NIST SP 838-4

Impacts

NIST Building & Fire Research Laboratory

U.S. Department of Commerce

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Introduction

The Building and Fire Research Laboratory (BFRL) of the National Institute of Standards and Technology (NIST) is dedicated to the life cycle quality of constructed facilities. NIST is the only federal technology agency with the specific mission of helping U.S. industry to strengthen its international competitiveness.

BFRL is the national laboratory for the building and fire communities. BFRL's mission is to enhance the competitiveness of U.S. industry and public safety through performance prediction and measurement technologies and technical advances that improve the life cycle quality of constructed facilities. The Laboratory performs and supports field, laboratory, and analytical research on the performance of construction materials, components, systems and practices, and the fundamental processes underlying the initiation, propagation, and suppression of fires. BFRL produces technologies to predict, measure, and test the performance of construction and fire prevention and control products and practices.

This report describes major effects of BFRL's program on building and fire research. Scientific and economic impacts are cited in Section 1; preliminary impacts are cited in Section 2. Although in no instance did BFRL alone accomplish the improvements in building and fire practices, BFRL has played a key role in improvements in building and fire practice producing annual savings amounting to tens of billions of dollars.

BFRL participates actively in about 150 national standardization committees; provides leadership in national and international standardization organizations and chairs more than 20 voluntary standardization committees. BFRL annually publishes over 230 reports, articles for research journals, and articles for professional and trade journals. BFRL staff annually makes hundreds of presentations to professional and technical meetings of building and fire community organizations. Over 70 guest researchers from industry, academia, Federal agencies, and international laboratories participate in 6 month and longer assignments at BFRL. The Laboratory annually presents a series of Building Technology Symposia in cooperation with other organizations concerned with building research and practice and hosts Fire Research Seminars for NIST staff and colleagues from the fire community. BFRL's Fire Research Information Service (FRIS) is a national and international fire research library and FIREDOC is BFRL's automated database of fire research literature. FRIS is the only comprehensive national library resource for the fire community.

SECTION 1 - IMPACTS

Structural Reliability

Problem. Quantitative knowledge of structural reliability is required to assure that structures are safe and serviceable throughout their intended service lives and that alternative structural materials and systems can compete equitably in the marketplace.

Approach. BFRL conducts research into structural loadings, structural resistance, and reliability-based design procedures.

Findings. Research results include design load criteria including live loads and live load reduction, distribution of extreme winds, gust factors and pressure coefficients, and provisions for general structural integrity and avoidance of progressive collapse.

Delivery Method. BFRL's findings are incorporated in building codes and standards e.g., ASCE 7- 1988 standard, *Minimum Design Loads for Buildings and Other Structures*. This Standard seeks to provide adequate and consistent reliability for all structural materials and systems, types of loadings and locations in the United States. It provides the technical basis for the loading provisions of the model building codes, national standards for design with the various structural materials and systems, loading provisions of state and local building codes, and loading requirements for engineers dealing with design situations not covered by local building codes.

Impact. These findings have provided consistent reliability across various types of materials for structural systems and various environmental loading. Catastrophic failures are reduced and costly excessive safety requirements are avoided.

Nondestructive Testing of Concrete

Problem. The present crisis to evaluate and repair the Nation's aging infrastructure demands the development of reliable, cost-effective nondestructive testing (NDT) methods for civil structures. The application of NDT methods to the inspection of civil structures has lagged behind the developments in other fields, such as the aerospace industry. Progress has been especially slow in the development of suitable NDT methods for complex heterogeneous materials, such as reinforced concrete and masonry.

Approach. BFRL established that the application of the principles of stress wave propagation held the potential for development of versatile NDT methods for locating flaws within concrete structures. Recent developments in signal processing and computational methods indicate that significant advances could be achieved. A multi-faceted research program composed of analytical modeling, controlled-experimental studies, and field verification was undertaken to establish the basis for this improved NDT method.

Findings. BFRL was successful in developing the technical basis for a new test method, which has become known as the "impact-echo method." Laboratory and field studies demonstrated that the method is capable of locating a variety of flaws within concrete, such as voids, honeycombing, and delaminations.

Delivery Method. The research results have been reported extensively in technical journals, workshops held, e.g., the FHWA and State highway agencies' Spring 1992 workshop on nondestructive test equipment, and presentations made at professional meetings. Research performed by one of the collaborators, who is currently at Cornell University, has expanded BFRL's research and extended the applicability of the method into development of a commercial test system.

