NIST SP 838-8

Project Summaries 1995

NIST Building & Fire Research Laboratory

U.S. Department of Commerce

Technology Administration

National Institute of Standards and Technology

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Noel J. Raufaste

August 1995

U.S. Department of Commerce
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Technology Administration
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National Institute of Standards and Technology
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National Institute of Standards
and Technology
Special Publication 838-8
Natl. Inst. Stand. Technol.
Spec. Publ. 838-8
192 Pages (Aug. 1995)
CODEN: NSPUE2

U.S. Goverment Printing Office
Washington: 1995

For sale by the Superintendent
of Documents
U.S. Government Printing Office
Washington, DC 20402

FOREWORD

Construction is one of the Nation's largest industries. In 1994, total construction amounted to about $847 billion which is 12.5 % of U.S. GDP (new construction put in place amounted to about $508 billion and renovation contributed about $339 billion). U.S. construction accounts for more than 10 million jobs.

Fires and natural disasters destroy a significant portion of constructed facilities every year. Costs of fire safety and fire losses exceed $128 billion a year. Natural disasters cause tens of billions of dollars annually. For example, since 1993, the United States has experienced significant property losses from the Mid-west Floods; Hurricanes Andrew and Iniki; the January 1994 Northridge Earthquake; the numerous west coast wildfires that resulted in significant damage to the built environment; among other natural phenomena that occur each year. The quality of constructed facilities directly affects the productivity of the U.S. building and fire communities and affects the safety and quality of life of all constructed facilities. Over 60% of the nation's wealth is invested in constructed facilities.

The National Institute of Standards and Technology's (NIST) mission is to promote U.S. economic growth by working with industry to develop and apply technology, measurements, and standards. NIST's direct customer is U.S. industry. Its work yields direct investments with and benefits for the private sector.

NIST's Building and Fire Research Laboratory (BFRL), one of NIST's eight Laboratories, enhances 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's efforts are closely coordinated with complementary activities of industry, professional and trade organizations, academe, and other agencies of government. The vision for BFRL, the structure of its technical programs, and the determination and timing of its technical products are based on analyses of industry needs and BFRL's own unique resources and capabilities.

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; fire suppression test facilities; and a fire simulation laboratory.

BFRL is a major nonproprietary source of technical information for development of voluntary standards by organizations such 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 the 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 and 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. More than 80 research associates from U.S. industry, guest researchers from foreign laboratories, and faculty members from universities worked at BFRL during 1994 for periods averaging about a year. BFRL has direct linkages with industry through its 20 Cooperative Research and Development Agreements (CRADAs).

BFRL participates in over 130 national and international standardization activities; provides leadership in these national and international standardization organizations and chairs more than 20 voluntary standardization activities. BFRL annually publishes over 220 reports, articles for research journals and articles for professional and trade journals, and 28 computer model software packages. BFRL staff annually makes hundreds of

presentations at professional and technical meetings of building community organizations, hosts more than 1,700 visitors to its facilities, and responds to more than 19,000 requests for information. For 25 years, BFRL has hosted a monthly Building Technology Symposia Series in cooperation with other organizations concerned with building research and practice and hosts bi-weekly Fire Research Seminars for NIST staff and colleagues from the fire community. These meetings 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.

At the beginning of FY 1995, BFRL had about 220 employees of which 138 are professional staff, 72 have Ph.D.s, and 18 are registered engineers. BFRL's budget for FY 1995 is $32 million. Funding comes from direct appropriations ($21 million), from other Federal agencies ($10 million) and from the private sector ($1 million).

This report summarizes BFRL's research for 1995. The report is arranged by its research programs: structural engineering, materials engineering, mechanical and environmental systems, fire safety and engineering, fire science, and applied economics. 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. Persons requesting information may want to contact BFRL using facsimile number 301-975-4032 or e-mail raufaste@micf.nist.gov.

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STRUCTURES DIVISION

EARTHQUAKE ENGINEERING

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

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Sponsor:
National Institute of Standards and Technology

Objective

To develop and verify guidelines for pre-qualification, prototype and quality control testing of seismic isolation systems.

Problem

Seismic isolation is effective in reducing the level of response in structures during strong earthquake ground shaking. In practice, the components of the isolation system undergo an extensive series of prototype and quality control tests before installation. Recently BFRL completed three volumes of draft guidelines for conducting these tests. They were developed with the assistance of an Oversight Committee of five experts from the field of seismic isolation.

Approach

During FY 1995, BFRL will develop the test program for assessing and evaluating guidelines that will involve:

1. Development of a detailed experimental and testing program plan, in consultation with the Oversight Committee. The testing plan will include a schedule of tests, personnel requirements, equipment and material needs. The first phase of tests will involve primarily uniaxial compression loading. A second phase is anticipated, which would involve simultaneous uniaxial compression combined with cyclic lateral shear loading. The feasibility and scope of this phase will require further study, and may be performed out in FY 1996.
2. Fabricate test fixtures, procure test specimens, calibrate transducers, assemble data acquisition system, and verify test control system.
3. Conduct tests, according to the procedures established by the "Draft Guidelines." Tests will be conducted in the BFRL Tri-directional test facility or the Large Scale Structural Test Facility, as appropriate.
4. Report and analyze data according to the provisions of the "Draft Guidelines." In addition, report on the adequacy and feasibility of the guideline test procedures, based on the observations and experience gained in the test program.
5. Summarize findings from test program and provide this feedback to the Oversight Committee.

The results from this research will be published as NIST research reports and in technical journals.

Recent Results

Shenton, H. W. III, *Draft Guidelines for Quality Control Testing of Elastomeric Seismic Isolation Systems*, NISTIR 5345, National Institute of Standards and Technology, 1994

Shenton, H. W. III, *Draft Guidelines for Pre-qualification and prototype Testing of Seismic Isolation Systems*, NISTIR 5359, National Institute of Standards and Technology, 1994

Shenton, H.W. III, *Draft Guidelines for Testing and Evaluation of Seismic Isolation Systems, ATC 17-1, Proceedings of a Seminar on Base Isolation, Passive Energy Dissipation and Active Control*, San Francisco, CA, March 11-12, 1993

Shenton,, H.W. III and Lin, A.N., *Relative Performance of Fixed-Base-Isolated Concrete Frames*, ASCE, Journal of the Structural Division, Vol 119, No. 10, October 1993

Seismic Performance of Precast Concrete Connections

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Sponsor:
National Institute of Standards and Technology

Objective
To revise the design guidelines developed for moment resistant precast concrete beam-column connections in FY 1994 for adoption into building codes and standards.

Problem
Proposed revisions to the building codes require careful attention to the content and wording of the proposed changes. Such attention is necessary to avoid conflicts with existing code requirements, the unintentional exclusion of materials and/or procedures, and potential mistakes caused by misinterpretation of the proposed changes.

Approach
During FY 1995, BFRL will collaborate with Englekirk and Nakaki, Inc. to develop the proposed changes and to present them to the SEAOC Ad hoc Committee on Precast Structures in Seismic Zones and the American Concrete Institute (ACI) Technology Transfer Committee. These committees will provide guidance as to the technical content and acceptability of the changes by the SEAOC Seismology Committee and ACI 318 Committee. Interaction with the ad hoc committee will include participation in the scheduled meetings to provide technical interpretation of the proposed design guidelines.

Recent Results
New project.

Seismic Performance of Steel Frame Structures

Principal Investigator:
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Sponsor:
National Institute of Standards and Technology

Objective
To develop guidelines for repairing damaged, rehabilitating existing, and designing connections of steel frame structures.

Problem
A large number of beam-to-column connections of moment-resistant steel frame buildings sustained serious damage during the January 1994 earthquake. Current design procedures presume that these connections can maintain their structural integrity through numerous cycles into the inelastic range of deformation. Observed failures of connections nevertheless invalidate the very basis of current design and construction practices for steel frames. As a result, there are thousands of steel frame buildings within high seismic risk areas of the United States that are now vulnerable to such damage in future earthquakes. Guidelines are urgently needed to repair, rehabilitate, and design of steel frames based on rational understanding of seismic behavior.

Approach
During FY 1995, BFRL will perform the following tasks:

1. Characterize and understand failures sustained.
2. Identify causes of failures and develop approaches to solutions.
3. Develop and evaluate reliable and cost effective guidelines.

A national workshop was held to develop an action plan to address the various issues associated with the repair and rehabilitation of damaged steel frame buildings. A selected

number of specific tasks selected from the action plan will be performed jointly with private sector groups and university researchers.

Recent Results

New project

Performance of Steel-Framed Structures

Principal Investigator:
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Sponsor:
Federal Emergency Management Agency
Mitigation Directorate

Objective

To document damage to steel moment frame buildings in the January 1994 Northridge Earthquake and to establish a national plan to address the inspection and repair of damaged buildings, rehabilitation of undamaged buildings, and design for new construction.

Problem

Steel-framed buildings have long been considered to be the best form and material for seismic resistant construction. This factor, along with others, has made steel-framed buildings an attractive alternative for the design and construction of mid-to high-rise buildings. According to the City of Los Angeles Building and Safety Department, steel-framed building made up half of all buildings constructed in Los Angeles during 1993.

However, after the Northridge earthquake, engineers have discovered wide-spread failures in the beam-to-column connections of steel moment-resisting frame buildings. Extensive cracks in the beams and columns have been found in at least 100 buildings, most of them located in the San Fernando Valley. A series of tests conducted at the University of Texas found that properly welded full-sized specimens cracked in the first inelastic cycle of loading demonstrating that no "quick fix" appears to be at hand.

Approach

During 1995, BFRL will perform comprehensive documentation of damaged steel frame buildings. Data collection will require a team effort since there are many damaged steel buildings in the Los Angeles area and inspection is time-consuming because the steel frame is often concealed by fire proofing and architectural finish. Such

documentation is necessary, however, to provide a solid basis for the establishment of an action plan to address the inspection and repair of damaged buildings, rehabilitation of undamaged buildings and design for new construction. To develop the action plan, a workshop will be held which will bring together experts from around the country to form a national perspective. The workshop will result in a document outlining how to approach and resolve this problem.

The documentation of failures and development of an action plan to address the inspection, repair, rehabilitation and design of steel moment-resisting frames will be a collaborative effort performed by BFRL and a team of experts.

Recent Results

Gross, J. L., *A Survey of Steel Moment-Resisting Frame Buildings Affected by the 1994 Northridge Earthquake*, NISTIR 5625, National Institute of Standards and Technology, April 1995

Youssef, N.F.G., Bonowitz, D., and Gross, J.L., *Proceedings: Invitational Workshop on Steel Seismic Issues*, SAC 94-01, Structural Engineers Association of CA, Sacramento, November 1994, 155pp.

Inelastic Damage Model for Rectangular Reinforced Concrete Columns

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Sponsor
Federal Highway Administration
Office of Engineering, Research, and Development
Structures Division

Objective

To calibrate an inelastic dynamic analysis model so that it may be applied to rectangular reinforced concrete columns with rectangular hoops.

Problem

There are currently available several computer-based analysis models which predict the dynamic performance of reinforced concrete structures in earthquakes, not only over the elastic range of behavior, but also in the inelastic range (e.g., IDARC, SARCF, DRAIN-2DX). These analysis models have the potential to enable engineers to design reinforced concrete structures which are both safer and more economical than structures designed using current design methods (such as equivalent static lateral load analysis, or elastic dynamic analysis). However, inelastic dynamic analysis models remain theoretical tools. They cannot be used with confidence in practical applications because they have never been systematically calibrated against laboratory test data.

Approach

During FY 1995, BFRL will demonstrate a calibration procedure for IDARC which could be adapted for use with other inelastic dynamic analysis software. A widely used three parameter hysteretic failure model is incorporated in the inelastic analysis program IDARC (Kunnath, Reinhorn and Lobo 1992). IDARC has been examined in past studies at NIST(Stone and Taylor 1993), and has been

found to be a promising approach to the seismic analysis of reinforced concrete buildings and bridges.

First, approximately 50 to 75 digital records from cyclic lateral load tests on rectangular columns, obtained in an earlier phase of this project, will be analyzed using the NIST system identification program NIDENT 3.0. NIDENT currently provides semi-automated capture of the three-parameter model coefficients used in IDARC ; NIDENT 4.0, which provides for identification of up to 15 parameters may also be employed if necessary. The three failure model parameters will then be determined for each specimen. Finally, the aggregate set of parameters from the full range of tests will be used to develop correlations between observed performance (e.g., strength degradation, stiffness degradation and pinching of the hysteresis loops) and the geometric and material properties of columns.

Recent Results

New project.

Digital Data Base of Cyclic Lateral Load Tests on Rectangular R/C Columns

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Sponsor
State University of New York
National Center for Earthquake Engineering Research (NCEER)

Objective

To develop a comprehensive digital data base of cyclic lateral load tests on rectangular reinforced concrete columns.

Problem

In order to develop confidence in inelastic analysis algorithms for reinforced concrete structures, the algorithms must be calibrated against laboratory data from tests on reinforced concrete members. Without such a calibration, the inelastic analysis algorithms are essentially useless. To support collateral work at BFRL on earthquake engineering for bridges, such a database for rectangular reinforced concrete columns will be developed. Because of the high variability inherent in tests of reinforced concrete members, and because of the wide range of member geometries and material properties covered by the analytical models, large data bases of experimental results are required for adequate calibration. There is currently no comprehensive, world-wide data- base of results from cyclic lateral load experiments on rectangular columns.

Approach

During FY 1995, BFRL will develop a comprehensive digital database of cyclic lateral load tests on rectangular reinforced concrete columns. As a first step, a literature review will be conducted to identify as many tests as possible throughout the world. Second, researchers will be contacted to obtain digital data (when available), copies of papers and test reports. Third, for those tests

which are reported only in analog format, the load-deflection plots will be digitized using a computer work station, digitizing tablet and special digitization software written expressly for this purpose at BFRL. Finally, the digital data will be arranged in a uniform format, auxiliary information about the tests will be tabulated, and the database will be described in a report accompanied by a computer disk.

Recent Results
New project.

Cyclic Lateral Load Tests of Circular Reinforced Concrete Bridge Columns

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Sponsor
California Department of Transportation (Caltrans)

Objective
To investigate experimentally the effect of varying cyclic lateral load paths on damage to circular reinforced concrete columns.

Problem
In earthquake engineering studies of reinforced concrete columns, a controlled, cyclic lateral load pattern with gradually increasing amplitude has traditionally been applied to columns tested in the laboratory. However, in an actual earthquake a bridge column is exposed to a random cyclic lateral loading pattern, which is much different from the laboratory loading pattern. Current American Association of State Highway and Transportation Officials (AASHTO) and Caltrans design provisions are based almost exclusively on tests in which traditional, controlled laboratory loading patterns have been applied to the specimens, rather than realistic earthquake loading patterns.

The differences between these types of loading have never been explored systematically. In this study both types of loading - controlled, cyclic lateral loads, and random earthquake type loads - will be applied to nominally identical columns, and the differences in observed damage will be studied.

Approach
During FY 1995, BFRL will analyze twelve column specimens. The specimens will be approximately one-fifth scale versions of prototype bridge columns designed using current Caltrans standards. They will be nominally identical: approximately 300 mm in

diameter by 1800 mm long, with the same material properties for all specimens. The specimens will be cast integrally with a reinforced concrete base block to simulate a bridge column footing.

The main variable in the test program will be the type of cyclic lateral load pattern applied to the specimen. The specimen base will be clamped to the laboratory reaction floor, then the column will be loaded at the top with simultaneous axial load and a cyclic lateral load, to simulate the weight of the bridge in combination with a cyclic earthquake load. The first specimen will be loaded with a monotonic lateral load to failure (pushover test) to determine basic specimen stiffness and strength. The next three specimens will each be loaded with cyclic lateral displacements of a constant amplitude for as many cycles as are necessary to cause complete failure of the specimen. The amplitude of displacement applied to each specimen will be a multiple of the yield displacement determined from the first test specimen. The fourth specimen will be loaded with a "standard" laboratory load pattern, which consists of cyclic lateral displacements with gradually increasing amplitudes. The final seven specimens will be loaded with simulated earthquake displacement patterns. The earthquake displacement patterns will be selected to simulate a range of earthquake types. The effects of applying multiple damaging earthquakes to the same column will also be investigated.

The data and visual observations obtained from these tests will be correlated with several analytical damage models which have been proposed by other researchers. The accuracy of the damage models will be evaluated in light of the test data, and recommendations will be made regarding the best methods for analytically modeling earthquake damage to circular reinforced concrete bridge columns. Recommendations will also be made regarding the appropriateness of using results from "standard" laboratory tests of columns, rather than simulated random earthquake motions, to develop codes and standards for the seismic design of reinforced concrete bridge columns.

Recent Results
New project

Seismic Performance of Cladding Systems

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Sponsor
Federal Emergency Management Agency
Mitigation Directorate

Objective
To evaluate seismic performance of exterior architectural cladding elements during the Northridge earthquake, and develop energy dissipating cladding systems for seismic retrofit and design of new buildings.

Problem
Although many cladding elements are not specifically designed for seismic forces, they participate in resisting lateral loads as they deform with the framing system. Cladding systems sustained damage during the Northridge earthquake, particularly those on steel frame structures. The seismic performance of buildings could be improved by utilizing effectively the cladding system to dissipate energy. Energy-dissipating cladding can be applied to both new construction and seismic retrofit.

Approach
During FY 1995, BFRL will perform four tasks:

1. Document the performance of architectural cladding systems during the Northridge and other earthquakes. Current design criteria and code requirements will be critically evaluated based on observed cladding performance.

2. Investigate the performance of energy dissipating cladding connector hardware will be studied. This will be primarily an experimental investigation, making use of existing test fixtures at BFRL and elsewhere. The goal of this phase will be to determine how different types of energy dissipating connectors behave (e.g. elastomeric connectors, steel clip angles, and other specially designed

steel connectors). The hysteretic properties of the connectors will be established, and desirable modes of connector performance will be defined.

3. Determine the contributions of cladding to the stiffness and damping of the overall structural system. Presently, it is not clear to what degree cladding systems participate with the main structural frame of a building during earthquake shaking. This work follows naturally on the connector performance studies described above, since the energy dissipating properties of connectors have a major influence on the interaction between the cladding system and the structural frame. This third task will be carried out by comparing analytical models of buildings with observed experimental full-scale and scale-model building performance data. Since few experiments have been performed on structures with and without cladding, additional experiments may be required in this phase.

4. Develop seismic design guidelines for building cladding systems.

Recent Results

Conducted a literature review of the state-of-the-art of cladding research.

Developed a research agenda on cladding.

Seismic Performance of Nonstructural Ceiling Components

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Sponsor:
National Institute of Standards and Technology

Object

To develop methods for reducing seismic damage to nonstructural components of buildings.

Problem

It has been observed in past earthquakes that damage to nonstructural components and secondary systems can have a great effect on the safety of occupants and loss of property, and in some cases the effects of nonstructural damage can be even greater than the effects of structural damage. When the buildings in a community are rendered nonfunctional due to nonstructural damage or to inoperative secondary systems, the well-being of a community can be severely jeopardized. Furthermore, in economic terms, indirect losses (in terms of damaged equipment, lost inventory and records, and lost revenue) can be two to three times greater than the cost of replacing collapsed buildings or structures, as repeatedly demonstrated in the 1989 Loma Prieta and the 1994 Northridge earthquakes.

The terms "nonstructural components" and "secondary systems" refer to a number of items. They include, for instance, cladding, ceilings, building contents, equipment, and HVAC, plumbing, and electrical systems. Most of the past efforts in the NEHRP program have focused on improvements of the *structural* design of buildings to prevent total collapse. As a result, most newly constructed buildings stand a good chance that they will not collapse from an anticipated earthquake. It is only recently that attention has been paid to the performance of *nonstructural* components and secondary systems.

In a FY 1994 BFRL study, a review was conducted of the seismic performance of

nonstructural components, and the state-of-the-art of seismic design methods for nonstructural components. A major problem observed in all recent major U.S. earthquakes has been the seismic performance of the components located in or above suspended ceilings in commercial office buildings. These include the suspended acoustical tile ceilings; fire sprinkler systems; light fixtures; and HVAC ducts. Problems arise because these components are co-located in the ceiling area, and their movements during an earthquake are often incompatible. For example, fire sprinkler heads usually project through suspended acoustical tile ceilings. During an earthquake, the movements of the suspended ceiling and the sprinkler pipes are incompatible, so that the sprinkler heads are damaged. Not only does this decrease the ability of the sprinkler system to suppress post-earthquake fires, but it also may result in broken sprinkler heads and flooding of the building contents. Another example is distortion of the acoustical tile ceiling grid, which may cause lighting fixtures and ventilation grills resting in the grid to fall.

Thus, studies of the interactions of components located in and above suspended ceilings are required to reduce nonstructural damage in buildings. Design guidelines should be developed to ensure compatible deformations and adequate seismic resistance of these components.

Approach

During FY 1995, BFRL will review existing seismic design standards for piping, such as those used in the process plant and nuclear power industries. This will be followed by evaluation of computer models which could be used to perform dynamic analyses of ceiling systems. These models would include provisions for real-time opening and closing of gaps between components; realistic component flexibility; and possibly progressive damage of components. Initial modeling would be in two dimensions (one horizontal axis and the vertical axis), and later modeling might be extended to three dimensions. Once a satisfactory modeling method has been established, realistic ceiling component data will be required. These include component masses, stiffness and strengths, layout of components in the ceiling area, and appropriate input seismic records. Some simple testing of typical components, such as fire sprinkler pipes, may be required to obtain stiffness data.

Several typical geometric layouts of ceilings systems will be defined, as well as three to five input earthquake records of varying magnitudes. Using the computer model, the typical ceiling systems will be subjected to all of the earthquake records, and the forces and differential displacements will be recorded. Observed problem areas, such as impact sites and locations of high stress will be studied, and remedial measures will be proposed. Alterations will be made to the computer model to remedy the problem areas, and the computer analyses will be repeated to assess the degree of improvement.

Based on the analytical studies, recommendations will be made for improving the seismic design of components within and above suspended ceilings in buildings. These provisions could include recommended minimum or maximum clearances between components; recommended strengths for anchorages; and recommendations for fixing some components or for freeing other components.

Recent Results

New project.

Performance of Power Transmission and Distribution Systems

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Sponsor:
Federal Emergency Management Agency
Mitigation Directorate

Objective

To develop guidelines that improved earthquake response of power systems and develop substation equipment fragility database using the damage information from the Northridge Earthquake.

Problem

The January 17, 1994 Northridge Earthquake in California has again demonstrated the vulnerability of power system facilities to earthquake damage. As a result of this earthquake, it was the first time in its history that the City of Los Angeles was completely out of power. The earthquake demonstrated the vulnerability of emergency power systems. Information, generated from strong motion coupled with the damaged documented from the earthquake, provides an unique opportunity to perform analyses and develop procedures to mitigate the effects of future earthquake disasters on power system facilities.

Approach

During FY 1995, BFRL will perform the following tasks using data gathered in the Northridge and other recent earthquakes:

1. Develop guides for the selection, installation, and operation of emergency power. Many facilities which must operate after a disruption of the commercial power supply, including that from damaging earthquakes, have installed emergency power systems. However, the performance record of these systems following Northridge earthquake has been relatively poor. In addition to installation adequacies, these systems also fail due to inadequate maintenance, testing, and operating procedures. The guidelines will ensure adequate performance of these emergency power systems.

2. Develop guides for the seismic evaluation and design of high voltage substation. Many factors contributed to the extensive damage that occurred at high voltage substations. They include design details associated with the installation of substation equipment. These guidelines will provide guidance for evaluating the seismic vulnerability of substations, focusing on the construction of new facilities.

3. Develop fragility curves for substation equipment. Several factors contributed to uncertainty in predicting earthquake damage to power equipment. They include the variations in earthquake damage to power equipment, the variations in earthquake motion from earthquake to earthquake, in local site characteristics, even with a substation, in the design and installation of equipment, and most of all, the large variation in the strength of porcelain. A case study will be conducted to evaluate the uncertainty in the various parameters that influence the fragility of substation equipment, including the analysis of strong motion, aftershock and ambient site data and the comparison of these results to dynamic response characteristics of selected substation equipment.

Based on the results of the above study, fragility data will be developed for several types of equipment for which seismic performance data is available. Fragilities based on the Northridge Earthquake data will form the basis of most estimates, but when available, data from other earthquakes will be used as appropriate. Geotechnical analysis may also be required using existing data to determine site characteristics and main shock ground motions. The results of this effort will be estimates of fragility curves for specific types of equipment.

The tasks will be carried out jointly by BFRL and a contractor selected through competitive process. The contractor selected to conduct these tasks will have the expertise and the representation of the electric power industry.

Results of this study will provide the electric power industry a set of guidelines for improving the performance of emergency power systems during future earthquakes and a set of guidelines for evaluation and design of high voltage equipment at substations. It also will result in a set of fragility curves for specific types of substation equipment.

Recent Results
New project.

Performance of Rehabilitated Masonry Buildings and Development of Performance Based Rehabilitation Guidelines

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Sponsor:
Federal Emergency Management Agency
Mitigation Directorate

Objective
To document the performance of rehabilitated unreinforced masonry buildings during the Northridge Earthquake, evaluate the effectiveness of current rehabilitation practices, and develop a compendium of rehabilitation techniques with guidance for designers.

Problem
Reinforced masonry construction has been used in California since 1934 after the Long Beach earthquake. However, many unreinforced masonry buildings (URMs) still exist in the Los Angeles area. Many of these buildings have been "rehabilitated" as the result of the rehabilitation requirements known as "Division 88" mandated by the City of Los Angeles. The requirements apply to all URMs other than one and two-family dwellings and small apartment buildings of less than five living units. Most rehabilitation schemes use through-bolts and face plates to connect masonry walls to the wood floor and roof diaphragms. These bolts are clearly visible on the building's exterior. The rehabilitation requirements also establish criteria for "complete" strengthening, which, in addition to through-bolts, may require adding interior shear wall partitions, incorporating new timber posts or other supplemental vertical load resisting elements, infilling openings, or increasing wall thickness.

While the City of Los Angeles has a mandated rehabilitation program for URMs, the city of Santa Monica has not. Nevertheless, rows of through-bolts and their face plates can be seen in many URMs in Santa Monica. Despite rehabilitation, many of the URMs in Santa Monica and in the city of Hollywood

were heavily damaged as the result of the January earthquake. As a life-safety measure, current rehabilitation practices appear to have been successful in this earthquake--there were no complete collapses and no deaths of occupants.

In contrast, a significant portion of the fatalities due to building failures during the 1989 Loma Prieta earthquake were the result of out-of-plane failures of URM walls which collapsed onto adjacent buildings, sidewalks, streets, and parking lots. Yet, the Northridge earthquake occurred at 4:31 a.m., making it unlikely for deaths or injuries to occur on the sidewalks adjoining the damaged URMs. Furthermore, rehabilitation was not successful in preventing property damage, which can lead to significant economic losses as the result of building repair and the associated business disruption.

The Northridge earthquake offers an unprecedented opportunity to examine the effectiveness of the current rehabilitation practices as exemplified by the implementation of "Division 88." There are many rehabilitated URMs that were affected by this earthquake. There is a need to systematically develop a database that is as complete as possible to document the locations of these URMs and their performance.

Approach

During FY 1995, BFRL will develop a database from building department records, rather than from site visits of individual buildings. This work will be performed in collaborations with outside investigators. A number of strong motion records were generated throughout the region as a result of this earthquake.

BFRL, with outside investigators, will perform a comprehensive evaluation of the effectiveness of current rehabilitation requirements based on comparison of URM location and performance to the characteristics of local strong motion records, as well as to traditional MMI Intensity maps. A compendium of rehabilitation techniques, for all levels of performance, will be developed, supplemented by design guidance where such guidance can be supported by existing research. Information gaps will be identified. This document will provide usable information for designers, and will complement the existing FEMA project to develop rehabilitation guidelines for multiple performance objectives for all building types by 1997.

Recent Results

New project.

Seismic Resistance of Partially-Grouted Masonry Shear Walls

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Sponsor:
National Institute of Standards and Technology

Objective
To define the strength and deformation of partially grouted masonry shear walls at the cracking and ultimate limit states, and determine the influence of critical parameters on wall behavior.

Problem
The behavior of masonry shear walls has been the subject of increased attention during the past 15 years. Most research has been aimed at fully grouted reinforced walls. Due to the lack of physical data on the response of partially grouted masonry walls to in-plane lateral loads, no acceptable design formulas are available for predicting shear strength of such walls. The limited data suggests that empirical formulas for shear strength of fully grouted, reinforced walls have limited applicability for determining the shear strength of partially grouted, lightly reinforced shear walls.

Approach
During FY 1995, BFRL will complete the second phase of a 3 year research program on partially grouted masonry shear walls. This research includes evaluating the influence of horizontal reinforcement and aspect ratio on partially grouted masonry shear wall behavior. Work includes testing of the second series of specimens of highest priority, which target the effects of amount of horizontal reinforcement, and height-to-length aspect ratio. This series of experiments will be conducted on partially grouted masonry shear walls made using hollow concrete units, and it encompasses a total of 12 specimens. This work will study the influence amount of horizontal reinforcement and aspect ratio on shear behavior of walls. Horizontal reinforcement ratios equal to 0, 0.0005, 0.0012, and 0.0021 are incorporated in the experimental program, along with aspect ratios of 0.5, 0.7 and 1.0.

Analytical activities will be conducted in parallel with the experiments, and these include development of semi-empirical simplified expressions for predicting cracking and ultimate shear strengths and deformations. Similar efforts at BFRL have led to the improvement of a shear strength formula for fully grouted, reinforced masonry shear walls. There is also a pressing need to study the behavior of partially grouted masonry shear walls using a more systematic procedure that can give global as well as local information regarding states of stress and strain at cracking and yielding. For this purpose, two levels of finite element analysis of partially grouted walls will be conducted. BFRL staff will use a nonlinear finite element computer package which is widely available to the structural engineering community and which is based on well-established principles. This effort seeks to verify the applicability of nonlinear finite element analyses for design use. In addition, a contract will be awarded for a contractor to conduct separate analyses using state-of-the-art finite element analyses with numerical models which incorporate fracture mechanics formulations for the constitutive relations of brittle materials. The purpose of these analyses is to provide greater insight on the localized behavior of partially grouted masonry walls over the entire range of load-displacement response.

Recent Result
Schultz, A. E., *NIST Research Program on the Seismic Resistance of Partially-Grouted Masonry Shear Walls,*, NISTIR 5481, National Institute of Standards and Technology, Gaithersburg, MD, June 1994.

Seismic Strengthening Methodologies for Existing Lightly RC Frame Buildings

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Sponsor:
National Institute of Standards and Technology

Objective

To contribute to the current development of rehabilitation design guidelines for existing lightly reinforced concrete (RC) frame buildings by translating existing and new research results obtained in BFRL research efforts into technologies usable by designers.

Problem

A recently completed BFRL program on strengthening lightly RC frame buildings with infill walls has produced a set of design considerations. In the development of these considerations, important data have been collected and research tools have been developed. However, difficulties in knowledge transfer arise in bridging the gap between the research and design communities. Research tools such as computer programs, equations, procedures, etc., developed when conducting the research are usually cumbersome and impractical for use by a designer. Design charts and procedures, tables, and simplified equations need to be developed to convert the research tools into practical tools and technologies are needed to support performance-based design approaches.

A major effort has been undertaken by FEMA to develop guidelines/commentary for seismic rehabilitation of buildings to better meet the designers needs. This work will be used in conduct of this research.

Approach

During FY 1995, BFRL will collaborate with FEMA by participating in its projects meetings and identifying gaps in the rehabilitation technology in the area of lightly RC frame buildings. A workshop on strengthening lightly RC fame buildings will be held to identify means to fill these gaps. The results of this project will be used in support of FEMA's effort in developing performance based guidelines.

Recent Results

Lew, H. S., Phan, L. T., and Todd, D. R., *Strengthening Methodology for Lightly Reinforce Concrete Frames - II,* Recommended Calculation Techniques for the Design of Infill Walls," NISTIR 5421, National Institute of Standards and Technology, Gaithersburg, MD, May, 1994

Lew, H. S., Phan, L. T., and Todd, D. R., *Empirical Expressions for Estimating Seismic Performance of Existing and Strengthened RC Frames,* Abstract submitted to the 1993 SEAOC Annual Convention, September 29 - October 2, 1993, Scottsdale, AZ

Lew, H. S., Phan, L. T., and Todd, D. R., "Strengthening Methodology for Lightly Reinforced Concrete Frames," *25th Joint Meeting of the UJNR on Wind and Seismic Effects,* May 17-20, Ibaraki-ken, Japan, 1993, pp. 265-272

Lew, H. S., Phan, L. T., and Todd, D. R., "Seismic Strengthening of Reinforced Concrete Frame Buildings," *Proceedings of the 1993 National Earthquake Conference,* May 2-5, Memphis, TN, Vol. 2, 1993, pp. 235-244

Lew, H. S., Phan, L. T., and Todd, D. R., *Strengthening Methodology for Lightly Reinforce Concrete Frames,* NISTIR 5128, National Institute of Standards and Technology, Gaithersburg, MD, February, 1993

Geotechnical Evaluation for Lifelines

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Sponsor:
National Institute of Standards and Technology

Objective
To refine the development of System Identification Method for reliable estimation of soil properties important to the sitting of lifelines, demonstrate the effectiveness of in-situ methods of estimating liquefaction propensity, and develop a new, energy-based method to interpret the collected data.

Problem
Lifeline systems are vulnerable to large earthquake induced ground displacements, such as those associated with liquefaction, landslides, lateral spreads, slope failures, and fault displacements. As new lifeline systems become more complex, their vulnerability also is often increased. While it is in most instances feasible to locate critical structures and support facilities on sites which are not susceptible to large ground displacement, similar precautions are not always possible for long linear system elements such as pipelines, communication and electrical transmission lines, highways, and rail lines. To rationally design lifelines in areas of potentially large displacements, it is necessary to map the location of critical areas; in this case those susceptible to liquefaction. Even more important is that many existing lifelines were constructed through regions where ground conditions can be a major factor to decide the performance of the systems. Needed are methods to identify locations where such problems may occur and to develop recommendations to improve lifeline safety.

Approach
During FY 1995, BFRL will focus on the central problem of determining the liquefaction susceptibility of a given soil profile. Three tasks will be preferred:

1. Extension of the system identification technique proven by last years work to the extensive Lotung, Taiwan test site data set to be made available by EPRI;
2. Verification of the efficiency of the SASW technique for lifeline applications; and
3. Development of an energy-based interpretation technique to enhance the use of in-situ shear wave velocity for estimating liquefaction potential.

A powerful alliance of government, industry, and academia will be established to address these problems in a cost-effective and efficient manner.

The first task on the use of system identification techniques to estimate soil properties from earthquake strong motions will continue. This program is leading to a method to determine, based on seismic records, if a site has liquefied. Work-to-date has resulted in many publications, and promises to provide an alternative, yet better method to estimate in-situ soil damping. The acquisition of data from the Lotung, Taiwan test site from EPRI will permit validation of the technique on 34 seismic events. In addition, the nature of the Lotung data will allow investigation into soil-structure interaction.

The second and third tasks will be performed in coordination with Bechtel Corporation, San Francisco. The second task will involve a full-scale field test of the automated Spectral Analysis of Surface Waves (SASW) technique. The technique is non-intrusive, and if cost-effective for "productive work," will allow the rapid mapping of shear wave velocities for lifeline right-of-ways.

The third task work involves the initial development of an analytical method that will provide a rational framework for deciding the liquefaction potential of sand. While the shear-based methods have a firm basis in physics; its basis is for small strains. There is a good correlation between shear wave velocity and accepted methods of estimating liquefaction potential, at some sites, while at other sites the correlation is poor. The traditional SPT-based methods are too empirical and are not based on fundamental mechanics. The proposed energy-based method would use the amount of energy needed to initiate liquefaction as a basis for

comparing laboratory and field measurements.

Recent Results

Chung, R. M., and Glaser, S. D., "Measuring Liquefaction of Sands In-situ," *Third International Conference on Geotechnical Engineering and Soil Dynamics* ,1995. (Accepted for publication)

Glaser, S. D.," System Identification and Its Application to Estimating Soil Properties," *ASCE Journal of Geotechnical Engineering, ASCE, 1994* (accepted for publication)

Glaser, S. D., "Surface Displacements due to Earthquake Excitation for Saturated Sands" *EERI SPECTRA,* 1994

Glaser, S. D., System Identification and Its Application to Estimating Soil Properties" ASCE *Journal of Geotechnical Engineering,* accepted for publication, 1994

Glaser, S. D., "Application of Parametric Models for Estimation of Soil Parameters," *8th International Conference of the Association for Computing Methods and Advances in Geomechanics,* Vol. 1, pp. 575-580, 1994

Glaser, S. D., "In Situ Methods for Estimating Liquefaction Potential," *EERI SPECTRA,* in review, 1994

Chung, R. M., and Glaser, S. D., "Back Calculation of Soil Properties with System Identification," Fourth U.S.-Japan Workshop on Effects of Earthquakes on Lifelines and Liquefaction, 1994

Comparison of Seismic Provisions of Codes to the NEHRP Recommended Provisions

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Sponsor:
Federal Emergency Management Agency
Mitigation Directorate

Objective

To compare the seismic provisions of the model building codes to the National Earthquake Hazards Reduction Program (NEHRP) Recommended Provisions, 1991 edition.

Problem

Seismic provisions contained in the model building codes, the ASCE standards, and the NEHRP Recommended Provisions are periodically updated, normally every 3-years. In the case of the ICBO Uniform Building Code, the BOCA National Building Code, the SBCCI Standard Building Code, and the CABO One and Two Family Dwelling Code, the comparison of their seismic provisions to the 1988 edition of the NEHRP Recommended Provisions were carried out in the 1991 NEHRP Provisions. Another comparison, similar to the 1991 study, is needed to assess the seismic provisions in the more current codes with respect to those contained in the 1991 NEHRP provisions. Similarly, it is recommended to conduct a comparative study on the 1993 ASCE-7 seismic provisions with respect to the 1991 NEHRP provisions. These studies too are required to provide a sound technical base to allow the use of various model codes and standards by the federal agencies in carrying out their tasks under the Executive Order 12699.

Approach

During FY 1995, BFRL will perform two Tasks:

1. Update the comparison of the model building codes to the 1991 NEHRP Recommended provisions that was performed in 1991; the results were published in Assessment of the

Seismic Provisions of Model Building codes NIST GCR 92598, July 1992. The most recent full editions (not interim supplements or amendments) of the four model buildings codes will be compared to the 1991 NEHRP Recommended Provisions. Only those items which changed between the 1988 and 1991 editions of the NEHRP Provisions, or between the edition studied in 1991 and the most recent edition of the model codes will be assessed. The same comparison techniques were used in the 1991 study will be used for the update. A report will be issued presenting the comparison, the results and conclusions. Each of the studied model codes will be identified as either being or not being "substantially equivalent to the 1991 editions of the NEHRP Recommended Provisions." The same criteria used in making the evaluation in the 1991 study will guide the recommendations made in the updated study.

2. Compare the seismic provisions of the ASCE 7-93 design standard to the 1991 NEHRP Recommended Provisions. The seismic provisions of the 1993 edition of ASCE7, "Minimum Design Loads for Buildings and Other Structures," will be compared to the 1991 NEHRP Recommended Provisions, using the criteria and a format similar to that used in the 1991 study. A report will be issued presenting the comparison, results and a conclusion.

Using findings from the above tasks, BFRL will develop recommendations that would allow the use of these codes and standards by the federal agencies in seismic design of their buildings.

Recent Results
New project

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

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Sponsor:
Federal Emergency Management Agency
Mitigation Directorate

Objective
To facilitate and expedite the work of the Interagency Committee on Seismic Safety in Construction (ICSSC), by providing the Chair and Technical 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 currently participate in the ICSSC. The National Earthquake Hazard Reduction Act (amended by Public Law 101-614) designates the director of NIST, or his deputy, as the chair of the ICSSC. NIST provides the Secretariat to the ICSSC, to facilitate, document, and disseminate the work of the committee. The ICSSC is currently developing implementation guidance for Executive Order (EO) 12941 which adopts seismic evaluation and rehabilitation standards for existing Federally owned and leased buildings.

Approach
During FY 1995, BFRL will continue to provide FEMA with technical support. Within one year of the signing of the Executive Order 12941 (by 1 December 1995), BFRL working with ICSSC Subcommittee 1, the ICSSC Steering Committee, the ICSSC Full Committee, and a private sector contractor will develop and ballot guidelines for use by Federal agencies in implementing the Executive Order on existing buildings.

BFRL will schedule, chair, and document at least two meetings per year of the full committee and at least one meeting per year of the steering committee. BFRL will produce

agendas for and minutes of these meetings, maintain membership rosters, and perform other administrative tasks as needed to maintain the smooth functioning of this committee.

Recent Results

Todd, Diana, *Seismic Safety of Federal Buildings - Initial Program: How Much Will It Cost?*, NISTIR 5419, National Institute of Standards and Technology, April 1994

Todd, Diana, ed., *Standards of Seismic Safety for Existing Federally Owned or Leased Buildings and Commentary*, NISTIR 5382, National Institute of Standards and Technology, April 1994

Support Implementation of EO 12699

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Sponsor:
Federal Emergency Management Agency
Mitigation Directorate

Objective

To support implementation of Executive Order (EO) 12699 on seismic safety of new Federal construction by providing technical assistance when requested by affected agencies, and by producing appropriate technical studies.

Problem

Many of the affected agencies may lack specific knowledge on seismic design and construction principles, and content and use of building codes. As model codes and source documents are updated, agencies often require guidance on which codes are appropriate for Federal use.

Approach

During FY 1995, BFRL will collaborate with a private sector contractor, to compose the seismic provisions of the most recent editions of the three major model codes and ASCE 7 to the 1991 NEHRP Recommended Provisions. A report commenting on the relative equivalence of the codes will be produced. When asked by a Federal agency, BFRL will continue to:

1. Provide a speaker knowledgeable on EO 12699 and implementation issues for meetings in the Washington, DC area.

2. Provide multiple copies of existing literature published by NIST supporting implementation of the Executive Order.

3. Review proposed implementation procedures or regulations for appropriateness of technical content.

4. Disseminate materials produced by affected agencies for purposes of information-sharing with other agencies (only at request of the producing agency).

Technical Assistance to FEMA Project Officer (Existing Buildings)

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Sponsor:
Federal Emergency Management Agency
Mitigation Directorate

Objective
To provide technical review of FEMA-funded projects to develop design and construction guidance documents for seismic rehabilitation of existing buildings.

Problem
FEMA is supplementing the capabilities of its own staff by using the technical expertise of BFRL personnel.

Approach
During FY 1995, BFRL will review:

1. Development of "Guidelines for Seismic Rehabilitation" by BSSC/ATC/ASCE, and
2. An update of FEMA 156 and 157, Typical Costs of Seismic Rehabilitation of Buildings.

At the request of FEMA Project Officer, BFRL staff shall participate in proposal evaluation panels, in advisory panel meetings, in users' workshops and selected technical seminars and meetings. BFRL staff will review findings from draft and final FEMA projects.

