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Building Technology Project Summaries 1988

Noel J. Raufaste

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

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NATIONAL BUREAU OF STANDARDS

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U.S. DEPARTMENT OF COMMERCE, C. William Verity, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

Foreword

Construction is a giant industry amounting to almost 10 percent of the U.S. Gross National Product. The quality of constructed facilities directly affects the productivity of all U.S. industry and the safety and quality of life of every citizen. The Center for Building Technology (CBT) of the National Bureau of Standards (NBS), is the Nation's central engineering measurement laboratory. CBT produces performance prediction and measurement technologies that are relied upon by private industry, state and local governments, and Federal agencies with building-related programs to provide technical bases for responsible and cost-effective construction decisions. CBT conducts laboratory, field and analytical research. The work focuses on removal of critical technical barriers leading to increased usefulness, safety, and economy of buildings and other constructed facilities. Its findings enhance the international competitiveness of U.S. building services and products. CBT's basic and applied research includes programs in structural engineering, materials, mechanical and environmental systems, and computer-integrated construction.

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

CBT is the Federal laboratory authorized by legislation to investigate the physical causes of major building and construction failures, such as the L'Ambiance Plaza apartment building collapse in Bridgeport, Connecticut, in 1987.

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 the preparation of recommendations for international standards and practices.

CBT staff totals about 130; 84 are professionals of whom 44 hold doctorates and 30 are registered engineers. Seventy-five research associates from U.S. industry, guest researchers from foreign laboratories, visiting faculty members from universities, and students complemented CBT's staff during 1987.

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

CBT's budget for 1988 is about $11 million. About one-third comes from direct appropriations from Congress; the remainder comes from other Federal agencies.

This report summarizes CBT's research for 1988; it is arranged according to CBT's research programs. Each summary lists the project title, its activities, the CBT point of contact, and the sponsor.

Contents

STRUCTURAL PERFORMANCE

ASHLAND TANK COLLAPSE INVESTIGATION

Principal Investigator: John L. GROSS
Structures Division
301.975.6068

Sponsor: National Bureau of Standards

The objective of this investigation is to determine the most probable cause of the 2 January 1988 failure of a 4-million-gallon oil storage tank at the Ashland Petroleum Company Floreffe terminal in West Elizabeth, Pennsylvania.

NBS was requested by the Governor of Pennsylvania and the Fire Marshal of Allegheny County to undertake an independent investigation of the failure of the Ashland oil storage tank. The failed tank was 120 ft in diameter and 48 ft high. It was in service for over 40 years near Cleveland, Ohio and had been recently dismantled and reconstructed on the Floreffe site. Tank failure occurred as it was being filled to capacity for the first time after reconstruction. An estimated 1 million gallons of fuel oil spilled into the Monongahela River about 25 miles upstream from Pittsburgh. The spill contaminated the water supply of many municipalities and affected more than 750,000 people.

The study includes a complete investigation of the site and collapsed structure; testing and analysis of materials used in the tank; evaluation of the fracture surface, subsurface exploration and soils testing; review of procedures; engineering analyses of the as-built tank; and evaluation of possible failure scenarios. This data, along with eyewitness accounts of the failure, will be used to reconstruct the circumstances surrounding the collapse and identify the most probable cause of failure. This work is being conducted jointly with NBS' Institute for Materials Science and Engineering.

A final report will be prepared providing complete documentation of procedures used and results obtained in the investigation. It will be submitted to the Commonwealth of Pennsylvania for use in connection with its regulatory responsibility and will be disseminated to the engineering profession. The investigation will provide the basis for a review of U.S. design and construction practices for re-use of welded oil storage tanks.

NDT METHODS FOR CONCRETE

Principal Investigator: Nicholas J. CARINO
Structures Division
301.975.6063

Sponsor: National Bureau of Standards

The objective of this project is to gain a fundamental understanding of the interaction of stress waves and electro-magnetic waves with internal discontinuities in concrete structures.

Presently there are no standard methods to locate internal defects in concrete structures. The impact-echo method, based on interaction of stress waves with internal discontinuities, has the potential to fill this need. Implementation of the technique requires a fundamental understanding of the interaction of transient stress waves with the types of discontinuities encountered in concrete.

Commercially available radar systems exist to probe within concrete structures. Little fundamental work has been done to readily understand the "signatures" produced by various types of defects. There has been no work performed on developing calibration standards for verifying the operation of the test system. These deficiencies limit the usefulness of a potentially powerful NDE tool.

CBT initiated a research program using the impact-echo method in 1983 to develop this knowledge. The feasibility of the impact-echo method was demonstrated under laboratory conditions using controlled-flaw specimens. The results compared favorably with results of dynamic finite element analyses of plates containing disk-shaped flaws and "honeycombing." High confidence was gained through experiments and analyses. Tests were performed with a laboratory-type system, and it remains to develop a system for field use. While the Fast Fourier Transform technique has proven to be a powerful signal processing tool, the presentation of impact-echo test results is cumbersome.

In 1988, research on the impact-echo method focusses on field implementation. First, a field test system is being developed to convert the individual tests results into a three-dimensional display of the test object. This will represent the first attempt of "acoustic imaging" for concrete structures. The instrumentation and data processing systems will lay the groundwork for a future automated imaging system. In addition, investigations will be performed using radar to determine whether it's possible to produce information about the size and location of reinforcing bars.

MEASUREMENT OF STRESS WAVES IN CONCRETE

Principal Investigator: Nicholas J. CARINO
Structures Division
301.975.6063

Sponsor: Air Force Armament Laboratory, Eglin AFB

The objectives of this research are to 1) develop procedures for measuring stress waves in concrete using polymer stress gages and 2) study the effect of discontinuities, such as reinforcing steel, on the stress distribution in concrete structures subjected to impact loading.

The presence of reinforcing steel, and other discontinuities, in concrete structures are believed to have significant effects on the maximum stresses which may develop during blast loading. If these effects could be quantified, design criteria could be developed to make structures more resistant to blast loading. Two approaches may be used to study the problem: experimental and analytical. Analytical methods are cost effective for parameter studies of the pertinent variables. However, a number of well-planned experimental studies are needed for verification of the analytical models. The measurement of internal stresses in a concrete structure during impact loading is a difficult procedure, and there are no routine methods. Recently, NBS developed a stress gage made from a piezoelectric polymer. This gage offers a promising approach for making such measurements.

This research consists of:

1. Developing a polymer gage. The gage needs to be suitable for embedment into fresh concrete. This work was performed in 1986. Using commercially available polymer film, a procedure was developed for producing gages that could be embedded in concrete and remain functional.

2. Testing using mortar specimens. Experiments will be performed using mortar specimens to verify if the polymer gage gives accurate measurements of the propagating stress pulse. Mortar will be used to more closely approximate an isotropic, elastic, homogeneous solid. The measurements will be compared with analytical solutions.

3. Testing using concrete. Using the techniques developed in 1 and 2, stress wave measurements will be performed in plain and reinforced concrete specimens. The plain concrete specimens will be used to determine the effect that aggregates have on the shape of the propagating stress pulse. Reinforced specimens will be used to study the effect of reinforcing steel.

PUNCHING SHEAR STUDY OF REINFORCED SHELL

Principal Investigator: H.S. LEW
Structures Division
301.975.6061

Sponsor: Minerals Management Service of the Department of the Interior and the Oil Industry

The objective of this research is to develop rational criteria for the design of heavily reinforced concrete shells, particularly of lightweight concrete, subjected to high intensity concentrated loads.

Concrete offshore structures offer great potential for the safe and economical development of mineral reserves in the Arctic region. Such structures may experience high concentrated loads from ice with intensities in the range of 100 tons/ft^2 (10 MPa). Under this a high intensity load, the outer shell, which serves as the ice wall, may experience punching shear failure. Experience has shown, if the shell was designed in accordance with existing guidelines, the exterior shells would become very thick.

The performance of concrete shell elements subjected to high local force will be studied. The behavior of shell and plate elements will be studied using small scale physical models. Tests will be made on 1/6-scale and 1/2-scale models to study the size effects. The experimental program will be supplemented with analytical studies to predict the expected performance of the test specimens. The analytical models will simulate the multiaxial stress states within thick members and will incorporate nonlinear material behavior.

The results of this study will be used to develop safety standards for the Minerals Management Service and will serve as guidelines for design of thick concrete shells.

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 of the Department of Interior

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

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

During 1988, CBT is:

- investigating the effect of Lighthill's nonlinear potential flow term on estimation of offshore structure hydrodynamic damping,
- maintaining consultations with American Bureau of Shipping, Det Norske Veritas, Department of the Navy, and other agencies with an interest in risk assessment applied to compliant offshore structures.

These findings will be used by the Minerals Management Service (MMS) to establish research needs about reliability approaches implicit in the design of these structures. This work will assist MMS in ensuring acceptable safety risks, for the public, in the operation of compliant offshore structures.

MEASUREMENTS FOR ASSESSING STRUCTURAL STIFFNESS

Principal Investigator: Richard D. MARSHALL
Structures Division
301.975.6071

Sponsor: National Bureau of Standards

The objective of this research is to develop instrumentation systems and techniques for obtaining reliable measurements of the effective stiffness of building structures and structural assemblies.

Field studies of full-scale building structures have been conducted to validate physical and analytical models of structural loading and response. These field studies have included measurements of parameters related to member forces, damping, and displacement. Even for rather modest equipment installations, the costs of monitoring response over the extended periods required to capture rare events such as extreme winds or strong ground motions have been prohibitive. Nevertheless, there is a continuing need for short- and long-term monitoring of structures and the collection of reliable information on which to base assessments of structural response and building performance.

Recent advances in computer-based instrumentation systems and intelligent sensors are making possible completely new approaches to full-scale measurements. With proper choice of sensors and data system components it should be possible to obtain field measurements that have never before been possible or affordable. Too, it should be possible with improved instrumentation to develop standard measurement techniques as a replacement for the expensive ad hoc techniques that have been used in the past.

This research consists of:

1. Assessing the state-of-the-art of smart sensors and microprocessor-based data acquisition and processing systems capable of extended operation in environments associated with full-scale studies. The study will build upon current sensor development work being carried out at NBS and work on computer data acquisition systems at other research establishments.

2. Hosting a workshop on instrumentation and measurement techniques for obtaining reliable measurements of the type(s) needed for assessing structural stiffness and response. The workshop will identify areas of instrumentation and measurement techniques that are in need of development work. Recommendations generated by the workshop will serve as a basis for the development of research proposals for consideration by the National Science Foundation and other agencies having an interest in structural engineering research.

3. Designing and constructing a prototype measurement system for unattended, long-term measurements of parameters required for the estimation of structural stiffness. Past experience with full-scale measurements and recommendations developed during the workshop will provide the basis for criteria to design a prototype instrumentation system. A key component of this system will be the electro-optical defection system developed at NBS approximately 10 years ago. When coupled with computer-based smart sensors, this system would be capable of highly accurate measurements of building motion and of displacements and rotations of structural subsystems.

4. Conducting a pilot study of one or more building structures to demonstrate the utility and reliability of the measurement system and to obtain basic information on the effective stiffness of building structures and structural subsystems.

STRENGTHENING METHODOLOGIES FOR STRUCTURAL MEMBERS

Principal Investigator: Long T. PHAN
Structures Division
301.975.6060

Sponsor: National Bureau of Standards

The objective of this research is to develop methodologies for strengthening existing structural members.

Recently, an increasing number of old structures have been strengthened to bring them to the levels of performance required by current codes and standards. Deficiencies in existing structures may result from errors in initial design and construction, change in occupancy, or deterioration during service-life of the structure.

In most cases, strengthening methods require bonding or attaching reinforcing members to existing structural members. These may include externally bonding steel plates to concrete beams, attaching concrete sections to existing columns, and placing infilled walls into existing concrete frames. Frequently, the bonding or attaching is accomplished by means of mechanical anchors. At present, the anchor behavior is not well understood when anchors are subjected simultaneously to both tension and shear. Without this information, it is not possible to evaluate accurately the effectiveness of strengthening procedures.

CBT is studying the cracking and failure modes of anchors in concrete using a finite-element model where fracture is simulated by a nonlinear discrete cracking approach. With substantiation of the computer solutions with physical tests, the mechanism of failure and therefore the strength of the anchors will be determined. The results of the anchor study will be applied to the development of strengthening methods in subsequent phases.

INELASTIC PERFORMANCE OF STEEL BRACED FRAME CONNECTIONS

Principal Investigator: John L. GROSS
Structures Division
301.975.6068

Sponsor: National Bureau of Standards

The objective of this research is to study gusset plate behavior and the connection of bracing elements to the beam-to-column juncture in steel frames.

AISC identified the design of the bracing connections in steel frames an area of primary concern. The force distribution within the gusset plate used in the connection is not well understood. Analytical studies have been financed by AISC at the University of Arizona to study this problem but no experimental tests have been conducted to validate the results.

CBT has performed experimental testings on planar braced steel frames. The selection of specific variables and specimen design was coordinated with analytical studies at the University of Arizona. The experimental tests will provide vitally needed information not yet available. The results will be a resource to serve as the basis for validating mathematical models.

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

Principal Investigator: Richard D. MARSHALL
Structures Division
301.975.6071

Sponsor: Federal Aviation Administration

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

The potential hazard of an aircraft colliding with approach lighting structures during landing or take off operations has led FAA to consider developing structural systems with low impact resistance. The goal of designing low impact resistant structures (LIRS) is to impart minimum damage to an aircraft in the event of an accidental collision. "Break-away" mechanisms implemented in structural systems have been considered by FAA to fulfill the goal. To ensure the effectiveness of such a system (1) the investigation of impact characteristics of structural systems, including mechanical components such as electrical conductors is required and (2) the development of analytical models for simulating impact phenomena is needed.

The research effort consists of four phases:

- Phase 1—develop computer-based analytical models to predict the response of LIRS systems subjected to aircraft impact.
- Phase 2—test selected LIRS under conditions simulating an aircraft collision. Data resulting from this testing will provide the basis for validating the analytical model(s) developed under phase 1.
- Phase 3—assess and improve the analytical models to bring their predictions into acceptable agreement with the response observed in full-scale tests performed in phase 2.
- Phase 4—perform static load test of a prototype LIRS and develop improved load criteria for designing LIRS for offshore exposures.