Impact. This technique improved the reliability of detecting flaws in concrete structural mem-

bers and bridge deck delaminations. BFRL's research was recognized by the American Concrete Institute (ACI); their prestigious ACI Wason Medal for Materials Research was awarded twice to BFRL researchers for papers dealing with the impact-echo method.

Structural Failure Investigations

Problem. The physical causes of significant structural failures should be ascertained and made public so that future failures may be avoided.

Approach. BFRL responds to requests from the U.S. Occupational Safety and Health Administration and others to investigate important failures during construction to determine their most probable cause of failure. Several of these investigations BFRL participated in are: the 1973 failure of a 23 story apartment complex in Fairfax County, Virginia that killed 14 workers and injured 34; the 1978 failure of a cooling tower in Willow Island, West Virginia that killed 51 workers; the 1981 failure of a 5 story condominium in Cocoa Beach, Florida that killed 11 workers and injured 23; the 1981 collapse of walkways at the Kansas City Hyatt Regency Hotel that killed 114 persons and injured 186; performed at the request of local officials and the cognizant Congressional officials; the 1982 failure of a highway interchange ramp in East Chicago, Indiana that killed 13 workers; the 1987 collapse of a building in Bridgeport, CT, that killed 28 construction workers; the 1988 collapse of a four million gallon capacity oil storage tank up river from Pittsburgh, PA.

Findings. Results of these, and other related, investigations are published and disseminated to designers, fabricators, contractors, building officials, owners and the public to assist in avoiding future failures. Since many of the failures resulted from premature reliance on the load carrying capacity of immature concrete, BFRL developed prediction and measurement techniques for the strength of concrete at early ages that have been incorporated into ASTM Standards and Occupational Safety and Health Administration regulations.

Delivery Method. BFRL's recommendations are acted on by the American Consulting Engineers Council, the American Society of Civil Engineers (ASCE), the National Conference of States on Building Codes and Standards (NCSBCS), American National Standards

Institute (ANSI), ASTM, and other building community organizations.

Impact. These results influenced the structural engineering profession to reassess and revise procedures for design review and quality control of the construction process. Stimulated by the reports of BFRL's failure investigations, the American Society of Civil Engineers (professional society of over 100,000 civil engineers worldwide) developed a quality control manual, *Quality in the Constructed Project*. BFRL's reputation for high quality post disaster investigations led to revising NIST's authorization legislation for fiscal year 1986: "The National Bureau of Standards, on its own initiative, ... may initiate and conduct investigations to determine the causes of structural failures in structures which are used or occupied by the general public."

Seismic Design and Construction Standards

Problem. A catastrophic earthquake poses perhaps the greatest natural hazard faced by the Nation. Dollar losses in one great earthquake (Richter magnitude 8 or greater, e.g., a 1908 San Francisco magnitude earthquake) could be many times the $10 billion losses suffered from to the October 1989 Loma Prieta earthquake; fatalities and injuries could be in the tens of thousands.

Approach. In the National Earthquake Hazards Reduction Program, established by Congress in 1977, BFRL is responsible for carrying out research and development for improved building codes and standards and practices for structures and lifelines. BFRL works closely with national standards and model building codes organizations to encourage implementation of research results, promotes better building practices among architects and engineers, and works closely with national standards organizations to develop seismic safety standards and practices for new and existing buildings and lifelines. BFRL provides technical support, manages, and chairs the Interagency Committee on Seismic Safety in Construction (ICSSC). The ICSSC assists Federal agencies involved in construction to develop earthquake hazards reduction measures and incorporate them in their ongoing programs. At the request of Congress, BFRL in support of the Federal Emergency Management Agency, developed a plan, including precise timetables and budget estimates, for developing and adopting, in consultation with appropriate private sector organizations, design and construction standards for lifelines.

Findings. BFRL staff developed analytical procedures for selecting appropriate structural systems for strengthening existing concrete buildings, developed an analytical procedure to design and analyze bridge columns based on damage criteria, assessed the effectiveness of current design approach for masonry shear walls and identified potential failure mechanisms of double-deck highway bridges similar

to the Oakland Nimitz Freeway which failed in the 1989 Loma Prieta Earthquake.

Delivery Method. Seismic design and construction provisions recommended by the Building Seismic Safety Council (BSSC) and the ICSSC are adopted widely in national standards, building codes, and requirements of Federal agencies. Portions of these revisions are in use by the three model building codes, and Federal agencies.