UJNR Bridge Workshop

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Sponsor:
Federal Highway Administration
Structures Division

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
During FY 1995, BFRL will plan and host a joint U.S.-Japan workshop to be scheduled at Tsukuba, Japan, May 1995.

Recent Results
The Second U.S.-Japan Workshop on Earthquake Protective Systems for Bridges, December 7-8, 1992, Technical Memorandum of Public Works Research Institute (PWRI) No. 3196, Tsukuba Science City, Japan, 1993.

Proceedings of the 10th U.S.-Japan Bridge Engineering Workshop, May 10-11, 1994, Lake Tahoe, Nevada

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

Principal Investigator:
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Sponsor
National Institute of Standards and Technology and
10 Federal Agency Members

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

Problem
Loss of life and property result from insufficient knowledge to adequately design and construct building and other structures cost-effectively against high winds and seismic loads. Improved mitigation practices are in early stages of development. Technical collaborations between experts in the United States and Japan continue to produce findings that improve natural hazard mitigation practices. Such improvements are possible through joint working relations with experts from the United States and Japan 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
During FY 1995, BFRL will:

1. Plan U.S.-side activities (18 Agency membership) through hosting two U.S. Panel's domestic meetings.
2. Manage the U.S. delegation's technical contributions to Annual Joint Meetings.
3. Plan and coordinate technical activities of the 10 Task Committees.
4. Manage U.S.-delegation to Japan-side hosted Meetings and Workshops and developing technical programs for U.S. hosted meetings.
5. Maintain liaison with U.S. and Japan Panel members and other experts associated with the Panel's activities.
6. Plan Japan Panel member visits to the U.S. under the auspices of the Panel e.g., post disaster investigations, special studies, data gathering.
7. Maintain administrative and technical records.
8. Prepare and distribute periodic activities reports, and other materials as appropriate to U.S.-side Panel and Task Committee members.
9. Participate in Joint Panel meetings and Task Committees, and
10. Prepare and publish annual Proceedings.

Recent Results
Raufaste, N.J. editor, *Wind and Seismic Effects, Proceedings of the 26th Joint Panel Meeting*, NIST SP 871, National Institute of Standards and Technology, September 1994

Proceedings of the 9th U.S.-Japan Bridge Engineering Workshop, May, 1993, Tsukuba, Japan

STRUCTURES DIVISION

STRUCTURAL ENGINEERING

Noise-induced Chaos and Chaotic Transport

Principal Investigator:
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Sponsor:
Office of Naval Research
Ocean Engineering Division

Objective
To develop measures of the probability of exit from a safe region for multistable stochastic systems.

Problem
Multistable stochastic systems may experience jumps from a safe to an unsafe region of phase space. Safe design of each systems requires knowledge of probability of occurrence of jumps and conditions guaranteeing that jumps do not occur.

Approach
During FY 1995, BFRL will extend and apply multistable stochastic systems tools for deterministic chaotic systems.

Recent Results
Simiu, E., "Melnikov Function for Stochastically Perturbed Slowly Varying Oscillators: Application to a Model of Wind-driven Offshore Currents" accepted for publication in ASME Journal of Applied Mechanics

Simiu, E., and Frey, M., "Melnikov Process and Noise-induced Exits from a Well," (accepted for publication), *Journal of Engineering Mechanics*, ASCE

Frey, M., and Simiu, E., "Noise Induced Transition to Chaos," *Spatio-Temporal Chaos*, NATO Advanced Research Workshop, Addison Wesley, 1995

Sivathanu, Y. Hagwood, C., Simiu, E., "Exits in Multistable Systems Excited by Coin-Toss Square Wave Dichotomous Noise," Submitted to *Phys. Rev. E.*

Simiu, E., and Franaszek, M., "Melnikov-based Open-loop Control of Escape for a Class of Nonlinear Systems", *Proceedings, 15th Conference on Mechanical Vibration and Noise*, (submitted to ASME Technical Design Conference September 1995)

Frey, M., Hagwood, C., and Simiu, Emil, Melnikov-based Necessary Condition for Noise-induced Escape from a Well," *Proceedings 7th International Conference on Applications of Statistics and Probability*, (submitted), July 1995

Franaszek, M., and Simiu, E., Crisis-induced Intermittency and Melnikov-Scale Factor, (submitted to *Physics Letters A*)

Franaszek, M. and Simiu, E., Efficient Open-Loop Control for a Class of Stochastic Multistable Systems, *Proceedings, 15th Canadian Congress on Applied Mechanics*, May 1995

High-Performance Concrete: Design and Construction Practices

Principal Investigator:
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Sponsor:
National Institute of Standards and Technology

Objective

To enhance the application of high-performance concrete in the construction of new and the rehabilitation of existing constructed facilities.

Problem

High-strength concrete offers the potential for cost savings in construction due to reduced member dimensions, the capability to accommodate rapid construction schedules, and enhanced service life. From a structural perspective, high-strength concrete is inherently more brittle than ordinary strength concrete. Therefore, failure mechanisms in structural members need to be understood before appropriate design criteria can be developed. Lacking the necessary knowledge, design codes have taken a conservative approach and limit the concrete strength that can be used to compute member resistance to tensile failure modes. This places a barrier on the exploitation of the potential properties of the concrete.

Testing of concrete is essential to assure that the concrete has the potential to develop the desired properties. Also, in-place testing is essential to assure that the finished product has the specified properties. Standards for acceptance testing have been developed based on experiences with ordinary strength concrete. Problems have been encountered when current standards are used to evaluate high-strength concrete specimens. Laboratories testing the same material have obtained divergent strength values, which has resulted in unnecessary disputes. Testing standards need to be updated to extend their applicability to high-strength concrete. The use of in-place tests has to be facilitated by developing tools that can be used in the field to evaluate test results in a rigorous fashion.

Curing of concrete is the most critical step in the construction process. Sufficient curing is needed to assure that the concrete properties will develop and that the finished product serves its intended function. On the other hand, unnecessary prolonged curing adds to construction costs. Existing curing standards are based on information from ordinary concrete mixtures. These concretes contained portland cement as the only binder and did not have set controlling admixtures. High-performance concrete typically contains a blend of cementitious materials and often includes chemical admixtures that affect early-age hydration. Thus current prescriptive curing requirements may not be applicable to high-performance concrete mixtures. In addition, current standards make no distinction between curing to obtain adequate strength and curing to obtain adequate durability. Because durability is influenced highly by the near-surface layer, different curing methods may be needed to achieve adequate durability compared with curing where the only concern is strength. A new look at the subject of curing is critical to assure that the potential benefits of high-performance concrete can be realized economically.

Research on the state-of-the-art of the shear strength of high-strength concrete was begun by BFRL in FY 1994.

Approach

During FY 1995, BFRL will investigate the applicability of alternative rational models to predict the shear strength of high-strength members. These models have been proposed instead of the empirical models in current use.

In cooperation with NRMCA, additional studies will be performed to address the effects of the mechanical properties of capping materials, the effects of testing machine stiffness, and effects of consolidation methods. These studies are needed to provide the basis for modification of existing ASTM standards to assure reliable results when testing high-strength concrete.

Previous BFRL work has resulted in a methodology to analyze in-place strength

tests. An impediment to their widespread use is the lack of convenient tools that can be used in the field to analyze test results. A useable, computer-based tool will be developed to fill this need.

A literature review will be conducted on the state-of-the-art of curing high-performance concrete. The knowledge from the review will be used to plan an experimental and analytical study to provide the technical basis for recommended curing practices that will be applicable to all types of high-performance concretes. An essential component of this effort will be gaining and understanding of water diffusion in hydrating concrete. Joint collaborative work will be performed with BFRL's Materials Division.

Recent Results

Carino, N.J., Gutrie, W.F., and Lagergren, E.S., *Effects of Testing Variables on the Measured Compressive Strength of High-Strength (90 MPa) Concrete*, NISTIR 5405, National Institute of Standards and Technology, October 1994

Carino, N.J., Guthrie, W.F., Lagergren, E.S., and Mullings, G.M., "Effects of Testing Variables on the Strength of High-Strength (90MPa) Concrete Cylinders," Proceedings of the ACI International Conference on High-Performance Concrete, Singapore, November 15-18, 1994, *ACI Special Publication 149*, pp 589-632

Next Generation Design Standard For Wind Loads

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Sponsor
National Institute of Standards and Technology

Objective

To develop key elements of an improved wind load design standard for establishing site-specific design wind speeds and the corresponding steady and fluctuating structural loads.

Problem

There are a number of significant deficiencies in the wind load design provisions of current U.S. codes and standards. They include: 1. extreme wind speeds and corresponding load factors derived from outmoded estimation methods; 2. exposure coefficients that cannot deal with complex wind exposures (the normal case); 3. gross simplifications of extreme pressures and loads that ignore the directional effects of wind; and 4. no distinction between design for safety and design for serviceability. Of major interest is the tail length of distributions that best fit a given set of annual extreme wind speeds. The widely used Gumbel distribution has an infinite tail length while physical grounds require that wind speeds be bounded. Recently, statistical methods for estimating those bounds have become available. In the case of complex wind exposures, analytical models based on fundamental principles of fluid mechanics and on certain empirical relationships offer a substantial improvement over current equilibrium boundary layer models on which site-specific wind speeds are based. Since force and pressure coefficients are direction-dependent, directional distributions of extreme wind speeds can be handled most conveniently in combination with these coefficients.

Approach

During FY 1995, BFRL will combine directional extremes for a given site with wind tunnel databases for force and pressure

coefficients that most closely match the geometry and/or dynamic characteristics of the structure. The development of reliability concepts will make it possible to match safety and serviceability criteria with given levels of risk under wind loading.

Recent Results

Simiu, E., and Hacker, N.A., *Extreme Value Distribution Tails: A Peak Over Threshold Approach*, BSS 174, National Institute of Standards and Technology, March 1995

Marshall, R., Proceedings, *Workshop on Research Needs in Wind Engineering*, NISTIR 5597, National Institute of Standards and Technology, February 1995

Wind Load Criteria for Manufactured Housing in Hurricane Zones Design

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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. Experience in south Florida during Hurricane Andrew suggests that these wind load requirements do not adequately describe the forces that a manufactured home is likely to experience in a hurricane. There is a need to critically examine the current wind load requirements 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 1995, BFRL will perform three tasks:

1. Assess significance of tornadoes versus extra-tropical storms and hurricanes as a wind load design consideration and develop recommended changes to the Manufactured Home Construction and Safety Standards (MHCSS) for basic wind speed zones.

2. Identify alternatives to current industry practice of supporting manufactured homes on unbonded, open-cell masonry units and providing

resistance against sliding and uplift by way of shallow soil anchors.

3. Develop final reports describing work from tasks 1 and 2 above and on the wind resistance of selected manufactured home components.

Recent Results

Marshall, R., *Manufactured Homes - Probability of Failure and the Need for Better Windstorm Protection Through Improved Anchoring Systems*, NISTIR 5370, National Institute of Standards and Technology, 1994

Marshall, R., *Wind Load Provisions of the Manufactured Home Construction and Safety Standards - A Review and Recommendation for Improvement*, NISTIR 5189, National Institute of Standards and Technology, 1993

Non-Line-of-Sight (NLS) Construction Metrology

Principal Investigator:
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Sponsor:
National Institute of Standards and Technology

Objective

To develop a standardized non-line-of-sight (NLS) system by which the real time position and orientation of any object on a construction jobsite may be determined, irrespective of the presence of intervening obstacles.

Problem

Current and emerging technologies for construction site metrics suffer from substantial limitations such as line-of-sight data acquisition requirements and severe limitations on resolution. For some years now a new construction site positioning system, based on the use of two or three scanning laser broadcasters and a receiving "wand" has been under development. This shows promise for initial site metrology at construction sites where line-of-site requirements between the broadcast units and the receiver can be met. In such cases this system is positioned to replace traditional total-station surveying systems for precision measurement. However, there are many situations for which the line-of-sight requirement cannot be reasonably met ... e.g., where constructed members and natural obstacles obscure the laser transmission path. A completely alternative means of site positioning is afforded by the use of the GPS (Global Positioning System) satellite network in which local coordinates may be acquired using inexpensive hand held units. However, this system has limitations as well. In general, it circumvents line-of-site problems (since the locating mechanism is situated "overhead") but it does suffer from a lack of resolution (10 meter accuracy is the norm for a hand held unit) and does not penetrate well through overhead obstacles (e.g., a building roof).

Approach

During FY 1995, BFRL will develop a standardized system by which the real time position and orientation of any object on the jobsite can be determined and made available to a remote management office by telephone and virtual reality. The problem of eliminating the line-of-sight requirement while achieving high precision in real time with a hand held receiver is a difficult one. Current systems rely on the use of high frequency radiation (laser light or high band RF) which has the characteristic of substantial dissipation when encountered by objects typical at most construction sites. Research conducted by BFRL in 1994 has indicated two approaches to solving these problems.

In order to penetrate engineering materials a different approach must be used. Research conducted by BFRL in 1994 indicated that ultra wide band transmission techniques (sometimes referred to as "impulse radar," "spread spectrum SAR," and "base band radar") appear to have the most promise for developing a practical engineering measurement system. Fundamental work will be performed with cooperative receivers to determine which part of the EM spectrum is most effective in penetrating engineering materials.

Once a suitable transmission technology has been identified, BFRL will construct a LPS (Local Positioning System) which takes the fundamental operational principles of GPS and applies them to site positioning by means of synchronized local transmitters known as "pseudolites."

Recent Results

New project.

Field Evaluation of the Marshall Hammer Calibration System

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

Objective

To evaluate the effectiveness of the recently developed BFRL/NIST Marshall hammer calibration system using "production" equipment at state or federal highway agency laboratories.

Problem

The Marshall test procedure is currently used by most state and local highway agencies for hot mix asphalt design. The results of many round-robin mix exchange programs have shown there to be wide variability in the mix design parameters when a given mix is compacted with different compaction hammers. Much of the scatter in Marshall test results is attributed to compaction hammer related variables, such as: pedestal support, hammer alignment, hammer mass and friction. The variability of test data implied the need for a calibration procedure for Marshall compaction hammers: a calibration system was recently developed by BFRL with support from the Federal Highway Administration. The system has been demonstrated in a laboratory evaluation program and shown to reduce the scatter in Marshall test results by up to 60% (based on standard deviation and spread of test results). The next step is to demonstrate the calibration system using field equipment.

Approach

During FY 1995, BFRL will select, with FHWA staff, test sites, from the Maryland, Pennsylvania, Virginia, West Virginia, Delaware, and New Jersey regions. Each site will be visited twice by the research team. During the first visit, 2 sets of 4 uncalibrated Marshall specimens will be prepared using the standard compactive effort of 50 and 75 blows, respectively. Diagnostic machine data

will also be collected using the calibration system during the first visit. During the second visit the site machine will be calibrated and the number of blows needed to achieve the target cumulative impulse for 50 and 75 blows established. Two sets of 4 calibrated Marshall specimens will be prepared using the number of blows determined in the calibration procedure. Bulk density, percent air voids, stability and flow will be measured for all calibrated and uncalibrated specimens. Results will be compared to determine the reduction in variability of the data for the calibrated specimens. Minor modifications or enhancements to the calibration device/system will be undertaken as part of this effort, prior to the start of the field evaluation program.

Recent Results

Shenton, H.M. III, Cassidy, M.M., *Field Evaluation of the System for Calibration of the Marshall Compaction Hammer*, NISTIR 5553, National Institute of Standards and Technology, 1995

Shenton, H.W.III, Cassidy, M. M., Savage, D.A., and Spellerberg, P.A., *A System for Calibration of the Marshall Compaction Hammer,* NISTIR 5338, National Institute of Standards and Technology, 1994

Outreach and Technology Transfer

Principal Investigator:
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Structures Division
301-975-6062

Diana Todd
Structures Division
301-975-5296

Sponsor:
National Institute of Standards and Technology

Objective

To support the activities that promote the use of BFRL structural related research findings by its customers.

Problem

One of the major requirements identified by the earthquake hazards reduction community is the need for outreach to transfer research results into practice. For example, only some of the successful research sponsored by the National Science Foundation has been implemented into practice; the rest remains on the bookshelves. In order to develop technological tools to advance state-of-the-art engineering practice in design, construction, inspection, repair, and strengthening of existing facilities, reseárch results supported by NEHRP must be synthesized and reformatted for use by designers through various forms of outreach and technology transfer.

Approach

During FY 1995, BFRL will identify media that has high payoff in transferring technologies such as the workshops, seminars, symposia, and conferences. In addition, short courses may be developed and conducted for continued education of professionals as they enhance their knowledge base. Some of the outreach efforts will be coordinated or jointly supported with other NEHRP agencies. Collectively these agencies are often the principal sponsors of major national or international conferences on earthquake hazards and engineering practices.

This work also supports the technology transfer of other BFRL structural related projects.

BUILDING MATERIALS DIVISION

CONCRETE

High-Performance Concrete

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Sponsor:
National Institute of Standards and Technology

Objective
To develop methods for measuring and predicting the rheological behavior and curing of high-performance concrete.

Problem
After years of relatively slow advances in concrete technology, a worldwide awareness has arisen that the performance of concrete can be significantly improved. This is cited in program plans of the CEB (Commission Euro-International de Beton) and the high-performance concrete research activities in Japan, Norway, and Canada. The concrete and structures program of the Strategic Highway Research Program (SHRP) and the NSF Center for Advanced Cement-Based Materials (ACBM) were established in response to the need for improved concretes and the recognition of the possibility of the development of high-performance concrete (HPC). The Civil Engineering Research Foundation (CERF) and the American Concrete Institute (ACI) have led the U.S. efforts in developing a comprehensive program on high performance concrete, and CERF has published a proposed program that deals with high-performance construction materials, *High-Performance Construction Materials and Systems: An Essential Program for America and Its Infrastructure*, CERF Technical Report 93-5011, April 1993. HPC technology is sufficiently different from that of conventional concrete that existing test methods and processing practices (e.g., mixing, consolidating and curing) may not be applicable. The CERF report listed the need to predict 1) the durability of HPC, 2) the rheological properties of HPC, and 3) the effect of different curing practices on the performance of HPC.

Approach
During FY 1995, BFRL will perform research on 1) the susceptibility of HPC to deleterious expansion by alkali-silica reactivity (ASR), 2) the rheological properties of HPC, and 3) the effect of curing practices on the performance of HPC. Studies on the susceptibility of HPC to deleterious expansion caused by ASR of aggregates were initiated in FY 1994. They are being performed by immersing mortar bars, of a range of water-to-cement ratios and ages, in a concentrated aqueous sodium hydroxide solution, at an elevated temperature, and measuring expansions and flexural strengths of the specimens. To determine if high-strength concrete has a sufficiently high tensile strength to resist the expansive stresses from ASR, an apparatus has been developed for measuring expansive forces in mortar bars caused by ASR. In this test, specimens are subjected to the testing condition described above and any resulting expansive forces are measured using a load cell. The results will indicate whether or not there is a need for testing the ASR of siliceous aggregates for use in HPC.

In the second task, a method will be developed to predict the rheological properties of HPC. BFRL will carry out a critical review of current knowledge on the rheology of cement-based materials, including rheological properties, test methods, and models. Method(s) will be selected and used for measuring the important rheological properties of cement pastes and mortars of a range of compositions and water-to-cement ratios. Also, the feasibility of applying hydrodynamic models to predicting the rheological properties will be explored. If successful, in FY 1996 the model will be extended to mortar and concrete. Based on the experimental and modeling efforts, correlations between the rheological properties of cement pastes and mortars and HPC will be sought. If reliable correlations are obtained, they should be useful for predicting the rheological properties of HPC based on simpler and more rapid tests on cement pastes or mortars.

In the third task to be performed in FY 1995, BFRL will determine the effects of moisture, temperature conditions, and time on the

curing and performance of HPC. An essential component of this study will be an investigation of moisture movement in hardening HPC. The results of the study on curing and the state-of-the-art report prepared by BFRL's Structures Division will provide an essential part of the knowledge base for an expert system giving recommendations for curing of HPC.

Recent Results

Two papers on the frost resistance of concrete, were published in 1994:

Snyder, K.A., and Clifton, J.R., "Measures of Air Void Spacing," *Proceedings of the 12th International Building Materials Conference*, Weimar, Germany, Vol. 1, pp. 155-158, September 1994.

Snyder, K.A., Clifton, J.R., and Knab, Lawrence I, "Freeze-Thaw Susceptibility of High Performance Concrete," *Proceedings of the 12th International Building Materials Conference*, Weimer, Germany, Vol. 1, pp. 139-142, September 1994.

Integrated Knowledge System for High-Performance Concrete

Principal Investigator:
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Sponsor:
National Institute of Standards and Technology

Objective

To develop and demonstrate an integrated knowledge system for high-performance concrete (HPC) which will be a model for other high-performance construction materials (HPCMs).

Problem

A major requirement for exploiting the benefits of HPCMs is making reliable information about these materials (composition, properties, and performance) available to producers, users and other decision makers. Owners, designers, and contractors need access to reliable information about HPCMs that can be quickly and economically retrieved. This can be accomplished by organizing the information in an integrated computer-based knowledge system. An integrated knowledge system for HPCMs should consist of databases integrated with mathematical models and expert opinion to assist engineers and contractors in using the most reliable and advanced knowledge for selecting and using HCPMs.

Approach

During FY 1995, BFRL will continue collaboration between the private and public sectors in planning the development of an integrated knowledge system for HPC including its conceptual design and architecture; available databases, mathematical models, and expert systems; standards for interfacing different types of knowledge; and the formation and linking of distributed knowledge bases. This was initiated from an FY 1994 workshop and symposium conducted by BFRL. A demonstration prototype integrated knowledge system will be developed for HPC, using models developed at BFRL and from

selected reports on HPC. Also, BFRL will modify its HWYCON expert system to make it more universal and incorporate HPC findings. In addition to selecting concrete materials, the extended expert system (HYPERCON - high-performance concrete) will give recommendations on proportioning, processing, and repairing HPC. Collaboration with industry and technical committees such as ACI, RILEM, and ASCE in the development of HYPERCON will be vital to its successful development.

Recent Results

Conducted a symposium and workshop that explored the development of an integrated knowledge system for HPC and other high-performance construction materials. Three thousand copies of HYWCON have been made available for distribution by the National Research Council's Transportation Research Board.

Transport Properties of High-Performance Concrete

Principal Investigator:
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Sponsor:
National Institute of Standards and Technology

Objective

To develop analytical and simulation models that predict transport properties of high-performance concrete (HPC), perform experiments to validate these models, and develop improved methods for measuring the important HPC transport properties.

Problem

Before reliable HPC service life predictions can be made, a fundamental understanding of the mechanisms controlling HPC degradation is needed. Many of the degradation processes are controlled by HPC transport properties. Due to the anticipated small pore sizes in HPC, the primary transport properties should be diffusion and capillary flow. Although diffusion in HPC has been investigated, there does not exist a comprehensive body of work that encompasses all the important factors controlling diffusion. In addition, no reliable test methods exist to measure the material properties (e.g., permeability, diffusion, and capillarity) that control the invasion of HPC by aqueous media. Experimental methods and standard procedures are needed to form a basis for reliable characterization of transport properties.

Approach

During FY 1995, BFRL will model the diffusion and capillary flow in HPC. Results from BFRL computer simulations will be compared to experimental data from BFRL and from W.R. Grace Co., Inc.

Recent Results

Martys, Nicos S., Torquato, S., and Bentz, D.P., "Universal Scaling of Fluid Permeability for Sphere Packings," *Physical Review E*, 50, 403-408, 1994.

Martys, Nicos. S., "Fractal Growth in Hydrodynamic Dispersion Through Porous Media," *Physical Review E*, **50**, 335-342, 1994.

Schwartz, L.M., Auzerais, F., Dunsmuir, J., Martys, N., Bentz, D.P., Torquato, S., "Transport and Diffusion in Three-dimensional Composite Media," *Physica A*, **207**, 28-36, 1994.

Nolle, C.S., Koiller, B., Martys, Nicos, and Robbins, Mark O., "Effect of Quenched Disorder on Moving Interfaces in Two Dimensions," *Physica A*, **205**, 342-354, 1994.

Bentz, D.P., Martys, Nicos, Stutzman, P., Levenson, M.S., Garboczi, E.J., Dunsmuir, J., and Schwartz, L.M., "X-Ray Microtomography of an ASTM CI09 Mortar Exposed to Sulfate Attack," *MRS Symposium Proceedings Series*, Vol. 370, 1995

Martys, Nicos S.,*Survey of Concrete Transport Properties and Their Measurement*, NISTIR 5592, National Institute of Standards and Technology, Gaithersburg, MD, (in review).

Microstructure-Transport Property Relationships in Random Porous Materials

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Sponsor:
National Institute of Standards and Technology

Objective

To develop new, more accurate relationships between microstructure and transport properties.

Problem

The degradation of the concrete infrastructure, worth on the order of six trillion dollars, is a national problem. The basic physical and chemical mechanisms of degradation processes in concrete need to be understood to make scientifically sound, nonempirical service life predictions. Most of the degradation processes that affect cement-based materials involve microstructure-related properties such as 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 put existing and future standard test measurements of transport and other properties on the firm scientific foundation needed to enable reliable production of high-performance materials.

Approach

During FY 1995, BFRL will develop new 3-D finite element shrinkage codes to enable analysis of C-S-H shrinkage phenomena and stresses caused by sulfate attack in variously-shaped specimens, and in 3-D models of C-S-H. A Cooperative Research and Development Agreement (CRADA) is being established with W.R. Grace, Inc., to cover some of this work. BFRL will use a digital-image-based approach with Monte Carlo techniques to simulate the formation of cement-based and ceramic materials at the most fundamental level that is possible and necessary. Using finite

element and finite difference techniques, coupled with fast conjugate gradient solvers, BFRL will develop software to simulate and compute physical processes and parameters as needed. These new microstructure and property simulation algorithms will then feed into the other modeling projects focused on the solution of specific problems. Experimental measurements are made as necessary, either at BFRL or in collaboration with other institutions like Northwestern University and Imperial College, to validate the model results.

Recent Results

Bullar, J.W., Garboczi, E.J., Carter, W.C., and Fuller, E.R., "Numerical Methods for Computing Interfacial Mean Curvature," *Computational Materials Science*, (in press).

Bentz, D.P., Quenard, D.A., Baroghel-Bouny, V., Garboczi, E.J., and Jennings, H.M., "Modelling Drying Shrinkage of Cement Paste and Mortar: Part I. Structural Models from Angstroms to Millimeters," *Materials and Structures*, (in press).

Three-Dimensional Microstructural/Kinetic Model of Cement Hydration

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Sponsor:
National Institute of Standards and Technology

Objective

To develop and validate a comprehensive model for cement hydration and microstructure development in three dimensions.

Problem

Prediction of the properties and performance of cement-based materials is hindered by a lack of a basic understanding of microstructural development and hydration kinetics. Progress in this area has been slow due to the complexity of the starting materials, water and a multi-size, multi-phase cement powder, and the number and the complexity of the reactions which occur during hydration. A comprehensive model incorporating both microstructural and kinetic considerations is needed to allow a priori prediction of the behavior of these materials under a variety of processing conditions.

Approach

During FY 1995, the first year of this three-year project, BFRL will develop the integrated computer model and experimental techniques to be used in model validation. The second and third years will focus on model validation and distribution and extensions to incorporate mineral admixtures such as fly ash. Characterization of the starting cement powder using scanning electron microscopy (SEM) and x-ray imaging allows the determination of, for a specific cement, the volume fractions and spatial distributions of the major phases (silicates, ferrites, sulfates, aluminates, etc.). A key step will be the integration of BFRL's microstructural model with an appropriate model for the kinetics of hydration. Model outputs will include phase volume fractions and solution concentrations as a function of time and a detailed three-

dimensional microstructural representation at any time of interest, as well as predictions of the heat release and water absorption behavior of a cement paste hydrated under isothermal, saturated conditions. These latter two phenomena will be investigated from an experimental viewpoint using a calorimeter and new equipment to measure chemical shrinkage during hydration, to be constructed specifically for this project. These measures will be compared to degree of hydration measurements performed using conventional loss on ignition techniques. An assessment will be made of the feasibility of performing chemical analysis of expressed pore solution to compare to model predictions.

Recent Results
New project.

Characterization of Clinker and Cement, and Flaws in Cement Paste and Concrete

Principal Investigator:
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Sponsor:
National Institute of Standards and Technology

Objective
To develop and demonstrate techniques for compositional and microstructural characterization of clinker, cement and concrete, and characterization of flaws in high-performance concretes.

Problem
Understanding material properties of cement, cement paste and concrete, each a complex multi-phase material, depends upon the ability to quantitatively characterize their compositions, microstructures, and microstructure development. While x-ray powder diffraction (XRD) analysis has long been used to identify crystalline materials, fewer than one percent of users apply XRD for the quantitative analysis of mixtures. There are difficulties in sample processing, data collection, measurement of individual phase diffraction pattern intensities, and matching reference phases to the unknowns that must be overcome to allow standardization of this potentially very important analytical technique.

Approach
During FY 1995, BFRL will use recent developments in imaging and x-ray diffraction analysis to facilitate improved quantitative characterization of each of the materials and to help show how compositional characteristics relate to material performance and durability. Interactive analysis using DATAPLOT, which is currently being tested using the NIST Reference Clinkers, will be applied. Least-squares fitting of reference patterns to the mixture pattern will provide weights that can be related to mass fractions of each component in the mixture. A new method, the Rietveld method, will be used in

calculations of the best-fit diffraction pattern for each phase as well as the best-fit combination of patterns to that of an unknown mixture. This method will provide quantitative phase abundance analysis and information on the chemical compositions and structural data for each phase in a mixture.

Application of backscattered electron imaging in the scanning electron microscope (SEM) will be used to investigate clinker, cement, hardened cement paste, and concrete microstructures with resolutions approaching 0.1 micrometers. With additional information provided by x-ray imaging and image analysis, BFRL will go beyond the usual identification of calcium hydroxide and calcium silicate hydrate and locate occurrences of monosulfate, ettringite, and gypsum. Video image analysis using real-color discrimination will assist in imaging and quantifying macro features such as aggregate type and distribution and fracture characteristics. Combined SEM/video analysis will facilitate quantitative descriptions of microstructures from meter to micrometer length scales and include measures of phase composition and distribution, porosity, and fracture characteristics. The combined application of these methods will facilitate concrete characterization and provide a means to identify macro- and microstructural features of material and construction flaws.

Recent Results

Stutzman, P.E., *Quantitative X-Ray Powder Diffraction Methods for Clinker and Cement*, NISTIR 5403, National Institute of Standards and Technology, Gaithersburg, MD, May 1994.

Stutzman, P.E., *Compositional Analysis of Beneficiated Fly Ashes*, NISTIR 5598, National Institute of Standards and Technology, Gaithersburg, MD, (in press).

Stutzman, P.E., *Guide for X-Ray Powder Diffraction Analysis of Clinker and Cement*, NISTIR, National Institute of Standards and Technology, Gaithersburg, MD, (in review).

A Study of Floor Leveling Components

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Sponsor:
General Services Administration
National Capital Region
Public Buildings Service

Objective

To evaluate the performance of self-leveling compounds for use in an office building.

Problem

A severe odor in some floors of a large office building was attributed to a complex interaction involving a self-levelling compound, carpet adhesive, and the carpet. Information about alternative levelling compounds is needed to aid the making of a decision as to what should be done to correct the problem.

Approach

During FY 1995, BFRL will evaluate information furnished by suppliers of self-levelling materials, consider their compositions, specific masses recommended, depths of cover, applications to concrete, curing times, and other factors which may affect their performance. The most promising materials will be selected for laboratory testing. Laboratory testing of selected self-levelling compounds will be performed, consisting in determining their flow, hardening, and shrinkage characteristics; measuring their compressive strengths and bond to hardened concrete; and observing their feathering characteristics such as crumbling at thin edges. The presence of any odors also will be recorded.

Tests also will be performed on a light-weight concrete to determine properties such as its flow, hardening and shrinkage characteristics, and its compressive strength and bond to hardened concrete. Also, the bond between the light-weight concrete and previously selected levelling compounds will be measured. Based on the tests, the suitability

of the light-weight concrete as a substrate for the levelling compound will be decided.

Recent Results

Periodic reports have been provided to the sponsor and a final report has been prepared. The results of the work were used by GSA in selecting a self-levelling compound.

BUILDING MATERIALS DIVISION

COATINGS

Integrated Knowledge System for Corrosion-Protective Coatings for High-Performance Steel

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Sponsor:
National Institute of Standards and Technology

Objective
To develop an information model and a computerized system for the representation and dissemination of organic coatings knowledge for protecting high-performance steel structures against corrosion, and develop a multi-media knowledge system to be a model decision-support system.

Problem
Coatings provide a versatile, cost-effective means for protecting steel structures against adverse environmental conditions, but decisions concerning coating system selection are often difficult to make. An improved decision-making process needs to be developed to extend the service life of these structures. Currently, coating system users must rely on information that is represented in many different forms and systems. These include manuals, guides, photographs and drawings, videos, databases, and other references. Often, the decision-making knowledge may be dispersed or unavailable. An integrated knowledge system that includes different forms of knowledge and presented in a coherent format is required to improve the specification, selection, and use of coatings systems for protecting steel.

Approach
During FY 1995, BFRL will analyze the various factors affecting the service life of coatings and the use of the information in the decision-making process. Liaison will be maintained with potential users of the knowledge system (e.g., coating manufacturers, distributors, and users) throughout its development. An investigation into the state-of-the-art for coatings knowledge systems and information standards for construction materials will be conducted. The feasibility of interfacing with existing information sources, such as the Smithsonian Institutions' spectral UV-radiation (solar) database, will be explored. High-level experts in the field of service life, diagnostics of coatings failures, and the selection of coatings, will be interviewed. A knowledge hierarchy will be established that will address the specific focus(es) of the system. Other factors, such as the effect of spectral UV-B radiation on the durability of coatings, will be identified and incorporated into the knowledge in the form of rules and models. An object-oriented expert system architecture will be used to represent and interface the different knowledge forms. Leading-edge computer techniques and resources will be used to develop the system. These will include CD-ROM, hypertext, digital images and drawings, video and sound. The system will be developed for desktop and field use.

The Internet wide-area network will be used to test the usefulness of decision-making in a geographically dispersed environment. The products of this research will be: 1) an information model that will assist in the decision-making process for the diagnosis and selection of coatings materials, 2) a multi-media integrated knowledge system that will assist users of industrial maintenance coatings, and 3) a worldwide network repository of coatings knowledge and information about coatings materials. The system will contain high-level expert knowledge, video and sound capabilities, databases, references, and images of coatings failures and testing procedures.

Recent Results
New project.

Coatings Service Life Prediction Consortium

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Sponsor:
National Institute of Standards and Technology and

Department of Transportation
Federal Highway Administration

Objective
To develop a method for predicting the service life of a coating system, methods for quantitatively characterizing exposure environments and material degradation, and demonstrate how environmental measurements of degradation can be made on coated steel structures.

Problem
An improved methodology for predicting the service life of coating systems exposed in their expected service environments is needed to reduce the time required to introduce new coatings into the marketplace. If new coatings should have to be developed to comply with new environmental regulations, a reliable methodology for service life prediction would help ensure that the products had adequate durability.

Approach
During FY 1995, BFRL will perform three concurrent tasks as part of the first 3-year phase of this industry/government consortium. This work is being performed under a Cooperative Research and Development Agreement (CRADA) with industry. The tasks are:

1. Quantify photodegradation effects of UV-radiation in the field and laboratory. Specimens will be exposed in field and laboratory tests. Spectral UV radiation will be monitored. Mathematical models derived from laboratory results will be used in predicting field performance results.
2. An interactive research program involving each participant in a research project related to their work. BFRL researchers will provide consultation, help formulate problems, and analyze and interpret results.
3. Develop user-friendly software for analyzing time-to-failure data. Life testing experiments are data intensive. Software will be used in analyzing the data.

This CRADA is an outgrowth of previously funded BFRL research quantifications of outdoor weathering environments.

Recent Results

Pommersheim, J., Nguyen, T., Zhang, Z., and Lin, C., "Cation Diffusion at the Polymer/Metal Interface," *Journal of Adhesion Science and Technology*, 2: 1-17, 1995.

Martin, J. W., Saunders, S.C., Floyd, F.L. and Wineberg, J.P., *Methodologies for Predicting the Service Life of Coating Systems*, NIST-BSS 172, National Institute of Standards and Technology, Gaithersburg, MD, 1994.

Martin, J.W., "Reliability Testing and Life Testing Analysis of Building Materials," *EuroCare Conference Proceedings*, meeting held in Hamar, Norway, June 1994.

Lechner, J.A. and Martin, J.W., "Modeling and Measuring Ultraviolet Irradiance to Predict Damage to Macromolecular Materials," *Proceedings of the American Chemical Society Division of Polymeric Materials: Science and Engineering*, Vol. 69, 1993.

Martin, J.W., "Quantitative Characterization of Spectral Ultraviolet Radiation-induced Photodegradation in Coating Systems Exposed in the Laboratory and the Field," *Progress in Organic Coatings*, 23(1):49, 1993.

Organic Coatings

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Sponsor:
Department of the Air Force
Air Force Civil Engineering Service Agency

Objective
To organize Tri-Service Coating Committee meetings, provide technical assistance to solve coating problems, and help meet new coating regulations.

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 (VOC) content and heavy metal content.

Approach
During FY 1995, BFRL will continue to maintain awareness of new technologies by attending industry meetings and help implement new technologies by sharing information during Tri-Service Protective Coatings Committee meetings. Efforts will focus on meeting the need for new coating specifications that comply with new regulations, continuing to chair the SSPC Committee on Coatings, and working in the ASTM D01 Committee on Paint and Related Coatings and Materials.

Recent Results
Tri-Service Coating Manual, MIL-HDBK-1110/1, Defense Printing Service Detachment Office, 700 Rollin Avenue, Philadelphia, PA 19111-5094, 1995.

Performance Criteria for Adhesively-Bonded Encapsulants for Lead-Based Paint

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Sponsor:
U.S. Department of Housing and Urban Development
Office of Lead-Based Paint Abatement and Poisoning Prevention

Objective
To develop preliminary performance criteria for adhesively-bonded encapsulants for lead-based paint in housing based on laboratory testing and limited field testing.

Problem
In a survey of the Nation's housing, the U.S. Department of Housing and Urban Development (HUD) found that about 57 million homes in the United States have lead-based paint (LBP) on at least one painted surface (comprehensive and Workable Plan for the Abatement of Lead-Based Paint in Privately Owned Housing, Report to Congress, U.S. Department of Housing and Urban Development, December 7, 1990). One way of helping to ensure that the hazards of LBP in housing are kept low is to stabilize the paint and protect it from abrasion and solvents by an adhesively bonded encapsulant. A major deterrent to the use of these encapsulants is the lack of performance standards and field performance data. Data are needed by ASTM Subcommittee E06.23 on Abatement of Hazards from Lead in Buildings, to develop a consensus standard for adhesively-bonded encapsulants.

Approach
During FY 1995, BFRL will develop preliminary performance criteria based primarily on early age or short-term laboratory and field tests, refine the criteria, and extend them to include preliminary criteria that address long-term performance. Performance requirements and test procedures for adhesively-bonded encapsulants will be identified. Encapsulants must, with an

acceptable probability, ensure that the lead is kept in place and prevented from contaminating the environment for the desired time. Therefore, performance criteria will address encapsulant material characteristics that prevent release of lead such as abrasion resistance, impact resistance, and the ability to prevent failure (e.g., peeling, flaking and chipping) of the underlying LBP layer.

In performing this work, BFRL will:

1. Visit several field sites where adhesively-bonded encapsulants have been installed or are being considered to identify specific requirements and selection of test materials.
2. Select substrate test materials and develop procedures for preparing them in a uniform and consistent manner to simulate conditions expected in the field.
3. Select candidate adhesively bonded encapsulants and control materials (e.g., wallpapers) to use in testing.
4. Select appropriate test procedures using ASTM tests where appropriate and prepare test specimens.
5. Subject specimens to laboratory performance tests under conditions in which the applied stresses are at the high ends of the ranges expected under service conditions, and
6. Based on the laboratory test results, carry out limited field testing.

Using both data sets, preliminary performance criteria will be developed. Results of the research will be provided to ASTM E06.23 to use in improving the technical bases for standards for encapsulants.

Recent Results

New project.

Method for Evaluation of Performance of Lead-in-Paint Measuring Devices Under Simulated Field Conditions

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Sponsor:
U.S. Department of Housing and Urban Development
Office of Lead-Based Paint Abatement and Poison Prevention

Objective

To identify and quantify factors affecting the field performance of portable x-ray fluorescence (XRF) devices for measuring lead in paint under a range of simulated field conditions, develop a laboratory test method suitable for evaluating portable XRF devices, and write a draft standard test method for the laboratory-based evaluation of portable XRF devices and present it to ASTM E06.23 for standardization.

Problem

Recent legislation (Housing and Community Development Act of 1992, PL 102-550) will phase in requirements for lead-based paint testing for all housing built before 1978. These requirements are expected to result in the development of several new x-ray fluorescence (XRF) devices. Because of both health and financial liabilities associated with these measurements, it is essential to have reliable estimates of the field performance parameters of the measurements (e.g., detection limit, precision, bias). For some XRF devices, research results have shown that estimates of these performance parameters obtained using existing laboratory evaluation procedures do not agree with estimates obtained using field-acquired data. Currently, field studies are being used to characterize additional devices. However, field studies are limited in several ways -- sites having parameters in the necessary ranges are difficult to find; systematic variation of the parameters is usually not possible; implementation of new technologies may be impeded; and advances in the fundamental understanding of a measurement procedure are limited. Thus, there is a need for a

laboratory-based field-simulation test protocol for the reliable evaluation of portable XRF devices which will overcome these limitations. An amended problem statement provides for NIST purchase of all instruments to ensure impartiality in the selection of instruments to be tested.

Approach

During FY 1995, BFRL will:

1. Characterize and model the scientific principles controlling the performance of portable XRF devices.
2. Design and perform laboratory experiments to simulate significant field conditions, as determined by modeling and other information.
3. Perform a limited field study to determine whether the laboratory results are consistent with field results.
4. Prepare a standard protocol for laboratory evaluation of portable XRF devices and present it to ASTM E06.23 for standardization.

A conceptual model of the measurement process will be constructed to portray the scientific principles involved, factors likely to affect instrument response, and characterization of typical field situations in terms of these factors. A mathematical model embodying a fundamental understanding of the measurement process and the effects of the composition and configuration of a test specimen upon the measurement response will be developed. The mathematical model will be used throughout the study to explore the implications of various material configurations and field conditions on instrument response and to aid interpretation of experimental results.

Using information obtained from the literature and other sources, and from the model, both a simulated field study and an actual field study will be statistically designed. The design for the laboratory-based field simulation study will include use of model wall sections each about one meter square containing materials in configurations typical of those found in residential buildings. The laboratory experiment will be carried out in a room with temperature and humidity controls that allow the conditions to be changed as needed. The model sections will be constructed in such a way that the materials and configurations within them can be systematically changed to represent ranges of field conditions to study their effects upon instrument response. The field experiment will be conducted to determine whether the estimates of measurement variability obtained in the laboratory and field are consistent with each other.

