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This report summarizes the Building and Fire Research Laboratory's research for 1993. 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.

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Noel J. Raufaste

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FOREWORD

The competitiveness of all U.S. industries and the quality of life of all people depend on the quality of the constructed facilities that shelter and support most human activities. Construction also is of great direct economic importance. Annually, in excess of $600 billion is spent in the United States on the design, construction, maintenance, repair, and renovation of constructed facilities, according to statistics from the U.S. Department of Commerce. New construction alone employs 6 million people. 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 the only federal technology agency with the specific mission of helping U.S. industry to strengthen its international competitiveness. NIST:

1. helps U.S. industry improve its competitiveness through new technologies, modernized production processes, improved quality control, and rapid commercialization;

2. improves public health, safety, and the environment; and

3. conducts fundamental research that advances science and engineering.

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 enhance the competitiveness of U.S. industry and public safety through performance prediction and measurement technologies and technical advances that improve the life cycle quality of constructed facilities.

BFRL performs and supports field, laboratory, and analytical research to understand the performance of construction materials, components, systems and practices, and the fundamental processes underlying the initiation, propagation, and suppression of fires. Its focus is on structural, materials, and mechanical engineering, and fire safety and sciences. BFRL's key customers include the architectural and engineering firms, manufacturing industries, the construction and fire safety industries, codes and standards officials, Federal and state agencies, and occupants and users of buildings and other structures including transportation conveyances.

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 pound) 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 a 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. Seventy-eight research associates from U.S. industry, guest researchers from foreign laboratories, and faculty members from universities worked at BFRL during 1992 for periods averaging about a year.

BFRL participates in about 150 national standardization activities; provides leadership in national and international standardization organizations and chairs more than 20 voluntary standardization committees. 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 23 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 201 employees of which 144 are professional staff, 74 have Ph.D.s, and 17 are registered engineers. BFRL's budget for FY 1993 is $24 million. Congress provides $12 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 Federal agencies ($10 million) for solving their mission needs and from industry ($2 million).

About this Report. This report summarizes BFRL's research for 1993. The report is arranged by its research programs: structural engineering, materials engineering, mechanical and environmental systems, fire safety engineering, and fire science. 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. The fax number is 301-975-4032.

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STRUCTURES
DIVISION

EARTHQUAKE ENGINEERING

Performance Requirements for Passive Energy Dissipation Systems for Buildings and Lifeline Structures

Principal Investigator:
Harry Shenton
Structures Division
301-975-6067

Sponsor:
National Institute of Standards and Technology

Objective
To develop standard performance criteria and test procedures to evaluate seismic base-isolation bearings.

Problem
Passive energy dissipation systems for seismic base isolation is effective in reducing the level of response in structures during strong earthquake ground shaking. The primary component of a base-isolation system, the bearing, must be capable of withstanding complex static and dynamic loads during the normal life of the system. However, there are no standard performance criteria and test procedures to evaluate seismic base-isolation bearings.

Approach
This research involves five tasks:

1. Perform a survey data from technical publications, journal articles and manufacturers reports on seismic isolation bearings used in buildings, bridges and other large structures. This survey includes information on materials, design, test procedures, performance characteristics, energy dissipation capacity, tension up-lift capacity, displacement limiting devices, fire protection, maintenance, and repair or replacement.

2. Create an oversight committee of individuals from the base-isolation community, with expertise in design, fabrication and testing, to act in an advisory capacity throughout the development of the draft standard.

3. Develop a summary of existing or potential performance criteria and testing procedures from reviews of data and input from the oversight committee. This information will serve as the basis for a workshop.

4. Conduct a two- or three-day workshop on performance criteria and test procedures for base-isolation bearings. Participants will be invited from the design, fabrication, manufacturing and research communities to discuss issues related to the standardization of performance criteria and test procedures, and provide input for the development of a draft standard.

5. Develop a draft standard using input from the oversight committee, workshop, and data survey.

The results of the research will produce a draft standard serving as a resource document for voluntary standard/specification writing bodies.

Recent Results
Shenton, Harry W., III, "Design Criteria for Base Isolation of Buildings," *Wind and Seismic Effects, Proceedings of the 24th US-Japan Panel on Wind and Seismic Effects*, NIST SP 843, National Institute of Standards and Technology, September 1992.

Shenton, Harry W., III, Lin, Albert N., and Lew, H.S., "Performance of Fixed and Isolated Structures," *Tenth World Conference on Earthquake Engineering*, Vol. 7, pp 2485-2490, July 1992, Madrid, Spain.

Shenton, Harry W., III and Lin, Albert N., "Relative Performance of Fixed-Base and Base-Isolated Concrete Frames," *ASCE, Journal of the Structural Division*, June 1992.

Lin, Albert N., "Design Force Levels for Base-Isolated Structures," *Proceedings, 1992 CIB World Congress*, Montreal, Canada, May 19, 1992.

Lin, Albert N. and Shenton, Harry W., III, "Seismic Performance of Fixed-Base and Base-Isolated Steel Frames," *ASCE, Journal of Engineering Mechanics*, Vol. 118, No. 5, May 1992.

Seismic Performance of Precast Concrete Connections

Principal Investigator:
William Stone
Structures Division
301-975-6075
Geraldine S. Cheok
Structures Division
301-975-6074

Sponsor:
National Institute of Standards and Technology
and
The American Concrete Institute
Concrete Research Council

Objective
The objectives of this project are 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 to prevent premature yielding of connections. 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 elements 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 arrangements, and fiber reinforced grout in the joints. Technical data are needed to establish provisions for code and standards, thereby promoting precast construction in seismically active regions.

Approach
Currently, there is limited guidance for the design and detailing of precast concrete structures for seismically active regions. The 1985 UBC permits the use of precast concrete elements to res. ' seismic forces when the design and detailing satisfies the Code requirements for cast-in-place concrete structures. The 1985 edition of the UBC Code was in use at the time this research was initiated. Precast structures tend to be less ductile and tend to have a less stable inelastic response than do cast-in-place monolithic structures. This is primarily because the inelastic strains are concentrated in the connections. Thus, the connections are often unavoidable weak links.

A task group of individuals form the academic research community, the Precast/Prestressed Concrete Institute, the Portland Cement Association, and the design profession, has been formed by ACI to provide technical guidance on the project. This task group will guide the design of specific joint details for BFRL's consideration. An experimental model study will be performed to characterize joint behavior. The experimental program is divided into four phases:

1. Exploratory phase to determine a viable connection.

2. Parametric study of details developed in Phase 1.

3. Effect of partially bonded tendons.

4. Effect of using low strength steel in conjunction with post-tensioning in a precast connection.

The successful completion of this project will have a broad impact on building construction in seismic zones. Precast moment-resisting frames can be erected at substantial time savings over traditional monolithic (cast-in-place) construction techniques. Furthermore, there is enhanced material quality control afforded by using pre-manufactured elements. Both of these factors will improve U.S. construction productivity and competitiveness.

Recent Results
Cheok, Geraldine, Stone, William, and Lew, H.S., "Seismic Performance Behavior of Precast Concrete Beam-Column Joints," Submitted to *Proceedings of the ASCE Structures Concrete*, April 1993.

Stone, William, "Model Precast Concrete Beam-to-Column Connections Subjected to Cyclic Loading," *PCI Journal*, accepted December 1992.

Cheok, Geraldine, Stone, William, and Lew, H.S., "Partially Prestressed and Debonded Precast Concrete Beam-Column Joints," *Proceedings of the Third Meeting of the U.S. Japan Joint Technical Coordinating Committee on Precast Seismic*

Structural Systems (JTCC-PRESSS), San Diego, CA, November 18-20, 1992.

Seismic Strengthening Methodologies for RC Frame Buildings

Principal Investigator:
Long Phan
Structures Division
301-975-6077
Diana Todd
Structures Division
301-975-5296

Sponsor:
National Institute of Standards and Technology

Objective
To develop seismic strengthening guidelines for lateral load resisting capacity of lightly reinforced concrete (RC) frame buildings.

Problem
Most RC structures in the eastern United States are not designed to resist large earthquakes. Thus, in the event of a strong motion earthquake, many RC buildings, which were designed primarily for gravity loads, are vulnerable to severe damage or even to total collapse. To minimize such vulnerability, local weaknesses in the buildings must be accurately identified, and the building as a whole must be strengthened with appropriate lateral load resisting elements to 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.

Analytical tools are not available to identify the weaknesses in a structural system and to assess proposed strengthening schemes, both at the sophisticated level needed for analytical research, and at the simplified level needed for day-to-day practice by design engineers. Also lacking is practical guidance for engineers to select and design retrofit schemes.

Approach
A systematic examination of available test data, performed by BFRL in FY 1992 has yielded empirical hysteresis models for one-bay, one-story bare frames, monolithic wall-frame constructions, frames strengthened by cast-in-place infilled wall, and frames strengthened by precast concrete panels. The models were incorporated into the program IDARC for use in inelastic analysis, successful validation of the model has been

obtained utilizing results of a one-bay, one-story test and a one-bay, three-story test.

During FY 1993, BFRL will develop hysteresis models of:

- Existing B-C joints,
- Columns strengthened by jacketing,
- Frames infilled by masonry walls, and
- Frames strengthened by steel bracing.

The complete set of hysteresis models will provide the program IDARC with an enhanced capability in inelastically analyzing existing RC structures and structures strengthened by the various schemes described above. This analytical capability will be used to perform a parametric study on a number of selected buildings.

The system identification method also will be used to develop empirical expressions, using the same experimental database, for ultimate shear capacity, energy absorption, and ductility factor of unstrengthened and strengthened structures.

These empirical expressions could be used by design engineers to predict the capacities of the structures before and after strengthening. The results of parametric study, coupled with the expressions for structural capacities, will provide the basis for developing guidelines for seismic strengthening of lightly RC structures in future years.

The results of this project are expected to produce guidelines for providing lateral load resisting elements. They will be used to evaluate the capacity of existing buildings and identify deficiencies; and to predict seismic performance of the buildings after strengthening and provide quantitative assessment of the improvement in seismic performance.

Recent Results

Phan, Long, T., Todd, Diana, R., Lew, H.S., "Seismic Strengthening of Reinforced Concrete Frame Buildings," submitted to the *1993 National Earthquake Conference*, Memphis, TN.

Phan, Long T., Todd, Diana, R., Lew, H.S., *Strengthening Methodology for Lightly Reinforced Concrete Frames-I*, NISTIR 5128, National Institute of Standards and Technology, Gaithersburg, MD, February 1993.

Geotechnical Options for Mitigating Liquefaction Effects

Principal Investigator:
Felix Y. Yokel
Structures Division
301-975-6069

Sponsor:
National Institute of Standards and Technology

Objective

To study the effectiveness of ground improvement and other options for mitigating or preventing liquefaction.

Problem

Many lifeline systems are vulnerable to the effects of liquefaction. While it is in most instances feasible to locate critical structures and support facilities on sites which are not susceptible to large ground displacements and other liquefaction effects, similar precautions are not always possible for long, linear system elements such as pipe and rail lines. Furthermore, there are many existing lifelines which are vulnerable to earthquake effects because of their location or because of antiquated design and deterioration due to age. Even when aging system elements are replaced, it is not always possible to relocate these systems in less vulnerable areas because of right-of-way restrictions or the geographical location of existing developed areas which must be served.

Two strategies are available for dealing with the liquefaction problem: (1) design the lifelines to resist or accommodate large ground displacements and other effects associated with liquefaction; and (2) implement ground or system improvements which will prevent liquefaction or modify its effects. Strategy (2) is of particular interest in conjunction with retrofit of existing systems. This project will concentrate on ground improvement. Known ground improvement options include drainage, densification and soil modification by grouting or other methods. The greatest impediment to ground improvement is cost.

Two problems need to be addressed: 1. determine the effectiveness of proposed methods; and 2. develop in-situ and laboratory performance tests which can measure the success of the implementation of the improvement and provide reasonable quality control in the field.

Approach
During FY 1993, BFRL will: 1. conduct analytical modeling of the soil improvement; and 2. develop in-situ and laboratory tests that can be used to measure the success of the improvement. For the former, analytical studies will be conducted in which various soil improvements will be modeled to determine the difference between the response of the improved and the unimproved site. Actual performance data, to the extent available, also will be collected. For the latter, various test methods will be examined, including in-situ tests (SPT, CPT, geophysical, ambient vibration effects) which can determine the change in soil density and possibly shear strength, and laboratory tests on undisturbed samples (as feasible).

Recent Results
New project late 1992.

Management of the Interagency Committee on Seismic Safety in Construction (ICSSC)

Principal Investigator:
Diana Todd
Structures Division
301-975-5296

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

Objective
The objective of this project is 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. Thirty Federal departments and agencies participate in 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 developing seismic evaluation and rehabilitation standards for existing Federally owned and leased buildings.

Approach
NIST schedules and chairs at least two annual meetings of the Full Committee and at least one annual meeting of the Steering Committee. BFRL develops the meeting agendas and minutes, maintains membership rosters, and performs administrative tasks as needed to maintain this Committee.

NIST, working with ICSSC's Subcommittee 1 and Full Committee, will develop consensus seismic standards for assessment and rehabilitation of existing Federally owned and leased buildings.

Recent Results
Council of American Building Officials, *Assessment of the Seismic Provisions of Model Building Codes*, NIST GCR 91-598, National Institute of

Standards and Technology, Gaithersburg, MD, July 1992.

Todd, Diana and Bieniawski, Ann, Eds., *Guidelines and Procedures for Implementation of the Executive Order on Seismic Safety of New Building Construction*, NISTIR 4852, National Institute of Standards and Technology, Gaithersburg, MD, June 1992.

National Conference of States on Building Codes and Standards, *Seismic Provisions of State and Local Building Codes and Their Enforcement*, NIST GCR 91-599, National Institute of Standards and Technology, Gaithersburg, MD, June 1992.

Development of Standards for Existing Federal Buildings

Principal Investigator:
H.S. Lew
Structures Division
301-975-6061
Diana Todd
Structures Division
301-975-5296

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

Objective
The objective of this project is 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 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. 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

Dagenkolb, H.J. Associates, Engineers, Rutherford & Chekene, Consulting Engineers, *Proceedings: ICSSC Issues Workshop, Development of Seismic Evaluation and Rehabilitation Standards for Federally Owned and Leased Buildings*, NIST GCR 92-617, National Institute of Standards and Technology, Gaithersburg, MD, October 1992.

Plan for Developing and Adopting Seismic Design Guidelines and Standards for Lifelines

Principal Investigator:
Riley M. Chung
Structures Division
301-975-6062

Sponsor:
National Institute of Standards and Technology
and
Federal Emergency Management Agency
Office of Earthquakes and Natural Hazards

Objective

To develop a National Plan, including technical issues, organizational requirements, timetable, and budget, for developing and adopting seismic design guidelines and standards for lifelines.

Problem

Lifelines are public works and utilities systems that support human activities. Lifeline systems include electrical power, gas and liquid fuels, telecommunications, transportation, and water supply and sewers. These systems are vulnerable to earthquakes. At least 39 of the 50 States are subject to severe or moderate earthquake hazards. Assessment of earthquake hazards indicate that one or more server earthquakes can be expected to strike U. S. metropolitan areas in the next decade.

While loss of life and property damage would be confined within an earthquake's felt area, economic losses, particularly those caused by the failure of lifeline systems, are widely spread throughout the nation as the result of the nation's close interdependency of its commerce activities. Public Law 101-614 mandated that NIST, working with FEMA, would create a Plan for developing and adopting seismic design and construction standards for lifelines. The Plan will be reviewed by FEMA, the NEHRP Advisory Committee, the ICSSC, and OMB as it is completed for submittal to Congress.

Approach

BFRL has worked with private sector experts through a Steering Group, conducted a September 1991 lifelines workshop, and prepared a first draft of the Plan in the spring 1992 for review by FEMA and the NEHRP Advisory Committee. The draft

incorporates comments of the Advisory Committee; a revised version is being reviewed by the Advisory Committee. It is expected that the proposed Plan will be forwarded to OMB in February and to Congress in the spring of 1993.

The Plan represents the consensus recommendations of the Federal agencies and the private sector recommendations for developing and adopting seismic design guidelines and standards for lifelines. Two reports will be published in the summer of 1993: 1. *Proceedings of the September 1991 Workshop on Lifelines*, and 2. *A Plan for Developing and Adopting Seismic Design Guidelines and Standards for Lifelines*.

Recent Results
Developed draft National Plan on seismic design guidelines and standards for lifelines.

UJNR Bridge Workshop

Principal Investigator:
H.S. Lew
Structures Division
301-975-6061

Sponsor:
Federal Highway Administration
Office of Engineering and Highway Operations
Research and Development

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 was planned and held at Tsukuba, Japan in May 1993.

Recent Results
New project 1993.

Geotechnical Evaluation for Lifelines

Principal Investigator:
Steven Glaser
Structures Division
301-975-6051
Felix Y. Yokel
Structures Division
301-975-6065

Sponsor:
National Institute of Standards and Technology

Objective
To assess and propose improved methods of site exploration and predictive models for large earthquake-induced ground displacements and their effect on lifelines.

Problem
Lifeline systems are vulnerable to large earthquake-induced ground displacements, such as those associated with liquefaction, land slides, slope failures and fault displacements. They also are vulnerable to pressure gradients and particle migration associated with liquefaction. Many older lifeline systems deteriorated by corrosion and other aging effects are especially vulnerable. As new lifeline systems become more complex, their vulnerability often is increased. While in most instances it is feasible to locate critical structures and support facilities on sites which are not susceptible to large ground displacements, similar precautions are not always possible for long linear system elements such as pipelines, communication and electrical transmission lines, highways, and rail lines. To design lifelines that resist or accommodate large ground displacements, it is necessary to map the location of critical areas and reasonably estimate the magnitudes of anticipated displacements.

Approach
Two aspects of this problem are of general interest: identification of vulnerable sites; and quantification of displacements which are potentially harmful to lifelines. The study approach will have two components: (1) assessment and refinement of soil exploration methods; and (2) assessment of models for predicting ground displacements.

Initially, the emphasis in this research is on liquefaction and its effects. Liquefaction potential may be ascertained by in-situ exploration methods such as SPT, CPT and SASW. BFRL will consider the possibility of applying system identification methods, such as those recently used by BFRL in a study of building response in the San Francisco Bay area, and consider state-of-the-art geophysical methods. BFRL will refine instrumentation, developed in a previous study, to measure forces and velocities in the drill rod below the anvil in the SPT. The instrumentation will be used in field studies conducted by others to determine whether the added information on the load-displacement function at the lower end of the rod can be used to improve the prediction of liquefaction potential and effects. The results of this work will provide sound estimates of actual performance of liquefiable sands during earthquake loading.

Recent Results
Glaser, Steven, D., *Estimating Soil Parameters Important for Liquefaction Siting Using Identification Techniques*, NISTIR 5143, National Institute of Standards and Technology, Gaithersburg, MD, March 1993.

Glaser, Steven, D., "Estimation of Soil Parameters Using System Identification Theory," *ASCE Journal of Geotechnical Engineering*, submitted February 1993.

Secretariat U.S.-Side Panel on Wind and Seismic Effects

Principal Investigator:
Noel J. Raufaste
BFRL Headquarters
301-975-5905

Sponsor:
National Institute of Standards and Technology
and
10 Federal Agencies

Objective
To provide the U.S. Secretariat of the U.S.-Japan Panel on Wind and Seismic Effects.

Problem
Loss of life and property from high winds and seismic loads often result from inadequate knowledge to cost-effectively design and construct buildings and other structures. The development of improved mitigation practices are in its early stages of development. Technical collaborations between experts in the United States and Japan need to continue to realize improvements in knowledge of natural hazard mitigation practices. Such improvements are possible through joint working relations with such experts through performing joint research projects and exchanges of research personnel, technical data and information, and research equipment. This Panel is part of the U.S.-Japan Natural Resources Development Program under the aegis of the U.S.-Japan Cooperative Science Program of 1961.

Approach
1. Planning U.S.-side activities (20 Agency membership), hosting two U.S. Panel's domestic meetings, and managing the U.S. delegation's technical contributions to Annual Joint Meetings.

2. Planning and coordinating technical activities of the Panel's 10 Task Committees.

3. Maintaining liaison with U.S. and Japan Panel members and other experts associated with the Panel's activities.

4. Preparing and distributing periodic activities reports and publishing annual Proceedings and other materials as appropriate for distribution to U.S.-side Panel members and users of such knowledge.

The Panel's generated data influences on-going U.S. and Japan structural engineering research, influences BFRL's structural engineering program planning, and guides improvements of building codes and standards of both countries. Data has advanced technologies in the areas of steel structures under seismic forces, large-scale testing of masonry structures, soil dynamics and liquefaction, large-scale bridge piers subjected to seismic loads, ground motion, pavements, and dynamic stability of embankment dams.

Recent Results
Raufaste, Noel J., *Wind and Seismic Effects, Proceedings of the 24th Joint Meeting*, NIST Special Publication 843, National Institute of Standards and Technology, Gaithersburg, MD, September 1992.

Tokida, Ken-ichi and Raufaste, Noel J., *List of Publications 1969-1991, Panel on Wind and Seismic Effects*, NIST Special Publication 835, National Institute of Standards and Technology, Gaithersburg, MD, April 1992.

Raufaste, Noel J. (Ed), *Earthquake Resistant Construction Using Base Isolation Volumes 1 and 2*, NIST Special Publication 832 Vol 1 & 2, National Institute of Standards and Technology, Gaithersburg, MD, April 1992.

STRUCTURES
DIVISION

STRUCTURAL BEHAVIOR

Nonlinear Chaotic Behavior of Dynamic Structural Systems

Principal Investigator:
Emil Simiu
Structures Division
301-975-6076

Sponsor:
National Institute of Standards and Technology

Objective
To develop a computational and experimental basis for the study of nonlinear and chaotic phenomena 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 earlier in this project, it will be shown that certain noise-driven stochastically unstable motions may be approximated arbitrarily by deterministic chaos orbits. The study will be conducted for oscillators whose unperturbed counterpart exhibits homo- and herteroclinic orbits and will make use of the generalized Melnikov distance, the attendant traveling horseshoe sequence concept, and the estimation of transport across pseudo-separatrices via one-sided flux. The approach will be developed by Gaussian and Non-Gaussian noise. The identity of the results obtained by this approach and by the Fokker-Planck approach will be verified in a canonical case.

Recent Results
Simiu, Emil and Grigoriu, M., "Non-Gaussian Noise Effects on Reliability of Multistable Systems," submitted to 12th International Conference on Offshore Mechanics and Arctic Engineering, June 1993.

Frey, E. and Simiu, Emil, "Noise-Induced Chaos and Phase-Space Flux," *Physica D Nonlinear Phenomena*, February 1993.

Simiu, Emil and Cook, Graham, "Empirical Fluid-elastic Models and Chaotic Galloping: A Case Study," *Journal of Sound and Vibration*, Vol. 154, No. 1, pp. 45-66, 1992.

Frey, E. and Simiu, Emil, "Deterministic and Stochastic Chaos," Computational Stochastic Mechanics, Cheung and Yang, eds. Elsevier (submitted Dec. 1992)

Simiu, Emil and Frey, E., "Melnikov Function and Homoclinic Chaos Induced by Weak Perturbations," *Physical Review A15*, in review.

Simiu, Emil and Frey, E., "Noise Modeling and Reliability of Behavior Prediction for Multi-Stable Hydroelastic Systems," *Proceedings of the 11th International Conference on Offshore Mechanics and Arctic Engineering*, June 1992.

Simiu, Emil and Frey, E., "Equivalence Between Motions with Noise-Induced Jumps and Chaos with Smale Horseshoes," *Engineering Mechanics, Proceedings of the Ninth Engineering Mechanics Conference*, ASCE, May 1992.

Design Wind Load Criteria for Manufactured Housing in Hurricane Zones

Principal Investigator:
Richard D. Marshall
Structures Division
301-975-6071

Sponsor:
Department of Housing and Urban Development
Office of Policy Development and Research
Innovative Technology Division

Objective
To develop revised wind load criteria for the design of manufactured housing intended for hurricane regions.