Impact. This work helped to create a consensus among the building community on a new generation of provisions for the seismic resistant design and construction of buildings. The model building codes have adopted these provisions. ICSSC has formulated seismic design guidelines for new Federal buildings, practices for evaluation of site hazards, and plans for cooperative Federal post-earthquake response activities in the event of a damaging earthquake. States and local jurisdictions can update their existing seismic guidelines by referencing the NEHRP recommended provisions. For a nominal increase in building construction cost, use of these technologies are expected to result in fewer lives lost and reduced property lost.

Rehabilitation Codes and Standards

Problem. During the late 1970's, there was a surge in the rate of building rehabilitation due to tax incentives, the high cost of new construction, and energy conservation retrofitting. Building code constraints to rehabilitation were a major roadblock to cost-effective rehabilitation.

Approach. BFRL provided technical support to formulate a new regulatory approach to rehabilitating existing buildings. The approach allows repairs, alterations, and additions to existing buildings without necessarily meeting new construction requirements and without sacrificing safety concerns.

Findings. BFRL produced several publications including 1. NBS Special Publication 623, *Removing Regulatory Restraints to Building Rehabilitation: The Massachusetts Experience*; 2. NBSIR 80-2171, *Selected Methods for Condition Assessment of Structural, HVAC, Plumbing, and Electrical Systems in Existing Buildings* (describes methods to determine the condition of existing buildings), 3. Technical Note 998, *Impact of Building Regulations on Rehabilitation - Status and Technical Needs* (documented the regulatory problems and technical needs for effective rehabilitation).

Delivery Method. BFRL's technology was adopted by the State of Massachusetts. The National Institute of Building Sciences (NIBS) included BFRL results in their 10 guidelines on building rehabilitation prepared for the Department of Housing and Urban Development (HUD). These guidelines were adopted in model building codes.

Impact. The model code organizations which produce the widely used *National Building Code*, *Standard Building Code*, and *Uniform Building Code* have revised and developed new provisions based on BFRL's work which permit a more rational approach to building rehabilitation while retaining essential requirements for health and safety. BFRL's reports provided the technical basis for the American Society of Civil

Engineers Standard 11-90, *Guidelines for Structural Condition Assessment of Existing Buildings.*

Alternative Refrigerants Research

Problem. The world faces an environmental crisis with depletion of the stratospheric ozone layer from the release of certain chlorofluorocarbons (CFC's) into the atmosphere. Scientists need to find alternatives to R-11 and R-12, CFC's commonly used as refrigerants. Worldwide recognition of this crisis resulted in 71 countries agreeing to eliminate world production of these CFC's by 1998.

Approach. BFRL and NIST's Chemical Science and Technology Laboratory (CSTL) researchers studied 860 industrial fluids to identify properties of new environmentally compatible refrigerants to help industry improve the effectiveness of air-conditioning systems and replace the ozone damaging CFC's. Thermophysical properties of the most promising environmentally acceptable replacements were measured. Simulation models of refrigeration systems and experimental equipment determined engineering properties of the replacements. Research is supported by DuPont Corporation, TRANE Co., the Electric Power Research Institute (membership composed of electric utility companies), the Air Conditioning and Refrigeration Institute (U.S. equipment manufacturer's trade association), and the American Society of Heating, Refrigerating, and Air Conditioning Engineers (over 50,000 member professional engineering society).

Findings. Mixtures of incompletely halogenated methane and ethane molecules in the chlorofluorocarbon family with little or no chlorine proved to be the most promising replacements. Scientists created a microcomputer-based predictive package *REFPROP*, showing thermophysical properties of the leading replacements R123 and R134a. *REFPROP* is in its third version and contains 25 other pure refrigerants and all possible combinations of up to five component mixtures of these refrigerants. The boiling heat transfer coefficient of R123 and R134a also were determined to aid industry design refrigeration system evaporators. The studies identified changes in the refrigeration system design to

take optimum advantage of the characteristics of the refrigerant mixtures.

Delivery Method. The Journal of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) published the original characterization of 860 industrial fluids and awarded this paper the best technical paper of the year. This research won the 1988 NIST Edward Uhler Condon Award for distinguished publication. NIST's Office of Standard Reference Data, in a special distribution agreement with the 170 members of the Air Conditioning and Refrigeration Institute (ARI), distributed the microcomputer-based program of thermophysical properties. BFRL staff published their data in the World Meteorological Organization Alternative Fluorocarbon Environmental Acceptability Study (AFEAS). BFRL staff authored a technical assessment of large building air conditioning for the United Nations on how the international agreement on eliminating world production of CFC's would affect this application of cooling. All these publications resulted in many international requests for further information from chemists, physicists, and engineers.