PULSE PROBING AND DECONVOLUTION IN THE DYNAMIC CHARACTERIZATION OF STRUCTURAL NETWORKS

Principal Investigator: Emil SIMIU
Structures Division
301.975.6076

Sponsor: Air Force Office of Scientific Research (AFOSR)

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

Structural systems are continually being developed for which the dynamic response must be determined with high accuracy up to frequency components of thousands of hertz. Such 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. Recently, it was shown it is advantageous to characterize such systems dynamically by the matrix of their dynamic Green's functions (i.e., the responses of the various coordinates to unit impulse excitations). In practice, especially for

purposes of control or 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 loads is mathematically ill-posed.

CBT will perform numerical experiments to assess the accuracy with which it is possible to recover the exact Green's functions by deconvolution of responses contaminated by noise. These capabilities will be based on recent mathematical research resulting in the development of pulses of the inverse Gaussian type and generalizations, which allow the systematic and accurate solution of the inverse problem described above.

It is anticipated that the research will result in application to structural engineering technology of new results of mathematics, structural dynamics, and measurement science research that contributes to defense, communications, and industrial purposes. Potential spinoffs include development of nondestructive testing methods for tethers of deep water compliant offshore platforms and for active control and damping of dynamic structural vibrations, e.g., docking loads on orbiting structures and seismic loads on buildings.

DYNAMIC CHARACTERIZATION OF STRUCTURAL NETWORKS

Principal Investigator: Emil SIMIU
Structures Division
301.975.6076

Sponsor: National Bureau of Standards

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

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

A parallel effort is aim at developing a testing capability for computer-driven rapid-acceleration actuators which reproduce the requisite pulses to within the accuracy needed.

CBT will develop an electronically controlled stand-alone actuator capable of creating definable pulses used to identify the dynamic behavior of flexible robot arms, for use in construction and to develop control software for the one-dimensional actuator. The device will generate sufficiently high control forces to proof test the theory. Initial tests will be aimed for one-dimensional excitation forces being applied to the structure with resultant 3D accelerations being recorded.

FY 1988 work addresses the deconvolution of responses due to forcing functions that deviate from inverse Gaussian pulses that is representative of what can be obtained by practical loading devices. Deconvolution will be accomplished by applying the algorithm based on infinitely divisible pulses recently developed by NBS' Center for Applied Mathematics.

It is anticipated that the findings will result in application to structural engineering technology of new results for mathematics, structural dynamics, and measurement science research, thereby contributing to the improved reliability of structural systems being developed for defense, communications, and industrial purposes. Potential spinoffs may include the development of nondestructive testing methods for tethers of deep water compliant platforms and for active control and damping of dynamic structural vibrations, e.g., docking loads on orbiting structures and seismic loads on buildings.

NONLINEAR BEHAVIOR OF STRUCTURES AND OTHER DYNAMIC SYSTEMS

Principal Investigator: Emil SIMIU
Structures Division
301.975.6076

Sponsor: National Bureau of Standards

The project's objective is to develop a computational and experimental basis for studying nonlinear and chaotic phenomena of potential interest in structural engineering.

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

The investigation will involve experimental and computational work. The feasibility of constructing a dynamic buckling/snap-through device demonstrating chaotic motions will be determined. Consultations will be held with NBS's Center for Applied Mathematics to determine the feasibility of identifying chaotic motion components from the analysis of time series records. These records pertain to dynamic phenomena exhibiting a combination of deterministic and nondeterministic components, including noise.

SHALLOW FOUNDATIONS FOR HIGHWAY BRIDGES

Principal Investigator: Felix Y. YOKEL
Structures Division
301.975.6065

Sponsor: Federal Highway Administration

The objective of this research is to develop a design procedure for shallow bridge foundation and a draft standard on shallow foundations.

One of the key decisions in selecting a foundation for a bridge is whether to use a deep foundation (piles or piers) or a shallow foundation (spread footings). Even though deep foundations are more expensive than spread footings, they are preferred in present practice for all bridges and are almost exclusively used for continuous-span bridges. The reason for this conservative approach is the perception that shallow foundations will experience excessive displacements resulting in structural damage.

Field data recently collected by FHwA on settlements of shallow foundations and on the tolerance of bridges to foundation displacements provide an opportunity to develop empirical approaches and calibrate rational approaches to the prediction of settlements and the determination of the tolerance of various bridge types to settlements. Analytical studies performed by CBT under this project indicate that, if the relevant limit states are considered (i.e. ultimate load capacity, fatigue strength, excessive deck cracking, tolerance of joints to displacements and reliability), it can be shown that most types of continuous span bridges in areas of competent granular soils can be safely supported by shallow foundations.

CBT will develop a draft for a design manual for shallow foundations, using a limit state design approach linked with probabilistically-determined load and resistance factors. The manual will be part of a comprehensive effort by the Transportation Research Board to introduce load and resistance factor design into the AASHTO Specifications, and will parallel recent developments in building design.

CBT also will develop a draft standard for shallow foundations for consideration for adoption by ASCE as part of the standards for foundations and excavations presently under consideration.

The research will eventually lead to a more extensive use of shallow foundations for highway bridges which in turn will lead to a considerable reduction in construction costs.

EARTHQUAKE ENGINEERING

CYCLIC LOADING OF MASONRY BUILDING COMPONENTS

Principal Investigator: Charles F. SCRIBNER
Structures Division
301.975.

Sponsor: National Bureau of Standards

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

There is lack of information on tentative seismic design provisions for unreinforced and reinforced masonry building components. CBT's research will involve experimental testing and analytical studies. Experimental tests will provide needed information not presently available to serve as a resource to investigators and will serve as the bases for development of mathematical models. Failure modes will be examined to identify the characteristics of failed masonry and the significant parameters affecting the different failure modes. Analytical expressions for design as a function of the key parameters will be developed. Key parameters include amount of reinforcement, effect of axial load, effect of aspect ratio, and effect of material properties.

Testing in 1988 focuses on investigating the effect of percentage and configuration of horizontal and vertical reinforcement on behavior and strength of slender masonry shear walls.

SEISMIC PRECAST CONCRETE STRUCTURES

Principal Investigator: Geraldine CHEOK
Structures Division
301.975.6061

Sponsor: National Bureau of Standards

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

Presently, there is limited guidance for the design and detailing of precast concrete structures for seismic design. The Uniform Building Code permits use of precast concrete elements to resist seismic forces providing the design and detailing used satisfies the Code requirements for cast-in-place structures. The state-of-knowledge indicates that precast structures tend to be less ductile and have a less stable inelastic response than cast-in-place monolithic structures. This occurs because inelastic strains are concentrated in the connections, which are small and weak in comparison to the precast elements themselves. Thus, the connections are often unavoidable weak links.

The Structural Engineers Association of California has been consulted to identify specific areas for research. They will work with CBT throughout the project. The Prestressed Concrete Institute also will provide technical guidance.

It is expected that this review group will guide the design of specific joint details for CBT's consideration. An exploratory experimental model study will be performed to characterize joint behavior. Computer based analytical models will be developed and tested under simulated cyclic loads. Analytical results will be verified by a limited number of full scale tests of beam-column joints.

TECHNICAL ASSISTANCE AND ENGINEERING EXPERTISE FOR SEISMIC CONSTRUCTION PRACTICES

Principal Investigator: Charles G. CULVER
Structures Division
301.975.6048

Sponsor: Federal Emergency Management Agency

The Federal Government sets an example for other organizations to emulate by the use of effective hazards mitigation measures for its facilities. In recognition of these needs, the Congress passed the Earthquake Hazards Reduction Act of 1977 (PL 95-124), and the President established the National Earthquake Hazards Reduction Program (NEHRP) the following year. The NEHRP established the Interagency Committee on Seismic Safety in Construction (ICSSC). The program also assigned the National Bureau of Standards responsibilities to work in the Federal and private sector to improve seismic design practices.

CBT provides the Technical Secretariat to the ICSSC. The purpose of this Committee is to assist the Federal agencies in implementing seismic planning. Efforts involve development of reports for improved practices for design of new and existing buildings and the response of Federal agencies to major earthquakes.

In the private sector, CBT works with the Building Seismic Safety Council (BSSC), an organization consisting of professional organizations, trade associations, and code groups. With CBT assistance, the BSSC has issued seismic design provisions for new buildings (NEHRP Provisions). BSSC is working to update these provisions to incorporate the results of recent research.

This CBT project is a continuation of work with the private sector through the BSSC and the Federal Government to develop improved seismic design criteria. CBT and BSSC are updating the NEHRP provisions and developing reports on existing buildings susceptible to earthquakes.

Results of CBT's effort will produce seismic design provisions for consideration by BSSC and standards developing organizations to improve building practices. Future implementation of provisions will be through the voluntary consensus standards process using data and information generated by BSSC. Seismic provisions for Federal buildings will follow ICSSC procedures. Improved seismic design provisions should lead to uniform safety and economy for all types of building construction.

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

Principal Investigator: Noel J. RAUFASTE
Structures Division
301.975.5905

Sponsors: National Bureau of Standards and Member Agencies

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

The U.S. Panel on Wind and Seismic Effects was created in 1969. Annual meetings alternate between Japan and the U.S. (odd numbered years in Japan; even numbered years in the U.S.). The Panel is composed of 15 Federal agencies participating in 10 task committees. The task committees

focus on specific national issues, e.g., earthquake hazards reduction, buried pipelines and telecommunication systems. The results of task committee workshops and conferences are shared at the annual joint meeting and often published as proceedings.

During FY 1988 the Panel will continue to:

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

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

3. conduct joint research in areas of strong winds, earthquakes, storm surge and tsunamis, publish findings from joint research efforts, and distribute proceedings of annual joint meetings;

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

The U.S. Side will host the 20th joint Panel Meeting at NBS during 17–20 May 1988. Four task committees will conduct their workshops just prior to the Panel Meeting with another scheduled for August. Proceedings of the meeting will be published in late 1988.

IMAGE PROCESSING

QUANTITATIVE CHARACTERIZATION OF THE SURFACES OF BUILDING MATERIALS VIA COMPUTER IMAGE PROCESSING

Principal Investigator: Jonathan W. MARTIN
Building Materials Division
301.975.6717

Sponsor: National Bureau of Standards

The project's objective is to measure the surface roughness of building materials and to determine the effects of surface roughness on service life.

Service life of building materials is largely controlled by the chemical and physical properties of the material's surfaces, e.g., surface roughness and surface contamination. The surface roughness of building materials is seldom measured because it is difficult to measure and characterize. Thus, the effect of surface roughness on the service life of building materials is largely unknown.

A new metrological procedure was developed to characterize the roughness of steel surfaces. Emissions from a steel surface are detected by an infrared camera and displayed as a thermographic image. The technique differs from current profile measurements e.g., profilometers or optical reflectance techniques, in the physics upon which it is based. It is superior to profilometers because measurements are much faster and are made without contacting the surface; hence, measurements could be made in a production line. The technique is superior to reflectance devices in the rapidity of measurements and measurements are not limited by the reflectivity or roughness of the surface.

In FY 1986, CBT successfully characterized the perceived roughness of blasted steel panels using fractal analysis techniques. In FY 1987, research was begun to transform the surface emission greyscale intensity map to its equivalent geometrical profile. Experimental work includes determining the profiles of roughness standards. Theoretical studies modeled the emission of photons from a heated surface.

In FY 1988, CBT is continuing the theoretical research as three parts:

1. using finite element analysis techniques, the temperature at any point on a well-characterized surface for a panel which is uniformly heated from the back will be determined,

2. knowing the surface temperature and the surface geometry, the photon emissions from each point on the surface will be modeled using the Stefan-Boltzmann equation, and

3. given the surface emission vectors and the infrared optical system, CBT will determine which rays from the surface can be detected by the optical system.

The emission patterns from the theoretical surfaces will be compared to those from similar laboratory emission patterns. If the emission patterns are comparable, then equations will be developed for the effects of surface geometry on the emissions from the simulated surface; hence, make the transformation between the thermographic greyscale intensity surface and its equivalent geometric surface. These data will provide the basis for improved measures of surface roughness which are essential to understanding, modeling and predicting degradation at the surfaces and interfaces of materials. The methods for measuring surface roughness are also expected to provide a basis for improved measurements in a number of industries.

DATABASE MANAGEMENT FOR A COMPUTER-IMAGE-PROCESSING-BASED EXTERIOR BUILDING CONDITION ASSESSMENT PROGRAM

Principal Investigator: Jonathan W. MARTIN
Building Materials Division
301.975.6717

Sponsor: Tri-Services Committee, DoD

The objective of this research is to establish and demonstrate a database management system for storing and cataloging building images and descriptions for use in exterior building condition assessments.

The Department of Defense maintains a large inventory of buildings at each of its military bases. At each base the engineering staff is confronted with assessing the exterior condition and prioritizing the buildings in their inventory to optimize maintenance efforts.

During 1986 and 1987, CBT researchers demonstrated the practicality of computer image processing techniques for acquiring and processing images for assessing the exterior condition of buildings. In 1988 CBT is establishing and demonstrating the usefulness of a database management system, which is integrated into its computer image processing system, for making maintenance decisions. The database is being created from buildings which were imaged during a field survey. CBT is assessing the exterior condition of buildings using computer image processing so that DoD engineering staff may extract pertinent information for making maintenance decisions.

CONCRETE

CEMENT HYDRATION

Principal Investigator: Leslie J. STRUBLE
Building Materials Division
301.975.6715

Sponsor: National Bureau of Standards

The project's objectives are to improve understanding of 1) the physics and chemistry of cement hydration, 2) the development of microstructure in pastes of portland cements, and 3) the effects of chemical admixtures on these processes through development and validation of mathematical models based on physical and chemical mechanisms.

