NISTIR 4796

Building and Fire Research Project Summaries 1992

Noel J. Raufaste

Building and Fire Research Laboratory
Gaithersburg, Maryland 20899

States Department of Commerce
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U.S. Department of Commerce
Barbara Hackman Franklin, *Secretary*
Technology Administration
Robert M. White, *Under Secretary for Technology*
National Institute of Standards and Technology
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FOREWORD

Construction is one of the Nation's largest industries. The 1992 industrial outlook says, in 1991, new construction was $415 billion, about 7.3 percent of the U.S. Gross National Product. During this same period, costs of unwanted fires exceeded $100 billion annually. The quality of constructed facilities directly affects the productivity of the U.S. building and fire community and affects the safety and quality of life of all constructed facilities. Over two-thirds of the Nation's fixed reproducible wealth is invested in the constructed facilities.

The National Institute of Standards and Technology (NIST) is recognized as the nation's science and engineering research laboratory. NIST develops measurement technology, testing procedures, quality assurance methods, and innovations that help build the infrastructure upon which much of the U.S. economy rests.

About BFRL

The mission of the Building and Fire Research Laboratory (BFRL), one of NIST's eight Laboratories, is to increase the usefulness, safety, and economy of constructed facilities, and reduce the human and economic costs of unwanted fires in buildings.

BFRL's work enhances the international competitiveness of U.S. building services and products through advancements in building and fire technology. BFRL performs and supports field, laboratory, and analytical research on the performance of construction materials, components, systems and practices, and the fundamental processes underlying the initiation, propagation, and suppression of fires. The Laboratory produces technologies to predict, measure, and test the performance of construction and fire prevention and control products and practices.

BFRL's laboratory facilities include: six-degree-of-freedom structural testing facility; large-scale structural testing facility with the 53 MN (12-million pounds of force) universal structural testing machine; environmental chambers; guarded hot-plate; calibrated hot-box; plumbing tower; building materials imaging and modeling laboratory; large burn facility for conducting experimental fires in full-scale and related combustion toxicity facility, large industrial fire test facilities, and fire suppression test facilities; and a fire simulation laboratory.

BFRL is the major nonproprietary source of technical information for development of voluntary standards by such organizations as ASTM; American Concrete Institute; American Society of Heating, Refrigerating and Air-Conditioning Engineers; American Society of Civil Engineers; Institute of Electronics and Electrical Engineers; and National Fire Protection Association. The resulting standards are widely used in building and fire codes.

BFRL works closely with its international peer organizations to maintain awareness of foreign research developments, as well as assure that generic research efforts are complementary, and U.S. interests are represented in the preparation of international standards and practices. BFRL cooperates closely with other U.S. and foreign laboratories in the conduct of its research. Sixty-three research associates from U.S. industry, guest researchers from foreign laboratories, and faculty members and students from universities worked at BFRL during 1991.

BFRL participates in over 200 national standardization activities; provides leadership in national and international standardization organizations and chairs more than 40 voluntary standardization activities. BFRL annually publishes over 230 reports, articles for research journals, and articles for professional and trade journals. BFRL staff annually makes hundreds of presentations to professional and technical meetings of building community organizations. For 22 years, BFRL has hosted a monthly Building Technology Symposia Series in cooperation with other organizations concerned with building research and practice and hosts weekly Fire Research Seminars for NIST staff and colleagues from the fire community. These are effective means of transferring the latest knowledge to practitioners and peer researchers. The Fire Research Information Service (FRIS) consisting of national and international fire research literature and FIREDOC, the automated database of fire research literature, is the only comprehensive national library resource for the fire community.

BFRL has 197 employees of which 139 are professional staff, 71 have Ph.D.s, and 17 are registered engineers. BFRL's budget for FY 1992 is $23 million. Congress provides $11 million to develop core competence in emerging research areas which will be used to assist in solving Federal agency and industry needs. The remainder, $12 million, is from other sources, primarily Federal agencies for solving their mission needs.

About this Report

This report summarizes BFRL's research for 1992. The report is arranged by its research programs: structural engineering, materials science and engineering, mechanical and environmental systems, fire science and engineering, and fire measurement and research. Each summary lists the project title, the BFRL point of contact, sponsor, research, and recent results.

For further information about BFRL, its facilities, opportunities for guest researcher assignments, collaborative programs, and contracted research contact BFRL's Office of Cooperative Research Programs, Building 226, Room B250, NIST, Gaithersburg, MD 20899.

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STRUCTURAL BEHAVIOR

NONLINEAR AND CHAOTIC DYNAMICS: APPLICATION TO DEEP WATER COMPLIANT PLATFORMS

Principal Investigator: Emil Simiu
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Sponsor: Minerals Management Service
Offshore Minerals Management
Technology Assessment and Research Branch

OBJECTIVE To understand hydroelastic phenomena including subharmonic oscillatory forms, deterministic chaotic motions, and chaotic motions with noise-induced jumps; and to develop related computational tools for use by offshore structural engineers to identify potentially unsafe designs in offshore structures with strong nonlinearities.

PROBLEM The development of appropriate tools for the effective hydroelastic analysis of compliant offshore structures is still in its infancy. Only recently has the role of nonlinearities and noise in inducing potentially catastrophic responses been demonstrated in hydroelastic systems both experimentally and numerically. Detection of such possible responses to ensure structural reliability is a task that has not yet been adequately addressed.

APPROACH In the first phase of this project fundamental studies are carried out on noise-induced jumps in a wide class of nonlinear systems subjected to (1) additive noise and (2) multiplicative noise. The studies will prove the new and striking result that for certain classes of systems and regions of phase space deterministic and stoichastic chaos are mathematically equivalent and can be dealt with by the same methods.

RECENT RESULTS "Noise Modeling and Reliability of Behavior Prediction for Multistable Hydroelastic Systems," Submitted to the *Proceedings of the Eleventh International Conference on Offshore Mechanics and Arctic Engineering,* June 7–11, 1992.

NONLINEAR/CHAOTIC BEHAVIOR OF DYNAMIC STRUCTURAL SYSTEMS

Principal Investigator: Emil Simiu
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Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop a computational and experimental basis for studying of nonlinear and chaotic phenomena of potential interest in structural engineering.

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

APPROACH Based on results of experimental and numerical studies obtained in an earlier phase of this project, it will be shown that certain noise-driven motions may be approximated arbitrarily closely by deterministic chaotic orbits. The study will be conducted for oscillators whose unperturbed counterpart exhibits homo- and

heteroclinic orbits and will make use of the generalized Melnikov distance, the attendant traveling horseshoe sequence concept, and the estimation of transport across pseudoseparatrices by way of one-sided flux. This research will constitute a basis for future practical applications to offshore platforms.

RECENT RESULTS

"Experimental and Numerical Chaos in Continuous Systems: Two Case Studies," *Mechanics Computing in 1990's and Beyond,* Proceedings/EM Div/ASCE, Columbus, OH, pp. 786–790, May 20–22, 1991.

"Foias-Temam Approximations of Attractors for Galloping Oscillators," *Mechanics Computing in the 1990's and Beyond,* Proceedings/EM Div. ASCE, Columbus, OH, pp. 781–785, May 20–22, 1991.

"Chaotic Motions of Coupled Galloping Oscillators and Their Modeling as Diffusion Process," Proceedings of Sixth International Conference on Applications of Probability and Statistics in Civil Engineering, Mexico City, Vol. 2, pp. 993–1000, June 1991.

"Necessary Condition for Homoclinic Chaos Induced by Additive Noise," First International Conference on Computational Stochastic Dynamics, Corfu, Greece, pp. 889–896, September 17–19, 1991.

"Chaotic Motions of Forced and Coupled Galloping Oscillators," *Journal of Wind Engineering and Industrial Aerodynamics,* 35, Elsevier Science Publishers B. V., Amsterdam-Printed in the Netherlands, pp. 1083–1094, 1990.

"Chaotic Motions of Self-Excited Forced and Autonomous Square Prisms," *Journal of Engineering Mechanics,* Vol. 117, No. 2, pp. 241–259, February 1991.

"Algebraic Approximation of Attractors for Galloping Oscillators," *Journal of Sound and Vibration,* 146(1), pp. 170–175, 1991.

"Periodic and Chaotic Oscillations of Modified Stoker Column," *Journal of Engineering Mechanics,* Vol. 117, No. 9, pp. 2049–2064, September 1991.

"Empirical Fluidelastic Models and Chaotic Galloping: A Case Study," *Journal of Sound and Vibration,* Vol. 152, No. 3, 1992.

"Melnikov Function and Homoclinic Chaos Induced by Weak Perturbations," Physical Review A15, submitted for review.

"Equivalence Between Motions with Noise-Induced Jumps and Chaos With Small Horseshores," *ASCE Ninth Engineering Mechanics Conference,* College Station, TX, May 1992.

"Noise-Induced Chaos and Phase Space Flux," manuscript in review (1992), to be submitted to *Physica D.*

INTERNATIONAL WORKSHOP IN RELIABILITY OF OFFSHORE OPERATIONS

Principal Investigator: Emil Simiu
Structures Division
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Sponsor: Minerals Management Service
Offshore Minerals Management
Technology Assessment and Research Branch

OBJECTIVE To organize, conduct, prepare, and edit workshop proceedings on reliability of offshore operations.

PROBLEM Considerable loss of life and property, and damage to the environment, that have occurred in recent years owing to insufficiently safe offshore operations have shown that improved safety assurance measures are necessary. To achieve improved safety levels, operational and regulatory experience accumulated since the 1984 workshop held at NIST on this theme must be put to use, and new research must be conducted.

APPROACH To provide a forum for review of methods for assessing the safety of offshore operations and discussing future action aimed at their improvement, a workshop was organized by and held at NIST. It brought together representatives of regulatory agencies, oil companies, classification societies, and consulting and manufacturing firms. NIST is responsible for the preparation of the proceedings.

RECENT RESULTS Workshop proceedings in review.

GUST FACTORS FOR HURRICANE WINDS

Principal Investigator: R. D. Marshall
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Sponsor: National Institute of Standards and Technology

OBJECTIVE To establish gust factor relationships that account for the differences in surface wind characteristics for tropical and extratropical cyclones.

PROBLEM For structural design purposes it is required that wind speed averaged over some reference period T be convertible to the probable maximum wind speed averaged over some shorter interval within that period. The usual approach is to define a gust factor, averaged over several sets of observations, as the ratio between the maximum gust speed of duration T to the corresponding hourly mean speed. The data and models used to establish the gust factor relationships used in contemporary wind load standards are based on observations made in extratropical storms. Recent analyses of selected stripchart records obtained from the eye-wall region of selected hurricanes suggest that current practice may underestimate hurricane gust speeds by 10 percent or more and that the gust loading effects may be underestimated by as much as 25 percent.

APPROACH BFRL will reexamine the basis for the current formulation of gust factors (commonly referred to as the Durst curve) which uses extratropical wind speed records obtained at Cardington, England, for the period 1925–1929, and at Ann Arbor, Michigan, in the 1930s. This will be accomplished using digitized data sets obtained at Lubbock, Texas, using state-of-the-art instrumentation positioned at four levels on a 60 m tower. Effects of instrument height and surface roughness at this site will then be applied to the hurricane wind speed database, resulting in a substantially larger set of records than is now available when only standard heights and airport exposures are used.

This research effort will result in a series of technical papers that critically examine the contemporary gust factor model and offer a revised formulation that accounts for higher gust factors in hurricanes as suggested by recent analyses of stripchart records.

RECENT RESULTS Krayer, W. R. and Marshall, R. D., "Gust Factors Applied to Hurricane Winds," American Meteorological Society Bulletin, to be published May 1992.

TEST METHODS FOR DETENTION LOCKS

Principal Investigator: Robert D. Dikkers
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301.975.5863

Sponsor: Department of Justice
National Institute of Justice

OBJECTIVE To develop standard test methods for various types of locks used in detention and correctional facilities.

PROBLEM Although there are several standards which cover the performance of various types of residential and commercial locks, there are no national standards which address important performance areas (impact, usage, operation under side load, etc.) for high security locks which are used in jails and prisons. Various studies have indicated that the lack of standards is one of the reasons that there has been a large number of failures of locks in new facilities.

APPROACH During FY 1992, test procedures will be identified and drafted, and a research program for laboratory testing will be prepared. Later this year and during FY 1993, laboratory tests will be conducted on a representative number of locks (manual-key, electric, pneumatic) to provide data for improving the draft test methods. Each major project step will be done with guidance from ASTM Committee F33 on Detention and Correctional Facilities.

RECENT RESULTS Review of existing standard test methods for locks including draft test methods under development by ASTM Committee F33.

EARTHQUAKE ENGINEERING

PERFORMANCE REQUIREMENTS FOR PASSIVE ENERGY DISSIPATION SYSTEMS FOR BUILDINGS AND LIFELINE STRUCTURES

Principal Investigator: Albert N. Lin
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Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop seismic design criteria for buildings and lifeline structures incorporating passive energy dissipation systems and to develop guidelines for standardized test procedures for the evaluation of passive energy dissipation systems.

PROBLEM Advances in materials and analysis techniques have resulted in the development of passive energy dissipation systems. These systems shift the natural period of the structure to put it beyond the range of the predominant earthquake motions. The systems also provide increased damping to dissipate the motions that are induced. Base isolation is the most commonly used method of passive energy dissipation. However, some significant technical issues must be resolved before the technology is more widely applied. One of these issues is the lack of data to compare the performance of base-isolated and fixed-base structures. Current recommended design practice results in base-isolated structures that are expected to significantly outperform fixed-base structures, and it does not appear possible to design a base-isolated structure to the same performance level as a typical fixed-base structure. A second issue relates to the need for development of a test protocol for base-isolation systems. Such testing is necessary to validate the analytical models of these systems and to provide quality assurance for individual units.

APPROACH To address the issue of comparable performance, a program of parametric analysis has been developed and is in progress. Four structural systems, 1) steel concentric braced frame, 2) steel moment resisting frame, 3) concrete moment resisting frame, and 4) concrete shear wall frame, were designed as fixed-base and base-isolated structures. The base-isolated structures were, in turn, designed to three levels of lateral force, a) code, b) 50 percent code, and c) 25 percent code. The response of these frames, subjected to three ensembles of earthquake ground motion, were then determined by a nonlinear time history analysis. The results of the study will allow for performance comparisons.

The issue of testing has not yet been resolved. A literature review of existing proposed test methods has not shown that a clear direction has been established. Further work, including some measurements of the response of prototype isolated structures, is under consideration.

The results of the project will provide engineers with guidelines for the design of loose-isolated structures that will allow for varying levels of performance depending on the occupancy requirements of the structure.

RECENT RESULTS Martin, J. W., *Long Term Performance of Rubber in Seismic and Non-Seismic Bearings: A Literature Review,* NISTIR 4613, National Institute of Standards and Technology, June 1991.

"Seismic Performance of Fixed-Base and Base-Isolated Steel Frames," *ASCE Engineering Mechanics Journal,* May 1992.

"Performance of Elastomers in Isolation Bearings; A Literature Review," *EERI Spectra* (submitted).

"Design Levels for Base-Isolated Structures," *CIB World Congress,* May 1992.

"Relative Performance of Fixed-Base and Base-Isolated Structures," *Tenth World Conference on Earthquake Engineering,* July 1992.

SEISMIC STRENGTHENING METHODOLOGIES FOR REINFORCED CONCRETE FRAME BUILDINGS

Principal Investigators: Long Phan
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Sponsor: National Institute of Standards and Technology

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

PROBLEM A strong motion earthquake will occur in the eastern United States. However, because only nondestructive earthquakes have occurred in this region in recent history, most reinforced concrete structures are not designed to resist large earthquakes. Typically, medium to highrise reinforced concrete frame structures designed primarily for gravity loads are vulnerable to severe damage or even to total collapse of the entire structure. In order to minimize such vulnerability, these structures need to be strengthened with lateral load resisting elements which provide adequate stiffness and strength to resist lateral loads produced by moderate earthquakes and sufficient ductility to absorb imparted energy of a strong earthquake without collapse.

It has been observed during past earthquakes that columns of reinforced concrete frame structures lacking adequate lateral load resisting capacity sustain severe damage beyond repair. Significant improvement of building performance can be expected if lateral loads are diverted from columns to lateral load resisting elements. This project aims to develop methodologies for providing lateral load resisting elements such as infilled shear walls and diagonal steel braces to improve seismic performance of reinforced concrete frame structures, and for strengthening beam-column connections which have inadequate capacity.

APPROACH A three-phase analytical and experimental studies are being performed. They include:

1. Analytical studies of judiciously selected reinforced concrete frame buildings are being carried out to determine their dynamic response characteristics.

2. Analytical studies are being performed to study the improved response characteristics of the selected reinforced concrete frame buildings strengthened by the addition of lateral load resisting elements. The results of recent experimental studies carried out at Cornell, NCEER and other academic institutions will be incorporated in modelling the concrete structures with infilled shear walls and steel braces. The analytical studies will identify the amount and types of strengthening elements needed for each type of structures.

3. One 3-story 1/3-scale single-bent frame will be tested experimentally to verify the analytical model and evaluate system performance.

Both analytical and experimental work will be carried out jointly with Cornell University.

The results of this work will provide researchers and practitioners with the following:

1. Hysteresis Models for Infilled Reinforced Concrete (R/C) Frames, Braced R/C Frames, Strengthened R/C Beam-Column Joints, and Strengthened R/C Columns.

2. A computer program which incorporates the above hysteresis models for use in evaluating building performance before and after strengthening and to assess the effectiveness of different strengthening schemes.

3. Guidelines for seismic strengthening of lightly R/C frame buildings.

RECENT RESULTS Extended the computer program IDARC to include the performance of both interior and exterior joints, using the experimental results from recent studies at Cornell, SUNY at Buffalo, Texas and elsewhere.

Analyzed three lightly reinforced concrete frame structures (3,6,10 stories) to determine their response to moderate earthquakes, and to determine potential weaknesses.

Conducted two experiments on retrofitted beam-column joints (at Cornell).

SEISMIC PERFORMANCE OF PRECAST CONCRETE CONNECTIONS

Principal Investigators: William C. Stone, Structures Division, 301.975.6075; Geraldine S. Cheok, Structures Division, 301.975.6074

Sponsor: National Institute of Standards and Technology

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

PROBLEM Careful attention to connection detail is required to ensure ductility and no premature yielding of connections. In order to exploit the benefits that exist in precast construction, ATC-8, the Proceedings of Workshop on Design of Prefabricated Concrete Buildings for Earthquake Loads, identified research on moment resistant joints between precast beam and column element as the top priority item.

Strength and ductility of joints of precast beam-column connections can be achieved by post-tensioning the precast elements, special reinforcing arrangement, and fiber reinforced grout in the joints. Technical data are needed to establish provisions for code and standards, thereby allowing safe precast construction in seismically active regions.

APPROACH Currently, there is limited guidance about the design and detailing of precast concrete structures for seismically active regions. The 1985 UBC permits the use of precast concrete elements to resist seismic forces provided the design and detailing used satisfy the Code requirements for cast-in-place concrete structures. The 1985 edition of the UBC Code was in use at the time this program was initiated. It has been presumed that precast structures tend to be less ductile and tend to have a less stable inelastic response than do cast-in-place monolithic structures. This is primarily because the inelastic strains are concentrated in the connections. Thus, the connections are often unavoidable weak links.

A task group consisting of individuals from the academic research community, the Precast/Prestressed Concrete Institute, the Portland Cement Association, and the design profession, has been formed to provide technical guidance on the project. The task group has been and will guide the design of specific joint details for NIST's consideration for study. An experimental model study will be carried out to characterize joint behavior. The experimental program is divided into three phases. Phase I of the program will be an exploratory phase to determine a viable connection. Phase II will involve testing of several test specimens as determined in Phase I. Phase III will examine the influence of on the connection behavior partially bonded tendons. Phase IV will involve the testing of specimens which consists of low-strength steel and prestressing steel. The specimen design for this phase will vary from the previous phases. Analytical modelling will be performed to define the effects of connection behavior on frame response.

RECENT RESULTS Cheok, G. S. and Lew, H. S., "Performance of 1/3-Scale Model Precast Concrete Beam-Column Connections Subjected to Cyclic Inelastic Loads—Report No. 2," NISTIR 4589, National Institute of Standards and Technology, June 1991

Cheok, G. S. and Lew, H. S., "Performance of Precast Concrete Beam-to-Column Connections Subject to Cyclic Loading," *PCI Journal*, Vol. 26, No. 3, June 1991.

Four precast test specimens, two Zone 4 and two Zone 2, were tested in FY 1991. Two precast, Zone 4 specimens tested in FY 1992.

COST EFFECTIVE SEISMIC RETROFIT TECHNOLOGY FOR BRIDGE COLUMNS

Principal Investigators: William C. Stone
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Sponsor: Federal Highway Administration
Structures Division

OBJECTIVE To develop a method for assessing the quantitative performance of prospective retrofit techniques for concrete bridge columns from the standpoint of cost, seismic resistance, and seismic region.

PROBLEM Throughout the United States there are tens of thousands of highway bridge structures situated in zones of potential seismic activity. Despite dozens of years of research in reinforced concrete behavior and the general acceptance of high performance computer work stations in design offices, the basic approach to the design for bridge piers remains the much the same as it was a decade ago. Serious

limitations presently exist, the most critical of which are the inability to account for the random nature of inertial loading at a specific construction site and the inability when one considers the issue of ascertaining the effectiveness of a particular retrofit technology to be applied to an existing column which may or may not be constructed in accordance with current design provisions and/or whose state of damage following previous earthquakes may or may not be known.

In 1991 BFRL proposed that a fundamentally different approach could be taken to predict the performance of bridge piers on the basis of the interrelations which exist at a particular construction site between bedrock motion, soil column signal modification, and inelastic structural response under reversed cyclic loading. It is anticipated that such an approach will ultimately permit the a priori design of a bridge column to withstand a specific magnitude earthquake while sustaining a quantifiable level of damage at the lowest possible construction cost.

This is a multidisciplinary research project in which BFRL has an opportunity to establish the initial standards in several areas including a world standard for digital laboratory test data for reinforced concrete elements; selection of parametric models for prediction of hysteretic behavior of reinforced concrete; the development of damage level predictive models; and the development of interactive means of assessment of the effectiveness of retro-fit technology for a specific bridge at a specific locality.

APPROACH

This multiyear project is aimed at advancing the state of the art for seismic design of bridge piers. It involves the integration of six specific tasks into an interactive, computer based analytical tool. The tasks include: 1) the automated selection of an appropriate "suite" of design bedrock motions (earthquakes) for a specific site; 2) the propagation of these motions to the surface through arbitrary soil columns; 3) the automated selection of appropriate hysteretic failure model parameters based on a priori design (material, geometric) properties; 4) the inelastic dynamic analysis of prospective designs in such a manner as to produce a quantitative "damage index"; 5) the development of empirical models relating the damage index to physical structural characteristics following inelastic loading; 6) and the development of an interactive system for assessment of initial section properties (moment curvature relationships) for arbitrary sections that might be employed in retrofit strategies. This latter capability will serve as a graphics-based front end to the overall analysis system which will rapidly permit the assessment of a wide range of generic retrofit approaches for any given seismic zone. Presently the program has been developed to handle single column bents with one or more cross sectional changes along the height of the member.

The results of this work will provide designers with the means to make detailed assessments of the seismic performance of concrete bridge piers. Designers will be able to determine the specific levels of damage expected in proposed designs, the level of damage experienced by existing structures which have undergone severe shaking, and the effectiveness of a variety of retrofit and repair techniques.

RECENT RESULTS

Stone, William, C. and Taylor, Andrew W., "System Identification of Spirally Reinforced Circular Bridge Columns Subjected to Cyclic Lateral Loading," *Wind and Seismic Effects,* Proceedings of 23rd Joint Meeting, National Institute of Standards and Technology, Special Publication 820, September 1991.

Stone, William C. and Taylor, Andrew W., "A Predictive Model for Hysteretic Failure Parameters," *Proceedings of the Tenth World Conference on Earthquake Engineering,* Madrid, Spain, July 19–25, 1992.

UJNR BRIDGE WORKSHOP

Principal Investigator: H. S. Lew
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Sponsor: Federal Highway Administration

OBJECTIVE To hold, under the auspices of the UJNR Panel on Wind and Seismic Effects, a joint U.S.-Japan bridge workshop to exchange the latest developments in wind and seismic design criteria, construction methods, and repair and strengthening techniques.

PROBLEM Both the United States and Japan continually update design criteria based on research and field performance data. Timely exchange of technical data is beneficial for both countries for updating design and construction standards for bridge structures.

APPROACH In cooperation with an academic institution, a joint workshop will be planned and held in the United States. Date and location of the proposed workshop will be determined at the 24th Joint Meeting of the U.S.-Japan Panel on Wind and Seismic Effects in May 1991.

RECENT RESULTS Abdel, Ahmed, M. ed, Sixth *U.S.-Japan Proceedings, Bridge Engineering Workshop—Analysis, Design, Performance, and Strengthening,* U.S.-Japan Panel on Wind and Seismic Effects, University of Southern California, May 1990.

PLAN FOR THE DEVELOPMENT OF SEISMIC STANDARDS FOR LIFELINES

Principal Investigator: Robert D. Dikkers
Structures Division
301-975-5863

Sponsor: Federal Emergency Management Agency
Office of Earthquakes and Natural Hazards

OBJECTIVE To prepare (by June 30, 1992) a plan for the development of seismic design and construction standards for lifelines (gas and liquid fuel, electrical power, telecommunications, transportation, water and sewage systems).

PROBLEM Section 8(b) of the National Earthquake Hazards Reduction Program (NEHRP) Reauthorization Act of 1990 requires FEMA, in consultation with NIST, to submit to the U.S. Congress, not later than June 30, 1992, a plan, including precise timetables and budget estimates, for developing and adopting, in consultation with appropriate private sector organizations, design and construction standards for lifelines. The plan is also required to include recommendations of ways Federal regulatory authority could be used to expedite the implementation of such standards.

