorial document (complete with models) will be drafted primarily for the benefit of other researchers and industry designers who are evaluating zeotropic systems.

RESULTS New project 1990.

PERFORMANCE EVALUATION OF CFC ALTERNATIVE REFRIGERANTS

Principal Investigator: David A. Didion
Building Environment Division
301.975.5881

Sponsor: National Institute of Standards and Technology

OBJECTIVE To determine how alternative refrigerants will perform in conventional and innovative refrigeration systems and determine the thermodynamic and transport properties of the alternate refrigerants.

PROBLEM

The model of a heat pump charged with a zeotropic mixture, HPBI, was developed at CBT and published in 1986. The original version of the model allows designers to evaluate the performance of a system charged with the mixture R13B1/R152a. Thermodynamic properties of the refrigerant mixture were evaluated by splines. In cases other than when the R13B1/R152a refrigerant mixture was used, new splines had to be developed for any single pair of studied fluids.

To alleviate the need to derive a new spline each time for a new fluid combination, the model was modified to employ a full algorithm of the Carnahan-Starling-DeSantis (CSD) equation of state developed by Morrison and McLinden. Tests of the CSD version of HPBI showed that the model required prohibitively extensive CPU times to converge even for the simplest convergence case (2–3 hours on Cyber 205). Large CPU requirements practically excluded the model from any intensive use.

APPROACH

CBT will modify the HPBI model to reduce significantly CPU requirements by implementing look-up table schemes for thermodynamic properties and modify the program so single-component refrigerants could be studied with the same hardware simulation package. CBT will expand the equation-of-state constants library to include two additional pure refrigerants and three mixtures. The thermodynamic properties calculations will be based on a set of look-up tables to reduce using the CSD equation-of-state routines. Saturation properties of vapor and liquid and two-phase dome properties will be evaluated by interpolating property values read from tables. The property tables will be generated by CSD EOS algorithms independent of HPBI once for a given refrigerant, mixture and composition. The library containing the equation-of-state constants will be expanded. Thermodynamic property measurements will be performed on two new refrigerants and three mixtures. A technical paper describing modifications to HPBI will be published in 1990.

RESULTS

Results of past year's efforts include:

McLinden, M. O. and Didion, D. A., "Thermophysical Property Needs for Environmentally-Acceptable Halocarbon Refrigerants," *Proceedings of the Tenth Symposium on Thermophysical Properties*, *International Journal of Thermophysics 10*, No. 3, pp. 563–576, May 1989.

Morrison, G. and McLinden, M. O., "Application of a Modified Hard Sphere Equation of State to Mixtures of Refrigerant Materials," *AIChE Journal* Manual #88PO1659, 1988.

Morrison, G. and McLinden, M. O., "Modeling Refrigerant Mixtures with Hard Sphere Equation of State," *AIChE Journal*, June 1988.

McLinden, M. O., "Thermodynamics Evaluation of Refrigeration in the Vapor Compression Cycle Using Reduced Properties," *International Journal of Refrigeration*, Vol. 11, pp. 134–143, 1988.

Gallagher, J., McLinden, M. O., and Morrison, G., "Thermodynamic Diagrams for Refrigerant Mixtures," *ASHRAE Transactions*, Vol. 94, Part 2, 1988.

SIMULATION OF REFRIGERATOR–FREEZERS OPERATING WITH NONAZEOTROPIC REFRIGERANT MIXTURES

Principal Investigator: David A. Didion
Building Environment Division
301.975.5881

Sponsor: Environmental Protection Agency

OBJECTIVE To modify an existing computer model of a vapor compression cycle to simulate a refrigerator's performance using different refrigerants and different configurations of components in the refrigerator.

PROBLEM An international agreement signed in 1987 in Montreal limits the world production of CFCs 11, 12, 113, 114, and 115–ozone layer depletes. "CFC-12" is used in a variety of vapor compression cycle based machines for home refrigerators and auto air conditioners. Other applications of CFC-12 include freezers, ice making machines, and centrifugal water chillers. The Montreal Protocol production limits of fully halogenated refrigerants put the refrigeration industry worldwide in a "crisis" situation. There appears little hope of finding a 100 percent CFC-12 compatible refrigerant; industry realizes that enormous effort is needed for readjustment and change of the established ways the systems are designed. This situation was reinforced by R134a, an ozone benign refrigerant replacement, not possessing the thermodynamic and thermophysical qualities of CFC-12; resulting in worse system efficiency.

APPROACH During 1990, CBT's research will focus on three tasks:

1. Perform a preliminary assessment of the performance of 11 candidate mixtures. The assessment will be based on the thermodynamic performance as simulated by the CBT simple cycle model. Work will focus on determining equation of state constants and assessing performance of the 11 mixtures.

2. Develop a first principles based, steady-state model of the Lorenz cycle refrigerator thermodynamic loop. The model will be of a modular structure. It will include independent models of major components linked together in the solution logic contained in the main program. The modular structure will allow model modifications to be introduced to investigate changes in hardware configuration. The model will allow performance simulation of systems charged with single component refrigerants and refrigerant mixtures. Thermodynamic properties of the working fluid will be calculated using the Carnahan-Starling-Desantis (CSD) equation of state with equation constants derived at NIST. Transport properties will be calculated using correlations and mixing rules (for mixtures), use data generated experimentally, or data generated by SUPERTRAPP. The model will be derived from a model developed a few years ago at CBT for a vapor compression heat pump operating with a nonazeotropic mixture, HPBI.

3. Validate a model using experimental data from an experiment conducted at the University of Maryland and then used as an extrapolation tool to suggest changes in the experimental setup which would promise performance improvements. Verification of a single evaporator model will include CFC-12 to establish confidence in the model and provide the "base" case data which performance of other analyzed systems will be compared. Simulation of a single evaporator refrigerator also will be performed for at least one addi-

tional single component refrigererant and one ternary mixture investigated as possible drop-in substitutes for CFC-12. The two evaporator model will simulate performance of several mixtures involving at least one component from the R140 series. Upon verification, other mixtures of any type for which sufficient property data exists may be simulated.

RESULTS New project 1990.

EVALUATION OF NONAZEOTROPIC HEAT PUMP CONCEPTS

Principal Investigator: David A. Didion
Building Environment Division
301.975.5881

Sponsor: Electric Power Research Institute

OBJECTIVE To experimentally evaluate new heat pump concepts that use nonazeotropic refrigerant mixtures by designing, constructing, modeling, and testing breadboard heat pump systems.

PROBLEM CBT has studied the use of nonazeotropic refrigerant mixtures in various heat pump cycles for the past 4 years under the sponsorship of EPRI and others. This work resulted in a considerable amount of quantitative data and has generated several engineering tools which enables an evaluation of specific designs of refrigerant systems using mixtures. Also, a general understanding has emerged of the requirements of a system design to maximize the performance benefits by mixtures under different operating conditions. From this data, 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.

APPROACH During 1990, CBT will perform five tasks:

1. Review present and proposed heat pump concepts that use nonazeotropic refrigerant mixtures and develop a recommended concept.
2. Develop a detailed breadboard design of the selected heat pump concept. Design the instrumentation, 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 check out 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 complete range of ARI (DOE) test points. Perform additional tests as necessary to establish annual performance for a variety of U.S. climates, characterize defrost operation, and establish oil compatibility with mixture components at both extreme high and low temperatures.

RESULTS New project 1990.

HEAT AND MOISTURE TRANSFER

ENVELOPE DESIGN GUIDELINES

Principal Investigator: Andrew K. Persily
Building Environment Division
301.975.6418

Sponsor: General Services Administration

OBJECTIVE To develop a thermal envelope design guide for Federal office buildings.

PROBLEM At present there are no guidelines for the design and construction of the thermal envelopes at office buildings even though large amounts of knowledge was generated during the past decade. During the 1980's many programs addressed field, laboratory, and analytical research to reducing energy use and to ensuring a comfortable and healthy indoor environment. Research focused on modeling: thermal performance of building envelopes, infiltration and air leakage in buildings, building ventilation systems, control of moisture damage in buildings. This work increased the knowledge of building envelope performance, building air tightness, principles governing air infiltration, migration of moisture into and through building envelopes, and interaction of building envelope tightness and performance of ventilation systems. This work revealed that the design of a cost-effective building envelope system which has good thermal performance, is air tight, resists moisture penetration and damage, and permits effective introduction of outdoor air into a building is not a simple process when all performance requirements are considered.

APPROACH CBT will develop a guide for the proper design and construction of Federal building thermal envelopes. The envelope design guide will be based on the principles involved in the design of a thermally efficient building envelope that is resistant to air-infiltration and moisture transfer. It also will address the importance of the envelope design on the performance of the building ventilation system. The emphasis of this guideline will be on the practical application of these principles to building design and construction. The information will be presented in a straightforward manner including case studies of "do's—don'ts" with graphic representations. The case studies will be aimed at a target audience of architects and engineers in order to have maximum impact on future building practice.

The development of this guideline builds on CBT's 1989 effort that included the development of a format for the guideline, the technical review of recent research on thermal and air tightness performance of commercial building envelopes and the identification of technical contributors that could serve as a resource to NIST in developing the guideline.