The experimental design will include coordination with the Midwest Research Institute's (MRI) lead-based wall program. Measurements of leaded-paint specimens on the wall will be made with the instruments used in the BFRL laboratory and field studies. In this way, links can be established between performance data obtained in the laboratory, the MRI wall and field studies.

Upon completion of the experimental study, a draft standard test method for evaluating the performance of portable XRF equipment will be written and presented to ASTM E06.23.

Recent Results

Completed conceptual model incorporating factors that will affect XRF instrument response.

Standards for Abatement of Hazards from Lead in Buildings

Principal Investigator:
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Sponsor:
The U.S. Department of Housing and Urban Development
Office of Lead-Based Paint Abatement and Poisoning Prevention

Objective
To develop technical data for development of needed standards for abatement of hazards from lead in buildings and structures.

Problem
An estimated 57 million homes in the United States contain some lead-based paint. Although there is general guidance for characterizing the lead concentrations in paint, dust, soil and air particulates and carrying out abatements, there are few standard procedures that address these issues. Thus, there is a need for an overall standard practice for abating hazards from lead in buildings and structures that include assessment and analysis of the problem, design of abatement strategy, abatement procedures and post-abatement management procedures. An ASTM Subcommittee, E06.23, was organized to meet this need.

Approach
During FY 1995, BFRL will continue to provide technical support to HUD and ASTM. The approach that ASTM E06.23 is using to develop the practice for abatement of hazards from lead in buildings and structures is to develop the basic standards to serve as the framework of the guide. These include standards to characterize the concentration of lead in paint, dust, soil and air particulates and perform abatements and hazard reduction.

Recent Results
Submitted technical basis for ASTM Standards on Lead-based Paint Abatement in Buildings, ASTM, Philadelphia, PA, 1994

Technical Assistance on Lead-Based Paint Issues

Principal Investigator:
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Sponsor:
U.S. Department of Housing and Urban Development
Office of Lead-Based Paint Abatement and Poisoning Prevention

Objective
To provide technical assistance on lead-based paint material-related issues and measurement procedures.

Problem
The Office of Lead-Based Paint Abatement and Poisoning Prevention, of the U.S. Department of Housing and Urban Development (HUD), receives many requests for technical assistance on issues regarding abatement of hazards from lead-based paint in housing. Some of these requests concern material properties and performance of paints and coatings and material-related measurement procedures.

Approach
During FY 1995, BFRL will provide, as needed, technical assistance on matters relating to the performance of paints and coatings, the abatement of hazards from lead-based paint, measurement of lead concentrations in paint films, and other material-related issues. In particular, BFRL will provide written descriptions of enclosures for lead-based paint. Outside experts will be used as required.

Recent Results
Provide a written description of enclosures for Lead-Based Paint for use in HUD lead-based paint hazard abatement guidelines.

BUILDING MATERIALS DIVISION

QUALITY ASSURANCE

Cement and Concrete Reference Laboratory (CCRL)

Principal Investigator:
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Sponsor:
American Society for Testing and Materials (ASTM) and

Department of the Army
Corps of Engineers

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, and the cost of construction of facilities amounts to about 10 percent of the gross domestic product. Over $4 billion of hydraulic cement is produced in the United States each year; the value of concrete construction is estimated to be in the order of $20 billion. Standardization of testing to enhance the reliability of quality assurance measurements is important. The productivity of the cement and concrete testing community can be increased by using correct procedures and apparatus that reduce testing errors and provide a sound basis for accepting cement on mill certificate. Efficient use of long-established construction materials is facilitated by dependable quality assurance programs.

Approach
With the support of ASTM Research Associates working under BFRL supervision, services are provided to public and private cement and concrete testing laboratories on a voluntary basis. These services include the laboratory inspection program and the distribution of proficiency test samples. Equipment and procedures used in performing conventional quality assurance tests are evaluated for conformance to applicable national standards. Related test apparatus is checked with inspection equipment calibrated by BFRL personnel. Proficiency test samples of portland cement, pozzolan, concrete, blended cement and masonry cement are distributed at regular intervals to obtain information on laboratory performance. Additionally, technical studies are conducted in areas related to these programs. These are often in conjunction with other NIST units.

During FY 1995, BFRL will continue to produce:
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.

Findings from BFRL technical reports, papers in outside journals, and oral presentations are used by the cement and concrete community in product development.

Recent Results
Spring, Curtis B., Pielert, James H., Leigh, Stefan, Heckert, N. Alan, *Graphical Analysis of the CCRL Portland Cement Proficiency Sample Database (Samples 1-72)*, NISTIR 5387, National Institute of Standards and Technology, Gaithersburg, MD, March 1994.

Inspected over 260 cement and concrete laboratories; distributed over 3000 proficiency samples; and CCRL provided performance examination as part of ACI certification program.

AASHTO Materials Reference Laboratory

Principal Investigator:
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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), a $150-million highway and bridge research program, which was completed in 1994. Standardization of testing to enhance the reliability of quality assurance measurements is important. The productivity of the testing community can be increased by using correct procedures and apparatus that reduce testing errors and provide a sound basis for the acceptance of materials on certificate. More efficient use of long-established construction materials and broader use of new materials are facilitated by dependable quality assurance programs.

Approach
With the support of AASHTO Research Associates working under BFRL supervision, services are provided to public and private laboratories on a voluntary basis. These services include the on-site inspection of the laboratory and the distribution of proficiency test samples. The scope of the laboratory inspection program (LIP) includes testing of soils, bituminous materials, and plastic pipe, and measurement of roughness and frictional properties of highways. Equipment and procedures used to perform 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 benefit the construction materials testing laboratories and others involved with the Nation's transportation systems by: 1) improving the quality of laboratory testing, 2) providing data to quantify standard measurement techniques, and 3) providing direct communications between testing laboratories and standards-writing committees.

Recent Results
During FY 1994, inspected 267 bituminous and soil laboratories; distributed over 4000 proficiency samples; implemented a quality system for the AMRL LIP; completed a draft report on the field evaluation phase of the Marshall Hammer study.

Performance of Tape-Bonded Seams in EPDM Roofing Membranes

Principal Investigator:
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Sponsor:
National Institute of Standards and Technology

U.S. Army
Construction Engineering Research Laboratories

Objective
To develop a test protocol and recommended criteria for evaluating the performance of tape-bonded seams in Ethylene Propylene Diene Terpolymer roofing membranes.

Problem
Since the introduction of EPDM roofing in the mid-1970s, several types of bonding systems have been used for fabricating seams. Most of the bonding systems have used organic solvent-based adhesives applied with or without primer. Some tape systems also have been employed but, until recently, not widely. Concern over the effects of organic solvents on the environment have lead to decreased use of solvent-based adhesives, and increased use of tapes. Users of EPDM roofing systems, such as contractors, consultants, and architects, want to be sure that the performance of the tape systems is properly evaluated. Based on the need for data to characterize and evaluate the short- and long-term performance of tape-bonded seams, NIST and industry formed an industry/government cooperative research project and developed a CRADA project. The Corps of Engineers is also providing sponsorship.

In an earlier study, creep-rupture experiments were used to characterize the behavior of liquid adhesive-bonded seams of EPDM membranes subjected to constant load over time. Field experience has shown that seams which were watertight when the roof was installed sometimes developed defects within the first three years of service. The development of seam defects so soon after installation implies that the cause may be the rheological (deformation/flow) behavior of the adhesive as opposed to chemically-induced deterioration. Consequently, evaluating the behavior of seams under load is important in understanding the effects of different application and environmental exposure variables on seam performance. Needed are creep-rupture experiments on tape-bonded seams of EPDM membranes to characterize the long-term performance.

Approach
During FY 1995, BFRL will perform research with industry through the CRADA focusing on laboratory experimentation complemented by field inspections. The laboratory experimentation will subject tape-bonded EPDM seam specimens to creep-failure testing under a range of application and environmental conditions. The seam specimens will be prepared using currently available EPDM membrane material and tape/primer systems. Additionally, seams specimens fabricated with a solvent-based butyl adhesive will be prepared as controls and included in some experiments. The laboratory research will be divided into three sequential phases.

In Phase I, to be conducted during FY 1995, the performance of tape-bonded seams will be compared to that of liquid-adhesive-bonded seams in long-term creep experiments. The creep-rupture tests will be conducted at room temperature using peel specimens. The study will be statistically designed to determine the times-to-failure of tape-bonded and liquid-adhesive-bonded seam specimens as a function of load.

Two subsequent phases will be carried out in FY 1996 and 1997.

Recent Results
Rossiter, Walter J., Jr., Martin, Jonathan W., Lechner, James A., Embree, Edward, and Seiler, James F., Jr., "Effect of Adhesive Thickness and Surface Cleanness on Creep-Rupture Performance of EPDM Peel and Lap-Shear Joints," *Roofing Research and Standards Development*, 3rd Volume, ASTM STP 1224, American Society for Testing and Materials, Philadelphia, PA, pp. 123-138, June 1994.

BUILDING ENVIRONMENT DIVISION

INDOOR AIR QUALITY

Monitoring the Environmental Performance Green Buildings

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Sponsor:
National Institute of Standards and Technology

Objective
To develop systems to monitor the environmental performance of green buildings and to implement a monitoring program in selected green buildings.

Problem
Green buildings are designed to have minimal impacts on global, local and indoor environments. A major consideration in their design is indoor air quality, primarily in terms of low indoor contaminant levels but also in terms of thermal comfort. The energy consumption of the building to provide a healthy indoor environment is an important consideration. While much effort has gone into discussions of the technical means to meet these design objectives, relatively little effort has been devoted to evaluating the actual performance of these buildings relative to these goals. To determine whether green buildings and the associated technologies are indeed performing as intended, field monitoring is needed in a variety of contexts. A key element to such performance evaluation is real-time monitoring of indoor environmental conditions, mechanical equipment operation and energy consumption.

Approach
During FY 1995, BFRL will perform a two-part effort:

1. Develop a real-time ventilation and indoor air quality monitoring system. This system will employ state-of-the-art computer hardware, data-acquisition software and gas sensor technology to achieve a flexible and reliable system to monitor ventilation system performance, building airflow rates and indoor contaminant levels. A major aspect of this system will be a real-time tracer gas subsystem for monitoring building ventilation. Based on efforts conducted in FY 1994, computer hardware components, tracer gas and contaminant instruments, and software approaches were evaluated for reliability and appropriateness and for their compatibility with each other. These components will be procured and the monitoring system will be assembled and tested.

2. Identify and analyze several green buildings for subsequent monitoring. Several green building demonstration projects are in progress, including the Fish and Wildlife Service facility in Prairie City, Iowa. During FY 1994, several buildings were evaluated for their appropriateness in the monitoring program based on the building type, mechanical system design, location and construction schedule. A small number of these buildings have been selected for a pre- and post-occupancy monitoring program. BFRL will work with the building design and construction firms to institute the monitoring program in the buildings as part of the construction and commissioning process. Based on the buildings and their construction and occupancy schedules, a multi-year green building monitoring plan will be developed and the initial phases will be implemented during this year.

Recent Results
New project.

Development and Application of Multizone Indoor Air Quality Models

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National Institute of Standards and Technology

Objective

To develop an advanced airflow and contaminant dispersal model in the CONTAM series (BFRL's multizone airflow and contaminant dispersal model).

Problem

Multizone airflow and contaminant models have been developed at BFRL, including AIRNET and CONTAM86 through CONTAM93. These models were all unique at the time of their development and were useful for the study of airflow and indoor air quality in multizone building systems. As the indoor air quality field continues to progress, the need for model development continues in the areas of user interface, component model development and system development. Component model development refers to models that describe airflow and contaminant dispersal processes for incorporation into a general model such as CONTAM93. Industry associations and manufacturers have shown much interest in using these models, but they are concerned about model validation and the evaluation of the effectiveness of products intended to control indoor air quality.

Approach

During FY 1995, BFRL will perform four tasks:

1. Modify CONTAM93 into CONTAM95. This revision will include changes to the user interface, the incorporation of component models of chemical reaction and aerosol transport, and the inclusion of exposure analysis as an output option. The revised version will be widely publicized and distributed to users in industry, building designers, design consultants, exposure analysts, and researchers.

2. Model validation efforts will be compared with datasets of field measurements against the predictions of the CONTAM model. These efforts will assess the ability of the model to predict temporal and spatial variations in indoor contaminant concentrations for a variety of different classes of pollutants, including reactive and nonreactive, and pollutants with point and distributed sources. The results of these validation efforts will increase the ability to make well-founded statements about the reliability of the model and increase its usefulness to solve problems.

3. Evaluate the effectiveness of specific products control indoor air quality as a joint effort with industry. BFRL will work with private industry to evaluate products and systems of interest and to transfer the ability to use CONTAM to their staff.

4. Use CONTAM to study indoor quality problems of relevance to the revision of ASHRAE Standard 62-1989. Based on the needs and concerns of the revision committee, this analysis will address issues including the lead/lag approach to ventilation system operation, adjustment for air cleaning and recirculation, and how to deal with transient occupancy schedules.

Recent Results

Walton, George N., *CONTM93, User Manual*, NISTIR 5385, National Institute of Standards and Technology, 1994

Fang, Jim B. And Persily, Andrew K., *CONTAM88, Building Input Files for Multi-Zone Airflow and Contaminant Dispersal Modeling*, NISTIR 5440, National Institute of Standards and Technology, 1994

Infiltration and Ventilation in Large Buildings

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Sponsor:
Department of Energy
Office of Building Technologies

Objective

To analyze energy impacts of large building infiltration and ventilation system airflows employing integrated building thermal analysis and network airflow analysis and to participate in industry consensus standards development activities.

Problem

Previous research and field investigations have shown that despite current design goals, the envelopes of modern office buildings often fall short of design expectations in terms of airtightness performance. In addition, field testing has shown that ventilation system airflows are often different from their design values, leading to over- and under-ventilation and increasing the pressure differences that drive envelope leakage. The existence of such envelope leakage and ventilation system airflows that are not in accordance with design, will increase the energy loads of a building. In addition to the energy penalties, envelope air leakage also can negatively impact indoor air quality, envelope material durability and occupant comfort. However, the energy implications of envelope leakage and ventilation system airflows are not known, in part, due to a lack of ability of thermal analysis models to properly account for the complexities of building airflows in large, multi-zone buildings. Although sophisticated network airflow analysis programs are available, such as BFRL's AIRNET, thermal analysis models are not able to incorporate the output of such airflow models. An integration of thermal and airflow analysis is necessary to properly account for the energy impacts of infiltration and ventilation system airflows.

Approach

During FY 1995, BFRL will perform two tasks:

1. Perform a comprehensive analysis of the energy impacts of infiltration and ventilation system airflow and assess the national impacts of energy conservation strategies in this area. This analysis will employ the building energy simulation program TRNSYS. TRNSYS is modular in nature, and there is currently a library of modules available for performing building energy simulations. TRNSYS modules will be used with a new TRNSYS module based on the multi-zone airflow program AIRNET to provide the needed simulation capability. The model will be implemented on the DOE-defined prototype buildings. BFRL will develop TRNSYS modules of AIRNET and CONTAM to analyze the energy impacts of infiltration and ventilation in large, multizone buildings. Also, BFRL will develop an analysis strategy to study these energy impacts based on the TRNSYS computer simulation program and begin the analysis needed to quantify these impacts.

2. Develop industry consensus standards and guidelines to provide them with DOE and BFRL research results. BFRL will assume leadership roles in the ASHRAE SSPC 62, Ventilation for Acceptable Indoor Air Quality, ASHRAE 129P, Method of Test for Ventilation Effectiveness, and ASHRAE Guideline 10, Indoor Environment.

Recent Results

Dols, W.S., Nabinger, S.J., and Persily, A.K., "Air Change Effectiveness Measurements in Two Modern Office Buildings," *Indoor Air,* Vol. 4, No. 1, 1994.

Persily, A.K., *Manual for Ventilation Assessment in Mechanically Ventilated Commercial Buildings,* NISTIR 5329, National Institute of Standards and Technology, 1994.

Study of IAQ Improvement Through the Use of HVAC Systems

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Steven J. Emmerich
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Sponsor:
Consumer Product Safety Commission
Directorate of Engineering Sciences
Division of Mechanical Engineering

Objective
To assess the impact of existing HVAC technology on residential indoor air quality and assess the potential for using HVAC systems to reduce indoor pollutant levels.

Problem
Despite the increasing interest in residential indoor air quality problems, little research has been conducted to analyze the impact of pollutant sources, residential HVAC system operation and building envelope leakage on indoor pollutant levels. Most of the research to date has employed simple models of the building and its systems, ignoring the multi-zone nature of the airflows involved. The use of such simple analytical procedures has limited our understanding of the impact of HVAC systems and other systems on residential indoor air quality and the possibility of using these and other systems to mitigate some indoor air quality problems.

Approach
During FY 1995, BFRL will complete Phase II of this two-phase project. BFRL will analyze computer simulations to evaluate the effectiveness of the IAQ control retrofits. Following the completion of the computer simulations, BFRL will conduct a one-day workshop to present the results of the project to a group of selected indoor air quality experts. The feedback from these experts will be used in preparation of the final report on the project and to develop suggestions for follow-up work.

Recent Results
Emmerich, Steven J. and Persily, Andrew J., *Indoor Air Quality Impacts of Residential HVAX Systems Phase I Report: Computer Simulation Plan,* NISTIR 5346, National Institute of Standards and Technology, 1994

Emmerich, Steven J. and Persily, Andrew J., *Indoor Air Quality Impacts of Residential HVAC Systems Phase II. A Report: Baseline and Preliminary Simulations,* NISTIR 5559, National Institute of Standards and Technology, 1995

Indoor Air Quality Commissioning Program for TWFN

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Sponsor:
Nuclear Regulatory Commission
Office of Consolidation

Objective
To develop and apply an indoor air quality commissioning program to the new Nuclear Regulatory Commission office building to ensure an acceptable workplace to the building occupants.

Problem
The occupancy of new office buildings has the potential for indoor environmental problems associated with new building materials, nonoptimized HVAC system operation, and the scheduling of partial occupancy while other portions of the building are still under construction. While many strategies have been proposed to reduce the potential for such problems, the technical bases for these approaches are limited. There has not been sufficient research on air quality in new, or existing, buildings to develop properly documented procedures for preparing new office buildings for occupancy.

The Nuclear Regulatory Commission (NRC) is in the process of constructing a new office building at 2 White Flint North. Based on experiences in other buildings, NRC is concerned about the possibility of experiencing indoor air quality problems in the new building associated with move-in. These concerns center on the staged occupancy approach that will be employed in the building, in which a portion of the building will be occupied while other areas in the building are still being finished. In addition, the activity of moving in the occupants and their belongings can be associated with unusual contaminant sources.

Approach
During FY 1995, BFRL will analyze the indoor contaminant measurement data, conducted on a year-by-year basis (after interior finishing, after the systems furniture was installed, and one month after occupancy), that was collected in the building last year and prepare a final report to NRC.

Recent Results
Dols, W.S., Nabinger, S.N., and Persily, A.K., Development and Application of an Indoor Air Quality Commissioning Program in a New Office Building. *ASHRAE IAQ '94 Conference,* 1994.

Dols, W. Stuart, Persily, Andrew J. and Nabinger, Steven J., *Air Quality Commissioning of a New Office Building,* NISTIR 5586, National Institute of Standards and Technology, 1995

Impacts of HVAC Operation on Radon Levels in Large Buildings

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Sponsor:
Environmental Protection Agency
Office of Research and Development

Objective
To assist EPA in planning and executing an experimental effort in Florida designed to study the impacts of building features and ventilation system operation on radon entry and radon transport within large buildings.

Problem
The issue of radon entry and radon transport within buildings has been extensively studied in single-family residential buildings, but relatively little work has been done in larger buildings. The fact that larger buildings are often multi-story, have different foundation types with larger ground contact areas, and are generally mechanically ventilated leads one to expect that these phenomena will be quite different in larger buildings. In addition to a need to understand the fundamental science, guidance is required regarding the design, construction and operation of buildings in order to control radon entry. Such guidance has been developed by EPA, ASTM and various state governments for single-family residential buildings, and efforts have been initiated to develop guidance appropriate to larger buildings. In particular, the State of Florida intends to develop such guidance and has contracted with EPA and others to perform the technical research to support such guidance and to develop the standard itself. In order to develop a large building standard for Florida, experimental studies of radon entry and radon transport must be performed in several large buildings.

Approach
During FY 1995, BFRL will complete the tracer gas data analysis and prepare a report on the results. In addition, BFRL will work with EPA and the subcontractors who performed the field measurements in the test building to develop a report on all of the test results for the building.

Recent Results
Fang, Jin B., Persily, Andrew, *Computer Simulation of Airflow and Radon Transport in Four Large Buildings,* NISTIR 5611, National Institute of Standards and Technology, 1995.

BUILDING ENVIRONMENT DIVISION

COMPUTER INTEGRATED CONSTRUCTION

Advanced Manufacturing and Network Testbed (AMSANT) for the Process Plant Industries

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Sponsor:
National Institute of Standards and Technology

Objective
To establish an experimental computing and communication facility that provides a baseline of industrial practice in process plant engineering and construction, and that serves as an open testbed for integration activities of industrial partners, and as a communications hub for all U.S. participants.

Problem
The process plant industries comprise highly competitive vendors and users of computerized systems for the design, construction, and maintenance of process plants. An open facility is needed in which these players can test proposals for integrating their computerized systems without bias or unnecessary disclosure of proprietary developments. This research supports a companion project, STEP for the Process Plant Industries, for testing the information models proposed for Standard for the Exchange of Product Model (STEP) application protocols.

Approach
During FY 1995, BFRL will develop a neutral external repository using software toolkits and linked to the commercial computerized systems in the AMSANT facility. The facility is a distributed component of the NIST-wide Advanced Manufacturing Systems and Networking Testbed (AMSANT). This repository will provide a mechanism for capturing process plant information sharable among these systems and will provide the basis for testing the information models being developed in PlantSTEP (a companion research project) and other process plant-related activities in STEP. The test case library being developed in a companion project, STEP for the Process Plant Industries, will be implemented in the AMSANT. This project also will contribute to the high performance networking experiments with companion AMSANT projects in NIST's Manufacturing Engineering Laboratory and Electronics and Electrical Engineering Laboratory.

Recent Results
Reports describing the facility and a taxonomy of process plant piping parts will be published during the Summer of FY 1995

A report describing a taxonomy of process plant piping parts will be published during the Summer of FY 1995.

STEP for the Process Plant Industries

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Sponsor:
National Institute of Standards and Technology

Objective
To assist the U.S. process plant industries in developing the STEP (Standard for the Exchange of Product Model Data) application protocols needed for exchanging and sharing information during the design and construction, and maintenance of process plants.

Problem
The U.S. process plant industries seek to improve their use of computerized systems through integration of information systems, e.g., automation of the exchange and sharing of information among systems. The many computerized systems in use can be integrated only at great cost because of their incompatible proprietary representations of information; information exchange today is accomplished largely through manual methods. Standard, neutral information representations and exchange methods are needed that allow system vendors to be innovative and yet allow system users to exchange and share information about process plants automatically. The evolving international standard ISO 10303, Product Data Representation and Exchange, is providing the base technology. STEP application protocols must be developed that meet the needs of the process plant industries.

Approach
During FY 1995, BFRL will establish expertise in the CAD/CAE/CAx systems used in the process plant industries and will build a test case library for validating the draft APS (application protocols) and evaluating prototype implementations of the APS. BFRL will work with industry to generalize the application reference model for ship piping systems developed by the Navy/Industry Digital Data Exchange Standards Committee (NIDDESC). BFRL will continue work with researchers at the University of Missouri-Rolla to assess piping and instrumentation diagrams (P&ID) information requirements. BFRL will work with PlantSTEP (a companion project) to complete the documentation and the ISO Committee Draft for the Plant Spatial Configuration STEP Application Protocol. BFRL will continue to co-lead the STEP Process Plant Application Planning Project in ISO TC184/SC4/WG3.

This is a multi-year project focusing on the development of a product data model to support 1) the selection and use of commodity items, 2) the dévelopment of piping and instrumentation (P&I) diagrams from process stream information, 3) the development of piping system geometry from P&I information, 4) the shape and physical arrangement information for related plant systems, 5) demonstrating compliance with EPA, OSHA, and ISO 9000 series standards, and 6) the exchange of piping system data from designer to fabricator. This project also addresses these issues through interactions with industry consortia, research programs, individual companies, and through the ISO STEP Process Plant Application Protocol Planning Project (PPAPPP).

Recent Results
Burkett, W., Kline, S., Palmer, M., and Skeels, J., *Group 1 for the STEP Plant Spatial Configuration Application Protocol*, NISTIR (to be published).

Beazley, W. G. and Chapman, J. B., *A Framework for Information Technology Research in Process Plant and Related Industries*, NIST-GCR-94-657, 1994

Palmer, M. E. And Reed, K., A., *"3D Piping IGES Application Protocol Version 1.1,"* NISTIR 4797, National Institute of Standards and Technology, 1994

Palmer, M. E. and Gilbert, M., *"Guidelines for the Development and Approval of STEP Application Protocols, Version 1.1,"* NISTIR 5110, National Institute of Standards and Technology, 1993

Process Plant Engineering and Construction: Structural Systems

Principal Investigator:
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Sponsor:
National Institute of Standards and Technology

Objective
To develop the technical basis for a virtual construction environment, based on STEP (Standard for the Exchange of Product Model Data) technologies, that supports the design and construction of structural systems for process plants.

Problem
The U.S. process plant industries seek to improve their use of computerized systems through integration, e.g., automation of the exchange and sharing of information among systems. Effective integration will enable the introduction of virtual construction environments by allowing engineers and constructors to visualize and manipulate a common process plant model from widely disparate viewpoints. In this environment, the plant design can be optimized for constructability and maintainability. The evolving international standard ISO 10303, Product Data Representation and Exchange, is providing the base technology needed for integration. STEP application protocols must be developed that meet the needs of the process plant industries, notably in the creation of virtual environments.

Approach
During FY 1995, BFRL will:

1. Conduct a review of current applicable computer technologies necessary for the development of virtual construction environment.

2. Develop a use-case model of the design and construction of process plant structural systems in a virtual construction environment.

3. Establish contact with the American Institute of Steel Construction (AISC) and explore possibilities of collaboration.

Based on the review and critique of CIMSteel in FY 1994 and the result of the use-case model in FY 1995, BFRL will 1) complete draft proposing refinement/development of application protocol for process plant structural systems, 2) demonstrate the proposed protocol to potential users for review, and 3) work with companion projects (AMSANT for the Process Plant Industries and STEP for the Process Plant Industries) toward improvement and implementation of the proposed application protocol.

Recent Results
NIST report summarizing the development of the test case, in review.

NIST report summarizing the review and critique of CIMSteel, in progress.

Computerized Maintenance Management Information

Principal Investigator:
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Sponsor:
National Institute of Standards and Technology

Objective
To develop digital data standards that facilitate the exchange of information with computerized maintenance management systems.

Problem
A major impediment to the implementation of computerized maintenance management systems is the high cost of manually gathering, formatting, and inputting the required information about the building and its systems. Typically, this information is available only in the paper forms such as "as-built" drawings, specifications, and manufacturer's data sheets and manuals.

Furthermore, current computerized maintenance management systems typically have different and often proprietary data formats that prevent automatic exchange of information from one to another, as from a work order scheduling system to a spare inventory system. Frequently, these exchanges are performed manually and at another high cost.

Approach
During FY 1995, BFRL will continue to work with committees to assess document type definitions (DTD's) developed in FY 1994, to develop ASTM-specific extensions, and to demonstrate their implementation with case studies.

Recent Results
A report summarizing this work and a draft will be published in June 1995.

BUILDING ENVIRONMENT DIVISION

THERMAL MACHINERY

Thermodynamic Performance of Natural Fluids as Alternative Refrigerants

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Sponsor:
National Institute of Standards and Technology

Objective

To evaluate the thermodynamic and heat transfer performance of natural fluids as a working medium for refrigeration systems.

Problem

With the ozone crisis eliminating the use of chlorine in the manufacturing of refrigerants, the industry is rapidly moving towards the use of hydrofluorocarbon compounds. This conversion has been and continues to be the most dramatic change this industry has ever faced. Virtually all their resources are focused on meeting the United Nations and U.S. Environmental Protection Agency schedules. However, on the horizon looms the global warming crisis and the carbon - fluorine bond of the alternative refrigerants causes them to be rather offensive; thus, it is generally conceded that they do not represent the ultimate solution. Since the atmospheric chemical kinetics of man-made materials are complex and difficult to predict it seems that any such fluid offers the potential for trouble for future generations and, thus, the only solution is the use of natural fluids as refrigerants. That is, ones that are either found in nature or are in such abundance in the atmosphere already that the marginal difference the refrigerant supply would make would be insignificant (e.g., carbon dioxide, hydrocarbons, ammonia, water vapor). Although these fluids have been used as refrigerants in the past, they (except for ammonia in industrial applications) have been disregarded for various safety or efficiency or economic reasons. There is a need to reevaluate these fluids to determine if these problems can be alleviated through modern technology and alternative cycle design.

Approach

During FY 1995, BFRL will determine the optimum vapor compression/absorption cycle for each fluid considered. This effort will require considerable modifications to BFRL's basic CYCLE-11 family of models. Optimization will focus on efficiency. Criteria for acceptance to the laboratory evaluation stage will be the same as traditional refrigerants; i.e., safety, oil compatibility, specific capacity, pressure ratio, maximum temperature, etc.

There will be considerable cooperation with NIST's Chemical Science and Technology Laboratory in performance of thermodynamics research. In addition, BFRL will collaborate with two compressor companies. The difficulties and economics associated with the development of a high pressure positive displacement compressor and a low pressure centrifugal compressor will be explored. Both the prototype costs and the cost estimates for production models will be considered before a selection as to which laboratory system construction begins first.

NIST heat pump simulation model, HPSIM, will be upgraded to utilize REFPROP 4 property routines for both thermodynamic and transport property evaluation. A property look-up table will be employed to cover most computational-intensive property ranges, while the REFPROP routines will be called directly for properties which are outside the table range. This look-up-table approach is needed to mitigate significant CPU requirements, which result from complexity of the model itself and the REFPROP routines.

The model will evaluate performance of an air-to-air heat pump charge with a mixture comprising up to five components. Several modifications will be made to better represent newer heat transfer surfaces introduced to the marketplace .

Recent Results

Domanski, P., Didion, D., Mulroy, W., and Parise, J., "A Simulation Model and Study of Hydrocarbon Refrigerants for Residential Heat Pump Systems," *Proceedings of the IIR conference: New Applications of Natural Working Fluids in Refrigeration and Air Conditioning in Hannover*, Germany, May 1994, International Institute of Refrigeration, Paris France

Thermodynamic Performance of Alternative Refrigerants and Refrigerant Mixtures

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National Institute of Standards and Technology

Department of Energy
Office of Building Technologies
Building Equipment Division

Objective
To quantify the practical limitations and performance benefits of using a zeotropic refrigerant mixture in a residential air-to-air heat pump.

Problem
The use of zeotropic mixtures as working fluids for refrigeration machines offers two basic advantages: 1) a gliding saturation temperature during the phase change of the working fluid (i.e., evaporation and condensation), and 2) an opportunity to vary the circulating working fluid's composition and, thus, the system's volumetric capacity. The indoor heat exchanger's temperature glide offers the opportunity to improve the system's COP if counterflow between the air and refrigerant can be established. The degree to which this ideal temperature profile matching can be achieved depends very much on the design of the heat exchanger, as well as the ideality of the mixture. Thus, practical trade-offs with other criteria demands on the hardware and fluid selection result in a certain degree of subjective judgment, based on experience, to be exercised in the design of an optimized system. Similarly, the system capacity control and variation limitations are dependent on reasonable sized distillation column design, where it is placed within the system, and how and when it is used. What is reasonable requires judgment. The problem then is to acquire sufficient data on the components to establish their ideal performance potential.

Approach
During FY 1995, BFRL will continue researching the counter-flow and cross-counter flow heat exchangers. Research will build on BFRL's composition-shifting study using a passive system (i.e., the accumulator) and an active distillation column that was designed and constructed. BFRL will fully evaluate the composition shifting capabilities of this distillation column and its impact on the heating performance of the heat pump. A modeling effort will begin on a parallel track and the complete optimum system will be designed, constructed, and evaluated.

The need for being able to predict, a priori, the composition shift under either controlled or uncontrolled conditions has resulted in the development of a computer simulation based on REFPROP. This program was developed by BFRL and needs to be verified by isothermal and adiabatic experiments. The apparatuses will be constructed and tests performed via gas chromatographic analysis.

Researching further into zeotropic mixture system design requires making decisions about secondary fluids (refrigerants). Inherent tradeoffs between pumping power and heat capacity currently results in performance penalties that significantly hurt the zeotropic concept. Such secondary fluid systems are traditionally based on specific heat capacity only. Heat of mixing and latent heat mechanisms will be studied to determine if they offer improvements.

Recent Results
Kim, M.S. and Didion, D.A., "Simulation of Isothermal and Adiabatic Leak Processes of Zeotropic Refrigerant Mixtures," *International Journal of Heating Ventilating, Air-Conditioning and Refrigerating Research*, Jan. 1995, Vol. 1, No. 1, American Society of Heating, Refrigeration and Airconditioning Engineering, (ASHRAE), Atlanta, GA.

Alternative Refrigerants in Heat Pumps

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Sponsor:
Trane Company

DuPont Corporation

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, R-22, is scheduled to be banned as environmentally unacceptable. The design of heat pumps has matured around this particular refrigerant. Replacement refrigerants or refrigerant mixtures must be identified. New refrigerant choices will affect system hardware design. For example, liquid-suction heat exchange, which has no benefit for R-22, tends to be of benefit for refrigerants nearer their critical point, 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 1995, BFRL will develop computer simulations for refrigerant selection with primary emphasis on mixture of R-32/125/134a. Previous BFRL tests on mixtures of R-32/125/134a show they give operating pressures near those of R-22. Tests at Trane and at BFRL on other refrigerants indicate that higher pressure and higher capacity refrigerants such as R-32/125, give improved efficiency in actual machinery as a result of an improved capacity/parasitic loss ratio and may offer savings in several areas of equipment design. Recently R-227ea and R-245cb have been suggested as alternative nonflammable, environmentally safe refrigerants with Normal boiling points similar to R-134a. Their use in mixtures also will be examined by simulation in the NIST CYCLE-11 crossflow model.

Primary laboratory efforts will be directed to evaluate of mixtures of R-32/125/134a (or R-125/143a/134a et al.) From an HCFC-22 pressure level to that of a composition of 50% R-32/50% R-125. These mixtures will be created by treating the blend of 50% R-32/50% R-125 as a single component for mixture with R-134a so that model for hermetic application in residential heat pumps), which has been modified for open drive by Battelle Institute, has been obtained through Gas Research Institute. This will allow direct measurement of power into the cycle without concern for variation of motor efficiency (or cooling) with speed or load. BFRL will perform laboratory tests with the compressor incorporated in an extensively instrumented residential heat pump supplied by Trane for a previous study.

Recent Results
New Project.

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

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Sponsor:
Electric Power Research Institute
Customer Services Division

Objective
To determine if there are 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 during the past four years has nearly exhausted pure fluid candidates as potential alternatives for new systems. These efforts have not produced drop-in candidates for existing systems. The emphasis placed on searching for alternatives among pure materials has limited the research for alternatives possessing the desired attributes. 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.

Approach
During FY 1995, BFRL will predict azeotropes, using a BFRL developed method and the degree of near azeotropy that a given set of components may demonstrate. Once candidate mixtures are identified (on relevant thermodynamic properties) their thermodynamic performance will be predicted using different versions of BFRL cycle model, CYCLE-11. The benefit of liquid-suction line heat exchange will be quantified for those candidates whose heat capacity is favorable.

Recent Results
New Project.

Calorimetric and Visual Study of Boiling Enhancements with Refrigerant 134a and Horizontal Two-Phase Flow of R-32/134a

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Sponsor:
National Institute of Standards and Technology

Department of Energy
Office of Building Technologies
Building Equipment Division

Electric Power Research Institute
Customer Services Division

Trane Company

Imperial Chemical Industries
Fluorochemical Application Laboratory

Objective
To generate heat-transfer data and visual observations for a thorough description of the boiling behavior of the refrigerant R-134a with various lubricants and heat transfer additives and to measure the horizontal flow boiling heat transfer coefficient for a new R-22 replacement: a 30% mass R-32/70% mass R-134a/mixture with various lubricant concentrations.

Problem
The introduction of alternative refrigerants has solved one problem (ozone destruction in the stratosphere by chlorine) and created another (lack of thermal design information for the new refrigerants). 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 so they must redesign equipment. This is of immediate concern to the industry since they have relatively little experience designing chillers for alternative refrigerants. Consequently, the refrigeration industry

needs accurate two-phase heat transfer correlations to redesigned evaporators and condensers to ensure the efficient and reliable operation of centrifugal water chillers and direct expansion evaporators.

Approach

During FY 1995, BFRL will advance alternative heat transfer research for the direct-expansion and flooded evaporator industries. The tube-side flow boiling study of the R-32/134a mixture will be conducted in an existing test apparatus and will aid the direct-expansion heat exchanger industry. The R-134a Additive/Lubricant study will be conducted in a pool boiling calorimetric/visualization rig and will assist the flooded evaporator industry.

BFRL will generate heat-transfer data and visual observations for a thorough description of the boiling behavior of three popular commercial enhanced surfaces with several combinations of alternative refrigerant, lubricant, and additive. Two refrigerants will be examined: R-134a and R-12 (as a baseline for comparison to R-134a). R-134a will be tested with four appropriate lubricants and one appropriate additive which has a potential to enhance the pool-boiling performance. The additives have not been previously tested. DuPont Corporation has developed the additives using speculative theory generated from a previous DOE/BFRL-sponsored project. This represents 21 separate tests for one particular lubricant and additive concentration. Each additional lubricant and additives concentration adds 30 tests. Each individual test includes many individual data points for various conditions. Consequently, the work will produce a substantial, encompassing data source for use by the refrigeration industry.

The R-32/134a mixture study will investigate horizontal flow boiling of both a 30% mass R-32/70% mass R-134a mixture, a R-32/125/134a mixture, and R-22 with lubricants. The mixtures are ones that have been chosen for study by the R-22 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."

Findings from this research will provide valuable heat transfer information for the design of new R-32/134a evaporators and condensers.

Recent Results

Kedzierski, M., and Kim, M.S., *Single Phase heat Transfer and Pressure Drop Characteristics of an Integral-Spine-Fin Within an Annulus,* NISTIR 5454, National Institute of Standards and Technology, 1994.

Kedzierski, M., and Kaul, M., "Horizontal Nucleate Flow Boiling Heat Transfer Coefficient Measurements and Visual Observations for R-12, R-134a, and R-134a, and R-134a/Ester Lubricant Mixtures," *International Symposium on Transport Phenomena,* Seoul, May 9-13, 1993.

BUILDING ENVIRONMENT DIVISION

MECHANICAL SYSTEMS AND CONTROLS

Communication Protocols for Building Controls

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Sponsor:
National Institute of Standards and Technology

Green Buildings

Department of Energy
Office of Building Technologies
Federal Emergency Management Program

Objective
To develop, evaluate, and produce 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 systems, 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 building owners from obtaining the most capable building service by not allowing them to choose, regardless of the manufacturer, the best Energy Management and Control system, best security system, the best fire detection system, or the best telecommunications system.

Approach
During FY 1995, BFRL will:

1. Complete and publish the BACnet standard. It will be published by ASHRAE.

2. Administer and participate with industry partners in a BACnet Interoperability Testing consortium. The objectives of the consortium are to:
   - o assist control system manufacturers in verifying the correctness and operability of their proprietary BACnet implementations;
   - o verify the technical soundness of the BACnet protocol;
   - o identify errors or omissions in the BACnet protocol specification before it becomes a final standard;
   - o identify ambiguities in the BACnet protocol which might lead to implementations which cannot interoperate and;
   - o develop insight into testing requirements which should be included in a future ASHRAE standard for testing conformance to BACnet.

3. Develop tools that can be used to establish an industry-run BACnet certification program.

4. Establish a BACnet test-bed demonstration project in a GSA building in San Francisco.

5. Begin work on international standardization of BACnet through ISO/TC 205.

6. Begin work on expanding BACnet to integrated building services, including life safety, security and transportation.

Recent Results
Bushby, S.T., "BACnet Promises a New Age in Building Control Systems," *Construction Business Review*, March/April 1994.

Bushby, S.T. and Newman, H.M., "BACnet: A Technical Update," *ASHRAE Journal*, January 1994.

Real Time Fault Detection and Diagnostics

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Sponsor:
National Institute of Standards and Technology

Department of Energy
Office of Building Technologies
Building Systems Performance

Objective

To develop methods for controlling and performing fault detection and diagnostics on mechanical equipment and systems in real time and to 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 systems is a complex procedure. With more and more emphasis on a combination of different and often conflicting performance measures, the processes, systems, and equipment being used in commercial and residential buildings are becoming more and more complex. New control and on-line analysis methods are needed to detect problems (faults) as they occur, determine which 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 1995, BFRL and Johnson Controls, Inc. (working under a CRADA) will use BFRL's Fault Detection and Diagnostics (FDD) Laboratory containing a VAV air handling system to study the problems associated with the control strategies and control algorithm that are commonly used today on VAV air handling systems. Experimental data will be gathered on the performance of various strategies and control algorithms under normal operating conditions and without/with the presence of typical faults. A detailed HVACISM+ based model of the VAV air handling system will be validated, and simulation studies will be performed to evaluate the performance of alternative control techniques and strategies and various fault detection/diagnostic methods. These technologies will be implemented and tested on the actual VAV air handling system in the laboratory. Various methods for on-line system identification, fault detection, and diagnosis will be explored in conjunction with the new control methods and used to support NIST/DoE participation in International Energy Agency Annex 25.

A BACnet test-bed demonstration project will be established in a General Services Administration (GSA) operated building in San Francisco. This site will be used in future years to evaluate the benefit of energy management systems, advanced/optimal building system control strategies, and fault detection/diagnostic methods and applications.

Recent Results

Kelly, G.E., et al., "Using Emulators to Evaluate the Performance of Building Energy Management Systems," *ASHRAE Transaction*, V. 100, pt. 1, pp. 1482-1493, No. 94-23-4 (1/94).

Peitzman, H., Park, C., et. al., "The Reproducibility of Tests on Energy Management and Control Systems Using Building Emulators," *ASHRAE Transaction*, V. 100, pt. 1, pp. 1455-1465, No. 9-13-1 (1/94).

Test Procedures for Furnaces, Boilers and Integrated Appliances

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Sponsor:
Department of Energy
Office of Energy Efficiency and Renewable Energy
Office of Codes and Standards Division

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

Problem
The ANSI/ASHRAE Standard 124-1991, *Method of Testing for Rating Combination Space Heating/Water Heating Appliances*, has been approved by the American National Standards Institute and ASHRAE. The Standard requires the testing of the 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. Rating descriptors for an appliance are derived from the two separate tests. The current test procedures for space heating and water heating published by the DoE do not cover the combination appliances. By referencing the ANSI/ASHRAE Standard 124-1991, BFRL will assist DoE in the development of a DoE test procedure for the rating of these type of combination appliances.