APPROACH Steering Group, made up of representatives from the American Society of Civil Engineers' Task Fore on Lifeline Earthquake Engineering, The National Center for Earthquake Engineering Research, NIST, The Federal Emergency Management Agency, other Federal agencies, and the private sector, has been organized

to establish a methodology and schedule for developing the plan. The steering group has also identified potential contractors and experts which NIST should negotiate with to help prepare and review draft plans for the development of seismic design and construction standards for lifelines.

The plan will include the following information: state-of-the-art description of the lifeline facilities relative to their seismic vulnerability; current design and construction practices and standards; available knowledge to improve existing practices; recommended standards to be developed for new and existing construction; recommended research to fill identified knowledge gaps; and recommendations for the most appropriate groups to develop draft standards and to process such draft standards into national voluntary consensus standards. The plan will focus on an eight-year period of standards development and research activities.

RECENT RESULTS Reviewed six draft plan recommendations by experts and other participants at a NIST workshop, Denver, CO, September 25–27, 1991.

EARTHQUAKE RESISTANT CONSTRUCTION OF LIFELINES SERVING, OR REGULATED BY, THE FEDERAL GOVERNMENT

Principal Investigator: Felix Y. Yokel
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Sponsor: Federal Emergency Management Agency
Office of Earthquakes and Natural Hazards

OBJECTIVE To assess the exposure of Federally owned, operated, or regulated lifelines to earthquake risks, and if necessary to recommend and initiate the development of Federal guidelines for earthquake resistant construction.

PROBLEM The Federal Government owns and operates, and in some instances regulates, lifelines which may be vulnerable to earthquake damage. Since the disruption of lifelines by an earthquake can result in loss of life and can have severe environmental and economic consequences, it is important to minimize the risk of earthquake damage. Individual Federal agencies in many instances take steps to mitigate the earthquake risks to new lifelines under their jurisdiction during the design and construction stage, particularly when these lifelines are located on the West coast. However, retrofitting of existing facilities and earthquake resistant construction of lifelines in the Central and Eastern United States are seldom considered.

APPROACH A target lifeline is selected. The vulnerability of the lifeline to damage in past earthquakes, as well as available standards and technologies to protect the lifeline against earthquake damage are reviewed. Relevant Federal agencies are contacted in order to determine measures taken by these agencies to protect lifelines under their jurisdiction against earthquake hazards. On the basis of this information an assessment is made whether Federal guidelines are necessary. The results of the review are presented in a joint FEMA/NIST report.

RECENT RESULTS Yokel, Felix, Y. and Mathey, Robert G., *Earthquake Resistant Construction of Gas and Liquid Fuel Pipeline Systems Serving or Regulated by the Federal Government,* NISTIR 4795, National Institute of Standards and Technology, March 1992.

MANAGEMENT OF THE INTERAGENCY COMMITTEE ON SEISMIC SAFETY IN CONSTRUCTION

Principal Investigator: Diana Todd
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Sponsor: Federal Emergency Management Agency
Office of Earthquakes and Natural Hazards

OBJECTIVE To facilitate and expedite the work of the Interagency Committee on Seismic Safety in Construction (ICSSC), by providing the Chair and Secretariat.

PROBLEM The National Earthquake Hazard Reduction Program (NEHRP) established the ICSSC to assist Federal departments and agencies develop, improve, and maintain seismic safety programs for all types of construction. Twenty-seven Federal departments and agencies currently participate in the ICSSC. The National Earthquake Hazard Reduction Act (amended by Public Law 101-614) designates the director of NIST, or his deputy, as the chair of the ICSSC. NIST provides the Secretariat to the ICSSC, to facilitate, document, and disseminate the work of the committee. The ICSSC is currently working on a project to improve seismic safety of new Federal construction through the implementation of Executive Order 12699, Seismic Safety of Federal and Federally Assisted or Regulated New Building Construction. Work is beginning on projects to recommend standards for new and existing lifelines and for evaluation and retrofit of existing buildings.

APPROACH BFRL will schedule, chair, and document at least two meetings per year of the full committee and at least one meeting per year of the steering committee. BFRL will produce agendas for and minutes of these meetings, will maintain membership rosters, and will perform other administrative tasks as needed to maintain the smooth functioning of this committee.

In support of the implementation of Executive Order 12699, BFRL will prepare two companion reports to supplement RP 2.1, "Guidelines and Procedures for Implementation of Executive Order on Seismic Safety of New Construction," for use by Federal agencies. BFRL, working with ICSSC Subcommittee 1 Steering Committee, and the ICSSC Full Committee, will develop a consensus recommendation of specific standards appropriate for use by Federal agencies in implementing the Executive Order.

RECENT RESULTS Todd, Diana, ed., *Guidelines and Procedures for Implementation of Executive Order on Seismic Safety of New Construction,* ICSSC Recommended Practice 2.1, NISTIR 4635, National Institute of Standards and Technology, July 1991.

DEVELOPMENT OF SEISMIC STANDARDS FOR EXISTING FEDERAL BUILDINGS

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Sponsor: Federal Emergency Management Agency
Office of Earthquakes and Natural Hazards

OBJECTIVE To meet the requirement of Section 8(a)(1) of Public Law 101-614, to develop standards for assessing and enhancing the seismic safety of existing Federal buildings.

PROBLEM Buildings constructed without adequate consideration of seismic safety present a significant potential threat to human life during an earthquake. No nationally accepted private sector standards currently exist to address this issue. The Federal Government wishes to set an example by establishing standards for the evaluation and rehabilitation of Federally owned and leased buildings. The standards developed will be used by Federal agencies.

APPROACH The standards to be forwarded to the President are to be approved by consensus of the ICSSC. A contractor will develop drafts of performance objectives, rehabilitation criteria, standards, and supporting documents. A trial design program will be implemented, using sub-contractors, to establish cost data for the recommended standards. ICSSC Subcommittee 1 (Standards for New and Existing Buildings) will review and revise the draft documents as appropriate. The revised draft standard will be forwarded to the full committee of the ICSSC for consensus approval. After OMB review and approval, the standard will be submitted to the office of the President.

Development of standards for federal use is expected to contribute to a long-term FEMA project to develop guidelines for national private sector use. When the standards are adopted and enforced, the seismic safety of existing federal buildings will be enhanced.

RECENT RESULTS New project 1992

SEISMIC RESISTANCE OF MASONRY WALLS

Principal Investigator: Charles W. C. Yancey
Structures Division
301.975.6073

Sponsor: National Institute of Standards and Technology

OBJECTIVE To determine the ultimate and cracking limit states of reinforced concrete masonry shear walls and to recommend formulas that reliably predicts the ultimate strength of fully-grouted and partially-grouted masonry shear walls.

PROBLEM

When subjected to earthquake loads, masonry shear walls can undergo one of several failure modes: in-place flexural failure characterized by yielding of vertical reinforcement, shear failure indicated by diagonal cracking of the walls, and combined flexural/shear modes of failure. It is highly desirable to design masonry shear walls to fail in a flexural mode, given its more ductile and less catastrophic behavior. To predict the likely mode of failure, analytical techniques are needed to calculate the flexural and shear capacities. Flexural analysis methods developed for reinforced concrete walls produce generally acceptable predictions of the flexural capacity of fully-grouted, reinforced masonry walls. To date, no generally acceptable formulas have been established for predicting the shear capacity of masonry walls under in-plane lateral load.

A review of the literature on masonry shear walls has revealed that about 700 shear walls have been tested, in the United States and abroad, in the past 15 years. Most of the investigations were uncoordinated. There was very little replication in the testing programs, and no known effort has been devoted to comparing and possibly synthesizing the diverse test data. Given the relative expense of testing full-scale masonry wall prototypes under cyclic lateral loads, future experimental programs are not likely to incorporate extensive replication. Thus, analytical algorithms that simulate the response of masonry walls to seismic and other loads must be developed and calibrated. Laboratory-based experimentation can then be conducted on a limited basis to fill in voids in the state-of-knowledge.

APPROACH

This year, BFRL is performing Finite Element Model analysis on a number of partially-grouted masonry walls which have been tested by others to determine the applicability of the model to this type of wall. The FEM/I program, which was used during last year on fully-grouted experimental walls, will be employed to analyze walls from three experimental programs which included partially-grouted walls. The results of the work on predictive formulas has been transmitted to the Limit States Design Subcommittee of the Masonry Standards Joint Committee as a contribution to the revised Draft Limit States Design Standard. The work on partially-grouted masonry shear walls will assist the masonry industry in predicting ultimate capacity of this type of construction.

RECENT RESULTS

Fattal, S. G., and Todd, D. R., *Ultimate Strength of Masonry Shear Walls: Predictions vs. Test Results,* NISTIR 4633, National Institute of Standards and Technology, August 1991.

Yancey, C. W. C., *Experimental Results Versus Finite Element Predictions for Masonry Shear Walls,* NISTIR, National Institute of Standards and Technology, to be published.

Fattal, S. G., *Prediction of Shear Capacity of Masonry Shear Walls,* NISTIR, National Institute of Standards and Technology, to be published.

Developed and conducted a BFRL symposium program on masonry research, construction and standards.

SITE CLASSIFICATION TEST FOR RADON SOURCE POTENTIAL

Principal Investigator: Felix Yokel
Structures Division
301.975.6065

Sponsor: Department of Housing and Urban Development

OBJECTIVE To develop a site classification method for radon source potential which can be used to assess the radon risk of building sites prior to construction, based on repeatable measurements.

PROBLEM Radon emission is a major health hazard in single and multi family dwellings and in office buildings. There is therefore a need to identify and measure site characteristics which contribute to the infiltration of Radon gas into the interior of buildings.

Present site evaluation methods use measurements which are sensitive to transient conditions (barometric pressure, soil moisture content, and temperature). This project will attempt to develop appropriate site exploration and testing protocols to serve a site classification method based on invariant soil properties (radium activity concentration, dry density and dry-gas permeability).

APPROACH Testing protocols will be developed for the following test methods. The test boring method in which the provision in ASTM D 1586 will be modified to add the following procedures: 1) retrieval of a relatively undisturbed soil sample for the split spoon sampler for in-place density determination; 2) a procedure for sampling and testing by γ spectroscopy for measurement of radium activity concentration; 3) a procedure for estimating permeability from index properties; and 4) a guideline for the number of borings and the number of depth of samples to be taken on a site. A manual procedure will be developed considering four options: 1) taking of an in-situ density sample which also will be used for measurement of grain size distribution, estimate of permeability, and γ spectroscopy; 2) use of nuclear density gage and hand held spectrometer in the field, combined with sample retrieval for measurement of grain-size distribution and estimate of permeability; 3) use of option 2) together with downhole density gage and spectrometer; and 4) adaptation of an existing test kit used specifically for radon potential evaluation by extraction and testing of a soil-gas sample.

The information developed in other studies in the United States and other countries also will be closely examined, and where appropriate used in the development of testing protocols, and methods of correlating test results with the radon source potential of sites. Liaison will be established with organizations in other countries, such as Sweden and Switzerland, who are in the process of developing testing protocols in order to insure that all the available technology is used.

RECENT RESULTS Prepared review of all published and ongoing work in site characterization.

CONCRETE

GUIDELINES FOR PREDICTING THE SERVICE LIFE OF CONCRETE

Principal Investigator: James R. Clifton
Building Materials Division
301.975.6707

Sponsor: National Institute of Standards and Technology

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

PROBLEM Until recently, little systematic attention has been given to predicting the service life of concrete. Usually, concretes have been designed on the bases of 1) empirical relationships between materials, mixture design, and the physicochemical properties of concrete, and 2) experience with the performance of concretes in various service environments. The premise has been that such concretes will have an adequate life, and no attempt has been made to be more quantitative. In most cases, the concrete has performed reasonably well. However, the importance of making quantitative and reliable life predictions in selecting concrete is now widely recognized because of 1) applications that require significantly increased service lives, 2) increased use of concrete in critical new environments, e.g., offshore, 3) the high cost of rebuilding and maintaining the nation's infrastructure, and 4) the development of high-performance concretes for which a record of performance is not available.

APPROACH During 1992, BFRL is developing a comprehensive approach to predicting the service life of a concrete structure which includes developing mathematical models, identifying experimental investigations to obtain data needed to solve and validate models, creating a database to provide a resource of experimental data and pertinent published data and, where necessary, developing new accelerated test methods to predict concrete performance. The approach will be demonstrated for a reinforced concrete structure exposed to corrosive levels of chloride ions. The rates of transport, reaction, and absorption of chloride ions and oxygen gas in the pores of concrete at different levels in the structure will be inputs to the models. Also, the effects on corrosion of carbonation and other environmental stresses such as temperature and moisture, will be considered. Then guidelines will be prepared and submitted to voluntary consensus standard committees for standardization.

RECENT RESULTS "Models for Predicting the Service Life of Concrete," *Durability of Building Materials and Components,* Proceeding of the Fifth International Conference, pp. 361–373, November 1990.

SERVICE LIFE PREDICTIONS OF EXISTING CONCRETE MATERIALS

Principal Investigator: James R. Clifton
Building Materials Division
301.975.6707

Sponsor: Department of Energy
Oak Ridge National Laboratory

OBJECTIVE To identify and evaluate models and accelerated aging techniques and methodologies used to make predictions of the remaining in-service life of concrete for nuclear power plants.

PROBLEM Nuclear power plants provide about 17 percent of the U.S. electricity; it is expected this level soon will increase to 20 percent. Many of the existing plants are approaching their design life and are not being replaced. If the existing nuclear plants are not relicensed, through plant degradation, the nation could suffer electrical shortages. The Nuclear Regulatory Commission (NRC) and the Oak Ridge National Laboratory (ORNL) are carrying out a 5-year program to develop a methodology to assist NRC staff in granting life extensions to existing nuclear power plants. Since there is much concrete in these nuclear power plants, consideration of any life extension requires an in-depth assessment of the remaining safe life of the concrete structures.

APPROACH The project consists of two major tasks. The first task was completed in FY 1991; it involved the evaluation of models which might be used for predicting the remaining service life of concrete exposed to the major environmental stresses and aging factors encountered in nuclear power facilities. Most of the available models had been developed to predict the life of new concrete and the modifications needed to make them applicable to in-service concretes were determined. Models were evaluated based on considerations of 1) their basis (e.g., theoretical, empirical, or some combination), 2) the correctness of assumptions used in their derivation, 3) the availability of data to solve them, 4) their applicability (e.g., a model may be applicable only to concrete immersed in seawater), and 5) the reliability of their predictions.

BFRL's FY 1992 work will focus on evaluating the reliability of nondestructive evaluation methods (NDE) to predict the strength of in-place concrete. NDE techniques being evaluated include rebound hammer, penetration probe, and ultrasonic pulse velocity measurements. Statistical correlations between these methods and in-place concrete strengths are being sought and analyzed. This study will provide a basis for estimating confidence levels for in-place strength predictions based on field NDE data.

RECENT RESULTS Clifton, James R., *Predicting the Remaining Service Life of Concrete,* NISTIR 4712, National Institute of Standards and Technology, November 1991.

COMPUTER SIMULATION OF THE TRANSPORT PROPERTIES OF CEMENT-BASED MATERIALS

Principal Investigator: Edward J. Garboczi
Building Materials Division
301.975.6708

Sponsor: Northwestern University
National Science Foundation Center for Advanced Cement-Based Materials

OBJECTIVE To develop and apply models for predicting the transport properties of cement-based materials.

PROBLEM The durability of cement-based materials depends in a large part on the rate at which deleterious agents can pass through their pore structure. Examples include chloride and sulfate ions, which can attack concrete constituents. The models being developed in this project, in collaboration with Prof. Hamlin Jennings of Northwestern University, will, for the first time, enable quantitative relationships to be made between microstructure and transport properties. Knowledge of these relationships is the basis for being able to make soundly-based theoretical predictions of service life.

APPROACH This work builds on the digital-image-based microstructural model developed by BFRL during previous years. This model gives a 3-D representation of cement-based material phases, which has been shown to be quantitatively accurate. Since the model is in the form of a digital image, with an underlying lattice, finite-difference and other lattice-based algorithms can be applied to exactly compute, within computer round-off error, various transport properties. Since the model requires at least 100^3 pixels to give reasonable accuracy, these computations require a large amount of time on very fast computers. A microstructure is built up using the growth rules of the model, and then a transport algorithm is applied to calculate a quantity that can be compared with experimental measurements.

RECENT RESULTS Developed an algorithm for solving the Navier-Stokes equation in arbitrary two phase 2-D and 3-D porous media.

Developed computer simulations to study the validity of using Brinkman's equation to match boundary conditions at free fluid-porous medium interfaces.

Developed an algorithm to simulate the ac electrical properties of random composite materials, and is being applied to understanding impedance spectroscopy results from joint research performed with Northwestern University.

"Computer Simulation of The Diffusivity of Cement-Based Materials," *J. of Mater. Sci.,* in press.

TRANSPORT PROPERTIES OF POROUS MEDIA

Principal Investigator: Edward J. Garboczi
Building Materials Division
301.975.6708

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop and apply analytical and computer simulation models of the transport of fluids and ions in the pore space of porous materials like hardened cement paste and concrete to the problem of service life. This is year 3 of a 5 year project.

PROBLEM The degradation of the concrete infrastructure, worth on the order of six trillion dollars, is a national problem. The basic physical and chemical mechanisms of degradation processes in concrete need to be understood in order for scientifically sound, non-empirical service life predictions to be made. Most of the degradation processes that affect cement-based materials involve the transport, through the pore space, of ions or water or both. The rate of degradation depends to a large degree on the rate of transport of these species. Fundamental computer-based models are necessary in order to quantitatively relate transport properties to the complex microstructure of cement-based materials. Such quantitative relationships will serve to put existing and future standard test measurements of transport properties on a firm theoretical foundation.

APPROACH The microstructure of cement paste, either bulk paste or interfacial zone paste, is simulated using the 3-D digital-image-based model developed in previous years. Once a microstructure is created, exact (within computer round-off error) algorithms are applied to compute desired transport properties. Improvements are constantly pursued in both microstructural simulation, and in the

development of new physical properties that can be computed on the model. Comparison of computed properties with experimental measurements is the driving force for improvements in microstructural simulation. A desire to tackle the complex problem of service life prediction is the driving force for new physical property simulations to be developed.

RECENT

"Percolation Properties of Cement Paste, with and without Mineral Admixtures," *Cement and Concrete Research,* June 1991.

"Computer Simulation of the Effect of Calcium Hydroxide Leaching on the Pore Space Diffusivity of Cement Paste," *Materials and Structures,* in press.

"Simulation Studies of the Effects of Mineral Admixtures on the Cement-Paste-Aggregate Interfacial Zone," ACI, *Mater. J. 88*, pp. 518–529, 1991.

COMPUTER SIMULATION OF THE ELASTIC AND FRACTURE PROPERTIES OF RANDOM MATERIALS

Principal Investigator: Edward J. Garboczi
Building Materials
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Sponsor: National Institute of Standards and Technology
Director's Reserve Fund

OBJECTIVE

To develop and apply modern random elastic network techniques to digital-image-based models of random materials, in order to calculate elastic properties and crack-path dependence on microstructure.

PROBLEM

Routine computer simulation calculations of the elastic properties of random cement-based and ceramic materials are needed to map the dependence of crack paths on microstructure. This has never been done for any complex, random material. These materials have important problems to be solved, in terms of being able to predict end use mechanical properties, and in terms of predicting durability, as many degradation phenomena in these materials involve complex interactions between elastic, diffusion, fluid flow, and fracture properties. Having elastic simulations routinely available will assist in solving these classes of important problems.

Real-world problems involving random materials cannot be solved by simple analytical equations. Only sophisticated computer simulation techniques can address the many-body complexity of random materials. Two important classes of such materials, whose elastic and fracture properties are crucially important in their major end-uses, are cement-based and ceramic materials. These materials have complex microstructures even in their pure state, and when composites are made using them as a matrix, questions about residual stress and interfacial bonding also become important.

APPROACH

Traditional ways of relating elastic and fracture properties to microstructure have been through empirical equations involving parameters like porosity. The development of digital-image-based microstructural models for both cement-based and ceramic materials in the Building Materials Division allows *quantitative* simulation of any property of interest, as long as appropriate algorithms can be adapted to the lattice structure of the model. To simulate elastic properties, model images

must be mapped into a random network of both central-force and three-body angular force connections. These connections can be thought of as springs or more complicated links, as needed. Once such a mapping is accomplished, strains, both external and internal, can be applied, and the effective elastic response determined using a fast relaxation algorithm. This approach is something like a traditional finite-element technique, but with the far greater speed and flexibility necessary for handling the many-body randomness of a random material. In the past, BFRL has carried out such work in 2-D using simple triangular networks of Hooke's law springs.

In FY 1992, BFRL is developing a 2-D square lattice elastic algorithm, which will be extended to 3-D, to be compatible with BFRL's 2-D and 3-D microstructure simulation models. BFRL will use the 3-D code to test analytical measures for elastic composites, and use the 2-D code to map out crack-path dependence on microstructure by direct simulation of crack method through a random microstructure.

RECENT RESULTS "The Elastic Moduli of a Simpli 2-D Isotopic Composite: Computer Simulation and Effective Medium Theory," in press.

HIGH PERFORMANCE CONCRETE

Principal Investigators: James R. Clifton
Building Materials Division
301.975.6707

Nicholas Carino
Structures Division
301.975.6063

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop guidelines for the formulation, evaluation, and engineering applications of high-performance concrete.

PROBLEM After many years of relatively slow advances in concrete technology, a worldwide awareness has arisen that the performance of concrete in areas such as ease of placement, strength development and durability can be significantly improved. This is evident from the program plans of the Euro-International Committee for Concrete (CEB) and the high level of concrete research activities in Japan, Norway, and Canada. In the United States, programs such as the Concrete and Structures program of the Strategic Highway Research Program and the establishment of the NSF Center for Advanced Cement-Based Materials are a response to the need for improved concretes and the recognition of the possibility of their development. However, because these programs are either of a problem-solving nature or of an exploratory nature, they are unlikely by themselves to provide the measurement technology and design guidelines needed for U.S. leadership in high-performance concrete technology. United States leadership in high-performance concrete technology can be a major contributor to enhancement of the competitiveness of the Nation's construction industry.

APPROACH This multiyear project is aimed at advancing the understanding of the properties and long-term performance of high-performance concrete and the development of guidelines for 1) the proportioning and mixing of high-performance concrete, 2) methods of evaluation, 3) structural design with high-performance concrete, and 4) field construction with high-performance concrete. One of the urgent research needs identified at the NIST/ACI workshop, held in May 1990, concerns

the factors affecting development of mechanical and physical properties of high performance concrete. To meet this need, work is required to i) develop standards for compressive strength testing, and to provide essential knowledge of: ii) the effects of external and internal thermal and moisture conditions on mechanical and physical properties; iii) factors affecting the elastic modulus; iv) factors controlling time-dependent properties and deformation capacities; and v) methods of measurement of in-place properties of high-performance concrete. Research on the first two items were initiated in FY 1991 and will be completed during this year. Research during FY 1992 will 1) develop a model to predict the elastic modulus of a concrete mixture based on the properties of the constituents; and 2) develop an understanding of the performance of HPC when subjected to cyclic freezing and thawing. Studies on the causes of flaws in high-performance concrete will be started.

RECENT RESULTS

Carino, Nicholas, J. and Clifton, James, R., *Outline of a National Plan on High Performance Concrete:* Report on the NIST/ACI Workshop, May 16–18, 1990, NISTIR 4465, National Institute of Standards and Technology, December 1990.

Carino, Nicholas and Clifton, James R., High Performance Concrete Research Needs to Enhance Its Use, *Concrete International*, Vol. 13, No. 9, pp. 70–76, September 1991.

Installation of 4.45-MN (1M-lb) compression testing machine.

Workshop on developing National Program on High-Performance Concrete.

EXPERT SYSTEMS FOR HIGHWAY CONCRETE PAVEMENTS AND STRUCTURES

Principal Investigator: James R. Clifton
Building Materials Division
301.975.6707

Sponsor: Strategic Highway Research Program
Construction Technology Laboratory, Inc.

OBJECTIVE

To develop the HWYCON (Highway Concrete) expert system to aid in identifying the causes of distress in highway concrete pavements and structures, selecting durable concrete materials for their construction and re-construction, and the selection of effective materials and approaches for their repair and rehabilitation.

PROBLEM

The Strategic Highway Research Program (SHRP) has sponsored research for improving the durability and performance of concrete highway pavements and structures under five major projects. The project "Optimization of Highway Concrete Technology" (OHCT), was established to coalesce the results of the SHRP-sponsored research on concrete and then combine it with other recent advances in concrete technology to form an integrated knowledge base. The knowledge base will cover concrete materials for new and reconstructed pavements, diagnostics of concrete distress, rehabilitation and repair materials and processes, and quality control and quality audit practices and methods.

APPROACH

BFRL is developing a diagnostics expert system that includes six tasks: 1) define the objective and scope; 2) develop the knowledge base and represent it in the

expert system shell format; 3) build a prototype system; 4) have knowledge domain experts, followed by state DOT staff, critique the system; 5) make necessary modifications to the system; and 6) document the system, including directions for its modification and enhancement. Sources of knowledge for the diagnostic system include research sponsored by the Federal Highway Administration and by SHRP, guides prepared by committees of the American Concrete Institute and AASHTO, dealing with pavement and structures, Army Corps of Engineer's manuals, and publications by the Portland Cement Association. A panel of experts has been established by SHRP to consult in the development and critique of the knowledge base. Potential users from 10 state DOT's have agreed to review the system. Meetings have been held to determine the types of existing distresses and approaches in identifying and dealing with distresses. Further meetings will be held with pavement and bridge engineers to: 1) learn of their rehabilitation procedures, 2) discuss the features of the expert systems that are important in decision making, and 3) to refine the systems to ensure they are practical for field use.

In addition to the expert system software, BFRL will prepare a user manual and documentation of the expert system which will aid in making further enhancements.

RECENT RESULTS

Kaetzel, Lawrence J. and Clifton, James R., Expert/Knowledge Based Systems for Cement and Concrete: State-of-the-Art Report, SHARP-C/UWP-91-527, Strategic Highway Research Program, Washington, DC, October 1991.