During 1990 CBT will work with the National Institute of Building Sciences to solicit voluntary contributions to the guidelines, to maintain liaison with organizations interested in the guideline development, and to coordinate a technical review of the guidelines when they are completed. CBT will prepare the envelope design guideline based on in-house expertise, the material obtained from outside technical experts and the material obtained by NIBS from voluntary contributors. A report on "Envelope Design Guidelines for Federal Office Buildings" will be published in 1990.

RESULTS Results of past year's efforts include:

Persily, Andrew K., *Development of Thermal Envelope Design Guidelines for Federal Office Buildings*, manuscript in review, expect publication spring 1990.

DYNAMIC EVALUATION OF THERMAL BRIDGES

Principal Investigator: Douglas M. Burch
Building Environment Division
301.975.6433

Sponsor: Department of Energy/Oak Ridge National Laboratory

OBJECTIVE

To develop and verify a mathematical procedure for predicting dynamic thermal performance of thermal bridges in building simulation computer models.

PROBLEM

Thermal bridges and anomalies have a significant effect on 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 1987, CBT developed a dynamic test method for calibrated hot boxes (CHBs) that characterized the dynamic thermal performance of wall specimens. This test method provided TFCs for a wall specimen that accounts for the effect of thermal bridges and anomalies. These empirical TFCs predicted the dynamic response of the wall specimen to sol-air diurnal temperature cycles. Based on this research, CBT prepared a draft ASTM standard dynamic test method.

APPROACH

The same approach will be applied to this research 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 thermal bridges to a dynamic excitation function. TFCs will be obtained by curve fitting the dynamic response to a transfer function equation. The TFCs will be used to predict heat transfer rates through each of the seven 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 a sophisticated building simulation computer model, called 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 computer simulations will be graphically compared. Analysis will be performed for northern, middle, and southern U.S. climates. Transfer function coefficients of seven thermal bridges will be predicted and included in computer simulations for a commercial building. A report on this research will be published in 1990.

RESULTS

Results of past year's efforts include:

TFCs were obtained for most of the thermal bridges in the building.

THERMAL RESISTANCE MEASUREMENTS OF CFC-REPLACEMENT FOAM INSULATION PRODUCTS

Principal Investigator: Robert R. Zarr
Building Environment Division
301.975.6436

Sponsor: Department of Energy/Oak Ridge National Laboratory

OBJECTIVE To establish a data base of the thermal properties at different mean temperatures for CFC-replacement foam insulation products entering the market.

PROBLEM The Environmental Protection Agency drafted regulations concurrent with international CFC restrictions agreed upon by 31 nations in Montreal on 16 September 1987. The treaty provides for limiting production of five fully-halogenated CFC refrigerants beginning July 1989 and phasing down production the following 9 years. Three refrigerants, R-11, R-22, R-113 are used to produce foam insulation products. As a result, the foam insulation industry will develop new foam products to replace those phased out of production. Thermal performance of the new products needs to be evaluated.

Industry requires a validated method for predicting the aging thermal characteristics of foam insulation using new CFC replacements. Several models were developed and published. In a collaborative effort with the researchers of these models, CBT will validate their models for the new materials by providing samples from the same lot that was measured with CBT's 1-meter guarded hot plate. The hot plate is capable of determining the thermal conductivity with an uncertainty of ± 1 percent.

APPROACH Five new foam materials of known age will be purchased from manufacturers. An initial set of thermal resistance measurements will be conducted using CBT's hot plate. The measurements will be conducted at three mean temperatures; 10 °C, 24 °C, and 38 °C in a one-sided mode of operation. The temperature difference will follow ASTM test method C-578; 28 °C. They will be repeated at regular time intervals at a mean specimen temperature of 24 °C. Time intervals will be 28 days, 90 days, and 90 days thereafter. An advisory panel with CBT and the model researchers will compare the experimental and analytical work to provide a correlation for modeling the thermal aging characteristics of the new foam product. A report on measurements will be published in 1990.

RESULTS New project 1990.

LONG-TERM THERMAL STABILITY OF CFC-BLOWN INSULATING FOAM BOARDS

Principal Investigator: Robert Zarr
Building Environment Division
301.975.6436

Sponsor: National Institute of Standards and Technology

OBJECTIVE To isolate the environmental and material factors adversely affecting the long-term, thermal performance of a CFC-blown, foam insulation board.

PROBLEM The R-value of CFC-blown foam boards changes over time as the thermal conductivity increases from air permeation into the foam cells after manufacture. This change is rapid at first, then slowing down to a long-term equilibrium value. This equilibrium value is used by architects to determine the thermal performance of the building envelope and eventually to size the heating and cooling equipment for a building.

In the past, this long-term equilibrium value was estimated by exposing foam panels in laboratory tests to high temperatures. Recent results from field exposed boards indicate laboratory obtained equilibrium value underestimates the true change in thermal performance of boards exposed outdoors. Results also indicate the need for additional knowledge on the interactions between the material and environmental factors which affect long-term thermal performance of foam boards.

APPROACH During 1990, CBT will determine the effects of laboratory exposure conditions on the physical and chemical properties of the cell walls of CFC-blown foam insulation board. The research will consist of characterizing the physical and chemical properties of the cell wall as a function of exposure environments. Among physical properties to be studied are cell wall thickness and integrity, cell wall modulus, and cell wall glass transition temperature using microscopic and thermal analytical techniques. Attempts to elucidate the mechanisms that lead to the changes in the rate of diffusion of the gases will be made. CBT will determine the thermal performance of these materials using its 1-meter guarded hot-plate. Specimens, one meter in diameter, will be cut from board stock of commercially available CFC-blown foams. Measurements of thermal conductivity will be performed at a mean specimen temperature of 24 °C (75 °F) at a temperature difference of 22 °C (40 °F) across the thickness of the specimen.

Techniques will be developed to sample and characterize physical and chemical properties of cell walls. A report will be published describing the results of the investigation during the summer of 1990.

RESULTS New project 1990.

MOISTURE TRANSFER MODEL FOR GENERATING MOISTURE GUIDELINES

Principal Investigator: Douglas M. Burch
Building Environment Division
301.975.6433

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

OBJECTIVE To develop a moisture property data base.

PROBLEM 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 absorbed within the outer layers of the wall. The accumulation of moisture within building materials has a profound effect on its thermal insulation properties. Mathematical models available are not able to accurately predict the degree of moisture accumulation in the components of typical

composite walls. As a result, costly experimentation is required because individual measurements cannot readily be extended to different wall geometries and different climates.

During 1989, the NIST Moisture Transfer Model was enhanced to include capillary transfer (i.e., transport by liquid water) and convection transfer (i.e., transfer by air infiltration and exfiltration). A computer program for the enhanced model was developed. This program is capable of predicting hourly moisture content distribution within different multilayer wall construction as a function of time. The program uses climate data from Weather Years for Energy Calculations (WYEC). This program was subsequently used to develop preliminary moisture control strategies for walls for inclusion in the DOE Moisture Handbook.

Reliable moisture property data needed as input for the NIST Moisture Transfer Model are unavailable in the literature. An examination of the moisture property data for each of common building materials reveals that 1) diffusion coefficients measured by different sources vary, 2) capillary diffusivity data exist for only a few common building materials, and 3) sorption isotherms (i.e., moisture content versus relative humidity) and suction curves (i.e., capillary pressure versus moisture content) do not exist for many common building materials.

APPROACH

During 1990 CBT will perform the following:

1. Determine the diffusion coefficient as a function of moisture content for 10 common building materials. Separate measurements will be performed at 24 °C and 6 °C.

2. Measure sorption isotherms for the 10 building materials. Separate adsorption and desorption measurements will be performed at 24 °C and 6 °C.

3. Develop measurement techniques to determine the capillary diffusivity of building materials. A measurement technique originally developed for wood will be applied to other building materials.

4. Compare the moisture property measurements from the above building materials to existing data in the literature, to determine the variability in the existing data.

5. Participate in the DOE Research Panel to provide technical guidance on developing a handbook containing moisture control guidelines and a research agenda.

A report on moisture property measurements will be published during 1990.

RESULTS

Results of past year's efforts includes:

Thomas, W. C. and Burch, D. M., "Experimental Validation of a Mathematical Model for Predicting Water Vapor Sorption at Interior Building Surfaces," *ASHRAE Transactions*, Vol. 96, Part 1, January 1990.

Burch, D. M., Thomas, W. C., Mathena, L. R., Licitra, B. A., and Ward, D. B., "Transient Moisture and Heat Transfer in Multilayer Nonisothermal Walls—Comparison of Predicted and Measured Results," *Proceedings of the ASHRAE/DOE/BTECC Conference, Thermal Performance of the Exterior Envelope of Buildings IV*, December 1989.

MOISTURE CONTROL IN MANUFACTURED HOUSING WALLS

Principal Investigator: Douglas M. Burch
Building Environment Division
301.975.6433

Sponsors: Department of Housing and Urban Development and
USDA, Forest Products Laboratory

OBJECTIVE To corroborate field measurements of eight test walls exposed to outdoor winter conditions in Madison, WI, using a mathematical model that predicts moisture accumulation in walls.

PROBLEM Many winter moisture problems in homes 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 from excessive indoor humidity—transported into the walls by way of air leakage. Conversely, results from previous research at 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.