Problem
The Manufactured Home Construction and Safety Standards (CFR Pt. 3280) were implemented in 1976. Section 3280.305 contains structural design requirements which include the effects of live loads, wind, and snow loads. Paragraph (c)(2) defines the designation Hurricane Resistive (Zone II) and requires that the home and each wind resisting part and portion thereof be designed for horizontal wind loads of not less than 25 psf (1.20 kPa) and net uplift of not less than 15 psf (718 Pa). Experience in South Florida and Louisiana during Hurricane Andrew suggests that these wind load requirements may not adequately describe the forces that a manufactured home is likely to experience in a hurricane. There is a need to critically examine the wind load requirements of CFR Pt. 3280 in light of this experience and develop revised wind load criteria which will improve the performance of manufactured homes in hurricane winds.

Approach
During FY 1993, BFRL will perform the following:

1. Review the current CFR wind load requirements in light of the corresponding provisions of the South Florida Building Code and ASCE 7-88 (Minimum Design Loads for Buildings and Other Structures).

2. Provide HUD with recommendations on issuance of interim wind load design criteria.

3. Assemble data on damage to manufactured housing units in the path of Hurricane Andrew and document the surface wind speeds associated with the passage of Andrew across South Florida.

4. Develop revised design wind load requirements based on existing data from full-scale and wind tunnel model studies. The revised criteria will address the effects of wind exposure, blockage, and channeling, and will address overall forces, internal pressures, and wind pressures on tributary areas.

5. Review the relevant structural load tests described in CFR Pt. 3280 and outline a program for the development of test methods that will ensure compliance with the revised wind load design requirements.

6. Prepare a report of findings and recommendations.

Recent Results
New project 1993.

Calibration of Marshall Compaction Hammers

Principal Investigator:
Harry Shenton
Structures Division
301-975-6067

Sponsor:
Federal Highway Administration
Office of Engineering and Highway Operations
Research and Development
Pavements Division

Objective
To develop a practical testing apparatus which can be used to "calibrate" mechanical hammers used in the Marshall asphalt mix design procedure.

Problem
The Marshall test procedure is currently used by most state and local highway agencies for asphalt mix design. The first step in the procedure consists of compacting mix specimens using a manual or mechanically operated Marshall compaction hammer. Tests are then performed on the compacted specimen to establish various design parameters. The results of many round-robin mix exchange programs has shown there to be a wide variation in mix design parameters when a given mix is compacted with different compaction hammers. Several hammer-related variables have been found to play a key role in influencing Marshall test results, a few include: pedestal support, hammer alignment, hammer mass and friction. A method for quantifying the effect of key equipment-related variables is needed, so a "standard" level of energy can be delivered to specimens using different compaction hammers. The desirable method should include the following attributes: simple to use, robust calibration device, suitable for a laboratory or field environment, and a calibration procedure.

Approach
Conduct a literature search to establish the state-of-knowledge on the effect of hammer-related variables on test result inconsistencies. Conduct a limited experimental investigation to determine the load-deformation and energy absorption characteristics of four typical asphalt mix designs. Based on the literature search and experimental investigation, one or more initial design concepts for the calibration device will be developed and presented to the Federal Highway Administration (FHWA) for review. The prototype calibration device will be fabricated and assembled into a testing equipment package. A calibration procedure will be established for adjusting the number of blows for a given set of Marshall equipment so a "standard" level of energy can be imparted to test specimens. BFRL will perform laboratory evaluation of the device by calibration under simulated conditions, similar to those determined from test result inconsistencies. Results will be documented in a final report and the prototype device delivered to the FHWA.

The results of this work are expected to provide more uniform asphalt pavement designs and higher quality pavements.

Recent Results
New project late FY 1992.

BUILDING MATERIALS
DIVISION

CONCRETE

High Performance Concrete

Principal Investigator:
Nicholas Carino
Structures Division
301-975-6063
James R. Clifton
Building Materials Division
301-975-6707

Sponsor:
National Institute of Standards and Technology

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

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 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 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 (HPC) technology. U.S leadership in high-performance concrete technology can be a major contributor to enhancement of the competitiveness of the nation's construction industry. As the Nation's central building research organization, BFRL is in a unique position to provide a focus for the development of high-performance concrete technology.

Approach
This multi-year 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. proportioning and mixing HPCs; 2. evaluating the physical properties and durability of HPC; 3. performing structural design with HPC; and 4. performing field construction with HPC. Two of the urgent needs identified at the NIST/ACI Workshop held in May 1990 were (1) information on the mechanical and physical properties of HPC, and (2) information on the durability of HPC compared with conventional concrete.

BFRL's research in FY 1991 included determining the applicability of the maturity method to HPC. In FY 92, work was initiated on developing a basis for standards for compressive strength testing of HPC and on determining the applicability of standard frost resistance tests for conventional concrete to HPC. The frost resistances of HPC and neat cement specimens with a water-to-solids (w/s) ratio of 0.38 were studied using ASTM C 666, "Resistance of Concrete to Rapid Freezing and Thawing." The effects of curing ages, between 1 and 91 days, and curing conditions were investigated. Also, different methods for measuring the rate of degradation were investigated. The results suggest that if non-air entrained HPCs are given a season of curing, they may have adequate frost resistance and that the curing time (14 days) in ASTM C 666 is not adequate for evaluating HPCs. In FY 1993, BFRL will evaluate the frost resistance of non-air entrained HPC with a w/s of 0.28. In these studies, relationships between degree of hydration, pore structure, and air bubble spacing of HPC and frost resistance are being investigated. These tasks will be completed in FY 1993. The work on standards for compressive strength testing of HPC involves a factorial design with five variables; HPC strength, test cylinder size, capping material and method, testing machine, and rate of loading. Based on the results of these tests, recommendations will be made for modification of ASTM Standards to improve test reliability.

In FY 1992, BFRL was given the responsibility by the ASCE's Civil Engineering Research Foundation (CERF) for leading the development of a national research plan for high-performance concrete and steel. Two working sessions, one on concrete and the other on steel, were held at NIST for the purpose of developing the plan. Participants in the working sessions were from academia, industry, and governmental agencies. The national plan will be submitted to CERF in FY 1993.

Recent Results
Carino, Nicholas J., Knab, Lawrence I., and Clifton, James R., *Applicability of the Maturity*

Method to High-Performance Concrete, NISTIR 4819, National Institute of Standards and Technology, Gaithersburg, MD, May 1992.

Stutzman, Paul E. and Clifton, James R., "Microstructural Features of Some Low Water/Solids, Silica Fume Mortars Cured at Different Temperatures," *Proceedings of 14th International Conference on Cement Microscopy*, International Cement Microscopy Association, 1992.

Transport Properties of Porous Media

Principal Investigator:
Edward Garboczi
Building Materials Division
301-975-6708

Sponsor:
National Institute of Standards and Technology

Objective
To develop and apply analytical and computer simulation models that predict the microstructure-property relationships of porous materials like hardened cement paste and concrete, and apply these relationships to the problem of service life.

Problem
The degradation of the concrete infrastructure, worth on the order of 6 trillion dollars, is a huge national problem. The basic physical and chemical mechanisms of degradation processes in concrete need to be understood before scientifically sound, nonempirical service life predictions can be developed. Most degradation processes that affect cement-based materials involve microstructure-property relationships for properties like diffusivity, permeability, and elastic moduli. Fundamental computer-based models are necessary to quantitatively relate such properties to the complex microstructure of cement-based materials. Such quantitative relationships will serve to put existing and future standard test measurements of transport and other properties on a firm theoretical foundation.

Approach
BFRL, using its 3-D digital-image-based model, is simulating the microstructure of cement paste (bulk paste or interfacial zone paste). Once a microstructure is created, algorithms are applied to compute desired transport properties. Improvements are pursued in microstructural simulation, and in 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 Results

Bentz, Dale P., Stutzmann, Paul A., and Garboczi, Edward J., "Computer Modeling of the Interfacial Zone in Concrete," *Interfaces in Cementitious Composites*, E & FN Spoon, London, pp 107-116, 1993.

Bentz, Dale P. and Garboczi, Edward J., *Guide to Using HYDRA3D: A Three Dimensional Digital-Image-Based Cement Microstructural Model*, NISTIR 4746, National Institute of Standards and Technology, 1992.

Martys, Nicos and Garboczi, Edward J., "Length Scales Relating Fluid Permeability and Electrical Conductivity in Random 2-D Porous Media," *Phys. Rev. B:*, 46, pp 6080-6090, 1992.

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 Northwestern University, are, for the first time, enabling 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 depends on the digital-image-based microstructural model developed by BFRL. This model gives a three-dimensional 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. This work is performed using NIST's Cray-YMP and Convex 3820 computers and BFRL's Convex C120 and SUN Galaxy computers. A microstructure is built up using the growth rules of the model and a transport algorithm is applied to calculate a quantity that can be compared with experimental measurements.

Recent Results

Coverdale, R.T., Garboczi, Edward J., Jennings, Hamlin M., Christensen, B.J., and Mason, T.O., "Computer Simulation of Impedance Spectroscopy in Two Dimensions: Application to Cement Paste," *J. Amer. Ceram. Soc.*, (in press).

Bentz, Dale P., Stutzman, Paul A., and Garboczi, Edward J., "Experimental and Simulation Studies of the Interfacial Zone in Concrete," *American Concrete Research*, 22, pp 891-902, 1992.

Christensen, B.J., Mason, T.O., Jennings, Hamlin M., Bentz, Dale P., and Garboczi, Edward J., "Experimental and Computer Simulation Results for the Electrical Conductivity of Portland Cement Paste," *Advanced Cementatious Systems: Mechanisms and Properties*, Materials Research Society, Pittsburgh, PA, pp 259-264, 1992.

Development of Microstructure and Permeability in Mortar and Concrete

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 study interphase regions in polymer-modified cement-based materials and develop rheological simulations for processing of cement-based composite materials.

Problem

The durability of polymer-modified cement-based materials like macro-defect-free (MDF) materials is limited by their sensitivity to moisture. Experimentally, the interphase region, a region where polymer and hydration products are intimately mingled that surrounds the unhydrated grains, has been shown to play a primary role in this moisture sensitivity. The percolation aspects of the interphase region will determine if the moisture sensitivity is localized and limited, or widespread and pervasive. The rheological properties of MDF materials and ordinary cement-based materials determine their processability. Their rheology is complicated, as their microstructure is complex and time-dependent.

Approach

During FY 1993, BFRL will study the moisture sensitivity problem in MDF, a transport property problem, using the interfacial zone percolation model developed in FY 1992. The percolation aspects of the interphase regions can be computed for any experimentally determined particle size distribution. The finite-element-based digital image elastic code will be generalized to allow for complex moduli and displacements, so time-dependent bulk complex moduli of complex suspensions, like those found in the processing of cement-based materials, can be computed.

Recent Results

Snyder, Kenneth A., Winslow, D.N., Bentz, Dale P., and Garboczi, Edward J., "Interfacial Percolation in Cement-Aggregate Composites," *Interfaces*

in Cementitious Composites, E & FN Spoon, London, pp 259-268, 1993.

Cementitious Materials Modeling Laboratory (CMML)

Principal Investigator:
Lawrence Kaetzel
Building Materials Division
301-975-5912

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

Objective
To advance the science of Cementitious Materials Research through developing, archiving, and distributing computer based models, standard formats, and other forms of knowledge (data-bases, 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 leads to collaboration between cementitious materials researchers in planning research to fill the gaps. Knowledge systems are being developed using protocols for developing and interfacing subsys-tems. 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 re-sources (computers, staff, networks), and devel-oping and publishing protocols and guidelines for models and experimental data. BFRL is perform-ing 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.

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 on 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
Published two issues of the Cementitious Materials Modeling Laboratory (CMML) newsletter, *CMML Newsletter*, Center for ACBM, Northwestern University, Evanston, IL 60208, Fall 1991 and Summer 1992.

Conducted the fourth annual computer modeling workshop, July 1992 with participation from academia and industry.

Whole-Pattern Fitting Methods for Quantitative X-Ray Powder Diffraction Analysis of Clinker and Cement

Principal Investigator:
Paul Stutzman
Building Materials Division
301-975-6715

Sponsor:
National Institute of Standards and Technology

Objective
To apply and test whole-pattern fitting routines to determine phase abundance of clinker and cement by x-ray powder diffraction and evaluate the technique to develop a standard test method or recommended practice.

Problem
Improved methods of characterization of clinker and cement are necessary for advances in cement and concrete technology and to aid in the prediction of the performance of concrete-making materials and concrete. X-ray powder diffraction is commonly used for phase analysis and is the only method for quantitative phase abundance analysis of fine-grained materials. While numerous schemes exist, there is no standard method for quantitative analysis by x-ray powder diffraction. Current techniques require decomposition of any peak overlaps, measurement of peak intensities, and calibration curves relating peak area ratios to concentration. Clinker and cement diffraction patterns are difficult to process because of severe overlapping of most of the intense diffraction peaks, leaving a few very low intensity peaks which are subject to particle orientation, counting and measurement errors.

Approach
This project involves four phases:

1. Obtain source code for the whole-pattern fitting procedure from The Pennsylvania State University, install the code, and, if necessary, modify the code to suit requirements.

2. Identify and procure phases and their polymorphs for calibrations.

3. Establish calibrations for each of the standard phases.

4. Test the method and calibrations with synthetic mixtures of known phase abundance composition and samples of the NIST Reference Material Clinkers to establish accuracy, precision, and detection limits.

The results will be presented to ASTM Task Group C01.23.01 on quantitative x-ray powder diffraction methods as a potential test method or recommended practice for phase abundance analysis of clinker and cement.

Recent Results
New project 1993.

Performance Criteria for Long Lived Concrete for Radioactive Waste Storage

Principal Investigator:
James R. Clifton
Building Materials Division
301-975-6707

Sponsor:
U.S. Nuclear Regulatory Commission
Waste Management Branch

Objective
To develop performance criteria for selecting concretes to be used in constructing structures with 500 year safe 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. 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.

Approach
In this multi-year project, the development of performance criteria involves 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.

BFRL's work performed during FY 1988 through FY 1992 included:

1. Identification of likely degradation processes and analyses of their mechanisms and potential rates.

2. Development of mathematical models of transport processes in concrete involving moisture, chloride ions, sulfate ions, and acids.

3. Experimental studies of chloride ion diffusion in cement pastes.

4. Evaluation of a new test method for determining the potential alkali-reactivity of siliceous aggregates.

5. Evaluation of the reliability of existing test for predicting the sulfate resistance of concrete exposed to ground water, and the development of a new cyclic wet-dry sulfate test.

BFRL's work in FY 1993 consists of completing the development of models for predicting the performance of concrete exposed to sulfate-containing ground waters. The models will consider the tricalcium aluminate contents of the cement and the concentration of sulfate in the ground water, and predict the rate of expansion. Simulation modeling will be undertaken to develop a basis for predicting the diffusivity of sulfate ions in concrete and the stresses developed by the formation of ettringite. Also, the effects of the pH of soil/groundwater on the rate of expansion will be determined by controlled pH studies. These activities will contribute to the development of an improved basis for predicting the service life of concrete exposed to sulfate-containing soils and groundwaters.

Also, BFRL will investigate the effects of microcracks on the transport properties of concrete. Both experimental studies and simulation modeling will be performed. Also, the possibility of the microcracks being sealed, e.g., by the hydration of unreacted cement will be investigated. The study on cracks will extend through FY 1994.

Recent Results

Philip, Jacob and Clifton, James R., "Nuclear Waste: An Overview," *Proceesings of Fly Ash, Silica Fume, Slag, and Pozzolans in Concrete*, 4th International Conference, Istanbul, Turkey, pp 713-730, May 1992.

Concrete Degradation Computer Code for LLW Performance Assessments

Principal Investigator:
James R. Clifton
Building Materials Division
301-975-6707

Sponsor:
U.S. Nuclear Regulatory Commission
Waste Management Branch

Objective

To develop computer models of concrete degradation to assess the performance of underground reinforced concrete structures used for disposing low-level radioactive wastes (LLW).

Problem

Reinforced concrete has been proposed by many states and compacts of states for the construction of engineered barriers for the disposal of low-level radioactive wastes (LLW). To meet the requirements of the Federal regulations for LLW disposal, 10 CFR 61, the concrete structures must demonstrate specific durability and performance attributes for periods of 300 to 500 years. The Nuclear Regulatory Commission (NRC) will be responsible for determining if proposed disposal facilities meet the requirements set forth in 10 CFR 61. To provide guidance to state and compact LLW personnel in designing LLW disposal concrete structures, the Nuclear Regulatory Commission is developing a Branch Technical Position/Regulatory Guide for LLW performance assessments. The assessment will include the use of models for predicting the effect of degradation processes on the properties of the concrete used in constructing LLW disposal vaults. The models need to be able to predict changes in the hydraulic properties of the concrete during 300 to 500 years of service.

Approach

BFRL is developing computer models for predicting the life of concrete used in the construction of underground vaults. The vaults are designed to contain low-level radioactive waste. BFRL is performing a companion project on Performance Criteria for Long Lived Concrete for Radioactive Waste Storage which will complement this work through development of prediction models.

The degradation processes which will be addressed by the models include corrosion of reinforcement, frost attack (possible before a vault is covered with earth) leaching, and sulfate attack. Effects of concrete degradation on its hydraulic properties will be predicted by linking the degradation models with Darcy's equation for hydraulic flow. Existing degradation models will be analyzed to determine if they are adequately reliable or can be satisfactorily modified. If necessary, new models will be developed. The models will be deterministic. The potential effects of intrinsic cracking such as plastic shrinkage, plastic settlement, early thermal cracking, and drying shrinkage on hydraulic properties will be considered. A user friendly, interactive computer code of the concrete degradation models for LLW performance assessment will be developed. The compiled code will be capable of being run on a micro-computer by the NRC staff. A manual will be prepared and training exercises will be conducted to assist NRC staff and state and compact personnel in using the computer models. The final report is expected in September 1994; it will provide recommendations on further model developments and their validation.

Recent Results
New project 1993.

Cracking in Parking Garage MLP-7A at NIH

Principal Investigator:
James R. Clifton
Building Materials Division
301-975-6707

Sponsor:
National Institutes of Health
Public Health Service

Objective
To verify the processes responsible for cracking in NIH parking garage MLP-7A and recommend actions for preventing further deterioration.

Problem
Significant map cracking has developed in the NIH parking garage MLP-7A, which appears to be caused by alkali-silica reactions (ASR). If the cracks are caused by ASR, it is likely that they will continue to develop and grow, possibly eventually affecting the structural integrity of the parking garage. NIH has requested BFRL's technical assistance to verify the occurrence of ASR and assessing the potential for further cracking. If there is a potential for further cracking, BFRL will advise as to whether there are ways of preventing it.

Approach
During FY 1993, BFRL will perform three tasks:

1. Perform petrographic examination of distressed concrete to verify the occurrence of ASR and determine if other degradation processes are occurring.

2. Evaluate the potential for further expansion and investigate the possible use of surface treatments to prevent the movement of moisture into the concrete.

3. Assess the condition of garage's concrete structural elements using non-destructive techniques.

Recent Results
New project 1993.

BUILDING MATERIALS
DIVISION

COATINGS

Modeling the Degradation of High-Performance Organic Protective Coating Systems

Principal Investigator:
Tinh Nguyen
Building Materials Division
301-975-6718

Sponsor:
National Institute of Standards and Technology

Objective
To provide scientific and technical basis for standards on high-performance coatings for steel used in buildings and other construction.

Problem
Corrosion-related problems in the United States are estimated to cost 4.2% of the gross national product, or about $220 billion in 1992. 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, including transport of aggressive species 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 will provide the basis for improved standards for high-performance coatings used to protect steel structures.

Approach
BFRL is developing and validating models to predict service life and other aspects of performance. This work consists of six tasks:

1. Develop conceptual models.

2. Verify degradation mechanisms.

3. Quantify the transport properties of environmental elements through the coatings and along the coating/metal interface.

4. Develop improved methods to characterize coating, its properties and reactions that control the degradation.

5. Develop and validate mathematical models for predicting service life using laboratory and field data.

6. Implement new knowledge developed in the above tasks through incorporation into new standards and through other appropriate means.

BFRL's research in FY 1993 will include:

1. Developing a mathematical model that describes the formation and growth of blisters formed due to corrosion reactions.

2. Developing a technique to measure the transport of water through a high-performance coating on a metal substrate.

3. Initiate research on characterizing microstructure and defects in a high-performance coating and at the coating/metal interface.

Defects in coatings and at the coating/metal interface are probably the sites of corrosion and blistering initiation. BFRL will continue implementing its research findings into practice through ASTM D-1 and other means of technology transfer.

Recent Results
Nguyen, Tinh, Byrd, Eric, and Bentz, Dale, "Quantifying Water at the Polymer/Substrate Interface," *Proc. Am. Chem. Soc.*, Vol. 66, 414, August 1992.

Nguyen, Tinh, Hubbard, J., and Pommersheim, James, "Mathematical Models for the Degradation of Intact Coatings on Steel in Electrolyte Solutions," *Proc. Am. Chem. Soc. Meeting*. Polymeric Materials Science and Engineering Division, Washington, D.C, August 24, 1992.

Nguyen Tinh, "Thermal-Wave Microscopy in Corrosion Studies," *Materials Characterization*, 28, 1044, June 1992.

Lin, C. and Nguyen, Tinh, Relation between AC Impedance Data and Degradation of Coated Steel. 1. Effects of Surface Roughness and Contamination on the Corrosion Behaviors of Epoxy Coated Steel, *Progress in Organic Coatings*, 20, 169, June 1992.

Pommersheim, James, Nguyen, Tinh, Hubbard, J., and Lin, C., *A Mathematical Model of Cathodic*

Delamination and Blistering Processes in Paint Films on Steel, Technical Note 1293, National Institute of Standards and Technology, May 1992.

Hubbard, Joseph B. and Nguyen Tinh, "A Model of Defect-Mediated Transport through Amorphous Membranes," *J. Chem. Physics*, 96, 3177, February 1992.

Developed a mathematical model for the transport of cations along the coating/metal interface from a defect in the absence of an applied potential. This model describes the delamination and blistering near a defect at the very early stage. Experiments carried out to test the models showed good agreement with model results.

Developed a novel spectroscopic technique for measuring cation *in-situ* at the coating/metal interface.

Coating Technology Consortium

Principal Investigator:
Geoffrey Frohnsdorff
Building Materials Division
301-975-6706

Sponsor:
National Institute of Standards and Technology

Objective
To advance coating technology by developing technologies, methodologies, and procedures for: characterizing, measuring, modeling, and controlling incoming materials and the painting process, and defining, measuring, standardizing appearance, and other quality attributes of the finished product.

Problem
The manufacturing processes of many U.S. industries include application of organic coatings. For coatings, as for other processes, international competition and the national agenda require that industry improve quality, reduce costs, reduce environmental effects, and reduce the time required to transfer new technology to practice. To help insure the competitiveness of U.S. industries that use coating technology, an industry/government consortium needs to be created to leverage national resources in advancing the technology.

Approach
The Coating Technology Consortium, under formation, will begin with five projects to be carried out over a four-year period at an estimated cost of $2.8 million. BFRL and four other NIST Laboratories will partner with about five industrial participants including Ford Motor Corporation, General Motors Corporation, and PreFinish Metals. These projects will focus on measurement technology that will enhance customer satisfaction and reduce manufacturing costs. This work includes the following:

1. Development of definitions of visual appearance attributes which are measures of the quality of the end product; the project focuses on the basic question of what defects a person can see when looking at a coated surface and will develop a psychophysical scale for the quantification of visible defects. The project also will establish

correlations between the psychophysical scale and an objective physical scale.

2. Wet-film thickness measurement of single- and multi-layered coating systems on metallic substrates; the project will provide a new measurement method for use in control of the coating process. This work addresses the development of a non-contact method for determining wet-film thickness.

3. Detection and quantification of defects in metallic substrates; this project concerns improvement in inspection of metal parts entering the coating operation through the development of a method for detecting defects in the metal.