Portland and related cements are essential to the nation's construction projects. Over $4 billion each year is spent on these materials which are used in concrete costing approximately $20 billion. In a recent special report (TRB 202), the Transportation Research Board characterized cement research as a neglected area and stated:

> "... cement and concrete research is diminishing just at the time when the quality, reliability, and utility of this basic material are of the most importance."

A National Materials Advisory Board Report (NMAB-361) published in 1981 called attention to "the present unsatisfactory level of research and development in cement and concrete" and recommended that:

> "government agencies with responsibilities for energy, materials, environment and construction increase their support of long-range fundamental research on the manufacture and use of cement and concrete."

The use of chemical admixtures to modify and control the rheological behavior and other concrete properties is rapidly increasing. However, selection of chemical admixtures is based largely on empiricism and use history. Fundamental understanding of the mechanisms by which chemical admixtures perform their intended functions is lacking. Recognizing the increasing importance of chemical admixtures in advancing construction technology, CBT's research is emphasizing this area.

CBT researchers have begun to study the rheological behavior of cement and concrete by developing a fundamental understanding of the interactions between particles and the effects of shear in a concentrated colloidal suspension. These studies are intended to provide a predictive understanding of rheological behavior that can subsequently be applied to concrete. The conceptual understanding and mathematical models already developed for the hydration and microstructure development of cement will be expanded to include the rheological behavior of cement pastes and concrete, effects of flocculation, and effects of superplasticizers.

Initial studies of interparticle forces and shear in dilute and concentrated suspensions will be carried out using a model cement consisting of monosize, submicron spherical particles. The conceptual and mathematical models developed using this model material will be expanded and focussed to describe various aspects of cement pastes and concrete—rheological behavior, the effects of superplasticizers on microstructure, and the effects on microstructure of shear imposed by the mixing process.

The basis for the mathematical model will be the cement microstructure simulation model already developed. The effects of interparticle forces on flocculation or dispersion will be incorporated, both in dilute aqueous suspensions and in solutions containing electrolytes and surfactants. Experimental sedimentation studies will be carried out to test whether the model is consistent with observed flocculation or dispersion. The effects of shear forces will be incorporated so as to describe the rheological behavior of the suspension and viscometric experiments carried out to test whether

the model is consistent with the observed flow properties. Finally, the effects of geometric constraints in concentrated suspensions will be incorporated, and additional viscometric experiments carried out to test whether the model is consistent with rheological behavior of concentrated suspensions.

The model will be applied to cement paste first by extending it to nonspherical particles, to a more coarse and broad particle size distribution, and to cement phases. The effects of cement hydration will be added to the forces acting between particles. Finally, the effects on flocculation of changes in the pore solution composition during the early hydration reactions and the effects on hydration kinetics and pore solution composition of the presence of superplasticizers will be modeled.

REPRESENTATION OF CONCRETE MICROSTRUCTURE

Principal Investigator: James R. CLIFTON
Building Materials Division
301.975.6707

Sponsor: National Bureau of Standards

The project's objectives are to 1) develop methods to characterize and represent the microstructures of cement particles, cement paste, and concrete; and 2) develop relationships between the microstructure characteristics and the performance of concrete.

Improved characterization of the microstructure of concrete is needed to provide a basis for predicting its physical and mechanical properties and its durability. Improved characterization will facilitate optimization of the microstructures of cement-based materials resulting in the design of higher-performance materials. The development of the relationships between the important properties of concrete and its microstructure will provide a diagnostics tool for predicting the remaining service life of existing concrete structures.

During FY 1986, work was started on the development of computer algorithms and analytical methods for analyzing images and for representing the microstructure of concrete. During FY 1987, a method for analyzing two-dimensional images of pore structures of cementitious materials from scanning electron micrographs was developed. In FY 1988, studies are aimed at exploring and developing algorithms to predict three-dimensional size distributions from two-dimensional images. A method for deducing three-dimensional size distributions will aid the determination from micrographs of cement pastes and concretes features such as particle size distributions, air void spacing factors, and the size distribution or grading of aggregate.

CHEMISTRY AND PHYSICS OF CEMENT-ADMIXTURE INTERACTIONS

Principal Investigator: Leslie J. STRUBLE
Building Materials Division
301.975.6715

Sponsor: National Bureau of Standards

The project's objective is to advance understanding of the time-dependent interactions between hydrating cements and chemical admixtures and the fundamental relationships between interparticle forces on dispersed cement particles and the microstructure of the hardened cement matrix.

One of the most important properties of fresh concrete is its ability to flow and remain plastic during placement. The initial floc structure of the hydrating cement controls the flow properties and is the

framework for development of the microstructure of the hardened cement paste matrix and its pore system. The performance of concrete is a direct result of the development of microstructure during mixing, setting, and hardening. The use of certain chemical admixtures (water-reducers and plasticizers) to modify and control the flow of fresh concrete is rapidly increasing. The selection of this type of chemical admixture is largely based on empiricism and use history. Fundamental understanding of the mechanisms by which chemical admixtures perform their intended functions is lacking. Information is needed for cement-water mixtures, with and without chemical admixtures, for understanding 1) factors affecting the interparticle forces and stabilities of cement flocs, 2) the effects of particle morphology and size distribution on microstructure and rheological properties, 3) relationships between particle interactions and flocculation kinetics, and 4) geometry of flocculated structures as a function of the factors that control rheological properties.

Research in 1988 emphasizes the development and testing of mathematical models based on conceptual models. The models address relationships between flocculation kinetics, interparticle forces, and rheological properties. The effects of these factors will be modeled. Experimental studies will obtain data needed to validate the models. Cements and individual cements used as starting materials are being characterized for particle size and shape distribution, specific surface areas, and chemical composition. The rheological behavior and microstructures will be compared to those of mixes with and without chemical admixtures. The effects of interparticle forces will be further studied by dispersing cement particles in nonpolar liquids. The microstructure of hardened cement paste will be characterized using scanning electron microscopy and image analysis techniques.

THE INFLUENCE OF INTERFACIAL MICROSTRUCTURE ON BONDING IN CONCRETE

Principal Investigator: Leslie J. STRUBLE
Building Materials Division
301.921.6715

Sponsor: Air Force Office of Scientific Research

The project's objective is to develop an improved understanding of the relation between the microstructure of hydrated cement paste in the region of its interface with other concrete constituents and fracture of paste in this interfacial region.

Concrete is a composite material, comprised of hydrated portland cement, coarse and fine aggregate, often reinforcing steel, and occasionally constituents such as steel or other fibers. The bonds that form between cement paste and the other constituents are widely considered to be important to concrete strength and durability. At its interface with aggregate, and probably with other concrete constituents, the microstructure of hydrated cement paste is known to be different from that in regions away from the interface. It is not understood, however, how this interfacial microstructure affects the fracture properties of the composite, and thus the strength of concrete.

During this third year of a 3-year project, the influence of the microstructure on fracture near the interface will be studied for normal and modified interfacial microstructures. The microstructural examinations will concentrate on determining the morphologies of the hydrated cement phases present, i.e. their size, shape, and interrelationships. The principal technique for microstructure examinations will be scanning electron microscopy, using a backscatter electron detector to examine specimens that have been impregnated with epoxy and polished. CBT will explore relationships between interfacial microstructure and fracture in the interfacial region. If appropriate, CBT will use the image analysis system presently being developed to represent concrete microstructural features. The relationships between interfacial microstructure and fracture will be tested and refined by studying the effect of modifications in microstructure on crack propagation and bond strength.

WATER AND CEMENT CONTENT OF FRESH CONCRETE

Principal Investigator: Lawrence I. KNAB
Building Materials Division
301.975.6712

Sponsor: Naval Facilities and Engineering Command

The project's objective is to identify and evaluate field methods for determining the water and cement contents of concrete before it is placed.

The strength and durability of concrete is controlled by its cement and water contents. The potential quality of concrete and its strength can be predicted based on knowledge of the cement and water contents. Therefore, determining the cement and water contents of concrete can serve as a basis for making decisions on the acceptance or rejection of ready-mixed concrete when delivered to a construction site. Needed is a method to determine the quality of concrete before it is placed rather than after testing 28-day standard compression cylinders.

The method used for determining the cement and water contents of concrete must be reliable and sufficiently rapid so these two variables can be measured in the field before the concrete is placed. Methods which appear to fulfill these two requirements will be identified and evaluated. Adequacy of the procedures for the most promising methods will be evaluated. One promising method for evaluating the water and cement contents is the Kelly-Vail method. The method can be performed in 15 minutes. Three versions of the Kelly-Vail method exist, differing mainly in the way of determining the cement content of the concrete.

This project will be conducted in two phases. In 1988, Phase 1 will involve a preliminary assessment of the existing methods of rapidly determining the cement and water contents for fresh concrete. The most promising of the existing methods will be selected for further evaluation in Phase 2.

In Phase 2 laboratory tests, the selected methods will be evaluated for their accuracy, precision, reliability, ease of use, and time to complete. Based on the findings, final selection of a method to measure the water and cement contents will be made. Procedures for its use will be reviewed and, if necessary, revised. Recommendations for using the method will be prepared. The method will be ready for field demonstration or use. Recommendations will be developed to improve existing standards or create new standards.

BOND STRENGTH OF WEAKLY CEMENTED SAND GRAINS

Principal Investigator: Lawrence I. KNAB
Building Materials Division
301.975.6712

Sponsor: Air Force Weapons Laboratory

The project's objective is to develop methods to measure the bond strength between two weakly-cemented sand grains.

The determination of the bond failure and bond strength of weakly-cemented sand grains in tension, compression, and torsion is needed to aid interpretation of the behavior of weakly-cemented sand. A research effort investigating the deformation characteristics of weakly-cemented sand grains at the microstructural level is sponsored by the Air Force Office of Scientific Research and performed by the Air Force Weapons Laboratory (AFWL). An important issue in the investigation is the relationship of bond behavior (soil grain-matrix interface) to the macroscopic response of the overall sample. AFWL requested CBT to investigate the bond behavior.

During 1988 CBT is developing methods to measure the tensile bond strength between weakly-cemented sand grains. The bond failure and bond strength will be determined in tension. Special microloading testing equipment will be developed capable of measuring the force required to pull apart two sand grains. A microscope will be used during the fabrication, testing, and analysis of the specimens. During 1989, CBT will investigate the bond failure and strength in torsion and compression.

The results of this research will assist in the establishment of a physical rather than a phenomenological basis for soil response prediction.

MODELS FOR DETERIORATION PROCESS IN CONCRETE

Principal Investigator: James R. CLIFTON
Building Materials Division
301.975.6707

Sponsor: National Bureau of Standards

The research objective is to develop models of the durability of concrete that mathematically describe the mechanistic paths and kinetics of the processes leading to concrete deterioration.

Durability and service-life of concrete are major national problems, as evidenced by the Strategic Highway Research Program, by ACI establishing a new committee on service-life design of concrete, and by the service life requirements adopted for concrete used to store radioactive waste. The recent National Materials Advisory Board publication, *Concrete Durability, A Multibillion-Dollar Opportunity* emphasized the need for long-term research programs on concrete durability, listing the most important concrete durability problems as 1) freezing and thawing, 2) sulfate attack, 3) alkali-aggregate reactions, 4) steel corrosion, and 5) thermal cracking.

This research is developing mathematical models of the mechanisms, kinetics, and thermodynamics of the degradation processes in concrete. Thermodynamic aspects of concrete deterioration, which have not been well studied, will be addressed to understand the parameters that characterize the boundary conditions under which deterioration is thermodynamically favorable to develop intelligently accelerated tests for kinetic studies. The effect of microstructure on deterioration processes will be studied to understand how the permeability and phase distribution of concrete influence reaction mechanisms and kinetics, because most deterioration processes involve the migration of pore solution in concrete.

The initial deterioration process to be studied is freezing and thawing. Deterioration from freezing and thawing is particularly important because the empirical relationships presently used to predict the performance of concrete may not be valid for high strength concretes. This approach involves studying the thermodynamics of freezing in very fine pores and the permeability of the pore system. The influence of such parameters as solution composition and pore size distribution on freezing thermodynamics, and pore connectedness on the permeability of hardened paste are being studied.

PERFORMANCE CRITERIA FOR LONG-LIVED CONCRETE FOR RADIOACTIVE WASTE STORAGE

Principal Investigator: James R. CLIFTON
Building Materials Division
301.975.6706

Sponsor: Nuclear Regulatory Commission

The project's objective is the development of performance criteria to select concrete for use in constructing structures for 500 year life.

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

Certain concretes could have average service lives of 500 years. Remnants of some concrete structures constructed during the Roman Age are still intact. These concretes, however, may not be representative of the typical concretes of their era and statistically only a small sample of the population. Some portland cement concrete structures have been in service for about a hundred years. Analysis of the permeability of concrete suggests that a high quality concrete could have an average service life exceeding 1000 years if the exposure conditions were not severe. A reliability approach needs to be developed to predict concrete service life.

This research will be performed in several tasks. In the first, CBT is identifying the likely deterioration processes. Deterioration is being analyzed for the mechanisms and rates, and the characteristics of the deterioration curves (e.g., determine if deterioration is a linear or nonlinear function of time). Mathematical models are being developed to predict deterioration rates.

In Phase Two, CBT will select and develop necessary accelerated test methods, and develop mathematical models for concrete deterioration. The modeling will form the basis for designing experiments in accord with ASTM E632, "Standard Practice for Developing Accelerated Tests to Aid Prediction of the Service Life of Building Components and Materials."

The end product of this research is the development of performance criteria for selecting long-lived concretes.

QUALITY ASSURANCE OF LABORATORIES

CEMENT AND CONCRETE REFERENCE LABORATORY (CCRL)

Principal Investigator: James H. PIELERT
Building Materials Division
301.975.6704

Sponsors: ASTM
Army Corps of Engineers

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

The productivity of the testing community in the cement and concrete fields may be increased by correctly using standard procedures and apparatus which reduce testing errors and provide a sound basis for accepting cement on mill certificates. More efficient use of long-established construction materials are facilitated by dependable quality assurance programs.