Completed the knowledge base CONPAV-D (Concrete Pavements), August 1991.

Developed CONPAV-D prototype, October 1991.

PERFORMANCE CRITERIA FOR LONG LIVED CONCRETE FOR RADIOACTIVE WASTE STORAGE

Principal Investigator: James R. Clifton
Building Materials Division
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Sponsor: U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Division of Engineering

OBJECTIVE

To develop performance criteria for selecting concretes for use in constructing structures with 500-years safe service lives for storing low-level radioactive wastes.

PROBLEM

The U.S. Nuclear Regulatory Commission (NRC) has the responsibility for developing a strategy for storing low-level radioactive wastes. According to one approach, the radioactive wastes would be disposed of in concrete vaults which are either buried in the earth or constructed above ground and covered with earth. A safe service life of 500 years is required for the storage vaults which may be left unattended for most of their life.

Several observations suggest that certain concretes could have average service lives of 500 years. For example, remnants of some concrete structures constructed during The Roman Age are still intact. Ancient concretes, however, contain cements of significantly different compositions from modern cements, and they did not contain steel reinforcement. Regarding the durability of modern concrete, there are some portland cement concrete structures which have been in service for around a hundred years. Recently, from analysis of the permeability of concrete, it has been predicted that a high-quality reinforced concrete structure could have a service life exceeding 1000 years, if the exposure conditions were not severe. This prediction, however, is based on the properties of unaged concrete and does not consider that the properties of concrete could degrade with time. Nevertheless, based on consideration of the past durabilities of concrete, it appears possible that concrete can be designed to give a service life of at least 500 years in favorable environments.

The present basis for selecting concretes and their constituents needs to be further advanced to increase the likelihood that concretes could achieve safe lives of 500 years. At least two approaches can be followed. In the first, accepted principles would be used to design the most durable concrete feasible and it would be assumed that it would have the desired life. The other and recommended approach is to develop required performance criteria based on knowledge of the possible degradation processes. The latter approach is being followed in this project.

APPROACH

In this multiyear project, the development of performance criteria involve many of the steps included in ASTM E 632, "Standard Practice for Developing Accelerated Tests to Aid Predictions of the Service Life of Building Components and Materials." Accelerated testing, along with mathematical modeling of the rate of deterioration of concrete, is being used in developing a basis for making service life predictions.

In the first task of the project, likely deterioration processes were identified. They include sulfate attack, corrosion of reinforcing steel, alkali-aggregate reactions, leaching by groundwater, and acid attack. The likely deterioration processes have been analyzed in terms of the existing knowledge on their mechanisms, rates, and characteristics of their deterioration curves. In FY 1988, an experimental approach for obtaining data needed to make service life predictions was developed, candidate concretes identified and the concrete materials obtained, and modeling on moisture transfer processes in concrete undertaken.

In FY 1989, development of models of transport processes in concrete involving the rate of moisture, chloride ion, and sulfate ion movement in concrete was completed. Experimental studies were carried out on the chloride ion diffusion coefficient in cements pastes. In FY 1990, a new test method for determining the potential alkali reactivity of siliceous aggregates was investigated. The work in FY 1991 consists of evaluating ASTM Test C 1012, Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate solution, for predicting the sulfate resistance of cements.

Preliminary studies indicate that this test does not maintain a reasonable constant sulfate concentration or pH in the test solution. An accelerated test is being developed which involves immersing mortars specimens is solutions with controlled pH's and controlled sulfate concentrations.

RECENT RESULTS

Clifton, James R., *Chloride Ion Diffusion in Low Water-to-Solid Cement Pastes,* NISTIR 4549, National Institute of Standards and Technology, April 1991.

CEMENTITIOUS MATERIALS MODELING LABORATORY

Principal Investigator: Lawrence Kaetzel
Building Materials Division
301.975.5912

Sponsor: Northwestern University
National Science Foundation Center for Advanced Cement-Based Materials

OBJECTIVE To advance cementitious materials research through the development, archiving, and distribution of computer-based models, other forms of knowledge (databases, image bases), computerized systems and networks.

PROBLEM Advances in the ability to process, store and retrieve knowledge are being realized through the application of state-of-the-art methods in computer programming, the visualization of scientific results, and world-wide network connectivity. Knowledge of concrete properties, performance, materials, etc., stored in computers will take on new importance as society's collective memory of concrete science and technology grows into a more integrated body of knowledge than it has previously been possible to assemble. The development of integrated knowledge systems draws attention to gaps in knowledge and can lead to collaboration between cementitious materials researchers in planning research to fill the gaps. Knowledge systems are being developed using protocols for developing and interfacing subsystems. The Cementitious Materials Modeling Laboratory is advancing computational materials science and technology of concrete by providing the infrastructure for bringing the necessary researchers and resources together within the Advanced Cement-Based Materials Center and by links to outside activities.

APPROACH The objective of the CMML is accomplished by maintaining an infrastructure of computing resources (computers, staff, networks), and developing and publishing protocols and guidelines for models and experimental data. BFRL is performing four tasks: 1) developing protocols for documenting and testing new models, and model design to facilitate the interfacing of models to databases and reasoning; 2) developing strategies for the establishment of scientific databases, and methods for querying distributed knowledge systems; 3) interacting with other research groups to facilitate the modeling of experimental data; and 4) disseminating knowledge gained through cementitious materials research through electronic information exchange, computer modeling workshops, publication of guidelines, and a quarterly newsletter.

The CMML is working closely with ACI Committees 126 on Databases, 225-2 on Computer Modeling, and 225-3 on Expert Systems, and ASTM E-49 on Computerization of Materials Property Data, RILEM 123 on Modeling of Cement-Hydration and Expert Systems, and with ACBM Faculty and private industry.

The CMML, through its computer based modeling activities will provide insight into materials performance, reliability as related to durability, and service life. Also, knowledge pertaining to research related to cementitious materials will be disseminated and preserved. This will enhance the research activities of ACBM investigators as well as other cementitious materials investigators.

RECENT RESULTS Kaetzel, Lawrence, J., Clifton, James, R., and Struble, Leslie, J., *Guidelines for the Development of Computer Based Models in a Cementitious Materials Modeling Laboratory,* NISTIR 4650, National Institute of Standards and Technology, August 1991.

Published a newsletter describing the CMML and ACBM cementitious materials computer-based modeling activities, July 1991.

Kaetzel, Lawrence, J. and Clifton, James, R., *Guide to the Use of the Cement and Concrete Research Remote Bulletin Board System (RBBS) Computer,* NISTIR 4473, National Institute of Standards and Technology, December 1990.

Conducted a computer modeling workshop, July 1991 with participants from the ACBM faculty and from private industry.

QUALITY ASSURANCE

AASHTO MATERIALS REFERENCE LABORATORY

Principal Investigator: James H. Pielert
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301.975.6704

Sponsor: American Association of State Highway and Transportation Officials (AASHTO)

OBJECTIVE To inspect soil and bituminous material testing laboratories, distribute proficiency test samples, and support the voluntary standards development process.

PROBLEM The quality of testing in construction materials laboratories is an important concern when considering the overall question of quality construction. The importance of the testing function is demonstrated by The Strategic Highway Research Program (SHRP) which was initiated in 1987 as a 5-year, $150-million highway and bridge research program. Standardization of testing to enhance the reliability of quality assurance measurements is of paramount concern. The productivity of the testing community can be increased by the use of correct procedures and apparatus which reduce testing errors and provide a sound basis for the acceptance of materials on certificate. More efficient use of long-established construction materials and broader use of new materials are facilitated by dependable quality assurance programs.

APPROACH With the support of AASHTO Research Associates working under BFRL supervision, services are provided to both public and private laboratories on a voluntary basis. These services include the on-site inspection of the laboratory and the distribution of proficiency test samples. The current scope of the laboratory inspection services includes the testing of soils, bituminous materials, and plastic pipe, and the measurement of roughness and frictional properties of highways. Equipment and procedures used in performing conventional quality assurance tests are evaluated for conformance to applicable national standards. Proficiency test samples of asphalt, soils, paint, aggregates and bituminous concrete are distributed at regular intervals. Additionally, technical studies are conducted in areas related to these programs, often in conjunction with other NIST units.

Specific products of this work include: 1) detailed inspection reports; 2) report on each round of proficiency sample testing; 3) input to the work of standards committees such as draft standards and precision data; and 4) reports on the results of technical studies. The AMRL programs provide the following benefits to construction materials testing laboratories and others involved with the nation's transportation systems: 1) improves the quality of laboratory testing; 2) provides data to quantify standard measurement techniques; and 3) provides direct communications between testing laboratories and standards-writing committees.

RESULTS Inspected 100 bituminous and 90 soil testing laboratories.

Distributed over 4000 proficiency test samples and issued test reports.

Prepared an AMRL Metals Laboratory Inspection Program for AASHTO and NIST approval.

CEMENT AND CONCRETE REFERENCE LABORATORY

Principal Investigator: James H. Pielert
Building Materials Division
301.975.6704

Sponsors: American Society for Testing and Materials (ASTM)

U.S. Army Corps of Engineers
Waterways Experiment Station

OBJECTIVE To inspect cement and concrete testing laboratories, distribute proficiency test samples, and support the voluntary standards development process.

PROBLEM The infrastructure represents a substantial portion of the nation's wealth. Construction of such facilities is one of the nation's largest industries usually amounting to about 10 percent of the Gross National Product. Over $4 billion of hydraulic cement is produced in the United States each year with the value of the concrete construction estimated to be in the order of $20 billion. Standardization of testing to enhance the reliability of quality assurance measurements is of paramount concern. The productivity of the testing community in the cement and concrete fields can be increased by the use of correct procedures and apparatus which reduce testing errors and provide a sound basis for the acceptance of cement on mill certificate. More efficient use of long-established construction materials is facilitated by dependable quality assurance programs.

APPROACH With the support of ASTM Research Associates working under BFRL supervision, services are provided to public and private cement and concrete testing laboratories on a voluntary basis. These services include the inspection of the laboratory and the distribution of proficiency test samples. Equipment and procedures used in performing conventional quality assurance tests are evaluated for conformance to applicable national standards. Related test apparatus is checked with inspection equipment calibrated by BFRL personnel. Proficiency test samples of portland cement, pozzolan, concrete, blended cement and masonry cement are distributed at regular intervals to obtain information on laboratory performance. Additionally, technical studies are conducted in areas related to these programs. These are often in conjunction with other NIST units. Specific products of this work include: 1) detailed inspection reports; 2) report on each round of proficiency sample testing; 3) input to the work of standards committees such as draft standards and precision data; and 4) reports on results of technical studies. BFRL technical reports, papers in outside journals, and oral presentations are used as appropriate.

RECENT RESULTS

Inspected over 260 cement and concrete testing laboratories;

Distributed over 3000 proficiency samples and issued reports of results.

Completed study of CCRL portland cement proficiency sample data.

QUANTIFICATION OF EXTERNAL WEATHERING STRESSES

Principal Investigator: Jonathan W. Martin
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301.975.6717

Sponsor: National Institute of Standards and Technology

OBJECTIVE To propose and demonstrate a methodology for characterizing the expected service environment to which a building material or component will be exposed, to develop methods for quantitatively characterizing service environments, to demonstrate how field and laboratory exposures are related, and to transfer the knowledge gained to the building community and, in the process, demonstrate how this technology will aid in predicting the service life of a wide-variety of building materials.

PROBLEM The current focus of the program is on the quantification of ultraviolet radiation (UV). Solar UV-radiation causes large economic losses to the nation and the world as a result of its detrimental effects on materials (cracking of bridge and house paints, degradation of road asphalt and embrittlement of roofing materials), humans (cataracts and skin cancer), and plants. These losses are likely to increase as a result of a reduction in the stratospheric ozone concentration, caused by the release of chlorofluorocarbons and sulfuric acid aerosols, leading to an increase in the UV-radiation flux.

At present, there are no national or international standards for measuring, collecting, or modelling UV-irradiance data. Also, unlike Europe, Japan, and Australia, the United States does not have a network of UV-radiation monitors for measuring and detecting changes in UV-irradiance. Standardized measurements and data collection, analysis, and dissemination protocols are necessary for predicting reductions in material, human, and plant performance and for predicting corresponding economic losses resulting from an increase in UV-irradiance.

APPROACH During FY 1992, BFRL will establish the mathematical and experimental basis for relating field and laboratory UV measurements and initiate the development of consensus standards for measuring UV radiation. For the standards-related objective, a workshop will be organized under the auspices of ASTM to define the standards needed and to outline a plan for establishing consensus standards for measuring UV-irradiation and standardizing the data collection, analysis, and dissemination protocols. Representatives from a wide-range of governmental (e.g., NIST, NOAA, NASA, NIH/HHS, Smithsonian, USDA, DoD, DOE, and EPA), industrial (e.g., automotive, building, and electrical industries), and non-industrial (conservation and university) groups will be invited to participate in the workshop and the standardization process.

BFRL will impose at least one preliminary deterministic model on the time series data obtained in 1991. The two sets of solar spectral UV-irradiance data were obtained from the Smithsonian Institution. The first data set is of fourteen years duration in which the readings were averaged over one hour time periods. The second data set is of 1-year duration in which the spectral readings were averaged over 12 minute time intervals. Some exploratory Fourier time series analysis were performed with the objective of determining if the Fourier coefficients of the time series analyses were normally distributed and to determine the magnitude of the variability in the data from day-to-day and from year-to-year. These models will

account for direct and diffuse ultraviolet radiation. Equations for the direct component appear to be well understood, while those for the diffuse component are less well understood. In imposing these models we will gain a better understanding of which components of diffuse radiation require improved measurement and standardization. For example, we expect that standards will be needed to quantify cloud cover and to account for the effects of cloud cover on UV-radiation.

RECENT RESULTS

"Gravimetric and Electrical Measurements of Moisture Absorption for Coated Panels Exposed under Well-Controlled Relative Humidity Conditions," *Journal of Coatings Technology,* January 1991.

REVIEW OF HUD GUIDELINES FOR ABATEMENT OF HAZARDS FROM LEAD-BASED PAINT AND DEVELOPMENT OF DRAFT STANDARDS

Principal Investigator: Mary E. McKnight
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301.975.6714

Sponsor: Department of Housing and Urban Development
Innovative Technology and Special Projects Division

OBJECTIVE

To critically review HUD document "Lead-Based Paint: Interim Guidelines for Hazard Identification and Abatement in Public and Indian Housing," plan and implement research needed to improve the technical basis for the Guidelines, prepare draft standards based on the Guidelines and submit them for standardization through the voluntary consensus process and provide leadership and technical support in the organization and operation of the ASTM Subcommittee on Abatement of Hazards from Lead-Based Paint in Buildings.

PROBLEM

Based on a HUD report to Congress, about 57 million homes in the United States contain some lead-based paint; thus, there is a need to identify and carry out research needed to improve the guidelines and to revise the guidelines to include results of research completed since the guidelines were developed.

APPROACH

During FY 1992, BFRL is reviewing the guidelines taking into account public comments that have been received by HUD. Emphasis will be placed on 1) correctness and clarity of the technical content, 2) needs for research to strengthen the technical basis for the guidelines, and 3) standards needed to facilitate the implementation of the Guidelines. The Guidelines will be provided to the ASTM Subcommittee on Abatement of Hazards from Lead-Based Paint in Buildings and recommended for use as a working document by the Subcommittee's task groups. Technical assistance will be provided to the ASTM subcommittee. Research will begin with procedures for evaluating coatings for encapsulating lead-based paint. Consumer standards provide a good mechanism for implementing research results and provide bases for decision making and contracting.

RECENT RESULTS

Chair ASTM E06.23 subcommittee on abatement of hazards from lead in buildings and structures. Subcommittee is drafting standards in full area, test methods, removal, encapsulation, accreditation and terminology.

DEVELOPMENT AND CERTIFICATION OF A LEAD IN PAINT REFERENCE MATERIAL FOR CALIBRATION OF PORTABLE XRF ANALYZERS

Principal Investigator: Mary McKnight
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301.975.6714

Sponsor: Department of Housing and Urban Development
Innovative Technology and Special Projects Division

OBJECTIVE To prepare reference lead-containing paint films for use with portable XRF devices.

PROBLEM Currently, there are no reference materials available to manufacturers of hand-held portable x-ray fluorescence (PXRF) devices or users of these devices. Since these devices are being used to test for lead-based paint in housing, a reference material is urgently needed to aid in the calibration of the instruments and as quality control checks for the users.

APPROACH BFRL is developing specifications for the reference materials. Manufacturer will first produce prototype materials. These materials will be evaluated to determine whether they meet the specifications (e.g., lead concentration, lead-concentration homogeneity, and durability). If the materials are found to be acceptable, then the entire lot of material will be fabricated and certified. Chemists in NIST's Chemical Science and Technology Laboratory are performing the analyses. This work is expected to contribute significantly to improving quality control measurements.

RECENT RESULTS New project 1991

LONG-TERM THERMAL STABILITY OF CFC-REPLACEMENT-BLOWN INSULATING FOAMS

Principal Investigator: Tinh Nguyen
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301.975.6718

Sponsor: National Institute of Standards and Technology

OBJECTIVE To study and compare the degradation rates of CFC-blown and CFC-replacement-blown insulating foams by 1992.

PROBLEM Thermal performance of CFC-blown insulating foams is known to degrade over time due to air permeation into the foam cells after manufacturing. BFRL's work during the past few years has indicated that the rate of degradation of the material properties depends greatly on the exposure conditions and times. Due to their detrimental effects on the environment, CFCs are being phased out as the blowing agent for insulating foams. The insulating foam industry is experimenting with various blowing agents as replacements for CFCs. However, there is no information on the rates of degradation of the insulation and the material properties of

foams blown with CFC replacement agents. This information is needed to provide a basis for development of models for predicting long-term performance of, as well as development of performance criteria for, CFC-replacement-blown foams.

APPROACH

Research in 1991 showed that relative humidities between 60 and 75 percent at a temperature of 60 °C produced the greatest insulation and material degradation rates among the environments studied on CFC-blown foams. This environment will be used as an accelerated test for the research in 1992. Specifically, in FY 1992, physical and chemical properties of the cell wall, and thermal insulation property of one CFC-blown and four representative CFC-replacement-blown foams will be measured periodically for 6 months on specimens that have been exposed to 72 percent RH and 60 °C condition. The degradation rates of chemical, physical, mechanical, and thermal insulation properties of these foams will be compared. An attempt will be made to deduce the degradation mechanisms of these materials and to use the rates of degradation of the material properties to predict the long-term thermal performance of CFC-replacement-blown foams.

RECENT RESULTS

"Effects of Environmental Exposure on the Performance of Polyisocyanurate Foams: Materials Properties," *Proceedings of the Second International Workshop on Long-Term Performance of Cellular Plastics,* June 1991.

"Effects of Environmental Exposure on the Performance of Polyisocyanurate Foams: Thermal Measurements," *Proceedings Second International Workshop on Long-Term Performance of Cellular Plastics,* June 1991.

COATINGS

MODELS OF THE DEGRADATION OF HIGH-PERFORMANCE ORGANIC PROTECTIVE COATING SYSTEMS

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

OBJECTIVE To provide a strong scientific and technical basis for standards for high-performance coatings for steel used in buildings and other construction, and to expeditiously transfer knowledge gained to the standards and industrial communities.

PROBLEM Corrosion-related problems in the United States are estimated to cost 4.2 percent of the gross national products, or about $220 billion per year. The use of polymeric coatings is one of the most effective, economical, and widely-used means to prolong the life of corrosion-prone construction materials. However, coated metals are susceptible to degradation under in-service environments. Research is needed to better understand the degradation mechanisms and transport through the coating and along the coating/metal interface, and support the development of mathematical models for predicting the service life of coating systems. The models are needed to provide the bases for improved standards for high-performance coatings used to protect steel structures.

APPROACH The approach is to develop and validate models for prediction of service life and other aspects of performance. This consists of 1) the development of conceptual models, 2) the verification of degradation mechanisms, 3) the quantification of the transport properties of environmental elements through the coatings and along the coating/metal interface, 4) the development of improved methods for characterizing coating characteristics, properties, and reactions that control the degradation, 5) the development and validation of mathematical models for predicting service life using lab and field data, and 6) the implementation of the new knowledge generated in each of the above areas through incorporation into new standards and through other appropriate means.

Research in FY 1992 will concentrate on 1) carrying out experiments to determine the modes and mechanisms of the degradation of high-performance coatings on steel substrate exposed to atmospheric conditions, 2) developing a preliminary mathematical model to describe the formation and growth of one of the most common forms of degradation of coated steel in atmospheric conditions, filiform corrosion, 3) developing a spectroscopic technique to measure cations at the coating/metal interface.

RECENT RESULTS

"In Situ Measurements of Chloride Ions at the Coating/Metal Interface," *J. Adhesion,* Vol. 33, pp. 241–252, February, 1991.

"A Mathematical Model for the Cathodic Blistering of Organic Coatings on Steel Immersed in Electrolytes," *J. Coatings Technology,* Vol. 63, No. 794, pp. 42–52, April 1991.

"A Novel Spectroscopic Method for In-Situ Studies of Water at the Interface between a Metal and an Opaque Polymeric Film," *Advanced Composite Materials,* Vol. 19, pp. 1051–1060, August, 1991.

"A Spectroscopic Technique for In Situ Measurement of Water at the Coating/ Metal Interface," *J. Adhesion Science and Technology,* September 1991.

"A Model of Defect-Mediated Transport through Amorphous Membranes," *Journal Chemical Physics,* October 1991 submitted.

"A Mathematical Model for the Cathodic Delamination and Blistering Processes in Paint Films," October 1991.

"Relation Between AC Impedance Data and Degradation of Coated Steel," and "Effect of Surface Roughness and Contamination on the Corrosion Behavior of Epoxy-Coated Steel," accepted for publication in *Progress in Organic Coatings,* October 1991.

ROOFING

PERFORMANCE CRITERIA FOR SINGLE-PLY ROOFING MEMBRANES

Principal Investigator: Walter J. Rossiter, Jr.
Building Materials Division
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Sponsor: National Institute of Standards and Technology

OBJECTIVE To obtain field data on the performance of polymer-modified bituminous membranes to guide subsequent laboratory research on these materials leading to performance criteria for single-ply roofing membranes needed to assist in their selection, evaluation, and maintenance.

PROBLEM Single-ply roofing membrane materials account for about two-thirds of the low-sloped membrane systems installed annually in the United States. Ease of installation, performance, cost, and architectural considerations have influenced the rapid acceptance of the materials. Nevertheless, survey information from the National Roofing Contractors Association (NRCA) indicates more performance problems with single-ply systems than with built-up systems. Of the problems reported, defective laps and seams have been the most frequent, accounting for about 24 percent of those reported. The 1987 BFRL/NRCA Round Table on Roofing Research stated that the roofing industry "lacks a significant data base of field performance on which service life may be predicted," and that "the factors affecting roofing performance must be more fully understood to assure success with new materials and systems."

In 1989, BFRL published Interim Criteria for Polymer-Modified Bituminous Roofing Membrane Materials, Building Science Series 167. While being a significant step towards the development of criteria for modified bituminous membranes, the report did not suggest criteria and test methods for some of the identified performance requirements. Two notable examples are seam performance and weathering resistance. Data from the field and laboratory are needed to support development of the needed criteria.

APPROACH BFRL is developing performance criteria for single-ply membranes for EPDM systems. The initial work is focusing on seam reliability and criteria are being developed for resistance to mechanical loads, water permeability, puncture resistance, and effects of the environment (durability). The criteria will be based on observations of failures in the field, calculations of stresses using mathematical models, laboratory test results, and existing domestic and foreign information on roof membrane performance.

During FY 1992, BFRL will be investigating the field performance of polymer-modified bitumens conducted in cooperation with the National Roofing Contractors Association (NRCA), the Asphalt Roofing Manufacturers Association (ARMA), and the Roof Consultants Institute (RCI). Based on the results of the field investigations, priorities for needed research on modified bitumens will be prepared and initiated. Collaboration with MIT researchers conducting analyses on stresses in seams will continue. BFRL researchers will continue to provide leadership in the ASTM and CIB/RILEM Roofing Committees. This work is expected to result in improved performance criteria for the U.S. roofing industry to aid in their proper selection, installation, and maintenance of durable single-ply roofing seams.

RECENT RESULTS

"A Performance Approach to the Development of Criteria for Low-Sloped Roof Membranes," NISTIR 4638, National Institute of Standards and Technology, July 1991.

Cosponsored and held the *Third International Symposium on Roofing Technology,* 1991.

"Factors Affecting the Strength and Creep-Rupture Properties of EPDM Joints," *Third International Symposium on Roofing Technology,* 1991.

"Pulse-Echo Ultrasonic Evaluation of the Integrity of Seams of Single-Ply Roofing Membranes," *Third International Symposium on Roofing Technology,* 1991.

"Characteristics of Adhesive-Bonded Seams Sampled From EPDM Roof Membranes," *Third International Symposium on Roofing Technology,* 1991.

"The Application of Thermal Analysis to the Characterization of EPDM Roofing Membrane Materials After Exposure in Service," *Third International Symposium on Roofing Technology,* 1991.

"Characteristics of Adhesive-Bonded EPDM Seams," Contractors Guide, April and May 1991.

"Is Your Adhesive Layer Thick Enough," *Professional Roofing,* May 1991.

"EPDM Single-Ply: One Owner's Experience," *RSI Handbook of Commercial Roofing Systems,* May 1991.

QUALITY ASSURANCE OF DOD ROOFING SYSTEMS

Principal Investigator: Walter J. Rossiter, Jr.
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Sponsor: Department of Defense
Tri-Services Committee

OBJECTIVE

To provide technical assistance to the Department of Defense (DoD) in improving the quality assurance of its roofing practices.

PROBLEM

Deterioration of roofing is a major DoD facilities problem. For example, in the late 1970s, the U.S. Air Force estimated that its built-up roofs were lasting, on the average, only 12 years instead of the intended design life of 20 years or more. Steps need to be taken by DoD to improve the quality assurance of its roofing practices. It should be assured that sound design criteria are used during construction of both new and remedial roofing. Causes of failure of DoD roofing systems should be understood so that steps may be implemented to avoid future problems. Research should be conducted to provide a sound technical basis on which quality assurance criteria are based.