4. Determination of the degree of curve of a coating; this project will provide a method for on-line determination of the degree of curve.

5. Survey of new developments in instrumentation and measurement technology with potential use in control of coating processes; this project will provide information to guide future research and development activities of the Consortium.

Recent Results
New project 1993.

Method for Measuring Water Stripping Resistance of Asphalt/Siliceous Aggregate Mixtures

Principal Investigator:
Tinh Nguyen
Building Materials Division
301-975-6718

Sponsor:
National Academy of Sciences
National Research Council
Transportation Research Board

Objective
To develop a method for measuring water stripping resistance of asphalt/aggregate mixtures.

Problem
The debonding of asphalt from mineral aggregates in the presence of water (commonly known as stripping) has been a problem since asphalt paving came into existence. Many studies have sought a solution to the problem, but it continues to occur. In recent years, there are more frequent premature failures of pavements due to stripping. When asphaltic concretes fail, they require large replacement costs. These costs could be reduced if there were effective methods for evaluating stripping resistance of asphalt/aggregate mixtures prior to use.

Approach
During FY 1993, BFRL will perform this work in two parts:

Part 1 involves the development of a test method for measuring the bond strength of an asphalt on an aggregate exposed to water. Two tasks will be performed:

1. Optimize film thickness for testing the bond strength of asphalt on an aggregate in water.

2. Test the stripping characteristics of four Strategic Highway Research Program (SHRP) asphalts on glass and granite substrates by using the optimum thickness obtained in Task 1.

Part 2 is the development of a nondestructive method for screening the stripping resistance of asphalts on a siliceous aggregate. Three tasks make up this work:

1. Study the *in-situ* measurement and quantification of water at the asphalt/aggregate interface of four SHRP asphalts, but for a thicker asphalt film than previously studied. This study utilizes FTIR-multiple internal reflection spectroscopy.

2. Determine the relationship between the results of Task 2 of Part 1 and Task 1 of Part 2. This relationship will be the framework for predicting the water stripping resistance of asphalt/siliceous aggregate mixtures.

3. Evaluate the relative effectiveness of five commercial anti-stripping agents using a model aggregate and FTIR-multiple internal reflection spectroscopy.

It is expected the results of this research will provide designers and contractors with an ability to assess and evaluate the water susceptibility of asphalts, anti-stripping agents, aggregates, aggregate/asphalt mixtures, mixing temperatures, and deicing agents.

Recent Results
Nguyen, Tinh, Byrd, Eric, Bentz, Dale, and Seiler, James, *Development of a Technique for In Situ Measurement of Water at the Asphalt/Model Aggregate Interface*, NISTIR 4783, National Institute of Standards and Technology, Gaithersburg, MD, March 1992.

Organic Coatings

Principal Investigator:
Mary McKnight
Building Materials Division
301-975-6714

Sponsor:
Department of the Air Force
Civil Engineering Support Agency (AFCESA)

Objective
To develop improved procedures for selecting, using, and specifying coating systems for use by DoD coating maintenance divisions.

Problem
Military facilities have an estimated $300 billion real property value and the annual cost of coating maintenance is about $400 million. Improved and updated criteria for the selection, specification, and use of protective coatings is needed to take advantage of new technologies and meet environmental regulations, e.g., those relating to volatile organic compound content and abatement of hazards associated with lead in existing paint films.

Approach
BFRL is working with the Tri-Service Protective Coatings Committees to review and revise the Tri-Service Painting Manual. Three chapters will be revised and a chapter on environmental concerns, including those relating to lead paint abatement, will be developed. Documents developed by the Civil Engineering Support Agency on guidance for detection and abatement of lead-based paint will be reviewed. BFRL chairs the SSPC Committee on coatings and will assist in the development of a low VOC alkyd coating specification and a surface tolerant coating specification.

Recent Results
New project 1993.

Long-Term Performance of Polymer-Based Encapsulants for Lead-Based Paint on Interior Walls of Air Force Buildings

Principal Investigator:
Mary McKnight
Building Materials Division
301-975-6714

Sponsor:
Department of the Air Force
Civil Engineering Support Agency (AFCESA)

Objective
To determine changes in physical, chemical, and mechanical properties of coatings as a function of accelerated weathering exposure.

Problem
The U.S. Air Force uses approximately 140,000 family housing units built prior to 1978. Assume that the fraction of these units containing lead-based paint is the same (0.75) as was identified by the U.S. Department of Housing and Urban Development in the survey of the Nation's private housing. Then the initial abatement cost of walls and baseboards using encapsulants is estimated at about $500 million less than using replacement or removal procedures. Long-term performances of encapsulants are unknown. Before encapsulants are widely used on Air Force Facilities, it is essential that information about their long-term performance be available, since premature failure would be very costly.

Approach
During FY 1993, BFRL will develop a generally applicable method for predicting long-term performance of an encapsulant. The method would serve as the basis for performance-based selection criteria and life-cycle cost analyses. BFRL will estimate life-time performance from the results of short-term, statistically-designed accelerated tests using reliability theory. The steps involved in developing the model are: 1. conducting an experimental study that addresses manufacturer's claims, and 2. developing a methodology for service-life prediction and performance-based selection criteria, that serves as the basis for material specifications. In the experimental study, three generic types of commercial, polymer-based encapsulants, and a latex paint will be subjected to three temperatures 10, 25, and 50 °C at 50 percent relative humidity. Performance data on properties which are important to performance as an encapsulant, such as cracking and peeling (adhesion) resistances upon impact, abrasion resistance, glass transition temperature, weight loss (thermogravimetric analysis), modulus, and chemical stability (spectroscopy) will be obtained. The experimental study will determine relationships between changes in physical, chemical and mechanical properties of encapsulant coatings and time of exposure in controlled environments. The results of these screening-type experiments will be used in testing the validity of manufacturer's claims and in preparing the comprehensive plan.

A report will describe results of experimental work and provide a comprehensive research plan and method serving as the basis for selection criteria for predicting long-term performance of lead-based paint encapsulants on interior walls.

Recent Results
New Project 1993.

Long-Term Performance of Polymer-Based Encapsulants for Lead-Based Paint on Interior Walls of Army Buildings

Principal Investigator:
Mary McKnight
Building Materials Division
301-975-6714

Sponsor:
Department of the Army
Engineering Housing and Service Center

Objective
To develop selection criteria for predicting long-term performance of lead-based paint encapsulants on interior walls.

This research complements and extends the Air Force sponsored research on this subject previously described.

Problem
The Department of Defense (DoD) uses approximately 500,000 family housing units that were built prior to 1978; many are likely to have surfaces coated with lead-based paint. Based on a recent U.S. Department of Housing and Urban Development report, the DoD should obtain significant cost savings if encapsulants can be used to abate surfaces with lead-based paint as compared with removal. However, before encapsulants are widely used on DoD Facilities, it is essential that information about their long-term performance be available, since premature failure would be very costly.

Approach
BFRL is developing a method for predicting long-term performance of lead-based paint encapsulants by estimating life-time performance from the results of short-term, statistically designed accelerated tests using reliability theory. This approach has been used successfully in the electronic and aerospace industries, and has recently been applied to protective coatings.

The experimental study will determine relationships between changes in physical, chemical, and mechanical properties of encapsulant coatings and time of exposure in controlled environments. The results of these experiments will be used to develop methods for service-life prediction. The information also will be useful in developing selection criteria. In the experimental study, three generic types of commercial, polymer-based encapsulants, and a latex paint, will be subjected to five environmental conditions, selected from a combination of three temperatures, 10, 25, and 50 °C, and three relative humidities. Performance data on properties, which are important to performance as an encapsulant, such as resistances to cracking, peeling (adhesion), damage upon impact, and abrasion; glass transition temperature; weight stability (thermogravimetric analysis), modulus, and chemical stability (spectroscopy) will be obtained.

Recent Results
New project 1993.

Coatings Suitable for Application to Damp Steel Surfaces

Principal Investigator:
Mary McKnight
Building Materials Division
301-975-6714

Sponsor:
Department of the Army
Construction Engineering Research Laboratory

Objective
To identify coatings for application to damp surfaces and evaluate early system properties.

Problem
The U.S. Army uses steel structures in environments in which the steel surfaces are nearly always damp. It is expensive and difficult to changing the local environment of surfaces of large structures by erecting containment structures and using heaters, driers, etc. Therefore, for coating maintenance operations, it is desirable to apply coatings to damp surfaces that will provide acceptable performance.

Approach
BFRL is performing five tasks:

1. Survey the coatings industry for coatings found acceptable.

2. In consultation with CERL, select a representative set of these coatings and obtain samples.

3. Develop an environmental chamber to control application conditions.

4. Brush apply coatings to steel panels which are damp.

5. Perform crosshatch or pull-off adhesion tests and solvent rub tests upon completion of coating cure as a screen of initial properties.

Recent Results
New project late 1992.

BUILDING MATERIALS
DIVISION

QUALITY ASSURANCE

Cement and Concrete Reference Laboratory

Principal Investigator:
James H. Pielert
Building Materials Division
301-975-6704

Sponsor:
American Society for Testing and Materials and
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 amounting in 1992 to over seven percent of the nation's GDP. 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 a major 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 are 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 NIST 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. 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
Kolos, Ray M., "Compressive Strength of Hydraulic Cements Produced in the United States," *Cement, Concrete, and Aggregates*, CCAGDP, Vol 14, No 2, pp 127-130, Winter 1992.

Inspected over 265 cement and concrete testing laboratories in FY 1992.

Distributed over 3000 proficiency samples in FY 1992 and issued reports of results.

AASHTO Materials Reference Laboratory

Principal Investigator:
James H. Pielert
Building Materials Division
301-975-6704

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

Objective
To inspect soil and bituminous 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 five-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 NIST supervision, services are provided to public and private laboratories on a voluntary basis. These services include the on-site inspection of the laboratory and the distribution of proficiency test samples. The 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.

Recent Results
During FY 1992, inspected 100 bituminous and 80 soil testing laboratories, distributed over 4000 proficiency test samples and issued test reports, and implemented the AMRL Metals Laboratory Inspection Program for AASHTO sponsored laboratories.

Construction of Addition to BFRL'S Concreting Materials Building

Principal Investigator:
James H. Pielert
Building Materials Division
301-975-6704

Sponsor:
American Society for Testing and Materials and American Association of State Highway and Transportation Officials

Objective
To expand the CMRL Proficiency Sample Facility (NIST's Building 206) to support the increasing laboratory participation in the Proficiency Sample Programs of BFRL's Cement and Concrete Reference Laboratory (CCRL) and its AASHTO Materials Reference Laboratory (AMRL).

Problem
Laboratory participation in the CCRL and AMRL Proficiency Sample Programs has increased significantly in recent years to a current level of almost 800 laboratories that receive 7000 samples annually. This increase is a reflection of the importance of the programs in promoting the quality of testing of construction materials in the United States. NIST's Building 206, where the proficiency samples are prepared, is fully used in meeting current commitments leaving little room for growth in existing programs or the addition of new programs.

Approach
Funding has been provided by the CMRL Sponsors (ASTM and AASHTO) to construct a 175 m^2 (1870 ft^2) addition to NIST's Building 206; the BFRL Proficiency Sample Facility. Construction will begin in the Winter of FY 1993 and be completed in about 1 year. CCRL and AMRL will be better able to provide services to the increasing number of laboratories using their proficiency sample program.

Recent Results
New project 1993.

Quantification of External Weathering Stresses

Principal Investigator:
Jonathan W. Martin
Building Materials Division
301-975-6717

Sponsor:
National Institute of Standards and Technology

Objective
To propose and demonstrate a method to characterize the expected service environment to which a building material will be exposed and characterize service environments to demonstrate how field and laboratory exposures are related.

Problem
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 chloro-fluorocarbons 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 modeling 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
In FY 1992, BFRL developed the mathematical and experimental basis for relating field and laboratory UV measurements and initiated the development of consensus standards for measuring UV radiation. In FY 1993, BFRL will focus its efforts to quantify ultraviolet radiation (UV) by providing technical support to ASTM G03, Durability of Nonmetallic Materials' Subcommittee on Service Life Prediction and to the RILEM/CIB Committee

on Service Life Prediction's Task Group on Environmental Characterization. Both activities were established in FY 1992 based on BFRL's recommendations.

Recent Results

Martin, Jon, "Quantitative Characterization of Spectral Ultraviolet Radiation-induced Photodegegration in Coating Systems Exposed in the laboratory and The Field," *Progress in Organic Coatings*, (accepted for publication).

Martin, Jon, Lechner, James A., and Varner, R.N., "Quantitative Characterization of Exterior Weathering Environments: UV-Radiation," *Accelerated and Outdoor Durability Testing of Organic Materials*, ASTM STP 1202, American Society for Testing and Materials, PA, 1993.

Performance Criteria for Single-Ply Roofing Membranes

Principal Investigator:
Walter J. Rossiter
Building Materials Division
301-975-6719

Sponsor:
National Institute of Standards and Technology

Objective

To develop performance criteria for single-ply roofing membranes to assist in the selection, evaluation, and maintenance of single-ply membrane materials.

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. Defective laps and seams are the most frequent problems reported. The 1987 NIST/NRCA Round Table on Roofing Research cited that the roofing industry "lacks a significant database 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 Building Science Series 167, *Interim Criteria for Polymer-Modified Bituminous Roofing Membrane Materials*. This report represented a significant step toward the development of criteria for modified bituminous membranes. Information was not available on criteria and test methods for seam performance and weathering resistance. Data from the field and laboratory are needed to support development of the needed criteria.

Approach

During FY 1993, BFRL will continue to provide leadership to ASTM Committee D08 on Roofing, Waterproofing, and Bituminous Materials, and to the RILEM/CIB Committee on Membrane Roofing Systems. These committees are developing stan-

dards or prestandards for single-ply and polymer-modified bitumen roofing membranes. Strong links will be maintained with the National Roofing Contractors Association in organizing the 1993 NIST/NRCA Roofing Conference.

Recent Results

Rossiter, Walter J. and Derchfield, Randy D., *Observations from a Field Study of the Performance of the of Polymer-Modified Bitumen Roofing*, NISTIR 4972, National Institute of Standards and Technology, Gaithersburg, MD, January 1993.

Materials and Processes for Durable Relocatable Rigid Wall Structures

Principal Investigator:
James R. Clifton
Building Materials Division
301-975-6707

Sponsor:
Department of the Army
NATICK Research, Development, and Engineering Center

Objective

To provide scientific and technical support to the DoD Joint Committee on Tactical Shelters in developing new material and processing standards and updating existing standards.

Problem

DoD requires standards for durable rigid relocatable structures to ensure desired performance. In addition to strength, durability, and environmental requirements, new requirements are being imposed by changes in military threat scenarios. With changing military requirements, many existing standards will need to be revised and new standards developed.

Approach

BFRL will address the technical needs of the DoD Joint Committee on Tactical Shelters in the development and revisions of standards through the voluntary standards generating process. BFRL provides scientific, technical, and administrative leadership to ASTM Subcommittee E06.53, "Materials and Processes for Durable Rigid Wall Structures." Subcommittee meetings will be organized and conducted and coordination provided between the Subcommittee and ASTM.

Recent Results

New project 1993.

BUILDING ENVIRONMENT
DIVISION

REFRIGERATION and MECHANICAL SYSTEMS

Calorimetric and Visual Study of Boiling Enhancements with Refrigerant 123 and Horizontal Two-Phase Flow of R32/R134A

Principal Investigator:
Mark A. Kedzierski
Building Environment Division
301-975-5282
David A. Didion
Building Environment Division
301-975-5881

Sponsor:
National Institute of Standards and Technology,
Department of Energy
Office of Building Technologies
Building Equipment Division, and
Electric Power Research Institute
Customer Systems Division

Objective
To measure the pool boiling heat transfer of R123 on several commercial enhanced surfaces and measure the local horizontal flow boiling heat transfer coefficient of a new R22 replacement: a 30% mass R32/70% mass R134a mixture.

Problem
Alternative refrigerants have solved one problem (ozone destruction in the stratosphere by chlorine) and created another (lack of thermal design information for the new refrigerants). Within the next few years, most new refrigeration equipment will be required by law to operate with ozone-safe refrigerants. Industry does not 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 information to redesign their equipment to operate with the new refrigerants. Material compatibility tests must be performed to find gaskets which will not deteriorate in the presence of the alternative refrigerants. Also, new oils are being developed which are miscible with the new refrigerants which are necessary for reliable compressor operation. Just as importantly, heat transfer data is required to redesign the evaporators and the condensers to ensure the efficient and reliable operation of the entire refrigeration system.

Approach
During FY 1993, BFRL will advance alternative heat transfer research for the direct-expansion and flooded evaporator industries. The tube-side flow boiling study of the R32/R134a mixture will be conducted in an existing test apparatus and will aid the direct-expansion heat exchanger industry. The R123/enhancement study will be conducted in a new test apparatus currently under construction and will assist the evaporator industry. In both cases, high speed films will be taken of the boiling process simultaneously with the heat transfer measurements. The films will be used to obtain a physical description of the boiling process.

The R123/enhancement study will investigate nucleate boiling of three of the leading commercial enhanced surfaces which are applicable to shell-side (external) boiling: (1) the TURBO-B of Wolverine Tube Inc., (2) the High-Flux of UOP, and (3) the GEWA-T of Wieland. The unique aspect of the research is all three surfaces will be adapted to a flat surface. The inherent boiling characteristics of the surfaces will be examined without the complicating circumferential effects that are encountered when testing tubes. Interpretation of the high-speed films is improved when the image is reduced from three to two-dimensions. Also, the accuracy of the heat transfer coefficient measurement on a thick, flat copper specimen is much greater than on round thin-walled tubes.

The R32/R134a mixture study will investigate horizontal flow boiling of both a 30% mass R32/70% mass R134a mixture and R22. The mixture has been chosen for study by the R22 Alternative Refrigerants Evaluation Program (AREP). This program was organized by the Air-Conditioning and Refrigeration Institute "to investigate and evaluate alternative refrigerants to replace HCFC-22 in major air-conditioning and refrigeration applications." This work will generate valuable heat transfer information for the design of new R32/R134a evaporators and condensers.

Recent Results
Kedzierski, Mark A., and Kaul, Michael P., "Horizontal Nucleate Flow Boiling Heat Transfer Coefficient Measurements and Visual Observations for R12, R134a, and R134a/Ester Lubricant Mixtures," 6th International Symposium on Transport Phenomena in Thermal Engineering (submitted), Seoul, Korea, May 1993.

Kedzierski, Mark A., Kim, J.H., and Didion, David A., "Causes of the Apparent Heat Transfer Degradation for Refrigerant Mixtures," ASME HTD-Vol. 197, *Two-Phase Flow and Heat Transfer*, pp. 149-158, 1992.

Kedzierski, Mark A., *Simultaneous Visual and Calorimetric Measurements of R11, R123, and R123/Alkylbenzene Nucleate Flow Boiling*, NISTIR 4948, National Institute of Standards and Technology, Gaithersburg, MD, October 1992.

Kedzierski, Mark A., and Worthington, J.L., "Design and Machining of Copper Specimens with Micro Holes for Accurate Heat Transfer Measurements," *Experimental Heat Transfer*, submitted for publication August 1992.

Thermodynamic Performance of Alternative Refrigerants and Refrigerant Mixtures

Principal Investigator:
David A. Didion
Building Environment Division
301-975-5881

Sponsor:
National Institute of Standards and Technology, and
Department of Energy
Office of Building Technologies
Building Equipment Division

Objective
To evaluate the thermodynamic and oil transport performance of different refrigeration systems using alternative refrigerants and/or refrigerant mixtures.

Problem
The R12 alternative R134a refrigerant has a potential for significant improvement in thermodynamic performance of refrigeration systems if the system hardware is altered. The decrease in the slope of the liquid saturation line with R134a causes a less-effective expansion process. This is important for residential refrigerator/freezers which are subjected to ever increasing energy standards by law.

Most supermarkets have a walk-in freezer in the stock room area for the back-up storage of frozen food. The refrigeration system for walk-in freezers are usually a bank of two or three reciprocating compressors in parallel and utilizing R502 as the working fluid. Since R502 is an azeotropic mixture containing R115, it will not be available after 1997. Several substitutes, all mixtures, have been developed and are under study by the chemical manufacturers (e.g., DuPont, Allied Chemical). Low temperature refrigeration applications (-40 °C) offer unique problems, particularly related to lubrication. Therefore, monitoring the lubricant performance (e.g., solubility) in actual systems is of equal importance as thermodynamic performance.

Approach
During FY 1993, BFRL will fabricate several expansion systems for a residential refrigerator/freezer and evaluate them in a newly-con-

structed experimental rig. These systems will incorporate a "new" constant area short tube expansion device in series and/or parallel in a breadboard refrigeration system. Also, system alterations, such as use of the economizer cycle will be considered. This work is being done in conjunction with Embraco, one of the world's largest compressor manufacturers. A guest researcher from Embraco will perform this work at BFRL during a two-year assignment.

A freezer system will be removed from a Giant Food Store and placed in BFRL's laboratory for study. The system will be instrumented for performance measurements and for monitoring the lubricant flow throughout the system. Ports for refrigerant and lubricant sampling also will be installed for composition and stability monitoring. Evaluations will be made of three alternatives as R502 substitutes. They are (1) R125/R32 azeotrope (Allied), (2) R125/R270/R22 near-azeotrope (DuPont), and (3) R218/R270/R22 near-azeotrope. Since the latter two contain the R22, they can at best be a temporary solution. The performance tests will include careful determination of system capacity, system efficiency, and compressor discharge temperature under conditions and load cycles specified by Giant. The laboratory data for lubricant flow will be taken from samples, in accordance with ASHRAE Standard 41.4-84. This evaluation should be of great interest to the refrigeration equipment industry because of the variety of new lubricants becoming available for the chlorine-free refrigerants.

Recent Results

Pannock, Jurgen, Didion, David, Radermacher, Reinhard, "Performance Evaluation of Chlorine Free Zeotropic Refrigerant Mixtures in Heat Pumps - Computer Study and Tests," International Institute of Refrigeration Conference, Purdue University, July 14-17, 1992.

Domanski, Piotr, Didion, David, Doyle, J., *Evaluation of Suction Line-Liquid Line Heat Exchange in the Refrigeration Cycle*, International Institute of Refrigeration Conference, Purdue University, July 14-17, 1992.

Pannock, Jurgen, and Didion, David, *The Performance of Chlorine-Free Binary Zeotropic Refrigerant Mixtures in a Heat Pump*, NISTIR 4748, National Institute of Standards and Technology, Gaithersburg, MD, December 1991.

Mixtures of Fluorocarbons on Alternatives for R11, R12, R22, and R502

Principal Investigator:
William J. Mulroy
Building Environment Division
301-975-5878
David A. Didion
Building Environment Division
301-975-5881

Sponsor:
Electric Power Research Institute
Customer Systems Division

Objective

To determine whether there exist environmentally acceptable binary and ternary mixtures of partially halogenated fluorocarbons that will act as an azeotrope or near-azeotrope alternative for R11, R12, R22, and R502.

Problem

Research performed in both industry and the public sector over the past 4 years have nearly exhausted pure fluid candidates as potential alternatives for new systems. These efforts have not identified drop-in candidates for existing systems. The number of alternatives is significantly expanded by including mixtures as possibilities. With mixing different fluids, there is the option of tailoring a material by modifying composition, the option not available with a pure material. Already, a couple of mixtures have been identified as drop-in candidates for existing systems.

Approach

A methodology recently developed by BFRL will be used to predict azeotropes and the degree of near azeotropy, that a given set of components may demonstrate. Once candidate mixtures are identified, based on relevant thermodynamic properties, their thermodynamic performance will be predicted using different versions of NIST cycle model, CYCLE-11. Both ideal and non-ideal cycle analysis will be used. In addition, the benefit of liquid-suction line heat exchange will be quantified for those candidates whose heat capacity appears favorable.

Recent Results
Identified two refrigerant mixtures suitable as alternatives and patent disclosures were prepared.