Approach
During FY 1995, BFRL will conduct tests on induced draft outdoor furnaces to develop a reliable and repeatable test procedure for this type of outdoor units. Research will continue on furnaces, boilers, and combination space/water heating appliances that will involve the following tasks:

1. Continue assisting DoE in publishing the Final Rule for furnaces/boilers and vented home heating equipment.
2. Procure, install, and conduct laboratory tests on an induced draft, outdoor furnace for the development of a tracer gas test procedure for the determination of the power burner draft factor.
3. Complete the development of 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.
4. Assist DoE in preparing responses to Requests for Waivers and draft Federal Register Notices of proposed Rule Making.

Recent Results
Liu, Stanley, Kelly, George, Terrlizzi, Charles, *Performance Testing of a Family of Type I Combination Appliances,* NISTIR 5626, National Institute of Standards and Technology, 1995.

Test Procedures for Heat Pumps and Air Conditioners

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Sponsor:
Department of Energy
Office of Energy Efficiency and Renewable Energy
Office of Codes and Standards
Appliance 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. DoE has, since 1975, relied on the National Institute of Standards and Technology's BFRL to assist in the development of the test and rating procedures.

Approach
DoE will publish, in 1995, a proposed rulemaking on the test procedures for heat pumps and air conditioners (Appendix M) and combined heat pump-water heating appliances (Appendix M1). During FY 1995, BFRL will complete work on both test procedures before the rulemaking is published. Appendix M work includes revising the nomenclature so it is consistent with Appendix M1 and making additions and modifications to address how to test units having features such as adaptive defrost controllers and variable-speed, constant air flow rate indoor blowers. With regard to the proposed test procedure for combined appliances, BFRL will generate a document having a single, generic calculation section. The 33 different calculation sections of the present proposed combined appliance test procedure will be published in multiple NIST internal reports. The final version of Appendix M1 will reference these internal reports. In addition, BFRL will continue its active participation on ASHRAE Standard 137P and ARI Standard 290P.

Following the close of the comment period on the proposed rulemaking, BFRL will assist DoE with resolving technical issues raised by the commenters. If laboratory testing is needed to resolve issues related to Appendix M, BFRL will contract with ETL (ETL Testing Laboratories, Inc.) to perform the needed testing, and BFRL will perform the necessary analysis. If laboratory testing is needed to resolve issues related to Appendix M1, this testing will be conducted at BFRL or ETL. At present, two different heat pumps that are equipped with the same active, variable flow rate, desuperheater would be the selected systems for test. Each system would be tested with at least two different size water heaters.

Through a combination of laboratory test results, HPSIM computer simulations, repeated bin-type calculations, and correspondence with ETL and ARI (Air-Conditioning and Refrigeration Institute), BFRL will generate a first draft of a metric DoE test procedure that is as compatible as possible with the ISO Standard. Approaches for more explicitly addressing talent heat removal capability within the test procedure will also be sought but probably will not be finalized until FY 1996.

BFRL expects to evaluate a few requests for waiver from the DoE heat pump and air conditioner test procedure during FY 1995. BFRL will review and make recommendations for changing ASHRAE Standard 16, *Method of Testing for Rating Room Air Conditioners and Packaged Terminal Air Conditioners*, which is used by DoE.

Recent Results
Provided sponsor with written reports.

Development of Revised Test Procedures for Refrigerator-Freezers

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

Objective
To conduct tests on residential refrigerator-freezers and use the data generated from tests to study whether test procedures for refrigerator-freezers should be revised.

Problem
The current DoE test procedure was developed nearly 10 years ago. The test procedure includes certain test conditions and assumptions which may not be realistic operating conditions (e.g., 32 °C ambient temperature is presently required during the test and the door opening is required only for the variable defrost control optional test) resulting in a higher energy consumption than obtained from tests. More advanced manufacturing techniques (lower anti-sweat heater energy, better cabinet insulation, better door gaskets, etc.), and operational features (e.g. electronic defrost operation, through-the-door ice service, etc.) are now used extensively. Review of the current test procedure is in order.

Approach
Two refrigerator-freezers were tested in FY 1994 to determine the energy effect of some operating factors. A two-state approach was used. The first stage screened the commonly believed energy affecting factors to identify the two factors that affect energy consumption the most. The second stage tested the energy consumption under various combinations of the two identified factors.

During FY 1995, BFRL will analyze the test data and review the DoE refrigerator-freezer test procedure. NIST will recommend test procedure revisions to cover automatic ice making devices, and to incorporate, if appropriate, the test findings in the refrigerator-freezer energy calculation procedures. In addition, the test results will be compared with the predictions of the Arthur D. Little refrigerator-freezer model.

Recent Results
New project.

BUILDING ENVIRONMENT DIVISION

HEAT TRANSFER

Test Procedures for Advanced Thermal Insulation Products

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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. However, 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 1995, BFRL will evaluate two advanced insulation panel concepts. Metal-class evacuated insulation panels will be evaluated over a wide range of conditions. Of all advanced insulation concepts, these panels offer the highest theoretical thermal performance. The particular metal-clad evacuated insulation panels under evaluation were supplied by Aladdin Industries under a NIST CRADA. Gas-filled insulation panels supplied by Lawrence Berkeley Laboratories also will be evaluated. Although gas-filled panels do not achieve the level of thermal resistance provided by the metal-clad evacuated panels, they should prove much less expensive to manufacture. Additional CRADAs may be established with other manufacturers.

The calorimeter facility will continue to be improved. Research has shown that, unlike conventional homogenous materials, the thermal resistance of metal-clad vacuum insulation panels changes with the imposed convective coefficients. As the surface convective coefficients increase, the temperature distribution across the panel becomes more uniform. This increases the heat transfer through the edges of the panel resulting in a lower overall thermal resistance. BFRL's calorimeter will be modified so the convective film coefficients on both sides of the panel can be varied. This modification will permit the relationship between convective film coefficients an surface-to-surface thermal resistance to be documented. Additional transducers will be added to the calorimeter such that the relative humidity on both sides of the panel can be monitored.

Also, BFRL will perform an indepth assessment of the applicability of infrared imaging systems and thermochromatic crystals to the evaluation of advanced insulation panels.

Recent Results
Fanney, A. H., "Test Procedures for Advanced Insulation Panels", Proceedings of the 1994 International CFC and Halon Alternatives Conference held October 24-26, 1994.

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

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

Objective

To conduct a one-dimensional analysis of the combined heat and mass transfer in attics and cathedral ceiling; develop guidelines and practices for preventing moisture problems in attics and cathedral ceilings; and develop a user's manual for MOIST to permit building engineers and architects to evaluate strategies for controlling moisture in hotel/motel building envelopes.

Problem

Appropriate moisture control guidelines for attics, cathedral ceilings, and crawlspaces are still debated by experts in the building community. Field studies are useful because they document a specific moisture problem as it relates to a particular building construction. Moreover, they often provide an understanding of the underlying physics. However, it is difficult to generalize individual field experiments to different constructions, outdoor climates, and indoor conditions. This is because complex interactions exist between the construction materials and the indoor and outdoor climates. It is impractical to carry out an adequate number of field experiments to cover all possible constructions and indoor and outdoor climates.

Approach

BFRL has developed a state-of-the art personal computer program, called MOIST, that predicts the combined transfer of heat and moisture in multi-layered building construction under non-steady-state conditions. This program predicts the moisture content and temperature of construction layers as a function of time of year. It includes moisture transfer by vapor diffusion and capillary flow. The program inputs a user-defined construction and hourly WYEC ASHRAE weather data which is available for 51 different cities of the United States and Canada.

During FY 1995, BFRL will perform four tasks:

1. Attics and Cathedral Ceilings. BFRL will extend MOIST to attics and cathedral ceilings. This new model will subsequently be used to investigate the viability for all attic and cathedral ceiling constructions given in the DoE *Moisture Control Handbook*. The moisture content of the construction materials will be predicted and plotted as a function of time of year. Hourly weather data for a cold winter climate (Madison, WI), a mixed climate (Washington, DC), and a hot and humid climate (Lake Charles, LA) will be used in the analysis. Based on the results of this analysis, guidelines and practices will be developed to control moisture problems in attics and cathedral ceilings. These computer simulations will resolve the contentious issue as to whether attic ventilation provides a "net" reduction in moisture accumulation of attic construction materials. Attic ventilation removes and transports moisture from moist attic materials to the outdoor environment. However, attic ventilation also may increase air leakage from the indoor space into an attic, thereby increasing the moisture load into the attic.

2. Measurement of Moisture Properties of Ten Roofing Materials. BFRL will measure spot permeability curves (permeability versus relative humidity) and sorption isotherms (moisture content versus relative humidity) for seven roofing materials. These measurements will support ongoing research at the Oak Ridge National Laboratory.

3. Develop a Recommended Procedure for Evaluating Envelope Moisture Control Strategies During Hotel/Motel

Guest Room Design and Construction. MOIST will be used to simulate typical construction used in hotels/motels. BFRL will prepare a user's manual describing how to use MOIST. This manual will be targeted for use by architectural/engineering firms involved in the design and construction of building envelopes.

Recent Results

Zarr, R.R., Burch, D.M., and Fanney, A.H., *Heat and Moisture Transfer in Wood-Based Wall Construction: Measured Versus Predicted*, NIST Building Sciences Series 173, National Institute of Standards and Technology, Gaithersburg, MD, February 1995

Burch, D.M. and Thomas, W.D., *MOIST: A PC Program for Predicting Heat and Moisture Transfer in Building Envelopes*, NIST Special Publication 853, National Institute of Standards and Technology, Gaithersburg, MD, September 1993

Burch, D.M., *Water Vapor Measurements of Low-Slope Roofing Materials*," NISTIR, in review.

Burch, D.M., Zarr, R.R., and Fanney, A.H., "Experimental Verification of a Moisture and Heat Transfer Model in Hygroscopic Regime," *Conference on the Thermal Performance of the Exterior Envelopes of Buildings VI.*

Burch, D.M. and Saunders, C.A., *A Computer Analysis of Wall Constructions in the Moisture Control Handbook*, NISTIR, in review

Rode, C.R. and Burch, D.M., "Empirical Validation of a Transient Computer Model for Combined Heat and Moisture Transfer," *Conference for the Thermal Performance of the Exterior Envelopes of Buildings VI.*

Effect of Indoor Climate on Moisture Performance of Walls

Principal Investigator:
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Sponsor:
National Institute of Standards and Technology

Objective

To incorporate a variable indoor climate model into BFRL's MOIST Program and to subsequently use this computer model to conduct a comprehensive computer analysis to investigate the effect of indoor climate on the moisture performance of walls composed to winter climate.

Problem

BFRL's MOIST predicts heat and moisture transfer in building envelopes. This model is used by more than 600 persons to investigate the moisture performance of wall constructions as a function of outdoor climate. MOIST is limited by requiring specified constant indoor temperature and relative humidity during an annual simulation. Indoor humidity has a significant effect on moisture accumulation within building envelopes. The indoor humidity within a building varies considerably during the year. Furthermore, buildings located in cold climates generally have lower indoor humidity. Indoor humidity depends on: outdoor climate, moisture production rate by the occupants, outdoor ventilation rate, and the hygroscopic storage of moisture at interior surfaces. The outdoor ventilation rate, in turn, depends upon the amount of mechanical ventilation, the building air tightness, the indoor-to-outdoor temperature difference, and wind speed. During summer, the mechanical space-cooling equipment removes moisture from the building.

Approach

During FY 1995, BFRL will incorporate a variable indoor climate model into its MOIST Program. This indoor climate model will permit the indoor water-vapor pressure to float and be calculated at each time step from a moisture balance of the whole building.

Here the moisture released by occupant activities will be equated to the transfer of moisture by ventilation and hygroscopic storage at interior surfaces. The indoor climate model will contain the following elements:

- LBL's infiltration model will be used to determine their natural ventilation rate from the effective leakage area, the indoor-to-outdoor temperature difference, and the wind speed. Natural and mechanical ventilation rates will be combined to give a total ventilation rate using algorithms in the *ASHRAE Handbook of Fundamentals*.

- Storage of moisture at interior surfaces will be predicted using a hygroscopic storage model developed by the Forest Products Laboratory. Parameters for this model (i.e., sorption constant per unit floor area and a time constant) have been measured for both manufactured and site-built homes.

- Operating regimes for the building (i.e., space heating, space cooling, or floating) will be determined by comparing the daily-average outdoor temperature to the appropriate balance point temperatures for variable-base heating and cooling degree-day models. Separate set-point temperatures for space heating and cooling will be specified.

In addition, a considerably more use-friendly input and output processor in a Windows environment will be developed for the enhanced MOIST Program. The processor will use pull-down menus to select different operating features of the program. A user will be able to highlight a data entry by clicking on it with a mouse and then entering revised data from the keyboard. After the program executes, it will be possible to select and plot specified output files on the computer screen without leaving the program.

The above enhanced MOIST model subsequently will be used to conduct a comprehensive sensitivity analysis to investigate the effect of indoor climate parameters on moisture accumulation in walls exposed to winter climate. The performance of several wall constructions will be analyzed for a cold climate (Madison, WI), an intermediate winter climate (Boston, MA), and a mild winter climate (Atlanta, GA). The impact of the following parameters will be investigated: building air tightness, outdoor climate, mechanical ventilation, indoor moisture production, and hygroscopic moisture storage at interior surfaces. For each computer run, the moisture content of the construction layers will be plotted versus time of year. A peak moisture content will be deemed to be unacceptable when the material becomes saturated (i.e., liquid water exists within the pore structure of the material).

Recent Results

Tsongas, G. and Burch, D.M., "A Parametric Study of Wall Moisture Contents Using a Revised Variable Indoor Relative Humidity Version of the 'MOIST' Transient Heat and Moisture Model," *Conference on the Thermal Performance of the Exterior Envelopes of Buildings VI*

Assessment of Reflective Roof Coatings Using TARP

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Sponsor:
National Institute of Standards and Technology

Objective
To assess the energy impact of reflective roofing materials for typical residential and commercial buildings using the Thermal Analysis Research Program (TARP).

Problem
A recent study on reflective surfaces for reducing the ambient air temperature of urban areas has increased interest in the use of reflective coatings for saving energy in buildings. In addition, several recent field studies conducted in hot climates of the United States have indicated significant savings in energy use. For example, a reflective coating applied to six houses in Florida reduced the energy usage and peak demand by an average of 23% and 27%, respectively. At a national level, these results may suggest a promising method for saving energy and reducing peak demand for the Nation's electric utilities. But are the effects the same in a cold climate or for a well-insulated building? (The authors of the Florida study noted that the savings were generally greater for roofing with low levels of thermal insulation.) In order to answer these questions, it is proposed that a series of computer simulations for a typical residential and commercial building be conducted using the TARP. TARP is a computer program capable of computing hour-by-hour heating and cooling loads for an arbitrary building under a variety of climatic conditions.

Approach
During FY 1995, BFRL will select for analysis two buildings as typical examples of residential and commercial construction. The residential construction will be chosen from one of the typical house designs produced by BFRL in the later 1970's. The commercial construction will be typical of a common warehouse building and selected after consultation with members from industry. The computer analysis will be conducted for each building using one year of weather data. In order to ascertain climatic effects, weather data will be selected from several of the 51 locations of ASHRAE Weather Year for Energy Calculation (WYEC) data.

After preparing the geometric models for the residential and commercial constructions, a "ruggedness" test will be conducted to identify and rank the factors that may affect the energy savings. Some of the factors to be considered include 1) level of attic (or roof) insulation; 2) attic infiltration rates; 3) nigh-setback for the air conditioning controls, and 4) level of reflection, for example. This experimental design will be prepared with assistance from the Statistical Engineering Division. After determining the main factors affecting the energy savings, the key factors will be analyzed for several geographic locations on the North American continent using the WYEC data. The findings will be summarized in an ASHRAE paper.

Recent Results
New project.

A Photovoltaic Solar Water Heating System

Principal Investigator:
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Sponsor:
National Institute of Standards and Technology

Objective
To develop a photovoltaic solar water heating system.

Problem
Numerous problems associated with solar thermal hot water systems have prohibited significant market penetration. Among these are high material and installation costs, freeze and fluid leakage problems associated with fluid transport loops, failure of differential temperature sensors and controllers, large thermal losses associated with fluid circulation loops, and extensive installation problems associated with roof penetrations for the piping that transports fluid to and from the solar collector array. A photovoltaic solar water heating system, by comparison, eliminates the installation problems associated with a solar thermal hot water system and offers the potential of a low cost means of supplying a significant portion of the energy consumed for domestic water heating.

Approach
During FY 1995, BFRL will design, construct, optimize, and evaluate for 12 months a prototype photovoltaic solar water heating system based upon the concepts in a patent, "Photovoltaic Solar Water Heating System," awarded to Fanney and Dougherty (March 1994). The initial design will focus on a two-tank system. The heating elements in the preheat tank will be removed and replaced with multiple heating elements. A controller connects these multiple elements, using series and parallel connections, in a manner that the photovoltaic array operates near its maximum power point for any given solar irradiance level and ambient temperature. The photovoltaic array will be sized to deliver a significant portion of the energy required to heat water for a typical residence. Various controller concepts will be evaluated to determine which of the concepts defined within the patent will results in optimum energy collection.

Recent Results
New project.

BUILDING ENVIRONMENT DIVISION

LIGHTING TECHNOLOGY

Test Procedures for Lighting Fixtures and Systems

Principal Investigator:
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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, required the Department of Energy (DoE) to prescribe test and rating procedures and minimum performance standards for various residential appliances. In addition, the 1987 amendments to EPCA require analysis of any test procedure amendments to determine their effect on minimum efficiency standards. DoE has, since 1975, relied on the National Institute of Standards and Technology (NIST) to assist in the development of the test and rating procedures.

Approach
During FY 1995, BFRL will continue to provide technical support and assist in DoE rulemaking activities. This will include refining test procedures and performing bench tests for HID lamps to identify any problems or inconsistencies which might merit revision. Work also will continue on the test procedure for vibration service incandescent lamps and colored incandescent and fluorescent lamps as definitions for these lamp types are refined and revised in response to manufacturers' comments and the results of laboratory measurements. BFRL will evaluate the ER and BR incandescent lamp exemptions, the impact of the minimum standards on mercury lamps, and the applicability of test procedures to new HID lamp technologies such as the sulfur lamp. BFRL will introduce the vibration service lamp test procedure, the colored lamp definition, and the luminaire performance evaluation procedure as proposed IES standards.

Recent Results
Treado, S., *Testing Procedures for Multilamp Luminaires*, NISTIR 5262, National Institute of Standards and Technology, Gaithersburg, MD, 1993.

Evaluation of Occupant Response to Lighting Retrofits

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

Objective

To evaluate occupant response to the lighting in offices at DoE Headquarters in Washington, DC.

Problem

The Department of Energy is undertaking a major renovation of the lighting system in its Headquarters as part of the Federal Relighting Initiative. This 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. Data from the post-occupancy evaluation of several U.S. Army facilities suggested that lighting levels were below IES minimum recommendations for the types of tasks done in DoE's facilities. Occupant satisfaction also was below that obtained in other areas in the same facility. Information is needed for the retrofits planned for the Forrestal Building to determine their overall effectiveness.

Approach

During FY 1995, BFRL will determine representative samples of interior and exterior offices (to assess any daylight contribution) and conventional and open-plan offices. A representative sample of occupants also will be performed. They 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 is 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 performed in past BFRL projects. This will provide baseline information on the conditions existing before the renovation and data on the effectiveness of the renovation in improving lighting conditions in the offices. During the course of the project, 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

Sanders, P. and Collins, B., *Post Occupancy Evaluation of the Forrestal Building*, NISTIR 5591, National Institute of Standards and Technology, Gaithersburg, MD, 1995.

FIRE SAFETY ENGINEERING DIVISION

FIRE MODELING AND APPLICATIONS

Performance Standards for Fire Safety

Principal Investigator:
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Sponsor:
National Institute of Standards and Technology

Objective
To develop a risk-based methodology for establishing the degree to which fire safety features and systems contribute toward the goals of a performance-based code.

Problem
Parallel efforts are underway in a number of countries to develop risk-based methods that can be used to assess compliance with performance codes. These methods incorporate identical frameworks and cite the same set of calculational procedures for the major portions of the calculations. Differences occur primarily in data or assumptions and stem from local experience. There is great interest among the participants to collaborate and harmonize the approaches into a single, standardized method.

Approach
A committee was established under the International Council for Building Research Studies and Documentation Working Group (CIB W14) on Fire; Bukowski is the chair. Initial efforts involve building consensus on risk objectives and an appropriate analytical framework. Task groups are working on the development of design safety factors which relate to total computational uncertainty, data resources, and impacts of management policies. Efforts to address concerns of U.S. code officials with equivalency analyses were initiated through ICBO with the objective of the sanctioning of specific methods for specific uses. As intermediate results are obtained through committee related activities, papers will be written to disseminate this information into the international community.

Work on the development and adoption in U.S. codes, of performance-based requirements for protected elevators recognized as a means of egress has been initiated. This proposal will be worked through the Life Safety Code. Water exposure to elevators is a significant limitation concerning elevator fire evacuation, and efforts are underway to develop a Cooperative Research and Development Agreement with the National Elevator Industry Inc. (NEII) to study the effects of water on elevator safety. This effect will provide a means to change the standards for elevator use during fires to accommodate evacuation and use by firefighters.

Recent Results
New project.

Related Grants
"Regulatory Decision Model for Performance-based Fire Safety Codes", Lehner, Paul, George Mason University.

"A Risk Assessment Methodology for Fire Safety Codes," Lehner, Paul, George Mason University.

A Risk Assessment Methodology for Fire Safety Factors in Performance-based Design and Buildings," Karedas, Demetrius, Factory Mutual Research Corporation.

Building Evacuation Manual for Disabled Occupants of Office Buildings

Principal Investigator:
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Sponsor:
Federal Emergency Management Agency
U.S. Fire Administration

Objective
To develop a manual for use by building managers (such as GSA, FEMA, BOMA) to inform disabled employees of appropriate procedures to use in the event of fire or other emergency.

Problem
Little specific guidance is available for disabled employees on emergency procedures. Procedures and systems are being retrofitted under the ADA to accommodate the needs of the disabled, but they and building managers have little written material on best practices.

Approach
During FY 1995, BFRL will prepare a manual in English and translated into Spanish. The booklet also will be produced in braille.

The topics to be covered include:
a. Proper placement and content of tactile signals for the visually impaired.
b. Installation of visual signals or use of tactile pagers for the hearing impaired.
c. Guidance in the development of evacuation plans (e.g., "buddy system" or wardens).
d. Use of protected elevators for egress and areas of refuge for mobility impaired.
e. Use of special wheelchairs for stairs or other special equipment.
f. Organizations which can act as information resources for building managers in special needs assessment.

Recent Results
New project.

Test on Fire Patterns to Determine the Origin of Fires

Principal Investigator:
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Sponsor:
Federal Emergency Management Agency
U.S. Fire Administration

Objective
To perform full scale tests and validate the results so evaluation criteria used by fire investigators to determine the origin of fire will be justified in court.

Problem
FEMA is assisting fire investigators in establishing that the criteria used to diagnose a fire are valid and admissible in court.

Approach
During FY 1995, BFRL will develop with the sponsor a work statement in coordination with an expert steering committee for a series of ten bedroom fire tests. The tests will be carried out in identical specified rooms built in BFRL's large full-scale burn facility with identical furnishings. These highly instrumented tests will be performed by BFRL. Members of the Steering Committee will observe the tests, and the Steering Committee will write the Technical Reports.

Recent Results
Four of ten tests have been completed and Reports of Tests have been prepared for the Steering Committee Members.

High Temperature Accelerant Fires

Principal Investigator:
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Sponsor:
Defense Nuclear Agency
Headquarters

Objective
To evaluate the burning characteristics of high temperature accelerants and predict the environment generated by high temperature accelerant fires in structures.

Problem
Several arson fires involving the use of suspected high temperature accelerants have been reported in the northwest U.S. There is insufficient data available to evaluate the impact of high temperature accelerant fires on structures.

Approach
During FY 1995, BFRL will perform three tasks:

1. Evaluate existing data on high temperature accelerant fires. Existing data from high temperature experimental fires will be evaluated to estimate the rate of mass production, and radiative and convective heat released rate fractions of high temperature accelerant fuels.
2. Conduct laboratory scale experiments to characterize a selected high temperature accelerant as a source of mass momentum, sensible and radiant energy, and smoke particulate.
3. Predict the impact of a high temperature accelerant on a selected structure. Predictions of high temperature gases and smoke movement, as well as thermal radiation incident on those spaces directly impacted by the accelerant will be used to estimate damage and life threatening conditions in the structure.

Recent Results
New project.

Experimental Application of Fire Hazard Analysis for U.S. Passenger Train Systems

Principal Investigator:
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Sponsor:
Department of Transportation
Federal Railroad Administration
Volpe Transportation Systems Center

Objective
To demonstrate the practicality and effectiveness of new generation test methods and hazard analysis techniques when applied to passenger rail transportation vehicle fire safety.

Problem
Considerable advances in fire safety engineering have been made in the decade since the original development of the current U.S. guidelines for passenger train material selection. Some requirements for system design, materials controls, detection, suppression, and emergency egress are included in the variety of requirements with each applying to distinct subsets of passenger-guided ground transportation. Better understanding of the underlying phenomena governing fire initiation and growth have led to the development of a new generation of test methods which can better predict the real-scale burning behavior of materials and assemblies. At the same time, advances in fire and hazard modeling are leading a revolution in the analysis of a material's overall contribution to fire hazard in a particular application. Such an approach allows evaluation of factors in addition to material flammability, and of tradeoffs in the fire-safe design of the entire fire safety system. These advances need to be incorporated in future designs of passenger trains.

Further testing and analysis is necessary to evaluate the suitability of these new techniques of mathematical modeling and fire hazard analysis when applied to typical fire scenarios in passenger rail vehicles.

Approach

This research will progress in three overlapping phases, bench and intermediate-scale heat release rate (HRR) tests of current materials, computer-based hazard analysis, and real-scale proof testing. During FY 1995, BFRL will evaluate selected materials that were tested to older generation test methods using the HRR methodology. This evaluation will define acceptance criteria for the use of HRR test methods in a context similar to the current Federal Railroad Administration guidelines and provide necessary data for hazard analysis specific to passenger train vehicles.

Recent Results

Peacock, R.D., Reneke, P.A., Jones, W.W., Bukowski, R.W., and Babrauskas, V., "Concepts for Fire Protection of Passenger Rail Transportation Vehicles: Past, Present, and Future", *Fire and Materials* (accepted for publication)

Peacock, R.D., Bukowski, R.W., Jones, W.W., and Reneke, P.A., "A New Concept for fire Protection of Passenger Rail Transportation Systems," International Association for Fire Safety Science, fire Safety Science, Proceedings, 4th International Symposium, July 13-17, 1994, Ontario, Canada.

Peacock, R.D., Bukowski, R.W., Jones, W.W., Reneke, P.A., Babrauskas, V., and Brown, J.E., *Fire Safety of Passenger Trains: A Review of Current Approaches and of New Concepts,* Tech Note 1406, National Institute of Standards and Technology, 1994

Peacock, R.D., Bukowski, R.W., Jones, W.W., Reneke, P.A., Babrauskas, V., and Brown, J.E., *Fire Safety of Passenger Trains,* DOT/FRA.ORD-93/23, U.S. Department of Transportation, Federal Railroad Administration, 1993

Field Guide on Compliance with 1992 Act Provisions for Detectors and Sprinklers

Principal Investigator:
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Sponsor:
Department of Housing and Development
Office of Research, Evaluation, and Monitoring

Objective

To develop guidance for HUD field offices on the technical aspects of compliance with the provisions of the Fire Administration Authorization Act as pertains to HUD properties, other than "rebuilt multi-family".

Problem

The Act requires HUD to install hard wired smoke detectors and sprinklers in several categories of housing, in accordance with NFPA 72 and with NFPA 13, 13R, or 13D (as appropriate). HUD field offices are generally unfamiliar with the required fire protection systems and with the governing standards. Prior attempts to install such systems under local mandates resulted in poorly installed equipment and excessive costs to the government.

Approach

During FY 1995, BFRL will develop a guide document for distribution to HUD field offices as a HUD document. This guide will provide a summary of the minimum requirements contained in NFPA standards including a discussion of alternative solutions or arrangements that provide more cost-effective approaches to compliance. The guide also will provide information for HUD field offices in solicitation, evaluation and award of contracts to perform the work contemplated by the Act. The guide will not address rebuilt multifamily properties which are required under the Act to comply with the Existing Apartment Chapter of NFPA 101, the Life Safety Code.

Recent Results

New project.

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

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Sponsor:
National Fire Protection Research Foundation

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

Federal Emergency Management Agency
U.S. Fire Administration

Objective

To examine the effect of complex ceiling geometry and obstructions on the distribution of heat and smoke to optimize requirements for automatic fire detector location found in NFPA 72E and for automatic sprinklers as covered by 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 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 also only applicable for flat, unobstructed ceilings. Since 72E includes recommendations for placing fire detectors in spaces with sloping or peaked ceilings, or open beams and joists, validation of these recommendations is necessary. Further, detector siting problems associated with stratification and high air movement from HVAC systems are mentioned in the standards, but only limited installation guidance is provided which is based only on judgement.

Approach

During FY 1995, BFRL will continue examining the effects of fire size, fire location, ceiling height, ceiling slope, typical ceiling beam or joist configurations; the effect of stratification on the distribution of heat and smoke from the fire; and 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 conducted earlier in this project; providing validation for the calculations. Additional geometries will be added in consultation with the Technical Advisory Committee of the project sponsors. Participation by ASHRAE is expected in the tasks relating to HVAC effects, and their expertise will be used to identify specific HVAC system configurations to be studied such that applicability of results will be maximized.

The study is designed to be applicable over a wide range of detector types and installation characteristics. Detector types will include those that respond to heat, smoke, and gas. The studies will be carried out numerically, using a field model, Harwell Flow3d, a commercial computer model that simulates fluid dynamics and heat transfer using a finite difference approach, to simulate the room geometries and fire growth, but selected experimental verification will be included when needed.

The model will be used to produce contour plots 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 then be used to develop engineering guidelines for detector/sprinkler placement, resulting in recommendations for changes to the appropriate NFPA standards. Validation of the numerical results for the study will be accomplished using a combination of existing fire experiments and, when necessary, by conducting additional experiments.

Recent Results

Davis, W.D., Forney, G.P., and Bukowski, R.W., *Field Modeling: Simulating the Effect of Sloped Beamed Ceilings on Detector and Sprinkler Response*, National Fire Protection Research Foundation, Quincy, MA 02269, 1994.

Balanced Design

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

Federal Emergency Management Agency
U.S. Fire Administration

Objective
To quantify the operational reliability of detection, sprinklers, and compartmentation as directed by the U.S. Fire Administration Act of 1992, PL-102-522.

Problem
Trade-offs between active and passive fire protection strategies are often made without technical foundation. As legislation mandates sprinklers and detectors in specified occupancies, the term "compartmentation" must be understood so overall safety is not compromised. Thus, *PL-102-522* required BFRL to conduct this study as a joint effort of the public and private sectors.

Approach
During FY 1995, BFRL will perform this work as four tasks:

1. Data Collection. Primary emphasis on Hotel and Office occupancies. In collaboration with insurance originators (FM, IRI, Cigna, and American Insurance Services Group) BFRL will collect data on other occupancies as background information to enrich the database.
2. Special Studies. In task 1, types of system impairments which reduce the ability of the system to perform will be identified. To the extent that these reduce but not prevent performance, special studies may be needed to quantify this reduction. This effect will require model development and testing of impaired assemblies.
3. Trade-offs. One of the study's objectives is to determine the conditions under which one or more of the systems can be reduced or eliminated without *unacceptable risk of loss*. What is "unacceptable" is likely to be a highly subjective measure which needs a public policy decision. A panel consisting of building owners, insurance, and regulators would be convened to seek a consensus view of what types and levels of losses would be acceptable to society.
4. Fire-resistive (FR) vs noncombustible construction (NC). Besides the basic difference in fire resistance ratings, field data compiled in task 1 will be analyzed to identify any other characteristics of these construction types which impact on their mitigation of risk. Given that fire resistance requirements are consistent with expected duration negating any issues relative to performance differences, these "reliability" aspects represent the relevant factors separating these construction types.

Recent Results
New project.

Enhanced GSA Engineering Fire Assessment System

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

Objective
To develop and deliver a computer software system operating under MS-Windows for the Fire Safety Evaluation System (FSES) for offices.

Problem
Current fire safety practice within GSA is rooted in the Life Safety Code prescriptions and the FSES for equivalency determinations. GSA's goal is to move this predictive practice to a risk management basis.

Approach
GSA is planning a long range program to develop and implement a fire risk management system for their properties by the turn of the century. It will be based on the evolution of the current FSES for offices to a risk basis, underpinned by an advanced FPEtool package and a life-cycle cost evaluation tool. This project represents the first stage of this longer term effort.

Recent Results
Developed a prototype automated FSES demonstration at the 1995 NFPA Annual Meeting.

FPEtool Advancement

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

Objective
To develop advanced state-of-art analytical tools for the practicing fire protection engineer and to enhance cross compatibility with other analytical techniques and the applicability to hazard and risk analyses.

Problem
FPEtool (BFRL/GSA developed software used to evaluate hazards and fire protection strategies in GSA Office buildings) is a highly popular software product among practicing Fire Protection Engineers (FPE's) and is used worldwide. Its utility will be enhanced when re-written in a structured language (C), and moved to a windowing environment.

Approach
During FY 1995, BFRL will complete its migration to a windowing environment (WINDX) and will coordinate it with the HAZARD product by replacing FIRE SIMULATOR, CORRIDOR, and THIRD ROOM with a 2-room version of CFAST (BFRL's building fire model). Further developments will be coordinated with GSA Enhanced Fire Safety Evaluation System Program.

Recent Results
Deal, Scot, *Technical Reference Guide for FPEtool Version 3.2*, NISTIR 5486, National Institute of Standards and Technology, September 1994.

Fire Research Information Services (FRIS)

Principal Investigator:
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Sponsor:
National Institute of Standards and Technology

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

Problem
A more effective and efficient mechanism to dissemination of BFRL documents electronically to the user community is required. Also needed is reduction of the physical space required to accommodate the BFRL collection without jeopardizing the availability and usability of the documents.

Approach
During FY 1995, BFRL will continue its demonstration of electronic access to BFRL documents through NIST site license to ACROBAT and its PDF format, and through ANONYMOUS FTP. Continue FIREDOC, the bulletin board and regular services. Evaluate the potential for digital storage of collected documents which would provide for reduced physical storage needs. Investigate means of capturing information in a way that will facilitate the creation of a remote access system to full documents.

Recent Results
Martin, Phyllis M., and Jason, Nora H., Editors, *BFRL Publications 1994,* NIST Special Publication (in press), National Institute of Standards and Technology, Gaithersburg, MD, 1995.

Martin, Phyllis M., and Jason, Nora H., Editors, *Fire Research Publications 1993,* NIST SP 878, National Institute of Standards and Technology, Gaithersburg, MD, 1994.

Computing and Network Resources

Principal Investigator:
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Fire Safety Engineering Division
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Sponsor:
National Institute of Standards and Technology

Objective
To provide improvements, day-to-day support and long range planning for scientific, network and administrative computing.

Problem
Needed is a uniform and consistent environment for scientific and administrative computer services.

Approach
During FY 1995, BFRL will configure, purchase and install new hardware and operating software for the local area networks that will provide a uniform and consistent system. An improved backup system will be developed for management and support staff. New users will be added to the LANs, and software will be upgraded as necessary. Attach LAN to new fiber-optic backbone and prepare plans for FDDI connection to LAN high end workstations. Maintain the local area network and assigned facilities with no significant downtime. Upgrade plans for LAN disaster recovery.

Recent Results
Provided increased emphasis on training and increased throughput of LAN and shared resources.

Fire Performance Design of High-Performance Materials Used in Construction

Principal Investigator:
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Sponsor:
National Institute of Standards and Technology

Objective
To develop performance-based methods for evaluating high performance (HP) construction materials under fire conditions.

Problem
The standard method of insuring integrity in fires of building components is based on the response of building materials to a standard-test-method fire exposure. Material categories, test method, and acceptance criteria are essentially unchanged since the early part of the century. HP steel, concrete, organic matrix composites, and combinations of these, are being considered for use in many types of modern construction. These materials have strength *versus* temperature and failure characteristics that can differ substantially from those of traditional construction materials. Existing temperature acceptance criteria too can be conservative because they do not account for advanced performance of modern materials. Also, fires involving modern furnishings and work environments may produce exposure conditions that differ substantially from those simulated by the standard test. Finally, in determining the integrity of a particular candidate component, and even in the design process itself, it will be increasingly more important for industry to use modern methods of engineering analysis to minimize the need for costly and burdensome furnace testing procedures. Such methods have to be developed and implemented.

Approach
During FY 1995, BFRL will perform four tasks toward developing evaluation methods of high performance construction materials under fire conditions:

1. Explore the long-term project plan with industry to establish partners in its implementation.
2. Modify the project plan, as required, to reflect interests of industry.
3. Develop reports on progress of implementation of the plan.
4. Develop report for a modified ASTM E119/UL 263/NFPA 251 methodology that accounts for the actual temperature-dependent structural properties of materials.

Recent Results
Fire Performance of High-Performance Construction Materials, to be presented by Leonard Y. Cooper at the 1st European Symposium of International Association for Fire Safety Science, August 1995.

Fire Model Evaluation

Principal Investigator:
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Sponsor:
National Institute of Standards and Technology

Objective
To develop protocols for quantifying the level of accuracy of computer-based predictive fire models and the experimental, statistical, and analytical techniques to support this method.

Problem
Fire models have progressed to the point of providing good predictions for some parameters of fire behavior. However, users and authorities are often asked to accept building fire safety design based on fire models without accepted statements of their predictive accuracy. It is important to be able to state with confidence, how close are the actual conditions to those predicted by the model. There is no domestic or international agreement on a procedure for quantifying fire model accuracy and demonstrating suitability for a particular application.

Approach
During FY 1995, BFRL will develop experimental and analytical studies to develop realistic fire descriptions and measurement techniques to compare model prediction with experimental results and will cooperate with other organizations to develop consensus on procedures for model evaluation, peer review of models, and sensitivity analysis. This work will be performed as four tasks:

1. Burning characteristics of products. Develop through real-scale testing, a selected set of burning characteristics for products which may become involved in fires. The measured data will be in a form which can be used by fire models.
2. Sensitivity analysis of complex fire models. Perform a detailed sensitivity analysis of the effects of changes in heat release rate on important calculated outputs for a complex fire model using BFRL's Consolidated Fire and Smoke Transport Model (CFAST) to provide input data for the analysis.
3. Techniques for comparing experimental and model data. Develop, using the experimental and model data collected in Task 2, appropriate statistical techniques for quantifying the level of agreement between experimental measurements and model predictions for calculated outputs which depend on the heat release rate.
4. Consensus on procedures. Continue fostering international cooperation, with organizations as ASTM, CIB, ISO, and VTT Finland in fire model evaluation to provide a well accepted framework for future efforts by BFRL and others.

Recent Results
Mitler, H. E., *The Use of Thermocouples in Reference Fire Tests*, National Institute of Standards and Technology 1995 (in press).

Peacock, R. D., Reneke, P. A., Forney, C. L., and Kostreva, M. M., *Understanding Sensitivity Analysis for Complex Fire Models*, journal article (in press).

Related Grant
"Sensitivity Analysis for Mathematical Model of Fire in Residential buildings," Kostreva, M.M., Clemson University.

Hybrid Model Development

Principal Investigator:
Glenn P. Forney
Fire Safety Engineering Division
301-975-2313

Sponsor:
Department of Navy
Naval Research Laboratory
Office of Naval Technology

Objective
To model fire and smoke transport in long corridors typical of passage ways on naval vessels.

Problem
There are lacking equations to model the horizontal momentum or velocity of a ceiling jet traveling down a corridor.

Approach
During FY 1995, BFRL will use its Consolidated Fire and Smoke Transport Model (CFAST). CFAST has features that make it attractive to further develop technologies to meet the objectives of this project. Matsushita, Japan and BFRL each have independently developed mathematical equations and a computational model to simulate this type of flow. These two modeling approaches will be analyzed and a determination made as to which approach is best suited for incorporation into CFAST.

Recent Results
Developed and implemented a procedure for modeling heat transfer between the floor and ceiling of a compartment.

Related Grant
"Computational Heat Transfer for Zone Fire Modeling", Moss, William F., Clemson University

Development of the Fire Data Management System (FDMS)

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 accommodates all fire related data for users who collect or use building fire data.

Problem
A unified method of accessing data is crucial to experimental and modeling efforts to develop the science of fire. The FDMS concept is well founded, and very important to experimentalists acquiring data, and to modelers and others using data related to fires and material properties. A stand-alone, PC version of the database exists which supports a limited number of fire test results. This version lacks some functionality, is not portable across computer platforms, and is dependent on third-party software libraries which are no longer supported.

Approach
During FY 1995 (third year of the project), BFRL will pursue acceptance of the FDMS database concept throughout the fire community. An international beta test with a sufficiently large database is being conducted. Available data including Cone Calorimeter (ASTM 1354/ISO 5660), Eurefic Room/Corner (NT 025/ISO 9705), and full-scale tests have been loaded for the beta test. New development has begun on the PC version of the Graphical User Interface (GUI) as a replacement for the existing FDMS 1.0. This will include import/export functionality, querying and report writing capabilities.

Recent Results
Portier, Rebecca W., *Fire Data Management System, FDMS 2.0, Technical Documentation,* National Institute of Standards and Technology, Gaithersburg, MD, 1994.

HAZARD II Alpha Test

Principal Investigator:
Walter W. Jones
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Sponsor:
National Institute of Standards and Technology

Objective
To plan and implement the next generation hazard methodology.

Problem
Traditional approaches to product design, product evaluation, and codes and standards development address fire safety in a piecemeal fashion, for example, evaluating heat release without considering product use, toxicity, or ignition propensity. Quantitative hazard analysis techniques have the potential of providing significant cost savings and reducing the time to bring successful products to market. In addition, measures are evaluated as an interacting system, including the impact of 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
The project is being performed on three tasks:
1. Advancing the physics in the model.
2. Improving the structure, interface and interaction of the individual components of the models of HAZARD
3. Publishing the methodology.

During FY 1995, BFRL will test the single-surface pyrolysis, detection and suppression algorithms and begin development of the "hybrid" concept to incorporate CFD algorithms into the zone model framework. Work will continue on the unification of the user interface with a new-generation input editor and hazard shell including a new unified input data file.

Recent Results
Incorporated new physical routines to the zone model such as flow through holes in ceilings and floors and another zone for each compartment that contains a fire (ceiling jet). To estimate heat loss from and to the ceiling much more realistic new radiation and conduction models were incorporated that solve the boundary discrepancy between convection/conduction and radiation and incorporate the conduction calculation directly into the differential equation set solved by CFAST.