APPROACH

BFRL is providing technical assistance to DoD in implementation of practices to improve its roofing per purposes of discussing the in-service performance of roofing, field problems, and research needed to solve the problems experienced; serve as Secretary of the Committee; 2) providing, as requested, technical review of

roofing documents prepared by DoD or individuals under contract to DoD; and 3) performing, as requested, inspections of selected DoD roofing materials and systems for purposes of characterizing in-service performance. The results of the study will meet research needs defined in Cullen, William, et al., *Low-Sloped Roofing Research Plan,* NBS SP 659, National Bureau of Standards, July 1983.

RECENT RESULTS

Consulted with and served as Secretary of the Federal Roofing Committee and prepared and distributed minutes of the three Federal Roofing Committee meetings.

REFRIGERATION MACHINERY

THERMODYNAMIC PERFORMANCE OF ALTERNATIVE REFRIGERANTS AND REFRIGERANT MIXTURES

Principal Investigator: David A. Didion
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301.975.5881

Sponsors: National Institute of Standards and Technology

Electric Power Research Institute

OBJECTIVE To evaluate the performance of the new refrigerants and refrigerant mixtures in vapor compression systems, and determine the system modifications necessary to optimize the performance.

PROBLEM The refrigeration industry has been searching for and trying out new ozone-safe refrigerants for virtually all of their products. Their prime concerns are refrigerant availability and equipment reliability, at least until the transition is completed.

APPROACH During FY 1992, BFRL is performing:

1. A computer/laboratory evaluation of a series of chlorine-free zeotropic mixtures for heat pump application;

2. A computer/laboratory evaluation of zeotropic mixtures performance in various expansion device subsystems; and 3) a field evaluation of a refrigeration system operating on R134a.

The evaluation of chlorine-free zeotropes for heat pumps has been going on for several years (in conjunction with EPRI) and is intended to be completed this year. All reasonable combinations of the fluorocarbons of the methane and ethane series were considered and those whose performance appeared to exceed R22, as indicated by CYCLE-11, were evaluated in our breadboard heat pump apparatus. Two mixtures, R134a/R32 and R152a/R32, were measured and a thorough analysis is underway. This analysis is on the performance of the mixtures in the system and leads to development of new analytical techniques to separate the machinery influence from the ideal refrigerants performance.

The expansion device/mixtures system evaluation is new in FY 1992 and its research duration is intended for two years. Research includes evaluation of theoretically and experimentally different hardware approaches to the expansion process of the vapor compression cycle. Focus will be on small systems (e.g., refrigerators and window heat pumps). New refrigerants, particularly mixtures, have sufficiently different thermodynamic properties such that the expansion process offers either a problem or an opportunity for increasing the cycle performance. Background studies will be performed to relate the merits of different expansion devices as a function of fluid properties and to design and evaluate experimentally an optimum system for the applications noted. A field evaluation of a R134a system will be conducted in conjunction with Giant Food, on a chilled air system for a meat preparation room.

Results of the project supports industry in their search for appropriate alternative refrigerants by determining the performance of some of the leading candidates. Note that this research involves working directly with a private company so that technology transfer is immediate in specific cases and general through publications that will be generated.

RECENT RESULTS

Chwalowski, M., Didion, D. A., and Kedzierski, M. A., "Evaporator Performance Investigation for Residential Air-Conditioning Application Using Mixed Refrigerants," *EPRI Final Report 2792-09,* February 1991.

EVALUATION OF A MODIFIED RESIDENTIAL HEAT PUMP USING A ZEOTROPIC MIXTURE

Principal Investigators: David A. Didion
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Pete Rothfleisch
Building Environment Division
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Sponsor: Environmental Protection Agency
Air and Energy Engineering Research Laboratory
Global Emissions and Control Division

OBJECTIVE

To experimentally evaluate in the laboratory the thermodynamic and operational behavior of an innovative, commercially-produced, residential heat pump equipped with a multiplate distillation apparatus for composition shifting of its zeotropic mixed-refrigerant operating fluid.

PROBLEM

Two advantages resulting from the use of zeotropic refrigerant mixtures in heat pumps have been identified. The first is thermodynamic cycle improvement by matching refrigerant temperature glides to the heat source and sink. The second is load matching by composition shifting to a higher capacity refrigerant at low operating temperatures (which primarily saves energy by the reduction of the need for electric resistance heating).

Ongoing NIST projects are evaluating benefits from glide matching. A previous NIST project has evaluated the potential for composition shifting via single-stage flash distillation.

The heat pump to be examined, manufactured by the national division of the Matsushita Corporation, is commercially available on the Japanese home market but is not available on the U.S. market. The ductless indoor unit, model CS-223GR, is comprised of the indoor coil, its blower, the thermostat and logic circuitry for a 0 to 10 V analog signal to the inverter, and a wireless, remote controller for thermostat set point, blower and damper control. The outdoor unit model CU-223GR, includes the outdoor coil, its fan, the inverter, the compressor and a multiplate distillation column. This multiplate distillation column is expected to provide the greatest amount of composition shifting practically possible and, hence, the greatest performance benefit likely from this control strategy with the chosen mixture, R22/R13B1. Previous conventional assumptions were that multiplate distillation was too expensive and complex for residential applications; however, this manufacturer has apparently solved these design problems. Since this unit also employs variable speed, the extent to which this control strategy is complimentary to composition shifting will also be considered as will the extent to which advantage has been taken of glide matching possibilities.

APPROACH During FY 1990 and 1991, tests were performed at the steady-state rating points of the DOE/NIST rating procedure for variable speed heat pumps. In addition to the data required by the DOE/NIST rating procedures, measurements were made of compressor suction and discharge pressures, evaporator return bend temperatures, and mixture composition. This additional data was used to evaluate the extent of composition shift attained and to help in evaluation of the zeotropic mixture effects on the cycle efficiency.

The results of the testing of this unit were disappointing. The controls of the unit did not allow for significant composition shifting. BFRL disassembled the control system and separately operate the distillation system for composition shifting and compressor speed. Now each will meet load demand independently and the respective performances determined. In addition, the mixture R22/R13B13B1 is slated for elimination from the marketplace due to the ozone problem and will be replaced by a mixture of R32 and R22. Results should give a measure of reduction in resistance heat demand that can be extrapolated across the United States.

RECENT RESULTS Rothfleisch, P. I., and Didion, *D. A., A Performance Evaluation of a Variable Speed, Mixed Refrigerant Heat Pump,* NISTIR 4597, National Institute of Standards and Technology, June 1991.

ZEOTROPIC WATER COOLED CHILLER

Principal Investigators: Piotr A. Domanski
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David A. Didion
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Sponsor: Trane Company

OBJECTIVE To determine the technical and economic feasibility of a water cooled water chiller using environmentally acceptable zeotropic refrigerants.

PROBLEM Zeotropic mixtures offer the potential for achieving higher heating and cooling Coefficient of Performance (COPs) than can be obtained with conventional refrigerants. The technology offers the most potential benefit in situations where counter-flow heat exchange is employed. These situations occur with refrigerant-to-water heater exchangers; most notably in both the condensing and evaporating side of water cooled chillers as well as in heat recovery heat pumps. Zeotropic mixtures are also attractive as alternatives to R22 in water chillers because of their potential for efficiency improvement due to their basic refrigerant properties.

APPROACH BFRL is providing technical assistance in modeling and data analysis and performing flammability tests of candidate alternative refrigerants on conventional and innovative water chillers. The Trane Company will perform proof-of-concept tests on conventional and innovative water chillers. The joint work here combines the design, manufacturing, and marketing capabilities of the Trane Company with BFRL's technical expertise in zeotropic refrigerants.

RECENT RESULTS Screened a large number of environmentally-acceptable refrigerants for the water-chiller application using CYCLE-11 and recommended those for further investigation.

Provided property data for preferred refrigerants to the Trane Company.

TECHNIQUES AND APPLICATIONS STUDY FOR ZEOTROPIC REFRIGERANT MIXTURES

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Sponsor: Department of Energy
Building Equipment Division

OBJECTIVE To determine the method of composition shifting that would be best suited for zeotropic refrigerant mixtures.

PROBLEM In general, composition shifting of zeotropic mixtures might have application anywhere variable speed compressors are being considered. Since both have the same intent, that of varying the capacity of the refrigeration system, one might consider the composition shifting system as a chemical analog to variable speed systems. The chemical system achieves the capacity increase by increasing the density (through shifting composition towards the higher pressure component) and the variable speed system increases the volume rate of refrigerant flow. The current need for such widely varying capacity demands (i.e., load variations) is best exemplified by the residential heat pump.

Residential single speed heat pump systems are sized for a design day total cooling load in order to maintain humidity control. Depending on the climate zone, the design heating load may be several times greater than the cooling load. As a result, the heating capacity will be insufficient to offset the building heat loss at low outdoor temperatures. Supplemental energy in the form of electric resistance heat will then be required to maintain the space temperature. As the percentage of seasonal heating energy obtained from the resistance heat increases, the HSPF will decrease. This is because the COP of resistance heat is equal to one, whereas the COP of the heat pump is greater than one.

At low outdoor temperatures, the resistance heat requirement can be reduced by increasing the heat pump capacity to match the building load. The benefits derived from decreasing the resistance heat requirement are a modest increase in the HSPF and a decrease in the peak loading of the electric utility. The capacity of a heat pump can be controlled by controlling the composition of a zeotropic refrigerant mixture. This study will show the degree to which these capacity control methods can be used to increase the HSPF as well as decrease the auxiliary heat requirement. For example, the HSPF would be improved by matching the entire heating load line and not just that portion below the balance point as has been considered in the past.

APPROACH BFRL is performing research to determine what type of composition shifting system should be used for particular system applications. Categorization of composition shifting systems will be performed for distillation and combinations of valves and vessels. Additional categorizations could relate to high pressure side storage (receiver) versus low pressure accumulator and refrigerant pairs which would be characterized by normal boiling point differences. Sorting these factors as a function of the different fluid properties is expected to identify which technique and fluid pairs are most appropriate for which application.

RECENT RESULTS New project 1992.

IMPACT OF SURFACE ENHANCEMENT AND NEW OILS ON THE HEAT TRANSFER OF ALTERNATIVE REFRIGERANTS

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David A. Didion
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Sponsors: National Institute of Standards and Technology and
Department of Energy

OBJECTIVE To develop data for the design of heat exchanger equipment using new alternative refrigerants-oil mixtures from calorimetric and visual data.

PROBLEM The introduction of alternative refrigerants has solved one problem (ozone destruction in the stratosphere by chlorine) and created another (lack of thermal design information for the new refrigerants). In a refrigeration machine, the refrigerant must be soluble with oil to ensure the lubricant returns to the compressor. Oils used with conventional refrigerants require chlorine in the refrigerant to affect solubility. Alternative refrigerants with little or no chlorine must operate with a new family of oils for which no heat transfer data exists. Just as importantly, heat transfer data are required to redesign the evaporators and the condensers to ensure the efficient and reliable operation of the entire refrigeration system.

APPROACH Two existing heat transfer/visualization rigs and one table-top "to be built" rig will be utilized in this investigation. The first existing rig (enhanced rig) will be used to determine the impact of surface enhancements on the heat transfer of alternative refrigerants without oil. The table-top rig will be used to evaluate and compare the heat transfer performance of as many combinations of alternative refrigerant/new oil mixtures as available to test. The test results will be shown to the manufacturers of the refrigeration oils and those refrigerant/oil mixtures that are interesting to the manufacturers will be examined more closely in the second existing rig (quartz-tube rig). In all cases, quantitative calorimetric data will be obtained in addition to completing the visualization studies.

The enhanced rig will be used to film at high speed the boiling process on current tube-side and shell-side surface enhancements. Check-out tests of the rig are currently underway. It is possible to test many different boiling surfaces (e.g., external, plain, and enhanced). Great care has been taken to design the rig and specimens so that accurate calorimetric data will be collected at the same location as the movies are being made so as to establish good correlation between the two independent data sources.

The oil rig will be used to film at high speed the boiling process of alternative refrigerant-oil mixtures at various compositions within a smooth tube. Although less accurate calorimetric data is available on this rig, the accuracy is sufficient to determine the influence of the polyalkyleneglycol (PAG) oils over their range of viscosity from ISO100 (automotive application) to ISO32 (refrigerator application) on the heat transfer effectiveness.

The Building and Fire Research Laboratory of the National Institute of Standards and Technology is working with two manufacturers of refrigeration oil for the alternative refrigerants. The manufacturers provided information on the

problems faced by the refrigeration industry and suggest test conditions that might prove informative. The research is also being conducted in collaboration with leaders in the field of heat transfer from the Pennsylvania State University and from Wieland-America Company.

The results of this project will aid refrigeration equipment manufacturers in their design of heat exchangers for the new alternative refrigerants.

RECENT RESULTS

Kedzierski, M. A., and Didion, D. A., "A Comparison of Experimental Measurements of Local Flow Boiling Heat Transfer Coefficients for R11 and R123," *Proceedings of the Third ASME-JSME Thermal Engineering Joint Conference,* Reno, NV, March 1991.

Kedzierski, M. A., and Worthington, J. "Technique for Machining Micro Holes in Copper for Use in Temperature Measurement," *Experimental Heat Transfer,* approved by Washington Editorial Review Board, May 1991.

A technique for the analysis of the image data has been devised based on the nucleate boiling and image data for R123 and R11.

ALTERNATIVE REFRIGERANTS IN HEAT PUMPS

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Sponsor: Trane Company

OBJECTIVE

To determine the technical and economic feasibility of a residential heat pump using environmentally acceptable refrigerants.

PROBLEM

The refrigerant used in current residential heat pumps, HCFC-22, is scheduled to be banned as environmentally unacceptable. The design of heat pumps has matured around use of this particular refrigerant. Replacement refrigerants or refrigerant mixtures must be identified. New refrigerant choices will affect system hardware design. For example, liquid-suction line heat exchange, which has no benefit for HCFC-22, is of benefit for most large molecule refrigerants and, if mixtures are employed, can be used for partial recovery of the lost work of expansion.

APPROACH

BFRL and Trane will cooperatively select and modify a residential heat pump to adapt it to efficient operation with zeotropic mixtures. BFRL will validate the concept and simulation programs. This work combines the design, manufacturing, and marketing capabilities of the Trane Company with BFRL's technical expertise in zeotropic refrigerants. This direct technology transfer from BFRL to industry will expedite the elimination of the need for usage of environmentally harmful refrigerants.

RECENT RESULTS

New project 1992.

HIGHLY COMPACT HEAT EXCHANGER SURFACES

Principal Investigators: Mark A. Kedzierski
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David A. Didion
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Sponsor: National Aeronautics and Space Administration

OBJECTIVE To evaluate a new highly compact heat exchanger surface for evaporating refrigerant for environmental control in space applications.

PROBLEM Environmental cooling of extraterrestrial habitats will involve the transfer of waste heat from areas such as accommodation modules, laboratories, etc., and delivery of that heat to radiators for dissipation to space. Current proposals for such requirements include a system of heat pumps delivering heat to (or from) thermal buses containing two-phase ammonia.

Systems of this type have heat exchangers for evaporation and condensation at each heat pump module, and integral heat exchangers are built-in to each radiator array. It is thought that substantial saving of weight is possible for these heat exchangers with the introduction of highly compact surfaces.

APPROACH The current year's activity will be conducted at the National Engineering Laboratory in the United Kingdom and monitored by the Building and Fire Research Laboratory (BFRL). The performance parameters of two different versions of the surface will be measured with refrigerant R113 to establish the sensitivity of performance, particularly pressure drop, to phase change, with a view to optimizing the surface for system requirements.

Two representative heat exchangers of plate-fin type sandwich form will be designed in consultation with NASA/BFRL and manufactured in an agreed material, using the National Engineering Laboratory high performance surface on both sides. Individual single-fluid modules will also be manufactured with electric surface foil heating. A particular feature of the designs will be to achieve a low mass. The surfaces will be orientated such that the refrigerant flow is horizontal to minimize any effects of gravitation on the evaporation process.

APPROACH The performance of the heat exchangers will be measured using the monitored heat flow on the water side and the system temperatures. A heat balance will be established with the cooling water in the condenser. The single-phase performance will be evaluated first to confirm the design. The main parameters to be varied in the two-phase tests will be the refrigerant flow rate and the water inlet temperature. The experimental results will be compared with predictions developed from previous single-phase tests on related modules, modified by appropriate two-phase flow analytical models.

The results of this study will assist the National Aeronautics and Space Administration in determining if the new heat transfer surface is suitable for spacecraft applications.

RECENT RESULTS New project 1992.

DEVELOPMENT OF A COMPUTERIZED ANALYSIS SYSTEM FOR HIGH-SPEED FILMS OF NUCLEATE FLOW BOILING

Principal Investigators: Mark A. Kedzierski
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David A. Didion
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Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop an artificial intelligence system for analyzing high-speed films of nucleate flow boiling.

PROBLEM Within the next few years, most new refrigeration equipment will be required by law to operate with ozone-safe refrigerants. Industry does not now have an ozone-safe, drop-in refrigerant for their equipment. What they do have are alternative refrigerants that are not compatible with the existing equipment. Consequently, the refrigeration industry needs heat transfer data to redesign the evaporators and the condensers to ensure the efficient and reliable operation of the entire refrigeration system.

APPROACH A personal computer with a frame grabber and a compatible programmer's subroutine library will be purchased. The frame grabber captures and stores the image in memory for manipulation. The library consists of basic Fortran subroutines which will be used to process and analyze images. The computer will be programmed to identify and measure fundamental boiling parameters. The high-speed image system data will analyzed and used to check the reduced data obtained from the image system.

The computer analysis system will greatly enhance the Thermal Machinery Group's two-phase flow measurement capabilities.

RECENT RESULTS New project 1992.

MECHANICAL SYSTEMS AND CONTROLS

EMULATION AND DIAGNOSTIC METHODS FOR EVALUATING BEMS PERFORMANCE

Principal Investigator: George E. Kelly
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Sponsors: National Institute of Standards and Technology

Department of Energy
Building Systems and Materials Division

OBJECTIVE To develop methods for evaluating the performance of and diagnosing problems with Building Energy Management Systems (BEMS).

PROBLEM The proper operation of complex buildings and building systems requires the development of a new generation of computerized Building Energy Management Systems (BEMS) and, in particular, test methods and diagnostic tools for evaluating their performance. Research is needed on: 1) the development of test procedures and instrumentation for evaluating the performance of current and future BEMS and 2) the creation of a new generation of "tools" which will provide fault detection and diagnostic information on BEMS application software. It is envisioned that these tools could be incorporated in the future into BEMS systems by manufacturers to assist in making real-time control decisions.

APPROACH BFRL's work in FY 1992 will concentrate on: 1) completing IEA Annex 17 research and Emulator exercises and help write final reports; 2) commencing work on IEA Annex 25, Real Time Simulation of HVAC System for Building Optimization, Fault Detection, and Diagnostic (BOFD); 3) supplementing and extending research being done under an NSF contract by University of Wisconsin (UW) and University of Colorado (UC) on the "Control and Performance of Centralized Heating/Cooling Systems; 4) developing simplified models of selected equipment and HVAC systems and carry out off-line optimization using different approaches, such as bi-quadrate optimization model, dynamic programming, and the generated reduced gradient method; 5) evaluating statistical techniques for determining when and where faults and/or errors in data occur; and 6) developing an HVAC Fault Detection and Diagnostic (FDD) Laboratory at NIST to evaluate various FDD techniques.

This research will assist the building control industry in the future development of Advanced Building Automation Systems (ABAS).

RECENT RESULTS Kelly, G. E., Park, C., and Barnett, J. P., "Using Emulator Testers for Commissioning EMCS Software, Operator Training, Algorithm Development, and Tuning Local Central Loops," *ASHRAE Transactions,* Vol. 97, Part 1, 1991.

Kelly, G. E. et al., "The Use of Building Emulators to Evaluate the Performance of Building Energy Management Systems," *Proceedings of the Building Simulation 1991 Conference,* Nice, France, August 1991.

COMMUNICATION PROTOCOLS FOR BUILDING CONTROLS

Principal Investigator: Steven T. Bushby
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Sponsors: National Institute of Standards and Technology

Department of Energy
Federal Energy Management Program

OBJECTIVE To assist the building industry in the development, evaluation, and conformance testing of Communication Protocol Standards for the open exchange of information between equipment from different control vendors and between different levels of control in both hierarchal and distributed building management systems (BMS).

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

APPROACH BFRL's work includes: 1) revision and refining BACnet standard as a result of public review process; 2) refining BACnet reference implementation and test for conformance testing; 3) developing conformance test system—a combination of hardware and software than can execute tests on vendor's products and evaluate the results of each test (pass, part, inconclusive) automatically or semiautomatically; 4) initiating informal conformance testing with interested manufacturers; 5) establishing a conformance and interoperability testing program in conjunction with industry, ASHRAE, and other government agencies; and 6) expanding BACnet to include integrated building services, including life safety, security, and transportation. The results of this project will be an ASHRAE/ANSI standard which will be used by control system manufacturers to build interoperable systems, and a methodology for testing conformance to the standard.

RECENT RESULTS Bushby, S. T., *A Draft Abstract Test Suite for Determining Conformance to the BACnet Protocol,* NISTIR 4563, National Institute of Standards and Technology, April 1991.

Bushby, S. T. and Newman, H. M., "BACnet-The Emerging Communication Protocol for Building Automation Systems," *ASHRAE Journal,* April 1991.

Developed a draft of Standard 135P, in conjunction with ASHRAE Standards Project Committee 135P; the draft standard was approved by the ASHRAE Standards Committee for public review.

Completed, draft "Test Implementation" of the ASHRAE Application Layer Protocol based on the NIST Abstract Test Suite.

HEAT AND MOISTURE TRANSFER

EXPERIMENTAL VALIDATION OF BFRL MOISTURE TRANSFER MODEL

Principal Investigator: Robert R. Zarr
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Sponsor: National Institute of Standards and Technology

OBJECTIVE To experimentally verify the BFRL Moisture Transfer Model for a wide range of different wall constructions to quantify the effect of accumulated moisture on the heat transmission under both steady and dynamic conditions.

PROBLEM BFRL has developed a distributed-moisture-capacity, one-dimensional, transient finite-difference model, called MOIST, that predicts the coupled transfer of heat and moisture within multilayer construction under nonisothermal conditions. The model can predict moisture transfer in both the diffusion and capillary flow regimes. It has a provision to account for convective moisture transfer by including embedded cavities which may be coupled to indoor and outdoor air. This model uses hourly WYEC weather data, and predicts the average moisture content of the layers of a wall as a function of time of year.

APPROACH BFRL is installing and instrumenting representative 1×1 m wall specimens in the support frame of the calibrated hot box. The exterior surfaces of the wall specimens are being exposed to the following three conditioning periods: a 1-month steady 7.2 °C winter condition, a 7-day dynamic winter condition, and a 15-day steady 32 °C summer drying condition. The dynamic condition will consist of a 17 °C peak-to-peak sine wave having an average value of 7.2 °C. During the three conditioning periods, the interior surfaces of the wall specimens will be exposed to ambient air at 21 °C and 50 percent RH.

During the three conditioning periods, the moisture accumulation within the exterior layers of the wall specimens and the rate of heat transfer at the interior surfaces will be measured as a function of time and compared to corresponding values predicted by the MOIST model.

In designing the experiment, wall specimens will be selected that verify the MOIST model as a function of the following parameters: the thermal resistance and moisture storage capacity of the insulation, the permeance of the vapor retarder, the permeance of interior and exterior paint layers, and the permeance of the sheathing. In addition, walls representative of current construction practice will be included in the study.

Each of these walls will be instrumented with moisture content sensors for measuring the moisture content of the exterior layers, thermocouples for measuring the temperature distribution, and a heat-flux transducer for measuring the rate of heat transfer at the interior surface.

The results of this project will experimentally verify NIST's moisture model MOIST. After MOIST is experimentally verified, it may be used with confidence by building designers and engineers to conduct moisture sensitivity analysis to develop recommended practices for controlling moisture accumulation in building construction.

RECENT RESULTS

Burch, D. M., Thomas, W. C., and Fanney, A. H., "Water Vapor Permeability Measurements of Common Building Materials," *ASHRAE Transactions*, Vol. 98, Part 2, 1992.

Richards, R. F., Burch, D. M., and Thomas, W. C., "Water Vapor Sorption Measurements of Common Building Materials," *ASHRAE Transactions*, Vol. 98, Part 2, 1992.

Burch, D. M., and Thomas, W. C., "An Analysis of Moisture Accumulation in a Wood Frame Wall Subjected to Winter Climate," NISTIR 4674, National Institute of Standards and Technology, October 1991.

Fanney, A. H., Thomas, W. C., Burch, D. M., and Mathena, L. R., "Measurements of Moisture Diffusion for Building Materials," *ASHRAE Transactions,* Vol. 97, Part II, 1991.

MOISTURE TRANSFER MODEL FOR GENERATING MOISTURE GUIDELINES

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Sponsor: Department of Energy
Building Systems and Materials Division

OBJECTIVE

To develop recommended design practices for protecting walls from moisture problems in hot humid climates, to measure capillary transport properties for common building materials, and to convert the BFRL Moisture Transfer Model into a user-friendly tool for building designers and engineers.

PROBLEM

BFRL previously developed a distributed-capacity, finite-difference model that predicts the combined transfer of heat and moisture in multi-layer construction under non-steady-state conditions. The model includes vapor diffusion, capillary, and convection transfers (i.e., transfer by air infiltration and exfiltration), and includes the important couplings between heat and moisture transfer. This model is capable of simulating the moisture performance of a wide range of constructions, and it uses weather data from Weather Years for Energy Calculations (WYEC).