Alternative Refrigerants in Heat Pumps

Principal Investigator:
David A. Didion
Building Environment Division
301-975-5881
William J. Mulroy
Building Environment Division
301-975-5878

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
During FY 1993, BFRL will develop software to select alternative refrigerants and will verify these predictions with laboratory tests. Laboratory tests will be performed on a three-ton heat pump. The heat pump is compatible with Trane's compressor calorimeter, allowing detailed data analysis. The performance variation possible from two-phase temperature glide with conventionally designed coils will be evaluated using a reversible indoor coil capable of being installed for either cross-counter or cross-parallel flow.

Recent Results
Completed new heat pump design and constructed and installed it in BFRL's laboratory.

Evaluation of a Modified Residential Heat Pump Using a Zeotropic Mixture

Principal Investigator:
David A. Didion
Building Environment Division
301-975-5881
Peter Rothfleisch
Building Environment Division
301-975-5868

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 multi-plate 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 are: 1. thermodynamic cycle improvement by matching refrigerant temperature glides to the heat source and sink; and 2. 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. 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.

Approach
Ongoing BFRL projects are evaluating benefits from glide matching. A previous NIST project has evaluated the potential for composition shifting via single-stage flash distillation. During FY 1990, 1991, and 1992, 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 data evaluated the extent of composition shift attained and helped evaluate 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 permit composition shifting. The sponsor requested BFRL to disassemble the control system and separately operate the distillation system for composition shifting and compressor speed. In this configuration, they each can meet load demand independently and the respective performances determined. In addition, the mixture R22/R13B1 is slated for elimination from the marketplace due to the ozone problem and will be replaced by a mixture of R32/R134a. Results should give a measure of reduction in resistance heat demand that can be extrapolated across the United States.

Recent Results
Rothfleisch, Peter I., and David A. Didion, *A Performance Evaluation of a Variable Speed, Mixed Refrigerant Heat Pump*, NISTIR 4597, National Institute of Standards and Technology, Gaithersburg, MD, June 1991.

Zeotropic Water Cooled Chiller

Principal Investigator:
Piotr A. Domanski
Building Environment Division
301-975-5877
David A. Didion
Building Environment Division
301-975-5881

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 coefficients of performance (COPs) than can be obtained with conventional refrigerants. The technology offers the most potential benefit in situations where counterflow heat exchange is employed. These situations occur with refrigerant-to-water evaporators and condensers of water cooled chillers, as well as in heat recovery heat pumps. Zeotropic mixtures are attractive alternatives to R22 in water chillers because of their potential for efficiency improvement due to their basic refrigerant properties. However, a number of technical issues have to be resolved before the potentials of zeotropic mixtures can realized be in a field application.

Approach
This project combines the design, manufacturing, and marketing capabilities of the Trane Company as prime contractor with BFRL's technical expertis in zeotropic refrigerants. BFRL will provide assistance in modeling and data analysis to Trane who will perform proof-of-concept tests on conventional and innovative water chillers. BFRL also will perform flammability tests of candidate alternatives.

Recent Results
Screened many environmentally acceptable refrigerants for the water-chiller application using CYCLE-11 and recommended ones for further investigation by TRANE.

Completed flammability tests on R32/R134a mixture.

Evaluation of Maintenance Practices of Large Centrifugal Chillers

Principal Investigator:
James Y. Kao
Building Environment Division
301-975-5871

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

Objective
To improve the reliability and performance by improved maintenance practices and reduce the loss of ozone-depleting refrigerants of large centrifugal chillers.

Problem
The majority of GSA managed buildings and building complexes use centrifugal chillers to provide cooling for comfort and process load. Good maintenance practices of these major pieces of mechanical equipment can improve their reliability, equipment life, load responses, and energy performance. Costly breakdowns of chillers in terms of machine repair expenses and interruptions to building usage can be avoided. In addition, GSA's Refrigerant Management Plan needs to be comprehensively reviewed along with the applicable requirements of the Clean Air Act and EPA regulations that were recently put into effect.

Approach
During FY 1993, BFRL will review GSA's maintenance practices and manufacturers' recommended maintenance procedures of large centrifugal chillers. Included are inspection and preventive maintenance requirements for chiller components (i.e., compressor and associated equipment, motor, gear transmission, evaporator and condenser heat transfer surfaces, lubrication system, purge system, capacity and temperature resetting controls, safety controls, automatic tube-cleaning system, water treatment, associated chilled and condenser water piping accessories, etc.), inspection and preventive maintenance schedules (i.e., daily, weekly, quarterly, semi-annually, and annually), and instrumentation calibration procedures and schedules. Also included will be predictive maintenance requirements based on preventive maintenance records. Currently

available nondestructive evaluation (NDE) methods which may be applied to chiller maintenance will be examined. BFRL also will review GSA's Refrigerant Management Plan, applicable parts of the Clean Air Act, and EPA regulations regarding the management of ozone-depleting refrigerants. Recommendations will be developed aimed at improving reliability and performance of centrifugal chillers through the use of nondestructive evaluation techniques and operational inspections and/or changes in existing maintenance practices. Also, recommendations will be focused at reducing the loss and/or risk of loss of ozone-depleting refrigerants through changes in current operational and maintenance practices and equipment modifications.

Recent Results
New project 1993.

Communication Protocols for Building Controls

Principal Investigator:
Steven T. Bushby
Building Environment Division
301-975-5873

Sponsor:
National Institute of Standards and Technology, and
Department of Energy
Office of Building Technologies
Federal Energy Management Program

Objective
To evaluate and perform 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
During FY 1993, BFRL will:

1. Revise/Refine BACnet standard as a result of public review process.

2. Refine BACnet Reference Implementation to reflect changes in the draft standard.

3. Develop Conformance Test System - a combination of hardware and software that can execute tests on vendor's products and evaluate the

results of each test (pass, fail, inconclusive) automatically or semiautomatically.

BFRL will commence work on developing a Conformance and Interoperability Testing Program in conjunction with industry, ASHRAE, and other government agencies. This may require BFRL to assume the role of a Conformance Testing Laboratory for a limited period of time. Work will be performed on expanding BACnet to include integrated building services, including life safety, security, and transportation.

Recent Results

Bushby, Steven T., *A Formal Analysis of the BACnet MS/TP Medium Access Control Protocol*, NISTIR 4777, National Institute of Standards and Technology, Gaithersburg, MD, April 1992.

Real Time Fault Detection and Diagnostics

Principal Investigator:
George E. Kelly
Building Environment Division
301-975-5870

Sponsor:
National Institute of Standards and Technology, and
Department of Energy
Office of Building Technologies
Building Systems Division

Objective

To develop methods for performing fault detection and diagnostics on mechanical equipment and systems in real time and participate in the International Energy Agency (IEA) Annex 25 Committee on Real Time Simulation of HVAC - Systems For Building Optimization, Fault Detection and Diagnostics (BOFD).

Problem

The operation of buildings and building systems is a complex procedure. With more and more emphasis on a combination of different and often conflicting performance measures, the processes/systems/equipment being used in commercial and residential buildings are becoming more and more complex. New, on-line analysis methods that detect problems (faults) as they occur are needed. These methods also must determine what component or system is failing or has failed and recommend maintenance or repair procedures. These methods can then be incorporated by the building controls industry into either the building energy management system (BEMS), "smart" building equipment, or into stand alone systems dedicated to fault detection and diagnostics.

Approach

During FY 1993, BFRL will perform the following tasks:

1. Conduct research in conjunction with IEA Annex, 25 participants, including Purdue University and Johnson Controls, on determining the most appropriate static and dynamic models to be used in detecting and locating faults in air-conditioning sensors, valve and actuators, and evaluate alternative identification algorithms for identifying model parameters in real time.

2. Use the newly developed BFRL Fault Detection and Diagnostic (FDD) Laboratory to develop standard data sets of a VAV air-handling system with and without faults for use by Annex 25 participants and U.S. industry in developing BOFD systems.

3. Develop an HVACSIM+ dynamic simulation model of the VAV air-handling system in the NIST FDD Laboratory to expedite future research on BOFD concepts by Annex 25 members. These research findings will assist the building control industry in development of more "intelligent" Building Automation Systems (BAS) for saving energy and reducing operating costs through proper adjustment, repair, and modifications of building control strategies, equipment, and HVAC systems.

Recent Results

Kelly, G.E. et.al., *Guidelines for Using Emulators to Evaluate the Performance of Energy Management and Control Systems*, NISTIR 4991, National Institute of Standards and Technology, Gaithersburg, MD, November 1992.

BUILDING ENVIRONMENT
DIVISION

HEAT AND MOISTURE TRANSFER

Experimental Validation of BFRL Moisture Transfer Model

Principal Investigator:
Robert R. Zarr
Building Environment Division
301-975-6436

Sponsor:
National Institute of Standards and Technology

Objective
To experimentally verify BFRL's 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 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 Weather-Year-for-Energy-Calculation (WYEC) weather data, and predicts the average moisture content of the layers of a wall as a function of time of year.

This model requires experimental verification. 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.

Approach
During FY 1993, BFRL will:

1. Complete moisture accumulation and heat transfer tests on 12 wall specimens using NIST's calibrated hot box.

2. Initiate wet-cup tests to determine the water-vapor permeance of materials used in the construction of the 12 wall specimens.

3. Analyze data collected from the calibrated hot box during the three-month test period.

4. Verify the program MOIST with the above test data.

This research will assist the building community in developing recommended practices for controlling moisture in buildings.

Recent Results
Burch, Douglas M. and Thomas, William C., "An Analysis of Moisture Accumulation in a Wood Frame Wall Subjected to Winter Climate," *Proceedings of the Thermal Performance of the Exterior Envelopes of Buildings V*, Clearwater, Florida, December 1992.

Burch, Douglas M., and TenWolde, Anton, *Controlling Moisture in the Walls of Manufactured Housing*, NISTIR 4981, National Institute of Standards and Technology, Gaithersburg, MD, December 1992.

Burch, Douglas M., *Controlling Moisture in the Roof Cavities of Manufactured Housing*, NISTIR 4916, National Institute of Standards and Technology, Gaithersburg, MD, November 1992.

Burch, Douglas M., Thomas, William C., and Fanney, A. Hunter, "Water Vapor Permeability Measurement of Common Building Materials," *ASHRAE Transactions*, Vol. 98, Part 2, 1992.

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

Burch, Douglas M. and Thomas, William C., *An Analysis of Moisture Accumulation in a Wood Frame Wall Subjected to Winter Climate*, NISTIR 4674, National Institute of Standards and Technology, Gaithersburg, MD, October 1991.

Fanney, A. Hunter., Thomas, William C., Burch, Douglas M., and Mathena, L.R., "Measurements of Moisture Diffusion for Building Materials," *ASHRAE Transactions*, Vol. 97, Part 2, 1991.

Advanced Thermal Insulation Products

Principal Investigator:
A. Hunter Fanney
Building Environment Division
301-975-5864

Sponsor:
National Institute of Standards and Technology

Objective
To evaluate thermal measurement techniques applicable to advanced insulation systems.

Problem
Advanced insulation products are being developed and introduced into the U.S. market. Examples of these products are aerogels, powder filled panels, and evacuated panels. These products offer extremely high insulating capabilities. For example, theoretical calculations reveal that an R-value approaching 100 may be achieved in a 25.4 mm thick evacuated panel.

Current test procedures for measuring thermal conductivity are only applicable to materials which are homogenous, have planar surfaces, and have, compared to advanced insulation products, relatively poor insulating capabilities. Appropriate measurement techniques are needed which will allow an accurate determination of the overall thermal conductance of advanced insulation systems.

Approach
During FY 1993, BFRL will conduct a literature search to document the types of advanced insulation products being developed. A finite difference model will be implemented to permit the prediction of heat flux levels and temperature distributions for a selected advanced insulation system. The potential of alternate measurement techniques will be assessed using the finite difference model. Measurement techniques which will be explored include the use of liquid crystals with an appropriate color imaging system, infrared thermography, heat flux transducers, and calorimetric techniques. The resolution, accuracy, and ease of use of each measurement method will determined.

Based upon this assessment, small-scale preliminary experiments will be conducted using the most promising measurement technique(s). An experimental design for full-scale testing will be developed. This experimental design will be used in FY 1994 to test full-scale advanced insulation systems.

Recent Results
New Project 1993.

Moisture Control Guidelines for Attics, Cathedral Ceilings, Crawl Spaces, and Walls

Principal Investigator:
Douglas M. Burch
Building Environment Division
301-975-6433

Sponsor:
Department of Energy
Office of Building Technologies
Building Equipment Division

Objective
To develop a user-friendly PC computer program for generating moisture control guidelines for attics, cathedral ceilings, and crawl spaces; determine moisture properties for 10 roofing materials; and investigate the viability of recommended construction practices for walls in DoE's Moisture Handbook.

Problem
A need exists to develop a PC computer program for building designers and engineers that accurately predicts the combined transfer and storage of heat and moisture in attics, cathedral ceilings, and crawl spaces. This PC computer program could subsequently be used to investigate which construction practices minimize moisture accumulation as it relates to climate and the type of construction.

Appropriate moisture control guidelines for attics, cathedral ceilings, and crawl spaces are still debated by experts in the building community. For example, DOE recently issued a Moisture Handbook. The Technical Oversight Committee for this Handbook sometimes could not reach a consensus on certain moisture control guidelines.

Approach
During FY 1993, BFRL will develop a sophisticated computer program that performs a moisture balance on a ventilated space (e.g., an attic, cathedral ceiling, or a crawl space) of a building. The BFRL MOIST Program (predicts moisture in walls) will be converted into a subprogram that predicts heat and moisture transfer within each of the bounding building components of the ventilated space. This program will predict and display the moisture content and temperature of each of the construction layers comprising the construction as a function of the time of year. The ventilated space will be convectively coupled to both the indoor and outdoor environments. The program will be converted into a user-friendly PC program that uses hourly weather data provided on floppy disks. It will be used to investigate the viability of the recommended construction practices for attics and crawl spaces found in the DOE Moisture Handbook. As part of this effort, computer simulations will be carried out for five recommended attic and five recommended crawl space constructions subjected to hourly weather data for Madison, WI (a cold climate), Washington, DC (a mixed climate), and a Lake Charles, LA (a cooling climate). One of the attic constructions will include a cathedral ceiling.

For each of the above cases, separate computer simulations will be carried out for an indoor relative humidity of 35% and 50%. The moisture content or surface relative humidity at locations having high moisture content will be plotted as a function of time of year. In winter climates, the construction will be deemed to be not viable, when the monthly mean moisture content of exterior layers of the construction are above fiber saturation. In hot humid climates, the construction will be deemed to be not viable, when the monthly mean surface relative humidity of interior surfaces exceed 80%. If a construction practice is found to be not viable, then additional computer simulations will be carried out to find alternative viable constructions. The results of the research will be made available to DOE's Technical Oversight Committee for inclusion in a revised edition of DOE's Moisture Handbook.

Newly developed BFRL measurement methods will be used to measure the water vapor permeability and moisture storage capacity of ten roofing materials supplied by the Oak Ridge National Laboratory (ORNL). ORNL will use these property values in computer simulation that predict drying times for built-up roof systems.

Recent Results
Burch, Douglas M., "An Analysis of Moisture Accumulation in Walls Subjected to Hot and Humid Climates," *ASHRAE Symposium on Combined Heat and Moisture Transport in Building Envelopes*, 1993.

Burch, Douglas M., Thomas, William C., Fanney, A. Hunter, "Water Vapor Permeability Measure-

ments of Common Building Materials," *ASHRAE Transactions 1992*, V. 98, Pt. 2.

Richards, R.F., Burch, Douglas M., and Thomas, William C. "Water Vapor Sorption Measurements of Common Building Materials," *ASHRAE Transactions 1992*, V. 98, Pt. 2.

Richards, R.F., "Measurements of Moisture Diffusivity for Porous Building Materials," *Proceedings of the ASHRAE/DOE/BTECC Conference on Thermal Performance of the Exterior Envelopes of Buildings V*; Clearwater Beach, FL; Dec. 7-10, 1992.

Burch, Douglas M., *Controlling Moisture in the Walls of Manufactured Housing*, NISTIR 4981, National Institute of Standards and Technology, Gaithersburg, MD, December 1992.

Burch, Douglas M., *Controlling Moisture in the Roof Cavities of Manufactured Housing*, NISTIR 4916, National Institute of Standards and Technology, Gaithersburg, MD, November 1992.

Burch, Douglas M. and Thomas, William W., *An Analysis of Moisture Accumulation in a Wood Frame Wall Subjected to Winter Climate*, NISTIR 4674, National Institute of Standards and Technology, Gaithersburg, MD, October 1991.

Thermal Resistance Measurements on Foam Insulation and Powder-Panel Insulation

Principal Investigator:
Robert R. Zarr
Building Environment Division
301-975-6436

Sponsor:
Department of Energy
Oak Ridge National Laboratory
Office of Building Technology
Building Systems Division

Objective
To determine the thermal resistance of foam insulation and powder-filled evacuated panel insulation using the guarded hot plate (ASTM C 177) and heat-flow-meter apparatus (ASTM C 518).

Problem
Manufacturers of refrigerator appliances are examining alternative insulations to foam insulation for insulating refrigerators. One alternative under consideration is evacuated panels of micro-porous powder that can obtain a foam insulation resistivity of 70 to 140 m·K per W. While providing a high resistance, these panels pose a difficult measurement problem because of increased potential of lateral heat flow from the meter area. Assessing the accuracy of the measurement for these evacuated panels is important to design the future generation of refrigerator appliances.

Approach
During FY 1993, BFRL will continue to conduct measurements on foams and powder-filled evacuation panels. These measurements will be made after consultation with staff at the Oak Ridge National Laboratory (ORNL) and may require ORNL to supply additional specimens to BFRL. BFRL will assess the accuracy in measuring the thermal resistance of the power-filled evacuation panels using the heat flow meter apparatus, ASTM Test Method C 518. BFRL has developed a technique to assess its accuracy by intra-laboratory comparison with its 1-meter guarded hot plate, ASTM Test Method C 177. Intra-laboratory comparison with BFRL will assist ORNL assess the accuracy of measurements of powder-filled evacuation panels.

Recent Results

BFRL provided ORNL staff with measurement data on specimens of expanded polystyrene and of powder-filled evacuated panels.

BUILDING ENVIRONMENT
DIVISION

RESIDENTIAL EQUIPMENT ENERGY USE

Monitoring an Advanced Variable Speed Integrated Heat Pump/Water Heating Appliance

Principal Investigator:
A. Hunter Fanney
Building Environment Division
301-975-5864

Sponsor:
Allegheny Power and
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 several innovations. For example, it has a low noise compressor; the variable-speed components, indoor humidistat, and smart controller permit enhanced temperature and humidity control for improved comfort; the cold blow associated with conventional air-source heat pumps is largely avoided. For an electric utility, the Carrier HydroTech 2000 provides multiple benefits. Improved comfort and high operating efficiencies make the appliance more competitive with fossil fuel heating systems.

Approach
During FY 1993, BFRL will perform an elaborate testing and rating procedure for this type heat pump in a project conducted in parallel for the Department of Energy (DOE) and the Electric Power Research Institute (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 is being 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
Completed analysis to document the average hourly energy demand of the heat pump/water heating appliance as function of outdoor temperature.

Test Methods for Heat Pumps and Air Conditioners Integrating Thermal Energy Storage and Water Heating

Principal Investigators:
Briar Dougherty
Building Environment Division
301-975-6396
George Kelly
Building Environment Division
301-975-5870

Sponsor:
Electric Power Research Institute
Customer Systems Division

Objective
To test a thermal storage heat pump and use the results to refine and validate a NIST-developed computer model.

Problem
Electric power 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). Thermal storage heat pumps provide the desired load shifting and also can save energy, thus helping the utilities in both areas. The acceptance of such appliances to the home buildar 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 FY 1991, 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 installed a commercially available thermal storage heat pump in two environmental chambers located in its laboratory. During FY 1992 and 1993, a series of tests were conducted to determine steady-state and transient performance characteristics for each of the eight different operating modes. The test results were used to evaluate and refine the computer model.

BFRL completed a partial validation of the computer model. Component models (e.g., compressor, water-on-coil evaporator, refrigerant-to-domestic water heat exchanger, etc.) were verified separately. The full model gives a reasonable prediction of performance for the thermal storage heat pump when operating in a cool storage mode of steady conditions. An interim report is being developed that describes progress and a work plan before initiating work on a proposed method for testing and rating.

Recent Results
Installed a thermal storage heat pump incorporating domestic water heating in BFRL's environmental chambers and conducted 50 laboratory tests.

Test Procedures for Heat Pumps and Air Conditioners

Principal Investigator:
Brian Dougherty
Building Environment Division
301-975-6396

Sponsor:
Department of Energy
Office of Building Technologies
Codes and Standards Division

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

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. Since 1975, DOE has relied on BFRL to assist in the development of the test and rating procedures.

Approach
During FY 1993, BFRL will:

1. Modify DOE's heat pump test procedure to accommodate variable-speed heat pumps that limit the maximum compressor speed at low outdoor temperatures.

2. Evaluate the existing heat pump test procedure to ensure that all engineering design options proposed in the air conditioning standards rulemaking can be tested using this procedure with results that are comparable across all heat pumps.

3. Evaluate DOE-recommended changes to the proposed test procedure for combined HP/WH appliances. BFRL will evaluate the equipment measurement tolerances specified within the proposed standard and develop multiple flow charts that detail those parts of the test procedure that are applicable for a given appliance type (e.g., two-capacity full condensing combined appliance that is a Double Mode COOL&WH unit, a Mode 2 HEAT&WH unit that uses an air-source defrost, etc.).

4. Following public review of test procedures for conventional heat pump and combined HP/WH appliances, BFRL will provide DOE the technical assistance needed to resolve the issues raised by commentors.

5. Develop the text needed to complete ASHRAE Standard 137P.

Recent Results
Provided DOE with proposed test procedures for rating combined heat pump/water heating appliances.

Completed a series of laboratory tests on a thermal storage heat pump.

Test Procedures for Furnaces, Boilers, and Integrated Appliances

Principal Investigator:
Stanley T. Liu
Building Environment Division
301-975-5880

Sponsor:
Department of Energy
Office of Building Technologies
Codes and Standards Division

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

Problem
The ASHRAE Standard 124-1991, Method of Testing for Rating Combination Space Heating/Water Heating Appliances, was recently approved by ASHRAE. The Standard requires the testing of space heating function of the appliance as a boiler in accordance with the ANSI/ASHRAE Standard 103-1988, and testing the water heating function as a water heater in accordance with a procedure similar to the DoE test procedure for water heaters. The ASHRAE Standard does not, however, address the problem that different sized boilers are combined with different sized tankless coils or storage water tanks. If all combinations had to be tested, it would place a significant testing burden on boiler manufacturers. An interpolation scheme and/or sampling technique must be developed.

In FY 1992, BFRL developed and delivered to DoE a recommended draft test procedure for furnaces and boilers that references ANSI/ASHRAE Standard 103-1988. The new procedure was prepared for publication in the Federal Register by DoE as a Proposed Rule Making in early FY 1993.

Approach
During FY 1993, BFRL will perform the following tasks:

1. Review comments received on the Proposed Rule Making for furnaces/boilers and assist DoE publish the Final Rule for this product.

2. Complete simulation studies on the performance of a family of boilers in combination with tankless coils and storage tanks to determine an interpolating methodology.

3. Procure and conduct laboratory tests on a selected family of boilers tankless coils and storage tanks to validate interpolating scheme.

4. Develop a recommended test procedure for evaluating the annual performance and cost of operation of Type I and Type II combined space/water heating appliances and assist DoE in preparing a Proposed Rule Making on this product in FY 1993 or early FY 1994.

5. Continue evaluation of input/output method as a possible future alternative for the current furnace/boiler test procedure by conducting laboratory tests on furnaces and/or boilers and comparing results with those obtained using the current DOE/NIST furnace/boiler test procedure.