The FPL is performing a field study, sponsored by HUD, to investigate the effects of indoor humidity and air leakage on the moisture accumulation within performance of manufactured housing walls. FPL will field expose eight test walls to outdoor climatic conditions in Madison, WI. Four walls of different construction will be tested with moderate indoor relative humidity (about 35%); other walls, identical to the four, will be tested with a high indoor humidity (50–60%). The effect of moisture on the heat transmission also is being investigated. CBT's mathematical model which predicts the time-dependent transfer of heat and moisture in multilayer walls, will be used to analyze the experimental results.

APPROACH During 1990, CBT will 1) provide and calibrate eight heat flux transducers to measure the effect of moisture on the heat transmission; 2) measure the permeability and sorption isotherms for wall materials for which transport property data is unavailable in the literature; 3) use FPL's measurements of hourly indoor and outdoor temperature and relative humidity to predict the measured moisture content for the eight walls; and 4) perform computer predictions using CBT's mathematical model to extend the field measurements for different indoor humidity conditions and outdoor climatic conditions. A final report will be published in the summer of 1990.

RESULTS New project 1990.

HEAT LOSSES FROM STRUCTURAL SUPPORTS OF DIRECTLY BURIED CONDUIT HEAT DISTRIBUTION SYSTEMS

Principal Investigator: Jin Fang
Building Environment Division
301.975.6417

Sponsor: Tri-Services Committee, Department of Defense

OBJECTIVE To predict the heat losses and surface temperatures of insulated piping and support systems and to determine the effects of thermal breaks on the reduction of the system heat losses.

PROBLEM Military facilities maintain approximately 6000 miles of heat and cooling distribution systems. The majority of these distribution systems are more than 25 years old. An extensive retrofit or replacement is anticipated from the deterioration of pipe insulation and corrosion of carrier pipes and conduit casings. The heat losses from insulated pipes to the surrounding soil account for the major portion of the operating costs. Piping system hangers and supports are a significant source of heat loss; they often are in contact with hot carrier pipes and form highly conductive heat flow paths.

CBT recently developed a computer program based on the finite element analysis to solve a two-dimensional steady-state heat transfer problems to quantify heat loss from thermal bridges due to pipe supports for shallow trench heat distribution systems. The calculated results indicated that slightly more than one-half of the total heat loss from the pipes occur at the supports and the omission of the supports in the estimation of the heat losses underestimates the heat loss by 100 percent. In the design of a new distribution system or for the improvement of the existing one, mathematical modeling can provide a relatively inexpensive and rapid means for evaluating the system performance with pipe supports. Such modeling can provide a basis for refining Guide Specification CEGS-15705 for improved design, construction and installation procedures of efficient heat distribution systems.

APPROACH During 1990, CBT's finite element computer models for directly buried conduit systems will be extended to predict heat losses and temperature distributions of sections of insulated pipes installed with typical piping hangers and supports. The computer programs will be implemented on a microcomputer as a user oriented software package. Validation of the mathematical models will be performed by comparing the predicted results with the field data obtained from the underground systems installed at Fort Jackson, SC, by the U.S. Army Cold Regions Research and Engineering Laboratory. A study will be performed to determine the effects of various thermal breaks applied to both direct-buried conduit and shallow trench heat distribution systems on the reduction of heat losses through pipe supports and anchors. A report, *Determination of Heat Losses Due to Structural Supports for Directly Buried Conduit Heat Distribution Systems*, will be published.

RESULTS Results of past year's efforts include:

Fang, Jin B., *Quantification of Heat Losses Through Structural Supports for Shallow Trench Heat Distribution Systems*, NISTIR 89-4134, October 1989.

Fang, Jin B. and Grot, Richard A., *Evaluation of Thermal Probe Method for Estimating the Heat Loss from Underground Heat Distribution Systems*, NISTIR 88-4009, December 1988.

INDOOR AIR QUALITY

INDOOR AIR QUALITY MODELING

Principal Investigator: Richard A. Grot
Building Environment Division
301.975.6431

Sponsor: Department of Energy

OBJECTIVE To develop validated computer models for predicting the temporal and spatial distributions of airflow velocity, contaminant concentration, and ventilation effectiveness within buildings.

PROBLEM The concentrations and duration of indoor pollutants in a space are a complex function of the proximity to pollutant sources, ventilation and infiltration, chemical reaction between pollutants, and adsorption or absorption of pollutants on indoor surfaces. To reduce energy consumption in buildings and to maintain acceptable indoor air quality, detailed information is needed of the flow field and concentration distributions of contaminants in rooms.

Finite difference computer models were developed by CBT to predict three-dimensional airflow fields and contaminant concentration distributions in ventilated compartments. These models were formulated based on mass, momentum, and energy balance equations coupled with expressions for transport of turbulence kinetic energy and its dissipation rate, and using primitive variables including flow velocity, pressure and temperature as dependent variables.

APPROACH During FY 1990, CBT will develop computational procedures to predict the ventilation efficiency in buildings using the micromodels. Numerical predictions will be performed to evaluate the effects of air exchange rates, the locations of inlet and outlet air diffusers and obstacles on airflow rates, ventilation effectiveness and indoor contaminant concentration distributions in a ventilated room. The predicted results from the micromodels will be compared with the experimental data obtained from CBT's research in a large commercial office building. Additions of chemical reaction and removal terms to the equation for conservation of chemical species will be incorporated into the micromodels so they are capable of simulating the transformation and removal processes of indoor contaminants. This research will be published as, *Mathematical Models Describing Ventilation Within a Room*.

RESULTS Results of last year's efforts include:

Kurabuchi, T., Fang, Jin, and Grot, Richard A., *A Numerical Method for Calculating Indoor Airflows Using a Turbulence Model*, NISTIR 89-4211, January 1990.

Fang, Jin B. and Grot, Richard G., "Numerical Simulation of the Performance of Building Ventilation System," *ASHRAE Transactions*, Vol. 96, Part 1, January 1990.

Axley, James W., and Grot, Richard A., "The Coupled Airflow and Thermal Analysis Problem in Building Airflow System Simulation," *ASHRAE Transactions*, Vol. 95, Part 2, June 1989.

Fang, Jin B., Grot, Richard A., and Kurabuchi, T., "Application of Mathematical Modeling to the Evaluation of Building Ventilation Systems," *Proceedings of 9th Air Infiltration and Ventilation Center Conference*, 1989.

VALIDATION OF INDOOR AIR QUALITY DISPERSAL MODELS

Principal Investigator: Richard A. Grot
Building Environment Division
301.975.6430

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop a laboratory facility for validating indoor air quality dispersal models and interzonal airflow models.

PROBLEM There is a need to develop a facility to validate indoor air quality models. Insufficient resource data exists to validate CBT's advance indoor air quality analysis models for predicting the extent, severity, and duration of indoor air pollution problems in buildings.

APPROACH A reconfigurable multizone test facility will be designed and constructed in one of CBT's environmental chambers to perform controlled experiments under simulated environmental conditions. This facility will be 1/4 to 1/2 scale to permit multizone configurations consisting of 5 to 10 zones and 1 to 4 floors. During FY 1990, an engineering study of the technical requirements for this facility and a study to assess the feasibility of modifying and using existing CBT facilities such as the heat-of-light facility for the validation of indoor air quality and multizone airflow models will be performed. A report on the technical specifications of a facility for validation multizone indoor air quality models will be published.

RESULTS New project 1990.

INFILTRATION/VENTILATION—LARGE BUILDINGS

Principal Investigator: Richard A. Grot
Building Environment Division
301.975.6431

Sponsor: Department of Energy

OBJECTIVE To develop test methods for evaluating air movement into and within large commercial buildings and to determine the efficiency of commercial building's ventilation systems as a method for removing contaminants at minimum energy cost.

PROBLEM In comparison to residential buildings, little data exists on air leakage and air movement in large commercial structures. Existing data indicates there is a wide range of air leakage rates in large buildings. Previous DOE/CBT research has demonstrated that large buildings experience under- and over-ventilation during their annual operation. 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.

In FY 1989, CBT developed test methods to evaluate the ventilation and indoor air quality of the Madison Building, Library of Congress. These test methods included measurements of air exchange rates, ventilation effectiveness and internal airflow rates. Also, measurements were made of contaminant levels and their

spatial distribution. The contaminants include CO_2, CO, respirable particles in five ranges spanning 0.3 to 10 micrometers, formaldehyde and radon.

APPROACH During FY 1990, CBT will evaluate ventilation and air distribution effectiveness using existing techniques and new procedures employing an integral pulse technique. These measurements produced 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 measurements will be directed toward quantifying the uniformity of ventilation air distribution in the building and determining exactly which procedures are most applicable for field applications. The results of this research will be published as two reports; *Use of the Pulse Injection Technique in Assessing Ventilation Effectiveness in Buildings* and *The Relationship of Ventilation System Performance and Indoor Levels of Contaminants in the Madison Building*.

RESULTS Results of past year's efforts include:

Persily, Andrew K., Dols, W. S., *Ventilation and Air Quality Investigation of the Madison Building Phase I Report*, NISTIR 89-4219, December 1989.