Related Grants
"Expansion of the Applicability of EXIT89," Fahy, R.F., National Fire Protection Association.

"Development of a Graphical Interface for Post-processing the Results of a CFAST Simulation," Barnett, J., Worcester Polytechnic Institute.

"Computational Heat Transfer for Zone Fire Modeling," Moss, W.F., Clemson University.

"Sensitivity for Mathematical Modeling," Kostreva, M., Clemson University.

RECENT GRANTS - FIRE MODELING AND APPLICATIONS

1. Regulatory Decision Models for Performance-Based Fire Safety Codes

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Objective
To develop a decision analytic methodology to incorporate computational fire models into the regulatory decision making process.

Problem
Computational fire models have been proposed as a foundation upon which performance-based fire codes can be established. As yet there does not exist an approach to using these models that would be considered acceptable to the regulatory process or would survive legal challenges.

Approach
Overall the proposed methodology involves the development of regulatory decision models, based on legally admissible sources of professional expertise, that incorporate the use of computational fire models. In this methodology, a decision model is used to support the policy makers' evaluation of alternative fire safety proposals. The parameter values in the decision model (and parts of the structure) are provided by assessments from various professional experts, whose judgment will be derived, in part, as a result of exercising computer models.

Before expert judgments can be incorporated into the decision model the process by which those judgments are arrived at must pass a set of criteria specified in a legal admissibility filter. The filter will reflect legal criteria for sources of expert testimony, which in some cases may mandate the use of fire models. For instance, for assessments of fire spread the use of one or more fire spread models may be required, since direct experience and field data in this area are limited.

During FY 1995, a decision model will be developed for evaluating some alternative fire safety options in manufactured housing. By working through a detailed case study, we will be able to better identify the specific benefits, problems, and regulatory issues associated with a decision analytic approach to fire safety regulation.

The emphasis during the first year will be on development of a decision model that examines selected aspects of fire safety in manufactured housing, and to determine how best to relate fire models and a decision model for evaluating proposed fire safety configurations. Most of the expert inputs into the decision model will be from professional experts whose primary expertise is in fire modeling and regulatory decision making.

Recent Results
Lehner, P. "Computational Domains Models and Normative Systems," 1995 Workshop on Normative Systems, May 1995.

Lehner, Pl. and Brannigan, V., "Computational Domain Models and Regulatory Decision Making," submitted International Conference on Fire Research and Engineering, September 1995.

Brannigan, V. And Lehner, P., "Performance-based fire codes: A regulatory effectiveness analysis," submitted International Conference on Fire Research and Engineering, September 1995.

2. A Risk Assessment Methodology for Fire Safety Factors in Performance-Based Corporation

Principal Investigator:
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Michael A. Delichatsios
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Objective

To develop an event tree algorithm that includes all engineering systems and operational conditions as well as inputs from deterministic and probabilistic models related to fire safety design of buildings. Also develop probabilistic and reliability models for various components of the building engineering system (e.g. detection, protection, alarm).

Problem

Performance-based standards for fire safety design of buildings are being advanced throughout the world to enhance existing prescriptive standards for fire safety design. To apply performance-based standards, one needs both deterministic and probabilistic models connected through the methodologies used in engineering risk analysis. The product of this engineering risk analysis is the identification and development of significant scenarios through an event tree which provides probability and consequences for each event tree path. Probabilities are deduced from the probabilistic models and consequences are deduced from the deterministic models. The proposed work will address and develop tools to implement this methodology for the fire safety design of buildings by a) developing event tree pathways for significant scenarios; b) advancing probabilistic models for determining probabilities of events such as ignition, and detection and protection system failures; and c) assembling databases for both deterministic and probabilistic models.

Recent Results

An automated event tree algorithm is being developed that includes all the relevant engineering systems for the fire risk analysis in buildings. For each building, all possible event trees can be generated including all relevant events. Such events or systems are: 1) fire initiation; 2) fire spread and growth; 3) detection/alarm; 4) protection; 5) ventilation/smoke management system; 6) evacuation; 7) emergency response/fire department. The output from the event tree analysis includes: a) at each location of the building (X), toxic concentrations, temperatures and heat fluxes which quantify the hazard as obtained from deterministic models; b) the time at which the effects of the fire cease, as determined both from deterministic mitigation measures (detection, protection), as well as from probabilistic models (e.g., emergency response, evacuation, human response); c) the probability that the estimated damage will occur. Probabilities on each event tree for various events can be obtained from probabilistic models for equipment reliability and various actions which depend on human factors such as evacuation and emergency response and fire department response. The description of fire from deterministic and probabilistic models is planned to be handled in the following way: a) The building will be divided into two areas - one around the room(s) directly involved in burning and the other in space involved only in smoke movement. For the area involved in burning, a two layer zone model (e.g. CFAST) will be used to determine the key parameters needed as inputs for the event tree; the burning area will increase with time as fire spreads through the building. For the smoke movement area, a nodal analysis for flows and pressures will be used to determine the smoke concentrations which will be considered locally uniform throughout space. b) The deterministic code will be run for a predetermined long time assuming that no fire intervention has occurred. Relevant outputs from the deterministic codes will be fed to the event tree program (these include: 1) time, 2) smoke concentrations, 3) temperatures and 4) heat fluxes). c) Probabilistic models for ignition, alarm, evacuation, etc. will provide needed response times to the event tree program.

3. Enhanced PC-based Building Fire Assessment System

Principal Investigator:
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Sponsor:
National Institute of Standards and Technology

U.S. General Services Administration

Objective
To develop a PC-based version of the current Fire Safety Evaluation System for office occupancies and integrated selected quantitative methods that will enable engineers to perform detailed fire hazard, risk equivalency, and cost optimization analyses for existing or planned buildings.

Problem
The need to accurately measure fire risk impact and estimate costs of different fire safety strategies on levels of fire safety in individual buildings is essential to achievement of an overall building risk management philosophy. Limitations in current prescriptive requirements represent significant inhibitions to needed design flexibility and general usefulness. This is particularly the case when comparing alternative impact. A growing need among building owners, local code authorities and design engineers is to the availability of quantitative methods to evaluate building fire safety within a broad, risk-based context which permits examination of "equivalent" alternatives.

Approach
This effort is being conducted in three phases. Phase I was completed in early FY 1995 and involved development of a PC-computer based version of the NFPA-FSES for business occupancies. This program was developed using the Microsoft Visual C/C++ Windows development platform and is fully compatible with the normal Windows environment. It contains explanatory text to assist the user in selecting the correct parameter conditions and utilizes visual prompts to guide the user through the FSES method.

The program contains four modules of encapsulated code, each with specific tasks. The Applications Module is the main program. This module controls the individual performance elements, including calculations, output, and interface parameters.

The Main Window Module is the outer framework of the Windows based program. It is analogous to the Program Manager in Microsoft Windows and allows the user access to file input/output features, print features, window controls, and program help.

The Document Module is the storage medium for user input. This module is invisible to the user. The document module contains all of the scoring functions, filters that check if data are complete and accurate, and all of the code for storing data to a file.

The View Module is the interface, used for entering data and selecting score categories. Currently, there are 15 elements in the view module. None of the viewing elements are erased when not in use unless user specified.

The current version of the program has been validated on a limited basis against the FSES method in NFPA 101A and can be utilized as an interim method for conducting FSES evaluations in office buildings.

Phase II will be initiated in FY 1995 and completed in FY 1996, and is directed at the necessary research to enhance the methodology to allow quantitative comparison of design options. This will include integration of appropriate elements of currently available engineering calculations (e.g., Hazard, FPEtool, etc.) and development of algorithms to assess reliability.

Phase III will include an attempt to integrate the results and methods developed in the initial phases into a computerized risk management program.

Recent Results
New project.

4. Sensitivity Analysis for Mathematical Modeling of Fires in Residential Buildings

Principal Investigator:
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Objective

To develop a prototype sensitivity analysis equipped fire model computer program, with the intention of analyzing the existing approach of HAZARD I, and evaluating and demonstrating recently obtained results on the mathematical foundations of fire models.

Problem

While HAZARD I is now an established computer tool for modeling fires in residential buildings, it is lacking a sensitivity analysis capability. Such a feature would allow the user to have a greater understanding about the importance of certain input data to the computational results. This understanding can be translated into better use of resources for data gathering, and a generally enhanced credibility of the modeling results. HAZARD I has successfully incorporated a succession of increasingly complex fire models: FAST, CFAST and CONRAD2. Some efforts need to be made to provide a corresponding set of sensitivity analysis equipped models.

Approach

The approaches to sensitivity analysis which were investigated with respect to the simple fire model of ASET, to a limited extent in Kostreva, et. al. 1989, will now be studied with respect to ASET, FAST, CFAST and CONRAD2. These include the local methods of finite difference type, together with the direct methods which involve some additional differential equations. Global methods, which involve averaging over a collection of preselected scenarios will not be studied at this time.

Results are contained in the paper Peacock, et al. 1995, in which a complete introduction to the methodology and the main issues of performing sensitivity analysis are provided. Tabular presentation of relevant sets of input parameters and model outputs orient the user to sensitivity analysis. Examples from currently available, zone-type room fire models are presented and relevant parameters are studied for fires involving up to four rooms. It is found that a limited analysis, considering a carefully selected subset of input parameters is feasible, even for the more complex models. Graphical presentation of the results allows a good qualitative understanding of the underlying relationships. Further studies involving CONRAD2 will documented in a forthcoming report.

Recent Results

Peacock, R.D., Reneke, P.A., Forney, C.L., and Kostreva, M.M., "Understanding Sensitivity Analysis for Complex Fire Models," submitted for publication, 1995.

Kostreva, M.M., Jarvis, J.P., and Forney, C.L., "Graphical Presentation and Numerical Analysis of Fire Data for Model Validation," Final Technical Report, Grant Number 60NANB6D0627, NIST, 1989.

5. Computational Heat Conduction for Zone Fire Modeling

Principal Investigator:
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Objective

To develop a two-dimensional model of heat conduction through walls and to incorporate it in a zone fire model. The fire model will provide for heat transfer between rooms via heat conduction through ceilings, floors, and walls.

Problem

By modeling temperature variation vertically in walls, as well as through walls, more realistic temperature profiles will be obtained.

Approach

In the NIST zone fire model CFAST, the four walls of the typical room are lumped together and divided into upper and lower sections by the smoke layer interface. A one-dimensional submodel for heat conduction into the upper

submodel for heat conduction into the upper and lower walls is implemented, but heat is not transferred between rooms. The radiation submodel used in CFAST computes configuration factors for the upper and lower walls which are functions of time because of the movement of the smoke layer interface. There are several disadvantages to this approach. First, it does not produce accurate vertical temperature profiles, especially in rooms of fire origin. Second, many of the configuration factors in the radiation submodel cannot be computed in advance. This slows down the radiation submodel computation. If the wall areas were fixed in time, the configuration factors for a room could be computed outside the solver loop which advances the solution from one output time to the next. Third, in the one-dimensional model the vertical temperature profile in the room and in the wall both jump at the smoke layer height which is clearly not correct. The advantage of the one-dimensional method is that there are only two solution variables for the walls, the upper wall temperature and the lower wall temperature. If heat conduction through the walls is modeled, then the walls must be subdivided into four panels and each treated separately. This leads to eight solution variables. On the other hand, if four wall panels are subdivided into five horizontal strips, twenty solution variable will arise.

A two-dimensional wall model has been developed in which each wall panel is divided into a number of horizontal strips. The two-dimensional model is much more complex than the one-dimensional model. It uses a bi-cubic Hermite method of lines to solve the two-dimensional heat equation. The resulting differential-algebraic equation system is solved using the backward Euler method. Because the problem is linear, the resulting system is also linear. Using columns interchanges, this system can be put into block form with the upper left block an identity matrix. The bandwidth of the lower right hand block increases as the number of breakpoints increases.

Recent Results

Moss, W.F., "Computational Heat Transfer for Zone Fire Modeling, Final Report: NIST Grant No. 60NANB2D1281, Covering the Period August 18, 1992 to June 1, 1994," Clemson University, 1994

Forney, G.P. and Moss, W.F., "Analyzing and Exploiting Numerical Characteristics of Zone Fire Models," J. of Fire Science and Technology, 14, 49, 1994.

6. Flow Through Vents in a Compartment Fire

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Sponsor:
National Institute of Standards and Technology

Objective

To carry out an experimental investigation on the flow of smoke and hot gases in vertical shafts, focusing on the effects of forced ventilation and on tall shafts. This is expected to lead to a better understanding of the flow in vertical shafts and to yield quantitative inputs which may be used in the modeling of building fires. Among the important aspects to be investigated are entrainment, dilution, speed of smoke spread and effects of forced ventilation.

Problem

The flow in vertical shafts is very important in the accurate modeling of fire-induced flows in multi-leveled buildings since a considerable amount of flow and thermal transport occurs in the shaft. The vertical shaft provides a crucial transport mechanism which must be included in the model for accurate prediction of the spread of smoke, hot gases and other combustion products, particularly toxic ingredients. Tall vertical shafts are of greater consequence in typical multi-storied buildings and usually some form of forced ventilation exists in these shafts. In addition, forced ventilation may be used effectively to reduce the spread of toxicants in the building,

allowing greater time for evacuation of the building.

Approach

A fairly versatile experimental system has been designed and fabricated. Heated air or smoke is injected into the shaft at a lower opening and the downstream flow is monitored by means of thermocouples, hot-wire anemometers, and visualization. The conditions at the outlet are also monitored to determine the effects of entrainment into the flow and heat transfer to the walls. Wide ranges of all the physical variables in the problem are obtainable, allowing the simulation of flow due to fire in multi-leveled buildings with vertical open shafts.

Typical values of the operating conditions have been investigated, ranging from high buoyancy levels, for which the flow stays close to the vertical wall of the shaft, to much lower levels, at which the flow enters the shaft with a significant flow velocity and spreads outward very quickly. With increasing temperature at the inlet, the buoyancy effect is larger resulting in higher velocities and shorter time to reach the top. This time is an important quantity since it indicates the speed with which smoke and other combustion products reach into the higher levels of the building. The effect of the inlet mass flow rate is smaller, with a larger flow rate resulting in smaller time. The temperature at the outlet depends on heat transfer to the walls as well as on the flow velocity. Since these two effects oppose each other, the resulting ratio of the outlet temperature difference to the inlet temperature difference does not show a monotonic variation with an increase in inlet temperature.

Several detailed and quantitative measurements on the velocity and temperature fields have also been taken. The different flow regimes that arise as the shaft geometry and inlet conditions are varied are investigated. The results obtained on the naturally vented, relatively short, vertical shaft indicate that the flow and temperature are not uniform across a horizontal plane in the shaft. A wall plume is generated which conveys the hot fluid rapidly along the shaft wall from the inlet to the outlet. A recirculating flow arises away from this wall and this flow affects the heat transfer and flow in the wall plume. This, in turn, affects the entrainment into the flow, decay of the temperature field and rate of downstream movement. Therefore, horizontally uniform conditions can not be assumed here, as employed in several earlier studies for tall shafts. The wall plume has to be modeled in this case, considering the entrainment into the boundary layer flow and the effect of the recirculating flow on the temperature field.

A detailed experimental study of the flow in tall vertical shafts, with both natural and forced ventilation, is presently being carried out. The flow conditions are varied from a forced/mixed convection circumstance to a natural convection one. The discharge velocity of the hot gases or smoke can be kept small to simulate the typical situation in building fires. The focus of this phase of the study is on large aspect ratio vertical shafts. The measurements include mass flow rates at the inlet and outlet channels, downstream decay of the temperature field, rate of smoke movement, and temperature and velocity fields in the shaft. The opposing velocity at which the downstream spread is negligible is an important result and will be determined. The results obtained are being compared with those from the first phase of the study on small aspect ratio shafts and natural venting. The results are obtained in dimensionless terms to facilitate their use in the modeling of typical building fire situations. The ranges of the governing parameters will be chosen to cover typical fires in multi-leveled buildings.

Recent Results

Jaluria, Y., Chiu, W.K.S. and Lee, S.H.-K., "Flow of Smoke and Hot Gases Across Horizontal Vents in Room Fires", Proc. 4th ASME/JSME Thermal Engr. Joint Conf., Hawaii, Vol. 3, pp. 75-81, 1995.

G.P. Mercier and Jaluria, Y., "Fire-Induced Flow of Smoke and Hot Gases in Open Vertical Shafts", Sym. Ther. Sci. Engg., San Francisco, Nov. 1995 (submitted).

7. Flows in Vertical Shafts

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Objective

To provide the data required for the development of computer-based models for flows produced by fires in vertical shafts and passages when the stack effect is not dominant.

Problem

Strong turbulent mixing can be driven by unstable density gradients, (cold, heavy gas above lighter, hot gas) in a vertical shaft. When the stack effect is weak, this process will control the vertical movement of hot products of combustion. This research program involves the development of a description of this process. In the absence of the stack effect, flows of this type are one of the primary means of transport of hot, toxic gas through ventilation and elevator shafts or stairwells in a multi-storied structure. The description of this process is not yet available for use in computer-based fire codes.

Approach

The basic study involves an investigation of the flow in a vertical shaft, sealed at the top and initially filled with cool air. The walls are held at room temperature. A typical experiment starts when the bottom of the shaft is suddenly opened and exposed to a large reservoir filed with hot gas. The subsequent penetration of the hot gas into the shaft occurs because of the unstable density gradient. The turbulent mixing process driven by this instability is the subject of this study.

The experimental configuration chosen for initial studies has the advantage that it is clearly defined and is as simple as we can study while still keeping most of the features of real flows.

In previous work, Cannon and Zukoski 1976, we have used the salt-water/water modeling technique to study this process in the absence of heat transfer. This older work forms a solid basis for the present study in which heat transfer from the gas to the walls cools the gas, reduces the unstable density gradient, and thus strongly affects the mixing process and the gas motion.

Understanding this process is the initial aim of this work. Later, we will investigate the effects on the flow of openings in the walls and will change the processes by which the hot gas is introduced into the bottom or sides of the shaft.

Experiments in which low density helium-air mixtures are substituted for the hot gas will be used to relate the current work with the earlier salt-water/water modeling work and to demonstrate the difference between the effects of density differences produced by molecular weight of the gas and by gas temperature.

The shaft and its instrumentation and the hot gas reservoir have been completed. Initial experiments were carried out in the first quarter of 1994 in a shaft that is 0.25 m square and 2.4 m high. The shaft is only open at the bottom and the walls, composed of 2.5 cm thick aluminum plates, remain close to room temperature during a typical experiment. The initial experiments show, as expected, that the presence of heat transfer has a dramatic impact on the rate of propagation of the mixed gas front up the shaft.

Recent Results

Cannon, J.B. and Zukoski, E.E., (1975), "Turbulent Mixing in Vertical Shafts Under Conditions Applicable to Fires in High Rise Buildings," Technical Fire Report No. 1 to the National Science Foundation, Calif. Institute of Tech., Pasadena, CA.

8. Further Enhancement of EXIT89 and Analysis of World Trade Center Data

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Sponsor:
National Institute of Standards and Technology

Objective
1) To enhance the applicability of the evacuation model EXIT89 to exiting scenarios in a variety of public buildings in order to assist in the development of performance based codes, particularly NFPA 101; and 2) to complete the analysis of data collected on the evacuation of the World Trade Center in February 1993.

Enhancement of EXIT89: EXIT89 was designed to handle the evacuation of a large population of individuals from a high-rise building. It has the ability to track the location of individuals as they move through the building so that the output from this model can be used as input to a toxicity model that will accumulate occupant exposures to combustion products.

The model was originally developed with particular emphasis on its ability to serve as a people movement module of HAZARD 1. EXIT89 was designed to use smoke input in a manner similar to EXITT and to output the information needed by toxicity model included in HAZARD 1, so that it could function as a replacement module for EXITT. It was specifically designed to handle high-rise buildings with large occupant populations.

Detailed results from U.K. building evacuations were used to compare the results generated by the model and add enhancements such as the option for evacuees to use familiar routes as opposed to calculated shortest routes.

Another of the data sources included the effects of disabled occupants on occupant evacuation. Comparisons from the observations from these evacuations and from the model's output were evaluated. The data on the impact of disabled occupants on the overall building evacuation was used to add the presence of disabled adults to the model. The model now includes the option of having some occupants travel at speeds set at a proportion of the speed of able-bodied evacuees around them.

Other modifications include the use of CFAST output for smoke input, and the inclusion of additional human behavior data by adding randomly assigned delays. The user can now specify a proportion of occupants for whom delays will be calculated and a distribution of evacuation times to be selected from.

Analysis of World Trade Center Data: On February 26, 1993, shortly after noon, a bomb exploded in a subterranean garage below the World Trade Center plaza in New York City. The explosion and subsequent fire caused extensive structural damage in several basement levels, caused damage that interfered with the operation of the fire protection and other emergency systems and resulted in the evacuation of up to 100,000 occupants of the complex.

The NFPA began a research project to study the human behavior of building occupants in this incident and to document, to the extent possible, those engineering details such as building design, fire safety features, and smoke spread, that affected behavior. Under this project, reports have been prepared discussing the actions undertaken by the evacuees in order to aid in the understanding of what people do in fires and why and how those actions may conform to or differ from the assumptions used in designing and planning for life safety in such a large building.

Survey responses show that there was a significant difference in perception of severity between the two buildings since the bomb was closer to Tower 1 than Tower 2. Also, where previous human behavior studies have shown that people will move through smoke, this incident demonstrated that people will not only move through smoke, but will move through worsening conditions.

Information on pre-movement times and activities before and during evacuation were

also obtained. Results to date indicate that all occupants of high-rise buildings need some level of training and that training should include enough information and/or education about basic fire physics to enable occupants to think for themselves.

Recent Results

Proulx, G. And Fahy, R.F., "A Study of the New York World Trade Center Evacuation," *Proceedings of AsiaFlam '95,* Kowloon, Hong Kong, March 1995.

Fahy, R.F., "EXIT89 - An Evacuation Model for High-Rise Buildings -- Model Description and Example Applications," *Proceedings of the Fourth International Symposium - IAFSS,* Ottawa, Ontario, 1994.

9. Development of a Graphical User Interface for Post-Processing the Results of a CFAST Simulation

Principal Investigator:
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Center for Firesafety Studies
Worcester Polytechnic Institute
Worcester, MA 01609
508-755-9937

Sponsor:
National Institute of Standards and Technology

Objective

To develop a modern output post-processor for the interpretation of CFAST\footnote{'CFAST' is the Consolidated Model of Fire and Smoke Transport, written by BFRL.} simulation results. This software needs to incorporate the concepts of user-friendliness, scientific visualization, and hardware platform independence.

The visualization software currently included with BFRL's fire simulation package CFAST does not encourage quick interpretation of simulation results due to the convoluted procedures that are necessary in order to get output. CFAST provides on-screen displays of simulation progress, however this display lasts only as long as the simulation itself.

Much information exists in the CFAST output 'history' file that could be very useful in visualization of the output, however this data is unused. This project has created a software package, named CVIEW, to address these concerns.

Research has proved the ability of the human eye to interpret and spot trends (and problems) in large data sets quickly and wit minimal effort, when compared to interpretation of text-based numerical information. The development of an advanced visualization system to be used with CFAST speeds interpretation of the simulation's results, in addition to reducing errors caused by looking through large volumes of text-based results.

Approach

Quick access to results without significant effort is a high priority in our efforts. Our aim is to use all the available data from the CFAST simulation to provide a much clearer picture of the simulated fire than possible with the current post-processors, REPORT and CPLOT.

CFAST's own history file reading routines are used as an interface to CVIEW; this prevents problems by ensuring that the reading routines will always be up-to-date. The CVIEW software is designed to work on many separate platforms, preventing complications with what machines are necessary for its use. Such platforms currently include MS-DOS and Windows 3.1-based PC's, as well as Sun SPARC-based machines. Through software purchase, the possible platforms may be extended to include other Windows versions,\footnote {This includes 16- and 32-bit Windows 3.1 as well as Windows 95 and NT.} Macintosh, Sun SPARC stations and Solaris machines. Such an extension will not require additional coding.

The CVIEW software developed at WPI allows extraction of two and three-dimensional views of rooms simulated in CFAST and their display on a local host. In addition, CVIEW can be used to generate graphs similar to those generated with CPLOT. These graphs and compartment-views ('floor plans') can be extracted from a CFAST History file in about one minute, with

relatively little prior knowledge of the part of the CVIEW user.

Future work is progressing under a grant from the Fire Research Station, UK. To extend C-VIEW's capabilities to other software. The thrust of the grant will be to enable users to quickly and easily compare JASMINE output (an advanced Field model) with CFAST results.

CVIEW has been written so that future developments in room fire model development can be simply and effectively integrated within the existing software. This will allow CVIEW to be a general purpose post-processor for all room fire simulation software packages.

FIRE SAFETY ENGINEERING DIVISION

LARGE FIRE RESEARCH

Fire Driven Flows

Principal Investigator:
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Sponsor:
National Institute of Standards and Technology

Objective
To develop a fundamental understanding of the mechanisms which control the generation and transport of heat and smoke in fires and develop a predictive capability which will allow the computer simulation of fires associated with constructed facilities to be based on the underlying physical principles.

Problem
Information is lacking about the interaction of fires with the physical environment in commercial, industrial, residential, and transportation facilities. The dominant problem of heat and smoke movement in these facilities is of interest to their builders, owners, operators, regulators, and insurers. Small scale combustion processes are the study of diffusion flames in a turbulent flow environment and are of interest to the general combustion community.

Approach
Theoretical and computational techniques applied to the study of transport, mixing diffusion, radiation, and reaction processes occurring at widely different 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
Baum, H.R., Ezekoye, O.A., McGrattan, K.B. and Rehm, R.G., "Mathematical Modeling and Computer Simulation of Fire Phenomenon," *Theoretical and Computational Fluid Dynamics* 6:125-139 (1994).

Baum, H.R., McGrattan, K.B., and Rehm, R.G., "Simulations of Smoke Plumes from Large Pool Fires," *25th International Symposium on Combustion,* The Combustion Institute, Irvine, CA, August 1994.

Baum, H.R., McGrattan, K.B., and Rehem, R.G., "Mathematical Modeling and Computer Simulation of Fire Phenonema," Fire Safety Science, proceedings of the Fourth International Symposium, Kashiwagi, T., Ed., International Association for Fire Safety Science, pp. 185-194, 1994.

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

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

"Numerical Modeling of Plume Dispersion and Smoke Deposition from large Scale Fires," Prof. Ghoniem, A.F., Massachusetts Institute of Technology

Northridge Postearthquake Fire Assessment

Principal Investigator:
William D. Walton
Fire Safety Engineering Division
301-975-6872

Sponsor:
Federal Emergency Management Agency

Objective
To examine the origin and spread of fires and evaluate the response of fire sprinkler systems following the Northridge earthquake.

Problem
The Northridge earthquake provides an opportunity to examine the causes of post-earthquake fires, effectiveness of building systems in suppressing and containing the fires, damage to the fire protection infrastructure, management of fire department resources in response to the fires, and the recovery from fire damage following an earthquake. Fire sprinkler systems are one of the most widely used active fire protection systems in buildings. There is preliminary evidence that the Northridge earthquake resulted in damage to a significant number of sprinkler systems.

Approach
During FY 1995, BFRL will work with grantees to analyze the information concerning the causes, effects, and response to fires following the Northridge Earthquake. The researchers will take into account the complex interactions of events related to fire to determine the actions which would be effective in reducing the lost due to fire and maintaining adequate fire protection after an earthquake. Work will involve three tasks:

1. Investigate the causes of postearthquake fires, the response of building systems to the fires, and the restoration measures taken,
2. Develop recommendations for retrofit and new construction to reduce the sources of fires, improve the reliability of fire protection systems, and reduce the recovery time,
3. Make recommendations related to the performance fire sprinkler systems.

Recent Results
New project.

Post-Earthquake Fires and Lifelines

Principal Investigator:
William D. Walton
Fire Safety Engineering Division
301-975-6872

Sponsor:
National Institute of Standard and Technology

Objective
To make recommendations that reduce ignitions and major fires following earthquakes through improved in fire protection and lifeline integrity.

Problem
Fires are common following earthquakes and the major ones can result in loss of life and significant property damage, such as resulted from the 1906 San Francisco earthquake and the 1923 Tokyo earthquake where thousands of persons died. The experience in recent earthquakes suggests that, the prevention of large fires will depend on reducing the number of ignitions and controlling the spread of fire in and between buildings. Lifelines - electric power, water, sewer, gas, liquid fuels, telecommunications, and transportation systems directly impact causes and control of fires. Failure of gas lines, liquid fuel lines, and electrical power distribution systems can result in fires, whereas failure of water lines, transportation systems, telecommunication facilities, and electric power can hamper fire fighting capabilities. Yet, lifelines have no nationally recognized seismic design or rehabilitation standards.

Approach
During FY 1995, BFRL will address two thrusts:

1. Identify causes of fires and the factors which lead to the spread of fires. Develop recommendations which will lead to a reduction in the number of fires, reduce the likelihood that fires will spread, and improve the fire department response to fires.
2. Develop recommendations for repair of damaged systems, strengthening methodologies for existing systems, and the design and construction of new systems.

BFRL will work closely with the experts to define the scope of the problem; identify a complete list of issues; document lessons learned from recent earthquakes, particularly the Northridge earthquake; to assess and analyze the data collected; review the current practices by the profession; collect the information developed from recent research in the areas related to these topics; and to develop recommendations for future improvement.

Recent Results
New Project.

Urban/Wildland Fires

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

Sponsor:
National Institute of Standards and Technology

Objective
To quantify the capability of different types of water based Class A foam to protect building exterior materials from ignition.

Problem
A promising concept for protecting buildings in the path of an advancing wildland fire is to cover the building with a water based (Class A) foam prior to evacuating the area. BFRL conducted a small scale study in 1988 on the ignition inhibiting properties of one type of Class A foam. The results of the study indicated that compressed air, Class A foam exhibited an ignition-inhibiting capability twice that of an equal mass of water for T-11 siding and the compressed air foam (CAF) displayed a retention efficiency approximately 20 times that of water on the test samples.

Approach
During FY 1995, BFRL will characterize several types of building exterior materials (i.e., T-11 siding, cedar shingles) for ease of ignition. Repeat the experiments with large scale samples of the materials that have been pre-treated with different types of Class A foam to quantify the exposure protection capabilities of Class A foam. Analyze the characteristics of the Class A foams which provide the best exposure protection, and quantify the results based on data for properties such as drain time, surface tension, and opacity. If successful, these experimental techniques could be used as a basis for a new standard test method for the evaluation of Class A foams as a thermal exposure shield for structures.

Recent Results
New project

Analysis of Large Industrial Fires

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

Sponsor:
National Institute of Standards and Technology

Objective
To assess the performance of combined installations of sprinklers and draft curtains.

Problem
There is lack of information about the interaction of draft curtains with sprinkler systems to protect industrial facilities, of draft curtain installation standards are separate, it is not clear that the interactions have not been studied in a systematic way. Fire models have the potential to provide substantial information about both beneficial and detrimental installation combinations. However, present fire models cannot analyze the performance of sprinkler systems as determined by the number of heads operated during fire suppression.

Approach
During FY 1995, BFRL will develop a model of an industrial facility with combined sprinkler and draft curtains using computational fluid dynamic methods, such as FLOW3D (a commercial package computer model that simulates fluid dynamics and heat transfer using a finite difference approach) and LES (Large Eddy Simulation). This model will be used to analyze fire scenarios and determine the combination of parameters which define beneficial and detrimental combined installations of sprinklers and draft curtains. Data from experiments that have been conducted by industry to examine these interactions will be used as much as possible to evaluate the accuracy of the models. BFRL will conduct specific new experiments in small scale as needed and in large scale facilities of opportunity to obtain data for a more complete evaluation of the predictions. Results will be reported in a form that facilitates the development of a performance based standard. As part of a long term fundamental research effort, BFRL laboratory support is being used by University of Maryland staff in a cooperative study to understand the effects of water additives on the cooling of surfaces by sprays and foam. Other grants related to industrial fires also are included as part of this project.

Recent Results
Jay Gore (Purdue University), *An Investigation of Oil and Gas Well Fires and Flares*, NIST-GCR 94-653, National Institute of Standards and Technology, June 1994.

In-situ Burning of Oil Spills

Principal Investigator:
Kevin McGrattan
Fire Safety Engineering Division
301-975-2712

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

Objective
To determine conditions where in-situ burning can be used effectively as a response method to accidental spills of crude oil on land and on water.

Problem
BFRL has established leadership in characterizing the combustion of large pool fires. In support of other Federal agency objectives to implement burning as a response method to oil spills, the burning characteristics of fresh, weathered, and emulsified oils must be known. In addition, predictions are needed to assess the impact of the smoke plume produced by burning on downwind locations. Explore tests need to be developed to evaluate equipment needed to conduct burning operations.

Approach
During FY 1995, BFRL will extend its previous work on fresh oil in stagnant pools to the burning of weathered and emulsified oils on water with waves. A new test facility will be used to perform field measurements of burns up to 7 m in diameter with waves. BFRL researchers are working with the State of New Jersey to secure a permit for testing and are looking for other facilities to perform relevant mesoscale experiments. Measurements on the ignition and burning characteristics of fresh and weathered and emulsified crude oils will be performed in controlled laboratory experiments to enhance the data base of material burning characteristics. A format will be designed to display technical information that will eventually be part of a practical guide for responders. The LES (large eddy simulation) model for smoke plume flow in the atmosphere will be modified to account for terrain in response to the needs in California and Alaska. Data will be collected to evaluate the accuracy of the LES model.

Recent Results
LaBelle, R.P., Tennyson, E.J., Galt, J.A., K.B. McGrattan, "1993 Spill Off Tampa Bay, A Candidate for Burning?" Proceedings of the Seventeenth Arctic and Marine Oil Spill Program (AMOP) Technical Seminar, June 8-10, 1994, Vancouver, British Columbia, pp. 635-649, (1994).

Putorti, A.D. Jr., Evans, D.D., Tennyson, E.J., "Ignition of Weathered and Emulsified Oils," Proceedings of the Seventeenth Arctic and Marine Oil Spill Program (AMOP Technical Seminar, June 8-10, 1994, Vancouver, British Columbia, pp. 657-667, (1994).

Jason, N.H., editor, "In-Situ Burning Oil Spill Workshop Proceedings," January 26-28, 1994, Orlando, Florida, NIST SP867, U.S. Government Printing Office, Washington, DC 20402, (1994).

Baum, H.R., McGrattan, K.B., Rehm, R.C., "Simulations of Smoke Plumes from Large Pool Fires," Proceedings of the Twenty-Fifth International Symposium on Combustion, The Combustion Institute, Irvine, CA, August 1994.

Walton, W.D., Twilley, W.H., McElroy, J., Evans, D.D., Tennyson, E.J., "Smoke Measurements Using a Tethered Miniblimp at the Newfoundland Offshore Oil Burn Experiment," Proceedings of the Seventeenth Arctic and Marine Oil Spill Program (AMOP) Technical Seminar, June 8-10, 1994, Vancouver, British Columbia, pp. 1083-1098, (1994).

McGrattan, K.B., Baum, H.R., Rehm, R.G., "Smoke Plume Trajectory from In-Situ Burning of Crude Oil in Alaska," Proceedings of the Seventeenth Arctic and Marine Oil Spill Program (AMOP) Seminar, June 8-10, 1994, Vancouver, British Columbia, pp. 725-733, (1994).

Related Grant
"Numerical Modeling of Plume Dispersal and Smoke Deposition from Large Scale Fires," Ghoniem, Ahmed F., Massachusetts Institute of Technology

Smoke Plume Trajectory from In-situ Burning of Crude Oil in Alaska

Principal Investigator:
Kevin B. McGrattan
Fire Safety Engineering Division
301-975-2712

Sponsor:
Alaska Dept. of Environmental Conservation
Division of Spill Prevention and Response

Objective
To determine the expected trajectory of smoke plumes from in-situ burning as a response method for oil spills in Alaska.

Problem
There is a need to determine the downwind concentrations of smoke particulates from the in- situ burning of oil on water.

Approach
During FY 1995, BFRL will verify its large eddy simulation (LES) model of a smoke plume trajectory. Downwind particulate concentration measurements from the in-situ burns conducted in September 1994 near Prudhoe Bay, Alaska will be analyzed and compared to numerical simulations.

Recent Results
McGrattan, K, et al, *Smoke Plum Trajectory from In-Situ Burning of Crude Oil in Alaska,* NISTIR 5273, National Institute of Standards and Technology, October 1993.

Helicopter Telemetry for Oil Spill Emissions and Smoke Sampling

Principal Investigator:
William D. Walton
Fire Safety Engineering Division
301-975-6872

Sponsor:
Department of Transportation
U.S. Coast Guard
Research and Development Center

Objective
To design and test of an oil spill emission and smoke plume sampling package that can be suspended from a helicopter and transmit real time data to the ground.

Problem
The ability to use helicopters to transport a smoke sampling package has been demonstrated during previous mesoscale burns. A smoke sampling package has been developed and tested which can be suspended from a helicopter and held in the smoke plume, however, it is unable to transmit real time data to the ground. Real time data from the spill emissions or smoke plumes are required to make decisions on spill and burn management.

Approach
The existing smoke sampling package contains air sampling pumps, collection media, and sample bags to provide time averaged measurements of smoke yield, smoke particle size distribution, PAH concentration, volatile organic compounds, basic metrology measurement of temperature, relative humidity, wind speed and direction, and barometric pressure. During FY 1995, BFRL will add two major new instruments to the existing sampling package to meet the need for real time data during an oil spill or burn. The instruments are an infrared carbon dioxide analyzer and photo-ionization organic vapor analyzer. A radio modem compatible with the existing data logger will be added to transmit the data real time to a ground station. A global positioning satellite receiver will be added to the package to provide absolute location data for the package during operation.

The helicopter transported sampling package will be evaluated during three mesoscale fuel oil burns at the Fire and Safety Test Detachment in Mobile, Alabama. BFRL will analyze the smoke yield, particle size distribution, and the real time carbon dioxide and organic vapor measurements. Another agency selected by the Coast Guard will provide the analysis of the PAH and volatile organic compound samples.

Recent Results

Walton, W.D., McElroy, J., Twilley, W.H., and Hiltabrand, R.R., "Smoke Measurements Using a Helicopter Transported Sampling Package", *Proceedings of the Seventh Arctic and Marine Oil Spill Program Technical Seminar*, Vancouver, B.C., June 6-10, 1994

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 called "work stations" have been identified as a source of large heat release rate 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. If the fire can not be suppressed in the room of origin, the impact of sprinklers on the smoke flow in the corridor is needed. While the impact of sprinklers has been demonstrated in BFRL experiments, this has not been included in the corridor flow model, because the data base and zone modeling techniques were not sufficient to continue development of the corridor flow model including sprinkler effects.

Approach

During the past 2 years experiments have been conducted examining smoke flow in a corridor and characterizing the heat release rates of open plan office fuel packages. Experiments also have been conducted on mitigating the hazard of such fires. During FY 1995, BFRL will conduct experiments to enable the modeling of the mitigation effects. Also, work on verifying FPEtool (BFRL software used to evaluate hazards and fire protection strategies in GSA Office Buildings) will continue. The water spray from sprinklers used in the large scale experiments will be quantified. This information will be used as input to BFRL's FIRE DEMAND model and as

input for field modeling of the corridor experiments. Large scale experiments on the effects of obstructed ceiling flows on sprinkler activation will be conducted. Experimental results will be compared with the current capabilities of FPEtool.

Recent Results
Three reports are in process.

Related Grants
"A Study of Occupant Load Factors and Fuel Load in Contemporary Office Buildings," Milke, James A., Department of Fire Protection Engineering, University of Maryland

The Evaluation of a DOD Interstitial Space Construction Design for Hospitals

Principal Investigator:
James R. Lawson
Fire Safety Engineering Division
301-975-6676

Sponsor:
Department of the Army
U.S. Army Corps of Engineers
Alaska District

Objective
To evaluate the fire endurance of a walk-on deck design incorporated into the integrated building system approach adopted by the military for use in some hospitals.

Problem
The walk-on deck and interstitial space design was based on a design evaluated by BFRL in 1985. Significant design changes have been proposed. It is necessary to verify that a 2-hour performance rating is still valid for the modified design.

Approach
During FY 1995, BFRL will contact a fire test assembly, representative of the interstitial space construction system planned for the Elmendorf Air Force Base Medical Center, in its large scale fire test facility. The test assembly will be constructed in accordance with the structural and architectural specifications supplied by the Corps. The test assembly will be instrumented and exposed to the fire and heat conditions specified by NFPA 251, 1990 edition for a minimum duration of 2 hours.

Recent Results
Lawson, J.R., Brown, E., DeLauter, L., and Roadarmel, G., *Fire Performance of an Interstitial Space Construction System*, NISTIR 5560, National Institute of Standards and Technology, February 1995.

Large Fire Research Facility

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

Sponsor:
National Institute of Standards and Technology

Objective
To perform large scale fire experiments and develop measurements on large fires to meet the needs of industry and government customers.

Problem
Use of BFRL's large fire research facility must be scheduled for timely performance of experimental programs. Modernization of equipment and facilities is continually required to address technology needs of environmental and workplace safety.

Approach
During FY 1995, BFRL will continue to provide daily management for its Large Fire Research Facility, which includes scheduling tests and timely execution, along with modernization of test equipment and facilities. Additional short term improvements will be developed and executed during the fiscal year, pending availability of funding. These plans will be developed in conjunction with researchers to assure that new and updated instruments fit the needs of the fire program and its customers. BFRL will develop methods to assure full compliance with Federal environmental requirements for large and small scale tests.

Recent Results
Commissioned design study to examine the installation of a regenerative thermal oxidizer for abating the combustion products from BFRL's Large Fire Research Facility.

Development of a Sizing for Firefighter Protective Clothing

Principal Investigator:
James R. Lawson
Fire Safety Engineering Division
301-975-6676

Sponsor:
Federal Emergency Management Agency
U.S. Fire Administration
Firefighter Health and Safety

Objective
To determine the critical factors of work/station garment size which affect the thermal protection and work dynamics of fire fighters during fire suppression operations.

Problem
As a result of recent changes in employment regulations in the fire service, the range of firefighter body sizes has increased. The fit of firefighter work/station uniforms has become more critical as it relates to function with and without protective garments in fire suppression operations. Therefore, a need exists for standardizing the size of work/station uniforms to enhance safety and efficiency in fire fighting activities. In addition, emergency responders from FEMA have no standards which provide guidance on protective clothing or equipment which is required when they are called to investigate emergencies or disasters.

Approach
During FY 1995, BFRL will perform a literature survey to identify applicable publications associated with the fit and function of firefighter work/station uniforms and clothing and equipment for use of FEMA personnel in emergency or hazardous environments. BFRL will obtain input from the fire services and apparel manufacturers to identify special needs of firefighters and the ability of industry to support the firefighter's needs. Input will be collected from emergency managers and investigators to identify their needs for protective clothing and equipment. Working with ASTM and NFPA Committees which produce protective clothing and equipment standards, BFRL will develop and establish standards for firefighter uniforms and a FEMA standard for FEMA

emergency managers, investigators and inspectors.