A significant number of mold and mildew problems have been reported at the interior surfaces of buildings located in hot humid climates by the Hotel/Motel Association. This problem is believed to be caused by outdoor moisture permeating inwardly through the construction and condensing at interior wall surfaces cooled by the building air conditioning system. In hot humid climates along the Gulf Coast, the outdoor summer dew-point temperature is frequently above the interior wall surface temperature, thereby providing a potential for moisture accumulation. A strong need exists to develop recommended design practices for controlling moisture problems in hot humid climates.

Capillary moisture transfer property data for common building materials are unavailable in the literature. The development of capillary transfer data would considerably extend the accuracy and usefulness of the BFRL Moisture Transfer Model.

APPROACH

During FY 1992, BFRL will perform the following:

Capillary Property Measurements will be carried out for five materials: gypsum board, sugar pine, southern pine, particle board, and plywood. For each material, the following measurements will be carried out: 1) liquid diffusivity; and 2) capillary pressure curves for suction head less than 0.1 atmosphere.

BFRL will develop recommended design practices for hot humid climates. In cooperation with members of the Hotel/Motel Association, several walls will be identified that have serious moisture problems in hot humid climates. The seasonal moisture performance of these selected walls will be analyzed using the BFRL Moisture Transfer Model. Using WYEC hourly outdoor weather data, the average moisture content of the wall components will be predicted as a function of time of year. A sensitivity analysis will be conducted to identify parameters which have a significant effect on moisture performance. Among the parameters which will be analyzed are the indoor temperature and humidity, the vapor resistance and air permeability of exterior parts of the wall, and the vapor resistance of interior parts of the wall. Limits for the significant parameters that maintain moisture contents in the wall below acceptable levels will be determined. These limits will be offered as recommended design practices.

Convert NIST Moisture Transfer Model into User-Friendly Design Tool by down loading it to a personal computer and converted into a user-friendly tool for building designers and engineers.

Participate in DOE Moisture Handbook Committee by continuing to provide technical support and guidance on the development of the DOE Moisture Handbook.

RECENT RESULTS

Burch, D. M., and Thomas, W. C., "An Analysis of Moisture Accumulation in a Wood Frame Wall Subjected to Winter Climate," NISTIR 4674, National Institute of Standards and Technology, 1991.

Burch, D. M., Thomas, W. C., and Fanney, A. H., "Water Vapor Permeability Measurements of Common Building Materials," *ASHRAE Transactions*, Vol. 98, Part 2, 1992.

Richards, R. F., Burch, D. M., and Thomas, W. C., "Water Vapor Sorption Measurements of Common Building Materials," *ASHRAE Transactions*, Vol. 98, Part 2, 1992.

Fanney, A. H., Thomas, W. C., Burch, D. M., and Mathena, L. R., "Measurements of Moisture Diffusion in Building Materials," *ASHRAE Transactions*, Vol. 97, Part 2, 1991.

MOISTURE CONTROL IN MANUFACTURED HOUSING WALLS

Principal Investigator: Douglas M. Burch
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Sponsor: Department of Housing and Urban Development (Division of Innovative Technology) through Department of Agriculture (Forest Products Laboratory)

OBJECTIVE To investigate the effectiveness of three practices for controlling moisture accumulation in the walls of manufacturered housing and to provide technical support for field experiments carried out at the Forest Products Laboratory.

PROBLEM All manufactured homes constructed and sold in the United States must meet the requirements specified in the HUD Manufactured Home Construction and Safety Standards. These standards require manufacturers to apply one of the following practices to control moisture accumulation in walls: 1) install a vapor retarder at the interior wall surface; 2) use permeable sheathing and siding that has a combined permeance higher than 2.9×10^{-10} kg/Pa·s·m^2 (5 perm); or 3) provide an outdoor ventilated cavity between the siding and wall insulation. For practices 2 and 3, a vapor retarder is not required. A strong need exists to investigate the viability of these practices.

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

The National Institute of Standards and Technology (NIST) has recently developed a transient, one-dimensional, finite-difference model that predicts the coupled transfer of heat and moisture in a multilayer wall under nonisothermal conditions (Burch and Thomas 1991). This model predicts moisture transfer in the diffusion through the capillary flow regimes. The moisture transfer resistance offered by vapor retarders and paint layers are readily included in simulations. The model has a provision to account for convective moisture transfer by including embedded cavities which may be coupled to indoor and outdoor air. NIST will use its moisture transfer model to theoretically investigate the viability of the above practices.

An expected benefit of this research will be the incorporation of improved practices for controlling moisture in walls into the HUD Manufactured Home Construction and Safety Standards.

BFRL is providing the following support to FPL:

1) *Calibration of Heat Flux Transducers*: BFRL will provide and calibrate eight heat flux transducers for measuring the effect of moisture on the heat transmission.

2) *Transport Property Measurements*: BFRL will measure the permeability and sorption isotherms of wall specimen materials to be used in the experiments for which transport property data is unavailable in the literature.

3) *Computer Predictions to Design Field Experiment*: Prior to the field experiments, BFRL will use the mathematical model to predict the moisture performance of the eight walls. The predicted results will be used to assist in designing the experiments, including the determination of where instrumentation should be placed.

4) *Computer Sensitivity Analysis*. BFRL will use its moisture transfer model to carry out a sensitivity analysis of wall systems used in manufactured housing walls will be investigated. The three practices include: 1) providing a vapor retarder; 2) using permeable sheathing and siding; and 3) providing an outdoor ventilated cavity between the siding and wall insulation.

RECENT RESULTS

Burch, D. M., *Indoor Ventilation Requirements for Manufactured Housing*, NISTIR 4874, National Institute of Standards and Technology, May 1991.

TEST PROCEDURES FOR RESIDENTIAL EQUIPMENT ENERGY USE

TEST PROCEDURES FOR CENTRAL HEAT PUMPS AND AIR CONDITIONERS

Principal Investigator: Piotr Domanski
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Sponsor: Department of Energy
Office of Codes and Standards

OBJECTIVE To provide equitable testing and rating procedures for determining energy performance of central heat pumps and air conditioners.

PROBLEM The current test procedure for central air conditioners prescribes methods for measuring total capacity which is used as the only measure of the system load matching capability. Likewise, the cooling load is also specified without differentiation between its components, i.e., the sensible load and latent load.

In real-life applications, it is essential to maintain a proper level of moisture content in the air as much as to control air dry-bulb temperature. This requires the latent and sensible capacities to be in proper proportions. System design trade-off exists between latent capacity and the Coefficient of Performance (COP); decreasing latent capacity results in an increase of COP.

There is a concern that, in the quest for higher SEERs, system latent capacities may be compromised. In single-speed systems, this may be obtained by oversizing of the indoor coil. In variable-speed systems, a more complicated scenario involving various compressor and indoor fan speeds can result in low latent capacity.

APPROACH BFRL is developing a methodology to determine the "latent capacity index" indicating system moisture removal capability over the season. The methodology will consist of the prescription of the test method and the algorithm which will allow the calculation of a value of the index. The goal is to obtain a procedure which will not require any additional tests. The product of this task will be an addendum for the current test procedure. BFRL will interact with industry throughout the procedure development.

RECENT RESULTS Domanski, P. A., "Simulation of an Evaporator with Nonuniform One-Dimensional Air Distribution," *ASHRAE Transactions,* Vol. 97, Part I, 1991.

Domanski, P., "Rating of Mixed, Split Residential Heat Pumps Operating in the Heating Mode," *ASHRAE Transactions,* Vol. 97, Part II, 1991.

TEST PROCEDURES FOR ADVANCED HEAT PUMPS

Principal Investigator: Brian Dougherty
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Sponsor: Department of Energy
Office of Conservation and Renewable Energy

OBJECTIVE To provide equitable testing and rating procedures for determining energy performance of advanced heat pumps.

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

APPROACH BFRL is presently completing a proposed test method for rating combined heat pump/water heating appliances. The test method will be used by the Department of Energy (DOE) in a proposed rulemaking for expanding the existing heat pump test procedure to cover combined appliances. Further analysis is expected to be required to resolve comments received by DOE during the proposed rulemaking. BFRL has already done extensive analytical and laboratory work on full condensing units. The majority of new analysis will probably pertain to rating desuperheaters. BFRL will perform limited testing on a heat pump having a desuperheater, if needed.

During 1990 and 1991, BFRL staff actively participated on the ASHRAE and ARI committees that are developing industry testing and rating standards for combined heat pump/water heating appliances. These industry testing standards are related by technology to the standards being developed for DOE but are distinctly different from the ones to be in the proposed DOE rulemaking.

During FY 1992, BFRL will complete the drafting of ASHRAE Standard 137P on desuperheaters. This will consist of writing the remaining sections into "standards language," creating all the tables and figures, and reviewing and incorporating the comments received from committee members. BFRL plans to provide the committee members with a completed draft standard prior to the semi-annual ASHRAE meeting in June.

Under sponsorship from the Electric Power Research Institute (EPRI) in FY 1991, BFRL developed a detailed computer program that models the transient performance of heat pumps incorporating thermal storage. During FY 1992, BFRL will conduct laboratory tests on a commercially available heat pump that incorporates thermal storage. The experimental work will be used as a starting point for the development of a standard test procedure for these units. During FY 1992, BFRL will report to DOE on the general progress of this work and the implications of the findings for the development of a DOE test procedure. Near the end of FY 1992, a report summarizing the project's status and BFRL's recommendations for steps to develop the test procedure will be completed to DOE.

The key outcome from the work will be the closer attainment of testing and rating standards for combined heat pump/water heating appliances. By the end of FY-92, the DOE standard should be published as a proposed rulemaking. Committee review of the ASHRAE and ARI standards will be ongoing at least until the first quarter of FY-93.

RECENT RESULTS

Fanney, A. H., and Dougherty, B. P., "Performance of a Residential Desuperheater," *ASHRAE Transactions,* Vol. 98, Part 1, 1992.

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

Principal Investigators: Brian P. Dougherty
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George E. Kelly
Building Environment Division
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Sponsor: Electric Power Research Institute
Residential Program
Customer Systems Division

OBJECTIVE

To gain information on a thermal storage heat pump and use the results to refine and validate a BFRL-developed computer model.

PROBLEM

Electric utilities want to delay building additional power generating facilities and shift the time when some power is used to periods where relatively low use now occurs (e.g., overnight). Using thermal storage heat pumps in residences can help. The acceptance of such appliances to the home builder and/or the homeowner and the willingness of utilities to offer rebates and favorable time-of-use schedules will be improved if a standard procedure for testing and rating thermal storage heat pumps exists.

APPROACH

During the previous year, BFRL developed a detailed computer program which models the transient operation of a heat pump that integrates thermal storage and domestic water heating. During FY 1992, BFRL will install a commercially-available thermal storage heat pump in two of its environmental chambers. After extensively instrumenting the unit, a series of tests will be conducted. The test results will be used to evaluate, refine, and eventually validate the computer model.

The majority of tests will be steady-state or quasi-steady tests. Tests will be conducted with the unit operating in an ice-making mode, an ice-making and water heating mode, a discharging (space cooling only) mode, the three comparable modes for the space heating season, and the two dedicated water heating modes. Tests will be repeated using different outdoor temperatures, inlet temperatures to the unit's refrigerant-to-potable water heat exchanger, and different stored energy levels (e.g., 0 ice vs. 50% ice, 100 °F vs. 130 °F). A few additional tests will be conducted that may last up to 24 hours. For these tests, the unit will operate in a manner more representative of a field application, i.e., charging/discharging cycles, with and without an intermittent hot water draw schedule.

Throughout the testing, the performance predicted using the computer model will be compared to laboratory-measured data (capacities, power use, refrigerant pressures and temperatures, water temperatures, etc.). Using the data from the

steady-state tests, the computer model will be evaluated by singling out those portions of computer code that model specific components of the thermal storage heat pump (e.g., compressor, ice-on-coil evaporator). Later, the computer model will be evaluated in its attempts to match performance during transient operation of the thermal storage heat pump.

The results of this work will provide NIST a validated computer model, laboratory data, and valuable testing experience. Information gained from exercising the computer model and from reviewing the laboratory findings will be the key resources as NIST works to develop a simplified testing and rating procedure for thermal storage heat pumps.

RECENT RESULTS Developed a computer program that simulates the transient operation of a heat pump that incorporates both thermal storage and domestic water heating.

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

Principal Investigator: A. Hunter Fanney
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Sponsors: Allegheny Power Systems

Potomac Edison Company

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

PROBLEM The Carrier HydroTech 2000 variable speed, integrated heat pump/water heating appliance incorporates notable innovations. For example, the compressor is packaged such that its noise level approaches that of a conventional refrigerator. The variable-speed components, indoor humidistat, and smart controller permit enhanced temperature and humidity control and thus improved comfort. The cold blow associated with conventional air-source heat pumps is largely avoided by the following: (1) using energy stored in the water heater rather than the conditioned space during a defrost and (2) having the appliance cycle on with the compressor at high speed while the indoor blower runs at minimum speed until the indoor coil warms up. To maximize the unit's contribution to water heating, the HydroTech 2000 actively controls the on/off status of the water heater resistive elements and can heat water by either full condensing or desuperheating. While in a combined space and water heating mode, the maximum water heating capacity is achieved by operating the compressor at maximum speed and varying the indoor fan speed to meet the space load. Because of the water heating only mode, the water heating contribution of the HydroTech 2000 will be significant even during the more temperate months like May and September.

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

The thermal performance and the electrical energy usage of the system will be monitored over a 24-month period. The influence of the appliance on peak demand loads of the Potomac Edison Company will be determined. The data will be compared with data from laboratory tests at BFRL on a similar unit and the results used to validate a proposed testing and rating procedure developed in a companion project being conducted for DOE and EPRI.

RECENT RESULTS Validated advanced computer models to predict the performance of state-of-the-art space conditioning equipment.

Determined accuracy of DOE rating technique.

HOURLY VALIDATION DATA FOR HPEAK

Principal Investigator: A. Hunter Fanney
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Sponsor: Electric Power Research Institute

OBJECTIVE To recast hour-by-hour experimental data from a HydroTech 2000 field monitoring project into a format compatible with the validation of HPEAK.

PROBLEM BFRL has extensively instrumented a Carrier HydroTech 2000 heat pump system in Hagerstown, MD. The efficiency, electrical energy usage, and the impact of the heat pump system on the peak electrical loads of the residence are being determined over a 24-month period. Hourly data is being recorded for the following variables: 1) electrical energy consumption of the heat pump while in various modes of operation, 2) electrical energy consumption by the supplemental resistive heating elements, 3) electrical energy consumption by the water heater, 4) energy delivered by the heat pump to the water heater, 5) thermal energy delivered to the air distribution system, 6) hot water load, 7) gallons of hot water consumed, and 8) indoor and outdoor ambient temperatures

APPROACH BFRL will format the existing data in a manner which is compatible with the HPEAK validation effort currently in progress at BFRL under RP2417-17. Any necessary data interpretation shall be provided by BFRL. A written summary of the residence characteristics, heat pump system installation, and data collection software will be provided for inclusion in the RP2417-17 final report.

RECENT RESULTS New project 1992.

TEST PROCEDURES FOR FURNACES, BOILERS, AND INTEGRATED APPLIANCES

Principal Investigator: George E. Kelly
Building Environment Division
301.975.5870

Sponsor: Department of Energy
Office of Codes and Standards

OBJECTIVE To provide equitable testing and rating procedures for determining energy performance of furnaces, boilers, and integrated appliances.

PROBLEM The ASHRAE Standard 124, Method of Testing for Rating Combination Space Heating/Water Heating Appliances, has been approved by ASHRAE and should be published shortly. Although BFRL is in general agreement with this Standard, there are still some issues which BFRL feels either could be handled better or need further study. These, along with simulation studies on the annual performance of various types of combination space/water heating appliances, should be addressed before DOE references this Standard in a test procedure for rating the performance of combined space/water heating appliances. There are different sizes of air handling units that can be combined with a single water heater to produce a combined space/water heating appliance. Similarly, many different sizes of tankless coils can be used with a specific boiler. It is impractical to require manufacturers to test all the different possible combinations. An interpolation scheme and/or sampling technique must be developed.

APPROACH In FY 1992, BFRL will perform the following tasks:

1. Complete analysis of ASHRAE Standard 124 when it is published and carry out simulation studies on the annual performance of various types of combination space/water heating appliances.

2. Conduct laboratory tests and solicit information from manufacturers to develop an interpolation scheme and/or sampling technique for rating combined space/water heating appliances without requiring testing of every possible combination of water heater and air handler or every combination of boiler and tankless coil.

3. Continue evaluation of input/output method as a possible future alternative for the current furnace/boiler test procedure which employs a heat loss method and a complicated calculation procedure.

4. Assist DOE in preparing responses to Requests for Waivers and draft Federal Register Notices of proposed Rule Making concerning the furnace/boiler test procedure or combination space/water heating appliances.

The development of test and rating procedures for integrated space/water heating appliances will help industry develop a market for these new products.

RECENT RESULTS Developed and delivered to DOE for publication in the Federal Register a new draft test procedure for furnaces and boilers that references ASHRAE Standard 103-1988R.

TESTING FOR COMPLIANCE WITH MINIMUM STANDARDS

Principal Investigator: James E. Hill
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301.975.5851

Sponsor: Department of Energy

OBJECTIVE To provide equitable testing and rating procedures for determining energy performance of various residential appliances.

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

APPROACH Proposed minimum standards are in place for refrigerators, refrigerator-freezers, water heaters, small gas furnaces, and mobile home furnaces. BFRL will assist DOE in determining compliance with these standards. This will involve selective testing of the appliances in question in BFRL laboratories and/or in commercial testing laboratories as appropriate.

RECENT RESULTS Reviewed and analyzed for DOE test reports from a manufacturer of small refrigerators imported from China.

INDOOR AIR QUALITY

COMPARISON OF VENTILATION MEASUREMENT TECHNIQUES

Principal Investigator: Andrew Persily
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Sponsor: Department of Energy
Bonneville Power Administration
Commercial Technology Section

OBJECTIVE To compare different methods of measuring outdoor air ventilation rates and assess the accuracy of these methods, and to make ventilation rate measurements in a mechanically ventilated office building for comparison to previous measurements in that same building.

PROBLEM Ventilation standards that specify minimum levels of ventilation for occupant health and comfort have existed for many years. These have traditionally been design standards, requiring that the building design specifications comply with the provisions of the standard. It has become increasingly apparent that design values for ventilation rates are not always realized in practice both when the building is constructed and later after the building has been in operation for some time. The realization that design objectives and the requirements of ventilation standards are not always achieved in practice, along with increased concerns about indoor air quality, has led to the need for onsite verification that building ventilation rates are in compliance with design values and/or ventilation standards. The requirement for on-site verification, or commissioning, has led to a need for cost-effective and accurate procedures for making field measurements of building ventilation rates. In addition, questions exist regarding how much building ventilation rates change over time and how often such field assessments need to be conducted.

APPROACH This project will involve two aspects of ventilation rate measurement in mechanically ventilated commercial buildings, a comparison of measurement methods and the reassessment of ventilation rates in an office building. The comparison of measurement methods will involve the application of several techniques for assessing ventilation in the Portland East Federal Building. These techniques will include tracer gas decay measurements of whole building air exchange rates, estimations of air exchange rates based on peak values of indoor carbon dioxide concentrations, direct measurements of airflow rates in the ventilation system ductwork using traditional airflow rate measurement devices (e.g., pitot tube and hot-wire anemometer traverses), and measurements of the percent of outdoor air intake using tracer gas, occupant generated carbon dioxide and temperature balances between the return, intake and supply airflows. These various measurement techniques will be applied in the Portland East Federal Building and the results will be analyzed for consistency and accuracy. In the second part of the project, a series of air exchange rate measurements will be conducted in the Portland East Federal Building using an automated tracer gas decay system. Air exchange rates were measured in this building several years ago by BFRL as part of a project sponsored by the Public Buildings Service of the General Services Administration. New measurements of air exchange rates will be conducted in the building during each season of the year in order to determine whether and by how much the air exchange rates in this building have changed over the years due to changes in ventilation system operation strategies, ventilation control system sensor calibrations, and other factors.

This project will enable BPA to provide their utilities with measurement procedures for determining compliance with ventilation guidelines.

RECENT RESULTS Dols, W. Stewart and Persily, Andrew, *A Field Comparison of Techniques for Assessing Ventilation Rates,* NISTIR (to be published).

PC VERSION OF EXACT3/CONTAM3

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Andrew Persily
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Sponsor: Department of Army
Chemical Research and Development and Engineering Center

OBJECTIVE To develop a personal computer version of the three-dimensional turbulent airflow computer program, EXACT3/CONTAM3, for use in modeling the release of material from a pyrotechnic device in a ventilated enclosure.

PROBLEM BFRL has developed the three-dimensional, turbulent room air motion model EXACT3 and the accompanying contaminant dispersal model CONTAM3 for use on mainframe supercomputers. These programs have been applied to ventilated rooms for the analysis of typical space conditioning problems and associated problems of contaminant dispersal. While these programs were originally developed on and for supercomputers, the technology of personal computers and work stations have advanced rapidly to the point where they are capable of handling complex three-dimensional airflow simulations. Initial work to develop personal computer versions of EXACT3 and CONTAM3 has been conducted, but the effort is not yet complete. Personal computer versions of these programs would greatly extend their availability and usefulness to deal with a wide range of interesting and important problems. Furthermore, the consideration of heat sources to date in the simulations has been relatively limited. Also, the contaminants which have been modeled have been nonreactive. There are numerous problems of interest with larger discharge fluid velocities and temperature variations, more significant heat releases, and reactive contaminants.

APPROACH This project will involve the development of personal computer versions of EXACT3 and CONTAM3 for use in analysis of the development of three-dimensional turbulent flows with buoyancy. A ventilated room with a transient pyrotechnic source will be modelled with the supercomputer and personal computer versions as a demonstration of their capabilities. The EXACT3 code will be modified to include contaminant transport. The addition of compressible flow and chemical reaction to EXACT3 and CONTAM3 will be investigated as a means of providing a more realistic description of transport processes involving pyrotechnic sources releasing material into a room. Documentation of the personal computer versions of these programs will be developed along with sample input files relevant to the pyrotechnic release case referred to above. The programs, documentation and sample files will be supplied to CRDEC for their use. Once the programs have been delivered to CRDEC, BFRL will provide technical support to CRDEC to assist them in setting up the programs and applying them to various problems of interest. This effort may be extended in the future to other areas of model development and the analysis of additional contaminant dispersal problems.

The results of this project will enable CRDEC to interpret the experimental results of field tests, to increase in understanding the physics of dissemination of contaminants released from a pyrotechnic device, and to conduct parametric design studies with the developed numerical prediction procedures.

RECENT RESULTS Developed a personal computer version of EXACT3/CONTAM3.

ADVANCED DEVELOPMENT OF THREE-DIMENSIONAL MODELS OF AIR AND CONTAMINANT MOVEMENT IN INTERIOR SPACES

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Sponsor: National Institute of Standards and Technology

OBJECTIVE To expand EXACT3, a three-dimensional computer model for predicting room air motion and contaminant dispersal, to include nonairflow dispersal mechanisms, and to develop a personal computer version of EXACT3.

PROBLEM The concentrations of indoor pollutants within a space are a complex function of the various physical mechanisms of contaminant dispersal such as absorption and chemical reaction. The level of thermal comfort within a space also depends on ventilation rates and air distribution along with the distribution and intensity of heat loads and other thermal characteristics of the space. The maintenance of acceptable indoor air quality within buildings, including the control of pollutant levels and the provision of adequate thermal comfort, at a reasonable energy cost requires a detailed understanding of flow fields and concentration distributions within ventilated spaces and the factors that affect these distributions. Finite difference computer models have been developed to predict three-dimensional airflow, temperature and contaminant concentration distributions in ventilated spaces. One such model, EXACT3/CONTAM3 has been developed at BFRL and has been used to study room air motion, thermal comfort, and contaminant dispersal. Currently this and other similar models only account for contaminant dispersal due to air flow and do not include the many other physical mechanisms that affect contaminant concentrations in buildings such as chemical reaction and absorption/desorption at surfaces. Another issue is that these programs are running only on supercomputers, which greatly limits their accessibility, particularly to the building design community.

APPROACH The finite difference program for predicting three-dimensional velocity and temperature fields EXACT3, and its companion program for predicting contaminant concentration distributions CONTAM3, have been formulated based on fundamental mass, momentum, energy and species balance equations coupled with expressions for the transport of turbulent kinetic energy and its dissipation. Contaminant concentration fields are predicted by imputing the velocity fields calculated from EXACT3 and contaminant source characteristics into CONTAM3. To predict the transient contaminant concentrations with time-varying velocity fields, the EXACT3 code will be modified to include the transport process of chemical species. In the current models, the contaminant dispersal is due only to transport by convection and diffusion mechanisms. Additional contaminant dispersal mechanisms will be added in order to enable more realistic and

useful predictions of contaminant dispersal. The nonairflow mechanisms to be considered include chemical reaction, surface adsorption and desorption and particle deposition. Existing theory of these phenomena will be studied and the computer program will be modified accordingly to produce an advanced version of EXACT3C.

A personal computer version of the current versions of EXACT3C will be developed. The current supercomputer version of the code will be transferred to the PC and will be modified to be compatible with commercially available FORTRAN compilers. Comparisons will be made between predictions made with the supercomputer and PC versions. A user's manual will be prepared for the personal computer version that will describe the code and its use, and present useful sample cases.

The results of this project will enable engineers/architects to predict room environments such as air distribution, thermal comfort and air quality in buildings, to design ventilation systems and optimum their operation, and to evaluate the ventilation performance of existing systems.

RECENT RESULTS

Fang, J. B., and Grot, R. A., "Numerical Simulation of the Performance of Building Ventilation Systems, *ASHRAE Transactions,* Vol. 96, Pt. 2, 1991.

Fang, J. B., and Persily, A. K., "Numerical Prediction of Airflow Patterns and Ventilation Effectiveness in an Open Office Environment," in review for *ASHRAE Transactions,* Vol. 97, Part 2, 1992.

Fang, J. B., and Persily, A. K., "Numerical Predictions of the Effect of Ventilation Parameters on Room Air Motion, Thermal Comfort and Ventilation Effectiveness," *Proceedings of 12th AIVC Meeting,* October 1991.