6. Assist DOE prepare responses to Requests for Waivers and draft Federal Register Notices of Proposed Rule Making.

Recent Results
Liu, Stanley T., Kelly, George E., and Terlizzi, Charles P., *Evaluating the Off-Cycle Losses of a Gas-Fired, Power Vented Furnace Employing Post Purge*, NISTIR 4908, National Institute of Standards and Technology, Gaithersburg, MD, August 1992.

Liu, Stanley T., Kelly, George E., and Terlizzi, Charles P., *Testing and Rating of an Atmospheric, Gas-Fired Furnace Equipped with a Burner Air Inlet Damper*, NISTIR 4717, National Institute of Standards and Technology, Gaithersburg, MD, November 1991.

Revised Test Procedures for Refrigerator-Freezers

Principal Investigator:
James Kao
Building Environment Division
301-975-5871

Sponsor:
Department of Energy
Office of Building Technologies
Codes and Standards Division

Objective
To develop revised test procedures for refrigerator-freezers in the DOE Energy Conservation Program for Consumer Products.

Problem
The current DOE test procedure was developed nearly 10 years ago. The test procedure includes certain test conditions and assumptions which are not realistic operating conditions (e.g., two ambient temperature conditions are required during the test: 32.2 $\pm$1 °C and 26.7 $\pm$1 °C dry bulb/19.4 °C wet bulb; and the door-opening during test is required only for the variable defrost control optional test, not for other tests.) More advanced materials (cabinet and door insulation, door gaskets, etc.), manufacturing techniques (lower anti-sweat heater energy, etc.) and operational features (e.g., electronic defrost operation, through-the-door ice service, etc.) now are used extensively. A thorough review of the entire test procedure is needed.

Approach
During FY 1993, BFRL will review DOE's test procedures for refrigerator-freezers and Standard HRF-1 of the Association of Home Appliance Manufacturers (AHAM). In its environment chambers, BFRL will conduct simulated tests on several representative units to determine their cooling, defrosting, and energy characteristics. Refrigerator-freezers types include single door, double door with top freezer, double door with bottom freezer, and side-by-side units. Different defrost operations (e.g., manual, partial automatic, and automatic) and through-the-door ice service will be considered. Usage factors will include door opening and ice consumption. The values for these two parameters will be determined by consulting previously published literature and/or industry sources. BFRL also will consult other organizations involved in refrigerator-freezer work, such as Lawrence Berkeley Laboratory. Using this data, BFRL will revise the DOE test procedure for refrigerator-freezers based on data obtained from the tests.

Recent Results
New project 1993.

Revised Test Procedures for Pool and Spa Heaters

Principal Investigator:
Stan Liu
Building Environment Division
301-975-5880

Sponsor:
Department of Energy
Office of Building Technologies
Codes and Standards Division

Objective
To develop test procedures for pool and spa heaters for inclusion in the DOE Energy Conservation Program for Consumer Products (Uniform Test Method for Measuring the Energy Consumption of Pool Heaters, Appendix P to Subpart B of Part 430).

Problem
DOE's test procedures cover only gas- and oil-fired pool heaters. The test procedure for gas-fired heaters references ANSI Standard Z21.56 (Standard for Gas-fired Pool Heaters). The test procedure for oil-fired heaters is limited – it calls for measurements and calculations to be performed in a manner similar to those required for gas-fired heaters. The DOE test procedures do not include resistance type electric heaters or heat pumps for heating pools and spas. These test procedures should be revised and expanded to include detailed measurement requirements, accuracy statements, calculation procedures, and test methods for evaluating the performance of both resistance type and heat pump pool/spa heaters.

Approach
During FY 1993, BFRL will review DOE test procedures and existing and proposed industry standards for pool and spa heaters, including the proposed ASHRAE Standard 146P. Heaters included are fossil-fuel type, resistance electric type, and air-source heat pump. Other related standards, such as those covering heat pumps and air conditioners, also will be evaluated to determine the applicability.

BFRL will use this data to revise DOE's test procedures for gas-fired pool heaters and oil-fired pool heaters, and develop new test procedures for resistance electric heater and heat pump pool/spa heaters.

Recent Results
New project 1993.

BUILDING ENVIRONMENT
DIVISION

INDOOR AIR QUALITY

Development and Application of Multizone Indoor Air Quality Models

Principal Investigator:
Jin B. Fang
Building Environment Division
301-975-6417
George Walton
Building Environment Division
301-975-6421

Sponsor:
National Institute of Standards and Technology

Objective
To develop refinements to CONTAM88, BFRL's multizone airflow and contaminant dispersal model and develop standardized building test cases for the application of this model to study indoor air quality.

Problem
Multizone airflow and contaminant models have been developed at BFRL, including AIRNET and CONTAM86 through CONTAM88. These models have been useful for studying contaminant dispersal problems in multizone building systems. Since the development of the most recently released model, CONTAM88, there is a need to improve this model in areas of ventilation system performance and contaminant sources and sinks. There is a need for greater analyses of indoor air quality in multi-zone building systems, including improved understanding of the important interactions with building equipment and energy use. Interest in indoor air quality analysis is expanding in many areas, including pollution exposure estimates and civilian emergency management. The recent initiation of the revision of ASHRAE Standard 62 makes the need for improved modeling tools even more pressing. Finally, improvements in the input/output features of these programs are needed to expand their accessibility to others than indoor air quality researchers.

Approach
During FY 1993, BFRL will improve the ability of CONTAM88 to model contaminant dispersal and develop standardized building cases for use in indoor air quality analysis. This work will be performed in two parts.

In the first part, the ventilation system and the source and sink models within CONTAM88 will be improved. A ventilation system description module will be developed to allow users to select and configure system components to construct realistic models of building ventilation systems. Contaminant source and sink terms will be added to the model based on the latest research in these areas, including adsorption models and source dependencies. Advanced graphical input/output approaches and interfaces with building equipment and energy models will be developed. Based on these modifications, a new version of CONTAM88 will be developed and documented.

In the second, work will address the application of CONTAM88 to indoor air quality analyses in buildings. A series of "standard" building descriptions will be developed to study indoor air quality control options, exposure assessment and the results of field surveys. These building descriptions will be based on the latest research results in the areas of building airtightness, contaminant source strengths, and building systems performance. A variety of building descriptions will be developed, including office, school, retail, institutional, and multi-family residential buildings. These building descriptions will be formatted as CONTAM88 input files, enabling straightforward analyses and modifications based on the objectives of the user. Analyses will be conducted to support the activities of the ASHRAE committee responsible for the revision of ASHRAE Standard 62-1989, Ventilation for Acceptable Indoor Air Quality. These analyses will include modeling the effects of filters and air cleaners, zone controls, heat recovery devices, and source control technologies on indoor contaminant levels.

Recent Results
Fang, J. B. and Persily, Andrew K., "Numerical Prediction of Airflow Patterns and Ventilation Effectiveness in an Open Office Space," *ASHRAE Transactions*, Vol. 99, Part 2, 1993.

Fang, J. B. and Persily, Andrew K., "Numerical Prediction of Ventilation System Performance in an Open Office Space," *ASHRAE Transactions*, Vol. 99, Part 2, 1993.

Persily, Andrew K., "Modeling Radon Transport in Multi-Story Residential Buildings" Modeling Air Change Rate and Airtightness in Buildings, *ASTM STP* 1205, 1992.

Ventilation Assessment in Commercial Buildings

Principal Investigator:
Andrew K. Persily
Building Environment Division
301-975-6418
W. Stuart Dols
Building Environment Division
301-975-5860

Sponsor:
Department of Energy
Bonneville Power Administration

Objective
To assess and compare different methods of evaluating ventilation performance in mechanically ventilated commercial buildings and develop a guidance document on ventilation performance assessment in commercial buildings.

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 when the building is constructed and 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 on-site 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 practical and accurate procedures for making field measurements of building ventilation rates.

Approach
Under previous research for Bonneville Power Administration (BPA), whole building ventilation assessment techniques were compared in the BPA Building in Portland. Measurement techniques were not developed that addressed ventilation performance on other than the whole building.

During FY 1993, BFRL will perform three tasks:

1. Evaluate methods to assess ventilation performance of individual floors and work stations.

2. Study ventilation performance assessment methods in small commercial buildings.

3. Develop a guidance document to assess ventilation performance in mechanically ventilated commercial buildings.

The research involves performing an investigation of procedures to assess ventilation of individual floors and work stations. Local ventilation performance will be conducted in the BPA Building and will involve a variety of techniques. The ventilation of individual floors and such mid-scale zones will be studied with traverses of individual supply air ducts, tracer gas measurements in zone returns, and carbon dioxide concentration measurements in zone returns. The ventilation assessment of individual work stations will include the use of traverses of individual supply air ducts, flowhood measurements at supply air diffusers, tracer gas measurements of ventilation effectiveness and carbon dioxide concentration measurements. In the individual floor and the work station measurements, the various techniques will be compared for their practicability, associated effort, and accuracy.

The comparison of ventilation performance assessment techniques in small commercial buildings will be conducted in three mechanically ventilated buildings in the Portland area. In each of these buildings, automated tracer gas decay and carbon dioxide concentration measurement systems will be installed for a period of several weeks. Building ventilation will be assessed with direct measurements of airflow rates in the ventilation system ductwork using traditional airflow rate measurement devices.

This work also includes development of a guidance document on ventilation system performance assessment in mechanically ventilated commercial buildings. This effort is being cosponsored by the U.S. Environmental Protection Agency. The guidance document will provide necessary information to evaluate ventilation in these buildings to compare actual ventilation performance with design intentions and to determine compliance with ventilation standards and guidelines. The document will describe the various methods available, including a detailed description of when and how to use them, a description of the equip-

ment and technical skill required, an estimate of the associated level of effort, and a discussion of the accuracy and interpretation of the results.

Recent Results

Dols, William S and Persily, Andrew K., *A Study of Ventilation Measurement in an Office Building*, NISTIR 4905, National Institute of Standards and Technology, Gaithersburg, MD, October 1992.

Development of a System for Ventilation Assessment in Commercial Buildings

Principal Investigator:
Andrew K. Persily
Building Environment Division
301-975-6418
Steven J. Nabinger
Building Environment Division
301-975-5860

Sponsor:
U. S. Environmental Protection Agency
Office of Research and Development
Air and Energy Engineering Research Laboratory

Objective

To develop equipment and procedures for assessing ventilation in public and commercial buildings.

Problem

Indoor air quality complaints have become more common in recent years. Although there has been insufficient research to establish the causes of many indoor air quality complaints, several have been suggested including poor ventilation system performance and the reduction of building air change rates. Air change rates and other ventilation system performance parameters have not been well characterized in commercial buildings. Many indoor air quality investigations have not included adequate assessments of ventilation, making connections between ventilation performance and indoor air quality even more difficult to establish. There lacks reliable means to assess ventilation system performance at a practical level of effort and expertise. Most research in ventilation system performance has involved sophisticated tracer gas analysis techniques that are not consistent with the resources and technical skills of most indoor air quality investigators. Standard engineering approaches to ventilation assessment such as duct traverses exist, but their application to real-world system evaluations is complicated by practical issues of system configuration and equipment operating schedules.

Approach

During FY 1993, BFRL will document and validate procedures for fabricating an automated ventilation monitoring system. This system is based on real-time monitoring of key ventilation system performance parameters. It consists of two

separate systems, one for monitoring local conditions and the other for monitoring air handler performance, both of which consist of various sensors and a data recording device. The local system employs a datalogger combined with temperature and relative humidity sensors, carbon dioxide monitors and hot-wire anemometers to monitor local ventilation operation for periods from several days to several weeks. The air handler monitoring system employs similar sensing equipment and a personal computer based data collection system. Both systems are designed to provide real-time information on system operation and performance. The system will be deployed in the field and the measurement results compared to other, more accurate, measurement systems. The field deployment will provide an opportunity to evaluate the system design and performance so it can be modified. In addition, the real-time data on ventilation systems operation and performance will further the understanding of how the monitoring systems perform and will assist in the development of evaluation protocols that capture the key aspects of ventilation performance.

Recent Results
New project 1993.

Fluid Mechanics of Airflow Measurement in Ventilation Systems

Principal Investigator:
Andrew K. Persily
Building Environment Division
301-975-6418

Sponsor:
National Institute of Standards and Technology

Objective
To employ recent developments in fluid flow measurement research to improve standard procedures for measuring airflow rates in ventilation systems.

Problem
Standardized procedures exist for measuring airflow rates in mechanical ventilation systems in the field. These procedures are typically pitot tube traverses in ducts, with estimated accuracies in the field from 5 to 10% under ideal conditions. However, it is acknowledged that common HVAC system configurations can lead to much larger errors or even preclude making the measurements. These procedures are based on results conducted during the 1960s and earlier. Since that time, fundamental research has been conducted into the fluid mechanics of fluid flow rate measurement. Based on the use of laser doppler velocimetry, velocity profiles in ducts have been studied, with specific attention given to the effects of elbows, constrictions and other obstructions. Based on the practical limitations of current airflow rate measurement procedures, their basis on dated research results and the existence of state-of-the-art approaches to airflow rate measurement, the opportunity exists for improvements in standardized approaches to airflow rate measurement in ventilation systems.

Approach
During FY 1993, BFRL will review the technical basis of current industry practice for airflow rate measurement and the latest research results in the area of fluid flow measurement. Given the results of recent research, technical shortcomings in current industry practice and areas where improvements are possible will be identified. These improvements will focus on the accuracy and reliability of the measurement results and on how the procedures address problems of system configuration that result in nonuniform velocity

profiles within the system ductwork. Based on these findings, recommendations will be developed for improvements in current practice. These recommendations will be transferred to industry through interactions with the Air Movement Control Association, the American Society for Heating, Refrigerating and Air-Conditioning Engineers, the National Environmental Balancing Bureau and the Sheet Metal and Air Conditioning National Contractors Association. This effort will be performed in cooperation with NIST's Chemical Science and Technology Laboratory.

Recent Results

Persily, Andrew K., *Building and HVAC Characterization for Commercial Building Indoor Air Quality Investigations*, NISTIR 4979, National Institute of Standards and Technology, Gaithersburg, MD, February 1993.

Large Building Ventilation Guide

Principal Investigator:
Andrew K. Persily
Building Environment Division
301-975-6418

Sponsor:
Environmental Protection Agency
Indoor Air Quality Division
Office of Radiation and Indoor Air

Objective
To develop a guide to assess ventilation in mechanically ventilated commercial buildings for use in determining their compliance with design objectives and ventilation standards and in indoor air quality evaluations.

Problem
Current investigations into the causes of air quality problems in commercial buildings include ventilation evaluation efforts ranging from no consideration of ventilation, to evaluations of design values for ventilation rates with no actual measurement, to unreliable or ill-advised measurement procedures. These circumstances exist in part because many investigators lack an adequate understanding of ventilation systems and building characteristics, a lack of familiarity with existing techniques for ventilation evaluation and their applicability in commercial buildings, and a perception that the only option for ventilation assessment is expensive, long-term tracer gas monitoring. The relationship between ventilation and air quality problems in buildings is poorly understood. There is no straightforward method to reliably determine whether a building is operated in compliance with its design goals or a particular ventilation standard, e.g., ASHRAE 62-1989. Given the upcoming revision of the ASHRAE standard, reliable and practical methods for determining compliance are needed. Ventilation assessment tools are needed for indoor air quality research efforts being conducted by a wide variety of federal and state agencies.

Approach
During FY 1993, BFRL will develop a ventilation assessment guide that describes procedures for evaluating the performance of mechanical ventilation systems in public and commercial buildings. The focus of the guide will be the reliable determination of outdoor air intake and supply airflow

rates. The effort will be developed based on BFRL expertise, input from other experts, and guidance already developed by organizations such as AABC (Associated Air Balancing Council), ADC (Air Diffusion Council), AMCA (Air Movement and Control Association), ASHRAE, NEBB (National Environmental Balancing Bureau) and SMACNA (Sheet Metal and Air Conditioning Contractors' National Association). The project will schedule a ventilation measurement workshop at NIST to obtain input from national experts in ventilation measurement and other interested parties.

The ventilation assessment guide will be directed to an audience of building engineers and other IAQ diagnosticians having basic knowledge of mechanical engineering and airflow measurement. The procedures described in the guide will employ standard airflow measurement techniques such as pitot and hot-wire traverses, flowhoods, temperature measurement and carbon dioxide measurement. The guide will describe all measurement procedures, equipment requirements, data analysis techniques and reporting formats.

Recent Results
New project 1993.

Radon Entry and Mitigation in Large Buildings

Principal Investigator:
Andrew K. Persily
Building Environment Division
301-975-6418

Sponsor:
Environmental Protection Agency
Office of Radiation Programs

Objective
To evaluate radon entry and air movement in a large, non-industrial building.

Problem
There has been much research conducted on the subject of radon in buildings. This research has focused on problem identification, mitigation, and source modeling in single-family residential buildings. Recently, attention has turned towards large buildings such as schools, commercial buildings, and multi-family residential buildings. While the fundamental issues about the relationship between radon, ventilation, and building features in small buildings has not been resolved, radon in large buildings is a more complex problem due to the multi-zone nature of airflow and contaminant dispersal in large, mechanically ventilated buildings. The technical issues that must be studied to understand radon transport in large buildings include the impacts of mechanical ventilation system operation, air movement through vertical shafts within tall buildings, and pressure differences at ground contact zones.

Approach
During FY 1993, BFRL will be monitoring ventilation parameters in a large, non-industrial building to evaluate radon entry and transport. This work employs using existing instrumentation systems and in-house expertise to study ventilation and air movement in conjunction with radon monitoring conducted by an EPA contractor. These simultaneous measurements will be used to develop an understanding of radon entry and transport within the building and to develop recommendations for reduction of radon levels through modifications of the ventilation system operation and other mitigation strategies.

The monitoring effort includes installation of an automated tracer gas monitoring system to

measure building air change rates and an automated carbon dioxide measurement system to obtain information on general indoor air quality within the building. One week of intensive, on-site measurements will be conducted to obtain detailed information on ventilation system performance. The mechanisms of radon entry and transport will be diagnosed and recommendations will be developed for mitigation approaches. After a mitigation approach is selected and implemented in the building, the automated systems will be employed to determine the effect on building ventilation rates and carbon dioxide levels.

Recent Results
New project 1993.

BUILDING ENVIRONMENT
DIVISION

COMPUTER INTEGRATED CONSTRUCTION

Building Industry Framework for Developing Step Application Protocols

Principal Investigator:
Mark E. Palmer
Building Environment Division
301-975-5858

Sponsor:
National Institute of Standards and Technology

Objective
To develop the planning structure, methods, and tools for defining and testing the Standard for the Exchange of Product model data (STEP) application protocols for the building industry.

Problem
National and international standards making organizations have 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 STEP, are proponents of this new method.

BFRL initially developed the AP methodology as a solution for ensuring reliable information exchange using the Initial Graphics Exchange Standard (IGES). With industry and other government agencies, BFRL developed the 3D Piping IGES Application Protocol to prove the methodology and to meet a high-priority data exchange requirement of industry and government. This is the first AP to be included in a DoD standard for digital product data and in a DoD procurement specification for CAD/CAE systems. With the commercialization of the 3D Piping IGES AP and the development of STEP APs by the ISO community, the basic AP methodology is being rigorously tested and refined. Industry and the standards making community require AP development tools and a quality management system for the cost-effective and timely delivery of quality APs.

To assure the rational development of the APs required by the building industry, standards writers and building industry representatives require a framework and a plan for defining, planning, and managing AP projects. This framework must provide a structure with which to classify APs, define AP scopes, and identify overlaps between application protocols.

Approach
A prototype AP framework was developed by BFRL in FY 1992 to provide a structure with which to classify APs and to begin planning the work of the ISO STEP community. In conjunction with the National PDES Testbed, the National Initiative for Product Data Exchange, and the DoD CALS Office, the framework will be tested against the requirements of the manufacturing industry. Concurrently, BFRL will extend the framework to accommodate the requirements of the building industry.

In order to deliver high-quality STEP APs, an effective AP development environment and a quality management system must be specified and implemented. With the National PDES Testbed, BFRL will develop the functional specifications for an AP development environment. BFRL will use the ISO 9000 standards and the lessons from the Malcolm Baldridge Award to develop an AP quality management (QM) structure. This QM structure will be delivered to the DoD CALS Office and the ISO STEP project for their implementations of AP QM systems.

Recent Results
Palmer, M.E., Gilbert, M.E., and Anderson, J.M., *Guidelines for the Development and Approval of STEP Application Protocols*, NISTIR 5110, National Institute of Standards and Technology, Gaithersburg, MD, February 1993.

Palmer, Mark E. and Reed, Kent A., *3D Piping IGES Application Protocol, Version 1.1*, NISTIR 4797, National Institute of Standards and Technology, Gaithersburg, MD, March 1992.

Kramer, Thomas R., Palmer, Mark E., and Feeney Allison Barnard, *Issues and Recommendations for a STEP Application Protocol Framework*, NISTIR 4755, National Institute of Standards and Technology, Gaithersburg, MD, January 1992.

Computer-Based Building Regulations and Standards

Principal Investigator:
Kent A. Reed
Building Environment Division
301-975-5852

Sponsor:
National Institute of Standards and Technology

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

Problem
Building regulations assure health, life safety, and welfare in buildings and building construction, and establish minimum levels of performance for buildings and building systems. Building regulations 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, for local and remote database access systems to CD-ROM; and standard 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 to integrate different representations into one unified model.

Approach
In FY 1992, the Standardized General Markup Language—SGML (ISO 8879)—was used to define a framework for the prototype unified model that incorporated elements of document publishing markup and of the Standards Analysis, Synthesis, and Expression (SASE) methodology developed previously at BFRL. A primitive SGML Document Type Definition (DTD) defined the unified model. Recent work in the international standardization effort, known colloquially as HyTime, will be applied this year to formalize the identification of informational links in standards.

The International Council of Building Research, Studies, and Documentation (CIB) Board of Directors agreed in January 1992 to create a new CIB Task Group that will study computers and building regulations and standards. Various approaches are being taken that are difficult to compare and contrast through the available descriptions. Several programs will be exchanged among the Task Group participants and exercised. Several participants are planning an intercomparison of approaches by applying them to a common text. This international effort will be led and coordinated by BFRL.

This research will assist standards writing organizations develop and deliver electronic representations of their standards.

Recent Results
Developed an encoding model for standards using standardized general markup language.

BUILDING ENVIRONMENT
DIVISION

LIGHTING TECHNOLOGY

Field Measurement and Modeling of Lighting Distributions

Principal Investigator:
Belinda L. Collins
Building Environment Division
301-975-6455
George Walton
Building Environment Division
301-975-6421

Sponsor:
National Institute of Standards and Technology

Objective
To develop and evaluate computer routines for modeling and assessing the distribution of illuminances and luminances in office spaces.

Problem
Evaluating and predicting the performance of lighting systems in actual office spaces is a complicated measurement and modeling problem requiring 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 related to luminance distributions. Recent research suggests the perception of lighting quality is determined in part by the balance between horizontal and vertical illumination.

Approach
During FY 1993, BFRL will assess occupant response to the lighting output of five different lighting configurations in real offices including two with interior obstructions. The subjective assessment of the effects of several different luminance patterns in typical office spaces will 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 offices selected to represent extremes in luminance distribution. These measures will be correlated with the detailed measurements of room luminances and surface reflectances 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. These data will be used as input in the development and evaluation of accurate computer algorithms for calculating surface luminances and reflectances in actual rooms. The accuracy of the ray tracing and view factor approaches will be assessed relative to the photometric measurements made with the luminance mapping device and the subjective assessments. Currently available lighting calculation programs such as Radiance and Lumen Micro will be evaluated in conjunction with researchers in NIST's Computing and Applied Mathematics Laboratory.

This research will 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 luminance mapping device. Data obtained with the mapper will be used to develop and verify the accuracy of computer algorithms for computing both surface luminances and reflectances in real rooms, including those with obstructions.

Results are expected to yield data which validate procedures for measuring and modeling luminance distributions in spaces with different interior configurations. It also will provide data on user response to these spaces and test the hypothesis that variations in the ratio of vertical to horizontal luminances are critical to impressions of lighting quality.