Hill, J. E., "Techniques for Investigating Building Indoor Air Quality," *Proceedings of the International Symposium on Heat and Mass Transfer in Building Materials and Structures*, Dubrovnik, Yugoslavia, September 1989.

Persily, Andrew K. "Ventilation Rates in Office Buildings," *Proceedings of ASHRAE IAQ '89 The Human Equation: Health and Comfort,* San Diego, CA, April 1989.

Persily, A. K. and Dols, W. S., "The Relation of CO_2 Concentration to Office Building Ventilation," *Proceedings of ASTM Symposium on Air Change Rate and Air Tightness in Buildings*, April 1989.

Persily, A. K. and Axley, J., "Measuring Airflow Rates with Pulse Tracer Techniques," *Proceedings of ASTM Symposium on Air Change Rate and Air Tightness in Buildings*, April 1989.

Axley, J. and Persily, A., *Integral Mass Balances and Pulse Injection Tracer Techniques*, NISTIR 88-3855, October 1988.

GASEOUS CONTAMINANTS FROM AIR STREAMS

Principal Investigator: Richard A. Grot
Building Environment Division
301.975.6430

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop methods for measuring the efficiency of filters to remove gaseous contaminants from air.

PROBLEM Filtering devices using granular materials called sorbers, such as activated carbons and chemically-treated alumina and other organic substances are used to remove or chemically change gaseous pollutants in buildings. These devices can

be incorporated into the building's heating, ventilation and air conditioning (HVAC) systems, similar to filters used for removing particulates. No general procedures are available for evaluating the effectiveness of these gaseous removal devices. Methods are needed to evaluate these devices for improved indoor air quality.

APPROACH

During FY 1990, CBT will use results from its FY 1989 research on test methods to evaluate the effectiveness of filter media for removing gaseous contaminants from air. Since source strengths of many gaseous contaminants vary with time, this effect will be considered in test procedure for gaseous removal equipment for indoor air quality control. Also, research will focus on the response of the gaseous filter to a single contaminant. Gaseous contaminants are not encountered individually in buildings and an effectiveness of the removal device in the presence of several contaminants will be included in the test procedure. The results of this work will be published as test procedure for gaseous removal devices.

RESULTS

Results of past year's efforts include:

Mahajan, Bal, *A Method for Measuring the Effectiveness of Gaseous Contaminant Removal Filters*, NISTIR 89-4119. July 1989.

COMPUTER INTEGRATED CONSTRUCTION

INFORMATION EXCHANGE TECHNOLOGIES IN THE BUILDING PROCESS

Principal Investigator: Mark E. Palmer
Building Environment Division
301.975.5858

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop the technical basis for correct and efficient information standards for the building industry.

PROBLEM Computers have well penetrated the building process: design, construction, and operation. Yet, little integration of these traditionally separate activities has occurred because there are few effective standards for expressing and exchanging information about buildings. Participants in the building process continue to be plagued by errors and inefficiencies. Reasons include: information is not available in digital form when needed; it is incorrectly transmitted from the sending system; or it is incorrectly interpreted by the receiving system. Rational techniques are needed for developing and testing 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), addresses basic data describing mostly geometric but some nongeometric elements and their graphical representation. The specification lacks protocols required to ensure its successful use in applications and the supporting methodology and test cases required to validate software implementation. Since IGES-based data exchange is the only choice for the building industry for the near future, development of application protocols is essential.

National and international committees are developing the next generation standard, called the Product Data Exchange Specification (PDES) in the United States and the Standard for the Exchange of Product Model Data (STEP) in the ISO TC/184. Unlike IGES, the new standard is intended to facilitate the exchange of complete product definition data sets rather than arbitrary collections of data elements. A method must be developed for smoothly bridging the existing IGES-based data exchange and the future PDES/STEP-based data exchange.

APPROACH During 1990, CBT will continue the development of AEC application protocols, work that was initiated in FY 1988. CBT with Federal and industrial partners will:

- refine and test the initial 3-D Piping Application Protocol whose underlying conceptual model was developed in FY 1989,
- develop an initial conceptual model of HVAC system information,
- explore the technical requirements to catalog data in the modeling of distribution systems, and
- coordinate its work with the national and international standardization committees.

CBT will continue to analyze, extend, and integrate conceptual models developed for the building industry in the PDES/STEP activity. They will focus on the technical problems that arise in dealing with differing levels of abstraction and with parameterizations. Work will continue on developing a building product

model prototype that was initiated in FY 1989 in a cooperative research project with the Technical Research Centre of Finland. CBT's work will serve as case studies to the PDES/STEP integration activity.

During 1990, reports will be published on parameterization of product models and on the integration of STEP/PDES information models describing successful and unsuccessful approaches.

RESULTS Results of past year's efforts include:

Overview of the IGES/PDES Testing Project—Version 1.0, NISTIR 89-4207, December 1989.

Guidelines for the Specification and Validation of IGES Application Protocols, NISTIR 88-3846, January 1989.

"Product Modeling of Buildings for Data Exchange Standards—From IGES to PDES/STEP and Beyond," Invited paper at joint CIB W74/W78 Seminar in Lund, Sweden, October, 24–28 1988.

PRODUCT DATA EXCHANGE STANDARDS IN SHIPBUILDING

Principal Investigator: K. A. Reed
Building Environment Division
301.975.5852

Sponsor: Department of Navy

OBJECTIVE To develop the technical basis for correct and efficient information interchange standards for the shipbuilding industry.

PROBLEM The Navy-Industry Digital Data Exchange Standards Committee (NIDDESC) was created in 1986 by the U.S. Navy Sea Systems Command and the National Shipbuilding Program of the Society of Naval Architect and Marine Engineers. NIDDESC is a cooperative effort involving Navy and industry technical experts in CAD applications.

NIDDESC is working toward implementations in three time frames. Their near-term implementation plan requires using the Initial Graphics Exchange Specification (IGES) for transferring 3-D geometry and builder's data. The tasks in this time frame are designed to give nearly immediate enhancements in the ability to transfer data between current CAD systems by defining recommended practices and application protocols for the use of IGES. The mid-range implementation plan involves development of enhancements to the IGES standard to facilitate the transfer of ship product data. The long-range implementation plan involves influencing the development of the Product Data Exchange Specification (PDES), known as the Standard for the Exchange of Product Model Data (STEP) internationally. Specific activities are the development of information models for ship structural systems and distribution systems.

APPROACH CBT is leading the development of the application protocol methodology in its role as the chair of the Application Validation Methodology Committee in the IGES/PDES Organization. Working with NIDDESC, CBT will perform six tasks:

1. Complete the development of the 3-D Piping IGES Application Protocol and submit it as a draft amendment to the MIL-D 28000 "Digital Representation for Communication of Product Data: IGES Application Subsets."

2. Wwith representatives of the process industry, generalize the piping application protocol where necessary to accommodate process plant data and ship data.

3. With NIDDESC and representatives of the construction industry, develop similar IGES application protocols for HVAC data and for structural data.

4. Serve as the IGES Editor for the IGES/PDES Organization and work with NIDDESC to develop requests for change and guide them through ballot and change order phases.

5. Enhance and integrate with other models, the ship structural systems information model that is in the First Draft Proposal for STEP.

6. Complete an information model for distribution systems and guide it through the committee process for inclusion in a future draft proposal.

A report will be published on NIDDESC at the end of 1990.

RESULTS New project 1990.

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

OBJECTIVE To develop an Emulator/Tester for evaluating the performance and diagnosing problems with Building Energy Management Systems (BEMS) and to represent DOE on the IEA Annex 17 Committee.

PROBLEM The proper operation and control of buildings involves the complex interaction of numerous control loops and many pieces of equipment. Buildings and building systems are complex; they require new generation of computerized Building Energy Management Systems (BEMS) and test methods and diagnostic tools for evaluating their performance. Research is needed on: 1) the development of test procedures and instrumentation for evaluating the performance of existing and future BEMS, and 2) the creation of rule-based systems which will provide diagnostic information on BEMS application software. These tools could be incorporated into the BEMS systems by manufacturers to assist in making real-time control decisions.

APPROACH Research in FY 1990 will concentrate on 1) completing an Emulator/Tester to evaluate BEMS performance and 2) creating a prototype expert system to be used with the Emulator/Tester to detect problems associated with BEMS application software. The Emulator/Tester work will be performed in support of IEA's Annex 17. It will employ a 386 machine using a multitasking operating system and a commercially available process control program. The latter will be interfaced with a data acquisition system and 3COM network to permit communication with another 386 computer running an HVACSIM+ building/HVAC simulation model.

RESULTS Results of past year's efforts include:

Kelly, G. E. and May, W. B., "The Concept of an Emulator/Tester for Building Energy Management System Performance Evaluation," *ASHRAE Transactions*, Vol. 96, Part 1, 1990.

Liu, S. T. and Kelly, G. E., "Diagnostic Method for Air Handling Unit Fault Detection Using Knowledge-Based Programming," *Proceedings of the International Building Performance Simulation Association—Building Simulation '89*, Vancouver, Canada, June 23-24, 1989.