Grot, R. A., User Manual NBSAVIS CONTAM88, NISTIR 4585, National Institute of Standards and Technology, June 1991.

VENTILATION RESEARCH IN OVERLAND FEDERAL BUILDING

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Sponsor: General Services Administration
Public Buildings Service
Office of Real Property Development

OBJECTIVE

To evaluate ventilation rates and carbon dioxide concentrations in the Overland Federal Office Building.

PROBLEM

The design and construction of modern office buildings places stringent requirements on the building's thermal and environmental performance. A better understanding of the thermal, environmental and operational characteristics of buildings is essential to avoid design, construction and operational errors that may result in a building unsuited to its tenants. Such information is especially important during the early occupancy stages, when many adjustments and modifications are being made in order to provide an acceptable level of performance.

The Overland Federal Building has been the subject of a detailed study of its ventilation and air quality performance, beginning before its initial occupancy in late 1990. The building was fully occupied in the middle of 1991 and several months of ventilation and air quality monitoring was conducted under these conditions. This full occupancy monitoring needs to be completed in order to obtain a thorough characterization of the building's air quality performance and to complement the epidemiological research being conducted in the building by NIOSH.

APPROACH

During FY 1992, BFRL is monitoring whole building air change rates and carbon dioxide concentrations using automated monitoring systems already installed in the building. Four months of monitoring will be conducted over a period of one year in order to characterize the impacts of weather and season on these parameters. Air change rates will be measured using the tracer gas decay technique (ASTM E 741) and an automated system that will operate continuously over the measurement period. Similarly, carbon dioxide concentrations will be monitored continuously with a companion system. The data will be analyzed by BFRL to determine the ventilation characteristics of the building, assessing the effect of weather, time of day and season on the building's air change rate. The carbon dioxide concentration data will be analyzed for variation due to air change rate and building occupancy patterns.

This research will provide GSA with performance data on new office buildings and assist them in developing improved operating strategies. The results of the research will be used to support the epidemiologic IAQ research project being conducted by NIOSH in the building.

RECENT RESULTS

Persily, A. K., Dols, W. S., Nabinger, S. J., and Kirchner, S., *Preliminary Results of the Environmental Evaluation of the Federal Records Center in Overland Missouri,* NISTIR 4634, National Institute of Standards and Technology, July 1991.

COMPUTER INTEGRATED CONSTRUCTION

COMPUTER-AIDED SYSTEM INTEGRATION FOR THE BUILDING INDUSTRY

Principal Investigator: William F. Danner
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Sponsor: National Institute of Standards and Technology

OBJECTIVE To ensure that the development of STEP (Standard for the Exchange of Product Model Data) facilitates the integration of computer aided systems used to meet the information requirements of the building industry.

PROBLEM Information requirements in the building industry include a unique interplay of product complexity, views from many diverse disciplines, and a long and detailed life cycle. Though information technology is capable of accommodating such features, the standardization process is responsive to those industries that are most actively involved. BFRL has made a major contribution to the development of necessary fundamental capabilities for the building industry in STEP. BFRL can now expand upon those fundamentals with capabilities responsive to more specific building industry requirements.

APPROACH BFRL will continue its work to be in the forefront of the development of STEP, as convener of ISO TC184/SC4/WG5 STEP Development Methods, project leader, and technical contributor to provide product data sharing capabilities required by the building industry.

RECENT RESULTS Danner, W. F., Sanford, D., and Y. Yang, STEP (Standard for the Exchange of Product Model Data) Resource Integration: Semantic and Syntactic Rules, NISTIR 4528, March 1991.

Danner, W. F., and Yang, Y., STEP (Standard for the Exchange of Product Model Data) Development Methods: Specification of Semantics for Information Sharing, N30, ISO TC184/SC4/WG5, January 1991.

Danner, W. F., and Yang, Y., STEP (Standard for the Exchange of Product Model Data) Development Methods: Resource Integration and Application Interpretation, N31, ISO TC184/SC4/WG5, January 1991.

APPLICATION PROTOCOL METHODOLOGY FOR THE DEVELOPMENT OF NATIONAL AND INTERNATIONAL INFORMATION EXCHANGE STANDARDS

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Sponsors: National Institute of Standards and Technology

Department of Defense
Office of the Computer-Aided Acquisition and Logistics Support

OBJECTIVE To test and refine the application protocol methodology and to develop a STEP application protocol framework which will be submitted to ISO.

PROBLEM National and international standards making organizations have recently adopted the application protocol (AP) methodology for developing information exchange standards. The IGES/PDES Organization, DoD CALS Office, Navy, Air Force, NASA, and ISO TC184/SC4, which is developing the Standard for the Exchange of Product Model Data (STEP), are proponents of this new method. To assure the rational development of APs, these specifications and standards writers require a framework for defining, planning, and managing AP projects. This framework must provide a structure with which to classify APs, define AP scopes, identify integration requirements, and accommodate overlaps and interfaces between APs.

APPROACH BFRL will initiate the development of a framework for defining, planning, and managing DoD/CALS AP projects. BFRL will review existing proposals for product data classification and enterprise integration frameworks and summarize relevant ideas for possible incorporation into the AP Framework. BFRL will develop a prototype AP Framework and apply the framework to current Air Force AP projects, and possibly CALS designated AP projects, to evaluate the utility and completeness of the prototype.

This project will deliver to DoD CALS and ISO TC184/SC4 the guidelines for developing STEP APs and the structure and criteria for effectively planning AP projects.

RECENT RESULTS "Guidelines for the Development and Approval of STEP Applications Protocols" was adopted by ISO TC184/SC4.

Palmer, M. E., and Reed, K. A., *3D Piping IGES Application Protocol*, NISTIR 4420, National Institute of Standards and Technology, September 1990. CALS MIL-D-28000 adopted as the first application protocol used as a military specification.

Kramer, T., Palmer, M., and Feeney, A., *Issues and Recommendations for a STEP Application Protocol Framework,* NISTIR 4755, National Institute of Standards and Technology, 1992.

A FRAMEWORK FOR A UNIFIED MODEL OF BUILDING CODES AND STANDARDS

Principal Investigator: Kent A. Reed
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Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop a framework for integrating different development and application representations of building codes and standards into one unified model.

PROBLEM Building codes assure health, life safety, and welfare in buildings and building construction, and establish minimum levels of performance for buildings and building systems. Building codes and their supporting engineering standards, hereafter collectively referred to as standards, have been the natural subject of computer automation efforts because of their number, size, and complexity. Standards development tools range from text editing systems to detailed content and arrangement analyzers; standards dissemination tools, from local and remote database access systems to CD-ROM; and standards usage tools, from keyword-in-context systems to hypermedia-based expert systems. Each computer

automation effort has developed its own representation of standards. Interchange of representations between computer applications is difficult and interoperability is impossible. A common framework is needed for integrating these different representations into one unified model.

In the United States, many political jurisdictions base their building codes on one of three model codes, while others write their own. Each building code references 300 to 400 primary standards; these standards, in turn, reference other standards.

APPROACH In prior work at BFRL and Carnegie Mellon University on standards analysis, synthesis, and expression (SASE), an explicit model was developed for the content and organization of standards. Basic elements of the SASE model include datums, provisions, requirements, decision tables, and classifier trees. The SASE model referenced but stood apart from the traditional document model, which includes chapters, sections, paragraphs, tables, and figures. At a minimum, the proposed unified model must integrate the elements of the SASE model with more traditional document elements such as chapters, sections, paragraphs, tables, and figures.

The Standard Generalized Markup Language—SGML (ISO 8879) will be used to define the framework for the unified model. SGML is a meta-language for defining how markup is to be defined, where markup means the text added to the data of a document to convey information about the document. An SGML application specifies formally in SGML the markup constructs that are to be used and informally in non-SGML form the semantics of the constructs. An SGML Document Type Definition (DTD) defines the rules that apply SGML to the markup of documents of a particular type, according to the SGML application.

The proposed framework will be defined as an SGML application and the resulting unified model will be defined by an SGML DTD.

This DTD will be used in an international cooperative study to be conducted in the new CIB Task Group 10, Computer Representations of Design Standards and Building Codes.

RECENT RESULTS New project 1992.

PRODUCT DATA EXCHANGE STANDARDS IN SHIPBUILDING

Principal Investigator: Kent A. Reed
Building Environment Division
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Sponsors: National Institute of Standards and Technology

Department of Navy
Navy Sea Systems Command

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

PROBLEM The U.S. Navy seeks to avoid costs associated with the regeneration of data bases by enabling the digital exchange of product model data between successive agents during the life cycle of a ship. Existing information exchange standards have been tried and found to be inadequate.

APPROACH

BFRL is working with the Navy/Industry Digital Data Exchange Standards Committee (NIDDESC) to complete and test shipbuilding application protocols for the emerging international standard ISO 10303, informally called the Standard for the Exchange of Product Model Data (STEP).

BFRL will review the six NIDDESC application reference models (ARMS) that define information requirements for completing the detailed design of ship structural systems, ship piping, ship HVAC, ship electrical and cableway distribution systems, ship outfitting and furnishing systems, and for using parts libraries. BFRL will provide technical support for testing and validating NIDDESC application reference models, including formal model analysis, database management system support and assistance in creating database queries. BFRL will provide feedback and proposed changes to the model owners.

BFRL will integrate the tested application reference models, harmonizing the resulting application protocols so that marine industry application programs will be able to interoperate. In FY 1993, this work will conclude with the development of a framework in which the marine industry application protocols can be extended to accommodate the information requirements of the construction industry.

BFRL will compare the NIDDESC ship piping distribution system model with the existing 3D Piping IGES Application Protocol (NISTIR 4420) and develop an entity map so that existing piping IGES data sets can be translated into STEP-compliant data sets.

BFRL will work cooperatively with the NIDDESC and the ISO TC184/SC4/WG4 to develop application interpreted models using the STEP integrated resource entities and STEP interpretation techniques developed in BFRL.

This effort will accelerate the completion and implementation of shipbuilding application protocols for STEP.

RECENT RESULTS

Developed and presented guidelines for testing and validating NIDDESC/STEP application protocols.

Reviewed and commented on ARMs for ship structural systems, library parts, ship configuration management and ship piping.

LIGHTING TECHNOLOGY

EVALUATION OF LIGHTING SYSTEMS

Principal Investigator: Belinda L. Collins
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Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop and evaluate measurement procedures for assessing the distribution of illuminances and luminances in office spaces, as part of a continuing effort in developing metrics for evaluating and predicting lighting quality.

PROBLEM Evaluating and predicting the performance of lighting systems in actual office spaces is a complicated measurement problem requiring both physical and user reaction assessments. Accurate measurement and prediction procedures for determining lighting system performance in real spaces are urgently needed, along with metrics for evaluating and predicting lighting quality as related to luminance distributions. Recent research has suggested that the perception of lighting quality is determined in part by the balance between horizontal and vertical illumination. The proposed research is intended to expand the analysis of lighting system performance and lighting quality metrics to real rooms with different lighting systems, surface reflectances, and interior obstructions using a recently acquired luminance mapping device.

APPROACH In the first phase of the research, BFRL will determine the photometric accuracy of the luminance mapping device in a round-robin series of photometric comparisons with the National Research Council of Canada (NRC) and the Building Research Establishment (BRE) of the United Kingdom. In this evaluation, the accuracy of the mapper will be compared against that of two laboratory quality photometers for a series of known targets in the three laboratories. Next, the performance of the mapper will be evaluated for five different lighting configurations in real offices including two with interior obstructions to provide photometric information on the light distribution, calculated contrast, visual comfort probability, and task visibility for real rooms. At the same time, occupant response to the lighting output from real lighting systems will be assessed for actual task and work station surfaces. The subjective assessment of the effects of several very different luminance patterns in typical office spaces will also be evaluated. The hypothesis that lighting quality can be related to luminance patterns, particularly the ratio of vertical to horizontal luminance, will be assessed for open offices and offices with systems furniture. Offices will be selected to represent extremes in luminance distribution. Detailed measurements of room luminance and surface reflectances will be made using the luminance mapper. Variations in color, specular (and matte) reflections, glare, contrast, task visibility, and variations in luminance distributions will also be measured. The project will allow development of a lighting quality metric which is sensitive to changes in obstruction, reflectories, and different lighting configurations.

RECENT RESULTS Worthey, J. A., "Lighting Research and Theory Can Create Business Prospects," *Lighting Design and Application,* September 1991.

Worthey, J. A., "Dealing with Obvious Issues in Lighting," *Lighting Design and Application,* August 1991.

Worthey, J. A., "The Role of Theory in Lighting Research and Design," *Lighting Design and Application,* July 1991.

Collins, B. L., "The Psychological Aspects of Lighting: A Review of the Work of CIE TC 3.16," *Proceedings of the Penn State University Symposium on Psychological Aspects of Lighting,* January 1991.

ASSESSMENT OF LIGHTING TECHNOLOGY IN FEDERAL OFFICE BUILDINGS

Principal Investigators: Belinda L. Collins
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Stephen J. Treado
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Sponsor: General Services Administration
Public Buildings Service
Office of Real Property Management and Safety

OBJECTIVE To assess current lighting technology and the GSA design process for Federal office buildings.

PROBLEM GSA's recent experience with "energy efficient" lighting has not been particularly successful. A major concern is the apparent failure of GSA lighting in facilities designed for 2 W/ft^2 or less. This approach has resulted in user complaints about lighting and measured illuminance levels that are below current IES recommendations for office lighting. While the design is intended to provide at least 50 fc on the working plane, in reality it is less. Recent addition of systems furniture with fixed task lighting also creates unsatisfactory lighting for many office tasks with illuminance levels below current recommendations. The existing standards, criteria, and guidelines for lighting design in GSA facilities do not appear to be adequate or effective. As a result, there is a need for accurate information on system and component performance as input for lighting design guidelines for Federal office buildings, and for detailed information on selecting and using energy efficient sources, ballasts, luminaires, and relevant office furnishings to maximize energy efficiently without sacrificing user acceptance and productivity.

APPROACH During FY 1991, BFRL expanded its laboratory facilities for research on lamp component and lighting system interactions. This allows for evaluation of lighting hardware components and system designs in a semi-realistic office setting. In FY 1992, BFRL will develop a matrix of lighting design components and systems to be evaluated and tested. Likely candidates include ballast technologies such as conventional, energy efficient magnetic, and electronic ballasts; tube designs such as T-8, T-12, and U-shaped; lamp phosphors such as cool white, triphosphor, and other enhanced phosphors; fixture designs such as lenses, parabolic louvers, and conventional louvers; and ceiling layout. The key parameters are lamp output and lamp temperature as influenced by fixture design. The performance of several innovative systems will be compared against one or more standard configurations currently used by GSA.

BFRL also will be assessing the role of interior furnishings, including systems furniture and space layout, on light distribution within offices. Since vertical obstructions appear to be a major problem, possible innovative solutions will be explored and identified for inclusion in calculation procedures. Similarly, the effect of flexibility in office layout will also be evaluated for its potential impact on lighting levels and distributions. In this portion of the project, the procedures used by GSA in the design process will be identified, with particular emphasis placed on unanticipated interactions between different aspects of the system.

Accurate detailed comparison of the performance of different types of lighting components and systems for use as input in selecting high quality, energy efficient lighting.

RECENT RESULTS New project 1991.

LIGHTING AND HVAC INTERACTIONS

Principal Investigator: Stephen J. Treado
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Sponsor: Department of Energy
Office of Codes and Standards

OBJECTIVE To develop improved evaluation methods and design tools for the design and operation of efficient lighting and HVAC systems in commercial buildings, along with strategies to control peak cooling loads due to lighting.

PROBLEM Lighting constitutes a substantial portion of commercial building electrical energy usage, typically ranging from 25 to 50 percent. Most of the energy dissipated to the building space eventually contributes to building cooling load. Due to the temperature dependence of fluorescent lighting power consumption and light output, there are significant interactions between the lighting and HVAC systems. As a result, lighting system light levels and efficiency, and cooling loads due to lighting, can vary substantially due to lighting and HVAC system design and operation. Previous results have indicated performance variations of up to 20 percent are possible. These effects influence the number of luminaires required to provide the design illumination levels and the size of HVAC equipment to meet the cooling loads contributed by the lighting system. This, in turn, influences the first cost of the lighting and HVAC systems, and the operating costs for energy, including demand charges for electrical power usage during peak periods. Such peak period power usage puts added pressure on electrical utilities to meet system-wide power demand by increasing generating capacity.

APPROACH BFRL is investigating the interactions between lighting and HVAC systems in commercial buildings through a combination of full-scale measurements and computer simulations. The results are being analyzed to provide the technical basis for design procedures and methods, which are also being developed, with assistance from Ross and Baruzzini under contract to EPRI. Full-scale measurements are being conducted at the BFRL Lighting Interaction Test Facility for various lighting system, HVAC system and room configurations, and operating conditions. Lighting system performance, thermal loads, and energy transfers are monitored to enable determination of optimum operating conditions and strategies.

A detailed computer model is being developed and verified using the measurement results. The model will be used to extend the results to a wide range of configurations so that the design guidelines will be more general and comprehensive. The computer model will serve as a stand-alone design tool, but will also be the basis of a sub-routine of larger building energy analysis computer programs such as BLAST and DoE-2. This will provide such programs with the capability of evaluating the interactions between the lighting and HVAC systems, a capability which they currently lack.

The results of this project will enable and encourage the design and operation of energy efficient lighting and HVAC systems by taking advantage of their interactions.

RECENT RESULTS

Treado, S. J., "Lighting and HVAC," *Lighting Design and Application,* July 1991.

Treado, S. J., and Bean, J. W., *Measurement and Evaluation of Lighting/HVAC Interaction,* NISTIR 4429, National Institute of Standards and Technology, May 1991.

Treado, S. J., "The NIST Lighting and HVAC Interaction Test Facility," *ASHRAE Journal,* April 1991.

Walton, G. N., *A Computer Program for Simulation of HVAC/Lighting Interactions: Initial Report,* NISTIR 4472, National Institute of Standards and Technology, December 1990.

Treado, S. J., and Bean, J. W., "Experimental Evaluation of Lighting/HVAC Interaction," *Proceedings of the ASHRAE/DOE/BTEEC Conference on Thermal Performance of Exterior Envelope of Buildings IV,* December 1990.

TEST PROCEDURES FOR LIGHTING FIXTURES AND SYSTEMS

Principal Investigator: Stephen Treado
Building Environment Division
301.975.6444

Sponsor: Department of Energy
Office of Codes and Standards

OBJECTIVE To provide equitable testing and rating procedures for determining energy performance of lighting fixtures and systems.

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

APPROACH BFRL will develop draft test procedures for multilamp fixtures based on review of the existing test procedures and preliminary experimental testing in its Lighting System Evaluation Laboratory. Proposed procedures will be prepared for individual components, including lamps such as T-12's, T-10's, and T-8's; ballasts such as

conventional and premium; and fixtures including deep cell parabolic and acrylic lens; and for systems comprised of these components.

Lighting component and system performance characteristics will be measured and evaluated using both reference standard and actual components. The component performance will be measured using reference standards (i.e., commercially available ballasts compared with reference ballasts, lamps measured with reference ballasts, etc.). The performance characteristics determined for individual components will be used to predict the performance of complete systems of those components and then compared to experimental system performance for assemblies of the components configured as entire lighting systems. The goal is to develop lighting component test procedures and an associated calculation procedure to obtain system performance. Such a method should be able to account for electrical, thermal, and photometric interactions between components.

Validation experiments will be conducted of proposed test procedures on three lighting system/fixture combinations in BFRL Lighting System Evaluation Laboratory. Use lighting system efficiency to determine energy usage for equivalent illuminance levels for three test cases. Feedback from the testing will be used to refine and improve the proposed test procedures.

The results of this project will form the basis for a rational scheme for evaluating and comparing lighting components and systems on a consistent basis.

RECENT RESULTS Evaluated existing IES and ANSI test procedures and identified major gaps identified in the treatment of multilamp fixtures, electronic ballasts, and lamp types such as T-8's, HID and incandescent lamps.

REQUIREMENTS FOR HIGH TECHNOLOGY WORKSTATIONS

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301.975.6445

Sponsor: Department of Transportation
Office of the Secretary
Headquarters Building Acquisition Project Office

OBJECTIVE To evaluate the requirements for workstation design for use in designing the new Department of Transportation (DOT) Headquarters facility.

PROBLEM DOT is planning a major new headquarters building and requires technical assistance in developing a design approach to meet its requirements. The building is estimated to cost at least $600 million, accommodate some 8,000 employees, and exceed 3.3 million m^2. It is to be the second largest Federal building in the Washington, DC, area—surpassed only by the Pentagon. DOT wants to apply the latest knowledge of building technology and workstation design in their proposed facility.

APPROACH In the first phase of the project, BFRL will schedule a workshop with selected experts to determine the state-of-the-art in intelligent building design. Participants will present papers and discuss issues related to new design technologies, experiences with high technology designs in the public and private sectors, workstation designs, ergonomic and human resource issues, and forecasts of office design trends.

In addition, a series of "white papers" are being prepared for DOT on issues such as lighting, security, and workstation design. BFRL will review and critique these papers.

This project will enable DOT to take advantage of the latest design practices and research findings in planning their new Headquarters facility.

RECENT RESULTS

New project 1992.

COMBUSTION AND FLAMMABILITY

BURNING RATE OF THERMOPLASTICS

Principal Investigator: Takashi Kashiwagi
Fire Science and Engineering Division
301.975.6699

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop mathematical models to predict the burning rates of thermoplastics and charring materials, based on physical and chemical insight developed through experimentation.

PROBLEM At present there are no models that calculate burning rate (heat release rate) of building contents. A fire source must be prescribed or estimated from bench scale tests for HAZARD I (BFRL's software that predicts the hazard to a building and occupants anywhere within a building). Hence, models to predict fire source are needed to predict fire hazard.

APPROACH BFRL's research for this project focuses on developing burning rate models for simple horizontal configurations. Experiments involve determining the energy feedback rates from a pool flame for various fuels and scales and to determine gasification rates of various thermoplastics. Gas phase combustion characteristics are measured for pool diameters from 4.6 cm to 100 cm burning fuels with widely different sooting tendencies. Global energy feedback models are developed as a function of fuel type and scale. In the condensed phase, a well-defined thermal radiation source is used to simulate energy feedback from a flame to heat a polymer sample; the gasification rates and the temperature distribution in a polymer sample are measured under nonflaming conditions at various radiant fluxes. Two gasification models are developed; one is an analytical model using an asymptotic expansion technique and the other is a numerical technique.

RECENT RESULTS

"Estimate of Flame Radiance via a Single Location Measurement in Liquid Pool Fires," *Combustion and Flame 86*, p. 223 (1991).

"Fuel Property Effects on Burning Rate and Radiative Transfer from Liquid Pool Flames," *Proceedings of the Third International Symposium on Fire Safety Science,* pp. 395–404, 1991.

"Measurement of Heat Feedback to the Fuel Surface in Pool Fires" submitted to *Combustion Science and Technology.*

"Radiative Head Feedback in a Toluene Pool Fire," submitted to the *Twenty-Fourth International Symposium on Combustion.*

"An Experimental Investigation of the Pulsation Frequency of Flames," submitted to the *Twenty-Fourth International Symposium on Combustion.*

GRANTS

"The Behavior of Charring Materials in Simulated Fire Environments," Eric Suuberg, Brown University.

"The Structure and Radiation Properties of Pool Fires," J. P. Gore, University of Maryland.

MODELING OF INTUMESCENT MATERIALS

Principal Investigators: Takashi Kashiwagi
Fire Science and Engineering Division
301.975.6699

Howard R. Baum
Fire Science and Engineering Division
301.975.6668

Sponsor: National Institute of Standards and Technology
Director's Fund

OBJECTIVE To develop an advanced mathematical model capable of describing flame resistant nature of intumescent polymers in fire.

PROBLEM With the recent public awareness for the adverse effects of certain halogenated compounds on the earth's ozone layer and the potential for producing corrosive combustion products. Thus, intumescent polymers and intumescent coatings are becoming an important alternative to traditional flame retardants. However, since there are so many complex sequence of processes, it is extremely difficult to determine the importance of each process and its relevance to flame retardant performance. In order to overcome this problem, theoretical models of intumescent polymers are critically needed to examine effects of each process separately on gasification rates of intumescent polymers during fire exposure. Theoretical models might be used as a guide for more effective flame resistant design of intumescent polymers.

APPROACH BFRL research will explicitly account for the generation of the porous structure of the intumescent material; the transport of heat and mass through the material will consider the porosity of the material. This will be accomplished by considering the material to be liquid with an Arrenius-like dependence of transport properties on the temperature. The liquid contains chemical agents which release gaseous products that generate the porous structure. The resulting model is expected to be at least a two dimensional axisymmetric situation of practical interest in fires.

RECENT RESULTS New project 1992.

FLAME RETARDANT STUDY ON ENGINEERING POLYMERS

Principal Investigator: Takashi Kashiwagi
Fire Science and Engineering Division
301.975.6699

Sponsor: General Electric Co.
Chemical Research Center

OBJECTIVE To establish and understand the effects of polymer structure and certain flame retardant treatment on flammability characteristics of specific engineering thermoplastics.

PROBLEM GE is interested in nonhalogenated flame retardant treatment to improve fire performance of its engineering thermoplastics. This collaborative project focuses on solving the need for better flame retardant treatments by a scientific approach instead of traditional try-and-error way.

APPROACH BFRL is conducting large scale calorimeter (using furniture calorimeter) and Lateral Ignition and Flame Spread Test (LIFT) type experiments to determine the effects of a sample size on how much is an intumescent amount of char and flammability properties, and conducting systematic study of pyrolysis/gasification of selected samples in nitrogen under various external thermal radiation fluxes comparable to fire. Heat transfer to substrate, degradation product analysis and char analysis will be conducted to understand the chemical and physical effects of the particular treatment on the gasification process. Full-scale burn experiments will be conducted for validation of flame retardant effectiveness of selected samples.