Recent Results
Collins, Belinda, L, Ouellette, M.J., Perry, M.J., Tiller, D.K. Treado, Stephen J., and Sanders, P.A., "Initial Procedure for Evaluation of a CCD Photometer," Proceedings *Lux Europa*, April 1993.

Collins, Belinda L, *Evaluation of Subjective Response to Lighting Distributions: A Literature Review*, NISTIR 5119, National Institute of Standards and Technology, Gaithersburg, MD, February 1993.

Collins, Belinda, L., Treado, Stephen, J., Ouellette, M.J. *Evaluation of Compact Fluorescent Lamp Performance at Different Ambient Temperatures*, NISTIR 4935, National Institute of Standards and Technology, Gaithersburg, MD, December 1992.

Lighting and HVAC Interactions

Principal Investigator:
Stephen J. Treado
Building Environment Division
301-975-6444

Sponsor:
Department of Energy
Office of Building Technologies
Building Systems Division

Objective
To develop improved evaluation methods and design tools for designing and operating efficient lighting and HVAC systems in commercial buildings to control peak cooling loads.

Problem
Lighting constitutes a substantial portion of commercial building electrical energy usage, typically ranging from 25 to 50%. 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% are possible. These effects influence the number of luminaries 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
During FY 1993, BFRL will be investigating the interactions between lighting and HVAC systems in commercial buildings. This work is being performed 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 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 systems, 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. It also will 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.

Recent Results
The Interaction of Lighting, Heating and Cooling Systems in Buildings, NISTIR 4701, National Institute of Standards and Technology, Gaithersburg, MD, March 1992.

Revised section on thermal considerations of lighting for new IES Handbook.

Test Procedures for Lighting Fixtures and Systems

Principal Investigator:
Stephen Treado
Building Environment Division
301-975-6444

Sponsor:
Department of Energy
Office of Building Technologies
Codes and Standards Division

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 require analysis of any test procedure amendments to determine their effect on minimum efficiency standards. Since 1975, DOE has relied on BFRL to assist in the development of the test and rating procedures.

Approach
During FY 1993, BFRL will be developing draft test procedures for multi-lamp fixtures based on reviews of the existing test procedures and preliminary experimental testing in BFRL's Lighting System Evaluation Laboratory. Proposed procedures will be prepared for individual components, including lamps as T-12's, T-10's, and T-8's; conventional and premium ballasts; 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 reference standard and actual components. 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.

Experiments of proposed test procedures on three lighting system/fixture combinations will be validated in BFRL's Lighting System Evaluation Laboratory. Lighting system efficiency will be used 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. It is expected the findings of this research will result in lighting component test procedures and an associated calculation procedure to obtain system performance. This method will account for electrical, thermal, and photometric interactions between components.

Recent Results
Completed experimental validation of test procedures for multi-lamp luminaires.

Developed test procedure for lamp performance evaluation.

Evaluation of Occupant Response to Lighting Retrofits

Principal Investigator:
Belinda L. Collins
Building Environment Division
301-975-6455

Sponsor:
Department of Energy
Office of Building Technologies
Codes and Standards Division

Objective
To evaluate occupant response to lighting in offices at DOE Headquarters in Washington, D.C.

Problem
The Department of Energy is undertaking a major renovation of its lighting system in its Headquarters as part of the Federal Relighting Initiative. The initiative is intended to reduce power consumption dramatically without compromising existing lighting quality. Determining the impact of the relighting on the occupants and on the lighting in their offices is a major part of the evaluation of the effectiveness of the relighting initiative. Recent reports by Collins, Fisher, Gillette, and Marans (1990), Collins and Rubin (1988), Collins, Gillette, Dahir and Goodin (1989) present data from post-occupancy evaluations of about 15 facilities in government and private industry. These assessments provided information on physical conditions, especially lighting, and the occupant reaction to it in the various buildings studied. They also found noticeable dissatisfaction with some lighting systems, particularly where fixed task lighting was combined with an indirect ambient lighting system. This system was associated with higher energy use (in terms of lighting power density), and higher illuminances, but lower ratings of lighting satisfaction than a comparable situation in which direct ambient lighting provided the primary illumination.

Approach
During FY 1993, BFRL will identify representative samples of offices and occupants including interior and exterior offices. Occupants will include professional, administrative, and support personnel. A two-part procedure is planned in which physical measures of the lighting in the offices are assessed, including measures of task illuminance, surround luminances, and typical task contrasts; and occupant reaction will be determined using questionnaire techniques developed in previous BFRL post-occupancy assessments. The number of measures required to characterize and describe the space will be determined using a conventional photometer and a luminance mapping device in conjunction with a statistical analysis procedure. After the photometric measures have been obtained, the spaces will be evaluated by human subjects using post-occupancy procedures similar to those described in Collins et al (1989). During the course of this work, a comprehensive procedure for measuring luminances in an office space will be implemented, along with a protocol for assessing occupant response. These procedures will be documented and validated during the assessment of the Forrestal Building for future use in other Federal Relighting Projects. Development of repeatable, valid procedures for measuring the effectiveness of relamped facilities will enable DOE to provide critical feedback information to building managers.

Recent Results
Collins, Belinda L., "Evaluation of the Role of Luminance Distributions in Occupant Response to Lighting," *CIBSE Proceedings*, National Lighting Conference, pp 1-10, April 1990.

Requirements for High Technology Workstations

Principal Investigator:
Belinda L. Collins
Building Environment Division
301-975-6455

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 Headquarters facility.

Problem
The Department of Transportation (DOT) is planning a major new headquarters building and requires technical assistance to develop a design approach to meet its requirements. The building cost is estimated at $450 million, it will accommodate 8000 employees, and its floor area exceeds 3.3 million m^2. It will be the second largest federal building in the Washington, D.C. 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, a workshop with selected experts was conducted as a means of determining the state of the art in intelligent building design. Participants presented papers and discussed 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.

During FY 1993, BFRL is preparing a series of "white papers" for DOT on issues such as lighting, security, and workstation design.

Recent Results
Rubin, Arthur, *Office Workspace for Tomorrow DoT Workshop*, NISTIR 4802, National Institute of Standards and Technology, Gaithersburg, MD, July 1992.

Rubin, Arthur, *Office Workspace for Tomorrow DoT Workshop, Contributing Papers*, NISTIR 4801, National Institute of Standards and Technology, Gaithersburg, MD, March 1992.

FIRE SAFETY ENGINEERING
DIVISION

LARGE FIRE RESEARCH

Simulation of Turbulent Combustion and Transport in Fires

Principal Investigator:
Howard R. Baum
Fire Safety Engineering Division
301-975-6668

Sponsor:
National Institute of Standards and Technology

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

Problem
Information is needed to understand the interaction of a fire with its environment. Such fires range from individual room fires to the large outdoor fires which affect the atmosphere. 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 applied to the study of 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.

Recent Results
Developed three-dimensional windblown smoke plume model that predicts rise and settling processes in idealized atmosphere.

Developed thermal element model for realistic combustion simulations.

Office Building Fire Research Program

Principal Investigator:
Daniel Madrzykowski
Fire Safety Engineering Division
301-975-6677

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

Objective
To quantify the impact of large fires on buildings and their occupants and investigate the use of current technology/resources for mitigating the hazards.

Problem
Systems furniture or "work stations" have been identified as a source of large HRR fires in office buildings. Because of the wide spread use of systems furniture, the potential fire hazard in an open plan office environment needs to be quantified. The conditions in a long corridor (means of egress) adjoining the fire compartment need to be determined. While the impact of sprinklers has been demonstrated in experiments at BFRL, this has not been included in the corridor flow model, because the existing data base and zone modeling techniques are not sufficient to continue development of the corridor flow model including sprinkler effects.

Approach
During FY 1993, BFRL will investigate the extent that materials or geometry effect the fire performance of systems furniture. A combination of laboratory scale and full scale tests will be used to quantify the fire development and address means of mitigating the potential fire hazard. Multiple work station fire tests will be conducted in a large compartment. The compartment will have one wall open to simulate the effects of a typical open plan office space.

The USCG's corridor fire test facility will be used to measure smoke flows down a corridor with and without sprinkler intervention. Results from these tests will be compared with predictions from the existing corridor model in FPEtool (BFRL software to evaluate hazard and fire protection strategies in GSA office buildings) and from the FLOW 3D field

model (a commercial computer model that simulates fluid dynamics and heat transfer using a finite difference approach).

The results of these studies will provide a technical basis for assessing the hazards associated with work stations in an open plan office environment and smoke flow in corridors.

Recent Results
New Project 1993.

In-Situ Burning of Oil Spills

Principal Investigator:
David Evans
Fire Safety Engineering Division
301-975-6897

Sponsor:
Minerals Management Service
Technology Assessment and Research Branch

Objective
To characterize the emissions and dispersion of products from weathering and in-situ burning of oil spills.

Problem
BFRL has established leadership in characterizing the combustion of large pool fires. In support of other agency objectives to implement burning as a response method to oil spills, information on the emissions and trajectory of the particulate material is needed to support its use. Information is also needed about the emissions from evaporation of spills that are not burned to examine the benefits of burning.

Approach
During FY 1993, BFRL will be analyzing data from previous laboratory and mesoscale experiments to support permit applications for offshore experiments in the Gulf of Mexico. Basic measurement methods used in the mesoscale tests have been scaled-up for at sea use. These instruments are being tested in mesoscale experiments in Mobile, Alabama. New ground level measurements of emissions from evaporating spill (pre-ignition) and during burning will be used to help assess relative air quality issues. The capabilities of Fourier transform infrared (FTIR) technology for this purpose will be evaluated. The analysis of plume flow from oil spill burns will continue with modeling of additional data collected in experiments.

Recent Results
Evans, David D., Walton, William D., Baum, Howard R., Notarianni, Kathy A., Lawson, James R., et al, "In-situ Burning of Oil Spills: Mesoscale Experiments," *Proceedings of the Fifteenth Arctic and Marine Oil Spill Program Technical Seminar*, June 10-12, 1992, Edmonton, Alberta, Ministry of Supply and Services Canada, Ontario, 1992.

Characterization of Large Fires

Principal Investigator:
David Evans
Fire Safety Engineering Division
301-975-6897

Sponsor:
National Institute of Standards and Technology

Objective
To develop measurement and analytical methods for characterizing large fires capable of threatening the environment or integrity of urban building complexes, industrial and commercial facilities, and transportation systems.

Problem
Even with the benefits of modern fire protection strategies and technologies, uncontrolled fires remain a constant threat. Fires such as those in the First Interstate Bank building in 1988, the Phillips Chemical plant in 1989, the Oakland Hills residential developments in 1991, and the oil fields of Kuwait in 1991 have potential for wide spread direct and indirect economic impacts. Yet, our knowledge of the near and far field characteristics of these fires, the threat they present to the structural integrity of buildings, facilities, and lifelines and means to mitigate the fire effects are meager. This lack of data is due substantially to the lack of measurement and analytical methods to characterize fires and their impact on the surrounds.

Approach
During FY 1993, BFRL will assess this national issue to determine priorities for research. This will be accomplished by conducting meetings with NIST staff and representatives of industry, government agencies, and other organizations performing fire research. The measurement and prediction of wind-blown smoke plume dispersion and particulate deposition are an important feature and generally a concern in all large fire events. To understand the dynamics of the wind-blown fire plume, near field measurement and predictions are needed. Measurements can be performed in wind tunnel facilities. Predictive methods can be developed based on the technology from BFRL's research, Simulation of Turbulent Combustion and Transport in Fires Project.

It is expected this work will result in a new initiative in fire research dealing with fires that grow beyond the single-room fire, which has been the focal point of research over the past 2 decades.

Recent Results
Ghonseim, A.F., Zhang, K., Knio, O., Baum, Howard, and Rehm, Ronald, "Dispersion and Deposition of Smoke Plumes Generated in Massive Fires," *J. Hazardous Materials*, (in press).

Madrzykowski, Daniel, Evans, David D., "Large Fires: Kuwait," Proceedings of the Twelfth Joint Panel Meeting of the UJNR Panel on Fire Research and Safety, October 1992, Tsukuba, Japan (in press).

The corridor fire test section of BFRL's Large Scale Test Facility is being modified for use as a wind tunnel.

Large Scale Test Facility

Principal Investigator:
Emil Braun
Fire Safety Engineering Division
301-975-6665

Sponsor:
National Institute of Standards and Technology

Objective
To perform large scale fire tests and provide data in support of other fire research projects; apply, refine, and develop methods and equipment that contribute to the successful conduct of large scale fire tests; and develop plans for the expansion and modernization of the facility.

Problem
Use of BFRL's Large Scale Test Facility (Building 205) must be scheduled for timely performance of tests, for upgrading aging equipment, and developing plans for an expanded facility.

Approach
In addition to the daily management of the facility, such as scheduling tests and their timely execution, plans will be developed for modernization for the test facility. These plans will encompass short term needs, i.e., improvement in utilization of existing facility and instrumentation, and long term needs, i.e., expansion of facility, introduction of new measurement techniques, etc. Short term and long term plans will be developed in conjunction with researchers to assure that new and updated instruments fit the needs of the fire program.

Recent Results
Numerous tests have been performed including 2/5 model, pool burns, smoke tunnel.

FIRE SAFETY ENGINEERING
DIVISION

FIRE MODELING

Ceiling Fires

Principal Investigator:
Henri E. Mitler
Fire Safety Engineering Division
301-975-6886

Sponsor:
National Institute of Standards and Technology

Objective
To develop an understanding of the effects of the presence of a ceiling on the evolution of a wall fire in a room, followed by the spread of the fire across the ceiling.

Problem
The effects of the ceiling on room fires is unknown. This lack of data limits our ability to predict the development of room fires. BFRL's wall-fire project (and others) have yielded reasonably successful models which predict wall fires. Most of these studies, however, neglect the effect of the ceiling.

Approach
BFRL will perform this study in three phases; one phase per year. In the first year, a literature survey of fires impinging on ceilings, including axisymmetric fires, wall fires, and corner fires, will be performed. Flame extensions, fluxes and their position dependence, entrainment rates, effect on combustion rates, and ignition of flammable ceilings will be analyzed. A preliminary algorithm will be developed that links the theoretical understanding of flows and combustion under ceilings with empirical observations. A detailed work plan for years two and three will be developed.

In the second year, a preliminary plan for writing a stand-alone ceiling fire computer program will be formulated; this will include the interaction with the wall-fire computer program SPREAD (which predicts the upward fire spread on walls) and plans for its insertion into BFRL's building fire model, CFAST. Numerical investigation of the fluid flows, using FLOW3D (a commercial computer model that simulates fluid dynamics and heat transfer using a finite difference approach), might supplement experiments to yield a quantitative understanding of this behavior. Scaling laws can be examined and/or established. Based on the new data, devise a much better algorithm, and publish a report on the work.

In the third year, calculate effects of ceiling ignition when ceiling is flammable, program the algorithm, merge it with SPREAD, and harmonize it with CFAST. Finally, validate the new program, write documentation, and incorporate the program into CFAST.

It is expected that a preliminary engineering-level algorithm will be developed by September 1993 and a superior one by September 1994 for incorporation into HAZARD.N by September 1995.

Recent Results
New project 1993.

Large Scale Smoke Movement

Principal Investigator:
John H. Klote
Fire Safety Engineering Division
301-975-6890

Sponsor:
National Institute of Standards and Technology

Objective
To develop and verify algorithms for modeling large scale smoke movement in buildings.

Problem
The simulation of smoke movement in HAZARD (BFRL's model that predicts the hazard to a building and occupants anywhere within a building) has limited applicability to large spaces such as corridors, atria, and shafts. There is a need to realistically simulate smoke transport in these spaces.

Approach
During FY 1993, BFRL will address four building elements:

Shaft: The approach to determining smoke flow in elevator shafts will consist of developing a zero order model and a first order model. The zero order model will neglect buoyancy of smoke in the shaft. Example calculations will be made to gain understanding of the impact of natural building flows in shafts on smoke transport and to determine if the zero order model is appropriate for some fire engineering applications. Based on FLOW3D (a commercial package computer model that simulates fluid dynamics and heat transfer using a finite difference approach) visualization and ongoing grants to California Institute of Technology and to Rutgers University, work will start on a conceptual first order shaft model. Smoke flow in stairwells will be addressed later in this project.

Corridor: Experiments and field modeling for corridor model validation will be performed contingent on funding.

Atrium: The experiments in atrium vent flow at the Fire Research Institute (FRI) in Japan will be completed, and a generalized mathematical model of atrium vent flow will be developed.

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

The algorithms developed by this project will allow realistic simulation of smoke transport in these spaces. The applicability of the HAZARD methodology will be extended to large scale smoke flow including office buildings, apartment buildings, homes for the elderly, and Navy and merchant ships.

Recent Results
Matsushita, T., and Klote, John H., *Smoke Movement in a Corridor-Hybrid Model, Simplified Model and Comparison with Experiments*, NISTIR 4982, National Institute of Standards and Technology, Gaithersburg, MD, 1992.

Cooper, Leonard Y. and Yamada, T., "Experimental Study of the Exchange Flow Through a Horizontal Ceiling Vent in Atrium Fires," 12th UJNR Joint Panel Meeting on Fire Research and Safety, Tokyo, 1992 (in press).

Hazard Development

Principal Investigator:
Richard D. Peacock
Fire Safety Engineering Division
301-975-6664

Sponsor:
National Institute of Standards and Technology
and
The U.S. Department of Navy
Naval Research Laboratory

Objective
To plan and implement the next generation hazard methodology (HAZARD 1.2).

Problem
Traditional approaches to product design, product evaluation, and codes and standards development address fire safety in a piecemeal fashion such as 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
This research is composed of two categories: 1) advancing the physics in the model and 2) improving the numerics and structure of the models comprising HAZARD. Single-surface pyrolysis and fire suppression algorithms will be incorporated in the fire model. BFRL will continue the unification of the user interface with new-generation input editor and hazard shell including a new unified input data file. The internal structure of the model will continue to be addressed by refining the internal data structures to be consistent with the streamlining of the solver routines completed last year. Customers include manufacturers, purchasers, architects, FPE's, code officials, and practitioners who evaluate safety performance, code equivalency, and code change proposal issues. The HAZARD 1.2 model is expected to be completed by August 1994.

The benefits of this research are: pyrolysis and fire suppression algorithms will allow the user to study fire scenarios without costly full-scale testing to develop input data for the model and improving the internal structure will allow easier inclusion of future algorithms and allow more researchers to contribute to development of the model.

Recent Results
Peacock, Richard D., Forney, Glenn P., Reneke, Paul A., Portier, Rebecca W., and Jones, Walter, W., *CFAST, The Consolidated Model of Fire Growth and Smoke Transport*, NIST Technical Note 1299, National Institute of Standards and Technology, Gaithersburg, MD, 1993.

Portier, R., Reneke, Paul A., Jones, Walter W., and Peacock, Richard D., *A User's Guide for CFAST, Version 1.6*, NISTIR 4985, National Institute of Standards and Technology, Gaithersburg, MD, 1992.

Moss, W. F. and Forney, Glenn P., *Implicitly Coupling Heat Conduction into a Zone Fire Model*, NISTIR 4886, National Institute of Standards and Technology, Gaithersburg, MD, 1992.

Forney, Glenn P. and Moss, W.F., *Analyzing and Exploiting Numerical Characteristics of Zone Fire Models*, NISTIR 4763, National Institute of Standards and Technology, Gaithersburg, MD, 1992.

Bukowski, Richard W., "Analysis of Happyland Social Club Fire with HAZARD I," *Fire and Arson Investigator*, 42 (3), 1992.

Braun, Emil, Lowe, Darren, L., Jones, Walter W., Tatem, P., Bailey, J., and Carey, R., *Comparison of Full Scale Fire Tests and a Computer Fire Model of Several Smoke Ejection Experiments*, NISTIR 4961, National Institute of Standards and Technology, Gaithersburg, MD, 1992.

Peacock, Richard D., Jones, Walter W., and Bukowski, Richard W., "Verification of a Model of Fire and Smoke Transport," *Fire Safety Journal*, (accepted for publication).

Development of the Fire Data Management System (FDMS) Database System for Fire Related Data

Principal Investigator:
Rebecca W. Portier
Fire Safety Engineering Division
301-975-6757

Sponsor:
National Institute of Standards and Technology

Objective
To develop a second generation database which can accommodate all fire related data for use by those professionals collecting and using data on building fires.

Problem
A unified method of accessing data is crucial to both experimental and modeling efforts in the development of the science of fire. The Fire Data Management System (FDMS) concept is well founded and important to experimentalists acquiring data, and to modelers and others using data related to fires and material properties. On-going work to develop the concept into a working program has had limited success. It lacks some of the functions, is not portable across computer platforms, and the software libraries are no longer supported.

Approach
This research will be performed over three years. During the first year, BFRL will examine the functionality as required by the FDMS specification and define additional fields needed for the export format to make this work compatible with the programs under development. An important aspect of this research is insuring that all data can be moved from previous versions of the FDMS databases, including the export format currently in use.

The second year effort will involve writing all functions including the query and report writing. The third year addresses writing interface modules for models and for general use, in particular, for data importing for round robin testing. BFRL's work is expected to include in its database the Cone, Lateral Ignition and Flame Spread Test Apparatus (LIFT), Eurefic corner tests, and furniture calorimeter data.

Recent Results
Portier, Rebecca W., A Programmer's Reference Guide to FDMS File Formats (in review).

FIRE SAFETY ENGINEERING
DIVISION

FIRE PROTECTION APPLICATION

Furniture Flammability

Principal Investigator:
Vytenis Babrauskas
Fire Safety Engineering Division
301-975-6681

Sponsor:
National Institute of Standards and Technology

Objective
To develop performance criteria leading to more fire-resistive upholstered furniture.

Problem
During the recent past, manufacturing technologies have emerged that allow modest-cost, fire-improved upholstered furniture designs to be realized. Systematic performance knowledge on these systems is not available; especially lacking are predictive methods which would allow some measure of performance to be gauged prior to conducting full-scale fire tests.

Approach
During last year's work, BFRL established the commercial viability of modest-cost systems for achieving fire-improved upholstered furniture designs. During FY 1993, BFRL will perform bench scale HRR tests on composites; evaluate techniques not requiring actual-use composite testing; evaluate possible successful matches between the various materials comprising this system; identify the geometric and construction factors leading to propagating versus non-propagating fires; and predict full-scale performance based on small-scale, lower cost tests.

This work includes:

1. Predicting an initial quantitative assessment of fire improved upholstery systems that use barriers as the protective mechanism. Barrier utilizing systems will be tested in mockup scale and in bench scale, with an objective of allowing performance predictions from Cone Calorimeter measurements.

2. Exploring the physical mechanism of failure associated with the seat cushion/side-arm juncture will be explored through mockup testing.

3. Studying one of the California Bureau of Home Furnishings (BHF) round robin materials which showed good performance in the mockup tests, yet high HRR in the Cone Calorimeter, will be studied further in the mockup scale to determine the reasons for the discrepancy.

Recent Results
Cleary, T.G., Ohlemiller, T.J. and Villa, K.M., *The Influence of Ignition Source on the Flaming Fire Hazard of Upholstered Furniture*, NISTIR 4847, National Institute of Standards and Technology, Gaithersburg, MD, 1992.

Babrauskas, Vytenis, "Toxicity, Fire Hazard, and Upholstered Furniture," *Third European Conference on Furniture Flammability*, Brussels, Interscience Communication Ltd, London, pp 125-133, 1992.

Merger of FPETOOL and HAZARD I

Principal Investigator:
Richard W. Bukowski
Fire Safety Engineering Division
301-975-6853

Sponsor:
National Institute of Standards and Technology

Objective
To use FPEtool (BFRL software to evaluate hazards and fire protection strategies in GSA Office Buildings) as a front end to HAZARD I (BFRL's model that predicts the hazard to a building and occupants anywhere within a building) for making initial estimates with shared data inputs.

Problem
Users such as FPEs, product manufacturers, regulators, and product specifiers of both these computer programs have requested that they be merged together to provide a more powerful and broader fire hazard prediction program.