CBT, through ASTM Research Associates, provides on-site assessment of laboratories and distributes proficiency samples. Procedures used in performing conventional quality assurance tests are observed for conformance to applicable national standards. Related test apparatus is checked with equipment calibrated by NBS. Proficiency test samples of portland cement, concrete, blended cement, masonry cement, and fly ash are distributed at regular intervals to obtain information on laboratory performance. Participation in the work of ASTM technical committees by CCRL staff is a mechanism used to provide the standards community with information developed by the laboratory assessment and proficiency sample program.

The primary benefit of the CCRL program is improvement in the quality of testing in construction materials laboratories throughout the U.S. and Canada. Products include: 1) a report for each assessment performed, 2) a report on each round of proficiency sample testing, 3) input to standards committees, and 4) general technical data for construction materials. Summaries of proficiency sample data are provided to ASTM Committees C1 on Concrete and Concrete Aggregated and C9 on Cements for developing or modifying standards. Collaborative efforts include interactions with AASHTO, FHWA, the U.S. Forest Service, Corps of Engineers, and on-going local laboratory accreditation programs in Massachusetts, North Carolina, and the District of Columbia. The CCRL program provides great benefits to materials testing laboratories and others involved with construction.

AASHTO MATERIALS REFERENCE LABORATORY (AMRL)

Principal Investigator: James H. PIELERT
Building Materials Division
301.975.6704

Sponsor: American Association of State Highway and Transportation Officials

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

The quality of construction materials testing laboratories is important to the quality of construction. The importance of testing is demonstrated by the creation of the Strategic Highway research program (SHRP), 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 of high concern. More efficient use of long-established construction materials and broader use of new materials are facilitated by dependable quality assurance programs.

This work focuses on testing soils and bituminous materials and measuring frictional properties of highways. Procedures used in performing conventional quality assurance tests are observed for conformance to applicable national standards. Proficiency test samples of asphalt, soils, aggregates and bituminous concrete are distributed at regular intervals to obtain information on laboratory performance. Participation in AASHTO's Subcommittee on Materials and ASTM committees by AMRL staff provides the standards community with information developed by the laboratory assessment and proficiency sample programs.

The prime benefit of the AMRL program is improvement in the quality of testing in bituminous and soils laboratories. Specific products include: 1) reports on inspections performed, 2) reports on each round of proficiency sample testing, 3) input to work of standards committees, 4) general technical data leading to improvement of quality assurance of soils and bituminous materials.

Use of AMRL services is voluntary; laboratory assessments are made and proficiency samples are distributed as requested by interested organizations serving the transportation industry. Supervisors of the using laboratories and staff engineers of the Federal Highway Administration and the Forest Service interact with CBT through authored AMRL reports.

COATINGS

ORGANIC COATINGS

Principal Investigator: Mary E. McKNIGHT
Building Materials Division
301.975.6714

Sponsor: Tri-Services Committee, DoD

The project's objective is to develop improved procedures for selecting, using, and specifying coating systems.

The annual cost of organic coatings in the U.S. exceeds $10 billion. More than one-half of these coatings are for buildings and structures. The military use about $400 million of coatings annually. An essential element in selecting and using coatings is performance criteria. However, because of recent regulations controlling several components of paint, e.g., volatile organics, lead, and chromate, the traditional method of estimating service-life based on in-service performance is no longer feasible. Currently available methods for predicting service life based on short-term tests do not adequately meet the need for data to aid selection, specification, and use of coating systems.

In 1987 CBT performed research that supported the development of improved material specifications for Volatile Organic Compounds (VOC) compliant materials for structural steel, developed methods to improve the characterization of surfaces, and authored major portions of the Tri-Services Paint and Protective Coatings Manual.

In 1988 CBT continues this research and is working with ASTM in development of their specifications for water-based coatings. CBT is investigating the applicability of thermography and color video to characterize abrasively blast-cleaned steel surfaces. Also, visits are being made to military installations and to coatings meetings to learn of existing and potential problems; perform laboratory studies to develop improved test procedures relevant to field use; and implement the results in the Tri-Services Manuals.

DEVELOPMENT OF PERFORMANCE TESTS AND CRITERIA FOR COATINGS

Principal Investigator: Mary E. McKNIGHT
Building Materials Division
301.975.2635

Sponsor: Federal Highway Administration

The project's objectives are to 1) develop improved procedures that predict service life of coatings for steel, and 2) report on current practices to protect bridge steel.

This work addresses two problems. The first is the need for improved short-term tests to aid quantitative service-life prediction of coating systems for bridges. This need is becoming more urgent because traditional coatings are being replaced by new coatings that meet stringent health and environmental regulations. Selection of traditional coatings usually has been based on in-service data. However, for new coatings, there is inadequate in-service data available to make adequate cost-effective selections. Hence, short-term tests that are predictive of performance are needed to aid in the selection of coating systems. The second problem is the need for improved guidelines for coating engineers to select coating systems.

CBT's approach to the first problem is based on reliability and life-testing analysis techniques. Three coatings are being exposed in a warm seacoast environment and in controlled laboratory environments. The three laboratory environments will be such that one selected degradation factor,

temperature, is changed from one exposure to another. The laboratory environment will include exposure to salt. The test panels will be quantitatively evaluated for corrosion and blistering and the data analyzed using life-testing techniques. Results from the laboratory and field tests, with the results of previous FHwA-sponsored coatings work, will be used to further the understanding of the relative importance of degradation factors and to develop reliable test methods, evaluation criteria, and predictive models.

For the second problem, the literature will be used to develop a document for coating engineers to aid in the selection of cost-effective systems based on best available information.

DEGRADATION OF ORGANIC PROTECTIVE COATING SYSTEMS

Principal Investigator: Tinh NGUYEN
Building Materials Division
301.975.6718

Sponsor: National Bureau of Standards

The project's objectives are to 1) develop data on the kinetics and mechanisms of the degradation of high performance coating systems; 2) develop models to predict the rates of deterioration; 3) implement use of the results through draft standards and performance criteria.

Corrosion-related problems in the U.S. are estimated to cost more than $100 billion annually. The use of polymeric coating systems (including substrate, primer, and topcoat) is one of the most effective, economic, and widely-used means to prolong the life of corrosion-prone construction materials. However, coating systems are frequently susceptible to degradation under in-service environments. Surface analysis indicates that changes at the substrate/coating (or primer) 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.

CBT's research focuses on:

- identifying and modeling mechanisms leading to blister formation and corrosion,
- developing improved methods to characterize coating system's reactions and properties that control degradation at the interfaces, and
- identifying mechanisms whereby inorganic zinc-rich primers affect the service lives of coating systems.

This research builds upon previous work by obtaining knowledge of the fundamental mechanisms of interfacial degradation between high-performance coatings, inorganic primers and steel substrates, including the identification of chemical reactions which contribute to the interfacial degradation. Also, methods for measuring and understanding the processes and factors which affect the permeation of water, oxygen, and ions through protective coating systems are being assessed. The data will be used to develop and validate models for predicting the service lives of protective coating systems.

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

Principal Investigator: Jonathan W. MARTIN
Building Materials Division
301.975.6717

Sponsor: National Bureau of Standards

The project's objective is to develop probability-based models to quantify external weathering stresses.

The service-life of a building material is largely controlled by its physical and chemical properties (resistance) and the environmental stresses (loads) to which it is exposed. For most building materials and exposure environments, the resistance and load factors are random variables and, hence, best modeled using probabilistic techniques. Of all the variables (material, application, and environmental) affecting the service-life of a building material, the variables which are least controlled, most poorly characterized, and probably display the highest temporal and spatial variability are those associated with outdoor environments. This is disquieting because the performance of a building material in an outdoor exposure environment is used as the standard for assessing the adequacy of proposed accelerated aging tests.

This research is the first step to developing probability models for quantifying external weathering stresses. The scope involves modeling an environmental load variable to facilitate comparison between field and laboratory results. The adequacy of the models will be assessed against field data.

Three environmental stresses typically dominate the degradation of organic building materials: temperature, ultraviolet radiation, and moisture. In this research, only temperature is being considered. Probability-based models are being developed to determine how good ambient temperature is in predicting the actual temperature of a material. Next CBT may need to develop an energy balance equation to predict the temperature of a material as a function of measurable environmental variables and to validate the model against field data. Finally CBT will develop distributional models for material temperature to compensate for specimen orientation and color, high and low temperature, and temperature cycles.

ROOFING SYSTEMS

RESEARCH NEEDS ON CORROSION OF FASTENERS IN ENERGY-EFFICIENT ROOF SYSTEMS

Principal Investigator: Walter J. ROSSITER
Building Materials Division
301.975.6719

Sponsor: Department of Energy

The project's objectives are to 1) summarize available information on corrosion of fasteners in energy-efficient roofing systems, and 2) develop a research agenda based on the need for research to correct for problems identified.

Energy-efficient, low-slope roofing systems, in many cases, have two layers of rigid-board insulation. On metal decks, the first (bottom) layer of insulation is secured in place with metallic mechanical fasteners; the second (top) layer is adhered to the first using hot asphalt. Another type uses a single thick layer of insulation board and a single-ply membrane which is secured to the deck using metallic mechanical fasteners. These roofing systems have the potential for corrosion of the metallic fasteners and steel deck accompanied by the loss of attachment (and failure) of the membrane system.

CBT is performing a two-part study. In the first, existing information on the corrosion of fasteners in service is being summarized to provide an overview of the extent of the problem. Sources of information include the archival and trade literature, discussions with researchers familiar with building and roofing performance, persons knowledgeable about roofing performance, and contractors, owners, and manufacturers' representatives.

In the second phase, a research agenda aimed at alleviating corrosion problems identified in Phase One will be prepared. The agenda will address basic research on corrosion and properties of building materials and also applied research addressing metallic fasteners in roofing systems. The agenda also will discuss technology transfer mechanisms for expediting the transfer of the research results into practice.

SERVICE-LIFE PREDICTION OF SINGLE-PLY ROOFING

Principal Investigator: Jonathan W. MARTIN
Building Materials Division
301.975.6717

Sponsor: National Bureau of Standards

The project's objectives are to 1) identify mechanisms of single-ply roofing failure, 2) develop methods to characterize membranes and systems, and 3) identify and model the key variables which control performance and service life.

A major change is taking place in low-sloped roofing technology with the substitution of single-ply roofing membranes for more conventional built-up roofing systems. Since the mid-1970's, the use of single-ply membranes for low-sloped roofs has increased from about 2% to over 50%. EPDM is presently used in approximately 60% of single-ply applications. Failure of bond joints (seams) is the most prevalent mode of failure in EPDM roofing systems. Key factors contributing to seam failures include thermally-induced mechanical stresses, temperature, moisture, and application parameters, such as surface contamination.

This research systematically addresses the barriers to predicting the service life of EPDM single-ply membranes. In 1986, CBT research led to the development of a probabilistic model that predicted the effect of mechanical stress, temperature, and moisture on the time-to-failure of bonded EPDM T-peel joints. In 1987, research was extended to include surface contamination and understanding failure modes.

In 1988, laboratory research continues to focus on the effects of surface contaminates, cure temperature, and adhesive type on the cure time, strength, and time-to-failure of EPDM roofing seams. CBT's researchers will model the degradation process and determine the sensitivity of seam failures to the experimental variables to isolate those which dominate the degradation process. This research draws on the use of computer image processing, probabilistic modeling, and Fourier Transform Infrared Spectrometric measurements. Work also includes keeping abreast of how single-ply systems perform in the field, conducting failure analyses on failed roofs, and gaining a better understanding of the modes and causes of failure.

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

Principal Investigator: Walter J. ROSSITER
Building Materials Division
301.975.6719

Sponsor: Naval Civil Engineering Laboratory

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

The problem most often registered with the National Roofing Contractors Association (NRCA) about single-ply membranes involves the seam. In practice, the quality of field-fabricated seams is often only assessed by visual inspection at the time of roofing construction. Large bubbles and "fish mouths" are readily detected by visual inspection. This method does not detect voids or delaminated areas in the hidden interior portions of seams that may lead to their failure.

In preliminary investigations of the feasibility of using nondestructive evaluation (NDE) methods to detect voids and delaminations in adhesive-bonded seams, the ultrasonic pulse-echo method, with a wheel transducer, was successful under certain laboratory conditions in detecting voids intentionally incorporated in seams between EPDM sheets. Although the method offers promise for field inspections of seams, suitable equipment for field use has not been assembled and evaluated for reliability. Further research is needed to develop the equipment and perform the evaluation. The availability of a field test procedure would provide a means to investigate the integrity of new seams at the time of installation and also of exposed seams, in cases, where their durability may be suspect.

This project will be conducted as two phases. In the first, the pulse-echo ultrasonic equipment needed for field testing will be developed. It is anticipated that currently available pulse-echo equipment will be suitable as a starting point, but that modifications, specific to the problem of evaluating seams in single-ply membranes in the field, will be necessary. Once the equipment is available, laboratory trials will be conducted to assure its proper functioning.

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

CRITERIA FOR MODIFIED BITUMEN ROOFING MEMBRANE MATERIALS

Principal Investigator: Walter J. ROSSITER
Building Materials Division
301.975.6719

Sponsor: Tri-Services Committee, DoD

The objective of this research is to develop preliminary criteria for selecting and specifying polymer-modified bituminous roofing membrane materials.

The use of polymer-modified bituminous membranes as the waterproofing component of low-sloped roofing systems is increasing rapidly in the U.S. Recent estimates indicate these materials account for 15% of the membranes installed; predictions suggest they will increase to 25% or more in the next 5 years. There are no criteria to help select and specify these membranes. Although an ASTM task group was formed to meet the needs for standards, it is estimated that ASTM standards will not be available for at least 4 years. Criteria are needed for interim use that could provide the technical basis for the development of voluntary consensus standards.

CBT is performing research, based on the needs identified in a 1987 study (a table of interim criteria was prepared), to develop the database needed for final criteria. The change in mechanical properties such as low temperature flexibility and load-elongation will be determined as a function of current (draft) ASTM conditions of UV-moisture exposure. In addition, changes in basic materials properties, determined using thermal analysis techniques, will be investigated. Since heat aging is considered one of the most critical conditions producing degradation, additional heat aging of heat exposure of polymer-modified bitumen roofing systems will be continued. In addition, some roofs will be inspected in service to observe performance and identify failure mechanisms.