RECENT RESULTS "Effects of Sample Mounting on Flammability Properties of Intumescent Polymers" appear in *Fire Safety J.*

FURNITURE FLAMMABILITY

Principal Investigator: Andrew J. Fowell
Fire Science and Engineering Division
301.975.6863

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop by 1994, a method by which furniture manufacturers can predict the Rate of Heat Release of residential furniture.

PROBLEM Previous work has shown that the peak rate of heat release (RHR) is the most significant fire property of residential furniture re life safety. RHR's in the range of 40 to 800 KW can be "safe" depending on the size of the compartment and the ignitability of adjacent furnishings. But furniture manufacturers have no way to choose a combination of fabric, foam, and possibly interliner, to meet this RHR criterion.

APPROACH During FY 1992, BFRL will use burn data in the required range from the California Bureau of Home Furnishings and manufacturers. Samples of the fabric, foam and combinations will be analyzed. This work will be done in three phases: develop a correlation between test results on the components and the Cone and Horizontal LIFT tests on the fabric-foam combination and an understanding of the mechanisms involved; test the Dietenberger model's ability to predict the furniture burn; and develop simpler alternatives to that model for Maximum Rate of Heat Release.

During 1993, BFRL will validate and extend the correlations so that small scale tests of the individual components can be used to predict the performance of a specific furniture design. It is hoped the prediction process will involve no more than charts, but if this cannot be attained, a program that will run on a PC will be developed.

RECENT RESULTS Bracketed the RHR range of interest and selected an improved ignition burner for California Test TB133.

FLAMMABILITY OF COMPOSITE MATERIALS

Principal Investigators: James E. Brown
Fire Science and Engineering Division
301.975.6483

Thomas J. Ohlemiller
Fire Science and Engineering Division
301.975.6481

Sponsor: U.S. Navy
David Taylor Research Center

OBJECTIVE To assess the flammability of composite materials used in the construction of ship components.

PROBLEM A major factor limiting this use is a lack of understanding and quantitation of the flammability hazards composite materials may present. Composite materials, consisting typically of several layers of an organic resin and woven glass fibers, can exhibit unique behaviors when strongly heated. These behaviors include delamination, which changes the local thermal properties, and channeled evolution of the gaseous degradation products, in the form of localized jets or of predominant flow to the sample edges.

APPROACH BFRL will assess the flammability behavior of composite materials, using its Cone Calorimeter and LIFT apparatuses to quantify ignitability, rate of heat release, and opposed flow flame spread behavior. Because of the potential for unique behaviors, BFRL has constructed special sample holders especially designed to inhibit gas flow out the sample edges, yielding results more pertinent to full scale applications. Its new radiant panel facility will make it possible to measure flame spread behavior on relatively large (at least 1.2 m [4 ft.] high) samples. The Quintiere/Cleary spread model will be used to predict the rate and extent of spread as a function of external heat flux on two composite materials. The input model parameters for these materials will be obtained in the Cone Calorimeter, using our modified procedures. If successful here, we should be in a good position to predict the potential for fire growth on the composite walls of a ship's compartment. An assessment of the effects of oxygen vitiation on the heat release process is needed for this; such measurements also are planned this year.

RECENT RESULTS Demonstrated that gas evolution from the sample edges does not alter opposed flow flame spread behavior, as measured in the LIFT apparatus but it does affect the details of the heat release rate behavior (and, therefore, possibly alter upward flame spread behavior, as well).

SIMULATION OF TURBULENT COMBUSTION AND TRANSPORT IN FIRES

Principal Investigator: Howard R. Baum
Fire Science and Engineering Division
301.975.6668

Sponsors: National Institute of Standards and Technology

Department of Interior
Minerals Management Service
Technology Assessment and Research Branch

OBJECTIVE To develop a fundamental understanding of the mechanisms which control the gas phase combustion and transport processes in fires and to develop a predictive capability which will allow the computer simulation of these processes to be based on the mathematical expression of underlying physical principles.

PROBLEM The interaction of a fire with its environment—an individual room in a building fire or the atmosphere in the vicinity of a large outdoor fire—is the problem under consideration. The transport and deposition of smoke generated in crude oil fires is of interest to MMS, the U.S. Coast Guard, the Defense Nuclear Agency, and the American Petroleum Institute. The interaction of fires with a room environment has been a major research topic for BFRL (and equivalent organizations in other countries) since its inception. Small scale combustion processes are the study of diffusion flames in a turbulent flow environment and are of interest to the general combustion research community.

APPROACH Theoretical and computational techniques are being performed to studying transport, mixing, diffusion, radiation, and reaction processes occurring at widely differing length and time scales. Detailed studies of individual phenomena are carried out in a manner that permits them to be assessed individually and later combined into overall simulations of problems of interest. Current applications include smoke transport from oil spill fires and in building corridors.

RECENT RESULTS Baum, H. R., Rehm, R. G., and Gore, J. P., "Transient Combustion in a Turbulent Eddy," *Twenty-Third Symposium (International) on Combustion,* the Combustion Institute, Pittsburgh, PA, pp. 715–722, 1991.

GRANTS "Fire Modeling," P. J. Pagni, University of California, Berkeley.

"Fire Propagation in Concurrent Flows," A. C. Fernandez-Pello, University of California, Berkeley.

"Radiation from Turbulent Luminous Flames," G. M. Faeth, University of Michigan.

RADIATIVE IGNITION AND SUBSEQUENT FLAME SPREAD OVER CELLULOSIC MATERIALS

Principal Investigator: Takashi Kashiwagi
Fire Science and Engineering Division
301.975.6699

Sponsor: National Aeronautics and Space Administration
Microgravity Science Program
NASA Lewis Research Center

OBJECTIVE To develop theoretical models of ignition and subsequent flame spread over a cellulosic material in a microgravity environment and calculate ignition and flame spread behavior using material characteristics determined in normal gravity.

PROBLEM There is need to enhance the understanding of combustion science by performing experiments in a microgravity environment.

APPROACH BFRL is developing and solving numerically, multidimensional (2D, 2D axisymmetric, and 3D) time-dependent theoretical models of ignition and the subsequent transition to flame spread in a microgravity environment. Two environmental conditions are being studied: one in a quiescent environment and the other in slow forced flows. Characterization of the sample such as the thermal and radiative properties and thermal degradation of the sample, as well as global oxidation rates of the evolved degradation products which are not affected by gravity, are determined experimentally in a normal gravity environment.

RECENT RESULTS "Heat and Mass Transport from Thermally Degrading Thin Cellulosic Materials in a Microgravity Environment," appear in *J. Heat Transfer.*

"Global Kinetic Constants for Thermal Oxidative Degradation of a Cellulosic Paper," appear in *Combustion and Flame.*

SPACECRAFT MATERIAL FLAMMABILITY TESTING WITH RADIATIVE SELF-HEATING

Principal Investigator: Thomas J. Ohlemiller
Fire Science and Engineering Division
301.975.6481

Sponsor: National Aeronautics and Space Administration
Lewis Research Center

OBJECTIVE To quantify the role of radiative self-feedback in promoting flame spread on NASA materials.

PROBLEM NASA currently tests candidate materials for spacecraft interiors using a simple upward flamespread test. At present, there is no quantitative relation between response to self-feedback and to burning of nonplanar materials as external radiation. Such radiation enhances the flammability of a material. No guidelines exist for NASA to evaluate the appropriate level of external radiation.

APPROACH

Radiative self-feedback is dependent on the view factor between the source and receiving surfaces, as well as on the source surface temperature and emissivity. The latter two factors are material dependent but the first is controllable via configuration and burn area. BFRL will fix the configuration (two parallel surfaces) and vary the burn area to control the strength of the radiative feedback. It will thus be varied over a range to ascertain the feedback level which just permits flame spread subsequent to ignition. In effect this calls for igniting various sized areas on the sample surface and looking at the subsequent behavior. BFRL will design and possibly build this apparatus; parametric studies are likely to be performed in FY 93. A related part of this study addresses the dependence of rate of heat release from thermally thin materials when burning on one surface versus two surfaces. These findings are expected to shed light on the impact of some of the configurational simplifications necessary in the self-feedback tests. BFRL developed a modified heat source for the Cone Calorimeter to be used for this purpose. It will be applied to three materials.

RECENT RESULTS

Demonstrated various materials which give acceptable behavior in the standard NASA test show varying degrees of enhanced flammability in the presence of added external radiation.

FIRE DYNAMICS

WALL FIRE SPREAD

Principal Investigator: Henri E. Mitler
Fire Science and Engineering Division
301.975.6886

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop a method for predicting the rate and extent of fire spread on interior surfaces in a room using the fire properties of the materials involved.

PROBLEM Assessing the fire hazard of interior finish materials currently requires expensive and time-consuming full-scale tests. Needed is a validated wall fire model to enable manufacturers, architects, and modelers to assess this hazard from bench-scale measurements with the use of the model. The results of this work will enhance the capabilities of BFRL's models CFAST (building-fire model) and HAZARD I (predicts the hazard to a building and occupants anywhere within a building).

APPROACH The heating fluxes from a flame burning in hot, vitiated air, such as is found in the upper layer of a burning room, have been found as a function of temperature and oxygen concentration. This will be written up as an algorithm and inserted into SPREAD (BFRL's software which predicts the upward spread on thick walls), yielding the resulting burning and spread rates in such an environment. The apparatus for carrying out validating experiments will be completed, and the experiments done and analyzed. Information on the flame lengths, plumes, and heating fluxes due to fires in corners will be collected and incorporated into an algorithm describing corner fires and will be incorporated into SPREAD.

RECENT RESULTS

Mitler, H. E., "Predicting the Spread Rates of Fires on Vertical Surfaces," *Twenty-Third International Symposium on Combustion*, The Combustion Institute, Pittsburgh, PA, 1991, p. 1715.

Mitler, H. E., "Mathematical Modeling of Enclosure Fires," Chapter 23, Numerical Approaches to Combustion Modeling, *Progress in Astronautics and Aeronautics*, Vol. 135, American Institute of Aeronautics and Astronautics, Washington, DC, 1991.

Mitler, H. E., *Mathematical Modeling of Enclosure Fires*, NISTIR 90-4294, National Institute of Standards and Technology, May 1991.

GRANTS

"Prediction of Fire Dynamics," R. Alpert and J. deRis, Factory Mutual Research Corp.

"Upward Flame Spread on a Vertical Wall," A Kulkarni, Pennsylvania State University.

"A Study of Fire-Induced Flow Along the Vertical Corner Wall," K. Saito, University of Kentucky.

TECHNICAL ASSISTANCE FOR THE EVALUATION OF FIRE BARRIER PERFORMANCE

Principal Investigator: Vytenis Babrauskas
Fire Science and Engineering Division
301.975.6681

Sponsor: Nuclear Regulatory Commission

OBJECTIVE To provide NRC with a review and evaluation of technical issues related to fire barrier systems.

PROBLEM NRC has questioned the efficacy of certain fire barrier systems installed in nuclear power plants and requires further information to assess the performance of the existing barrier systems and, possibly, to recommend remedies.

APPROACH BFRL's work during FY 1992 involves nine steps: 1) review NRC's requirements and guidance documents; 2) review technical documentation; 3) perform chemical analysis of fire barrier materials; 4) perform technical input to testing options; 5) design test program; 6) examine in-plant conditions; 7) identify independent testing laboratory candidates; 8) provide instruction and training to NRC staff and to testing laboratory staff; and 9) perform toxicity tests on the gaseous products of barrier materials exposed to a fire.

RECENT RESULTS New project 1992.

BFRL's FIRE TEST FACILITY CAPABILITY UPGRADE

Principal Investigator: Darren L. Lowe
Fire Science and Engineering Division
301.975.6667

Sponsor: National Institute of Standards and Technology

OBJECTIVE To upgrade instrumentation in BFRL's large burn facility i.e., data acquisition systems, to assure the quality of measurements made under the furniture calorimeter, and to install and test real time combustion product component measurement instrumentation (Fourier Transform Infrared).

PROBLEM The present data acquisition system needs to be upgraded to assure quality real time data from fire test experiments. The current data system does not facilitate portability between tests and there are problems in downloading experimental data. In addition, the instrumentation used on the Furniture Calorimeter does not accommodate multi-component analysis of combustion products. Recent experiments run under the Furniture Calorimeter have indicated that instrumentation, exhaust stack routing and data reduction techniques are error prone, and modifications are necessary to improve results.

APPROACH To resolve the shortcomings of the data collection system in BFRL's large burn facility, new data acquisition systems will be purchased, installed and tested. Ultimately, there will be three data systems, one will be dedicated to the Furniture Calorimeter, the second will be dedicated to collecting data from full-scale fire tests and the third will be used as a back-up system or for new experiments. The

data reduction program RAPID will need to be analyzed to determine if modifications are necessary.

In addition, a FTIR device will be installed and tested to provide real time measurements of combustion product concentrations. The configuration of the device has not yet been determined but may require additional plumbing to route the gas stream through the IR cell.

RECENT RESULTS Data acquisition systems were purchased and new data acquisition software has been written that provides the user a more friendly interface to configure the data system; the new software also eliminates some of the problems in the RAPID data reduction software.

FIRE AND THERMAL CHARACTERISTICS OF NAVY FIREFIGHTER TRAINERS

Principal Investigator: Robert S. Levine
Fire Science and Engineering Division
301.975.6671

Sponsor: Department of Navy
Naval Training Systems Center

OBJECTIVE To develop fire safety procedures and prediction computer programs for U.S. Navy firefighter trainers.

PROBLEM Skilled firefighting is vital to the survivability of Navy vessels. Under current conditions, a seaman receives hands-on training approximately once in a three-year hitch. The Navy is developing a series of realistic trainers and will install thirty assorted trainers at various Naval Stations within the United States. These trainers use propane gas as fuel; the fire is controlled by valves which are controlled by microprocessors that react according to data from sensors. The sensors are affected by the adequacy of the trainees in applying agent to the fire. The trainees require safety assurance and reliability for the Navy.

APPROACH During FY 1992, BFRL is measuring air and wall temperatures, atmospheric composition, radiant fluxes, vent flows, and other pertinent characteristics of prototype trainers to evaluate realism and to delineate possible training safety hazards. Prototype trainers are located at Mayport Naval Station, Florida; Groton, Connecticut, submarine station; Great Lakes Naval Station (recruit trainer); Treasure Island (San Francisco); and San Diego. Measurements are made with the BFRL instrument van and/or portable equipment, and the results are reported to the sponsors. Gas species analyses are performed and meetings to discuss them are arranged to obtain site permits from local Environmental Protection Agencies. On occasion, special analyses are performed by BFRL and other NIST researchers to obtain information to solve developmental problems. These have included, for instance, metallurgical analysis of slag from a failed smoke generator, electron microscope examination of ceramic insulation to determine the cause of failure, and field equation modeling of possible solutions to problems caused by wind affecting the flames on a carrier deck fire trainer, the 19F4.

RECENT RESULTS Performed measurements and set procedures to satisfy Navy Fleet Project Team safety and operational concerns on 19 F4 trainer.

BUILDING FIRE PHYSICS

LARGE-SCALE SMOKE MOVEMENT

Principal Investigator: John H. Klote
Fire Science and Engineering Division
301.975.6890

Sponsor: National Institute of Standards and Technology

OBJECTIVE To verify algorithms for modeling large-scale smoke movement in buildings.

PROBLEM The simulation of smoke movement in HAZARD I (BFRL's software that predicts the hazard to a building and occupants anywhere within the building) has limited applicability to large spaces such as corridors, atria, and shafts. Needed are algorithms to permit realistic simulation of smoke transport in these spaces. The applicability of the HAZARD methodology will be considered for extension to large-scale smoke flow including office buildings, apartment buildings, homes for the elderly, and Navy and merchant ships.

APPROACH BFRL in collaboration with Matsushita, Japan are developing improved corridor research models based on an earlier BFRL corridor model. A set of partial differential equations for corridor smoke flow were derived from the Navier Stokes equations, and computer code was written for solution of these equations. The code is being debugged and will be used to simulate corridor experiments. To further verify the model, BFRL is simulating experiments with FLOW3D (a commercial package computer model that simulates fluid dynamics and heat transfer using a finite difference approach). This model is applicable to a wide range of conditions as opposed to semi-empirical models which are only expected to be appropriate for the range of data on which they are based.

BFRL is developing an atrium algorithm by performing experimental and analytical efforts of smoke flow in atriums. The research is being further defined in a preliminary study with Japanese counterparts working in Japan.

Radiation between walls and gases can have a significant effect on gas temperature and flow, and a simplified wall and gas radiation model will be developed for FLOW3D. While this model will be specifically developed for field model simulation of room fires; it will be based on Forney's radiation models in CFAST, BFRL's building-fire model.

Research for shafts will include the development of a conceptual model based on FLOW3D visualization. Shaft smoke flow will be studied later in this project.

RECENT RESULTS New project 1992.

FIRE EVACUATION BY ELEVATORS

Principal Investigator: John H. Klote
Fire Science and Engineering Division
301.975.6890

Sponsor: General Services Administration
Public Buildings Service
Office of Real Property Management and Safety

OBJECTIVE To develop the feasibility requirements of using elevators for general fire evacuation.

PROBLEM In many tall buildings, fire evacuation by stairs can be very time consuming. Further, there are people who cannot use stairs because of physical disabilities. The adaptation of elevators for general fire evacuation is a potential solution to these problems. This project will develop performance based techniques for occupant use of elevators during building evacuations, develop analysis methods for these techniques, and evaluate these techniques.

APPROACH This is a two Phase project. In Phase 1, four Tasks will be performed. Task 1 develops conceptual systems for elevator evacuation based on information from the literature and contacts with the elevator industry. Task 2 identifies practical concerns (elevator door jamming, reliability of power, exposure to water, etc.) with these systems, and seeks reasonable (within project context) solutions to these problems. Task 3 develops methods of evacuation analysis and smoke protection analysis for these elevator evacuation systems. Task 4 evaluates human behavioral response to these systems. The feedback from Task 4 is essential to assure that the earlier tasks are going in an appropriate direction.

Phase II analyzes the elevator evacuation systems in four typical buildings by using the information developed in Phase I. This information will be useful to GSA and to many organizations concerned with the problems of the physically disabled.

RECENT RESULTS Klote, John H., and Alvord, Daniel, *Routine for Analysis of People Movement Time for Elevator Evacuation,* NISTIR 4730, National Institute of Standards and Technology, February 1992.

FIRE SAFETY ENGINEERING

FIRE PROTECTION ENGINEERING ANALYSIS TOOLS

Principal Investigator: Harold E. Nelson
Fire Science and Engineering Division
301.975.6869

Sponsors: National Institute of Standards and Technology and
General Services Administration
Public Buildings Service
Office of Real Property Management and Safety

OBJECTIVE To advance the development and use of scientifically based models and other computational tools in the solution of fire safety problems faced in activities such as design, regulation, and fire investigation.

PROBLEM In order for the advances in science to have their full effect in enhancing or replacing existing less accurate methods, it is necessary to develop and present tools that can be used properly by practitioners faced with real world problems.

APPROACH BFRL is working to determine the appropriate algorithms for use in programming FPETOOL (BFRL's software used to evaluate hazard and fire protection strategies in GSA office buildings) or another tool, and test results against best available data. Work is underway in reviewing existing documentation on hazard and risk methods for similarities and differences aimed at deriving a consistent approach. Applying fire models to fire investigations, in coordination with leading Federal investigation authorities, to develop a guide for fire investigators who use modeling techniques in performing fire incident analysis.

RECENT RESULTS Nelson, H. E., *FPETOOL—Fire Protection Engineering Tools for Hazard Estimation,* NISTIR 4380, National Institute of Standards and Technology, 1990.

Nelson, H. E., *FPETOOL—User's Guide,* NISTIR 4439, National Institute of Standards and Technology, 1990.

Developed training manual for GSA and conducted training courses for GSA staff.

GRANTS "Fire Safety in Board and Care Homes," Carl M. Harris, George Mason University.

FIRE RESEARCH INFORMATION SERVICES

Principal Investigator: Nora H. Jason
Fire Science and Engineering Division
301.975.6862

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop and maintain NIST's Fire Research Information Services (FRIS) online literature collection and database, FIREDOC, for fire community users.

PROBLEM A fundamental factor in the quality of research is the availability, completeness and use of the conpendium of scientific literature. To achieve this, it is necessary to maintain and advance the FRIS collection and to make it available to the fire research community.

APPROACH

Literature reviews, contacting leaders in the field, document exchange programs, and staff input are the primary techniques in collection development. Disseminate information to the BFRL fire staff to increase awareness and communication. Organize and manage information-related activities for technology transfer. Chair inFIRE Advisory Committee to the Society of Fire Protection Engineers' Board of Directors and work within the inFIRE membership to continue technological advancement in the fire information profession. Create a bibliographic database, BUILD, to contain references and, if available, abstracts to publications by BFRL building staff from 1965–1989.

RECENT RESULTS

Richard W. Bukowski and Nora H. Jason, International Fire Detection Bibliography, 1975–1990, NISTIR 4661, National Institute of Standards and Technology, September 1991 (under sponsorship of the National Fire Protection Research Foundation.

Nora H. Jason, Summaries of BFRL Fire Research In-House Projects and Grants, 1991, NISTIR 4686, National Institute of Standards and Technology, October 1991.

FIRE HAZARD ANALYSIS

HAZARD DEVELOPMENT

Principal Investigator: Richard D. Peacock
Fire Measurement and Research Division
301.975.6664

Sponsor: National Institute of Standards and Technology

OBJECTIVE To plan and implement the next generation hazard methodology (HAZARD 1.2) (BFRL's advanced software that predicts fire hazard to a building and occupants anywhere within a building).

PROBLEM Traditional approaches to product design, product evaluation, and codes and standards development address fire safety in a piecemeal fashion—for example, evaluating heat release without considering product use, toxicity, or ignition propensity. Quantitative hazard analysis techniques have the potential of providing significant cost savings. In addition, measures are evaluated as an interacting system, including the impact of both structure and contents. Alternative protection strategies can be studied within the hazard analysis framework to give the benefit-cost relation for each. Providing these alternatives promotes the design flexibility which reduces redundancies and cost without sacrificing safety.

APPROACH During FY 1992, BFRL will be continuing enhancing HAZARD sub-models. Flame spread, wall conduction, ceiling jet, and detection algorithms will be incorporated or enhanced in the fire model. Efforts on quantifying the level of accuracy of the fire model will continue with comparisons to experiments of wall flame spread conducted by BFRL in FY 1991. We will begin the unification of the user interface by defining the content of the unified input file, beginning the development of an enhanced input module to support the new algorithms, and streamlining BFRL's building-fire model code, CFAST, with a new differential equation solver and support routines which has the potential for significant speed-up of the model. It is expected the results of this research will benefit manufacturers, purchasers, architects, FPE's, code officials, and practitioners who evaluate safety performance, code equivalency, and code change proposal issues.

RECENT RESULTS Peacock, R. D., Jones, W. W., Bukowski, R. W., and Forney, C. L., *HAZARD, Version 1.1,* Handbook 146, National Institute of Standards and Technology, June 1991.

Peacock, R. D. and Babrauskas, V., Analysis of Large-Scale Fire Test Data, *Fire Safety Journal*, 17, pp. 387–414, June 1991.

Peacock, R. D., Davis, S., and Babrauskas, V., Data for Room Fire Model Comparisons, *Journal of Research* 96(4), pp. 411–462, National Institute of Standards and Technology, July 1991.

Enhanced CFAST model with new wall and multiple-layer radiation, vertical vents, and streamlined numerics which speed simulation time by up to three orders of magnitude.

GRANTS "Mathematical Modeling of Human Egress from Fires in Residential Buildings," Michael Kostreva, Clemson University.

"Modifications to Furniture Fire Model for Hazard System," Mark Dietenberger, University of Dayton.

VALIDATION OF SMALL-SCALE RADIANT HEAT SMOKE TOXICITY METHOD

Principal Investigator: Barbara C. Levin
Fire Measurement and Research Division
301.975.6682

Sponsor: National Institute of Standards and Technology

OBJECTIVE

To compare the results of the new radiant heat small-scale smoke toxicity method with real-scale room wall burns to determine if the small-scale data are predictive of the real-scale results. An interlaboratory evaluation (ILE) of the radiant heat smoke toxicity method is necessary for the acceptance of this measurement method as a standard by national and international standards bodies such as ASTM, ISO and NFPA.

PROBLEM

Currently, there are many smoke toxicity measurement methods available for use in the U.S. and Europe. Due to major flaws in each of these tests, none has been deemed acceptable as a national or international standard by any standards body. The Radiant Smoke Toxicity Method was specifically developed to address the problems of past methods. This method is currently under evaluation by ASTM and NFPA and appears to have a high probability of being accepted nationally and internationally as a standard. Additional data are needed to validate the small-scale radiant smoke toxicity method. The larger the database on which the validation is built, the better the package presented to the various standards organizations—ASTM, ISO, and NFPA—when the method is proposed as a standard. An interlaboratory evaluation of the method is necessary to complete the information needed for final acceptance.

Three materials were compared last year in the cup furnace, radiant furnace and the full-scale burn facility. This comparison showed good agreement between the small-scale and full-scale tests. This year, three additional materials were examined in the radiant small-scale toxicity method and full-scale wall room burns. For the ILE, five additional products will be evaluated three times in the small-scale radiant system by four laboratories. When completed, we will have a database on a wide range of materials.

APPROACH

Obtain toxicity data on additional materials in the small-scale radiant toxicity apparatus according to the published methodology and compare results with full-scale room wall burns during post-flashover. Identify the products to be tested in the ILE. These products will be tested first at BFRL to determine if appropriate for the ILE. Five of these products will then be chosen for the ILE. The plan is for each of the four participating laboratories to test each of the five products three times according to the test protocol.

RECENT RESULTS

Levin, B. C., Gann, R. G., Babrauskas, V., Paabo, M., Harris, R. H., Jr., Peacock, R. D., and Yusa, S., "A New Approach for Toxic Potency Measurement for Fire Hazard Analysis," *The Toxicologist* 12:237, 1992.

Levin, B. C., "The Development of a New Small Scale Toxicity Test Method and Its Comparison with Full Scale Fire Tests," to be presented at the VI International Congress of Toxicology, Rome, Italy, June 28–July 3, 1992.