ADVANCED BUILDING SYSTEM SIMULATION

Principal Investigator: George Walton
Building Environment Division
301.975.6421

Sponsor: Department of Energy

OBJECTIVE To explore the development of a methodology to incorporate the short term, dynamic effects of local control loops in long term energy calculations in support of the future Energy Kernel System (EKS) under development by Lawrence Berkeley Laboratory.

PROBLEM Lawrence Berkeley Laboratory proposed an EKS based on a prototype software system called SPANK (Simulation Problem Analysis Kernel). Studies at CBT in FY 1988 using SPANK, HVACSIM+, ESP, and other simulation programs showed that one of the biggest obstacles to developing EKS is the local control loop dynamics in long term energy simulations. 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 have generally been unsuccessful. Needed is a method which incorporates the effect of these short-term dynamics into longer-term, less dynamic variables for use in energy studies.

APPROACH During 1990, CBT is simulating various types of local control loops commonly encountered in building systems using its HVACSIM+ Program, TRNSYS, and other simulation tools capable of computing highly nonlinear differential equation. Studies will be conducted to determine the effect of typical variations in state variables, as loads, temperatures, flow rates, control parameters, on control loop performance as it effects energy consumption. Simulation experiments will be conducted 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 short- and long-term dynamics. A report summarizing results of various simulation studies for short-term control loop dynamics in long-term energy calculations will be published in 1990.

RESULTS Results of past year's efforts include:

"Airflow Network Models for Component Based Building Airflow Modeling," *ASHRAE Transactions*, Vol. 95, Part I, 1989.

"Considerations for Advanced Building Thermal Simulation Programs," *Proceedings of the International Building Performance Simulation Association—Building Simulation '89,* Vancouver, Canada, June 23–24, 1989.

AIRNET—A Computer Program for Building Airflow Network Modeling, NISTIR 89-4072, April 1989.

COMMUNICATION PROTOCOLS FOR BUILDING CONTROLS

Principal Investigator: Steve Bushby
Building Environment Division
301.975.5873

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop, evaluate, and test communication protocol standards for the open exchange of information between equipment from different control vendors and between different levels of control in both hierarchal and distributed building management systems.

PROBLEM For 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 made it possible to distribute "intelligence" throughout a building. Centrifugal chillers and package air handling systems are manufactured with their own digital controls. 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.

The previous and present generation of EMCS and DDC systems generally employ proprietary communication protocols which prevent systems supplied by different manufacturers from communicating with each other. This results 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. Needed are standard communication protocols for building management systems and DDC building control systems. The computer, data processing, and communication industries are working on standard network protocols through standard writing organizations such as ISO, IEEE, and CCITT. ASHRAE has established a Standards Project Committee, SPC 135, to develop standard Messaging Protocols for EMCS applications.

APPROACH During 1990, CBT will:

1. Develop, with ASHRAE and the building industry, standard communication protocols to exchange building service information between different vendor systems and between different levels of intra-system communication.

2. Develop testing and evaluating facilities to study different protocols and determine compliance of vendor's equipment to proposed or finalized standards.

3. Develop and verify a "reference implementation" of proposed and finalized protocol standards and develop procedures for performance and compliance testing.

4. Develop a compliance testing suite to facilitate protocol evaluation at each level of system communication to serve as diagnostic tools for trouble shooting and assigning responsibility in cases 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.

6. Develop techniques for designing and evaluating building communication systems encompassing integrated services.

This research will be performed with industry; they will use CBT's facilities to evaluate the interconnectability of their systems to those of other manufacturers. Two reports on EMCS protocols will be published in 1990. One will address protocol reference implementation; the other will focus on compliance testing.

RESULTS Results of past year's efforts include:

Bushby, S. T., "Testing Conformance to Energy Management and Control System Communication Protocols—Part 1: Test Architecture," *ASHRAE Transactions*, Vol. 96, Part 1, 1990.

Bushby, S. T., "Testing Conformance to Energy Management and Control System Communication Protocols—Part 2: Test Suite Generation," *ASHRAE Transactions*, Vol. 96, Part 1, 1990.

Bushby, S. T. and Newman, H. M., "Standardizing EMCS Communication Protocols," *ASHRAE Journal,* Volume 31, No. 1, pp. 33–36, January 1989.

DESIGN GUIDELINE FOR VAV SYSTEMS

Principal Investigator: James Kao
Building Environment Division
301.975.5871

Sponsor: General Services Administration

OBJECTIVE To develop a design guideline for variable air volume (VAV) Systems in GSA owned and operated buildings.

PROBLEM VAV systems are effective energy saving air handling systems for modern office buildings. However, numerous problems associated with their design and operation were documented. These problems include poor air quality, inadequate supply of ventilation air, control instability, system noise, inability to meet loads under certain conditions, poor humidity control, insufficient ventilation air, and pressurization imbalances making it difficult to open doors. The sources of most of these problems are well understood and can often be traced to inadequate design.

CBT surveyed two GSA buildings during FY 1989 to determine the general characteristics of installed VAV systems and to identify problems associated with different designs and operating practices. The survey included discussing VAV operating and performance issues with building managers, operating staff, and occupants, and analyzed data on zone airflow rates, zone temperatures and ventilation air quantities, where available.

APPROACH In FY 1990, CBT will expand its survey to 12 buildings selected by GSA. The knowledge gained from these surveys on what works and what does not, and relating problems to design inadequacies, coupled with information obtained from a review of published research results on the performance of VAV systems, and recommendations provided by technical experts in the field (particularly those associated with control companies) will be used to develop a Design Guideline for VAV Systems in Federal Office Buildings. CBT will author a report on recommended revisions to "Facilities Standards for PBS" and the design guidelines publication in 1990. The guidelines will address configuration, zoning, equipment, controls, types of components, sizing, noise, ventilation, and distribution.

RESULTS Results of past year's efforts include:

Completed a literature search on the performance of VAV systems and field surveys on two Federal Buildings in Boston and Spring Field, MA.

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

OBJECTIVE To provide equitable testing and rating procedures for determining the energy performance of central residential furnaces, boilers, and household heating equipment.

PROBLEM The Energy Policy and Conservation Act (PL 94-163) (EPCA), as amended, requires DOE to prescribe test and rating procedures and minimum performance standards for various residential appliances. Its 1987 amendment requires 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.

Combination appliances are increasingly common and new designs which integrate the functions of space heating, space cooling, domestic hot water heating, and zoning, are continually entering the market. CBT is using its HVAC Simulation Plus (HVACSIM+) Program as the basis for modeling the performance of new integrated space and water heating equipment as they develop these test procedures. In FY 1988, NIST developed HVACSIM+ compatible component models for boilers equipped with tankless coils for domestic water heating, water storage tanks, water-to-water and water-to-air heat exchangers. In FY 1989, the boiler and tankless coil models were validated through experimental studies and a test procedure was developed and proposed for ASHRAE Type I appliances (boilers with tankless coils).

APPROACH In FY 1990, CBT's efforts will concentrate on integrated space/water heating appliances as five tasks:

1. Complete experimental and simulation research on ASHRAE Type II appliances—water heaters with external storage tanks.

2. Evaluate proposed ASHRAE Standard 124P and develop new testing and rating procedures for Type II appliances as required.

3. Perform simulation studies on the annual performance and annual cost of operation of various types of combination space/water heating appliances and publish the results as an ASHRAE Technical or Symposium paper.

4. Assist DOE in preparing a draft Federal Register Notice of Proposed Rulemaking on the Furnace Test Procedure, including waivers that were granted such as fan delay settings. Also, assist in evaluating possible adoption of ASHRAE's Standard 103 for Furnaces and Boilers and Standard 124 for Combination Space/Water Heating Appliances for inclusion in the DOE Test Procedures.

5. Assist DOE in reviewing petitions for waivers from the Furnace Test Procedure such as for use of inlet burner dampers.

6. Perform experimental testing of an advanced small mass boiler to determine the effect of hot water purging and storage tank stratification on annual performance and determine how to account for these effects in the proposed combination space/water heating test procedure.
7. Perform research to assist ASHRAE SPC 103, in making corrections and future refinements to the Furnace Test Procedure.

Two reports will be published in 1990. One will address testing and rating methodology for ASHRAE Type II appliances, including results of experimental validation. The other will focus on the energy performance and cost of operating various types of combined space/water heating appliances.

RESULTS Results of past year's efforts include:

Park, C. and Kelly, G. E., *A Study of the Performance of Residential Boilers for Space and Domestic Hot Water Heating*, NISTIR 89-4104, June 1989.

TEST METHODS FOR HEAT PUMPS AND AIR CONDITIONERS INTEGRATING THERMAL ENERGY STORAGE AND DOMESTIC WATER HEATING

Principal Investigator: George E. Kelly
Building Environment Division
301.975.5870

Sponsor: Electric Power Research Institute

OBJECTIVE To develop a uniform test method for integrating thermal energy storage and domestic water heating in heat pumps and air conditioners.

PROBLEM During the recent past, various electric utilities are offering demand-side management programs to their residential and commercial customers. Unitary heat pumps with integrated heat and cool storage could improve the electric utility residential demand-side management programs by shifting some on-peak electric demands to off-peak periods. These systems are in the emerging technology stage. Manufacturers have unique hardware design and unique control strategies. There is a complex coupling between the building load and operating mode of the integrated heat pump which extends over a 24-hour, or longer, period. EPRI's report, "Assessment of Unitary Cool Storage Systems" [EPRI CU-6376], describes some of the different designs employed for heat pump systems with integrated heat/cool storage. The equipment and control strategies illustrated in the EPRI report are indicative of the complexity of the modeling, testing and rating, and performance evaluation problems associated with heat pumps with integrated storage.