PERFORMANCE OF MODIFIED BITUMEN ROOFING

Principal Investigator: Walter J. ROSSITER
Building Materials Division
301.975.6719

Sponsor: U.S. Army Corps of Engineers

The project's objective is to develop measurement methods to characterize polymer-modified bituminous membrane materials which have performed in the field for various periods of time under different environmental conditions.

The use of polymer-modified bituminous roofing membranes for low-sloped roofing has increased rapidly in the U.S. Today, about 150 products are available; they account for about 15% of membranes installed annually. Annual use is expected to reach 25% within 5 years. Data is needed on the field performance of these membranes to help provide the technical basis for the development of voluntary consensus standards.

Polymer-modified bituminous membrane specimens will be obtained from newly-installed Army roofs. Selected properties of these membrane materials will be measured in the laboratory. The properties will be selected based, in part, on deliberations of the ASTM task group working on the development of a standard for these materials. Properties determined in the testing will include strain energy, tear resistance, low temperature flexibility, and moisture absorption. The installation of the roofs will be monitored to observe whether abuse of the membranes occurs during application. The results of the field observations and laboratory testing will provide baseline data on the characterization and inservice performance of these roofing membrane materials.

QUALITY ASSURANCE

TEST METHODS FOR FRIABILITY OF SPRAYED FIREPROOFING AND INSULATING MATERIALS

Principal Investigator: Walter J. ROSSITER
Building Materials Division
301.975.6719

Sponsor: General Services Administration

The project's objective is to develop a field test method to measure the friability of soft, loosely bound, sprayed-applied fireproofing and insulating materials containing asbestos fibers.

The predominant uses of asbestos-containing material in buildings have been sprayed-on fireproofing and thermal and acoustical insulation on structural members and on walls and ceilings. These materials, which were extensively used in building construction, may be readily crumbled or pulverized to release airborne asbestos fibers into the building environment. The degree of friability of the asbestos-containing fireproofing and insulation may vary between installations because of deterioration. The test method currently used in the U.S., considered to be subjective, consists of a measure of ease of crumbling, using hand pressure. There is no quantitative field test method. The development of a quantitative friability test method will provide GSA with a method to assess the condition of asbestos-containing materials, establish priorities for abatement programs, and select appropriate abatement options.

The research involves a two-phase approach. The first, completed in 1987, resulted in a prototype test apparatus for measuring friability of asbestos-containing materials.

In Phase Two, the prototype equipment from Phase One will be evaluated. In-depth laboratory and field studies will be conducted to determine the effectiveness of candidate methods in quantitatively measuring friability. Candidate methods include: a surface compression/adhesion test, a bulk compression/adhesion test, an indentation test, an abrasion test, and an impact test. Steps involved in performing this phase include: 1) preparing a set of friability evaluation samples, 2) designing and fabricating field test equipment, and 3) performing laboratory and field evaluation studies to determine the effectiveness of the developed test methods.

IMPROVING THE PROCESS FOR DEVELOPING GUIDE SPECIFICATIONS

Principal Investigator: Robert G. MATHEY
Building Materials Division
301.975.6709

Sponsor: Naval Facilities and Engineering Command

The project's objective is to produce a process for developing more concise and logically completed guide specifications applicable to specific NAVFAC construction and design contracts.

The Department of Navy has over 300 guide specifications which are used to develop their design and construction plans and contracts. The guide specifications reference ASTM Standards, Federal and military specifications, ACI guides, and building code manuals. The referenced documents are often of little relevance and, in some cases, contain conflicting requirements. This makes it difficult to determine if the contract documentation is complete and consistent and causes difficulties for NAVFAC and their contractors to demonstrate compliance of the contracted work with the applicable requirements and specifications.

Ninety-five percent of Navy construction is contracted out; therefore, specifying only the needed information relative to a construction project is essential in streamlining the acquisition-design-construction process. This procedure will enable a better understanding of construction and design requirements and result in a more certain bidding process, less rework, and higher quality of the resulting facilities.

This study will 1) develop a logical hierarchy for technical provisions in the guide specifications and 2) develop a method to eliminate superfluous information and references to unnecessary and conflicting specifications and documents. The first task develops decision rules in the form of questions to be used in deciding which of the referenced specifications can be deleted and if others need be added. This task includes discussions with Navy guide specification preparers and construction contractors. The adequacy of the preliminary decision rules will be evaluated by analyzing them against the need for the referenced specifications in the Navy guide specification on Cast-in-Place Concrete (TS-03300). After the decision rules are tested by analyzing the need for the referenced specifications in the guide specification TS-03300, then the decision rules will be further evaluated by analyzing the need for the referenced guide specifications on Cast-in-Place Concrete (TS-03300), Minor Building Construction (NFGS-03302), and Insulating Concrete Roof Deck System (TS-03501).

The second task involves developing a procedure for applying the decision rules. This task also will be performed using Navy guide specifications. For example, the Navy guide specification on Cast-in-Place Concrete (TN-03300) will be conducted to 1) form the basis of a logical hierarchy for technical provisions in the guide and 2) identify unneeded or unenforceable criteria and provisions and unneeded verbosity. As necessary, the decision rules and the hierarchy for technical provisions will be revised. Then the application of the decision rules will be demonstrated by revising a sufficient portion of the guide to determine the feasibility of the procedure. Also, the guide specification will be reviewed to determine if the criteria and provisions adequately address significant performance and durability problems. Recommendations about updating the criteria and provisions will be made.

TRI-SERVICES TECHNICAL AND SCIENTIFIC SUPPORT

Principal Investigator: Robert G. MATHEY
Building Materials Division
301.975.6709

Sponsor: Tri-Services Committee, DoD

The project's objective is to assist the Tri-Services Building Materials Investigational Program Committee in developing criteria, specifications, and other information needed in making engineering and management decisions.

The Tri-Services are interested in using new materials and systems for which standards and criteria are not available. Test methods are needed to evaluate and select materials. The solutions to building problems and the availability of information about the performance of new materials and systems will benefit other government agencies and the private sector through improved design criteria.

CBT provides skills for managing the Tri-Services Program at NBS and performs laboratory analysis, evaluations, and field investigations. Recommendations are for the selection of materials and systems and their application and performance. CBT identifies Tri-Services problems with building materials and systems, develops proposals, and performs research.

COMPUTER INTEGRATED CONSTRUCTION

KNOWLEDGE REPRESENTATION AND USE IN THE BUILDING PROCESS

Principal Investigator: Kent A. REED
Building Environment Division
301.975.5852

Sponsor: National Bureau of Standards

The project's objective is to demonstrate and refine the principles for the representation and use of knowledge contained in building standards.

CBT, in cooperation with leading universities such as Carnegie-Mellon University (CMU) and the University of Illinois (UI), has developed systematic methods for representing and analyzing building standards; for expressing their requirements in computer-usable form; and for interfacing them to computer-aided design systems. This work has produced two major software systems. The first, Standards Analysis Synthesis and Expression (SASE) software provides standards-writers with an integrated set of tools for constructing and testing decision tables, developing information networks, constructing and manipulating classifier trees, and developing scope-lists, indices, organizations, and outlines. The second, Standards Interface for Computer-Aided Design (SICAD) software system is an experimental test bed that demonstrates how the provisions of a standard can be used correctly in an application programming environment when they are expressed as an extended SASE-model.

In prior years, these software systems and their underlying principles were tested with portions of building standards. The most complete, consists of parts of four chapters of the American Concrete Institute's Building Code Requirements for Reinforced Concrete (ACI-318) implemented as a code checker program using SICAD.

During 1988 CBT is working with the American Society of Mechanical Engineers (ASME) and its boiler code to apply the existing SASE/SICAD technology. A team of researchers were selected in CBT and a counterpart research committee was formed in the standards organization. The SASE principles will be used to analyze and express the contents and organization of the building standard. The standard will be implemented either stand-alone (functioning as a knowledge-based expert advisor) or integrated to a computer-aided design environment (functioning as an automated design checking program).

INFORMATION EXCHANGE TECHNOLOGIES IN THE BUILDING PROCESS

Principal Investigator: Mark E. PALMER
Building Environment Division
301.975.5858

Sponsor: National Bureau of Standards

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

The use of computers has penetrated every aspect of the building process, including design, construction, and operation. Little integration of these traditionally separate activities has occurred, because there exist no effective standards for expressing and exchanging information about buildings beyond geometric elements and their graphical representations. The existing national standard which addresses geometry and graphics—the Initial Graphics Exchange Specification (IGES)—lacks the supporting testing methodology and test cases for validating software implementations. Participants in the building process continue to be plagued by errors and inefficiencies that occur because information is not available in digital form when needed, is incorrectly transferred out of a

sending system, or is incorrectly interpreted by the receiving system. Rational techniques are needed to develop and test information exchange standards if computer integration of the building process is to be achieved.

During 1988 CBT continues to develop the IGES/AEC Translator Forum activity, initiated in 1987, demonstrating the current state of IGES translators supported by AEC (Architecture, Engineering, and Construction) CAD system vendors. Vendor systems will be in CBT laboratory space and round-robin transfers of data will be conducted using IGES as the intermediate file format. Objectives of this work includes 1) development of information to assess the quality of IGES implementations for entity mapping and complex data structures, 2) identification of weaknesses in the IGES standard to AEC data structures, 3) collection of data to develop performance measures and guidelines for using IGES in the building industry, and 4) development of a suite of benchmark files which represent the range of AEC CAD data exchange requirements. CBT chairs the AVM (Application Validation Methodology) Committee of the IGES/PDES Organization and leads the development of IGES Application Protocols for achieving consistent and complete exchanges of product definition data.

CBT continues to analyze, extend, and refine a prototype semantic data model for "as-designed" building information to define AEC requirements for Product Data Exchange Specification (PDES), the next generation data exchange standard. CBT is identifying elements required in the semantic data model to allow code-checking of a building design.

MECHANICAL SYSTEMS AND CONTROLS

BMCS COMMUNICATION PROTOCOLS LABORATORY

Principal Investigator: Steven T. BUSBY
Building Environment Division
301.975.5873

Sponsor: National Bureau of Standards

The project's objectives are to 1) expand CBT's Building Management and Control Systems Laboratory to include a new BMCS Communication Protocols facility and 2) 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 hierarchical and distributed building management systems.

Over the last 15 years, automatic control systems in buildings have changed from predominately pneumatic control systems to supervisory Energy Management and Control Systems (EMCS) to distributed direct digital control (DDC) systems. 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.

A lack of communication capability between control systems by different manufacturers prevents the building owner from obtaining the most capable building service by not allowing him to choose, regardless of the manufacturer, the best EMCS system, the best digital controllers, the best security system, the best fire detection system, or the best telecommunications system.

CBT's research in 1988 concentrates on developing the BMCS Communication Protocols Laboratory and providing technical assistance to ASHRAE's SPC 135 committee, Messaging Protocols for BMCS, through the evaluation of existing protocols. A variety of building control systems are being obtained from different manufacturers for all levels of building communication and services. Communication networks involving different types of physical media are being assembled and used to interconnect different control systems with both actual building equipment and system emulators. Private industry will be encouraged to aid in this research and to use the CBT facilities.

ADVANCED BUILDING CONTROLS AND DIAGNOSTICS

Principal Investigator: Cheol PARK
Building Environment Division
301.975.5879

Sponsor: National Bureau of Standards

This research will develop real-time model estimation algorithms, an Emulator/Tester to evaluate Building Energy Management Systems (BEMS) performance, and diagnostic procedures to improve the operation of buildings and building systems.

The proper operation and control of buildings involves complex interaction of numerous control loops and many pieces of equipment. For example, an air handler may use a discharge air temperature controller to control the temperature of discharged air by sequencing the cooling coil, the outdoor exhaust, and relief air dampers, and one or more preheat coils. It may have a separate controller that operates an economizer cycle under certain sets of loads and outdoor conditions. Another device will typically protect the unit from freezing coils by operating the preheat system at low ambient temperatures. There are other factors in the operation of building controls, e.g., variable air flow rates, multi-zone control, and complex building control strategies which involve numerous system interactions. Bundling control strategies or algorithms together with "patches" to remedy situations where known conflicts exists, doesn't work.

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

1988 research concentrates on 1) developing an Emulator/Tester for evaluating BEMS performance and 2) creating a prototype expert system for determining the performance of mechanical HVAC systems and controls and for producing diagnostic information for use by building operators. CBT's BEMS Laboratory is being used to study how real-time models, "tuning," and estimation techniques, optimal control theory, and rule-based expert systems can be combined to evaluate control system performance, make control strategy decisions that optimize building performance, and advise the BEMS operator or building manager on building operations, diagnostics, and maintenance requirements. A simplified, "on-line" model of a building will be developed and used as the starting point for this research. Data collected from buildings in the field will be used to identify and develop performance parameters, procedures and algorithms for control system operation, maintenance or repair problems.

The Emulator/Tester work will be performed in support of IEA's Annex 17. The work on the rule-based system will be done on a PC or AT. The integration of the optimization and diagnostic functions, with statistical information, to create a new generation of "intelligent" BEMS will be performed in future fiscal years.

ADVANCED BUILDING SYSTEM SIMULATION

Principal Investigator: George N. WALTON
Building Environment Division
301.975.6421

Sponsor: Department of Energy

The project's objective is to develop dynamic HVAC system component models to serve as prototypes for a future Energy Kernel System (EKS) proposed by Lawrence Berkeley Laboratory.

Lawrence Berkeley Laboratory proposed an Energy Kernel System (EKS) based on a prototype software system called SPANK (Simulation Problem Analysis Kernel). SPANK uses concepts from network analysis and object-oriented programming to describe and solve whole building simulation problems. The capabilities of SPANK have been successfully demonstrated for solving HVAC problems involving sets of steady-state, algebraic equations. However, research remains to determine if the SPANK approach can be effectively applied to real world simulation problems involving dynamic, nonlinear building systems.