Recent Results

Developed a draft standard for sizing and fit of fighter station/work uniforms, *ASTM Standard Practice for Taking body Measurements and Size Selection of Fire Rescue Service Station/Work Uniforms,* ASTM F-23 Subcommittee on Human Factors. The draft standard is being updated based on ballet comments.

RECENT GRANTS - LARGE FIRE RESEARCH

1. Computational Modeling of Large Fire Plumes

Principal Investigator:
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Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

Graduate Research Assistants
I. Lakkis
M.C. Soteriou

Sponsor:
National Institute of Standards and Technology

Objective
To develop a computationally based large fire plume model in which buoyant fluid mechanics, combustion, radiative transport, and their mutual interactions are all fundamentally represented using physically sound approximations, and well resolved spatially and temporally. The model's computational efficiency, achieved by using Lagrangian schemes to simulate each of these processes, should allow practical simulations to be performed on an advanced engineering workstation.

Problem
Simulation of fire plumes yielding burning rates, pollutant formation rates and the radiation field is necessary as a tool for the assessment of the environmental impact of large fires. Computational modeling of these fires is complicated by the presence of several complex physical processes, including turbulence, transport and chemistry. The wide range of physical scales present in these processes complicates their numerical modeling even further. The overall dynamics is essentially unsteady and thus should be the model. Conventional numerical approaches could be very expensive since the domains of these fires are often extremely large.

Approach
To overcome the difficulties described above, we are developing a computational model of fire plumes based a Lagrangian simulation of all significant physical processes involved. The vortex method is used to obtain solutions of the Navier-Stokes equations, including the buoyancy terms and the baroclinic terms, using computational elements distributed along the layer separating the plume (fuel and products) and the surrounding (air and products), in the turbulent regime. The mixing and combustion processes are simulated using the transport element method in which only species concentration and temperature gradients are computed, and only where vortex elements exist. The fast chemistry assumption is used in the computation of the burning rate, temperature and major species distribution. The concentration of the computational elements within the narrow zone of plume boundaries endows the approach with the necessary efficiency.

During FY 1995, we performed an extensive validation study of both the isothermal plume and the reacting plume models. For the first, we established the correspondence between the puffing frequency and the pool diameter, and compared the results with experimental data. For the reacting case, we repeated the same study and obtained good agreement with experiments. In both cases, we concluded that puffing is a buoyancy instability formed at the base of the plume near the pool due to the tendency of the rising plume to accelerate upward thus by reducing the plume diameter below that of the pool. The conical interface is subject to gravitational, or Rayleigh-Taylor type instability which leads to the roll-up of the material interface and the concomitant puffing. The latter is responsible for the strong entrainment field into the fire plume and the high upward penetration of the flames.

For the balance of the year, we plan to incorporate (I) a soot formation model, and (ii) a liquid-gas interface boundary condition at the pool surface. The first is necessary for the computation of the radiative transport fluxes, which contribute significantly to the fuel evaporation and pyrolysis, while the second is intended to establish a physical basis for determining the vaporation rate of the fuel. For the FY 1996 we plan to develop and incorporate a Lagrangian-based radiative transport algorithm.

Recent Results

Recent Results
Lakkis, I., Soteriou, M. and Ghoniem, A.F., "Numerical Simulation of Large Fire Plumes," to be presented at the International Conference on fire Research and Engineering, Sept. 11-15, 1995, Orlando, FL.

Zhang, X. and Ghoniem, A.F., "A Computational Model for the Rise and Dispersion of Wind-Blown, Buoyancy-Driven Plumes-III. Penetration of Atmospheric Inversion," Atmospheric Environment, vol. 28, No. 18, pp. 3019-3032, 1994.

2. Large Fire Analyses

Principal Investigators:
Professor Patrick J. Pagni
Professor Dorian Liepmann
Dr. Nicholas A. Dembsey
Dr. Javier Trelles
Mechanical Engineering Department
University of California
Berkeley, CA 94720-1740

Sponsor:
National Institute of Standards and Technology

Objective
To develop a comprehensive, modular, fundamentally sound model for fire growth in the urban/wildland intermix.

Approach
Fire induced winds in large scale fires determine the local characteristics of the fire environment. The Baum and McCaffrey model serves as the foundation for a three dimensional description of fire-induced winds. A resultant plume module has been added which determines the asymptotic nature of the flow after the multiple plumes from a large number of independent surface fires have fully merged.

The resultant plume model developed here accounts for the velocity and temperature profiles along the centerline by introducing a shift Z1 and for the broadening of the plume with a shift Z2. These two shifts are determined from the exact conservation integrals for mass and momentum. Energy is automatically conserved throughout the plume. Below a ceiling determined by plume overlap, the net conservation fluxes are modeled as the sum of the individual plumes. The equality between the two regions facilitates the determination of the two shifts for the resultant plume. Performing algebra on the coupled system of equations yields an implicit equation for Z1. A second equation emerges from the manipulation of the coupled system depends on both shifts but, since Z1 is already known, it is only a function of the unknown, Z2. Brent's method is used to solve for the shifts. The ability to reduce the original system to 2 equations which can be solved by univariate techniques makes the determination of the shifts reliable and robust. The two regions are joined to provide a smooth flow field. With the velocity field determined, firebrands can be convected through this flow model to yield valuable information regarding flame spread based on active firebrand arrival distributions. Firebrand transport is of utmost importance in this environment since it is a proven mode for transmitting burning material across sizable fire breaks. Also, firebrand transport has not been studied nearly as well as flame-to-fuel ignition. Modules for conventional fire spread will be added at a later date.

An experimental program is planned to determine the flaming life span of wood shingles similar to Tarifa's work on spheres and cylinders. Wind tunnel experiments in our fluid mechanics laboratory will determine shingle weight loss and aerodynamic drag as functions of time. These results will be used to predict the trajectories of brands produced by burning structures and transported by the mass fire plume described above.

Recent Results
Dembsey, N.A., Pagni, P.J., and Williamson, R.B., "Fire Near-Field Entrainment Measurements," in press, Fire Safety Journal.

Dembsey, N.A., Pagni, P.J., and Williamson, R.B., "Compartment Fire Experiments: Comparison to Models," submitted to Fire Safety Journal.

3. A Study of Two Phase High Liquid Loading Jet Fires

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Sponsor:
National Institute of Standards and Technology

Objective
To construct a laboratory scale burner for measurements and correlation of visible flame length and radiative heat loss fractions of high liquid loading spray jet fires.

Problem
Two phase jet fires, similar to the oil well blowout fires observed after the war in Kuwait, can result from effective atomization of a liquid fuel by small quantities of trapped gases upon depressurization. Existing studies of accidental fires have not considered the generic problem of two phase jet fires and experimental data and correlations for radiation, flame length, and pollutant emission hazards associated with such fires do not exist.

Approach
An effervescent atomizer burner was developed for the simulation of the physical processes involved in accidental fires involving high liquid loading two phase jets. A technique based on a single point measurement of radiative heat flux for the estimation of total radiative heat loss fraction of the jet fire was developed. Initial measurements involved crude oil fires (Dutta et al., 1994). While more recently toluene, heptane and other flammable industrial liquids are being considered (Wade et al., 1995).

Four factors were considered to be the possible contributors to the variation in length of apparently momentum dominated, two phase spray fires; (1) the length required for the evaporation of the liquid fuel, (2) the rate of entrainment of surrounding air due to the two phase flow effects, (3) persistent effects of buoyancy due to differences in the momentum o f the two phases, and (4) effects of variations in radiation hat loss and soot properties.

Evaporation lengths were measured using Mie scattering in the near injector region while accounting for possible interference from soot particles. The results showed that the evaporation length increased by up to a factor of 3 for conditions with large drops and high liquid flow rates. However, the evaporation length was found to be a small fraction of the total visible flame length. Furthermore, the changes in the visible flame length do not track those in the evaporation length. Hence, evaporation length was eliminated as a significant factor for the present flame conditions.

Radiative heat loss fractions showed three different trends with heat release rates. For flames with high MLR, radiative fractions were in the 10-15% range and decreased with increasing heat release rates. For flames with low MLR, radiative fractions remained almost constant or increased a little and then decreased as heat release rate was increased. Measurements of soot volume fractions and temperatures indicate that radiative coupling is a significant factor in determining the visible flame length.

The burner has been scaled up to 200 kW and effects of radiative coupling and two phase flows are being currently studied.

Recent Results
Dutta P., Gore J.P., Sivathanu Y.R., and Sojka P. E., "Global Properties of High Liquid Loading Turbulent Crude Oil + Methane/Air Spray Flames," *Combustion and Flame,* 97, 251, 1994.

Wade R.A., Sivathanu, Y.R. and Gore J.P., "Soot Volume Fraction and Temperature Properties of High Liquid Loading Spray Flames," *Combustion Fundamentals and Applications Proceedings of the Joint Technical Meeting of the Central, Western States and Mexican National Sections of the Combustion Institute and American Flame Research Committee)* (J.P. Gore, Ed.), 1995.

4. Computing the Effect of Draft Curtains on Sprinkler Response

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Sponsor:
The National Institute of Standards and Technology

Objective
To provide preliminary information for the development of a fire model to predict under what conditions draft curtains and heat and smoke vents enhance or diminish the performance of sprinklers and to search for an appropriate site for validation of this model through small and large scale fire tests in an actual industry setting.

Problem
Over the past twenty years there has been much debate concerning the interaction of sprinklers and draft curtains or heat and smoke vents in large facilities. At issue is to what extent and under what conditions draft curtains enhance or diminish the performance of sprinkler systems. It is believed that substantial insight can be gained through a program to develop an advanced fire model of sprinkler response and then verify its predictions through small and large scale experiments.

Approach
This grant is for two specific tasks, the searching for available information to provide data for a computer model and to find potential sites for small and large scale fire tests to validate the model. To accomplish this the following are being done:
1. Performing Information Search:
- o Globally search and attempt to capture the presently unknown quantity of existing data from both fire loss experience and small and full scale laboratory fire testing related to industrial fires with sprinklers and smoke and heat vents or draft curtains.
- o Organize, catalog and analyze the data found to determine the state and completeness of information available. Evaluate existing data in an attempt to develop a baseline for future testing.
- o Format the data determined to be of interest into the NIST developed FMS format for use in future research and modeling.

2. Performing Building Search:
- o Set physical criteria for required facility.
- o Contact local government environmental offices for approval for fire testing.
- o Contact Automotive and other industrial concerns for listings of their potential sites.
- o Visit potential sites and prepare a report on all sites worth consideration.

5. Measurement of Flame Temperature using IR Technique and Air-entrainment Velocity using PDPA

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Sponsor:
National Institutes of Standards and Technology

Objective
This project began in August, 1994 with the support from NIST. Tasks that have been completed are summarized below. In order to complete the project, we need to conduct further experiments described in the Proposed Tasks, which will require a one-year effort. A graduate student who has participated in this project has made significant progress toward the completion of his thesis by the beginning of 1996. Since we have all the equipment needed for the proposed experiments, and a new $150,000 fire-test facility will be

completed by this summer with the support from our University, we will be able to conduct the proposed tests at a very reasonable budget.

Approach
IR images were taken for small scale pool fires with diameter, 5 cm to 20 cm; they were compared to the thermo-couple temperature measurements. A black body source was placed behind the pool fires, and the radiant energy transmitted through each pool fire was measured by IR camera. We also measured the radiant energy directly emitted from the pol fire by the IR camera. Using these data, we calculated the emissivity of each pool fire, and the relationship between the emissivity and the pool diameter was established. We need to extend the same series of experiments for larger scale pool fires. We designed a small scale pool fire apparatus and a laser-sheet particle-track system for flow-visualization tests. We conducted a series of flow visualization for a 10 cm diameter pool fire and visualized stream lines of air entrained through the primary anchoring zone, which is the bottom part of the pool fire. These data are new and expected to help us understand the mechanism of flame anchoring in pool fires, one of the important problems related to the flame extinction and the flame stabilization. Therefore, we wrote a paper on the flame anchoring mechanism and submitted it to Combustion and Flame.

Our new fire test laboratory will be completed by this summer. This laboratory is especially designed for our experimental fire research. Now we have all the equipment necessary for the small to medium scale pool-fire experiments. With the continuous support from NIST, a graduate student who has mastered the measurement technique will be able to work on this experiment and complete the project. (2) We have a two component LDV system and a transmission measurement system. Using these apparatus, we will be able to measure velocity profiles around the pool fires and distributions of sot particles for pool fires up to 1 m diameter. Based on these data, we will develop scaling relationships in order to predict the structure of large scale pool fires. In the future, these predictions will be tested using our technique.

Recent Results
Ito, A., Narumi, A., Saito, K. And Cremers, C.J., Temperature measurement by holographic interferometry in liquids. *Proc. Eighth International Symposium on Transport Phenomena in Combustion,* Edited by S.H. Chan, 1995.

Qian, C., Tashtoush, G., Ito, A., and K. Saito, Structure of large scale pool fires. *International Conference on Fire Research and Engineering,* Orlando, FL, September 10-15, 1995.

Venkatesh, S., Ito, A., and Saito, K., Why pool fires are anchored? submitted to *Combustion and Flame.*

Qian, C., Arakawa, A., Ishida, H., Saito, K., Cremers, C.J., Temperature measurement by infrared images with application to fire research, *Thermal Conductivity 22,* Edited by Tong, T.W., Technomic Publishing Corp., Lancaster, PA, 1994, pp. 973-984.

6. Fire Protection in Large Industrial Fires

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Sponsor:
National Institute of Standards and Technology

Objective
To evaluate and optimize the performance of fire fighting agents used to protect structures and to prevent the spreading of fire in large industrial settings such as a large petro-chemical storage facility.

Problem
The most common active methods to mitigate and contain large industrial fire in petro-chemical storage facilities encompass water sprays and water firms. These techniques require massive amount of water due to the significant duration of these fires. The

mental concern. An integrated approach to identify cost-effective, environmentally safe agents and their application strategies is sought.

Approach

The specific goals of this research include: a) the evaluation of the active techniques currently used; b) the experimental and theoretical study of the basic mechanisms governing their interactions with the fire environment; c) the extension of these findings to identify the optimal agents to be used; d) the identification of the most cost-effective, environmentally safe application methodology; and e) the setting of guidelines for the design and performance prediction of preventive measures and fire mitigation strategies applicable to large industrial settings.

Protein foams exhibit characteristics which are of particular interest for these applications. They show; a) good expansion characteristics to provide significant volume of foam per unit volume of liquid; b) good performance in terms of burnback resistance when exposed to fire; and c) low mobility which makes them ideal to coat vertical and underhung as well as horizontal surfaces. Fire trials, which test the overall effectiveness of foams, are available. However, the data compare foams based on the time before ignition of the protected surface. Human factors and outdoor uncontrolled environmental conditions are common obstacles to the consistent repeatability of these kind of tests. Nonetheless, the test procedures and product rating reflect this overall approach.

Preliminary activities in FY 1994 include the design and construction of a fire box where layers of foams coating a 0.09 m^2 metal surface are tested under radiant heat input of 20-30 kW/m^2 in a controlled environment. During FY 1995, instrumentation and data acquisition system are installed. Extensive efforts are devolved to the design, construction and testing of a foam generation system that yields a repeatable, well characterized foam over a broad range of expansion ratios. Foam properties characterization is also ongoing. A separate test apparatus has been designed and constructed to measure thermal diffusivity during a slow heat-up transient of a foam layer. In parallel with these characterization efforts, burning tests in the fire box are also executed to gather preliminary data on the behavior of the foam.

These data, allow the construction of a first-cut model of the foam destruction process. The objective of this model is to ensure that the major governing parameters are identified and that the relative importance of the different effects is properly quantified. To limit the scope of this initial effort, a steady-state solution is considered. It turns out that, for high radiant heat fluxes, this is a reasonable first-order approximation. The heat transfer by conduction in the foam (which is modeled as a variable properties, porous material) is considered along with the advancing destruction front and with the radiant heat input deposition in the foam layer near the exposed surface. The expansion of the foam is considered for its feedback on the thermal and physical properties.

Encouraging results from this model are obtained. These results allow to chart the future direction of the experimental programs for the determination of the foam properties and for the gathering of data concerning the overall foam destruction processes. Presentation of these results is forthcoming.

7. Airborne Lidar Characterization of Oil-Burn Effluent Plumes

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Sponsor:
Minerals Management Service and
National Institute of Standards and Technology

Objective

To provide data on the transport and diffusion of the smoke plume resulting from burning of oil on water surfaces that can be used to validate models of the environmental consequences of burning spilled oil as a

method of achieving rapid environmental recovery.

Problem
Map the three-dimensional smoke plume with high spatial and temporal resolution over long downwind distances from the oil burn.

Approach
During October 1994, three oil-spill simulation tests were conducted at the U.S. Coast Guard Fire and Safety Test Detachment Facility on Little Sand Island in Mobil Bay, Alabama. For each test about 17,000 l of diesel oil overlaying water in a 15.2 m square pan were ignited. The resulting atmospheric effluent plume was observed with the two-wavelength (0.53 and 1.06 um) airborne lidar plume and haze analyzer (ALPHA-2) flown on the SRI Queen Air in vertically downward viewing direction. The aircraft was flown in cross-plume directions at various distances from the source as the elongated effluent cloud moved downwind. Backscatter signatures were processed for real-time height/distance color-modulated video displays that were used to help direct aircraft operations for achieving optimum plume sampling. The backscatter signatures along with aircraft location and time information were recorded on an optical disk for use in subsequent data analysis programs.

The three burn events clearly demonstrated the importance of atmospheric conditions on establishing the downwind structure of the oil-burn effluent plume and concentrations at the surface level. Effluents from the first test rapidly penetrated an elevated temperature-inversion and directional wind-shear layer that resulted in convective cloud formation and a significant change in the plume downwind transport direction. The second and third tests were conducted under more stable atmospheric conditions, resulting in less plume penetration across the elevated inversion layer and greater impaction of effluents on the surface at long downwind distances.

The data analysis program is on-going with emphasis on the second and third burn tests. Aircraft flight paths have been represented as best-fit straight line segments on a base map of the area. The backscatter signatures have been corrected for the inverse range-squared dependence and resulting records have been supplied to NIST on CD-ROM. A program was developed to plot the data in gray-scale picture format on a Raytheon Spectrum Analysis Recorder. The recorder provides high-quality cross-plume (altitude/distance) plotting without the distortions normally associated with video plotting of long data records. Data examples have been supplied to BFRL, and the remaining data are being processed. We expect to conduct a two-wavelength analysis of particle size that may be useful for estimating downwind smoke densities.

Recent Results
New Project.

8. A Study of Occupant Load Factors and Fuel Load in Contemporary Office Buildings

Principal Investigator:
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Sponsor:
National Institute of Standards and Technology and
General Services Administration

Objective
To provide a method of determining the occupant load in a wide variety of contemporary office buildings *i.e.* open plan vs. compartmented. In addition, a method to collect fuel load data in office spaces is being explored.

Problem
Questions have been raised concerning the accuracy of currently accepted values for occupant load and fuel load in office buildings. The concerns have resulted from preliminary studies conducted in open-plan and compartmented contemporary office buildings.

Approach
A literature survey was conducted to review the occupant load survey procedure and data collection forms used previously, *e.g.* by Bourdeau at the University of Maryland. This review resulted in the development of a preliminary data collection procedure and

preliminary data collection procedure and form for trial use. This approach was used to conduct an occupant load surveys in public- and private-sector office spaces in the Washington metropolitan area.
In an occupant load analysis, two parameters are needed: the number of building occupants at any given time and the area of the floor space. Essentially, the approach consists of counting building occupants present along with indicating workstations which appear to be occupied normally. However, accounting for an individual not being at the workstation is a source of inaccuracy as the worker may be absent on the day of the survey or elsewhere in the building. Further, an assessment of guests or visitors in the building need to be accounted. Accounting for building maintenance, custodial staff or contractors. These individuals are readily identified due to the different working attire.

An approach for the fuel load evaluation is to survey office spaces prepared for moving. This process significantly simplifies the process of weighing or estimating the quantity of loose materials.

FIRE SCIENCE DIVISION

SMOKE DYNAMICS RESEARCH

Carbon Monoxide Production and Prediction

Principal Investigator:
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Sponsor:
National Institute of Standards and Technology

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

Problem
CO generated by fires in enclosures is responsible for roughly two-thirds of fire deaths. The conditions necessary and the mechanisms responsible for the generation of high concentrations of CO are poorly characterized. As a result, it is currently impossible to predict the generation of CO by fires.

Approach
During FY 1995, BFRL will continue performing both fundamental and engineering investigations. The engineering studies are designed to develop correlations for CO formation for fires in enclosures and provide the necessary knowledge to incorporate the findings into existing BFRL fire models. The fundamental investigations are to identify the principal chemical and physical mechanisms responsible for the formation of high CO concentrations in fires and to theoretically justify the use of the engineering correlations. Ultimately, the findings will be incorporated into a simple physical model for CO production in enclosure fires.

Recent Results
Johnsson, E.L., Bryner, N.P., and Pitts, W.M., Fire-induced Mass Flow into a Reduced-scale Enclosure, *Fire Safety J.* (to appear)

Pitts, W.M., Bryner, N.P., and Johnsson, E.L., "Carbon Monoxide Formation in Fires by High-temperature Anaerobic Wood Pyrolysis", *25th Symposium (International) Combustion* (to appear)

Bryner, N.P., Johnsson, E.L., and Pitts, W.M., *Carbon Monoxide Production in Compartment Fires-reduced-scale Enclosure Test Facility*, NISTIR 5568, National Institute of Standards and Technology, December 1994

Leonard, S., Mulholland, G.W., Puri, R., and Santoro, R.J., "Generation of CO and Smoke During Underventilated Burning," *Combustion and Flame* **98** 20, 1994

Pitts, W.M., *The Global Equivalence Ratio Concept and the Prediction of Carbon Monoxide Formation in Enclosed Fires*, Monograph 179, National Institute of Standards and Technology, June 1994

Pitts, W.M., "Application of Thermodynamic and Detailed Chemical Kinetic Modeling to Understanding Combustion Product Generation in Enclosed Fires," *Fire Safety J.* 23, 271, 1994

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

Study of Smoke Agglomerates

Principal Investigator
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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
Needed is a general hardware design and data analysis methodology for studying smoke agglomerates in an orbiter facility.

Approach
During FY 1995, BFRL will use its Transmission Cell-Reciprocal Nephelometer 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 radius of gyration as the agglomerates grow. The results will be compared with light scattering calculations for a computer simulation of smoke agglomeration.

Recent Results
Mulholland, G.W., Bohren, C.F., and Fuller, K.A., "Light Scattering by Agglomerates: Coupled Electric and Magnetic Dipole Method", *Langmuir* **10**, 2533, 1994

Comparison of Smoke Produced at 1 g and μ g

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Sponsor:
National Aeronautics and Space Administration
NASA Ames Research Center,
Space Science Division

Objective
To evaluate the feasibility of collecting smoke agglomerates generated during a drop tower experiment for subsequent analysis.

Problem
There are several experiments proposed for the Gas-Grain Simulation Facility (GGSF) involving agglomerate structures. These experiments take advantage of the reduced gravity in the GGSF to study the evolution of agglomerates over a much greater length of time and much greater range of particle sizes than is possible at 1 g. An important issue in these studies is the initial condition; that is, what is the initial primary sphere size and chemical content of smoke agglomerate produced at μg compared to 1 g?

Approach
During FY 1995, BFRL will operate a laminar-jet diffusion burner in the 5 second NASA Lewis drop tower. Minor modifications of an existing burner facility will enable BFRL's collection of smoke agglomerates. The smoke collection apparatus consists of a cascade impactor/filter assembly and battery operated pump. The collected samples will be analyzed for particle size and chemical content.

Recent Results
New project.

Chemical Inhibitor Effects on Diffusion Flames in Microgravity

Principal Investigator:
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Sponsor:
National Aeronautics and Space Administration
Lewis Research Center
Space Systems Branch

Objective

To determine the effects of flame inhibitors on the physical characteristics (height, shape, color, and luminosity) and stability limits (ignition, extinction, lift-off and blow-off) of gaseous diffusion flames in the presence of halogenated fire suppressants in microgravity; and to develop quantitative analytical models for the observed behavior, including chemical kinetic effects, to understand the mechanisms of inhibition of halogenated compounds in gaseous diffusion flames in microgravity.

Problem

Fire safety in space is one of the main reasons to investigate combustion phenomena in microgravity. Since halogenated compounds will remain the fire suppressant of choice in many space missions, there is a need for experimental evidence on the effectiveness of these compounds for diffusion flames under zero buoyancy conditions.

Approach

During FY 1995, BFRL will perform experiments of normal and microgravity studies of laminar jet and co-flow diffusion flames inhibited by halogenated suppressant in the air or fuel stream. In microgravity, visual and temperature diagnostics will be used to detect flame shape, dynamics, and stability limits. Normal gravity experiments will use additional chromatographic and spectroscopic diagnostics in addition to visual and temperature experiments. Analytical and computational work will be performed using existing general 2-D codes with chemical kinetic models for comparison with the observed results.

Recent Results

VanDerWege, B.A., Bush, M.T., Hochgreb, S., and Linteris, G.T., "Effect of CF_3H and CF_3Br on Laminar Diffusion Flames in Normal and Microgravity," *Third International Microgravity Combustion Conference*, NASA, 11-13 April 1995, Cleveland, OH

Species Production for Turbulent Flame Modeling

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Sponsor:
National Institute of Standards and Technology

Objective
To establish models for in-flame species concentrations and post-flame species yields as a function of residence time, equivalence ratio, temperature, and strain and scalar dissipation rates.

Problem
Data base, metrology, phenomenology, and models for well controlled flame environments are required to provide the foundation for predicting flame radiation and the production of toxic gases and smoke for buoyant, turbulent diffusion flames for a wide range of combustion conditions.

Approach
During FY 1995, BFRL will select and experimentally examine laminar flame environments with temperature, residence time, equivalence ratio, and strain and scalar dissipation rates characteristic of buoyant, turbulent flames. Emphasis will be placed on planar imaging approaches using laser-induced fluorescence and scattering signatures, as well as quantitative measures of the soot field. Initial studies will focus on time-varying and underventilated laminar diffusion flames. Characterize the in-flame and post-flame chemical species, flow velocity, and temperature fields. Apply GC-MS and laser ionization-mass spectroscopy (previously used for graphitic smoke) to the analysis of the mostly organic smoke produced during underventilated combustion. Test and develop models incorporating the wide range of combustion conditions using the new data base.

Recent Results
Shaddix, C.R., Harrington, J.E., and Smyth, K.C., "Quantative Measurements of Enhanced Soot Production in Flickering Methane/Air Diffusion Flame," *Combustion and Flames* **99**, 723-732, 1994

Smyth, K.C., Harrington, E.L., Johnsson, E.L., and Pitts, W.M., "Greatly Enhanced Soot Scattering in Flickering CH_4/Air Diffusion Flames," *Combustion and Flame*, **95**, 229-239, 1993

Related Grants
"Fundamental Studies of Diffusion Flame Chemistry," Miller, J. Houston, George Washington University

"Aerosol Fractal Aggregates: Light Scattering, Diffusion and Aggregation", Sorensen, Christopher M., Kansas State University

Experimental Study of the Optical Properties of Soot & Smoke", Choi, Mun Young, University of Illinois.

"Mixing and Radiation Properties of Buoyant Luminous Flame Environments", Faeth, Gerald M., University of Michigan.

Vortex-Chemistry Interactions in Methane/Air Diffusion Flames

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William M. Pitts
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Sponsor:
Gas Research Institute

Objective
To determine how chemical production and destruction rates for soot, CO, and NO depend upon local flame conditions.

Problem
Increasingly tighter regulations from the Clean Air Act and its 1990 amendments control pollutant emissions. In cases where the chemical kinetics are well established, e.g., CO production and destruction, emission levels cannot be predicted from practical combustion devices over a range of operating conditions.

Approach
During FY 1995, BFRL will study chemistry-flowfield interactions using flickering methane/air diffusion flames. Axisymmetric flames will be acoustically locked to a pulsed dye laser system at 10 Hz, allowing interrogation of the flame dynamics as a function of height, phase angle, and forcing amplitude. These flames exhibit a much wider range of local strain and scalar dissipation rates than those found in steady, co-flowing laminar flames. Emphasis will be on planar imaging approaches for species and soot concentrations and LDV velocity and thin-filament pyrometry temperature measurements. These results will provide critical tests of current models for production of toxic gases and smoke from buoyant, turbulent diffusion flames for a wide range of combustion conditions.

Recent Results
New project.

RECENT GRANTS- SMOKE DYNAMICS RESEARCH

1. Experimental and Modeling Studies of Soot and Polynuclear Aromatic Hydrocarbon Oxidation in Post-flame Gases

Principal Investigator:
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The George Washington University
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Objective
To developed fundamental kinetic data and mechanistic insight for the oxidation chemistry of condensed phase carbon (soot and polynuclear aromatic hydrocarbons) in conditions typical of upper layers in room fires.

Problem
Emissions from real fires, and laboratory enclosure fires which are meant to mimic their behavior, are found to be closely linked to the global equivalence ratio [Pitts (1994)] (GER), defined as the ratio of fuel to oxygen in the system divided by the stoichiometric ratio:

Of major concern is the production of CO which is often the primary cause of fire death [Harwood and Hall (1989)]. The level of carbon monoxide emitted from a fire is expected to reach toxic levels for underventilated fires [Pitts (1994)]. Although some of the CO emitted from these fires is attributable to gas-phase chemistry, a majority may be attributable to post-flame oxidation of condensed phase carbon, i.e. soot. Previous studies in shock tubes [Roth *et al.* (1990), Park and Appleton (1973)], in flames [Neoh *et al.* (1985), Garo *et al.* (1990), Puri *et al.* (1994)], and thermogravimetric investigations [Noirot *et al.* (1994), Wicke *et al.* (1986), Gilot *et al.* (1993)] have provided kinetic data on soot oxidation, but not under conditions analogous to those found in the upper layer of room fires.

Approach
In our experiments the emissions from laminar diffusion flames are passed through a long quartz tube held in a tube furnace. The entire apparatus is fully-enclosed so that the GER can be varied. Both optical and extractive diagnostics are used to characterize the flame emissions before and after the furnace region. In early experiments tunable diode laser absorption spectroscopy was used to monitor CO levels while extinction of the red beam of a HeNe laser was used to determine soot volume fractions. By measuring the temperature profile through the system, local velocities could also be estimated. From the time-temperature behavior of the disappearance of soot and the formation of carbon monoxide, a simple kinetic expression for particle oxidation was derived. Preliminary results from these experiments have recently been presented (Tolocka and Miller, 1994).

More recent experiments have focused on the use of on-line mass spectrometry to determine residual gas concentrations in the oxidation tube. We also have performed extractive chemical procedures on the soot sampled in these experiments. Preliminary results of these studies show dramatic increases in adsorbed PAH on the soot when the GER approaches 2. Evidence exists for partially oxidized PAH in this sampled material.

Recent Results
Noirot, R., Gilot, R. Gadiou, R., and Prado, G., (1994) *Combustion Sci. and Tech.,* **95**:139.

Tolocka, M. And Miller, J.H. (1994), *Chem. Phys. Processes in Combust.,* 242-245.

Leonard, S. Mulholland, G.W., Puri, R., and Santoro, R.J., (1994) *Combustion and Flame,* **98**:20.

Gilot, R., Bonnefoy, F. Marcuccill, F., and Prado, G., (1993) **95**:87.

Garo, A., Prado, G. And Lahaye, J., (1990) *Combustion and Flame,* **79**:226.

Harwood, B. and Hall, J.R., (1989) *Fire J.* **83**:29.

Neoh, K.G., Howard, J.B., and Sarofim, A.F., (1985) *Twentieth Symposium (International) on Combustion/The Combustion Institute.*

2. Dynamics, Transport and Chemical Kinetics of Compartment Fire Exhaust Gases

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Objective
To determine when high concentrations of carbon monoxide (CO) are transported to locations remote from the building fire origin and develop correlations to predict the amount of CO which is transported to these locations.

Problem
Two-thirds of the deaths which are caused in building fires are attributed to smoke and toxic gas inhalation. The majority of these deaths occur at locations distant from the fire origin and are caused by CO inhalation. Models need to be developed to predict when and the amount of CO that is transported to remote locations in building fires.

Approach
In a number of building fires where people died of CO inhalation, ambient air was entrained into the room containing the fire while the rest of the building was not able to entrain ambient air. The reduced-scale building fire facility at VPI&SU which consists of a compartment connected to the side of a hallway was used to investigate the conditions necessary for transport of high concentrations of CO. The facility was altered so limited oxygen entered the hallway and the compartment. Two scenarios have been addressed thus far. In the first case, oxygen containing combustion gases are entrained into the compartment from the hallway via a doorway connecting the two. The second set of experiments had a controlled amount of ambient air entering the compartment with the compartment and hallway connected by a window size opening.

In the experiments with oxygen being entrained from the hallway, the compartment temperatures were only 950 K and the compartment upper-layer was seen to drop all the way to the floor. The CO concentration 0.05 m below the ceiling in the hallway fell to 1.6% after being transported approximately 0.71 m down the hallway and then remained constant for the rest of the hallway length. This was due to the hallway upper-layer temperatures being less than 700 K after traveling just 0.71 m down the hallway. The CO was being transported down the hallway in the presence of approximately 6% O^2 in the upper-layer of the hallway. CO yields downstream of the hallway were 0.25 which is comparable to yields previously seen inside the compartment.

In the experiments where a controlled amount of ambient air enters the compartment, a decrease in the air entrainment rate into the compartment resulted in higher global equivalence ratios (GER). The CO concentration 3.76 m downstream of the compartment was seen rise with a rise in GER up to a GER of 1.8-2.0 (with no external burning). For GER greater than 1.8-2.0, the CO concentration 3.76 m downstream of the compartment stayed relatively constant. At these higher GER, 1% CO was leaving the hallway with external burning occurring. Most of what was being oxidized in the external burning was unburned hydrocarbons and not CO. With higher GER, the upper-layer inside the compartment fell down close to the floor. As the GER was increased, the temperatures inside the compartment and the hallway approached those seen in the experiments where oxygen was entrained from the hallway.

By limiting the amount of oxygen entrainment into the hallway and the compartment, high levels of CO can be transported to the remote locations in the building. Further research will be performed to determine the effects the fluid mechanics inside the hallway and the stoichiometry of the gases entering the hallway have on the transport of CO.

Recent Results
Lattimer, B.Y., Ewens, D.S., Vandsburger, U. and Roby, R.J., 1995, "Transport and Oxidation of Compartment Fire Exhaust Gases in an Adjacent Corridor", *Journal of Fire Protection Engineering*, Vol. VI, No. 4.

Lattimer, B.Y., Vandsburger, U., and Roby, R.J., 1995, "Carbon Monoxide Production, Transport and Oxidation from a Compartment Fire with a Combustible Ceiling", 8th Int. Sym. on Transport Phenomena in Combustion, San Francisco.

3. Experimental Study of the Optical Properties of Soot and Smoke

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Objectives
To measure the dimensionless extinction constant for soot generated from various fuels using gravimetric sampling and simultaneous light extinction techniques. Determine the effects of soot morphology, sampling temperature, burner configurations on the measured extinction constant. The focus of the proposed study is on the development and use of Gravimetric Sampling/Light Extinction technique to measure Ke. This technique consists of isokinetically sampling the soot at a known flow rate, measuring the mass of soot collected and determining the density of soot using helium pycnometry. The soot volume fraction determined simultaneously using optical extinction measurements (to be performed in the spectral range of 600 nm to 3000 nm) will then be calibrated using the soot volume fraction determined from the gravimetric technique. In this manner the magnitude and the spectral variation of Ke can be determined without relying on the refractive index of soot or making drastic assumptions regarding its scattering characteristics.

Approach
In the fire and combustion community, light extinction is commonly used to measure the soot volume fraction. This technique is attractive because it provides instantaneous and relatively non-intrusive measurements. Some of the applications for light extinction technique include the study of soot formation and growth in flames, monitoring of particulates for smoke plume modeling, measurement of soot concentration for fire detection and assessing visibility reduction in buildings.

The soot volume fraction measurements are very sensitive to the choice of dimensionless extinction constant used in the calculations. Recent measurements indicate that there are significant uncertainties in the dimensionless extinction constant due to the use of limiting assumptions and inaccurate optical property data for soot which can result in errors of up to 50%. Thus, in order to improve the light extinction technique for use in combustion and fire applications, this study proposes to accurately measure the dimensionless extinction constant without relying on the available optical properties of soot or limiting assumptions.

Recent Results
Zhou, Z. and Choi, M.Y., "Measurement of Dimensionless Extinction Constant of Soot Generated Using Various Fuels," To be presented at the *Central/Western/Mexican Sections of the Combustion Institute*, San Antonio, TX, April, 1995.

Vander Wal, R.L., Z. Zhou and M.Y. Choi, "Spatially Resolved Spectral and Temporal Characterization and Gravimetric Sampling Calibration of Laser-Induced- Incandescence," *Combustion and Flame, Submitted,* 1995.

4. Mixing and Radiation Properties of Buoyant Luminous Flame Environments

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Sponsor:
National Institute of Standards and Technology

Objective
To complete measurements of the mixing and radiation properties of luminous buoyant

turbulent flame environments, and to exploit these results to develop and evaluate advanced models of practical unwanted fires.

Problem

Turbulent mixing and radiation from luminous flames are major mechanisms controlling the rates of spread, growth and combustion of unwanted fires; therefore, these properties are important elements of contemporary models of unwanted fires; that find application for quantifying fire hazards while avoiding the time and cost of full-scale fire tests. Unfortunately, available information about the properties of buoyant turbulent flow is very limited, which has impeded model development and evaluation. In addition, radiation from soot in luminous flames is the dominant radiation mechanism of fires but is poorly understood due to uncertainties about soot optical properties. Thus, both these issues are being addressed during this investigation.

Approach

The study of buoyant turbulent flows is concentrating on self-preserving buoyant turbulent plumes because they are fundamental classical flows that are independent of source properties and can be numerically simulated with modest computational requirements. Present work began with self-preserving round buoyant turbulent plumes using laser-induced fluorescence and laser velocimetry to measure mixing levels and velocity properties, respectively. These measurements revealed that earlier work did not extend far enough from the source to reach self-preserving conditions, and that self-preserving round turbulent plumes were narrower, and had larger scaled mean values near the axis, than previously thought. Mean and turbulence properties satisfied self-preserving behavior and were measured to facilitate model development.

Attention has now turned to the classical problem of self-preserving plane (or line) buoyant turbulent plumes for several reasons. First of all, the streamwise rates of development of self-preserving round and line buoyant turbulent plumes is fundamentally different which provides a useful evaluation of modeling improvements needed to treat the complex flows of practical fire environments. Secondly, the line buoyant turbulent plume is a necessary precursor for gaining a better understanding of turbulent flows along surfaces. Finally, reaching self-preserving flow conditions is more difficult for line than round plumes; therefore, concerns about existing measurements that claim to represent self-preserving behavior must be resolved before this information can be exploited for model development.

Work on the radiation properties of luminous flames is concentrating on the optical properties of soot because continuum radiation from soot is the most important source of radiation in fires. Measurements and computations during initial phases of the study showed that the popular Rayleign and Mie scattering theories were not effective for soot as massfractal aggregates of primary soot particles, was effective for the conditions of interest. Measurements revealed that the fractal properties of soot aggregates were robust; therefore, current large uncertainties about the refractive indices of soot, and how they vary with fuel type and flame condition, are the greatest impediment to reliable estimates of soot optical properties.

In view of these findings, work is concentrating on soot refractive indices. The first phase of this work involves the use of insitu methods based on extinction and scattering measurements for the ultra-violet and visible wavelength ranges (200-800 nm), considering soot in both nonpremixed and premixed flame environments. The next phase of the work will involve the use of ex situ reflectively measurements in the visible and infrared wavelength ranges (500-1000 nm) for the same soot populations. This approach allows both comparison of effects of in situ and ex situ methods and evaluation effects of soot temperatures on refractive indices. Given this information, the final phase of the investigation will evaluate predictions of radiation from soot-containing flames using present methods, based on radiation measurements for well-characterized luminous laminar flames.

Recent Results

Dai, Z., Seng, L.-K. And Faeth, G.M., "Velocity Statistics of Round, Fully-developed Buoyant Turbulent Plumes," *J. Heat Trans.*, 117, 138, 1995.

Dai, Z., Tseng, L.-K., and Faeth, G.M., "Structure of Round, Fully-Developed, Buoyant Turbulent Plumes," *J. Heat Trans.*, 116, 409, 1994.

Farias, T.L., Carvalho, M.C., Koylu, U.O., and Faeth, G.M., "Computational Evaluation of Approximate Rayleigh-Debye-Gans/Fractal-Aggregate Theory for the Absorption and Scattering Properties of Soot," *J. Heat Trans.*, 117, 152, 1995.

Koylu, U.O., and Faeth, G.M., "Optical Properties of Overfire Soot in Buoyant Turbulent Diffusion Flames at Long Residence Times," *J. Heat Trans.*, 116, 152, 1994.

Koylu, U.O., and Faeth, G.M., "Optical Properties of Soot in Buoyant Laminar Diffusion Flames," *J. Heat Trans.*, 116, 971, 1994.

Koylu, U.O., Faeth, G.M., Farias, T.L., and Carvalho, M.G., "Fractal and Projected Structure Properties of Soot Aggregates," *Combust. Flame*, 100, 621, 1995.

5. Post-Flame Soot

Principal Investigator:
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Objective

To develop a morphological description of large soot aggregates that can escape from a diffusion flame and relate morphology to the soot cluster optical properties and the kinetics of their creation.

Problem

Carbonaceous soot released from combustion processes is a major atmosphere pollutant effecting both visibility and health. Such soot at much higher concentrations in building fires is also the source of the extreme obscuration and is a major cause of fatalities in such a situation. Thus it is important to know what this soot is, i.e., how to describe it physically. This proposed morphological description will be the basis for understanding its optical properties, transport, and kinetics of creation.

Approach

Post-Flame Soot is the soot that escapes unburned from the top of a fuel rich flame. It is composed of large fluffy aggregates which continue to grow in the post-flame environment. For certain fuels and burning conditions these aggregates may grow to become visible to the unaided eye. How do these aggregates or "supersoot" form? Is there a different physical route to form these particles than for in-flame soot, or can the growth be explained in terms of stochastic Brownian dynamics? What is their morphology, are they fractals, and how is the morphology related to the kinetics of their formation? And what are their optical properties and can these properties be related to their morphology in a straightforward manner?