Babrauskas, V., Levin, B. C., Gann, R. G., Paabo, M., Harris, R. H., Jr., Peacock, R. D., Yusa, S., *Toxic Potency Measurement for Fire Hazard Analysis,* SP827, National Institute of Standards and Technology, December 1991.

Babrauskas, V., Harris, R. H., Jr., Braun, E., Levin, B. C., Paabo, M., and Gann, R. G., "Large-Scale Validation of Bench-Scale Fire Toxicity Tests," *J. Fire Sciences* 9, pp. 125–148, 1991.

Babrauskas, V., Harris, R. H., Jr., Braun, E., Levin, B. C., Paabo, M., and Gann, R. G., *The Role of Bench-Scale Test Data in Assessing Real-Scale Fire Toxicity*, Technical Note 1284, National Institute of Standards and Technology, January 1991.

GRANTS "The Effect of Oxygen Concentration on the Evolution of Toxic Gases from Douglas Fir, Rigid Polyurethane Foam and PVC," Arthur Grand, Southwest Research Institute.

CIGARETTE IGNITION METROLOGY

Principal Investigator: Richard G. Gann
Fire Measurement and Research Division
301.975.6866

Sponsor: U.S. Consumer Product Safety Commission

OBJECTIVE To fulfill NIST responsibilities under P.L. 101-352, the Fire-Safe Cigarette Act of 1990, by August 9, 1993. This entails three tasks for the Consumer Product Safety Commission: 1) develop a standard test method to determine cigarette ignition propensity; 2) compile performance data for current cigarettes using the method; and 3) conduct laboratory studies on and computer modeling of ignition physics to develop a predictive capability.

PROBLEM To help reduce these losses, a means is needed for measuring the propensity of a cigarette to ignite furniture and bedding. This will enable the cigarette industry to determine the improved fire safety of their future products.

APPROACH Research during FY 1992 will build on expertise developed in prior related projects, especially the Cigarette Safety Act of 1984. BFRL will pursue primary (standard mock-up) and secondary (surrogate substrate) test beds. These results will be related to established performance of prior set of experimental cigarettes. Round-robin(s) of the new test method will be conducted in FY 1993. Performance data will be generated on current market cigarettes. Laboratory experiments will be performed to measure the thermal behavior of the cigarettes and substrates. Prior first-cut models of cigarette smoldering and substrate ignition will be revised.

RECENT RESULTS Revalidated experimental cigarettes, identified approaches to primary and secondary methods, and made significant additions to computer model of igniting substrate.

SMOKE DYNAMICS

SOOT FORMATION AND EVOLUTION

Principal Investigator: Kermit C. Smyth
Fire Measurement and Research Division
301.975.6490

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop a predictive model for the formation of soot in flames and the evolution of smoke components from flames.

PROBLEM The capability to accurately predict within flame soot production and the smoke yield from flames and its optical properties is needed to assess radiation properties of fires and their production of toxic gases.

APPROACH BFRL is performing optical and mass spectrometric measurements to obtain accurate and quantitative species profile data, particularly for radicals, in hydrocarbon diffusion flames. The experimental results are being compared with detailed computations of Smooke at Yale University. Bilger's and Peters' reduced 4-step oxidation mechanisms will be tested against BFRL's diffusion flame results and add appropriate reduced mechanisms and/or global rate expressions for soot inception, growth, and oxidation. BFRL also will develop computational method for describing the optical properties of soot agglomerates over a wide range of particle size.

The results of this work will help to formulate a global model of soot formation and oxidation processes, as well as improve strategies for incorporating chemistry into turbulent flow fields.

RECENT RESULTS Smyth, K. C., Norton, T. S., Miller, J. H., and Smooke, M. D., "Experimental and Computed Profiles of Radical Species and Temperatures in Two-Dimensional Mehtane/Air Diffusion Flames," submitted to the Twenty-Fourth Symposium (International) on Combustion, 1992.

Puri, R., Moser, M., Santoro, R. J., and Smyth, K. C., "Laser-Induced Fluorescence Measurements of OH-Concentrations in the Oxidation Region of Laminar Hydrocarbon Diffusion Flames," submitted to the Twenty-Fourth Symposium (International) on Combustion, 1992.

GRANTS "Soot Morphology in Buoyancy Dominated Flames," Richard A. Dobbins, Brown University.

"Modeling of Soot Formation in Diffusion Flames," Ian Kennedy, University of California at Davis.

"Simplifications of Diffusion Flame Chemistry: A Theoretical and Experimental Study of the Structure of Laminar Diffusion Flames," J. Houston Miller, George Washington University.

"Fundamental Mechanisms for CO and Soot Formation in Diffusion Flames," Robert J. Santoro, Pennsylvania State University.

"Light Scattering Studies of Fractal Soot Aggregates in Flames," Chris Sorensen, Kansas State University.

EFFECTS OF STRAIN RATE ON COMBUSTION CHEMISTRY IN BUOYANT, HYDROCARBON DIFFUSION FLAMES

Principal Investigator: Kermit C. Smyth
Fire Measurement and Research Division
301.975.6490

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop an experimental capability to optically probe time-varying, transitional hydrocarbon diffusion flames and to characterize the time and temperature dependence of soot formation processes as a function of the local strain rate.

PROBLEM The concentrations of intermediate hydrocarbons and soot do not obey universal state relationships as a function of the local mixture fraction, with the result that a second parameter such as the strain rate must be included in any description of chemistry-turbulence interactions.

APPROACH An axisymmetric, pulsating hydrocarbon diffusion flame will be acoustically locked close to its natural frequency of oscillation. Two-dimensional imaging experiments will then be carried out to measure the concentration fields of radical species (OH·), soot precursors (polycyclic aromatic hydrocarbons) and soot particles. Particular emphasis will be placed on studying the vortex-shedding region, which exhibits a wide range of local strain rates. Results are expected to extend optical investigations into transitional flames, where the effects of chemistry-turbulence interactions can be probed effectively.

RECENT RESULTS New project 1992.

CARBON MONOXIDE PRODUCTION AND PREDICTION

Principal Investigator: William M. Pitts
Fire Measurement and Research Division
301.975.6486

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop a fundamental understanding of the mechanisms of carbon monoxide formation in flames sufficient to produce an estimation model and a detailed predictive model.

PROBLEM CO generated by fires in enclosures is responsible for roughly two-thirds of fire deaths. The conditions necessary and the mechanisms responsible for the generation of high concentrations of CO are poorly characterized. As a result, it is currently impossible to predict the generation of CO by fires. Such a predictive capability is required by Laboratory fire models such as Hazard.

APPROACH During FY 1992, BFRL is performing fundamental and engineering investigations to develop an understanding of CO formation in flames. The engineering studies are designed to develop appropriate correlations for CO formation for fires in enclosures and provide the necessary knowledge to incorporate the findings into

existing BFRL fire models. The fundamental investigations are to identify the principal chemical and physical mechanisms responsible for the formation of high CO concentrations in fires and to theoretically justify the use of the engineering correlations. Ultimately, the findings will be incorporated into a simple physical model for CO production in enclosure fires.

RECENT RESULTS Developed prototype global equivalence ratio meter to measure the global equivalence ratio in the upper layer of a fire within a reduced-scale enclosure.

GRANTS "Fundamental Mechanisms for CO and Soot Formation in Diffusion Flames," Robert J. Santoro, Pennsylvania State University.

"Radiation From Turbulent Luminous Fires," Gerard M. Faeth, University of Michigan.

"Experimental Study of the Environment and Heat Transfer in a Room Fire," Edward E. Zukoski, California Institute of Technology.

"Compartment Fire Combustion Dynamics," Richard J. Roby, Virginia Polytechnic Institute and State University and C.L. Beyler, Hughes Associates.

"Simplification of Diffusion Flame Chemistry: A Theoretical and Experimental Study of the Structure of Laminar Diffusion Flames," J. Houston Miller, George Washington University.

STUDY OF SMOKE AGGLOMERATES

Principal Investigator: George W. Mulholland
Fire Measurement and Research Division
301.975.6695

Sponsor: National Aeronautics and Atmospheric Administration
Ames Research Center
Solar System Exploration Branch

OBJECTIVE To test the validity and utility of fractal concepts in describing the growth and properties of large smoke agglomerates.

PROBLEM Provide NASA with the general hardware design and data analysis methodology for studying smoke agglomerates in an orbiter facility.

APPROACH Make use of a Transmission Cell-Reciprocal Nephelometer recently developed at BFRL to monitor the extinction cross section and total scattering cross section as the agglomerates grow. The angle dependent scattering will be used to monitor the fractal dimension and average radius of gyration as the agglomerates grow. The results will be compared with light scattering calculations for a computer simulation of smoke agglomeration.

RECENT RESULTS Designed the Large Agglomerate Optics Facility.

AEROSOL 0.1 MICROMETER CONCENTRATION STANDARD

Principal Investigator: Nelson P. Bryner
Fire Measurement and Research Division
301.975.6868

Sponsor: National Institute of Standards and Technology
Office of Standard Reference Material

OBJECTIVE To develop a low-cost prototype aerosol generator for an aerosol concentration standard.

PROBLEM Particle contamination is a significant cause of defects in the production of integrated circuits. There is no agreed upon standard for the number concentration calibration for optical particle counters. A major application of these counters is to monitor particle contaminants in facilities where integrated circuits are assembled. Factors of two difference in number concentration measured by two instruments for the same aerosol are not uncommon.

APPROACH BFRL's research in FY 1992 focuses on examining the results of stability and reproducibility study completed during FY 1991 and incorporating critical elements of generator design into prototype generator to achieve stability and reproducibility in concentration standard.

RECENT RESULTS Completed series of experiments to examine short- and long-term stability, reproducibility, and performance characteristics of three aerosol generators.

FIRE SUPPRESSION

CHARACTERIZATION OF LARGE FIRES

Principal Investigator: David D. Evans
Fire Measurement and Research Division
301.975.6897

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop methods that quantify the combustion process in large fires and predict the long range dispersion and deposition of smoke from the fires.

PROBLEM Much knowledge has been acquired about the burning characteristics of fuels and the dynamics of fire flows and heat transfer on a laboratory scale. However, this knowledge is difficult or impossible to translate into engineering information about the hazards of large fires at the scale of industrial accidents or natural disasters. In order to assess any fire situation basic information about the energy release rate, radiation, emissions, smoke plume trajectory, and particulate deposition are needed. Non-intrusive means should be developed to characterize the burning of large fires. Using this information predictive methods, need to be developed to assess the potential long range impact of the fire through modeling of the smoke plume dispersion and particulate deposition processes.

APPROACH BFRL is modeling the fire plume dispersion and particulate deposition to better understand the range over which fire effects may be felt. Modeling of the fire plume rise and dispersion downwind is underway making use of vortex element computational methods. To assess the accuracy of this computational method, measurements of scalar quantities in a buoyant plume flow are needed. Although measurements in large plumes have been made, there are difficulties in experimental control, repeatability of measurements, and cost that prohibit validation of computations using only large scale fire tests. Furthermore recent experiences of NOAA, NASA, and EPA in measurements of emissions from the Kuwait fires, are good indicators of the expense, difficulty and uncertainty of large scale fire measurements using the best technology available today. To assess the mixing processes in a buoyant plume, and examine a situation that is less complex than any actual fire flow, laboratory scale salt water simulations may be used to provide initial data for evaluation of the models.

Salt water modeling to represent fire flows within enclosures has been studied extensively at BFRL. The question of how well, salt water simulations can duplicate buoyant flows that simulate the important features of large fire plumes remains to be determined. One dominate feature of fire plumes is the regular pulsations observed which are dependent on the diameter of the fire. As part of the initial experiments a modest effort will be made to determine if buoyant salt water plume simulations of large fires exhibit the expected pulsation frequency. Existing video records of previous salt water studies at BFRL will be examined to determine if the frequency of observed pulsations in the salt water flow are related to published measurements of pulsations in actual fires. If so there is a strong indication that salt water modeling may be used to simulate near field plume flow. To evaluate the predictive models in the far field, the dispersion of a salt plume in a water tunnel must be studied. Measurements of salt concentration at hundreds of fire diameters down stream should be related to the concentration of major combustion products such as carbon dioxide in the actual fire plume. An effort will be made to locate existing facilities (water tunnels) that are suitable for experiments needed to evaluate the predictive model and available to BFRL. The advantages and disadvantages of each over building a new facility at BFRL for

future studies will be examined. Results of this investigation will be incorporated in the long range (nominally 5 years) plan for future BFRL large fire research.

RECENT RESULTS

Mulholland, George W., Benner, Bruce A., Fletcher, Robert A., Steel, Eric, Wise, Steven A., May, Willie E., Madrzykowski, Daniel, and Evans, David, *Analysis of Smoke Samples from Oil Well Fires in Kuwait,* Report of Test FR 3985, June 20, 1991.

GRANTS

"Computer Simulation of the Rise, Dispersion and Ground Deposition of Large-Scale Smoke Plumes," Ahmed F. Ghoniem, Massachusetts Institutes of Technology.

"A Study of Simulated Oil Well Blowout Fires," Jay Gore, Univesity of Maryland.

EFFECTS OF FIRE SUPPRESSANTS ON SAFETY RELATED EQUIPMENT

Principal Investigator: Robert S. Levine
Fire Science and Engineering Division
301.975.6671

Sponsor: Nuclear Regulatory Commission
Office of Nuclear Regulatory Research

OBJECTIVE

To collect data on the effects of fire suppressants on equipment important to safety in nuclear power plants.

PROBLEM

Nuclear power plants have many installed fire protection systems. When inadvertent operation occurs, the suppressant (water or CO_2 or halon are used) may damage operating equipment and/or interfere with safety circuits or create spurious signals. This project used Navy Safety Center data on a large variety of operating system incidents on ships and shore facilities to gain insight into effects that might occur and to enrich the limited statistical data from nuclear power plant experience.

It was found that on ships, when sea water was not used, the incidence of damaging effects was much less than the shore facility experience. The fresh water used on ships comes from a closely controlled pure potable water main. It is postulated that the reason for many of the deleterious effects in Nuclear Power Plants is impure (high electrical conductivity) water. This may be largely due to rust buildup in water residing in sprinkler systems. Incidently, when sea water is used to extinguish fires, there is a high probability that electrical equipment exposed to it will be damaged.

APPROACH

BFRL will test the hypothesis above and determine how much water impurity can be tolerated in fire protection systems. This work is in support of SNL/INEL (Sandia National Laboratory) work on NRC Generic issue 57.

RECENT RESULTS

It was found that the population of inadvertent events in shore facilities paralleled Nuclear Power Plant experience, yielding about 100 cases per year for the 10 years analyzed. This data allowed the Sandia analyst to derive a calculated unreliability about one-fifth that calculated from Nuclear Power Plant experience alone.

IN-SITU BURNING OF OIL SPILLS

Principal Investigator: David D. Evans
Fire Measurement and Research Division
301.975.6897

Sponsors: Department of Interior
Minerals Management Service
Technology Assessment and Research Branch

U.S. Coast Guard
Environmental Safety Branch

American Petroleum Institute
Health and Environmental Sciences Department

OBJECTIVE To analyze and report results from FY 1991 meso-scale test conducted in Mobile Alabama, and prepare for measurements during FY 1992 at sea field tests.

PROBLEM Data is lacking on the emissions and trajectory of burning particulate material to characterize the combustion of large pool fires.

APPROACH Basic measurement methods used in the meso-scale tests including chemical analysis being provided by outside organizations will be scaled up for at sea use. Analysis of plume flow from large fires will integrated to provide a prediction of the rise, dispersion, and settling of smoke particulate.

RECENT RESULTS Evans, D. D., Walton, W. D., Baum, H. R., Mulholland, G. W., Lawson, J. R., Koseki, H., and Ghoniem, A. F., "Smoke Emission From Burning Crude Oil," Proceedings of the Fourteenth Arctic and Marine Oil Spill Program Technical Seminar, Vancouver, British Columbia, Canada, June 12–14, 1991.

Completed a major series of meso-scale pool fire burns up to 15 m^2.

EVALUATION OF THE USE OF THE GSA ENGINEERING FIRE ASSESSMENT SYSTEM FOR PREDICTING THE RESPONSE OF SPRINKLERS AND DETECTORS IN LARGE SPACES

Principal Investigator: Kathy A. Notarianni
Fire Measurement and Research Division
301.975.6883

Sponsor: General Services Administration
Public Buildings Service
Office of Real Property Management and Safety

OBJECTIVE To verify and provide recommendations for the use of the GSA Engineering Fire Assessment System for predicting the response of sprinklers and detectors in large spaces.

PROBLEM Fire sprinkler and thermal detector activation predictions are an integral and important aspect of the GSA Engineering Assessment System which are frequently used for small and medium sized rooms. Virtually no verification

experiments have been conducted for large spaces. Although large spaces are frequently of historical significance, contain large quantities of fuel, and present special life safety problems, there is considerable uncertainty when applying the system to these spaces.

APPROACH BFRL will make measurements using FPETOOL (BFRL software to evaluate hazard and fire protection strategies in GSA buildings) and LAVENT (Link Actuated VENTS—user friendly computer code) during fire tests conducted in an aircraft hanger with a ceiling of 30 m (100 ft) high. Tests are being conducted by Factory Mutual Engineering Association for the purpose of testing the facility's detection system. Fire gas temperatures and disk temperatures will be measured above the fire and along the ceiling in locations corresponding to the expected location of sprinklers or detectors. The results of the fire experiments will be compared to the predictions from the two computer models in order to determine the limits of applicability of the models and to develop recommendations for use in large spaces.

RECENT RESULTS New Project 1992.

EVALUATION OF THE EFFECT OF RECESSED SPRINKLER INSTALLATION ON SPRINKLER ACTIVATION TIME

Principal Investigator: Daniel Madrzykowski
Fire Measurement and Research Division
301.975.6677

Sponsor: General Services Administration
Public Buildings Service
Office of Real Property Management and Safety

OBJECTIVE To develop factors, which modify the response time index (RTI) to account for the effect of recessed sprinkler installation, for input into sprinkler activation models.

PROBLEM Sprinkler activation models are being used by the General Services Administration (GSA) in their design/evaluation of fire protection systems. These models have evolved from direct application of single step engineering correlations to models considering the secondary effects of; heat loss to the ceiling, the hot gas layer, and the position of the sprinkler link below the ceiling. All of these models assume the sprinkler link is fully exposed.

In an effort to make the ceilings in sprinklered buildings more aesthetically pleasing, sprinklers have been recessed into the ceiling or recessed and covered with decorative temperature activated plates. Currently, the models do not account for the effects of recessing the sprinklers into the ceiling, or covering the sprinkler with a plate.

One of the critical input parameters to the sprinkler activation models is the RTI of the sprinkler. The test used to measure the RTI does not consider the effects of the recessed installation on the RTI. Large scale fire tests conducted by BFRL for GSA have shown that recessing the sprinkler increases the sprinkler activation time.

APPROACH BFRL is 1) selecting a representative cross section of commercially available sprinklers including those used in previous GSA studies; 2) conducting tests in the BFRL plunge test apparatus with the sprinklers in fully exposed, recessed and shielded configurations; 3) analyzing plunge test results and correlate them with large scale test results from previous GSA studies; and 4) utilizing resulting recessed installation effect factors in the GSA Engineering Fire Assessment System to generate predicted sprinkler activation times which will be compared with experimental (actual) activation times.

Research findings will be published and will serve as input to GSA facilities design requirements and will be used in BFRL's on-going work in the development of the GSA Engineering Fire Hazard Assessment System.

RECENT RESULTS New Project 1992.

INTERLABORATORY EVALUATION OF REVISED ASTM E648

Principal Investigator: J. Randall Lawson
Fire Measurement and Research Division
301.975.6676

Sponsor: The Carpet and Rug Institute

OBJECTIVE To conduct, analysis, and report on an interlaboratory evaluation of selected floor coverings, leading to a revised standard protocol for ASTM with a revised Precision and Bias Statement in ASTM E 648.

PROBLEM The ASTM E 648 test method showed that some significant reproducibility problems existed between various testing laboratories. BFRL conducted a research project sponsored by the Carpet and Rug Institute that demonstrated that certain changes to the apparatus and procedure could reduce the test procedures variability. This interlaboratory test program is being conducted to quantify precision and bias for the modified test procedure.

APPROACH BFRL will visit five laboratories in Dalton, Georgia and one in Pennsylvania to evaluated and assist laboratory preparedness for the flooring round robin. Technical support will be provided to the laboratories as needed. BFRL will collect and analyze the test results and prepare a report for ASTM including a Precision and Bias Statement for Subcommittee ballot. Presuming a successful interlaboratory evaluation, BFRL will provide limited support responding to negative Subcommittee ballots.

The results from this study will present a statistical base for developing a precision statement for the ASTM E648 standard test procedure. These results will provide the carpet industry, codes bodies and product users with information on the expected variability of the test procedure used to certify carpets relative to surface flammability.

RECENT RESULTS Lawson, Randall J., *An Evaluation of Precision for the ASTM E648-91a Standard Test Method for Critical Radiant Flux of Floor-Covering Systems,* NISTIR, in press.

EXPLORATORY FIRE TECHNOLOGIES

ADVANCED FIRE DETECTION SYSTEMS

Principal Investigator: William L. Grosshandler
Fire Measurement and Research Division
301.975.6679

Sponsor: National Institute of Standards and Technology

OBJECTIVE To demonstrate principles for the response of detection systems to the stimuli of early fire events while discriminating against false signals.

PROBLEM A properly designed detection system must be able to identify in a matter of seconds a fire event which may occur only once in one hundred years, and the identification must lead to an action which is appropriate to the space being protected. This disparity in time scale and the variability in geometry, content and occupancy of the space impose great demands on the system. False alarms, maintenance problems, incomplete or inaccurate information, and inappropriate suppression responses are problems which can plague current fire detection systems, especially when cost is an overriding constraint. The phase out of Halons and the increased capital investment in modern industrial facilities in need of protection make early sensing and suppression even more imperative.

APPROACH The general approach is to greatly increase the amount of information upon which a decision is made, and to do this in the minimum amount of time. Advances in the sensing of temperature, species concentrations, particulates, and acoustic and electromagnetic radiation will be surveyed to determine their applicability to fire detection. Of particular interest are optical and solid-state sensors for CO, infrared sensing of hydrocarbons and acid gases, fiber-optic integrated sensors, micrometer-size sensors, and subacoustic and super-acoustic sensors. Software will be developed to recognize unique acoustic and infrared signatures of various fire events. The details of extinction and pre-ignition phenomena will begin to be investigated, if resources permit, to determine the minimum amount of suppression agent required to inhibit ignition, the application being to ultra-fast detection/suppression in high-value Halon-protected systems.

RECENT RESULTS New project 1992.

HEAT FLUX MEASUREMENTS IN NBS SMOKE BOX

Principal Investigator: Richard L. Smith
Fire Science and Engineering Division
301.975.6870

Sponsor: Federal Aviation Administration
FAA Technical Center

OBJECTIVE To provide a faster and more accurate method of setting the heat flux in the NBS smoke density chamber for use by the FAA.

PROBLEM Reliable measurements of the rate of heat release and the generation of smoke are needed to evaluate aircraft cabin interior materials. FAA is using the ASTM E 662-83, "Standard Test Method for Specific Optical Density of Smoke

Generated By Solid Materials." In this method, the FAA believes there is a significant variation of the in cident heat flux over the surface of the specimen. In addition FAA is not satisfied with the heat flux gauge prescribed in this test method and seek one that makes faster measurements and is easier to calibrate.

APPROACH A series of heaters will be selected or designed and then their profiles will be measured using a 0.635 cm. Gardon gauge. A profile measurement technique will be developed for the new heater and the Gardon gauge. As a consequence of this project, the manufacturers which must comply with FAA regulations for the smoke generated by materials will have a faster and more accurate method of setting the heat flux in the NBS Smoke Density Chamber.

RECENT RESULTS New project late 1991.

POLYMER FLAMMABILITY MODELING

Principal Investigator: Marc R. Nyden
Fire Measurement and Research Division
301.975.6692

Sponsor: National Institute of Standards and Technology

OBJECTIVE To develop a technical basis for the design of a new generation of fire resistant materials which, while retaining their intended-use properties, will be low in combustion toxicity and safe for the environment.

PROBLEM As standards for acceptable performance and safety become more demanding, the traditional "trial and error" approach to materials design becomes more expensive and less successful. There is a strong correlation between char residue and fire resistance since char is always formed at the expense of volatile fuel. Furthermore, surface char tends to insulate the unburnt material from the heat generated in gas phase combustion. The thermal degradation chemistry of some polymers can be altered to favor the formation of a char with chemical additives and/or by direct modification of the structure of the polymer. The challenge is to achieve significant levels of fire resistance without adversely affecting intended-use properties, cost and the toxicity of these materials.

APPROACH During FY 1992, BFRL is experimentally determining kinetic and flammability data to calibrate a computer model of thermal degradation. The dynamics trajectories of the polymers are being calculated from Hamilton's equations of motion. Macromolecular systems, which may be too costly or too complex to synthesize on a routine basis, can be modeled and systematically varied, all the while examining their tendency to form high molecular weight crosslinked structures.

RECENT RESULTS Obtained experimental verification of computer predictions that radiation cross-linked polyethylene and chemically cross-linked polyurethyl methaglate.

"Molecular Dynamics of Initial Events in the Thermal Degradation of Polymers," Marc R. Nyden and Donald W. Noid, *J. Phys. Chem.* 95, 1991.

Nyden, Marc R., Forney, Glenn P., and Brown, James E., "Molecular Modeling of Polymer Flammability: Application to the Design of Flame Resistant Polyethylene," *Micromolecules,* in press.

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This report summarizes the Building and Fire Research Laboratory's research for 1992. The report is arranged by its research programs: structural engineering, materials engineering, mechanical and environmental systems, fire science and engineering, and fire measurement and research. Each summary lists the project title, point of contact, sponsor, research, and results.

BFRL's mission is to increase the usefulness, safety, and economy of constructed facilities, and reduce the human and economic costs of unwanted fires in buildings.

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