Impact. This research stimulated industrial interest to produce replacements for CFC's. These results helped avert losses in market share for the U.S. chemical, refrigeration, and machinery industries. More than 5,000 American companies rely on CFC's to produce goods and services valued at more than $28 billion a year. Also, these findings assisted industry redesign the more than $135 billion worth of installed CFC-dependent equipment.

HVAC Simulation Models

Problem. Many unsolved problems in building energy conservation, indoor air quality, and alternative refrigerants research require a wealth of data on equipment, system, and building performance. One approach to solving these problems is to conduct many experiments under a wide range of experimental conditions and document the performance of the proposed system or solution. Given current constraints in time and resources, this approach is not feasible.

Approach. BFRL researchers developed a variety of simulation models that accurately predict the performance of building heating, ventilation, and air conditioning (HVAC) systems, and associated controls. The models also predict performance of refrigeration equipment used as part of these systems, intra-building air and contaminant movement, and moisture migration and accumulation in building facades. BFRL validated these models under controlled experimental conditions. BFRL and other researchers around the world used these models to propose solutions to energy conservation, indoor air quality, and alternative refrigerant problems.

Findings. BFRL developed *HVACSIM+*, a modular program designed to simulate the thermal performance of a building shell, its heating, ventilation, and air conditioning systems, and its building controls. Although other modular programs preceded it, HVACSIM+ uses variable-time-step, advanced equation-solving techniques that make it uniquely suited for studying energy advances through control. *HPSIM* was designed to simulate the thermodynamic performance of all refrigeration equipment operating on the vapor compression cycle, such as heat pumps and air conditioners. It simulates the behavior of the refrigerant and the equipment components from first principles and can account for such detailed phenomena as heat transfer differences from tube to tube in an air-to-refrigerant evaporator. Researchers developed *AIRNET* to predict inter-room airflows through building openings, such as doorways and through HVAC systems. Using new,

efficient mathematical techniques, AIRNET solves a network of nonlinear equations iteratively on a personal computer, something that had only been done on a mainframe computer prior to AIRNET'S development. Researchers developed *CONTAM* to build on the capabilities of AIRNET. Unique contaminant dispersal equations combined with AIRNET now gives researchers a tool to predict both interzone airflow and contaminant movement in multi-zone buildings. *MOIST* is a computer simulation of moisture migration and accumulation within a multi-layer building facade. It predicts localized moisture levels throughout the structural elements as a function of time of year, given material composition and weather conditions for the year.

Delivery Method. Researchers validated all simulation models using experimental data, documented them through users manuals and publicized them through presentations and technical papers for the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). Colleagues and researchers throughout the world received copies of the programs. For example, more than 120 copies of *HVACSIM*$^+$ have been distributed since 1984. Thirty-three copies of *HPSIM*, available since 1983, have been distributed to colleagues during the past 3 years alone.

Impact. BFRL has used *HVACSIM*$^+$ to study the dynamic performance of an 11-story office building on the NIST campus and to model advanced heat pumps with built-in thermal storage. In Europe, where controls research is prevalent in universities and government institutions, researchers use *HVSIM*$^+$ extensively. The International Energy Agency (IEA) has adopted the program for use by seven countries which are cooperating to construct a building emulator for testing advanced control systems. BFRL has used *HPSIM* to suggest modifications to conventional heat pumps that improved their performance by more than 30%. At least five U.S. universities have used *HPSIM* in graduate student research. Researchers from Canada, Brazil, and Singapore have published numerous technical papers based on *HPSIM* simulations. *AIRNET* has been incorporated into the primary building energy research program in Europe, the University of Strathclyde's ESP program. It also has been used as the main tool in three ASHRAE-sponsored research projects in U.S. universities. In one of the studies, *AIRNET* was the best of all available algorithms for airflow predictions in smoke control systems, reliably solving all test cases in an order of magnitude faster than ASHRAE's previously recommended algorithms. BFRL has used *MOIST* to examine new practices being considered by HUD in their standards for the moisture control in the walls and ceiling/roof cavities of manufactured housing and to examine recommended designs for the DOE Moisture Control Handbook now under development.