Approach
The FPEtool code will be incorporated into the HAZARD I package as a "front end," to produce initial estimates before performing detailed calculations. FPEtool outputs will be displayed through the HAZARD I plotting routines and both will be able to share databases for "objects." Hooks to SURVIVAL (the integrated evacuation and tenability routine for future versions of HAZARD) will be established to allow for person impact determinations to be made from FPEtool. FPEtool also will be part of HAZARD to multiple computing platforms. In addition to unifying the BFRL modeling effort, the combined software will provide users with access to both models and eliminates the requirement to incorporate interface techniques.

Recent Results
This activity was discussed at the Hazard I/FPEtool Users Conference, fall 1992. User training will begin during summer, 1993.

Cone/Lift/Toxicity Support

Principal Investigator:
Andrew J. Fowell
Fire Safety Engineering Division
301-975-6865

Sponsor:
National Institute of Standards and Technology

Objective
To provide technical support for standards activities associated with BFRL's Cone Calorimeter, Lateral Ignition and Flame Spread Test Apparatus (LIFT), and BFRL's development of the NIBS Toxicity Test.

Problem
As originator of the Cone, LIFT, and NIBS toxicity protocol, and promoter of bench-scale measurements to provide input to predictive fire models, BFRL needs to continue providing answers to technical inquiries by new users of the tests at ASTM and ISO standards meetings, and at technical meetings addressing material flammability measurement. Each protocol is undergoing a round robin series of tests in which BFRL agreed to be a participant or provide technical assistance.

Approach
During FY 1993, BFRL will:

1. Attend ASTM E.5 and ISO TC 92 committee meetings to propose appropriate changes to the protocols and ensure that any changes made are technically correct.

2. Question material manufacturers and testing labs (customers for these protocols) to identify problems.

3. Make presentations at meetings addressing subjects such as, rate of heat release and material flammability.

4. Complete data analysis and report for the LIFT round robin testing program.

It is expected the European Community will adopt the Cone and the LIFT protocols as European standards to replace the variety of tests currently used by the individual EC countries.

Recent Results

ASTM, 1992a, "Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter," *ASTM Standard E1354-92*, ASTM, Philadelphia, PA, 1992.

ISO, 1992, "Fire Test-Reaction to Fire-Rate of Heat Release from Building Products," *ISO Standard 5660*, 1992.

The Heat Release Institute was formed as a result of information and data developed by this project.

Comprehensive Fire Risk Assessment Method

Principal Investigator:
Richard W. Bukowski
Fire Safety Engineering Division
301-975-6853

Sponsor:
National Institute of Standards and Technology

Objective

To develop an internationally accepted fire risk calculation method that serves as the basis for a performance fire code.

Problem

Most worldwide fire research organizations are involved in developing comprehensive fire risk assessment methods for establishing compliance with provisions of performance based codes. For example, the Japanese have developed a prototype method which demonstrates equivalence to their code. Their method is being extensively revised. Australia is developing a similar system and has published the framework for public review. England, Norway, Sweden, New Zealand, and Finland are actively pursuing risk methodology development. Denmark, Germany, The Netherlands, and Singapore have interest in pursuing this subject area. Researchers from most of these countries' fire research laboratories have met under the auspices of the International Council for Building Research, Studies, and Documentation (CIB) Working Commission on Fire Research (W14); International Organization for Standardization TC92/SC4; or the FORUM for international cooperation on fire research. They agreed that a collaboration resulting in a single, harmonized method should be undertaken.

BFRL, in a 4 year project funded by the NFPA Research Foundation, developed a product fire risk evaluation method which also can be used for building risk assessment.

Approach

BFRL will contribute to a newly established international cooperative effort. A working group will be established to review the literature generated on this subject and identify elements to form the final method. BFRL will quantify the input and output needs of each step so alternative methods can be applied in a consistent and uniform man-

ner. BFRL also will prepare a paper on the application of Bayesian statistics to the fire risk assessment problem and will provide access to its software for performing risk calculations.

Recent Results

Bukowski, Richard and Tanaka (BRI, Japan), "Performance Fire Codes," *Fire and Materials*, 15, pp 175-180, 1991.

Bukowski, Richard, "Review of International Risk Prediction Methods," *Proceedings of International Fire Safety Engineering Conference, The Concepts and the Tools*, Sydney, Australia, 1991.

Heat and Smoke Movement Influence on Detector and Sprinkler Response in Enclosed Spaces with Complex Ceiling Geometries

Principal Investigator:
Richard W. Bukowski
Fire Safety Engineering Division
301-975-6853

Sponsor:
National Fire Protection Research Foundation

Objective

To examine the effect of complex ceiling geometry and obstructions to distribution of heat and smoke for optimizing requirements for automatic fire detector location found in NFPA 72E and for automatic sprinklers in NFPA 13, 13D, and 13R.

Problem

Recommendations for placing automatic fire detectors (NFPA Standard on Detection Devices [72E]) are based on engineering judgement or on experiments done by Heskestad and Delichatsios on flat, unobstructed ceilings. In the implementation of these data, tables and curves were developed from calculations with a zone model which are applicable for flat, unobstructed ceilings. Since 72E includes recommendations for placing of fire detectors in spaces with sloping or peaked ceilings, or with open beams and joists, some validation of these recommendations is necessary. Further, detector sighting problems associated with stratification and high air movement from HVAC systems are mentioned in the standards but limited installation guidance is provided.

Approach

During FY 1993 and FY 1994, BFRL will examine the effects of fire size, fire location, ceiling height, ceiling slope, typical ceiling beam or joist configurations, and the effect of stratification on the distribution of heat and smoke from the fire. During FY 1995 and FY 1996, BFRL will evaluate the effects of HVAC systems on fire detectors and sprinkler activation.

Specific geometries to be examined have been selected to coincide with experimental studies identified in the literature review being performed during FY 1993.

This project's approach is designed to be applicable over a wide range of detector types and installation characteristics. Detector types include those that respond to heat, smoke, and gas. The studies will be carried out numerically, using a field model, Flow3D (a commercial package computer model that simulates fluid dynamics and heat transfer using a finite difference approach), to simulate the room geometries and fire growth; selected experimental verification will be included as needed.

Contour plots will be developed of temperature, velocity, and smoke concentration near the ceiling at the level of the sensing components of typical detectors and sprinklers. These detailed distributions will be used to develop engineering guidelines for detector/sprinkler placement, resulting in recommendations for changes to the appropriate NFPA standards.

Recent Results
Forney, Glen P., Davis, William D., and Klote, John H., *Simulating the Effects of Beamed Ceiling on Smoke Flow, Part I Comparison of Numerical and Experimental Results*, NISTIR 4994, National Institute of Standards and Technology, Gaithersburg, MD, 1992.

Technical Assistance for Evaluating Fire Barrier Performance

Principal Investigator:
Vytenis Babrauskas
Fire Safety Engineering Division
301-975-6681

Sponsor:
Nuclear Regulatory Commission
Office of Reactor Regulation

Objective
To provide specialized BFRL expertise to NRC in reviewing and evaluating technical issues related to fire barrier systems.

Problem
The Nuclear Regulatory Commission questions the efficacy of certain fire barrier systems installed in nuclear power plants and requires information to assess the performance of the existing barrier systems and possibly to recommend remedies.

Approach
BFRL's work involves:

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.

9. Perform toxicity tests on the gaseous products of barrier materials exposed to a fire.

Recent Results
Prepared summaries of results from pilot scale fire endurance testing.

Effects of Fire Suppressants on Safety Related Equipment

Principal Investigator:
Robert S. Levine
Fire Safety Engineering Division
301-975-6671

Sponsor:
Nuclear Regulatory Commission
Office of Nuclear Regulatory Research

Objective
To evaluate the effects of fire suppressants on safety equipment important in nuclear power plants.

Problem
Nuclear power plants have many installed fire protection systems. When inadvertent operation occurs, the suppressant (water, CO_2, or Halon are used) may damage operating equipment and/or interfere with safety circuits or create spurious signals.

It was observed, when sea water was not used onboard ships to fight fires, the incidence of damaging effects was much less on ships than that experienced by 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. When sea water is used to extinguish fires, there is a very large probability that electrical equipment exposed to it will be damaged.

Approach
BFRL has reviewed data provided by the Navy Safety Center to address the variety of operating system incidents on ship and shore facilities to gain insight into effects that might occur and to enrich the limited statistical data from nuclear power plant experience.

Recent Results
Identified 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. NRC determined that the problem of inadvertent operation of fire protection systems was not severe enough to require changes to existing power plants systems.

Fire and Thermal Characteristics of Navy Fire Fighter Trainers

Principal Investigator:
Robert S. Levine
Fire Safety Engineering Division
301-975-6671

Sponsor:
Department of Navy
Naval Training Systems Center

Objective
To support the development and implementation of prototype fire fighter trainers.

Problem
There is need to improve the reliability of fire trainers – do not cause injuries to trainees and at the same time provide trainees with realistic training experiences.

Approach
During FY 1993, BFRL will continue to measure 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.

Special analyses are being performed by BFRL and other NIST personnel to obtain information for solving developmental problems. For example, BFRL is performing metallurgical analysis of slag from a failed smoke generator; examining by electron microscope, ceramic insulation to determine the cause of failure; and modifying field equation modeling of possible solutions to problems caused by wind affecting the flames on a carrier deck fire trainer.

Recent Results
BFRL obtained and analyzed data on prototype trainers. These results are presented to the Naval Training Systems Center and to the Naval Project Team meetings on the various trainers.

Live Fire Testing

Principal Investigator:
Robert S. Levine
Fire Safety Engineering Division
301-975-6671

Sponsor:
Office of the Secretary of Defense
Office of Live Fire Testing

Objective
To support critical review of live fire test plans and analysis.

Problem
There is a need to confirm adequacy of instrumentation and analysis methods to discern effects of resulting fire and toxic gases on personnel, and the effects of fire on the operational capability of equipment under test, and structural degradation due to fire.

Approach
During FY 1993, BFRL will provide consultation services on aspects of the test plans and the analysis. Subjects for study will be assigned by the Office of Live Fire Testing through the Institute of Defense Analyses (IDA). On some technical problems, BFRL personnel will work closely with IDA personnel.

Emphasis will be placed on providing technical assistance for tests related to the SSN-21 (SEAWOLF) Sea Control Submarine and the DDG-51 Frigate. Here, effects of fire will be predicted as functions of time and suppression action.

Recent Results
FIRST 30 (Harvard single room fire combustion model) and LAVENT (Link Actuated VENTS user friendly computer code) programs have been modified to calculate "hot spot" bulkhead temperatures (in addition to average temperatures). The modified programs will be validated against Navy (China Lake) Hull Vulnerability Program (HULVUL) data and Ex-SHADWELL (Mobile Bay) test data to calculate time required for Class A Fire Growth under battle damage scenarios.

Public Education Booklet on Household Fire Warning Equipment

Principal Investigator:
Richard W. Bukowski
Fire Safety Engineering Division
301-975-6853

Sponsor:
U.S. Fire Administration

Objective
To develop a booklet describing household fire protection methods, rationale for using the methods, and the relationship between these methods and fire requirements in national standards.

Problem
There is a lack of information about the fundamental reasons for making decisions about household fire protection because code provisions are arbitrary.

Approach
During FY 1993, BFRL will develop a report that addresses home fire hazards and fire prevention, self-contained smoke (and heat) detectors, residential fire alarm systems (including remote monitoring services), and residential sprinkler systems. The interface between residential sprinklers and alarms will be covered. The material will draw on published materials from the USFA, NFPA, and others. The report will be drafted in a way to show sensitivity to concepts which will motivate both english-speaking and hispanic audiences.

Recent Results
Developed an illustrated booklet, *Protecting Your Family From Fires*, written in English and Spanish for publication by the U.S. Fire Administration who will distribute the booklet free of charge through their resource catalog.

Escape Planning for Board and Care Facility Residents

Principal Investigator:
Scot Deal
Fire Safety Engineering Division
301-975-6891

Sponsor:
U.S. Fire Administration

Objective
To develop an occupant evacuation plan in the event of a fire in a board and care (B&C) facility.

Problem
Formal guidelines for development of effective escape plans for board and care facilities do not exist. Plans must include staff actions and procedures to ensure the safety of residents including those with unusual or special needs. Training guidelines also are needed for the facility staff.

Approach
The work will build upon research funded by the Department of Health and Human Services. It addresses five tasks:

1. Identify representative sample of B&C facilities that meet different editions of the life safety code.

2. Characterize staff and occupant evacuation capabilities using FSES E-score system.

3. Identify representative fires in B&C facilities from existing review articles:

a. historical fires significant for reasons of life loss
b. historical fires significant for reasons of frequency
c. plausible fires significant for reasons of hazard

4. Evaluate egress conditions with an engineering analysis using the following tools:

a. computer models which simulate the fire environment
b. models predicting people movement
c. models predicting human debilitation from heat and chemical loading

5. Identify strategies and tactics which might improve occupant and staff ability to safely evacuate.

This research will provide regulatory officials with a checklist to determine if board and care facilities comply with the fire safety code for evacuation training.

Recent Results
Levin, Bernard M., Groner, N., E., Paulsen, R., *Affordable Fire Safety in Board and Care Homes: A Regulatory Challenge*, NIST-GCR-92-611, National Institute of Standards and Technology, Gaithersburg, MD, May 1992.

Sprinkler Standard for Board and Care Facilities

Principal Investigator:
Scot Deal
Fire Safety Engineering Division
301-975-6891

Sponsor:
U.S. Fire Administration

Objective
To develop an analytical method for evaluating installation requirements for sprinkler systems for inclusion in a fire protection standard for board and care (B&C) facilities.

Problem
The current Life Safety Code contains requirements for sprinkler protection of new and substantially renovated B&C facilities according to NFPA 13D. For existing facilities, a strong compartmentation option is provided. In all cases, smoke detection is required in limited areas. Information is needed to understand the potential impact of fires beginning in spaces not required to be sprinklered under 13D, especially in light of the limited capacity of many B&C home residents to react properly and quickly.

Approach
During FY 1993, BFRL will perform an engineering analysis of the fire protective systems required in the Life Safety Code to assess its potential to address the needs of residents and staff in an emergency. The analysis will draw on results of experimental studies in the literature and on computer modeling in situations where test data are not available or appropriate. Fire scenarios representative of those occurring in B&C homes will be drawn from a review of actual fire incidents in this occupancy. This work will evaluate the efficiency of sprinkler protection (compared to alternate approved approaches) in maintaining a safe environment for board and care occupant survival and evacuation during fire emergencies. National Fire Code committees will have a resource to evaluate their choices when developing new regulations.

Recent Results
New project 1993.

Fire Research Computer Bulletin Board System (FRBBS)

Principal Investigator:
Scot Deal
Fire Safety Engineering Division
301-975-6891

Sponsor:
National Institute of Standards and Technology

Objective
To improve and operate the FRBBS as an effective means of technology transfer for the BFRL fire program.

Problem
The FRBBS serves as the primary means for distribution of much of the software developed by the fire program. The system logs 2300 users per year making 2500 file downloads. Without this system for automatic access, staff would spend much time performing this task.

Approach
In the 4 years that FRBBS has been in operation, the hardware and software has become obsolete. The system will be upgraded to a faster computer with the capability of multiple line access. The computer will be equipped with a new modem capable of 9600 baud (V.32bis/V.42bis compliant). New software with a similar but simple user interface will be procured.

Once the FRBBS capabilities have been upgraded, several new methods to enhance system use will be tried such as:

1. Posting of new BFRL publications (with abstract).

2. Posting of fire program project summaries.

3. Establishing two way information exchange for fire reconstructors using models. This method will allow persons to solicit advice from BFRL and from other users.

Recent Results
The FRBBS received significant acclaim from the fire community; the labor savings from allowing users to download software has paid for the system.

Fire Research Information Service

Principal Investigator:
Nora H. Jason
Fire Safety Engineering Division
301-975-6862

Sponsor:
National Institute of Standards and Technology

Objective
To maintain BFRL's Fire Research Information System (FRIS) as the world's preeminent fire research library and to expand its role to provide access to resources needed to apply fire science findings.

Problem
FRIS is a crucial resource to BFRL's fire program and is growing in importance to the international community. FRIS needs to take the lead in defining and implementing the transition of fire libraries into technical information and dissemination resources in support of the application of fire science.

Approach
During FY 1993, this work will continue its thrust of inputing BFRL documents into FIREDOC. The FIREDOC system will greatly expand its international access through connection into the INTERNET system by migrating to a UNIX platform. In combination with the UNIX platform and improvements to the BBS hardware, an increased outside utilization of these resources is expected.

FRIS will take the lead in developing data resources in support of calculational procedures by implementing FDMS and HAZARD I databases for access through INTERNET and telephone. Once implemented, inFIRE members will be recruited to both collect data in their own areas for addition to the system and to implement databases of their own for support of local needs.

FRIS also will complete the needed expansion of facilities to reduce the current overcrowding.

Recent Results
Nora H. Jason, Ed, *Summaries of BFRL Fire Research In-House Projects and Grants 1992*, NISTIR 4918, National Institute of Standards and Technology, Gaithersburg, MD 20899, September 1992.

Nora H. Jason, *Building and Fire Research Laboratory Publications, 1991*, NISTIR 4827, National Institute of Standards and Technology, Gaithersburg, MD 20899, April 1992.

FIRE SCIENCE
DIVISION

SMOKE DYNAMICS RESEARCH

Carbon Monoxide Production and Prediction

Principal Investigator:
William M. Pitts
Fire Science Division
301-975-6486

Sponsor:
National Institute of Standards and Technology

Objective
To develop procedures for engineers and material designers to make accurate predictions of the quantity of CO produced under specified conditions.

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 CO generated by fires. A predictive capability is required similar to fire models as HAZARD (BFRL's software that predicts the hazard to a building and occupants anywhere in the building).

Approach
BFRL is performing engineering and fundamental investigations to predict CO production in fires. The engineering studies are developing appropriate correlations for CO formation for fires in enclosures and provide knowledge to incorporate the findings into existing BFRL fire models. The fundamental investigations are identifying the principal chemical and physical mechanisms responsible for the formation of high CO concentrations in fires and theoretically justifying the use of the engineering correlations. These findings will be incorporated into a simple physical model for CO production in enclosed fires.

Recent Results
Pitts, William M., "Reactivity of Product Gases Generated in Idealized Enclosure Fire Environments," *Twenty-Fourth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp1737-1746, 1992.

Bryner, Nelson, Johnsson, Erik L., and Pitts, William, *Carbon Monoxide Production in Compartment Fires--Reduced-Scale Enclosure Test Facility*, National Institute of Standards and Technology, Gaithersburg, MD, 1993, in press.

Pitts, William, M., *The Global Equivalence Ratio Concept and the Prediction of Carbon Monoxide Formation in Enclosure Fires*, National Institute of Standards and Technology, Gaithersburg, MD, 1993, in press.

Davis, William D., *Analysis of a Reduced Scale Enclosure Using a Field Model*, National Institute of Standards and Technology, Gaithersburg, MD, 1993, in press.

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

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

"Compartment Fire Combustion Dynamics," U. Vandsburger, Virginia Polytechnic Institute and State University and R. J. Roby, Hughes Associates.

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

Soot Formation and Evolution

Principal Investigator:
Kermit C. Smyth
Fire Science Division
301-975-6490

Sponsor:
National Institute of Standards and Technology

Objective
To develop a prediction method of the formation of soot in flames and the evolution of smoke components from flames.

Problem
There is inadequate information available to make accurate predictions of within flame soot production and smoke yield from flames and its optical properties to assess radiation properties of fires and their production of toxic gases.

Approach
During FY 1993, BFRL is:

1. Performing optical and mass spectrometric measurements to obtain accurate and quantitative species profile data, particularly for radicals such as OH, in hydrocarbon diffusion flames.

2. Comparing experimental results to detailed computations of Smooke when soot is not present and with Kennedy when soot is included.

3. Making accurate measurements of the optical properties of soot particles emitted from hydrocarbon diffusion flames.

4. Making new measurements of soot and radical concentrations in time-varying diffusion flames to explore the influence of a wide range of residence time, temperature, strain rate, and local stoichimetry upon soot production processes.

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

Recent Results
Norton, T.S., Smyth, K.C., Miller, J.H., and Smooke, M.D., "Comparison of Experimental and Computed Species Concentration and Temperature Profiles in a Laminar, Methane/Air Diffusion Flame," *Combustion Science and Technology*, 90, pp 1, 1993.

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," *Twenty-Fourth Symposium (International) on Combustion*, pp 1015, 1992.

Harrington, J.E. and Smyth, K.C., "Laser-Induced Fluorescence Measurements of Formaldehyde in a Methane/Air Diffusion Flame," *Chemical Physics Letters*, (in press).

Smyth, K.C., Harrington, J.E., Johnsson, E.L., and Pitts, W.M., "Greatly Enhanced Soot Production in Flickering CH_4/Air Diffusion Flames," submitted to *Combustion and Flame*.

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.

"Experimental and Modeling Studies of Soot and Carbon Monoxide in an Ethylene/Air Diffusion Flame," J. Houston Miller, George Washington University.

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

Study of Smoke Agglomerates

Principal Investigator:
George W. Mulholland
Fire Science Division
301-975-6695

Sponsor:
National Aeronautics and Space Administration
Exobiology Flight Experiments Program

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 method for studying smoke agglomerates in an orbiter facility.

Approach
Make use of Transmission Cell-Reciprocal Nephelometer recently developed by 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. The results of this research provide an assessment method of the accuracy and utility of fractal optics for large agglomerates and to provide optical property information needed for estimating the climatic impact of massive fires.

Recent Results
Mulholland, George W, and Bryner, Nelson P., "Radiometric Model of the Transmission-Cell Reciprocal Nephelometer," *Atmospheric Environment* (submitted for publication).

Smoke Sampling Techniques Training Course and Smoke Sampling in Saudi Arabia

Principal Investigator:
Nelson Bryner
Fire Science Division
301-975-6868

Sponsor:
Kingdom of Saudi Arabia
Ministry of Defence and Aviation

Objective
To train three Saudi professionals in smoke sampling techniques, collect samples in Saudi Arabia, and jointly analyze smoke samples.

Problem
Health and safety problems result from acute exposure to unhealthy environmental conditions, such as smoke from oil well fires.

Approach
This work includes training three Saudi professionals at BFRL, during a two-week period, on techniques for sampling smoke. Two NIST personnel (BFRL and Chemical Science and Technology Laboratory) will perform follow-up discussions and smoke and gas sampling in Saudi Arabia. Split-sample analysis will be conducted with some of the samples being analyzed by the Saudis and others by BFRL for more specialized analysis such as laser microprobe analysis.

Recent Results
Transferred smoke sampling techniques to three Saudi professionals and collected ambient smoke and gas samples in Saudi Arabia.

FIRE SCIENCE
DIVISION

MATERIALS FIRE RESEARCH

Polymer Flammability Modeling

Principal Investigator:
Marc R. Nyden
Fire Science Division
301-975-6692

Sponsor:
National Institute of Standards and Technology

Objective
To develop the technical basis for designing 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
Flammability is a major concern when polymeric materials are used in buildings, aircraft, ships, and clothing. The need for a more rational approach to designing fire resistant materials has become more pressing as standards for acceptable cost, performance, and safety become more demanding.

Approach
There is a strong correlation between char residue and fire resistance since char is always formed at the expense of volatile fuel. Surface char also insulates unburnt material from the heat generated in gas phase combustion reactions and obstructs the outward flow of combustible gases generated in the degradation of the interior. 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.

BFRL's approach is based on using its molecular dynamics model of the thermal degradation of polymers. The dynamic trajectories of the polymers are calculated from Hamilton's equations of motion. Macromolecular systems, which are 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.

This research will benefit the chemical industry and consumers using their products by establishing a technical basis for designing a new generation of fire resistant materials.

Recent Results
Nyden, Marc R. and Brown, James E., "Computer-Aided Molecular Design of Fire Resistant Aircraft Materials," International Conference for the Promotion of Advanced Fire Resistant Aircraft Interior Materials, Atlantic City, NJ, February 1993.