Dynamic component models will be completed for several different Variable Air Volume (VAV) system designs and control options for providing ventilation in buildings. These models, which include the dynamic response of these systems to control actions and changes in zone load, are being developed in formats suitable for use with SPANK, HVACSIM+ (a simulation program developed at CBT), and ESP (a simulation program developed by the University of Strathclyde). Simulation studies are being performed using these three programs to intercompare the strength and weaknesses of each approach.

COMMISSIONING OF MECHANICAL BUILDING SYSTEMS

Principal Investigator: James Y. KAO
Building Environment Division
301.975.5871

Sponsor: General Services Administration

The project's objectives are to develop inspection and test procedures for commissioning HVAC equipment and systems and to revise GSA's heating, ventilating, and air-conditioning guide specifications to apply commissioning requirements in select GSA buildings.

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

During the past 2 years, CBT has been developing HVAC equipment and systems commissioning procedures for GSA. Inspection and testing procedures were developed for chillers, boilers, air handling units, and other major equipment and systems commonly used in buildings. Further efforts need to successfully apply these procedures in GSA building projects. GSA guide specifications have few requirements for field testing and do not reflect the commissioning procedures being developed by CBT.

CBT is developing guide specifications for mechanical systems which will incorporate commissioning procedures. This work is being coordinated with GSA's contractor charged to develop a new GSA guide specification. CBT is recommending changes, reviewing draft specifications, and revising the contractor's final guide specifications to insure that they reference the commissioning procedures. CBT next will monitor the commissioning procedures in field use. CBT will interpret the procedures, observe the commissioning process, provide independent evaluation, refine the commissioning procedures, and improve the guide specifications.

ASSESSMENT OF ROBOTICS OF IMPROVED BUILDING OPERATION AND MAINTENANCE

Principal Investigator: James E. HILL
Building Environment Division
301.975.5851

Sponsor: General Services Administration

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

The use of robotics in the factory environment has exploded within the past decade with over 16,000 robots in used in the United States and more than 30,000 in use world wide. The large use is due to the ability of robotics to increase productivity in manufacturing. One area of new interest is in construction and large-scale assembly. The first international conference on construction robots was held in Pittsburgh in 1984. The Japanese are particularly active with more than 20 kinds of construction robots developed or under development.

GSA is interested in potential applications of robotics for operation and maintenance functions such as window cleaning, floor cleaning, trash compacting, and miscellaneous materials handling. Some

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

CBT will make a comprehensive assessment of the possible application of robotic devices to a variety of building operation and maintenance functions. The assessment will include a state-of-the-art survey of robot technology with potential use in building operation and maintenance. The assessment will include an analysis of the operation and maintenance functions in a building identifying those that are potentially promising for robotic application. In general, the most promising ones will be where the work must be done in dangerous or hazardous conditions (e.g., window cleaning on the exterior of multi-story buildings), where the environment is very structured and the tasks are repetitive, and/or where high quality and high skill levels are required and skilled workers are in short supply.

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

REFRIGERANT MIXTURES

MEASUREMENTS OF MODIFIED HP CYCLES USING NONAZEOTROPIC MIXTURES

Principal Investigator: David A. DIDION
Building Environment Division
301.975.5881

Sponsor: Oak Ridge National Laboratory

The project's objective is to experimentally evaluate the thermodynamic and operational behavior of modified heat pump cycles and systems hardware using nonazeotropic refrigerant mixtures.

Interest in nonazeotropic binary mixtures for refrigeration systems has been increasing. It is unlikely that new single component refrigerants can be developed because there are a limited number of elements available for combination to produce volatile, nonflammable, nonpoisonous, chemically stable compounds. Consequently, improvements to refrigerant's performance is expected to result from applying mixtures of known refrigerants. CBT developed a heat pump model for nonazeotropic mixtures, under EPRI sponsorship, which uses a hard-sphere equation-of-state. A new model will be verified through comparisons with data obtained from hardware tests to help design the test program.

The technical approach is in three phases. The first develops a thermodynamic performance evaluation for selected refrigerant mixtures. Tests will be conducted for various mixtures to compare their respective merits for particular representative applications. The mixture R114/R22, known for improved cycle efficiency and R12/R13, with increased capacity at lower temperatures, were tested in 1987. One or two additional mixtures are being selected for tests this year.

The second phase determines the heat exchanger characteristics that best exploit the mixture. An evaluation of the performance of counterflow heat exchangers using two or three flows will be performed.

In phase three, using the empirical work from above, CBT will determine the capacity and efficiency of traditional vapor compression cycles operating with a mixture in counterflow heat exchangers. The experiment will focus on modifying the vapor compression cycle to take fuller advantage of the performance benefits available when a mixture is employed.

Lastly, experimental research will focus on those mixtures that performed well. These mixtures will be used to determine the merits of an advance cycle concept using three fluids.

EVALUATION OF NONAZEOTROPIC HEAT PUMP CONCEPTS

Principal Investigator: David A. DIDION
Building Environment Division
301.975.5881

Sponsor: Electric Power Research Institute

The project's objective is to experimentally evaluate new heat pump concepts that use nonazeotropic refrigerant mixtures by designing, constructing, modeling, and testing breadboard heat pump systems.

During the past 4 years CBT has performed research on nonazeotropic refrigerant mixtures in heat pumps. The research produced quantitative data and engineering methods to evaluate specific heat pump refrigerant systems using different refrigerant mixtures.

During 1988 CBT is reviewing heat pump concepts that use nonazeotropic refrigerant mixtures. Working with EPRI, the concepts will be reviewed with one selected for development into a detailed breadboard design. CBT will design the instrumentation, data acquisition and reduction system, and facility modifications necessary for test and evaluation.

CBT is developing computer simulation of the breadboard heat pump system using existing heat pump and refrigeration mixtures models. The models will be designed to allow interpolation and extrapolation of test data and allow predictions of the system's performance in application. The breadboard, instrumentation, data acquisition and reduction systems, and test facility will be constructed.

Finally, CBT will acquire and analyze test data sufficient to characterize the heating and cooling outputs, electrical energy consumption, and energy efficiency as a function of source and sink temperatures over the complete range of ARI (DoE) test points. As necessary, additional tests will be performed to establish annual performance for a variety of U.S. climates, characterize defrost operations, and establish oil compatibility with mixture components at both extreme high and low temperatures.

NONAZEOTROPIC REFRIGERANT PROPERTY EVALUATION

Principal Investigator: David A. DIDION
Building Environment Division
301.975.5881

Sponsor: National Bureau of Standards

The objective of this research is to determine the values of the thermodynamic and transport properties of nonazeotropic refrigerant mixtures to evaluate the performance impact these mixtures have in specific applications.

1988 research addresses the impact refrigerants have on the atmosphere's ozone layer. CBT is developing the technical bases of nonazeotropic refrigerants for industry in support of their search for substitute refrigerants for R-11 and R-12. CBT is providing the thermodynamic data for R134a (the leading substitute candidate for R-12) while industry studies the characteristics of toxicity and oil compatibility.

Research also focuses on identifying a substitute by examining the properties of certain binary and ternary mixtures to determine if the azeotropes, near azeotropes, and saddle points are appropriate. CBT's research also addresses two-phase flow in compact heat exchangers and in micro slots. The experimental work is estimating the basic tradeoff between increased heat transfer for increased pressure drop for refrigerant applications.

TEST PROCEDURES FOR APPLIANCE ENERGY USE

A RATING METHODOLOGY FOR INTEGRATED HEAT PUMP-WATER HEATING APPLIANCES

Principal Investigator: Brian P. DOUGHERTY
Building Environment Division
301.975.6396

Sponsors: Electric Power Research Institute
Department of Energy

The project's objective is to develop a rating method for predicting the seasonal performance of integrated heat pump water heating appliances.

Integrated heat pump-water heating appliances are expected to be commercially available by December 1988. These appliances are expected to provide a significant portion of the energy required for domestic water heating. Their design features include variable speed components, e.g., compressor and indoor fan, state-of-the-art HVAC controls, and innovative defrost mechanisms. Manufacturers claim these appliances can yield higher space heating and cooling efficiencies, quieter operations, and improved comfort when compared to conventional heat pump systems.

CBT has research underway to develop an hour-by-hour simulation program that predicts the annual performance of a generic integrated heat pump-water heating appliance. Results from this simulation will serve as a basis for evaluating the performance rating methods for the integrated heat pump-water heating appliances. The investigation is specific to residential, air-to-air heat pumps capable of fully condensing, integral water heating. The first phase of this project will address the modification of the hour-by-hour simulation program to be representative of the first generation integrated heat pump-water heating appliances.

The second phase of the project will focus on developing and evaluating potential rating methods. Methods resembling the existing rating procedure for variable speed, air-to-air heat pumps will be considered first. An algorithm that will accurately account for the water heating contribution within the existing procedure (which uses a bin method) will be sought.

The project is a first step to designing a formal rating and testing procedure for integrated heat pump-water heating appliances. The rating method will serve as a reference point for rating other integrated/combined appliances.

CORRELATION PROCEDURE FOR THERMOSYPHON SYSTEMS

Principal Investigator: A. Hunter FANNEY
Building Environment Division
301.975.5864

Sponsor: Department of Energy

The project's objective is to develop a correlation procedure for thermosyphon solar hot water system to predict long-term performance from short-term measurements.

Correlation procedures were developed for pumped and integral collector storage SDHW systems which permit the prediction of long-term performance using short-term thermal performance measurements. The remaining solar hot water system for which a correlation procedure does not currently exist is the thermosyphon system which this project addresses.

Long-term high quality outdoor thermal performance data for a close-coupled thermosyphon solar hot water system are being collected for a wide range of meteorological conditions. The data is being stored in an archival manner and transferred to the University of Wisconsin. The results of this project will permit more accurate evaluation of the technical viability of thermosyphon solar hot water systems. It will provide needed data to support the development and validation of design tools.

HEAT PUMP AND AIR CONDITIONER TEST PROCEDURES

Principal Investigator: David A. DIDION
Building Environment Division
301.975.5881

Sponsor: Department of Energy

The objective of this research is to develop test and rating procedures that determine the seasonal energy performance of central residential air conditioners and heat pumps.

The existing test procedure for heat pumps and air conditioners does not address mixed systems or like components by different manufacturers. CBT has developed a procedure for rating mixed systems without testing the entire systems. The rating procedure for the cooling mode, will be published in the Federal Register. The final product will be a procedure to assist the consumer select a more energy efficient replacement unit, evaluate mixed and matched system ratings for comparison to the national standards, and a basis for utility companies to determine their rebate programs.

CBT also will refine the rating procedure for a variable speed heat pump. CBT's efforts have been limited to evaluation of possible operating modes of a variable speed system. Laboratory tests are planned to run throughout 1988.

FURNACES, BOILERS, AND HOUSEHOLD HEATER TEST PROCEDURES

Principal Investigator: George E. KELLY
Building Environment Division
301.975.5870

Sponsor: Department of Energy

The project's objective is to develop a test and rating procedure to determine the seasonal energy performance of central residential furnaces, boilers, and household heating equipment.

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 applications. The 1987 amendments to EPCA requires analysis of any test procedure amendments to determine their effect on minimum efficiency standards. DoE relies on CBT to develop the test and rating procedures.

During 1988, work centers in the area of integrated appliances and support to ASHRAE Standards. For the former, CBT will use its simulation program, HVACSIM+ as the basis for modeling the performance of furnaces, boilers, household heaters, new space heating and domestic hot water heating equipment appearing on the market, and, in particular, new integrated appliances. The simulation program—HVAC SIMulation PLUS other systems—is a research tool for whole building system studies. Experimental studies will verify HVACSIM+ compatible component models to ensure results are compatible with existing DoE appliance test and rating procedures.

CBT supports ASHRAE's Standard Project Committee 103R and 124P in developing draft test procedures for furnaces/boilers and combination space heating/water heating appliances, respectively.

INDOOR AIR QUALITY

A GENERAL INDOOR AIR POLLUTION CONCENTRATION MODEL

Principal Investigator: James W. AXLEY
Building Environment Division
301.975.5867

Sponsor: Department of Energy and
Environmental Protection Agency

The project's objective is to develop a comprehensive validated computer model that simulates dynamic pollutant movement and concentration variations in buildings.

There is need for a general and comprehensive model which can predict the extent, severity, and duration of outdoor air pollution. The model must be useful to evaluate various indoor air quality control systems and used for energy and environment policymaking. Most previous work reported for indoor air pollution modeling is based on a simplistic one-room dilution model which ignores the thermal effects and mixing dynamics. A comprehensive analysis of pollution migration in buildings requires accurate simulation of all processes affecting pollutant concentration. These processes are infiltration, generation, dilution, reaction, removal, and exfiltration.

CBT recently developed a comprehensive dynamic building simulation model called TARP. The model computes thermal interroom airflows calculations by considering the flows through all openings (doors, cracks, etc.) and requires a mass balance in each room. The flows are a function of wind, stack effect, and forced ventilation. TARP is being expanded to include determination of the generation, reaction, and removal of various contaminates to simulate forced interroom airflows and filtration devices, and to better understand the effects of interroom convection.

CBT developed:

- a framework for indoor air quality models,
- a model for residences which treats each room as a single, well-mixed zone, and
- a model that predicts indoor air quality in large buildings.

In 1988, CBT is developing physical models to predict the sources and sinks of various contaminants. These models are being incorporated into the general IAG model.

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

Principal Investigator: Richard A. GROT
Building Environment Division
301.975.6418

Sponsor: General Services Administration

The objective of this research is to develop evaluation methods for thermal and environmental performance of advanced-technology office buildings.

Previous research showed the value of diagnostic evaluations in assessing building performance and the importance of building envelope air leakage when determining space conditioning loads. Many air leakage and insulation problems can be avoided by using diagnostic tests early in construction and repairing the identified defects.