In the first year of this work we studied the morphology of soot collected from a laminar acetylene diffusion flame in still air. The burner was simply a 0.9 cm ID tube through which acetylene flowed at a rate of 3.2 cm^3/sec. Soot was sampled both thermophoretically and via impaction, using a sampling device that held the collection TEM grid or microscope slide in the flame for 15 msec. The thermophoretic samples were viewed with a TEM at 20800x magnification. The impaction samples were viewed with an optical microscope at 72x. Photographs were digitized and analyzed with a computer. Over a 1000 soot clusters were analyzed to obtain N, the number of monomers per cluster, a, the monomer radius, and Rg, the cluster radius of gyration. From these measurements the fractal dimension Df and the prefactor ko were obtained by fitting to Morphological studies were very successful. Our largest soot clusters were nearly 1 mm across ($Rg \sim 0.4$ mm). The range in Rg was four orders of magnitude; in N it was several orders of magnitude. We found that throughout this great range the morphology was the same: fractal with $Df = 1.80 \pm 0.1$ and $ko = 2.3 \pm 0.6$.

These results are important because they study soot two orders of magnitude larger (in

Rg) than any previous work. They establish that the same morphology holds from clusters of a few monomers up to clusters of 100 million monomers! Both Df and ko, which we measured over this vast range of sizes, are key variables for future optical characterization. Finally, our results strongly imply that Diffusion Limited Cluster Aggregation (DLCA) is the kinetics of formation throughout this large size range.

Future work will study the optics of these large clusters based on this morphological understanding.

Recent Results

Sorensen, C.M., and Feke, G.D., "Morphology of Macroscopic Post-Flame Soot," submitted to Combustion and Flame.

FIRE SCIENCE DIVISION

MATERIALS FIRE RESEARCH

Polymer Flammability Modeling

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Sponsor:
National Institute of Standards and Technology

Federal Aviation Administration
Technical Center

Objective

To develop an integrated model of thermal degradation and char formation in burning polymers leading to the development of technical bases for the design of a new generation of fire retardants and fire resistant materials.

Problem

Flammability is a major concern when polymeric materials are used in buildings, aircraft ships and clothing. Today's standards for acceptable cost, performance and environmental safety have made the traditional "trial and error" approach to materials flammability obsolete.

Approach

There is a strong correlation between char residue and fire resistance since char is always formed at the expense of volatile fuel. Furthermore, the presence of a surface char 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 char formation 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.

During FY 1995, BFRL will research micro- and macroscopic phenomena. The microscopic approach is based on a molecular dynamics model of the thermal degradation of polymers which was developed at BFRL. 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.

Modification of BFRL's molecular dynamics model to accept geometrical input from INSIGHT II, (a commercial product developed and maintained by Biosym Technologies) was completed in FY 1994. This is the first step in developing the capability to model the thermal degradation of a wide range of polymers. The molecular forcefield also has been expanded to permit simulations of the degradation of polyvinyl alcohol. The application to other vinyl polymers should be possible, however, the extension to polyaromatics will require a completely new programming approach and access to proprietary databases consisting of forcefield parameters for a much wider range of molecular structures. Work will focus at predicting the rate-of-heat-release in combustion of vinyl polymers.

The macroscopic model simulates the dynamics of the swelling process as the result of an ensemble of expanding and migrating bubbles. The motions of bubbles and the material surface obey the flow field obtained by summing the contributions from all bubbles. Material properties and bubble growth rate depend on local temperature and the chemistry of the gasification process.

Recent Results

Lomakin, S.M., Brown, J.E., Breese, R.S., and Nyden, M.R., "An Investigation of the Thermal Stability and Char Forming Tendency of Cross-linked Poly(methyl methacrylate)," *Polym. Deg. and Stab.*, 41, 229,1993.

Nyden, M.R., and Brown, J.E.,"A New Generation of Fire Resistant Polymers: Part I Computer Aided Molecular Design," *Proceedings of the 12th Joint Panel Meeting of the UJNR Panel on Fire Research and Safety,* 257, 1992

Chemistry of Polymer Flammability

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Sponsor:
National Institute of Standards and Technology

Objective

To characterize the chemical structure of polymer residues which are generated at well-defined fire simulated conditions, for the purpose of determining the links between original polymer structure, non-halogenated additives, char characteristics and flammability properties for polymer materials.

Problem

Two recent trends which have started to affect the U.S. plastics industry are polymer recycling and a demand for non-halogenated flame retardant treatments. The degradation products of polymers with such treatments are corrosive and some may be toxic. One alternative flame retardant approach is to form char during polymer burning. This approach is ideal in that carbon atoms retained in the condensed phase, as char, lessen the available fuel for flaming combustion even as they help insulate the polymer from the heat of the flame. However, at present, there is very little quantitative information about the relation between polymer structure, char properties, the effect of non halogenated additives, and realistic flammability properties.

Approach

During FY 1995, BFRL will evaluate candidate polymer/additive systems, using its Cone Calorimeter, for novel (improved) flammability behavior. Preceramic polymer/organic polymer blends will be prepared and evaluated.

The solid state decomposition chemistry of promising candidates will be characterized primarily using CP/MAS 13C NMR. Samples at intermediate stages of decomposition will be generated, from the preceramic/organic polymer blends, in an inert-flow-pyrolysis apparatus at many different temperatures. Char yield, C/H ratio, aromatic/aliphatic ratio (CP/MAS 13C NMR and PAS-FTIR), crosslink density (swelling tests) will be measured. For higher heating rate conditions, the samples will be evaluated under fire-like (non-oxidizing) conditions in a gasification apparatus which exposes large compression molded samples (100 g, disks) to a radiant heat source (25-40 kW/m^2) in a N_2 atmosphere. Gaseous degradation products for the selected polymer samples may also be analyzed using the pyro-probe FTIR.

Recent Results

Gilman, J., W., Vanderhart, D.L., and Kashiwagi, T., "Fire and Polymers," *Symposium Series Book*, American Chemical Society, Fall ACS 1994 Meeting, Washington, D.C. (in press)

Burning Rate of Materials

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National Institute of Standards and Technology

Objective

To improve the understanding of the physical and chemical gasification processes of thermoplastics and char forming polymers; to develop theoretical models to predict the gasification rates of polymers exposed to fire conditions; to improve understanding of energy feedback mechanisms of pool fires and to develop theoretical models to predict energy feedback rates from a pool flame to the fuel surface; to determine heat transfer rate from flame to horizontal surface near a rectangular shape fuel source under external wind for simulation of flame spread; to improve mathematical models to predict the burning rate of thermoplastics; and to develop models for char forming polymers by combining the gasification models with the energy feedback rate models.

Problem

At present, models are not available 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). In order to improve the prediction of fire hazard, accurate description of fire source is urgently needed.

Approach

During FY 1995, BFRL will develop burning rate models (global and field equation) of polymeric materials (including char formers) for simple horizontal configurations. This research consists of coupling between experiments and modeling; it is divided into two parts; one is to determine energy feedback rates from a pool flame for various fuels and sizes and the other is to determine the gasification rate of various polymers. Gas phase combustion characteristics are measured for a variety of fuels with pool diameters up to 100 cm. 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 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 nonflaming condition for various radiant fluxes. Gasification models for thermoplastics and char forming polymers are developed. The results of this project will be applied for understanding combustion characteristics of noncarbon based polymers such as silicone, (a CRADA with Dow Corning).

Recent Results

Choi, M.Y., Hamins, A., Mulholland, G., and Kashiwagi, T., "Comparison of the Soot Volume Fraction Using Gravimetric and Optical Techniques," to appear in *Combustion and Flame,* 1994.

Kashiwagi, T., "Role of the Condensed Phase in Polymer Combustion and Flammability," to appear in the *Twenty-Fifth International Symposium on Combustion.*

Rushmeyer, H.E., Hamins, A., and Choi, M.Y., "Case Study: Volume Rendering of Pool Fire data," to appear *IEEE Computer Graphics and Applications*, Special Issue, Visualization Case Studies (Ed. by Silver, D., and Robertson, P.)

Choi, M.Y., Hamins, A., and Kashiwagi, T., "Simultaneous Optical Measurement of Soot Volume Fraction and Temperature in Premixed

Flames," *Combustion and Flame,* **99**, 174-186, 1994.

Yang, J.C., Hamins, A., and Kashiwagi, T. "Estimate of the Effect of Scale on Radiative Heat Loss Fraction and Combustion Efficiency," *Combustion Science & Technology,* **96**; 183-188 (1994).

Hamins, A., Klassen, M., Gore, J., Fischer, S., & Kashiwagi, T. "Heat Feedback to the Fuel Surface in Pool Fires," *Combustion Science & Technology,* **97**: 37-62 (1994).

Choi, M.Y., Hamins, A., Rushmeyer, H.E., and Kashiwagi, T., "Simultaneous Optical Measurement of Soot Volume Fraction, Temperature, and CO^2 in Heptane Pool Fires," to appear in the *Twenty-Fifth Symposium on Combustion*, 1994.

Related Grants

"A Study of Entrainment and Flow Patterns in Pool Fires Using Imaging Velocimetry," Gore, J.P., Purdue University.

"Modeling of Combustion, Fluid Mechanics, and Radiation in Buoyant Turbulent Fires," Ezekoy, O. A., University of Texas at Austin.

Combustion of Silicone

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Sponsor:
Dow Corning Company

Objective

To understand the combustion mechanism of siloxane.

Problem

The heat release rate (HRR) of burning materials increases significantly with an increase in external thermal radiant flux applied to the burning surface. This is true for noncharring materials and also for charring materials. However, the burning behavior of siloxanes differs markedly from carbon-based materials. Perhaps most significant, the HRR for siloxanes (chain length > 15 Si-O units) does not increase significantly with an increase in external thermal radiant flux. Whereas carbon based materials may form products of incomplete combustion such as soot and carbonaceous chars, siloxanes form very minimal char but produce substantial amounts of solid amorphous silica (SiO_2) as a major product of combustion. Previous studies suggest that amorphous silica plays a significant role in mediating the burning behavior of siloxanes.

Approach

During FY 1995, BFRL will:

1. Determine gasification rate of siloxanes having different chain length in nitrogen and derive the relationship between external radiant flux and global heat of gasification, and
2. Collect silica particles at various locations of D4 pool flame and characterize their nature.

Recent Results

Buch, R., Hamins, A., Mattingly, D., Shields, J., Borthwick, P., and Kashiwagi, T., "Pool Burning of Silicon Fluids," *1994 Fall Technical Meeting,* The Eastern States Section of Combustion Institute, pp204-208, 1994

Flammability of Structural Composites

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Sponsor:
National Institute of Standards and Technology

Objective
To develop quantitative procedures for assessing the impact of fire on structural composites.

Problem
Composites are highly attractive materials for a wide variety of structural uses. However, the organic resins that comprise roughly 50% of these materials are flammable and subject to loss of strength in a fire. The available quantitative information on these concerns is limited. Two research issues need resolution:

1. Impact of composite formulation. Resin chemistry is foremost here but fiber form, loading and distribution may also interact significantly with flammability behavior through thermal properties and rate of gasification. The ability of current models of fire growth to deal with the practical ranges of these variables needs to be assessed.

2. Impact of structural configuration. Current models and data only deal with a single flat surface. Concave or convex surfaces of more complex structural members introduce new thermal issues that can influence fire growth potential. The possible variations in structural member shape are unlimited so only general guidelines, based on modeling and experiment, are possible.

While all of the preceding considerations have been enumerated in the context of fire growth, they bear equally on the issue of the strength of composites during fire exposure. An additional complication is that fire growth and composite reaction to loading during a fire may interact since ply delamination phenomena influence composite thermal properties.

Approach
During FY 1995, BFRL will focus its effort on understanding fire growth in the absence of structural loading. The first issue to be addressed is the role of fiber loading and the protective abilities of available surface coatings. BFRL's Cone Calorimeter and lateral flame spread devices will be used to derive quantitative measures of ignitability, heat release rate and opposed-flow flame spread characteristics. The thermal conductivity of these materials, before and after fire exposure, will be measured. The potential impact of the observed range of the variables on upward flame spread will be assessed in the context of BFRL's models of this process, with limited experimental checks. The composites will be based on a vinyl ester resin and woven glass.

Recent Results
New project.

Radiative Ignition and Subsequent Flame Spread Over Cellulosic Materials

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

Objective
To develop new models that describe the characteristics of heat transfer and flame spread along a narrow diameter polymer rod in microgravity.

Problem
This project is one of NASA Microgravity Science projects to enhance understanding of combustion science by taking unique advantage of a microgravity environment. Knowledge is lacking about the ignition and subsequent flame spread over a thermally thin cellulosic material in a microgravity environment to a thermally thick material.

Approach
During FY 1995, BFRL will expand current multi-dimensional code (axisymmetric, two-dimensional, and three-dimensional) to include thermally thick materials. Two environmental conditions are being studied: one in a quiescent environment and the other in slow forced flows. Validation experiments are planned for a shuttle flight in 1996. The experimental design, fabrication, experimental parameters and procedures are being developed with NASA's Lewis Research Center. Exploratory experiments with a similar hardware will be conducted using the Japanese 10 seconds drop tower in March 1995. A new model describing heat transfer and flame spread along a narrow diameter polymer rod in microgravity will be developed.

Recent Results
Nakabe, K., McGrattan, K. B., Kashiwagi, T., Baum, H. R., Yamashite, H., and Kushide, G., "Ignition and Transition to Flame Spread Over a Thermally Thin Cellulosic Sheet in a Microgravity Environment," *Combustion and Flame*, **98**; 361-374, 1994

McGrattan, K.B, Kashiwagi, T., Baum, H.R., and Olson, S.L., "Ignition and Wind Effects on the Transition to Flame Spread in a Microgravity Environment," submitted to *Combustion and Flame*.

Combustion of a Polymer (PMMA) Sphere in Microgravity

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Sponsor:
National Aeronautics and Space Administration
Lewis Research Center

Objective
To determine the burning rates of PMMA spheres in a low gravity environment under various ambient conditions.

Problem
The need to use polymeric materials that may be flammable cannot be totally eliminated aboard the space shuttle or the future manned permanent space-station. Knowledge is required to understand potential fire threats caused by the presence of polymeric materials. The use of spherical geometry has many advantages - a spherical flame, which is one-dimensional, is amenable to simple mathematical analysis and facilitates a detailed examination of the many interesting phenomena associated with the combustion of a solid phase material without involving the complications of flame-spread, which is an active research area.

Approach
Reduced gravity is achieved by performing the experiments aboard a learjet, a DC-9 or a KC-135 aircraft flying a parabolic trajectory. During FY1995, BFRL will evaluate different ignition techniques to determine the optimal method for igniting a PMMA sphere. A mechanism for deploying an unsupported sphere will be developed. Experiments using suspended spheres will be conducted. Suspended spheres will be obtained by supporting the spheres at the tip of a thermocouple. Results will be compared with those obtained under normal gravity condition. NASA will provide technical assistance to the initial design phase of the experiment and will conduct flight experiments.

Recent Results
New project.

Lean Flammability Limit as a Fundamental Refrigerant Property

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Sponsor:
Air-Conditioning & Refrigeration Institute

Objective
To demonstrate that a counterflow burner can be used to establish the lean flammability limit of HFC-32 and identify the critical flammability ratio of HFC-32/HFC-125 mixtures.

Problem
A critical element of the risk analysis of alternative refrigerants is the lean flammability limit, which is currently determined according to ASTM E681-85. Variations in flammability limits are observed depending on the initial conditions chosen for conducting the test. There is a need to eliminate these variations and to establish invariant, fundamental lean flammability limits which can be attributed to refrigerant mixtures in a manner similar to fundamental thermodynamic properties like enthalpy of formation and adiabatic flame temperature.

Approach
During FY 1995, BFRL will modify an existing burner facility will be modified to operate in a symmetrical, adiabatic mode, with independent control of the gaseous refrigerant and air flows. The burner will be calibrated using methane CH_4 to ensure that the facility is capable of reproducing the published values of the lean flammability limit. Stoichiometric flames of HFC-32 and air will be examined. The flow velocity will be varied to establish the extinction strain rate and to identify the dynamic range of the burner using a less flammable fuel. The fuel/air equivalence ratio will be varied about the stoichiometric point and the strain rate will be adjusted to identify the most robust mixture (normally slightly rich for hydrocarbon flames). The lean flammability limit of HFC-32 will be found using the zero strain rate extrapolation method. The critical flammability ratio can be found either by slowly increasing the fraction of HFC-125 in

the HFC/air mixture while maintaining the overall equivalence ratio and strain rate fixed, or by fixing the concentrations of all constituents and slowly increasing the strain rate by reducing the spacing between the upper and lower burners.

Recent Results
New project.

Furniture Flammability

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Sponsor:
National Institute of Standards and Technology

Objective
To develop an initial set of guidelines for furniture manufacturers to design upholstered furniture with low rate of heat release.

Problem
The flammability of upholstered furniture continues to be a substantial problem in residential and public occupancies. This is a smoldering and a flaming ignition problem. The smoldering problem, primarily in residences, is currently being addressed by a voluntary industry program and by consideration of regulations on cigarette ignition propensity. The flaming ignition problem and its consequences in terms of heat release are being addressed in differing manners which depend on occupancy in which the furniture is used. California Technical Bulletin 133 requires that public occupancy furniture respond to an arson-like 18 kW igniter with a peak heat release rate of 80 kW or less. This severe test has encouraged the development of barrier technology (a protective fabric layer between fabric and foam); the technology is sufficiently cost effective in this context that it is not meeting strong industry resistance. However, there are so many variables in furniture design that only very large companies are able to perform the large number of empirical tests needed to assure compliance across their product line. This, coupled with the technical attractiveness of barriers for controlling heat release behavior in any upholstered furniture (including residential), has prompted BFRL's ongoing efforts to develop a quantitative understanding of the various factors that control the heat release curve in a CB 133 test environment using mock-ups containing various barrier fabrics.

Approach

During FY 1995, BFRL will study the relationships between small-scale test data (Cone Calorimeter, LIFT) and full-scale mock-up behavior. Currently, the focus is on mock-ups containing a barrier fabric. Results of related studies such as by the Association for Contract Textiles and the European Community will be considered as BFRL develops its guidelines for industry. Having completed in FY 1994 such a study of barrier effects for several fabrics in a fixed mock-up geometry, BFRL will vary the geometry systematically. This calls for a series of mock-ups involving a very limited material selection but wide variations in seat, seatback and arm cushion dimensions. The design rules that emerge from this research will be tested against real furniture, both isolated and in a room context.

This program contributed substantially toward the increasing acceptance of CB 133 as a meaningful basis for assessing the heat release hazard of a furniture fire.

Recent Results

Cleary, T., Ohlemiller, T., and Villa, K., "The Influence of Ignition Source on the Flaming Fire Hazard of Upholstered Furniture," *Fire Safety Journal*, **23**, p79, 1994

Ohlemiller, T. and Shields, R., *Behavior of Mock-ups in the California Technical Bulletin 133, Test Protocol: Fabric and Barrier Effects*, NISTIR, National Institute of Standards and Technology, (in review)

Evaluation of Fire Barrier Performance

Principal Investigator:
Kenneth D. Steckler
Fire Science Division
301-975-6678

Sponsor:
U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulations

Objective

To provide technical expertise in reviewing and evaluating for NRC staff technical issues related to fire-barrier systems used in nuclear power plants.

Problem

The NRC requires technical assistance for evaluating the fire performance of certain fire barrier systems intended to satisfy the fire protection of safe shutdown capability as specified in certain NRC documents.

Approach

During FY 1995, BFRL will perform reduced-scale fire-endurance tests on certain fire-barrier materials used in nuclear power plants. BFRL will make arrangements to have some of the materials tested according to ASTM E-84 at a commercial laboratory and chemical analysis performed on pre-test specimens by NIST's Chemical Science and Technology Laboratory.

BFRL will research the development of the ASTM #E-119 temperature-time fire-severity curve, analyze past efforts to develop curves for other specific applications, and assess the feasibility of developing and implementing nuclear-power-plant-specific fire-severity curves.

Recent Results

Steckler, K.D., *Pilot-scale Fire-Endurance Tests of Fire-Barrier Materials, Blankets, and Panels,* Report of Test FR3994, National Institute of Standards and Technology, March 1994

Calibration Facility for Particle Size and Concentration

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

Sponsor:
National Institute of Standards and Technology

Objective
To develop a facility for accurately measuring particle size and concentration and for depositing monodisperse particles of specified size, number, and chemistry on calibration artifacts.

Problem
The detection, quantification and characterization of particulate contamination on semiconductor surfaces is essential to advanced semiconductor manufacturing. The present practical limit for particle detection is 0.1 μm diameter. The National Technology Roadmap for Semiconductors calls for the ability to detect and quantify particles with 0.06 μm equivalent diameter by 2001. There is a need for accurately sized monodisperse particles in the size range from 0.07 μm to 0.2 μm for developing and calibrating improved wafer scanners.

Approach
During FY 1995, BFRL will create a laboratory with state-of-the-art instrumentation for generating monodisperse aerosols, for accurately characterizing the size and concentration, and for depositing the particles on a calibration artifact. Key instruments for the laboratory are constant output nebulizers, an electrical mobility analyzer, condensation nucleus counter, aerosol electrometer, bipolar charger, cascade impactor, and optical microscope. The basic approach is to nebulize a suspension of spheres in water, evaporate the water, classify the particles with an electrostatic classifier, and measure the concentration with a condensation nucleus counter. A major element in the facility will be the calibration of the basic physical quantities including the flows and the voltage.

Recent Results
New project.

RECENT GRANTS - MATERIALS FIRE RESEARCH

1. A Study of Entrainment and Flow Patterns in Pool Fires Using Particle Imaging Velocimetry

Principal Investigator:
Jay P. Gore
Thermal Sciences and Propulsion Center,
Purdue University
West Lafayette, IN 47907-1003
317-494-1452

Objective
To measure entrainment flow field around pool fires using Particle Imaging Velocimetry (PIV) in order to resolve the large discrepancies between existing data and correlations. Utilize the entrainment data to demonstrate the capabilities and limitations of a fundamentally sound fire induced flow field model (Baum-McCaffrey model) developed at BFRL.

Problem
Rate of air entrainment into pool fires affects their heat feedback, burning rate and toxic material production. Empirical correlations of entrainment rates show up to an order of magnitude scatter and are therefore not reliable for use in fire prediction models.

Approach
Flow field induced by pool fires in a quiescently seeded, screened enclosure with well-defined boundary conditions is examined. In FY 1992 and 1993, it was discovered that the fire induced flow field did not allow a simple definition of the entrainment rate as the change of mass flow rate (from zero to infinite radius) in the axial direction with height. In fact, a finite surface (or radius) over which the entrainment occurred had to be explicitly or implicitly defined. While the classical definition required integration to infinite radius, several suggestions regarding the proper specification of a finite surface were quickly made by members of the combustion and fire communities (Zhou and Gore, 1995). These included: (1) the visible flame surface, (2) the turbulent interface, and (3) the vorticity interface. However, none of the experimental data and correlations in the literature defined or identified the interface. Thus the reasons for the order of magnitude differences became clear. At this point it was recognized that the idea of a universal correlation for entrainment rates should be replaced by one that considered the basic physics of the fire induced flow field correctly but did not involve a direct numerical simulation of the turbulent reacting flow.

The kinematic approach developed by Baum and McCaffrey is based on such an idea. Thus attention has been focused on the utilization of this model as the recipe for calculation of the fire induced flow field and the resulting entrainment rate. The model inputs include the heat release rate distribution, the fire plume vorticity distribution and a specification of the type of boundaries (solid wall or floor or free atmospheric air) existing on all sides of the fire. Given these inputs, the model is capable of predicting the entire fire induced flow field in a matter of seconds on a personal computer and therefore is no more complicated than using a correlation if one existed. The user can find the mass flow rate into any computation domain of interest.

The efficacy of such an approach was demonstrated with excellent qualitative results in Zhou et al. (1995). By considering fires with and without a floor, the dramatic difference in the flow field caused by a "simple" change in boundary conditions was shown. Quantitative demonstration must await improved heat release rate and vorticity measurements inside the fire.

2. Modeling of Combustion, Fluid Mechanics, and Radiation in Buoyant Turbulent Fires

Principal Investigator:
Professor O.A. Ezekoye and Z. Zhang, Doctoral Candidate
Department of Mechanical Engineering
The University of Texas at Austin
Austin, TX 78712

Objective
The continued development of appropriate strategies for fire safety engineering will rely upon both experimental and computational data on fires. Adequate computational

formulations of fire physics are still very much in the development stages. Among the various computational approaches being developed to model fires becoming increasingly clear that the method for future computations will be Large Eddy Simulations (LES). In Large Eddy Simulations, the large scale dynamics of a flow field are resolved on the available scales and subgrid scale models are introduced into the simulation to model phenomena occurring below grid scales. For fire modeling, these phenomena include the combustion processes and also some aspects of the radiative transfer phenomena.

In our research program we are developing a subgrid scale Lagrangian flamelet (thermal element) model to be used in conjunction with LES fire codes. As with all flamelet strategies, the laminar nature of the flamelet implies that direct computation of the necessary combustion reactions can be performed for any level of detail required. Thus, reaction chemistry can be specified to be either detailed or simplified. Various levels of chemical mechanism specification are investigated in our project. An appropriate level of physical processes must be specified on the thermal element such that the radiation field from asimulated fire flow field may be accurately modeled. This implies that both the soot species and temperature distributions should be accurately computed on the flamelet.

The Lagrangian element has also been used to aid in the clarification of processes such as radiative extinction of diffusion flames. A theoretical analysis for transient radiative extinction was formulated in the context of high activation asymptotics using the formalism first introduced by Fendell and Linan. The effects of transient processes within diffusion flames were described using a propane mechanism with aphenomenological soot model. Subsequently, we've focused on fuel specific computations with well specified (within the literature) reaction mechanisms for fuel species (detailed and reduced) as well as for soot species (Leung-Lindstadt). Recently, the combustion history of acetylene-air diffusion flames was computed using two modeling strategies that are generally assumed to yield the same results (state relationships and finite rate chemical mechanisms). The result of these computations was the construction of unsteady computational state relationships. It was found that the effects of finite rate chemistry were quite important in describing the combustion process in cases where the net radiative loss fraction was large, as well as points near ignition and extinction. The implication is that there will be situations where there will be large deviations from the state relationship predictions of fuel burnout.

Recent Results

O.A. Ezekoye and Z. Zhang, "Modeling of a Lagrangian Flamelet with Radiation Interaction," *Combustion Science and Technology*, accepted 1995.

Z. Zhang and O.A. Ezekoye, "Computational Study of State Relationships for Acetylene-Air Diffusion Flames with Soot Radiation," to appear in HTD bound vol. *ASME NHTC*, Portland, OR, August, 1995.

H.R. Baum, O.A. Ezekoye, K.B. McGrattan, and R.G. Rehm, "Mathematical Modeling and Computer Simulation of Fire Phenomena," *Theoretical and Computational Fluid Dynamics*, vol 6., 1994.

Z. Zhang and O.A. Ezekoye, "Combustion of a Spherical Diffusion Flame in a Radiative Field," HTD bound vol. 296 *ASME IMECE*, Chicago, Ill December 1994.

H.R. Baum, O.A. Ezekoye, K.B. McGrattan, and R.G. Rehm, "Large Eddy Simulation of Fire
Phenomena," *Ninth Symposium on Turbulent Shear Flows,* Kyoto, Japan, August 1993.

O.A. Ezekoye and H.R. Baum, "A Lagrangian Element Analysis of Combustion Processes in Fires," Central & Eastern States Sections of the Combustion Institute joint meeting, New Orleans, LA, 1993.

3. Fire Growth Models for Materials

Principle Investigator:
James Quintiere, Prof.
Fire Protection Engineering
University of Maryland
College Park, MD
301-405-3993

Objective

The proposed research seeks to determine transient burning rate models that can be used to generalize data from the Cone Calorimeter. This will involve several models built upon a consistent framework. Each model will be appropriate to a specific *Class of Materials*.

Problem

Bench-scale test methods developed by the BFRL fire program have become standards, and offer the potential for scientifically based assessments of flammability. These test methods, based on the Cone Calorimeter and the LIFT apparatuses, provide material data on ignition, flame spread and burning or energy release rate for small samples. There is a need for utilizing these data to describe the fire hazard of materials. The problem is to identify the form of these data consistent with general models for ignition, burning rate, and spread.

Approach

A model with good accuracy has been successfully demonstrated for thermoplastic-like materials. This is based on an integral method that leads to a closed form analytical solution for constant heat flux. As a result, applications of that model will be examined. First, it has been suggested to examine the case of step changes in irradiance to see if the current model can still yield accurate results in the Cone Calorimeter. This will investigate the ability of the model to handle sudden changes in fire heat flux. Second, the effect of transient burning rate on upward flame spread prediction will be examined. This will test the current simplifying assumption of quasisteady burning used in fire growth models. Third, the model will be extended for charring materials, maintaining the same simplicity as the thermoplastic model. The effect of char will be considered as a growing insulated layer. Useful data formats will be developed for the Cone Calorimeter to provide the basis for generalized solutions. In this way, it is intended to build upon Cone type data for general fire hazard predictions.

Recent Results

Hopkins, D. Jr., *Predicting the ignition Time and Burning of Thermoplastics in the Cone Calorimeter,"* MS Thesis, Department of Fire Protection, U. Of MD, May 1995.

J. Quintiere and N. Iqbal, "An Approximate Integral Model for the Burning Rate of a Thermoplastic-like Material," *Fire and Materials*, Vol. 18, 89-98, 1994.

N. Iqbal and J. Quintiere, "Flame Heat Fluxes in PMMA Pool Fires," *SFPE Journal*, Vol. 6, No. 4, 153-162, 1994.

B.T. Rhodes and J.G. Quintiere "Burning Rate and Heat Flux for PMMA in the Cone Calorimeter," presented at the Fire and Materials Conference, Crystal city, VA, October, 1994; and submitted to the *Fire Safety Journal*.

J.F. Quintiere, "Estimating the Fire Growth on Compartment Interior Finish Materials," SFPE Engineering Seminars, *SFPE*, San Francisco, CA, May 16-18, 1994.

J. G. Quintiere, "Fire Tests and Hazard Evaluation," 7th International Research and Training Seminar on *Regional Development Planning For Disaster Prevention-Improved Firesafety Systems in Developing Countries* - 17 October 1994 - Tokyo, Japan; and *The International Conference on Fire and Smoke Resistant Materials*, National Academy of Sciences, November 8-10, 1994, Washington, D.C.

FIRE SCIENCE DIVISION

FIRE SENSING AND EXTINGUISHMENT

Advanced Fire Detection

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

Sponsor:
National Institute of Standards and Technology

Objective
To measure the chemical and physical products formed very early in industry-accepted standard fires, and to design a universal test bed for evaluating the effectiveness of conventional and novel fire sensors.

Problem
A new generation fire detection system is needed in order to protect American homes and industrial production capability. It is necessary to sense a fire and its location and suggest the correct suppression strategy before the fire does significant damage and without generating false-fire alerts. The disparity in time scales between when a threat needs to be identified (seconds) and how often a true fire event occurs (once in tens of years), along with the variability in geometry, content and occupancy of the space, impose great demands on the system, especially when cost is an overriding constraint.

Approach
During FY 1995, BFRL will perform two activities:

1. Perform experimental measurements of the chemical and physical products formed very early in a fire. This activity follows from BFRL's review of fire products performed in FY 1994, which identified significant holes in the database. Measurements of temperature, infrared radiation, particulates, and stable species will be made within the plume directly above standard UL and EN fires before the heat release exceeds 50 kW.

2. Develop a universal fire emulator/detector evaluator (FE/DE) in which the velocity, individual gas species, particulate matter and temperature will be controlled as a function of time. Interaction will take place with representatives from the fire detector systems industry, UL, NFPA and FM to more adequately understand their requirements for such a device and how it can be best utilized to discriminate satisfactory from unsatisfactory detection systems and hasten the best ideas to market.

Recent Results
Grosshandler, W. "Towards the Development of a Universal Fire Emulator/Detector Evaluator," 10th Internationals Konferenz Uber Automatische Brandentdeckong April 1995 *AUBE '95* Proceedings, Duisburg, Germany, April 1995.

Grosshandler, William L., *A Review of Measurement and Candidate Signatures for Early Fire Detection*, NISTIR 5555, National Institute of Standards and Technology, 1995.

Grosshandler, W., and Jackson, M., "Acoustic Emission of Structural Materials Exposed to an Open Flame," *Fire Safety Journal 22*, 209-228, 1994.

Grosshandler, W., and Braun, E., "Early Detection of Room Fires Through Acoustic Emission," *Fourth International Symposium on Fire Safety Science*, Ottawa, June 13-17, 1994.

Smith, R.L., *Performance Parameters of Fire Detection Systems,* NISTIR 5439, National Institute of Standards and Technology, Gaithersburg, MD, June 1994.

Grosshandler, W., "Novel Fire Detection Concepts," *NFPA 98th Annual Meeting,* May 1994.

Related Grants

"Development of an Economical video-Based Fire Detection and Location System," Plumb, O.A., and Richards, R.F., Washington State University.

"Smart Fire Detection Using Neutral Networks," Milke, J.A., and McAvoy, T.J., University of Maryland.

"Advanced Infrared Systems for Detection of Building fires," Serio, M.A., Advanced Fuel Research, East Hartford, CT, Phase 1 SBIR.

"Decision-theoretic Control of Centralized Fire-alarm Systems, Knowledge industries," Shwe, M., Palo Alto, CA, SBIR Phase 1.

"Advanced Fire Detection Based on Combined Smoke and CO Sensors," Roby, R., Hughes Associates, Inc., Columbia, MD, SBIR Phase II.

Low Environmental Impact Fire Extinguishment

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

Sponsor:
National Institute of Standards and Technology

Objective

To develop the physical and chemical principles leading to identification and use of an optimal set of clean, effective, environmentally safe fire suppressants, and to demonstrate to the suppression system manufacturing and user industries green alternatives to halon-based technologies for total flooding and streaming applications.

Problem

Fire protection of facilities requires suppressants that will not harm the environment. Current alternatives to the halons have some ozone depletion potential and/or are significant greenhouse gases. Other approaches to fire protection have features that make them less desirable from an operational standpoint than the halons they are to replace. For example, sprinklers can cause excessive water damage to a structure, dry-powder suppressants leave a residue, and fluorocarbons produce corrosive gases after passing through a flame. Requiring an alternative which has the low toxicity of many halons constrains selection choice of chemicals even more, suggesting that improved means for storage and delivery of less effective (but inherently safe) materials need to be addressed.

Approach

During FY 1995, BFRL will continue researching the extinction mechanisms of flames; the dynamics of transport of suppressants to the fire zone; a way to screen potential aqueous, gaseous and particulate agents; and the local and global environmental impact resulting from release of the suppressant into a fire and during installation, maintenance, and false discharge. Performance of the entire fire suppression system will be considered over the extended

period of this research. Efficient storage of the agent, delivery to the space being protected, and interaction of the agent with the fire will be a major focus of the research. Means to evaluate alternatives to halons on a bench-scale which reliably predict full-scale performance will be developed. Inert gas systems and fine water sprays are the only alternatives currently known to have no detrimental environmental impacts. Methods to enhance their effectiveness as fire fighting agents and overcome their deficiencies (large quantity requirements and possible asphyxiation for inert gases, and significant collateral damage for water sprays) will be investigated. Other currently proposed halocarbons are saddled with known or potential negative impacts on stratospheric ozone depletion or global warming, and it is unlikely that new compounds from this family will have both short atmospheric lifetimes and zero ODP. Approaches to more precisely predict the chemistry of alternative compounds in the atmosphere and to hasten their conversion to the most environmentally-friendly end-state will be sought.

Recent Results

New project.

Fire Suppression Chemistry

Principal Investigator:
Gregory T. Linteris
Fire Science Division
301-975-2283

Sponsor:
National Institute of Standards and Technology

Objective

To provide a fundamental understanding of the flame extinguishing action of inert and chemical flame inhibitors to facilitate the development of the next generation of suppression agents and technologies.

Problem

Fire suppressants and their application methods should be effective, fast-acting, economical, have low toxicity, permit a habitable environment during suppression, and cause no collateral damage to the protected space. Existing suppressants, however, are non ideal: water from sprinklers can cause excessive damage; powdered suppressants leave a residue; and the currently favored suppressants, the halocarbons, produce corrosive gases after passing through a flame. There exists a continuing need for better suppressants and suppression methods, but limited scientific understanding of how existing chemical inhibitors act to extinguish flames hinders development of new agents.

Approach

During FY 1995, BFRL will research the chemical and physical mechanisms of existing suppressants through laboratory measurements of both global properties and detailed species concentration profiles. In order to understand the simultaneous thermodynamic, fluid mechanic and chemical kinetic effects of the inhibitors, the experimental results will be interpreted through numerical calculations of the flame structure using existing well developed codes. These experimental and modelling 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. A new counterflow burner for flame inhibition studies

will be constructed. Work will be completed on assembling a chemical kinetic mechanism for hydrofluorocarbon inhibitors (including C2 chemistry), and flame experiments are planned to reveal the means by which Fe(CO)5 acts so effectively.

Recent Results

Linteris, G.T., and Truett, L.F., "Burning Rates of Premixed Methane-air Flames Inhibited by Fluorinated Hydrocarbons," Halon Options Technical Working Conference, Albuquerque, NM, May 3-5, 1994.

Linteris, G.T., King, M.D., Liu, A., Womeldorf, C., and Hsin, Y.E., "Acid Gas Production in Inhibited Diffusion Flames," Halon Options Technical Working Conference, Albuquerque, NM, May 3-5, 1994.

Seshadri, K., and Ilincic, N., "The Asymptotic Structure of Nonpremixed Methane-air Flames with Oxidizer Leakage of Order Unity," submitted for publication in *Combustion and Flame*, Feb. 1994.

Linteris, G.T., and Truett, L.F., "Inhibition of Premixed Methane-air Flames by Fluoromethanes," submitted to *Combustion and Flame,* October 1994.

Linteris, G.T., "Effect of Inhibitor Concentration on the Inhibition Mechanism of Fluoromethanes in Premixed methane-air Flames," accepted to Halon Replacements: Technology and Science, American Chemical Society Symposium Series, (Eds Miziolek, A.W., and Tsang, W.), Washington, D.C., 1995

Linteris, G.T., "Numerically Predicted Frame Structure and Burning Rates of Premixed CO-Ar-O^2-H^2 Flames Inhibited by CF_3H," submitted to Combustion and Flame, February 1995.

Hochgreb, S., Hsin, E.Y., and Linteris, G.T., "Laminar Flame Speeds of CF_3H-Propane-air Mixtures at Elevated Pressures," NIST Annual Conference on Fire Research, October 1994.

Linteris, G.T., and Truett, L.F., "Burning Rate of Premixed methane-air Flames Inhibited by Fluorinated Hydrocarbons," NIST Annual Conference on Fire Research, October 1994.

Linteris, G.T., and Truett, L.F., "Experimental and Numerical Burning rates of Premixed Methane-air Flames Inhibited by Fluoromethanes," Paper #068, *Eastern States Section Meeting*, Clearwater Beach, FL, December 1994, the Combustion Institute, Pittsburgh, PA.

Linteris, G.T., and Gmurczyk, G., "Inhibition of Premixed Methane-air Flames by Iron Pentacarbonyl," submitted to *15th International Colloquium on the Dynamics of Explosions and Reactive Systems,* July 30-Aug 4, 1995, Boulder, CO, the Combustion Institute, Pittsburgh, PA.

Trees, D., Grudno, A., Ilincic, N., Weissweiler, T., and Seshadri, K., "Experimental and Numerical Studies on Chemical Inhibition of Methane-air Diffusion Flames by CF3Br and CF3H," *Western States Section Meeting*, April 23-26, 1995, San Antonio, TX, The Combustion Institute, Pittsburgh, PA

Seshadri, K. and Ilincic, N., "The asymptotic structure of inhibited nonpremixed methane-air flames," submitted for publication in *Combustion and Flame*, April 1994.

Related Grants

"Chemical Inhibition of Methane-Air Diffusion Flames," Seshadri, T., University of California, San Diego.

"Basic Research on Fire Suppression," Atreya, A., University of Michigan.

Agent/System Compatibility for Halon 1301 Aviation Replacement

Principal Investigator:
Richard G. Gann
Fire Science Division
301-975-6866

Sponsor:
Department of the Air Force
Wright-Patterson Air Force Base
Survivability Enhancement Branch

Department of the Army
Tank Automotive Command

Objective
To evaluate 12 USAF-specified candidate halon 1301 replacements for compatibility with flight systems, people, and the environment; recommend 3 candidates for further examination; and perform longer-term evaluations 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 committed to begin implementing an alternative at the end of FY 1995. Screening of potential alternatives is needed to narrow the number of chemicals for full-scale testing.

Approach
During FY 1995, BFRL, working with NIST's Materials Science and Engineering Laboratory, will perform bench-scale determinations of non-volatile residue; stability during long-term storage; compatibility with 8 metals, 5 elastomers, and 3 lubricants; develop prediction method for HF formation during suppression; determine potential human exposure levels and summarize environmental regulations.

Recent Results
Grosshandler, William L., Gann, Richard G., William M. (editors), *Evaluation of Alternative In-flight Fire Suppressants for Full-scale Testing on Simulated Aircraft Engine Nacelles and Dry Bays*, NIST SP 861, National Institute of Standards and Technology, April 1994.

Suppression of High Speed Turbulent Flames in a Deflagration/Detonation Tube

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

Sponsors:
Department of the Navy
Air Systems Command

Department of the Air Force
Wright Laboratory

Objective
To determine the effectiveness of HFC-125 and CF_3I, relative to FC-218, in suppressing turbulent flames in shocked propane/air mixtures, and to determine if pressure ratios less than 7:1 are sufficient to produce enhanced pressure build-up during suppression.

Problem
HFC-125 has been observed to produce very high over-pressures under certain conditions in the deflagration/detonation tube apparatus. It is not known if a dangerous situation could arise under different sets of achievable conditions, or to the extent to which the previous experiments represent a realistic threat scenario. A related, but less severe, problem exists with CF_3I, in which small amounts of the chemical effectively inhibit the quasi-detonation; but as the concentration is increased, pressures increase to a point exceeding the uninhibited situation. It is unknown why this occurs, making it impossible to predict the performance of CF3I under substantially different conditions.

Approach
During FY 1995, BFRL will continue analyzing its data taken in FY 1994, reviewing it for consistency and preparing a final report describing the experiments.

Recent Results
Gmurczyl, G., and Grosshandler, W., *Suppression of High Speed Turbulent Flames in a Detection/Deflection Tube*, NISTIR (in review), National Institute of Standards and

Technology, April 1995

Gmurczyl, G., Grosshandler, W., "Suppression of High-speed Flames with C1-halocarbons," *Twenty-fifth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA (in press), 1995

Gmurczyl, G., Grosshandler, W., and Lowe, D., "Suppression Effectiveness of Extinguishing Agents Under Highly Dynamic Conditions," *Fire Safety Science - Proceedings of the Fourth International Symposium,* Kashiwagi, T. Ed, IAFSS USA, pp 925-936, 1994

Suppression of Simulated Engine Nacelle Fires

Principal Investigator:
Anthony Hamins
Fire Science Division
301-975-6598

Sponsor:
Department of the Air Force
Wright Laboratory
Survivability Enhancement Branch

Department of the Navy
Naval Air Systems Command

Department of the Army
Tank Automotive Command

Federal Aviation Administration
FAA Technical Center

Objective

To document guidelines for fire suppression system performance based on improved understanding of the influence of various parameters on fire suppression in engine nacelles.