APPROACH CBT's research involves six tasks:

1. Survey existing simulation programs, public domain and licensable or purchasable computer programs for simulating heat pump, air conditioner, thermal energy storage system and water heater capacity, and power demand (e.g., HPEAK, TESCOMP, TRNSYS, EPRI's water heater codes, and others) as a basis to begin developing computer models.

2. Review existing equipment, technical literature, and other information on the performance parameters, operating modes, and control schemes of IHPs on the market or in the advanced development stage.

3. Develop a general flow chart for the proposed simulation model, identifying the major submodels and subroutines and the general computational sequence. Identify input data requirements and the form of output reports, including graphic displays. This model will conform (but not be limited to) the following specifications:

   - conform to programming guidelines and section documentation of EPRI personal computer software specifications;

   - use, as appropriate, data from standard laboratory tests of DOE, ARI, GAMA, and ASHRAE test procedures for rating the performance of heat pumps, air conditioners, and water heaters, and identify additional test points as required;

   - capable of using standard NOAA weather data;

   - produce electric energy consumption, power demand, efficiency, and other performance data to the appropriate hourly, daily, monthly, seasonal, and annual intervals, to allow comparison of IHP systems to conventional pace conditioning and water heating equipment.

4. Develop detailed work plan/program development and validation, including task and major subtask schedules and timing of deliverables.

5. Write and test computer code in conformance with the program outline of task 3. Document written computer code and maintain a glossary of constants and variable names, constant values used as parameters, names of input and output files, functions and subroutines, flags, and loop parameters which will assist other users to understand the code.

6. Develop work plan for a phase II—laboratory benchmark testing and simplified testing and rating method development.

Reports on this portion of the research will be published in the fall of 1990.

RESULTS New project 1990.

HEAT PUMP AND AIR CONDITIONER TEST PROCEDURES

Principal Investigator: David A. Didion
Building Environment Division
301.975.5881

Sponsor: Department of Energy

OBJECTIVE 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.

PROBLEM The Energy Policy and Conservation Act (PL 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 requires analysis of any test procedure amendments to determine their effect on minimum efficiency standards. Since 1975, DOE has relied on CBT to assist in the development of the test and rating procedures.

APPROACH This work is being performed in six tasks:

1. Participate in ASHRAE Standard Project Committee 116 on developing a standard for evaluating the seasonal performance of air conditioners and heat pumps. CBT has contributed a significant amount of the technical material making up the proposed ASHRAE Standard. CBT will participate in the review of the standard and will respond to public comments from its public review and will prepare the final draft of the Standard.

2. Evaluate various design options for future air conditioners and heat pump's efficiency improvements for various design options. The evaluation will consist of computer verification using the steady-state heat pump model, HPSIM, and laboratory experiments.

3. Develop a performance data base for the "first generation" of variable heat pumps to evaluate performance improvements in new models. A variable speed, commercially available system will be tested according to DOE's cooling and heating mode rating procedure.

4. Evaluate feasible seasonal operating cost savings through employing smart controls in air conditioners. CBT will perform a parametric study to evaluate potential operating cost savings resulted from various operating schemes. The operating advantages may materialize from various facets of operation. The work will be based on computer simulations performed for conditions within the comfort zone along the constant comfort lines. The CBT heat pump model—HPSIM, will be used. This work will focus on finding the limits of feasible savings in operation for the cooling season.

5. Complete a rating procedure for mixed systems operating in the heating mode early in 1990 and provide the basic correlations on a floppy disk. CBT will review alternate rating procedures proposed by manufacturers and recommend to DOE whether they are technically acceptable.

6. Assist DOE in reviewing petitions for waivers from the Federal Test Procedure. Early in FY 1990, CBT received a petition to review from a European manufacturer, a windowless, ductless, evaporative spot cooler for consideration under the FTC labeling program.

RESULTS Results of past year's efforts include:

Aaron, D. A. and Domanski, P. A., "Experimentation, Analysis, and Correlation of R-22 Flow Through Short Tube Restrictors," *ASHRAE Transactions*, Vol. 96, Part 1, January 1990.

Domanski, P. A., *EVISM—An Evaporator Model Accounting for Refrigerant and Air One Dimensional Distribution*, NISTIR 89-4134, August 1989.

Aaron, D. A. and Domanski, P. A., *An Experimental Investigation and Modeling of the Flow of Refrigerant 22 Through the Short Tube Restrictor*, NISTIR 89-4120, July 1989.

Domanski, P. A., *Rating Procedure for Mixed Air Source Unitary Air Conditioners and Heat Pumps Operating in the Cooling Mode—Revision 1*, NISTIR 89-4071, May 1989.

Chwalowski, M., Didion, D. A., and Domanski, P. A., "Verification of Evaporator Computer Models and Analysis of Performance of an Evaporator Coil," *ASHRAE Transactions*, Vol. 95, Part 1, January 1989.

A RATING METHOD FOR INTEGRATED HEAT PUMP/WATER HEATING APPLIANCES

Principal Investigator: Brian P. Dougherty
Building Environment Division
301.975.6396

Sponsors: Department of Energy and Electric Power Research Institute

OBJECTIVE To provide equitable testing and rating procedures for determining the energy performance of integrated heat pump/water heating appliances.

PROBLEM The Energy Policy and Conservation Act (PL 94-163), as amended, requires DOE to prescribe test and rating procedures and minimum performance standards for various residential appliances. DOE has, since 1975, relied on CBT to assist in the development of the test and rating procedures; and to be a technical consultant on waiver petitions from industry for needed changes to existing DOE test procedures so they adequately cover new appliances.

During the past year, CBT developed a proposed methodology for rating appliances where a heat pump and a storage-type water heater are integrated.

APPROACH During 1990, CBT is performing extensive laboratory testing on an integrated heat pump/water heating appliance that possesses many technical innovations (variable speed modes, water-source defrost cycles). The information will provide a means for evaluating the appropriateness of the proposed tests and insight for making any needed modifications. A report summarizing the tests conducted and the test results will be published in 1990.

RESULTS Results of past year's efforts include:

Dougherty, B. P., *A Proposed Methodology for Rating Air-Source Heat Pumps that Heat, Cool, and Provide Domestic Water Heating*, NISTIR 89-4154, August 1989.

WATER HEATER TEST PROCEDURES

Principal Investigator: A. Hunter Fanney
Building Environment Division
301.975.5864

Sponsor: Department of Energy

OBJECTIVE To provide equitable testing and rating procedures for determining the energy performance of conventional water heaters.

PROBLEM The Energy Policy and Conservation Act (PL 94-163), as amended, requires the Department of Energy (DOE) to prescribe test and rating procedures and minimum performance standards for various residential appliances. In its 1987 amendments, analyses are required for 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.

APPROACH CBT will perform five tasks:

1. Analyze test results of the first-hour rating procedure for residential water heaters as published in the March 1987 Federal Register and prepare a revised first-hour rating procedure. The published rating procedure was claimed as not producing repeatable results.

2. Continue developing a test procedure for an "Off-Peak" water heater.

3. Install a humidity transducer within the water heater laboratory so heat pump water heaters may be tested in the future.

4. Assist DOE in their review of petitions for waivers from the Federal Test Procedure.

5. Assist in the design and fabrication of the integrated heat pump laboratory.

A report on the field performance of desuperheated water heaters will be published in 1990.

RESULTS Results of past year's efforts include:

Fanney, A. H., "The Measured Performance of Residential Water Heaters Using Existing and Proposed Department of Energy Test Procedures," *ASHRAE Transactions*, Vol. 96, Part 1, January 1990.

MONITORING OF AN ADVANCED VARIABLE-SPEED INTEGRATED HEAT PUMP/WATER HEATING APPLIANCE

Principal Investigator: A. Hunter Fanney
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301.975.5864

Sponsors: Allegheny Power and Potomac Edison Company

OBJECTIVE To instrument and monitor a field installation of a variable-speed integrated heat pump/water heating appliance.

PROBLEM The Carrier HyrdoTech 2000 variable-speed integrated heat pump/water heating appliance incorporates various innovations. A testing and rating procedure for this type heat pump is needed for validation purposes.

APPROACH CBT will perform an elaborate testing and rating procedure for this type heat pump in a project conducted in parallel for DOE and EPRI. The procedure involves approximately 20 laboratory tests and a calculation procedure using a modified bin technique. This field experiment will provide unique data for CBT to validate the proposed testing and rating procedure.