During past GSA research, CBT developed design specifications for installing a diagnostic center and performance criteria and programming directives for installing a diagnostic center in advanced technology buildings. The diagnostic center concept was applied to programming requirements for three federal buildings in Portland, Oregon; Overland, Missouri; and Long Beach, California. Evaluations of these advanced technology buildings include building envelope; thermographic inspection, thermal resistance measurements, pressurization tests for tightness, and tracer gas analysis of air exchange and monitoring indoor levels of contaminants.

During 1988, CBT continues to: install a diagnostic center in the Long Beach building, analyze output of the diagnostic center in the Portland building, and monitor pre-occupancy and move-in testing of the buildings in Overland and Long Beach. Based on the pre-occupancy and move-in period testing in the three buildings, CBT will develop guidelines for building operating procedures and servicing during building commissioning and move-in.

This research serves to validate the use of diagnostic techniques for evaluating performance issues as envelope thermal integrity, ventilation and indoor air quality, and to establish cause and effect relationships between these performance issues and building features and operation.

INFILTRATION/VENTILATION—LARGE BUILDINGS

Principal Investigator: Andrew K. PERSILY
Building Environment Division
301.975.6418

Sponsor: Department of Energy

The research objectives are to develop test methods for evaluating the movement of air into and within large commercial buildings and to determine the efficiency of the ventilation systems of commercial buildings.

In comparison to residential buildings, little data exists on air leakage and air movement in large commercial structures. Data indicates there is a wide range of air leakage rates in large buildings. Previous DoE/NBS research 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.

Test methods developed since 1985 for measuring ventilation efficiency will be applied to three office buildings. Measurements of the distribution of contaminants will be made. The contaminants include CO_2, CO, respirable particles in five ranges spanning 0.3 to 10 microns, formaldehyde, and radon. These measurements will produce a data set of contaminant concentrations in office buildings and an assessment of the usefulness of these ventilation efficiency measurement techniques in characterizing the ability of building ventilation systems to remove contaminants.

With NIOSH, CBT will study the relationship between the level of contaminants and the operation and design of the ventilation system in one of the buildings. NIOSH also will measure the levels of micro-organisms and allergens in the building. These data will be analyzed by CBT and NIOSH to determine the relationship between the performance of the ventilation system and the levels of indoor contaminants.

CBT will study ventilation and air quality in the Madison Building, Library of Congress. This work will be conducted with the J. B. Pierce Foundation of Yale University. The Pierce effect concerns occupant reaction to the indoor environment in relation to thermal comfort and ventilation, and the development of surrogate measures for indoor air quality. CBT's work involves the measurement of air exchange rates, ventilation effectiveness and levels of carbon monoxide, carbon dioxide, formaldehyde, radon, and particulates.

DEVELOPMENT OF PREPROCESSOR FOR A GENERAL INDOOR AIR POLLUTION CONCENTRATION MODEL

Principal Investigator: Richard A. GROT
Building Environment Division
301.975.6430

Sponsor: Consumer Product Safety Commission

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

CBT with DoE and EPA is developing a computer program (CONTRAM) that will predict the quality of indoor air. The program development has progressed where it could be used by other agencies to analyze indoor air quality, define measurement systems, and make exposure predictions. At present, the program inputs are not user friendly or a direct link between this program and other programs such as AIRMOV (an air movement program) and TARP (a thermal analysis program) which may be needed for complete analysis.

During 1988 CBT will:

- develop several modules, or preprocessors, needed to make CONTAM user friendly. These modules include, an input program, source/sink module, and an environmental module.

- perform Beta-Testing of the Program for CPSC. CPSC will use this information to verify the usefulness of the program, perform Beta testing (e.g., testing feedback) and to make suggestions for possible improvements.

- identify and evaluate presently available models that are of potential use in CONTAM, e.g. source emission models, sorption/desorption models and chemical reaction models. This task will identify source/sink models development needed to improve IAQ models for CPSC use.

- perform a preliminary validation of the CONTAM Program. CBT in cooperation with CPSC shall select the items to be validated and the method of validation.

MICRO-MODELING OF CONTAMINANT CONCENTRATION IN A SPACE

Principal Investigator: Jin B. FANG
Building Environment Division
301.975.6417

Sponsor: National Bureau of Standards

The project's objective is to develop micro-models for predicting the temporal and spatial distributions of flow velocity and contaminant concentration within spaces in buildings.

Indoor pollutants are emitted into building spaces by unvented or improperly-vented combustion appliances, direct applications or spills of cleaning chemicals and paints, tobacco smoking, and construction materials such as urea-formaldehyde foam insulation and particle board. The concentration levels and duration period of pollutants present in a space are a complex function of the proximity to pollutant sources, chemical reaction between pollutants, air ventilation and infiltration, and adsorption or absorption of pollutants on indoor surfaces. To protect human occupants from long-term chronic exposure or short-term peak exposure, detailed information is needed of the flow pathways and concentration levels of contaminants.

The finite difference computer models were developed to predict two- and three-dimensional air flow fields and contaminant concentration distributions in ventilated compartments. These mathematical models were formulated based on mass and momentum balance equations coupled with the expressions for transport of turbulent kinetic energy and its dissipation rate, and using primitive variables including flow velocity and pressure as dependent variables. The performance of these micro-models were evaluated by comparing the predicted results with some available experimental data, and exhibit an encouraging agreement. The existing micro-models will be modified to simulate the transformation and removal processes of typical contaminants through additions of chemical reaction and removal terms to the equation for conservation of chemical species. The energy equation will be incorporated into the models as an additional governing equation so the models can handle the case of buoyancy-driven enclosure flow. Laboratory experiments using a scale-room within an environmental chamber will be performed to obtain data for validation of the developed micromodels. Parametric sensitivity studies using the models will be carried out to examine effects of contaminant mass diffusivity, temperature difference between walls, air exchange rates, and the locations of inlet and outlet air diffusers and obstacles on air flow patterns and contaminant concentration distributions in a ventilated room.

PERFORMANCE OF RESIDENTIAL GASEOUS FILTER DEVICES

Principal Investigator: Bal M. MAHAJAN
Building Environment Division
301.975.5856

Sponsor: Consumer Product Safety Commission

The project's objective is to develop a test method to evaluate gaseous filter devices used in residences and to obtain data about factors effecting the performance of filter devices for removing gaseous contaminants in residences.

Filters used to remove harmful gaseous contaminants from air are being marketed for residential forced-air heating and cooling systems and for stand-alone units. At present there is no standard test method for evaluating the effectiveness of the performance of these devices. In 1987 NBS initiated a 2-year project "Methods for Measuring the Effectiveness of Devices for Removing the Gaseous Contaminants from Air Streams" to develop a standard methodology for recognition as a national voluntary standard. The emphasis of the project is devices used in commercial and industrial buildings.

During 1988 CBT will extend and modify its test method for air stream gaseous filters to include types commonly found in residences. The test method will be designed so laboratory data obtained from the test method can be used to predict the performance of the gaseous cleaning device under expected conditions of air flow, temperature, pollutant concentrations, and relative humidities found in residential applications of the device. The method will be based on an idealized test procedure which will yield the parameters needed to predict the performance of gaseous cleaning device. CBT will develop a test method based on its test duct system to evaluate domestic gaseous filter/devices for effectiveness in removing contaminants such as CO, NO_2, volatile organics and chlorinated hydrocarbons. Factors affecting the performance of the filter/devices such as air flow rate, pollutant concentration, reduction in air flow due to the filter, absorption capacity, compound concentration, competing compounds, and desorption will be measured for several representative devices to assess the test method developed and to obtain data on the performance of the devices.

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

Principal Investigator: Bal M. MAHAJAN
Building Environment Division
301.975.5856

Sponsor: National Bureau of Standards

The project's objective is to develop methods to measure the efficiency of filters to remove gaseous contaminants from air.

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

Test methods will be developed to evaluate the effectiveness of filter media for removing gaseous contaminants from air. The test methods will employ a test loop system where a sample filter media is challenged with known gaseous contaminants introduced into the intake air at desired concentrations. The contaminant concentration both upstream and downstream of the filter media will be measured using gas chromatography. Data on contaminant penetration (efficiency) through the filter media as a function of elapsed time and other relevant variables will be collected. Some other important variables include: temperature, relative humidity, and speed of the carrier air; physical and chemical properties of the filter media; granule size, pacing density, and bed depth of sorber media; and properties and concentration of contaminant gases. These data will be used to determine the breakthrough conditions and capacity of the filter media. It will then be possible to compare the performances of different filter media and to estimate system effectiveness and economic analysis of various alternatives.

CBT will maintain close cooperation with ASHRAE's Technical Committee on Gaseous Air Contaminants and Gas Contaminant Removal Equipment (TC 2.3). It is expected that ASHRAE would use the results of the study as a basis for promulgating a consensus standard.

HEAT TRANSFER

QUANTIFICATION OF HEAT LOSSES DUE TO STRUCTURAL SUPPORTS AND AIR LEAKAGE FOR SHALLOW TRENCH HEAT DISTRIBUTION SYSTEMS

Principal Investigator: Jin B. FANG
Building Environment Division
301.975.6417

Sponsor: Tri-Services Committee, DoD

The objectives of this research are to 1) perform modifications of the existing finite element computer program to quantify the heat losses through pipe supports and air leakage into and from heat distribution systems, and comparison of the predicted results with the available test data and 2) develop in-situ methods for measuring the heat losses due to structural supports and air leakage for shallow trench underground systems.

A centralized plant for heating and cooling with associated distribution systems installed in large institutions and military facilities is more efficient and economical than a number of smaller units. However, this advantage is not realized unless the operating cost due to heat loss through the underground system is low. During 1987 a computer program developed at CBT, based on the finite element analysis to solve a two-dimensional steady-state heat transfer problem, was used to calculate the heat loss from two insulated pipes installed in a concrete trench. The quantification of heat losses associated with pipe supports and air leakage can provide a basis for the retrofit of existing pipelines, and furnish information required for improved design and construction procedures of underground systems.

During 1988, the existing finite element computer program is being modified to account for the pipe supports and air leakage, and extended to three-dimensional configuration for detailed analysis of heat transfer and flow of fluids in long underground pipes. Computer simulations with varying numbers of nodes or triangular elements will be made to determine the optimum element number, which is sufficiently large and does not affect the calculation results. Mathematical modeling of heat transfer characteristics and temperature distribution of underground systems will be performed on typical piping support systems and unsealed trench conditions using the modified computer codes. The predicted results will be compared with the available experimental data. A simulated scale model of an underground system will be constructed in later years to obtain test data to validate the computer models using the in-situ measurement technique to be developed.

VALIDATION OF MOISTURE-TRANSFER MODEL

Principal Investigator: Douglas M. BURCH
Building Environment Division
301.975.6433

Sponsor: National Bureau of Standards

The project's objective is to conduct a series of laboratory experiments to validate a mathematical model for predicting the combined flow of heat and moisture in multi-layered walls.

During the winter season, the moisture content inside buildings is considerably higher than the outdoors. As a result, water vapor permeates into walls and becomes adsorbed at the outer layers of walls. The accumulation of this moisture has a negative effect on thermal insulation properties. Mathematical models are not available to predict time-dependent moisture accumulation within building components.

CBT has recently developed a mathematical model for predicting the time-dependent transfer of heat and moisture in building materials. An experiment was constructed to condition two wall specimens with moisture to verify the accuracy of the above mathematical model. Moisture diffusion transport property data was developed for the components of the wall specimens. Sorption isotherms for cellulose and gypsum board were determined from equilibrium moisture content measurements of these materials. Existing sorption isotherm data for wood were reviewed and found to be adequate for use in the model.

During 1988, the following activities are being performed:

1. Moisture diffusion transport coefficients for the components of the wall specimen will be measured using ASTM cup method. Saturated salt solutions will be used to provide a range of vapor pressures inside the cups.

2. Instrumentation will be installed to measure the moisture accumulation in the wood siding of each wall specimen, the rate of heat transfer through the specimen, interior temperatures, and the air temperature and humidity conditions on both sides of the specimens. The experimental set-up will be assembled to condition the two specimens and to collect data for verifying the mathematical model. A data acquisition software program will be prepared.

EXPERIMENTAL EVALUATION OF DYNAMIC TEST PROCEDURES

Principal Investigator: Douglas M. BURCH
Building Environment Division
301.975.6433

Sponsor: Department of Energy (ORNL)

The project's objective is to develop an experimental method for a calibrated hot box to characterize the dynamic thermal performance of building walls.

For many types of buildings, the transient heat-transfer rate through the building envelope comprises a significant portion of the total space heating and cooling loads. Computer programs are widely used to perform hourly building energy simulations which predict the building envelope heat-transfer rate. Building designers, architects, and owners use these computer programs to size HVAC equipment, to predict peak demands and to predict annual energy costs. Moreover, such programs are used to minimize annual energy costs by investigating tradeoffs in the envelope design, selection of HVAC systems and equipment, and by analyzing various methods of building operation.

There is need to develop an experimental method using a calibrated hot box to provide a "general" characterization of the dynamic thermal performance of walls. Such a method would permit the measured thermal response under one set of boundary conditions to be readily extended to different boundary conditions. More importantly, such a research study would permit the existing computer programs mentioned above to be used with greater confidence.

CBT is using a ramp test method on a simple masonry wall having known heat-transfer properties. The National Research Council of Canada developed a "slow ramp" test method. NBS improved the NRC test method by using a "fast ramp" instead of a "slow ramp" excitation function. This test method has considerable promise and potential for determining empirical transfer-function coefficients (TFCs) that predict the time-dependent heat-transfer rate through complex building components having significant thermal bridges and anomalities.

In the fast ramp test method, a fast ramp excitation function is generated in the climatic chamber. The metering chamber, maintained at a typical indoor condition, is used as a calorimeter. The

specimen heat-transfer rate is determined from an energy balance of the metering chamber at hourly time intervals. From the measured transient specimen heat-transfer rate, CBT will determine the poles and residues for a Laplace transform analytical solution. These mathematical parameters subsequently will be used to determine TFCs.