Nyden, Marc R., and Brown, James E., "A New Generation of Fire Resistant Polymers: Part I Computer-Aided Molecular Design," Proceedings of the 12th Joint Panel Meeting, UJNR Panel on Fire Research and Safety, Tsukuba, Japan, 1992 (in press).

Burning Rate of Materials

Principal Investigator:
Takashi Kashiwagi
Fire Science Division
301-975-6699

Sponsor:
National Institute of Standards and Technology

Objective
To develop burning rate models (global and field equation) of polymeric materials (including char formers) for simple horizontal configurations.

Problem
Models have not yet been developed that can calculate the burning rate (heat release rate) of building contents. Therefore, a fire source is 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). To improve fire hazard predictions, accurate description of a fire source is urgently needed.

Approach
BFRL is performing this work as two parts:

1. Determining energy feedback rates from a pool flame for various fuels and sizes.

2. Determining the gasification rate of various polymers.

Gas phase combustion characteristics are being measured for a variety of fuels with pool diameters up to 1 m. Global and field equation energy feedback models are developed as a function of fuel type and size. In the condensed phase, a well-defined thermal radiation source is being used to simulate energy feedback from a flame to a polymer surface. The gasification rate, temperature, and density distributions in the polymer are measured under non-flaming conditions for various radiant fluxes. Gasification models for thermoplastics and char forming polymers are under development.

Recent Results
Yang, J.C., Hamins, A., and Kashiwagi, T., "Estimate of the Effect of Scale on Radiative Heat Loss Fraction and Combustion Efficiency," submitted to *Combustion Science and Technology*, 1992.

Hamins, A., Yang, J.C., and Kashiwagi, T., "An Experimental Investigation of the Pulsation Frequency of Flames," *Twenty-Fourth Symposium (International) on Combustion, The Combustion Institute*, Pittsburgh, PA, pp 1695-1702, 1992.

Klassen, M., Gore, J., Hamins, A., and Kashiwagi, T., "Radiative Heat Feedback in a Toluene Pool Fire," *Twenty-Fourth Symposium (International) on Combustion, The Combustion Institute*, (in press), 1992.

Grants
"A Study of Structure and Radiation Properties of Pool Fires," J.P. Gore, Purdue University.

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

Flame Retardant Study on Engineering Plastics

Principal Investigator:
Takashi Kashiwagi
Fire Science Division
301-975-6699

Sponsor:
General Electric Company
Chemical Research Center
Corporate Research and Development

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

Problem
GE is interested in nonhalogenated flame retardant treatment for use in improving fire resistance performance of its engineering thermoplastics.

Approach
During FY 1993, BFRL is:

1. Conducting a systematic study of pyrolysis/gasification of selected samples in nitrogen under various external radiant fluxes comparable to fire conditions.

2. Measuring heat transfer to substrate, degradation products and analyze residual char layers slicing from the top surface to the inside to obtain history in char structure by measurements of C/H ratio, aliphatic/aromatic components using an elemental analysis and NMR.

3. Measuring flammability properties of grafted PPO samples and also composite samples to determine the effects of the flame retardant treatments of these samples. The results of this collaborative project are expected to produce better flame retardant treatments by understanding the chemical and physical nature of char and flammability properties.

Recent Results
Kashiwagi, Takashi and Cleary, Thomas, "Effects of Sample Mounting on Flammability Properties of Intumescent Polymers," *Fire Safety J.* (accepted for publication).

Kashiwagi, Takashi and Cleary, Thomas, "A Nonhalogenated Flame Retarded Polycarbonate," International Conference for the Promotion of Advanced Fire Resistant Aircraft Interior Materials, Atlantic City, NJ, February 1993.

Fire Resistant Aircraft Materials

Principal Investigator:
Marc R. Nyden
Fire Science Division
301-975-6692

Sponsor:
Federal Aviation Administration
Aviation Safety Division

Objective
To assess the viability of using high energy irradiation to reduce the flammability of materials suitable for use in the interiors of commercial aircraft.

Problem
Synthetic polymers comprise a significant fraction of the fire load borne by commercial aircraft interiors. The flammability, smoke, and toxicity characteristics of these materials may impact passenger survivability in the event of an in-flight fire or a postcrash fire.

Approach
There is a strong correlation between char residue and fire resistance since char is always formed at the expense of volatile fuel. Surface char also insulates unburnt material from the heat generated in gas phase combustion reactions and obstructs the outward flow of combustible gases generated in the degradation of the interior. 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.

BFRL will use its molecular dynamics model to determine the thermal degradation of polymers. The dynamic trajectories of the polymers are calculated from Hamilton's equations of motion. Macromolecular systems, which are 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.

The results from this work are expected to increase the fire resistance of existing aircraft materials and develop the technical basis for the design of a new generation of ultra-fire resistant polymer grafts and composites used in commercial aircraft interiors.

Recent Results
Nyden, Marc R., Forney, Glenn P., and Brown, James E., "Molecular Modeling of Polymer Flammability: Application to the Design of Flame Resistant Polyethylene," *Macromolecules*, **25**, 1658, 1992.

"Molecular Dynamics Modeling of Polymer Flammability," Proceedings of the Spring Meeting of the Materials Research Society, 1992.

Nyden, Marc R. and Noid, Donald W., "Molecular Dynamics of Initial Events in the Thermal Degradation of Polymers," *J. Phys. Chem.*, **95**, 940, 1991.

Lomakin, S.M., Brown, James E., Breese, Robin S., and Nyden, Marc R., "An Investigation of the Thermal Stability and Char Forming Tendency of Cross-linked Poly(methyl methacrylate)," *Polym. Deg. and Stab. Journal* (in press).

Radiative Ignition and Flame Spread Over Cellulosic Materials

Principal Investigator:
Takashi Kashiwagi
Fire Science Division
301-975-6699
Howard R. Baum
Fire Safety Engineering Division
301-975-6668

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

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
This project is one of NASA's Microgravity Science projects to enhance understanding of combustion science by taking unique advantage of a microgravity environment.

Approach
BFRL is developing multi-dimensional (2D axisymmetric and 3D) time-dependent theoretical models of ignition and solving 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. Validation experiments are planned for USML-2 flight in 1995. The conceptional experimental design, fabrication, experimental parameters and procedures will be developed working jointly with NASA Lewis Research Center. Exploratory experiments with a similar hardware will be conducted using drop towers and KC-130 flight.

Recent Results
Kashiwagi, Takashi and Nambu, H., "Global Kinetic Constants for Thermal Oxidative Degradation of a Cellulosic Paper," *Combustion and Flame*, 88, pp 345-368, 1992.

Kushida, G., Baum, Howard, R., Kashiwagi, Takashi, and Blase, C., "Heat and Mass Transport from Thermally Degrading Thin Cellulosic Materials in a Microgravity Environment," *J. Heat Transfer*, 114, pp 494-502, 1992.

Yamashita, H., Baum, Howard R., Kushida, G., Nakabe, K., and Kashiwagi, Takashi, "Heat Transfer from Radiatively Heated Thick Material in a Low Reynolds Number Microgravity Environment," *J. Heat Transfer* (accepted for publication).

Kevlar Barrier Effectiveness in CB 133

Principal Investigator:
Thomas J. Ohlemiller
Fire Science Division
301-975-6481

Sponsor:
DuPont Company
Fibers Division

Objective
To develop simple bench-scale measures on upholstery material mock-ups that predict the effectiveness of Dupont's Kevlar barrier material in the California Bulletin (CB) 133 test of furniture flammability.

Problem
Dupont makes a fire barrier material for upholstered furniture that could be used with thousands of fabric and cushioning combinations in attempting to pass CB 133 requirements for public occupancy furniture. Dupont seeks simple predictors of the likelihood of success with this barrier with classes of materials. This same approach may be applied to residential furniture in the foreseeable future.

Approach
BFRL is performing work on 15 fabrics in its Cone Calorimeter and its Lateral Ignition and Flame Spread Test Apparatus (LIFT) to characterize the impact of this barrier material on heat release rate and flame spread behavior. A subset of these fabrics will be made into chairs and subjected to the CB 133 heat source. The results will be analyzed for bench-scale/full-scale correlations. These findings will help manufacturers meet the requirements as specified in CB 133.

Recent Results
Completed bench-scale tests of the 15 fabrics.

FIRE SCIENCE DIVISION

FIRE SENSING AND EXTINGUISHMENT

Advanced Fire Detection Systems

Principal Investigator:
William L. Grosshandler
Fire Science Division
301-975-2310

Sponsor:
National Institute of Standards and Technology

Objective
To develop an intelligent, low false alarm-rate fire detection system, determine the limitations of acoustic emission detection for room fires, and identify the specific difficulties of interpreting open-path fourier transform infrered (FTIR) spectra for sensing and monitoring fires.

Problem
A properly designed detection system must be able to identify, in a matter of seconds, a fire event; 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 processes make early sensing and suppression even more imperative.

Approach
BFRL is collecting and analyzing information on advances in temperature sensing species concentrations, particulates, and acoustic and electromagnetic radiation to determine their applicability to fire detection. Of current interest are infrared sensing of hydrocarbons and acid gases, and super-acoustic sensors. Software will be developed to recognize unique acoustic and infrared signatures of various events, and to intelligently interpret the response of multiple temperature sensors to fire and non-fire situations.

Recent Results
Grosshandler, William L. and Jackson, M., *Acoustic Emission of Structural Materials Exposed to an Open Flame*, NISTIR 4984, National Institute of Standards and Technology, Gaithersburg, MD, December 1992.

Grosshandler, William L., "An Assessment of Technologies for Advanced Fire Detection," ASME Winter Annual Meeting, December 1992.

Grants
"Smart Fire Detection Using Nural Networks," Milke, James A. and McAuog, Thomas J., University of Maryland.

"Development of an Economical Video-based Fire Detection and Locating System," Plumb, O.A. and Richards, R.F., Washington State University.

Detecting and Monitoring Fires with Open-Path FTIR Spectroscopy

Principal Investigator:
William L. Grosshandler
Fire Science Division
301-975-2310

Sponsor:
National Institute of Standards and Technology

Objective
To determine if the Open-Path Fourier Transform Infrared (OP-FTIR) Spectroscopy apparatus shows promise for monitoring the products formed during the overheating of materials or smoldering prior to ignition and for measuring the concentration of noxious combustion products created in a flaming fire and during active suppression.

Problem
FTIR spectroscopy is a well-established and powerful means for measuring molecular species which have infrared activity. Traditionally, gases are extracted and placed in a sample cell through which an infrared beam is passed. Recently, a new version of the FTIR spectrometer has become available which circumvents the need to physically remove the gas sample from the volume of interest. Line-of-sight measurements along paths extending over a kilometer have been demonstrated. The problem is to learn how to adapt the FTIR to open path monitoring of the products formed during pyrolysis, flaming combustion, and fire suppression. Sensitivity, time response and interpretation of complex spectra in a background of particulate radiation need to be established before the OP-FTIR can be integrated into an early warning fire detection system or used to assist the fire suppression process.

Approach
During FY 1993, BFRL will perform three tasks using its OP-FTIR:

In the first, the transmission spectra of a 0.6 m diameter oil pool fire will be examined to identify the range of organic and other infrared active compounds present within, above and adjacent to the fire. This will be compared to spectra taken during a large scale oil fire. Methanol also will be burned to eliminate the soot and reduce the number of organic compounds present, making interpretation of the spectra more straight forward. The instrument will be operated in the emission and absorption modes.

The second application involves measuring the products of pyrolysis and early stages of combustion of solid fuels within the ASTM standard room in BFRL's large burn facility. Emission and absorption spectra will be taken as a function of time and space within the room to determine when the fire can be detected unambiguously. Spatial measurements will be facilitated through a special scanning mirror system which will be designed and constructed for this purpose. The OP-FTIR will be used to detect a suite of important combustion products (*e.g.*, CO_2, H_2O, CO, HCl, HCN, NO, and unburned hydrocarbons) at a single instant (≈ 2 s), and will be compared to continuous analyzer measurements of CO, CO_2, and total unburned hydrocarbons using an extractive sampling systems.

For the third application, the same ASTM room will be used to measure the dispersal of halogenated firefighting agents with and without a fire present. In the first case, the instrument will yield the concentration of pure agent; in the second, there are likely to be a number of decomposition products which are critical to quantify, including HF, HCl, and COF_2.

Difficulties in interpretation of the results stem from overlapping spectra of multiple species, strong temperature and concentration gradients along the line of sight, fluctuations in concentrations during the sampling period, and obscuration by smoke. BFRL's understanding of radiative heat transfer in nonisothermal environments with and without soot will be applied to the FTIR spectrum to develop narrow-band models of the important chemical species. Carbon monoxide will be targeted first because it is a simple diatomic molecule with a known vibrational-rotational structure and because it is critical to fire science.

Recent Results
New Project.

Dynamics of Fire Suppression

Principal Investigator:
Gregory T. Linteris
Fire Science Division
301-975-2283

Sponsor:
National Institute of Standards and Technology

Objective
To develop a fundamental understanding of the mechanisms of flame extinction to enable next generation agent technologies and increase knowledge of fire suppression capabilities of water mist systems.

Problem
Fire suppressants and their application methods should be effective, fast-acting, economical, have low toxicity, permit a habitable environment during suppression, leave no residue, and cause no damage to the protected space. Existing suppressants, however, are non-ideal: water can cause excessive damage, metal-based suppressants leave a residue, and the currently favored suppressants, the halons, may leave a corrosive residue after passing through a flame. Also, because of their suspected destruction of stratospheric ozone, the most effective halons are being phased out. There exists a continuing need for better suppressants and suppression methods.

Although great advances have been made in combustion science in the past eighty years, existing suppressants are based on scientific knowledge of a century ago. Modern methods of combustion science have not been applied, per se, to the study of fire suppression. The modes of action of the more effective suppressants are still not fully understood. A detailed examination of the behavior of existing fire suppressants will provide a basis for development of advanced suppressants.

Approach
During FY 1993, BFRL will be studying the chemical and physical mechanisms of existing suppressants using a laboratory scale burner to establish the relationship between the characteristic times of the chemistry and fluid dynamics. To understand the simultaneous thermodynamic, fluid mechanic, and chemical kinetic behavior of the inhibitors, the experimental results will be interpreted through limited numerical calculations of the flame structure using existing well developed codes. These experimental and modeling results should lead to a unified method of describing, and an improved fundamental understanding of the mechanisms of flame inhibition, extinction, and stabilization relevant to the advanced suppression of fires.

Parallel to this effort will be a shorter term of study of fire suppression by water mist. This work will identify the technical direction through a workshop which focuses on the technological barriers restricting commercialization of these systems. A BFRL research plan that addresses this technology need will result.

Recent Results
New project 1993.

Grants
"Experimental Studies on the Extinction of Diffusion Flames Using Halon Substitutes," Seshadri, K., University of California-San Diego.

"Evaluation of Fire Suppression Effectiveness," Atrega, A., University of Michigan.

Agent Screening for Halon 1301 Aviation Replacement

Principal Investigator:
William L. Grosshandler
Fire Science Division
301-975-2310

Sponsor:
U.S. Air Force
Wright Laboratory

Objective
To establish a comprehensive experimental program for screening specified gaseous agents and chemicals for identifying the best candidates for an aircraft fire extinguishment evaluation program.

Problem
The search for chemicals to replace halon fire extinguishing agents is proceeding too slowly for the implementation of alternatives before current supplies of halons become depleted. There are few organizations participating in the search, the market is small, and technology availability is limited. None of the proposed alternatives have both a low ozone depletion potential (ODP) and a high fire suppression efficiency. The federal government uses halon 1301 in a multitude of aircraft applications, including engine nacelle and dry bay protection, with little understanding of phenomena which control extinguishment in these situations. The Air Force has imposed a deadline for the installation of replacement in-flight fire extinguishing systems, with full-scale testing to be done in FY 1994, and has requested that NIST identify the best three agents for their test program.

Approach
The effectiveness of a fire suppression agent is related to its thermodynamic properties, its behavior during two-phase flow, its interaction with flame chemistry, the timing of its release, and the nature of the fire. During FY 1993, BFRL is performing a series of experiments to examine each of these factors, singly, and in combination. Theoretical models will be used to interpret the results, to increase understanding of the suppression process, and to predict behavior over an expanded range of operating conditions. In particular, control of those phenomena which dominate the actual suppression process is sought, be they the chemical reactivity of the agent, the thermal quench or dilution provided by the agent, or the properties associated with the physical mixing of the agent into the fire.

BFRL is performing five tasks:

1. Determine the thermal properties and dynamics of the agents as they exit the containment vessel. A pressure vessel with a rupture disc will be used to discharge the agent (initially at 4 MPa) into the atmosphere. The equilibrium pressure will be measured over the range of temperatures the vessel is likely to experience in flight, and the thermodynamic state during the expected 50 ms discharge will be monitored. Nine pure fluorocarbons, two mono-chlorinated fluorocarbons, a fluorocarbon azeotrope, and sodium bicarbonate powder are to be tested mixed with nitrogen or CHF_3.

2. Investigate agent dispersion and fluid mechanics outside the vessel. The objective of this task is to predict the concentration of the agent in the jet which is formed. The flow will be measured with high speed photography of the exiting spray illuminated by a laser sheet, schlieren photography of the spray and high density plume, Mie scattering from the droplets, and point sampling with hot wire probes in the gaseous plume.

3. Develop flame extinction measurements. The major issue is to determine the minimum concentration of agent required to suppress the deflagration in each apparatus. Four different facilities will be involved: a. a cup burner, b. an opposed flow diffusion flame burner, c. a turbulent jet spray flame, and d. a detonation tube.

4. Investigate flame/agent chemistry. The work centers on using chemical kinetic modeling and the results of diffusion flame measurements to determine whether the dominant mechanism of suppression is chemical or physical.

5. Identify additional agent screening. This task will identify additional agents with high flame suppression efficiency and low ODP.

Recent Results
Presentations were made to Air Force sponsors and at BFRL's Annual Fire Conference which described preliminary results of the fluid mechanics, flame extinguishment and agent screening tasks.

Agent/System Compatibility for Halon 1301 Aviation Replacement

Principal Investigator:
Richard G. Gann
Fire Science Division
301-975-6866

Sponsor:
U.S. Air Force
Wright Patterson AFB
Survivability Enhancement Branch, and
U.S. Army Tank Automotive Command

Objective
To provide data for appraising twelve USAF-specified candidate halon 1301 replacements for compatibility with flight systems, people, and the environment; recommend three candidates for further examination; and perform longer-term testing to increase confidence in the preliminary results.

Problem
The current suppressant for in-flight fires, halon 1301, is rapidly being phased out. The Air Force has begun a program to implement an alternative to halon 1301 by the end of FY 1995. Screening of potential alternatives is needed to narrow the number of chemicals for full-scale testing.

Approach
BFRL, working with researchers from NIST's Material Science and Engineering Laboratory, are involved in five tasks:

1. Performing bench-scale determinations of non-volatile residue.

2. Evaluating stability during long-term storage.

3. Determining compatibility with eight metals, five elastomers, and three lubricants.

4. Developing prediction method for HF formation during suppression.

5. Determining potential human exposure levels and summarize environmental regulations.

The results of this project will establish methods for evaluating future candidate suppressents, while providing the best possible assessment of current candidates.

Recent Results
New project late 1992.

Risk Analysis for the Fire Safety of Airline Passengers

Principal Investigator:
Richard L. Smith
Fire Science Division
301-975-6870

Sponsor:
Federal Aviation Administration
Technical Center

Objective
To develop the initial version of a generic method and computer program to compute the fire risk for airline passengers.

Problem
Airline fire safety is important for the airline passengers and the potential flying public to be assured of fire safety. The public has demonstrated a willingness to pay for flight safety when it is cost effective. FAA's fire safety regulations needs to provide demonstrable safety improvement at an acceptable cost.

Injuries or death from an airplane fire is a rare event. There is not a large body of relevant statistical data that can be used to determine the impact of various fire safety strategies. In the last decade considerable progress have been made in developing and/or improving risk analysis. The major motivators were the Three Mile Island nuclear reactor disaster and the NASA Challenger space shuttle disaster.

Similarly, there has been major advances in Artificial Intelligence in dealing with reasoning with uncertainty or vague knowledge. Some advances have used such approaches as Bayesian Probability Theory, Dempster-Shafer's rule for combining evidence, and expert systems. Also, probability theory has been impacted significantly by developments in Bayesian Probability Theory and new applications of the Maximum Entropy theory.

Approach
During FY 1933, BFRL will apply the advances in these three fields to the risk analysis for the fire safety of airline passengers. A generic method and a computer program will be developed to calculate airline passengers fire risk. The program will be capable of using the state-of-the-art safety analysis technology, the historical data on fire losses in airplanes, the results of experiments and tests, the predictions of physical science models, and experts opinions. However, the user will control exactly what knowledge is used and what assumptions are made. The program will be capable of recording an individual analysis so it can be reviewed by others.

Recent Results
New Project.

Cigarette Ignition Metrology

Principal Investigator:
Richard G. Gann
Fire Science Division
301-975-6866

Sponsor:
U.S. Consumer Product Safety Commission

Objective
To develop a standard test method that determines cigarette ignition propensity; compile performance data for current cigarettes using the standard test method; and conduct laboratory studies on and computer modeling of ignition physics to develop a predictive capability.

Problem
Cigarette-initiated fires continue to be the largest single cause of fire fatalities. P.L. 101-352, the Fire-Safe Cigarette Act of 1990, directs NIST to perform research to help reduce losses from cigarette induced fires.

Approach
During FY 1993, BFRL is:

1. Pursuing furniture ignition and secondary cigarette extinguishment test methods.

2. Comparing results to established performance of prior set of experimental cigarettes.

3. Conducting round-robin(s) of the new test methods.

4. Generating performance data on current market cigarettes.

5. Performing laboratory experiments, measuring the thermal behavior of the cigarettes and substrates.

6. Upgrading prior first-cut models of cigarette smoldering and substrate ignition.

The results will enable the cigarette industry and the public safety officials to measure progress toward less fire-prone cigarettes.

Recent Results
Conducted inter-laboratory evaluation of two candidate test methods.

Completed a user-friendly computer model of ignition of an upholstered surface.

Smoke Movement and Smoke Layer Development in High Bay Areas

Principal Investigator:
Kathy A. Notarianni
Fire Science Division
301-975-6883

Sponsor:
National Aeronautics and Space Administration
Goddard Space Flight Center

Objective
To develop data on smoke movement and layer development in high bay areas.

Problem
There is a special need to address fire protection issues for high ceiling height large spaces such as in atriums, aircraft hangers, and warehouses. Can the current fire zone models accurately predict detection and activation in these spaces? How large a fire is needed to activate a detector or sprinkler at the ceiling? Do the smoke and products of combustion stratify prior to reaching the ceiling?

Approach
BFRL will verify a field model for a 30.4 m high space using BFRL measurements of fire gas temperatures and disk temperatures along the ceiling of a 30.4 m aircraft hanger during live fire tests. Measurements will be compared to prediction of a field model. NASA specifications for high bay storage will be reviewed with NASA to collect appropriate inputs for field modeling. Field modeling will be used to model a high bay space to predict smoke movement and smoke layer development in a NASA high bay area.

Recent Results
New project late 1992.

Evaluation of Metal Versus Plastic Piping in Fire Sprinkler Systems

Principal Investigator:
Kathy A. Notarianni
Fire Science Division
301-975-6883

Sponsor:
U.S. Fire Administration

Objective
To compare and evaluate performance of metal versus plastic piping for use in fire sprinkler systems.

Problem
Plastic pipe is used mainly in residential occupancies. Information on the performance characteristics of metal vs. plastic piping is needed to make informed decisions about the use of plastic piping for various occupancy classifications.

Approach
During FY 1993, BFRL is comparing and evaluating the following variables:

- corrosive conditions
- materials degradation during a fire
- maintenance
- economics
- occupancy classification limitations
- system modification limitations
- materials limitations with types of systems
- system design (hydraulic calculations)
- hanger and bracing considerations
- high water pressure

Recent Results
New project 1993.

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