The thermal performance and the electrical energy use will be monitored over a 2-year period. The influence of the appliance on peak demand loads of the Potomac Edison Company will be determined. The data will be compared with data from laboratory tests at CBT on a similar unit and the results used to validate a proposed testing and rating procedure developed in a companion project being conducted for DOE and EPRI. CBT will instrument the heat pump installation and develop the needed software to collect and analyze the experimental data. CBT will report on: 1) monthly heat pump electrical energy use in the cooling and heating mode, peak value and associated time of occurrence, and value at APS monthly peak; 2) coefficient of performance for the heat pump system, maximum and minimum values during the month and their associated time of occurrence, and value at APS monthly peak; 3) monthly water heater electrical use and supplemental heater energy consumption, peak value and associated time of occurrence, and value at APS monthly peak; 4) monthly quantity of energy delivered to the water heater from the HydroTech 2000 while operating in a combined mode and while operating in a dedicated water heating mode, 5) monthly average indoor and outdoor ambient temperatures, water main temperature, and gallons of hot water consumed. Hourly data will be recorded and stored on floppy disks and forwarded to Potomac Edison Company on a monthly basis. A report summarizing this work will be published.

RESULTS New project 1990.

LIGHTING RESEARCH

EVALUATION OF LUMINANCE DISTRIBUTIONS

Principal Investigator: Belinda L. Collins
Building Environment Division
301.975.6455

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop measurement procedures to evaluate the distribution/pattern of luminances in nonuniformly-lit office spaces.

PROBLEM A recent report by Collins, Gillette, Fisher, and Marans (1989) reported that particular lighting system configurations, specifically fixed task lighting combined with an indirect ambient lighting system, were associated with higher energy use (in terms of lighting power density), and higher illuminances, but lower ratings of lighting satisfaction than a comparable situation in which direct ambient lighting provided the primary illumination. A preliminary analysis of the photometric data suggested that the average luminance for the task indirect lighting system was much lower, about 25–50 percent of that for the direct system. This analysis provided some insight into why occupants consistently rated these spaces as "dim" even though their task illuminances were within IES guidelines and comparable to those measured for the direct system.

The analysis of average luminances assumes that all luminances measured in a space contribute equally and it was based on a small set of measures which were not necessarily obtained consistently and which may not have represented the full range of luminances present in the space. Replication of measurements is difficult as is characterizing luminance patterns and distribution in office spaces. Measurement of task illuminance is not enough. The capacity exists of using luminance mapping meters to measure the visual environment more precisely and completely. These luminance maps must themselves be analyzed and related to the occupant in response to the space.

APPROACH During 1990, CBT's work focuses on measuring luminances in office spaces. CBT is developing reliable metrics for determining the lighting variables for measuring lighting quality. The number of measures required to characterize and describe the space will be determined using a conventional photometer and a luminance mapping device with a statistical analysis procedure. A protocol for assessing occupant response will be developed. The procedures will be analyzed for:

- direct ambient lighting with prismatic lenses,
- direct ambient lighting with parabolic lenses,
- task lighting alone—fixed,
- task lighting alone—adjustable,
- task lighting plus direct lighting,
- indirect lighting,
- indirect lighting plus task lighting.

To the extent possible, task illuminance will be maintained at a constant level. After the photometric measures have been obtained, the spaces will be evaluated using rating procedures similar to those described in Collins et al. NISTIR 89-4069 below. This research will extend measurements of the luminance distribution

by several orders of magnitude, allowing a more comprehensive assessment of visibility and occupant response conditions.

Two publications will be published: one will address procedures for evaluating subjective responses to lighting; the second will be published on procedures for evaluating luminance distributions in buildings.

RESULTS Results of past year's efforts include:

Collins, B. L., Gillette, G. L., and Dahir, M. S., *Post-Occupancy Evaluation of Several U.S. Government Buildings*, NISTIR 89-4175, September 1989.

Collins, B. L., Fisher, W. S., Gillette, G. L., and Marans, R. W., *Evaluating Office Lighting Environments—Second Level Analysis*, NISTIR 89-4069, April 1989.

Boyce, P. R., Berman, S. M., Collins, B. L., Lewis, A. L., and Rea, M. S., *Lighting and Human Performance—A Review*, National Electrical Manufacturers Association, Washington, DC, January 1989.

EVALUATION OF ELECTROLUMINESCENT EXIT SIGNS

Principal Investigator: Belinda L. Collins
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Sponsor: U.S. Army, Corps of Engineers

OBJECTIVE To evaluate the visibility of electroluminescent exit sign lights under different conditions of smoke and environmental lighting.

PROBLEM There are no specifications for the visibility of electroluminescent signs, nor have procedures for measuring visibility been established. Current standards for exit signs are based on electric exit signs usually wired into the building's emergency power system. Electroluminescent signs, because they are not dependent on building power and are not likely to be affected by failures in the emergency power, appear to be an attractive alternative for ensuring occupant safety during an emergency. Yet, their phosphors fade over time and may not be as luminous initially as conventional signs. As a result, basic information is needed on their visibility under different viewing conditions. Needed measures include luminance, contrast, and color as a function of different background conditions.

APPROACH During 1990, CBT is performing a literature review to assess the effectiveness of existing specifications and research for evaluating conventional exit signs. Based on this review, a plan for evaluating sign and light visibility will be developed. These procedures will be applied to at least four exit signs under different viewing conditions. Methods will be developed to provide information about the visibility of specific signs under particular viewing conditions. Also, procedures will be developed to evaluate exit signs and to compare conventional and electroluminescent signs.

This research will provide a technical basis for evaluating exit sign visibility. A report on evaluating electroluminescent exit lights will be published on the literature review, testing procedures, and results.

RESULTS Results of past year's efforts include:

Collins, B. L., *Evaluation of Colors for Use on Traffic Control Devices*, NISTIR 88-3894, November 1988.

VISIBILITY OF EXIT SIGNS AND MARKINGS

Principal Investigator: Belinda L. Collins
Building Environment Division
301.975.6455

Sponsor: National Electrical Manufacturers Association (NEMA)

OBJECTIVE To assess the visibility of exit signs and markings under clear conditions.

PROBLEM The existing standards for measuring the visibility of exit signs were developed by UL (UL-924, 1989). They do not provide information about the relative visibility of words and arrows. Proposed revisions to NFPA 101 call for words and arrows that are equal in size. A recent research paper by UL (Subject 924, 1988-1 and 1988-2) evaluated the relative visibility of exit signs and markings (words and arrows). Because relatively few subjects (1–2 for some conditions), unknown adaptation and illuminance levels, and unclear visibility criteria were used, it is difficult to determine that the visibility of the exit sign and marking were in fact equivalent. In addition, current standards for exit signs (such as NFPA 101) do not adequately specify the visibility of such signs, nor do they specify procedures for determining visibility. As a result, basic information is needed on the visibility of exit signs and markings, including measures of luminance, contrast, and color. Furthermore, information is needed on the relative effectiveness of arrows and signs for guiding people in buildings as input to the NFPA revisions.

APPROACH CBT is developing a test methodology to evaluate the visibility of exit signs and markings (arrows). In the first of three tasks, CBT is developing a plan to evaluate the visibility of exit signs and markings. In task 2, these procedures will be applied to conventional exit signs and markings to determine which arrow configuration is as visible as an exit sign. In task 3, the effectiveness of the arrows identified as most visible in task 2 will be compared with exit signs, in terms of their ability to direct behavior in spaces. A final report, *Visibility of Exit Signs and Markings*, will summarize the literature review, testing procedures, and results.

RESULTS Results of past year's efforts include:

Collins, B. L., *Evaluation of Colors for Use on Traffic Control Devices*, NISTIR 88-3894, November 1988.

OPTICAL PERFORMANCE OF COMMERCIAL WINDOWS

Principal Investigator: Stephen J. Treado
Building Environment Division
301.975.6444

Sponsor: Central Intelligence Agency

OBJECTIVE To identify and evaluate commercially available window systems relative to their ability to protect against optical security threats.

PROBLEM The traditional purpose of building fenestration systems, including windows, skylights, and clerestories is to admit daylight to building interior spaces and to allow building occupants a view of the outside. Important performance characteristics of fenestration elements include transmittance, reflectance, and refraction as functions of wavelength, along with thermal transmittance, structural integrity, and long-term durability. Usually, the interest in window performance relates to the transfer of solar energy or visible light from the exterior environment to the building interior. However, windows can allow the transmission of visible light in either direction, thus affording a view into a building under some conditions. This may present security problems from unwanted visual access to building interiors. Yet, elimination of windows has undesirable effects on building occupants and the quality of the workplace. A related optical threat associated with windows is the potential for information to be obtained via use of lasers.

Durability, or more precisely, the stability of window performance characteristics over extended periods of time exposed to exterior solar and environmental conditions is another concern. Weathering and/or aging may degrade the performance characteristics of a window system to the point that it is no longer acceptable. Knowledge of the optical characteristics of windows and films is urgently needed in order to design and build more secure window systems.

APPROACH Research during 1990 will consist of seven tasks:

1. Identify window performance characteristics and testing procedures and evaluate their optical properties and influence on optical security.

2. Complete a comprehensive survey of window systems and materials based on manufacturers' performance specifications.

3. Compare the characteristics of the window systems to the desired characteristics; promising window candidates will be identified and obtained.

4. Test the window candidates to fully characterize their performance; conduct laboratory measurements of the spectral optical properties covering all important wavelengths; evaluate the effect of various lighting conditions on the transmission of visible information.

5. Rate the window candidates and compile the results to allow comparison of the performance of various window systems, including their relative strengths and weaknesses.