Problem

An engine nacelle encases the jet engine compressor, combustor, and turbine. A nacelle fire is typically a turbulent diffusion flame stabilized behind an obstruction in a moderately high speed air flow. The most likely source for a fire in the nacelle are fuel lines carrying jet fuel or hydraulic fluid, that can feed the fire either as a spray or as a pre-vaporized gas. Temperatures as high as 150 ° C are common in normal operating engine nacelles.

Extinguishment occurs when a critical amount of agent is transported to the flame, where it is entrained into the primary reaction zone. The extinction process is affected by a number of parameters, including the velocity of the air flow, the type and quantity of fuel, the system temperature, agent properties and concentration, and the flow field geometry (e.g., the location of obstacles in the flow field).

Halon 1301 (CF_3Br) has been used as the fire extinguishing agent for protecting aircraft

engine nacelles because of its many positive attributes. However, its production will cease at the end of 1995, leaving many aircraft needing an alternative. The Air Force will soon begin testing three candidate alternatives to halon 1301 in its full scale Engine Nacelle Test Facility. There are, however, a number of different aircraft and operating conditions for which a new suppressant is needed. Because testing cannot be performed for all possible aircraft and conditions, knowledge is needed which will provide guidance in the extension of the full-scale data to untested systems and conditions.

Recently, the Air Force funded an experimental study which involved simulating an idealized engine nacelle fire. A coaxial turbulent spray burner was used, with jet fuel and hydraulic fluid as the fuels with the air at ambient and elevated temperatures. This project will extend that study to a broader range of suppression and re-ignition conditions, typical of in-flight engine nacelles.

Approach

During FY 1995, BFRL will continue making flame suppression measurements in its modified turbulent spray burner. Agents tested include CF_3I, HFC-125, and HFC-227. The effect of various flow parameters on the amount of agent needed to suppress a fuel-spray fire will be tested. The parameters being tested include system pressure, air, and agent temperatures, air velocity, and agent delivery rates and duration. The effectiveness of ignition suppression by the agents will also be tested.

A computational fluid dynamic model using FLOW3D (a commercial package computer model that simulates fluid dynamics and heat transfer using finite element difference approach) of conditions in the engine nacelle was developed in FY 1994. Information about criticality of the number, placement, and orientation of agent injection nozzles and the rate of gaseous agent injection will be determined. The flow field model will be experimentally validated to demonstrate the capability of computational fluid dynamics to model gaseous agent concentration in a generic engine nacelle.

The knowledge gained from this research will be integrated into guidance tools to assist suppression system designers. Information about concentration/duration requirements as a function of fire zone conditions will be included. Results will be used to give guidance for adjusting the needed concentration of candidate fire suppressants over a range of engine nacelle fire conditions.

Recent Results

Presser, C., Hamins, A., Vazques, I., and Grosshandler, W., "Suppression of Simulated Engine Nacelle Fires," Presented at the Annual AICHE Meeting, San Francisco, CA, November 1994.

Grosshandler, W., Presser, C., Lowe, D., and Rinkinen, W., "Assessing Halon Alternatives for Aircraft Engine Nacelle Fire Suppression," to appear in *J. Heat Transfer*, 1994.

Vazquez, I., Grosshandler, W., Rinkinen, W., Glover, M., and Presser, C., "Suppression of Elevated Temperature Hydraulic Fluid and JP8 Spray Flames," to appear in the *Proceedings of the Fourth International Symposium on Fire Safety Science*, 1994.

Grosshandler, W., Lowe, D., Rinkinen, B., Presser, C., "A Turbulent Spray Burner for Assessing Halon Alternative Fire Suppressants," *ASME Paper No 93-WA/HT-23*, 1993.

Halon 1301 Surrogates for Engine Nacelle Fire Suppression System Certification

Principal Investigator:
Carole Womeldorf
Fire Science Division
301-975-4415

Sponsor:
Department of the Navy
U.S. Naval Engineering Center

Objective
To determine the physical properties which dominate the dispersion process, experimentally test and recommend an environmentally acceptable candidate for use in simulating the dispersion of ambient temperature halon 1301 in an aircraft engine nacelle.

Problem
Existing Navy aircraft fire suppression systems require certification to ensure the fire-fighting agent is present in sufficient quantity and for a long enough period to extinguish a possible fire. In the past, certification was accomplished by discharging the halon 1301 and measuring its concentration over time at various locations in the nacelle. This procedure is now not acceptable because (a) the reserves of halon 1301 are limited since (no longer in production), and (b) halon 1301 released to the atmosphere contributes to unwanted depletion of stratospheric ozone. An alternative chemical is needed to fill the certification role formerly by halon 1301.

Approach
During FY 1995, BFRL will coordinate chemical tests with Walter Kidde Aerospace in their full-scale fire bottle discharge facility of their small-scale aircraft engine simulator. These tests will be based on data from a wide range of chemicals reviewed by BFRL during FY 1994 for physical similarity to halon 1301 to identify prospective candidates for discharge certification. These will be compared to pipeline flow and spray discharge experiments performed in BFRL facilities. A report will be prepared documenting the search for surrogates and conclusions on agents for certifying field system performance.

Results
Reports have been provided to the sponsor.

Optimization of Aircraft Fire Suppression System Discharge

Principal Investigator:
Jiann C. Yang
Fire Science Division
301-975-6662

Sponsor:
Department of the Air Force
Wright Laboratory, Flight Dynamics Directorate

Department of the Navy
Naval Air Systems Command, Subsystem Branch

Department of the Army
Army Aviation and Troop Command

Federal Aviation Administration
Technical Center

Objective
To provide discharge test data for four recommended agents in simulated drybay and engine nacelle applications and to establish engineering correlations for pressure drop estimation in delivery piping systems.

Problem
None of the gaseous agents being screened for the Air Force has exhibited the chemical activity of halon 1301. The mass concentrations of many of the agents needed to suppress the laboratory flames are closely clustered. The thermodynamics properties of these agents, however, vary significantly.

Approach
During FY 1995, BFRL will develop temperature-pressure data on the recommended fluids, pure and in mixtures with nitrogen to fit the binary interaction coefficients in the computer program PROFISSY (a computer program to calculate pressure-temperature characteristics of the fire extinguisher containing the four selected agents). Discharge rates of the four agents directly into an unconfined space (to simulate dry bay applications) will be compared under different initial bottle conditions and release mechanisms. Discharge simulation using the computer code KIVA or CONCHAS SPRAY also will be carried. The performance of the recommended fluid agents flowing through various piping geometries and components in transient operation will be determined.

Recent Results
Cleary, T.G., Grosshandler, W.L., and Yang, J.C., "Flow of Alternative Agents in Piping," paper presented at the Halon Options Technical Working Conference, May 3-5, 1994, Albuquerque, New Mexico.

Yang, J.C., Cleary, T.G., and Grosshandler, W.L., "Simulation of Dry Bay Discharge of Alternative Agents," poster presented at the Halon Options Technical Working Conference, May 3-5, 1994, Albuquerque, New Mexico.

Real-Time Suppressant Concentration Measurement

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

Sponsor:
Department of the Air Force
Wright Laboratory
Survivability Enhancement Branch

Objective
To evaluate possible methods for real-time measurements of concentrations of alternative fire fighting agents for airplane dry bay and nacelle fire applications.

Problem
The use of halon 1301 for suppressing dry bay and nacelle fires on aircraft is being phased out rapidly. In order to design and test effective replacement systems, instrumentation must be available to measure concentrations of potential replacements with good temporal resolution. At the present time, such analytical capabilities do not exist.

Approach
BFRL has evaluated the performance of two possible instruments-aspirated hot-film and differential infrared absorption--for making the necessary concentration measurements. In addition, the literature has been reviewed to determine if other, more promising approaches have been demonstrated. Both of the tested instruments were found to be sufficiently promising that feasibility studies in the full-scale dry-bay test facilities at Wright-Patterson AFB were carried out.

Recent Results
Month reports were submitted to the sponsor. The final report is in preparation.

Minimum Mass Flux Requirements to Suppress Burning Surfaces with Water Sprays

Principal Investigator:
Jiann Yang
Fire Science Division
301-975-6662

Sponsor:
Federal Emergency Management Agency
U.S. Fire Administration

Objective
To determine how the orientation of a burning surface and its location relative to the water spray nozzle affects the mass flux of droplets required to extinguish the flame.

Problem
Prescriptive relations exist which allow a fire protection engineer to estimate the amount of water necessary to suppress a fire in a given enclosure using conventional sprinklers. However, the fear of collateral damage created by high water flows, in the case of a fire or false discharge, discourages their use. This is particularly problematic since halon 1301 is no longer available for protecting water-sensitive equipment. Fine water sprays are an alternative which may be applied instead of sprinklers or halon-type systems, but the dynamics of the spray/fire interaction are insufficiently understood to optimize fine water spray systems.

Approach
During FY 1995, BFRL will determine the response of a burning object to the discharge of the water spray. Small slabs of combustible solids will be ignited, and after a designated pre-burn time, a small concentration of water droplets will be allowed to flow towards the object for a fixed period of time monthly the conditions are close to constant. The water flow, size distribution and velocity will be measured; and if the fire is not extinguished, the test will be stopped, the sample replaced, and the water flow increased until suppression occurs. The experiment will be repeated at different locations within the spray to cover the full range of expected velocities and size distributions. The fuel will be oriented

upward, downward and vertically. Experimental conditions will be chosen which are likely to be of direct use to residential-type system designs.

Recent Results

Grosshandler, W.L., Lowe, D., Notarianni, K., and Rinkinen, W., *Protection of Data Processing Equipment with Fine Water Sprays*, NISTIR 5524, National Institute of Standards and Technology, 1994

High Heat Flux Measurement Standards

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

Sponsor:
National Institute of Standards and Technology

Objective

To develop a prototype facility that extends current heat flux measurement standards to convective flows with much higher energy fluxes, and to develop for industry new techniques for applications to critical technologies.

Problem

Heat flux requirements are ever increasing in magnitude, ranging from about 50 kW/m^2 in an unwanted fire to as high as 10^3 kW/m^2 in a boiler. The challenge is to determine ways in which heat flux can be measured accurately and unobtrusively under operational extremes, and to develop standard test-beds in which new heat flux measurement devices can be calibrated. Unlike temperature, heat flux is a derived quantity which is application dependent. Standard methods exist for calibrating thermal radiation detectors at flux levels extending to 10 kW/m^2 using controlled blackbody cavities, and up to 40 kW/m^2 using a monochromatic laser radiation source. However, heat flux transducers are often used under conditions where convection is dominant, where radiation emanates from a source with different spectral character, or where the flux levels exceed 40 kW/m^2.

Approach

A steady flow of hot gas over a cooled flat plate represents a simple, yet generic, element common to fires, chemical manufacturing processes, thermal treatment of metals and ceramics, and combustion engines. During FY 1995, BFRL will construct an experimental facility consisting of a cooled plate in which a heat flux transducer can be mounted flush to the surface. A laminar gas jet impinging on the surface and fully-developed pipe flow around a bluff object on the centerline will be considered. The gas temperature,

velocity, flow geometry and imposed radiant field will be variable, with designed heat fluxes at the surface exceeding 100 kW/m^2. The facility will be constructed to permit flow visualization, LDA and hot-wire probing, thermocouple and Schlieren measurements, thermal imaging of the surface, and temperature measurements in the solid. Plans will also be developed to increase the heat flux capabilities of purely radiometric calibrations. Direct numerical simulation of the gas phase energy transfer will be coupled to the solution of the conduction equation in the flat plate, using numerical methods for the internal heat transfer previously developed for the thermal analysis of various solid-state devices. The capabilities of existing heat flux measuring techniques, including thin and thick film gauges, microelectronic devices, thermopiles, and gardon gauges, will be investigated in following years in consultation with the heat flux measurements industry, to determine their specific calibration needs and design suggestions.

Recent Results
New project.

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
NASA Headquarters

Objective
To develop data on smoke movement and smoke layer development in high bay areas to permit NASA to make decisions on fire detection and suppression in their high bay spaces.

Problem
There is a special need to address fire protection issues for high ceiling height (high bay) spaces. NASA has numerous high bay spaces that are used to perform a variety of functions. Many of these functions are critical to meeting the goals of the NASA strategic plan. Examples of high bay spaces at NASA include those used for clean rooms, shuttle simulators, assembly/storage, vacuum and vibration chambers, vehicle assembly, and/or testing facilities with payloads. These spaces represent some of the most difficult fire protection challenges in that detection of a fire in a large space may be delayed due to the distance smoke and products of combustion must travel to reach the detector, the large amount of ambient air for smoke dilution, the high dollar value of these spaces, and the low damage threshold of a clean room. Some of these spaces also involve forced airflow.

Approach
During FY 1995, BFRL will model NASA high bay spaces using FLOW 3D (a commercial package computer model that simulates fluid dynamics and heat transfer using a finite difference approach). The spaces are categorized into a matrix divided by ceiling height, maximum acceptable fire size, type of detection, and airflow. Sets of recommendations for each category of spaces will be determined from results of the computer calculations, and other BFRL expertise.

Results

Notarianni, K.A., and Davis, W.D., *The Use of Computer Models to Predict Temperature and Smoke Movement in High Bay Spaces*, NISTIR 5304, National Institute of Standards and Technology, 1993.

Analysis of High Bay Hangar Facilities for Detector Sensitivity

Principal Investigator:
Kathy A. Notarianni
Fire Science Division
301-975-6883

Sponsor:
Department of the Navy
Naval Facilities Engineering Command

Objective

To provide the Navy with scientific data on flame detection, smoke detection, and smoke movement in high bay aircraft hangers using aviation fuels.

Problem

Fire protection criteria for aircraft hangers employ "best engineering judgment" using NFPA codes and standards which are based on maximum ceiling heights of 9.1 m (30 ft). For years, DoD and the private sector have extrapolated data from research conducted in buildings with conventional ceiling heights. There are no actual data to support the current design practices for fire detection and suppression systems which may be located 30.4 m (100 ft) or more above the fuel level. The effects of stratification, wind, and the movement of smoke and heat in high bay areas such as aircraft hangers are not presently known. Consequently, the reaction time and effectiveness of fire detection and suppression systems in aircraft hangers poses many questions.

Approach

During FY 1995, BFRL will determine the heat release rate vs. time curve for aviation fuels to be used in full-scale tests. Instrumentation for the fire tests will include thermocouples to measure ceiling temperatures, plume temperatures, and velocities. Also, actual response time of numerous types of fire and smoke detectors, and the response times of a variety of sprinkler heads will be measured. Instrument locations will be determined by appropriate installation standards and by prior simulation of the fire tests using a CFD model. Twelve full-scale tests will be conducted in each of two high bay hangar facilities, one in a cold climate location and one in a warm climate location for the purpose of

understanding how smoke movement and detector sensitivity is impacted by ambient temperature. The fire size, fuel type, and wind conditions will be varied. Each set of experiments will be analyzed using the measurement data and the CFD model. The analysis will include appraisal of the following: 1) the effectiveness of ceiling detectors for high bay structures; 2) the effectiveness and placement strategy for IR and UV detectors; 3) the approximate minimum fire size for delectability for each detector type; 4) the effect of fuel type on the effectiveness of each type of fire detector; 5) the impacts of wind and temperature stratification on the effectiveness of each type of fire detector; 6) optimal overall strategies for providing fire detection for the spaces in question.

Recent Results

New project.

RECENT GRANTS - FIRE SENSING AND EXTINGUISHMENT

1. Development of an Economical Video Based Fire Detection and Location System

Principal Investigators:
O.A. Plumb and R.F. Richards
Department of Mechanical and Materials Engineering
Washington State University
Pullman, WA 99164-2920

Sponsor:
National Institute of Standards and Technology

Objective
To develop and demonstrate an inexpensive video based system to detect, locate, and size accidental fires. The system involves a video camera which monitors color-changing, temperature-sensitive sensors to gather transient temperature information around a fire, and an inverse problem solution algorithm which uses the transient temperature data to predict the fire+s location and heat release rate.

Problem
Industrial facilities such as warehouses and factory floors may combine significant fire risks with minimal human monitoring for extended periods. When accidental fires do occur in industrial settings the time the fire burns undetected plays a crucial role in the destructiveness of the fire. As a result there is a critical need for an economical means to automatically monitor work spaces and quickly determine the presence of a fire and assess the threat to life and property.

Approach
The video based fire detection system consists of color-changing, temperature-sensitive sensors, a video camera, a frame-grabber and a PC based inversion algorithm.
Temperature-sensitive labels are arranged in a grid on the ceiling of a room. A video camera is placed in the room at a vantage point such that the temperature-sensitive labels are arranged in a grid on the ceiling of a room. A video camera is placed in the room at a vantage point such that the temperature-sensitive sensors are within its field of view. If a fire is accidentally ignited, a buoyant plume of hot combustion gases will be generated. The buoyant plume rises to the ceiling of the compartment and upon reaching the ceiling will turn and then flow radially outward as a ceiling jet. As the ceiling jet flows across the ceiling, temperature sensitive labels are heated to their detection temperature and one by one will display a visible color change. Transient temperature information about the expanding ceiling jet is passed on to the PC by the frame grabber in the form of a time-series of digitized video images. The series of digitized images is then analyzed in the PC to provide the data needed by the invasion algorithm to predict the fire+s location and size.

A prototype video fire detection system has been built. Testing of the prototype system under controlled laboratory conditions has demonstrated the ability of the system to locate a flame source within 40 cm and determine the flame+s heat release rate within 50% (99% confidence intervals).

Recent Results
Richards, R.F., Munk, B.N., and Plumb, O.A., "Fire Detection and Location through Inverse Problem Solution," *Proceedings of the 10th International Conference on Automatic Fire Detection*, AUBE 95, Duisburg, Germany, 1995.

2. Large-Scale Experiments of Fire Signatures to Develop a Discriminating Fire Detector

Principal Investigators:
James A. Milke and Thomas J. McAvoy
Departments of Fire Protection and Chemical Engineering,
University of Maryland at College Park
College Park, MD

Sponsor:
National Institute of Standards and Technology

Objective
To determine the characteristics of a fire detector which has the capability to promptly

react to smoke while discriminating between smoke from fire and non-fire sources.

Problem

Improvements in fire detectors are needed to reduce the response time and also the frequency of false alarms. In an effort to describe the characteristics of a detector with the noted capabilities, patterns of signatures associated with fire and environmental signatures via experiments must be identified.

Approach

Most recently, work has been conducted to continue the experimental effort reported previously [1-3]. The research is being conducted at the University of Maryland by teams in the Departments of Fire Protection Engineering and Chemical Engineering. The fire protection engineering team is concentrating on identifying signatures from fire and non-fire sources. The chemical engineering team is investigating the applicability of neural networks to discriminate between signa-[1] tures.

Large-scale experiments were conducted in a 3.6 m x3.6 m x2.4 m (height) room. Measurements included temperature, mass loss of the fire sources, CO, CO_2 and O_2 concentrations, light obscuration and the voltage output from two metal oxide sensors (Taguchi model 822 and 880). In addition, two commercial smoke detectors (one photoelectric and one ionization) were located on the ceiling, at the center of the room. Mass loss measurements were used to estimate the yield fractions of the signatures from the fire sources. A variety of sources were used to generate conditions within the room. The sources were intended to be representative of residential fire and nuisance sources.

A research link has been established with NIST's Process Measurements Division, Chemical Science and Technology Laboratory. Preliminary work has been conducted to integrate thin film sensors and neural networks for processing the sensor information.

Data from the sensors was reviewed to identify patterns associated with the categories of sources. Concentrating on the maxima for each sensor, an expert system was formulated. An improvement in the success rate for characterizing the source has been achieved using a PCA. Results from the application of the PCA for smoldering sources provides a 87% correct classification rate, while only 25% of the smoldering fires were detected by commercial smoke detectors. The time for detection with the PCA-based intelligence (the "prototype detector") was significantly less than that for the commercial detector. The time required for detection was reduced an average of 45 s for the flaming fires and 245 s for the non-flaming fires.

Dr. William Grosshandler is the technical monitor. The assistance of Mr. Randy Edwards, Fire Control Instruments, and Mr. Seth Cowles, Notifier Division of Pittway, is recognized in lending assistance with commercial smoke detection systems used in the study.

Recent Results

Milke, J.A., and McAvoy, T.J., "Analysis of Signature Patterns for Discriminating Fire Detection with Multiple Sensors," *Fire Technology*, to be published.

Milke, J.A., "Application of Neural Networks for Discriminating Fire Detectors," presented at the 10th Int. Conference on Fire Detection, AUBE '95, Duisburg, Germany, April 5, 1995.

Milke, J.A., B. Hagen, T. McAvoy and D. Pan, "Large-scale Experiments of Fire Signatures to Develop a Discriminating Fire Detector," presented at the Annual Conference on Fire Research, Gaithersburg MD, October 19, 1994.

Milke, J.A., Denny, S.A, McAvoy, T.J. and Pan, D., "Initial Application of Neural Networks to Discriminate Between Fire and Non-fire Odors," presented at the Annual Conference on Fire Research, Rockville, MD, October 19, 1993.

3. Basic Research on Fire Suppression

Principal Investigator
Arvind Atreya
Department of Mechanical Engineering
and Applied Mechanics
The University of Michigan
Ann Arbor, MI 48109-2125
313-747-4790

Sponsor:
National Institute of Standards and
Technology

Objective
To develop a quantitative understanding of the chemical and physical mechanisms of fire suppression by water through small-scale experiments and models and focus on understanding the gas-phase effects.

Problem
Water has two well-known physical suppression effects: (I) cooling of the burning solid by water evaporation, and (ii) smothering caused by dilution of the oxidizer and or the fuel by water vapor. In addition to these two well known effects, there are three more effects, namely: (iii) enhanced radiative heat loss due to increased water concentration, (iv) enhanced mixing as a result of columetric expansion caused by water evaporation, and (v) a little known but significant chemical enhancement effect which reduces the soot concentration and decreases the flame radiation. Our experiments show that the last two effects significantly increase the combustion efficiency and reduce the suppression effectiveness of water. Thus, it is necessary to quantify the gas-phase effects [i.e. ,(ii) through (v)] important if water mist is used for fire suppression.

Approach
Two experimental configurations were used for this study: (I) Stagnation-point flow apparatus: which allows studying both gas-phase and condensed-phase suppression and enables transient chemical measurements in the exhaust. These measurements are used to study the suppression mechanisms and quantify the suppression effectiveness. (ii) Counterflow diffusion flame apparatus: which allows detailed flame structure measurements to study suppression mechanisms (chemical and/or physical), but is limited to steady state.

Experiments were conducted for different 02 concentrations (to change the soot volume fraction) and for different constant water application rates (applied both as liquid water and as water vapor). Methane and ethylene were used as fuels, and fuel and oxidizer flow rates were held constant to maintain constant strain rates. The overall transient species composition measurements in the exhaust of the stagnation-point flow apparatus were used to calculate the effect of water on the overall heat release rate. An increase in the CO^2 production rate and the 0^2 depletion rate corresponds to an increase in the burning rate and vice versa. Also, detailed flame structure measurements in the presence of water vapor were made in the steady counterflow diffusion flame and numerical calculations were performed to help interpret the data and understand the suppression mechanisms. The dilution effect of H_20 is compared with the dilution by N^2 & CO^2, enhanced radiative heat loss is calculated via a model and mixing and chemical enhancement effects are investigated experimentally and theoretically.

Recent Results
Suh, J. And Atreya, A., "The Effect of Water Vapor on Radiative Counterflow Diffusion Flames." submitted to the Symposium on Fire and Combustion Systems, 1995 ASME IMECE, being prepared for submission to *Combustion and Flame.*

Crompton, T., and Atreya, A. "Quantifying the Effectiveness of Fire Suppression in a 1-D Laminar Diffusion Flame," Proceedings of the Eastern Section of the Combustion Institute, 1993.

4. Required Water Density for Fire Extinguishment or Control

Principal Investigator:
Michael A. Delichatsios
Factory Mutual Research Corporation
Norwood, MA 02062
617-255-4981

Objective

To characterize material properties which affect water surface application requirements for fire extinguishment and/or control, together with developing measurement techniques for critical water surface application rates and incorporating these results into modeling and predictive techniques for fire growth mitigation by water surface application.

Extinguishment and control of a fire by water is one of the most efficient and general protection methods. Although many technical water application requirements have been established through careful large-scale or intermediate scale experiments, there is lack of fundamental understanding of extinguishment or control. For example, it is difficult to answer simple questions, such as what properties of material affect the required water densities for either extinguishment or control of fire. The reason is that there are several phenomena involved that are difficult to separate. The present work intends to separate and investigate two phenomena: surface cooling (which directly reduces the heat flux to the surface) and inserting of the pyrolyzing gases (which reduces the luminous radiation heat feedback) as they emerge out of the surface. We do not intend to investigate in detail the effectiveness of droplet evaporation, sold in-depth water absorption or inserting of ambient air by water vapor. A transient investigation of the pyrolysis rate and burning owing to water application is necessary and will be taken into consideration in the program. We plan to use already developed models for pyrolysis and combustion and flame spread to complete the analysis.

Approach

The current program includes both experimental and analytical work. Three areas will be addressed; a) what are the minimum requirements for extinguishment by surface water application, and how these requirements depend on material properties; b) how the pyrolysis rate varies with time as water is applied on the surface; and c) what are the minimum water surface requirements to prevent flame spread but not necessarily extinguishment of the initial fire. Previous experimental results together with some new experiments will be used to address questions (a) and (b). A horizontal flame spread experiment and a parallel vertical wall experiment will be designed to address item (c).

Recent Results

Demonstrated that current extinction theories of diffusion flames on condensed surfaces can not capture the observed experimental results.

Modified an integral transient pyrolysis code to account for sudden cooling owing to water application rate.

BFRL HEADQUARTERS

OFFICE OF APPLIED ECONOMICS

Economics of New Technology Materials

Principal Investigator
Harold E. Marshall
Office of Applied Economics
301-975-6131

Sponsor
National Institute of Standards and Technology

Objective
To develop life-cycle economic methods for evaluating the economics of substituting new materials, such as composites or high-performance concrete and steel, for traditional materials in civil engineering applications.

Problem
The construction industry needs sophisticated, practical methods and guidelines for evaluating alternative building materials in a consistent manner over their life cycle. The need for standardized, improved methods and guidelines stems in large part because high up-front costs of new technology construction materials discourages their application even when warranted by life-cycle criteria. Providing a method for evaluating life-cycle cost effectiveness will give decision makers a tool to help them select, both for research and applications on the job, those materials that will make firms most competitive and deliver the nation's infrastructure at least life-cycle cost.

Approach
During FY 1995, BFRL will begin developing a life-cycle cost method designed specifically for evaluating the cost effectiveness of composites in relation to conventional construction materials. Working jointly with BFRL's Building Materials Division, a method will be developed that would enable analysts to estimate the cost effectiveness of composites in a typical engineering application. A case study will be performed for a bridge building application based on data collected in collaboration with the Building Materials Division.

In subsequent years, additional methods, such as the adjusted internal rate of return and net savings methods, will be developed. A multi-criteria decision method that allows users to simultaneously evaluate multiple economic and engineering criteria when choosing among alternative materials will also be developed. Techniques for taking into consideration economic uncertainty and risk will be explored. Through participation in the ASTM Building Economics Subcommittee (E06.81), efforts will be made to have these methods and techniques consistent with existing and future ASTM building economics standards. Case studies using these methods and techniques will be prepared for other applications such as high performance roofing and building systems. Decision support software will be developed to implement the methods and techniques.

Recent Results
New project.

Economic Data for Benchmarking Construction and Building Program Goals

Principal Investigator
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Office of Applied Economics
301-975-6137

Sponsor
National Institute of Standards and Technology

Objective
To identify economic data that provides benchmarks of current practice and measures of progress of the U.S. construction industry to the stated goals of the National Science and Technology Council's Construction and Building Subcommittee (NSTC/C&B).

Problem
BFRL is co-chairing the Construction and Building Subcommittee of the Civilian Industrial Technology Committee of the National Science and Technology Council. The Preliminary Research Plan published by the C&B Subcommittee has established goals for Federal research in the construction industry. Economic data are needed to benchmark current practice and measure progress of the U.S. construction industry with respect to these goals.

Approach
During FY 1995, BFRL will support this effort by:

1. Reviewing all the documentation produced by the C&B Subcommittee relevant to National Construction and Building Goals.
2. Conducting a preliminary search for possible data sources.
3. Identifying those goals for which adequate data sources were found to support benchmarking and progress measurement.
4. Developing a conceptual approach for bench-marking current practice and measuring progress with respect to these identified goals.
5. Collecting the necessary data.
6. Preparing a report describing the data and the benchmarking and progress measuring methods for each of these goals.

Recent Results
Developed economic data on the life cycle of constructed facilities to provide input to this research.

Economic Methods for Building Standards

Principal Investigator
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Office of Applied Economics
301-975-6131

Sponsor
National Institute of Standards and Technology

Objective
To provide a comprehensive plan for economic analysis to support BFRL's goals and contribute to the revision of old and development of new standard economic methods, guides, and classifications to help the national and international building communities evaluate new technologies and achieve affordable buildings that meet performance objectives.

Problem
The building community needs sophisticated, practical methods and guidelines for evaluation of alternative building technologies in a consistent manner. The need for standardized, improved methods and guidelines stems in large part from the high costs of building materials, the high costs of construction due to safety and environmental regulations, the alleged slow growth in construction productivity, the uncertain costs of energy, and the uncertain life-cycle costs associated with new technologies.

Approach
During FY 1995, BFRL will prepare a comprehensive plan for economic analysis to support BFRL's goals. The plan will include proposed projects such as standard methods for measuring the cost effectiveness of new technologies, e.g., composite materials; standard methods and supporting computer programs for promulgation through ASTM; support of the economics of the Construction and Building (C&B) Subcommittee of the Civilian Industrial Technology Committee (CITC) of the National Science and Technology Council (NSTC); and recruitment targets and staff assignments to achieve the plan.

Economic methods and supporting analyses will be developed for application to building problems. The principal avenues for transferring them to the building community will be the ASTM Building Economics Subcommittee, the C&B Subcommittee, and the International Council for Building Research (CIB) Building Economics Working Commission.

Administrative and technical leadership will be provided the ASTM Subcommittee. In FY 1995, the major technical effort will be in developing and balloting a new standard method for multi-attribute decision analysis. A report on multi-attribute decision analysis will be authored to serve as the basis for the new standard. BFRL staff will continue to chair the Building Economics Subcommittee and to perform technical work that contributes to new and revised standards. The ongoing effort on a Workbook to accompany the "Choosing Methods for Economic Evaluation" video will be completed and a NIST report published.

Technical and administrative support will be provided CIB W.55. Work will center on co-editing a book on project evaluation: the first volume of a CIB-sponsored Building Economics Reader Series.

Recent Results
Marshall, H, and Petersen, S., "Building Economics," *Mechanical Estimating Guidebook for Building Construction*, 6th edition, Gladstone and Humphreys, editors, McGraw-Hill (in press).

Marshall, H., "Sensitivity Analysis", *The Engineering Handbook*, CRC Press, Boca Raton, FL (in press)

Completed society balloting, UNIFORMAT II, based on, *UNIFORMAT II: A Recommended Classification for Building Elements and Related Sitework*, NIST Special Publication 841, National Institute of Standards and Technology, 1992

Marshall, H., *Compilation of Building Economics*, Third edition ASTM, Philadelphia, 1994

Marshall, H., co-author, "Life-cycle Costing," *Architectural Graphic Standards* ninth edition, 1994

Marshall, H., "Choosing Methods for Economic Evaluation," 3rd NIST video in the three-part series on *Least-Cost Energy Decisions for Buildings*, National Institute of Standards and Technology, 1993

Selecting Environmentally-Efficient Building Materials

Principal Investigator
Barbara C. Lippiatt
Office of Applied Economics
301-975-6133

Sponsor
National Institute of Standards and Technology

Objective

To develop decision-support software for selecting building materials that achieve the most appropriate balance between life-cycle environmental and economic performance.

Problem

Environmental and economic performance are two key factors in decision making by consumers and producers of building materials. Consumers include architects, developers, and homeowners, while producers include materials manufacturers and the building products industry. The environmental performance of building materials, however, is not readily assessable and comparable to economic performance. A method is needed to assess and compare environmental performance against economic performance. To maximize technology transfer, the method should be implemented in user-friendly decision-support software for consumers and producers.

Approach

During FY 1995, BFRL will assess the environmental performance of building materials based on the concept of life-cycle assessment. Life-cycle assessment evaluates and aggregates environmental impacts from all phases in the life of a material -- from cradle to grave. These phases include raw materials extraction, transportation, manufacture, installation, use, and eventual reuse, recycling or disposal of the building material. Environmental impacts include ecosystem, resource, and human health impacts. These result from depletion of energy, water, land, and raw materials, and from environmental releases such as atmospheric emissions, water effluents, and solid waste. Life-cycle assessment data for building materials are being collected for this project

by the U.S. Environmental Protection Agency, with guidance from BFRL's Office of Applied Economics (OAE). OAE is developing a multi-attribute decision analysis methodology to combine these data into measures of overall relative environmental impact. Probabilistic techniques are being incorporated into the methodology to treat the uncertainties inherent in the underlying life-cycle assessment data.

The economic performance of building materials is being assessed based on the life-cycle cost concept. Life-cycle costs include those incurred over the useful life of the building material, including the costs of acquisition, maintenance, repair, replacement, and disposal. This data is being collected from widely used data sources, such as R.S. Means, Inc. and the U.S. Army Corps of Engineers. The method will be disseminated as an economics standard proposed for incorporation in ASTM Subcommittee E50.06, Green Buildings.

Recent Results

Developed multi-year research plan for project (involving collaboration with EPA).

Provide Economic Support to NIST Advanced Technology Program

Principal Investigator
Stephen F. Weber
Office of Applied Economics
301-975-6137

Sponsor
National Institute of Standards and Technology
Advanced Technology Program (ATP)

Objective

To support the economic and program evaluation missions of NIST's Advanced Technology Program (ATP) by designing and developing economic questionnaires and implementing them in software to permit electronic submission by ATP awardees of quarterly and annual reports on economic and marketing progress.

Problem

ATP management is developing questionnaires to track the technological and economic progress of awardees. Economic consulting is needed to review the questions, and software is needed to implement them in electronic form.

Approach

During FY 1995, BFRL will be supporting NIST's ATP by:

1. Reviewing the questionnaires for their economic content and working with ATP economists to specify data requirements and to design efficient ATP awardee questionnaires to support economic impact models.
2. Developing data structures, files, and data relations for collecting in the field and storing in a centralized database at ATP headquarters questionnaire responses.
3. Computerizing in separate, executable, software modules each of the six ATP awardee questionnaires. The screen layout and user prompts and instructions will be similar to the paper form being developed by ATP. Some data validation features will be included, as well as help screens.
4. Develop software utilities for creating distribution diskettes and for

consolidating data from floppy diskettes into a centralized relational database at ATP headquarters.

Recent Results

Completed the software for collecting data for the ATP Quarterly Report on Business Plan and Developments and the software utility to automate creation of diskettes for ATP's Quarterly Report.

Provide Economic Support to NIST Manufacturing Extension Program

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Sponsor
National Institute of Standards and Technology
Manufacturing Extension Partnership (MEP)

Objective

To support the economic and program evaluation missions of MEP by identifying economic data sources, developing economic data analysis software, developing economic maps, and modeling economic impacts.

Problem

MEP management needs economic consulting support for planning, reporting, and program evaluation.

Approach

During FY 1995, BFRL will support MEP by reviewing and developing economic questions used in the MEP quarterly reporting system. BFRL will develop software macro procedures to automate the display and analysis of quarterly reports. BFRL will support MEP by:

1. Providing economic data and maps to define the scope, scale, and geographic distribution of manufacturing establishments and Manufacturing Extension Centers (MECs).
2. Conducting a survey and evaluation of alternative economic impact simulation models and recommend one for use by MEP.
3. Developing models of direct economic impacts resulting from Technical Assistance Projects (TAPs) of MECs that are compatible with the selected economic impact simulation model.
4. Evaluating and testing the application of Data Envelopment Analysis to measure, and suggest improvements in, the relative efficiency of MECs.

Recent Results

Completed analysis of MEP surveys of small manufacturing firms and of technology consulting firms and developed economic maps showing the county locations and densities of small and medium manufacturing establishments and of defense contractors in the U.S.

Rating Buildings by Historic Significance

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Sponsor
U.S. General Services Administration
Public Buildings Service
Office of Portfolio Management

Objective

To develop decision-support software for rating buildings by their historic significance.

Problem

Sixty percent of the buildings owned by the Public Buildings Service are classified as historic structures based solely on their age. Some of these buildings are truly historic, while others have little historic significance. In order to manage them effectively, PBS needs to know their relative historic importance. PBS has developed and is currently implementing the Building Preservation Plan (BPP), a system for collecting detailed data on the historic properties of its buildings. The objective of this project is to use these data to develop a consistent, reliable method for rating the portfolio of PBS buildings by their historic significance, and to implement the method in decision support software for PBS. This project is using the wealth of detailed data the PBS collects on each of its historic buildings to develop a true scalar rating of historic significance.

Approach

During FY 1995, BFRL will use multi-attribute decision analysis (MADA) techniques to develop three separate rating systems corresponding to the three levels of detail, or stages, at which the BPP system evaluates historic significance: 1. building elements, such as door glazing and wall trim, 2. building zones, or sections of the buildings based on historic significance or function, and 3. the building as a whole. The three rating systems will be integrated into a comprehensive rating system to measure the combined historic significance at all levels of building detail. This is known as the architectural rating. Finally, another MADA-based rating system

will be developed to compute a community rating, reflecting the combined extent of community support (neighborhood, state and local, and national) the PBS can expect for a rehabilitation project for the building. The PBS will use the architectural and community support ratings to help allocate funds among competing building investment projects.

Recent Results

Developed the rating systems for computing the element, zone, building, and overall architectural ratings, implemented the rating methods in Beta Test decision support software for PBS, and developed an interim report describing the technical details underlying these rating methods and documenting their algorithms.

Life-Cycle Costing Methodology

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Sponsor
U.S. Department of Energy
Office of Assistant Secretary for Energy Efficiency and Renewable Energy
Federal Energy management Program

Objective

To provide, on a continuing basis, economic analysis methods, data, software, training, and consulting to the Federal Energy Management Program (FEMP) in support of energy and water conservation projects in federal buildings and facilities.

Problem

The National Energy Conservation Policy Act directs NIST to provide expert consulting to DOE related to economic analysis of energy conservation projects in federal buildings. Executive Order 12902 of March 8, 1994, requires that energy usage in federal facilities be reduced by 30% by the year 2005 relative to 1995 levels, *in a cost-effective manner*. The objective of this project is to provide the expert services available in BFRL to FEMP pursuant to this goal. Methods of economic analysis are to be based on established methods used in the private sector. The products are used widely by federal, state, and local governments and in the private sector.

Approach

During FY 1995, BFRL will perform five tasks:

1. Methodology. BFRL will assist DOE in the development and modification of FEMP LCC rules, as promulgated in 10 CFR 436 Subpart A. BFRL will amplify these rules and procedures in NIST Handbook 135, *Life-Cycle Costing Manual for the Federal Energy Management Program*, which is being revised to reflect many changes in the FEMP rules since it was published in 1987.
2. Data. Each year BFRL computes the discount rate to be used in the analysis of federal energy and water con-

servation projects, using the procedure specified in 10 CFR 436. In addition, BFRL computes tables of discount factors and energy price indices, based on this discount rate and on energy price projections received from DOE/EIA for this purpose. These data are published each October 1 in NIST's *Annual Supplement to Handbook 135*, and included in electronic form with the BFRL LCC software.

3. Software. BFRL has developed four computer programs for economic analysis of energy and water conservation projects: BLCC, Quick Input, DISCOUNT, and ERATES. These programs are maintained, updated, and enhanced with new analytical capabilities annually. These programs are distributed by DOE and numerous private-sector software vendors. User manuals are provided with each program, and full documentation is underway. This software also has been incorporated into several other software projects outside NIST, sponsored by DOE.
4. Training. BFRL conducts five LCC workshops annually at locations throughout the United States, primarily for federal engineers and energy managers, but attended by representatives from state and local government, utilities, and consultants from the private sector. BFRL designed this course and updates the course materials on an annual basis. In addition, BFRL has recently trained 16 instructors, mostly university professors, to conduct this LCC workshop, and is providing them with required teaching materials. These trainers are now conducting many additional workshops throughout the United States, greatly expanding the reach of NIST research activities. FEMP also has developed three training videos related to LCC analysis and is finalizing the training manual for the last of these.
5. Consulting. BFRL provides consulting to DOE related to methods of economic analysis for federal energy and water conservation projects on a continuous basis. For example, changes to the FEMP LCC rules in 10 CFR 436 are made in consultation with BFRL; users of BFRL publications and software frequently call with technical questions related to these materials and to interpretation of 10 CFR 436; and BFRL is working with FEMP to reconcile differences in DoD's LCC methodology with the FEMP methodology used by other federal agencies.

Recent Results

Revised Fuller, S.K. and Petersen, S.R., Life Cycle Costing Manual for FEMP, NIST Handbook 135, National Institute of Standards and Technology, June 1995

Revised Petersen, S.R., *BLCC User's Guide and Reference Manual and Programmer's Documentation*, NISTIR 5185-2, National Institute of Standards and Technology, January 1995

Conducted 5 two-day workshops on Life-Cycle Cost Analysis of Energy Conservation Projects on Federal Engineers, FY 1995.

Petersen, S.R., *Present Worth Factors for LCC Studies in the Department of Defense (1995)*., NISTIR 4942-2, National Institute of Standards and Technology, October 1994.

Revised LCC training manual, Fuller, S.K., and Petersen, S.R., *Life-Cycle Cost Workshop for Energy Conservation in Buildings: Student Manual*, NISTIR 5165, National Institute of Standards and Technology, October 1994

Annual Supplement to Handbook 135, Petersen, S.R., *Energy Price Indices and Discount Factors for LCC Analysis 1995*, NISTIR 85-3273-9, National Institute of Standards and Technology

AutoBid Software to Support Police Vehicle Acquisition Decisions

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Sponsor
National Institute of Standards and Technology
Office of Law Enforcement Standards (OLES)

Objective
To update and publish **AutoBid** software to support police vehicle acquisition decisions.

Problem
AutoBid software that supports police vehicle acquisition decisions needs to be updated to include the latest 1996 model year data on police vehicle performance. The current version of **AutoBid** is directly dependent on a specific set of data files that each cover one vehicle model year. The data files contain the performance test results for police patrol vehicles published annually by the Michigan State Police. The specific data files expected to be present are explicitly referenced in the source code of the software. This feature requires that the source code be modified each year when the new model year data become available. As a result, the entire program must be recompiled each year.

Approach
During FY 1995, BFRL will assist OLES in preparing the data files compatible with **AutoBid** for the 1996 model year, as soon as the police patrol vehicle performance data become available. Work will center on redesigning the software to automatically recognize any vehicle model year data files in the current directory and provide the user with a menu to select any given year for which the data are present.

Recent Results
Recompiled **AutoBid** software and included 1995 model year police patrol vehicles.

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