A complex masonry wall having significant thermal bridges will be selected through a consensus process with industry and government representatives and installed in the NBS Calibrated Hot Box. This masonry wall will be exposed to the following excitation functions: a fast ramp, a sol-air diurnal waveform, and a four-harmonic diurnal waveform. TFCs for this masonry wall will be determined using the ramp test method. Each set of TFCs will be used to predict the transient specimen heat-transfer rate for the other dynamic tests. Recommendations will be made concerning a preferred dynamic test method for using a calibrated hot box to measure the dynamic thermal characteristics of walls.

DEVELOPMENT OF A HIGH-TEMPERATURE STANDARD REFERENCE MATERIAL

Principal Investigator: Robert R. ZARR
Building Equipment Division
301.975.6436

Sponsors: U.S. Department of Energy (ONRL)
National Bureau of Standards

The project's objective is to establish a thermal Standard Reference Material (SRM) having a low thermal conductivity for use over an extended temperature range.

As better insulating materials are developed, there is need to develop a new Standard Reference Material that has low thermal conductivity. Materials having high thermal resistance values require special measurement considerations for accurate determination of thermal properties. A low thermal conductivity SRM is needed to calibrate instruments and to serve as a base for comparison of thermal property measurements.

CBT is measuring the thermal conductivity of 10 to 20 specimens, from one lot, of fumed-silica (board insulation). Each specimen will be measured at 24 °C (75 °F) using the NBS 1-m Guarded Hot Plate. Specimens will be tested as received with no high-temperature heat treatment and at atmospheric pressure. Since the apparent thermal conductivity of fumed-silica depends on the barometric pressure, an attempt will be made to modify the guarded hot plate to control the barometric pressure under test conditions. Instrumentation will be installed to automatically measure barometric pressure and control the new equipment.

If the pressure control modification to the existing equipment is successful, three specimens from the sample set will be tested at controlled atmospheric pressure over the temperature range of the apparatus (approximately 0 °C to 60 °C). At each temperature point the pressure will be changed allowing thermal conductivity measurements at different pressure levels. This will provide accurate data to calculate the thermal conductivity as a function of mean temperature and barometric pressure for the lot of material.

Two other specimens from the sample set will be selected to study the effects of high humidity on the specimens. Data from this study will establish the humidity levels which are acceptable for storage of the SRM specimens.

LIGHTING RESEARCH

INTERACTION BETWEEN LIGHTING AND HVAC SYSTEMS

Principal Investigator: Stephen J. TREADO
Building Environment Division
301.975.6444

Sponsor: Department of Energy

The project's objectives are to 1) obtain the heat distribution characteristics of various lighting systems in typical room thermal environments, 2) develop a database for detailed lighting heat transfer calculations, 3) analyze the components of lighting heat transfer, and 4) evaluate the influence of wall and floor construction and HVAC design on lighting and cooling/heating loads.

This project is a combined effort between the Department of Energy (DoE), the Electric Power Research Institute, Dubin-Bloom Associates and Ross & Baruzzini, Inc., and NBS.

ASHRAE studies show, electric energy consumption in commercial buildings use as much as 50% of the total building energy. Since the early 1970's efforts were made to reduce the lighting energy consumption without reducing its illumination performance by developing high efficiency ballasts, high efficacy light tubes, and using daylighting. Current cooling procedures can introduce as much as 50 CFM of room air or return air into the luminar. The efficiency with which the removed heat is applied to the winter heating requirement, and the effect of the cooling loads, is influenced by the design of the lighting and HVAC systems. An optimization design method is needed to minimize the net annual energy consumption by optimizing the design procedure through an improved understanding of the heat transfer process from the lighting fixture.

During 1988, the thermal performance of lighting systems in actual room environments is being examined using a test facility constructed in NBS's large environmental chamber. Detailed measurements of heat flows, cooling load, lighting energy, and temperature are being conducted for various lighting and HVAC designs. The results are being analyzed to develop design guidelines and procedures for effective use of lighting. A second set of tests are being conducted to investigate night temperature setback and solar loading effects on lighting and HVAC performance.

The resulting lighting/HVAC design and analysis procedures will enable the design of more energy efficient buildings, resulting in a minimization of building energy requirements. Particular attention will be paid to peak cooling loads.

PHOTOMETRIC AND THERMAL PROPERTIES OF LUMINAIRES

Principal Investigator: Stephen J. TREADO
Building Environment Division
301.975.6444

Sponsor: National Bureau of Standards

The project's objective is to develop metrics for evaluating lighting quality and procedures for designing effective lighting systems.

The Illumination Engineering Society (IES) has expressed the need for techniques to measure and predict lighting quality. The Lighting Research Institute (LRI) has recently stated; measurement of the near-field effects of lighting fixtures and their interaction with the thermal and luminous environment is a critical research need. Of particular concern are the luminaires recommended for use with VDT displays. The dramatically different configurations of parabolic and acrylic lens diffusers significantly influence lamp wall temperature and thus the luminous efficacy and thermal performance of the lamp. These in turn affect the luminous environment-luminance, contrast, spectral

composition, glare of the visual task. LRI also recognizes a conflict in recommended criteria for ceiling mounted luminaires for VDT terminals. The new ANSI standard conflicts with the CIE standard in recommended criteria for ceiling mounted luminance and minimum shielding angle, and thus light quality. Accurate specification of the luminance and contrast for visual tasks (both paper and VDT) as a function of the luminaire is the initial step in developing effective lighting quality metrics.

CBT is using its Lighting/HVAC interaction chamber to measure the photometric and thermal properties of different lamp/luminaire configurations with different types of visual tasks. This research focuses on measuring the luminaire in detail, its immediate surroundings, and the effect on visual tasks. The project involves the application of near-field photometry, detailed measurement and micro-modeling of the luminaire heat and light transfer, and detailed mapping of the luminous environment surrounding the visual task (including illuminance, spectral composition, and contrast). Using CBT-developed modeling and attendant data tables will provide a method to select lamp/fixture combinations that produce a specified visual and/or thermal condition. The results will be provided to ANSI/CIE for setting lighting standards for VDT displays.

LIGHTING ENVIRONMENT ASSESSMENT

Principal Investigator: Arthur I. RUBIN
Building Environment Division
301.975.6445

Sponsor: Army Intelligence and Security Command

The objectives of this research are to evaluate physical conditions in a few Army security facilities and the reaction of the staff to these conditions and to develop standards and criteria for improving new and existing facilities.

Many military and civilian employees work in environments characterized by windowless spaces, highly automated equipment, and work tasks that require concentration. These conditions may lead to lowered performance and employee health problems resulting from lighting, air quality, thermal conditions and isolation—lack of a view to the outside. Of the problems faced by these employees, poor lighting conditions was identified most important. Integrated research is needed to identify the existing problems and to develop guidelines for environmental changes.

The research is being performed in two phases. Phase 1 consists of a literature search, interviews with experts, and planning and conducting a pilot study at two field sites. CBT is performing Phase 2 during 1988. Its primary purpose is to measure a representative set of existing environmental conditions and user reactions in several Army security facilities, determine Army problem areas, and develop design recommendations.

OFFICE LIGHTING AND ENVIRONMENT EVALUATION

Principal Investigator: Belinda L. COLLINS
Building Environment Division
301.975.6456

Sponsor: Army Electronics Materiel Readiness Activity

The object of this research is to produce a comprehensive, integrated evaluation of the lighting and other environmental conditions in the U.S. Army Electronics Materiel Readiness Activity (U.S. AMEMRA) facilities.

Many military and civilian employees are required to work in windowless offices using highly automated equipment and performing demanding tasks. Environmental conditions as lighting, thermal conditions, noise, air quality, and lack of a view to the outside have been areas of employee complaints. These conditions are questioned by the Army because they may have an effect on productivity.

In this research, CBT's questionnaire and environmental measurement protocol developed for the Army Intelligence and Security Command, a parallel project, will be administrated in these facilities. A comprehensive evaluation of lighting conditions such as luminance, illuminance, contrast, color, contrast rendering factors, glare, and noise, temperature, and indoor air quality conditions will be made, including an assessment of the occupants' reaction to the spaces.

This work is designed to measure the physical conditions in a variety of areas and assess the employee's reaction. Since the physical facilities are being upgraded, the assessment can be done with facilities that have been upgraded, and with ones that have not. There is also an opportunity for results of the initial assessment to affect the final design of at least one facility, as well as, provide guidelines for improving existing facilities.

This research will result in a better understanding of the environmental conditions, particularly the lighting systems, and contribute to an eventual improvement of secure Army facilities.

ASSESSMENT OF HIGH TECHNOLOGY OFFICE DESIGN ON PRODUCTIVITY

Principal Investigator: Arthur I. RUBIN
Building Environment Division
301.975.6445

Sponsor: General Services Administration

The project's objective is to develop design criteria for automated offices, based on understanding the relationship of lighting and other environmental conditions on productivity.

Automation is brought into office environments 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 to accommodate paper tasks. These new systems are the source of many complaints about resulting office conditions. This has led researchers, designers, and using organizations to seek better understanding of the relationships between office lighting, thermal, and noise conditions, furnishings, and other design features on office worker productivity, primarily professionals and managers.

In 1983, GSA instituted an advanced technology building program directed toward cost effective design, emphasizing environmental control, thermal performance, and occupant productivity. This program is being used in new construction projects, e.g., the Portland, Oregon Federal Building and the Federal Records Center, Overland, Missouri, and others.

During 1988, CBT is determining:

- the contribution of environmental conditions such as lighting, to productivity,
- the interrelationships such as lighting, noise, thermal, air quality, and ventilation conditions to productivity; i.e., the extent to which contributions are additive,
- measurement approaches to productivity, e.g., those useful immediately, and those requiring additional work,

- the sensitivity of various measures, time, and costs to complete important tasks,
- the evaluation of "high quality" design and environmental features, such as systems furniture, to enhancing office productivity.

Initial measurement techniques will be tested and refined during the course of studying the Portland building and in subsequent buildings such as those in Overland, Missouri and Long Beach, California. The first productivity measures will focus on lighting, furniture systems, "high quality office," and space flexibility issues.

RE-EVALUATION OF COLOR SPECIFICATION FOR TRAFFIC CONTROL

Principal Investigator: Belinda L. COLLINS
Building Environment Division
301.975.6456

Sponsor: Federal Highway Administration

The objective of this research is to re-evaluate the current chromaticity specifications for highway signs and markings.

Current highway standards specify the chromaticity coordinates for seven colors—red, orange, yellow, green, blue, white, and brown. The current specifications differ markedly from the ISO specifications for safety colors and from the ANSI Z53.1 (1979) specifications. The result is that the colors are quite dark and not sufficiently conspicuous or easily recognizable. Specifications are needed for retroreflective (and possibly fluorescent) colors. As a result, the existing specifications should be reviewed to determine the need for, and ways to, improve the conspicuity and recognizability of highway safety colors.

Because the current specifications are for highly saturated colors with low lightness, there have been many complaints about the darkness of these colors and the difficulty of recognizing them accurately. CBT is reviewing the effectiveness of the existing chromaticity specifications by thoroughly searching relevant scientific research. Based on this review, new specifications will be suggested where it is clear that the current ones are not adequate.

MEASUREMENT OF LUMINOUS BACKGROUND

Principal Investigator: James A. WORTHEY
Building Environment Division
301.975.6446

Sponsor: U.S. Coast Guard

The objective of this project is to develop measurement and spatial characterization of the luminous intensity, color, and location of lights in New York City Harbor at night from specified locations.

A serious problem facing mariners and others attempting to negotiate waterways at night is the visual clutter created by numerous bright, colored, flashing lights. Signals and aids to navigation must be tested against a background of similar lights, making it difficult to identify them accurately. Although color and/or pulses have been added to some signals to increase their effectiveness, they are still similar to some shore lights. As a result, there is need to increase the conspicuity of lighted aids and signals relative to the background against which they must be seen. The first step in increasing conspicuity is to characterize the background lighting conditions in harbors through detailed measurements and observations.

A two-part technical approach using both photometric and photographic techniques is being used. Three locations in New York City Harbor were selected to perform detailed photometric measurements of illuminance and luminance and as a series of color and black and white photographs. Frequency counts of the number of lights meeting specific criteria for illuminance, flash rate, and color in selected segments will then be made.

The visual scene from the observation point will be divided into segments 5° by 5° for the three observation points. Information such as illuminance, average luminance, color, and histograms of illuminance within these segments will aid in the characterization of the harbor.

BUILDING SECURITY

PERFORMANCE CRITERIA FOR BUILDING MATERIALS, EQUIPMENT AND SYSTEMS IN CORRECTIONAL FACILITIES

Principal Investigator: Robert D. DIKKERS
Building Environment Division
301.975.5863

Sponsor: Department of Justice

The project's objective is to develop performance criteria for building materials, equipment, and systems used in detention and correctional facilities.

During 1988 CBT has been developing performance criteria for correctional facilities. The need was identified by a Project Review Committee which met at NBS on July 28–29, 1987. The Review Committee consisted of representatives from the National Sheriffs' Association, Association of State Corrections Administrators, American Jail Association, American Correctional Association (ACA), Adult Local Detention Committee, ACA Design and Technology Committee, and the AIA Committee on Architecture for Justice.

The performance criteria considers aspects of planning, design, and construction which are different from conventional building by reason of their security, safety, and durability considerations. The document will be organized on the basis of performance criteria dealing with security systems, components, equipment, and materials and their integration into the building or facility. Performance statement entries will be presented in the Requirement, Criterion, Evaluation, and Commentary format.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The Center for Building Technology (CBT) of the National Bureau of Standards (NBS) is the national building research laboratory. It works cooperatively with other organizations, private and public, to improve building practices. It conducts laboratory, field, and analytical research. It develops technologies to predict, measure, and test the performance of building materials, components, systems, and practices. This knowledge is required for responsible and cost-effective decisions in the building process and cannot be obtained through proprietary research and development. CBT provides technologies needed by the building community to achieve the benefits of advanced computation and automation. CBT does not promulgate building standards or regulations, but its 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 projects underway in the Center during 1988.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

building research; building technology; criteria; measurement and test methods; performance criteria; project summaries; standards; technical bases

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