6. Publish a report summarizing the results of the survey, testing and evaluation, including manufacturers, availability and pricing. The report will include window performance characteristics including energy, durability, and structural considerations.

7. Perform follow-up testing to document and verify actual field performance immediately following installation and at periodic intervals to monitor changes to weathering or aging.

This research will provide a technical basis for selecting windows to minimize security threats. A report will be published at the end of 1990 on Daylighting, Window Management Systems and Lighting Controls.

RESULTS New project 1990.

DAYLIGHTING STATE OF THE ART REVIEW

Principal Investigator: Arthur I. Rubin
Building Environment Division
301.975.6445

Sponsor: Lighting Research Institute

OBJECTIVE To evaluate the current state of the art in daylighting research.

PROBLEM Electric lighting is a significant energy user in buildings, accounting for 25–50 percent of primary energy usage. Various predictions suggested that daylighting can be usefully substituted in some instances for electric lighting and reduce cooling loads and lighting energy use. Various design guidelines, tools and methods have been developed for predicting and using daylight. The knowledge base is fragmented and needs to be reviewed, evaluated, and summarized into a single planning document.

During the 1970's and early 1980's, there was considerable research in daylighting for energy conservation. Although this research is still valuable, it remains somewhat piecemeal with no clear direction for the future. As environment issues such as global warming surface, it becomes important to re-evaluate daylighting and synthesize this information to determine if there are additional areas of research which should be investigated.

APPROACH CBT will perform a literature review and workshop to determine future directions. A working document will summarize the major issues and topic areas. This document will be reviewed by five to six daylighting experts at a 2-day roundtable at NIST. At the roundtable, the document will be edited, revised, and expanded to reflect the diversity of opinions and knowledge of the experts.

RESULTS Results of past year's efforts include:

Rubin, Arthur I., *Lighting Issues in the 1990's*, NIST Spec. Publ. 587, July 1990.

Treado, S. J., *Illumination Conditions and Task Visibility in Daylit Spaces*, NISTIR 88-4014, March 1989.

THE INTERACTION OF LIGHTING AND HVAC SYSTEMS IN BUILDINGS

Principal Investigator: Stephen J. Treado
Building Environment Division
301.975.6444

Sponsor: Department of Energy

OBJECTIVE To develop improved procedures for predicting and evaluating the thermal and illumination performance of lighting systems.

PROBLEM Lighting is a significant energy user in buildings accounting for 25–50 percent of primary energy usage. Cooling loads, due to lighting, amount to an additional 10–15 percent. To take advantage of the interactions between the lighting and HVAC systems in buildings, detailed information must be compiled about the thermal performance of typical systems under normal operating conditions. This knowledge is essential for development of design and analysis procedures needed to select efficient systems. Current design procedures, such as the ASHRAE weighing factors, IES thermal factors, and building energy simulation computer programs are limited in their applicability and are based on tests performed over 25 years ago, using outdated equipment and designs. As a result, it is difficult for designers to accurately predict the performance of lighting and HVAC systems developed using current design practices. In addition, the determination of system designs for optimum energy performance is not possible. Detailed measurements are needed of the thermal performance of innovative lighting and HVAC system designs to promote development of more efficient and effective systems.

APPROACH CBT will complete its research to develop a detailed computer model of the interaction of lighting and HVAC systems. This model will allow a large number of design options to be evaluated by computer simulation, thereby increasing the usefulness and generality of the results. It will serve as a sophisticated design tool itself, allowing detailed evaluation of different design options, and generate cooling load profiles and weighing factors. It also will form the basis of a lighting/HVAC interaction subroutine for incorporation in subsequent years into whole building energy simulation computer programs such as BLAST and DOE2. This will provide these programs with the lighting interaction capabilities they currently lack.

This research is being conducted in CBT's sophisticated test facility which emulates a full-size office; this facility is in CBT's large environmental chamber. Test conditions are controlled and monitored using a PC-based data acquisition system which samples 400 variables every 12 seconds, and averages and records data every 2 minutes. The measurements include energy flows, light levels, temperatures, and electrical powers. Steady state and transient tests are being performed, including periodic operation of the lighting system and auxiliary electric power, night set-back, and constant or variable air supply volume operation.

The measurements will be incorporated into the design tables and ultimately ASHRAE weighting factors and the results will be used to calibrate and improve the computer model to enable extension. The impact of this research will be the synthesis of design recommendations, particularly for innovative designs.

A report describing the results of this research will be published in 1990.

RESULTS Results of past year's effort include:

Treado, Stephen, J., "Experimental Evaluation of Lighting/HVAC Interactions," *ASHRAE Transactions*, Vol. 96, Part 1, January 1990.

Treado, Stephen J., "The Effect of Building Envelopes on Cooling Loads Due to Lighting," *Proceedings of the ASHRAE/DOE/BTECC Fourth Conference on the Thermal Performance of Exterior Envelopes of Buildings*, Vol. 96, Part 1, January 1990.

Treado, Stephen J., "The Interaction of Building Lighting, Heating, and Cooling Systems," *Proceedings of the 1989 IES Annual Conference*, 1989.

Treado, Stephen J., *The Interaction of Lighting, Heating and Cooling Systems in Buildings—Interim Report*, NISTIR 89-3860, September 1988.

STAGE ONE MODEL FOR THE INTERACTION OF LIGHTING AND HVAC SYSTEMS

Principal Investigator: George N. Walton
Building Environment Division
301.975.6421

Sponsor: Electric Power Research Institute and Ross and Baruzzini

OBJECTIVE To develop improved procedures for predicting and evaluating the thermal and illumination performance of lighting systems and design recommendations and guidelines for optimizing design performance.

PROBLEM Lighting is a significant energy user in buildings, accounting for 25–50 percent of energy use. Cooling load requirements from lighting amount to an additional 10–15 percent. Energy use from lighting and cooling loads are maximum during times of peak electrical power demand for electric utilities. This results in significant costs to the building user as demand charges and larger equipment sizes and to electric utilities from user demand for increased power generation capacity. There is need to develop methods where lighting and HVAC systems can be designed to achieve energy efficiency while minimizing peak cooling loads due to lighting.

To take advantage of the interactions between the lighting and HVAC systems in buildings, detailed information must be compiled about the thermal performance of typical systems under normal operating conditions. This knowledge is needed for the development of design and analysis procedures to enable the selection of efficient systems. Currently, available design procedures, such as the ASHRAE weighing factors, IES thermal factors and building energy simulation computer programs are limited in their applicability and are based on tests performed over 25 years ago, using outdated equipment and designs. As a result, it is difficult for designers to predict accurately the interactive performance of lighting and HVAC systems developed using current design practices. In addition, the determination of system designs for optimum energy performance is not possible.

APPROACH The existing computer models by Sowell and Treado will be reviewed and evaluated for their effectiveness in translating project findings to the design community. Their effectiveness will be evaluated against the requirements specified by Ross and Baruzzini for development of a useful design tool. The development of a model which accurately describes the performance of the NIST test chamber will be completed. The model is an essential precursor toward a more generalized model to allow designers to predict the likely effects of changes in the configuration of the lighting and HVAC systems.

CBT's work in developing a detailed computer model of the interaction of lighting and HVAC systems will allow a large number of design options to be evaluated by computer simulation, thereby increasing the usefulness and generality of the results. It also will provide a sophisticated design tool itself, allowing detailed evaluation of different design options, and the generation of cooling load profiles and weighing factors. It will form the basis of a lighting/HVAC interaction subroutine to be incorporated in subsequent years into whole building energy simulation computer programs, such as BLAST and DOE2.

This research will produce a model for improved design procedures and recommendations. Results from this work are estimated to reduce energy use for lighting and cooling by 5–20 percent and reduce peak electrical loads due to cooling by as much as 15–30 percent. During 1990, CBT will publish a report on program and documentation for stage one model of the Light/HVAC Facility.

RESULTS New project 1990.

ASSESSMENT OF HIGH TECHNOLOGY OFFICE DESIGN ON PRODUCTIVITY

Principal Investigator: Arthur I. Rubin
Building Environment Division
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Sponsor: General Services Administration

OBJECTIVE To 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.

PROBLEM 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. The effects of these new systems resulted in many worker complaints about office conditions. These comments led researchers, designers, and owners 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. Research "tools" do not yet exist to perform office productivity studies under "real world" conditions.

APPROACH During 1990, CBT will complete two research activities addressing evaluation of "high technology" buildings. Work will focus on evaluating the environmental, furnishings, and other design features of offices of the new Portland Federal Office Building, Portland, OR, before and after moving into the facility. The

evaluation is examining successful and unsuccessful design features from the standpoint of the office employee. These findings are based on a questionnaire survey. The evaluation will be supplemented by data obtained from interviews, and questionnaire findings from other Federal agencies. A second study will report the findings of a questionnaire survey administered to facility managers of "Fortune 500" companies, summarizing their design expertise with new office technologies.

Two reports will be published in 1990—one on environmental assessment of new office interiors and workstations; the other on pre and post move-in findings of the Portland Federal Office Building.

RESULTS Results of past year's efforts include:

Rubin, Arthur and Gillette, Gary, *Guideline for Workstation Design*, NISTIR 89-4163, September 1989.

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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 1990.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

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