Thermal Insulation

Problem. NIST research on heat transfer through thermal insulation began in 1910 and in 1912 led to development of the first Guarded Hot Plate apparatus for precise measurement of heat transmission. This device and its successors have provided the basis for calibration of the measurement devices used by industry and regulatory authorities for determining the thermal resistance of insulation. Twenty-five millimeter thick calibration transfer standards were routinely supplied to industrial laboratories for calibration purposes prior to the 1970's. Concerns for energy efficiency after the 1973 Oil Embargo led to routine use of thick 150 to 450-mm low density insulation in U.S. buildings. In 1978-79, the Federal Trade Commission proposed requiring manufacturers to label their products for thermal resistance at thickness representative of typical installation. Industry representatives, concerned for the accuracy of labeling, requested that the rule be deferred until their measurement devices could be calibrated with full thickness, low-density insulation calibration transfer standards. Otherwise, industry estimated they would need to use an additional 20 percent of material to be assured of the validity of the labeling and would have to pass these costs on to their customers.

Approach. In the late 1960's, BFRL staff formulated a radical new approach for accurately measuring heat transmission through thermal insulation, a circular line-source Guarded Hot Plate. At industry's and the Federal Trade Commission's request, BFRL built a 1 m diameter version of the Guarded Hot Plate capable of full thickness measurements up to 380 mm to within one percent uncertainty and made calibration transfer standards available to industry.

Findings. BFRL completed the 1-m circular line-source Guarded Hot Plate in 1981 that met design specifications. BFRL subsequently developed two standard reference materials (SRM); a fibrous-glass blanket (SRM-1451) in 1985 and a fumed silica board (SRM-1449, 1459) in 1990. To date, approximately 60 SRM's have been sold and an additional 70 special calibrations have been completed for U.S. industry to support the accurate testing, production, and labelling of thermal insulation.

Delivery Method. BFRL staff have presented results of this research at conferences of the American Society for Testing and Materials (ASTM), the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), and International Thermal Conductivity Conferences (ITCC). BFRL staff have published approximately 20 technical papers in the proceedings of these conferences and in the *Journal of Thermal Insulation* and *Review of Scientific Instruments*. BFRL served as a major participant in a round-robin testing program organized by the International Standards Organization (ISO) in 1983 and two additional programs organized by ASTM in 1987 and 1990. The results of the latter round-robin programs were used to refine the precision and bias statements in ASTM Standard C687.

Impact. In 1984, The U.S. Chamber of Commerce testified to Congress that the measurement capability of the Guarded Hot Plate saves consumers $90 million per year.

Residential Equipment Energy Efficiency

Problem. Residential energy consuming equipment accounts for 20 percent of our national energy consumption. A goal of the Energy Policy and Conservation Act of 1975 was to provide for the improved energy efficiency of this equipment. Under the Act, BFRL was directed to develop test procedures for the determination of their annual efficiency and operating costs.
The test procedures were to reflect energy efficiency during a representative average use cycle and not be unduly burdensome to conduct.

Approach. BFRL staff used simulation models, laboratory tests, and field tests to understand the principal independent variables affecting the energy efficiency of the equipment. BFRL proposed test procedures for each type of equipment covered under the law. BFRL worked closely with industry representatives experienced in testing the equipment to obtain their review and recommendations, particularly for energy conserving innovations that were being considered for future products.

Findings. BFRL staff developed entirely new test procedures for central air conditioners, central heat pumps, furnaces, and boilers that accounted for the dynamic performance of the equipment under transient or "part-load" conditions. BFRL modified as necessary test procedures already used in industry for refrigerators and refrigerator-freezers, water heaters, room air conditioners, home heaters, dishwashers, clothes washers, clothes dryers, television sets, kitchen ranges and ovens, and humidifiers and dehumidifiers.

Delivery Method. The test procedures are used by manufacturers to label the annual operating costs of their products in a mandatory program administered by the Federal Trade Commission. The test procedures for central furnaces and boilers, and for central air conditioners and heat pumps were adopted by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) as consensus standards. The Gas Appliance Manufacturers Association (GAMA) developed its efficiency certification program for oil and gas furnaces based on the test procedures. The Air-Conditioning and Refrigeration Institute (ARI) standards and certification program for central air conditioners and heat pumps are similarly based on these test procedures.

Impact. These test procedures have supported substantial increases in appliance efficiency. The American Council for an Energy Efficient Economy (ACEEE) reports average efficiency increases from 1972 to 1987 of 96% for refrigerator-freezers, 35% for central air conditioners and heat pumps, 30% for room air conditioners, and 18% for gas furnaces. The most efficient equipment now coming on the market is shown by the test procedures to be as much as 75% more efficient than the average new equipment. The test procedures are stimulating even more energy efficiency for the future through the integration of more than one function in future equipment. Examples are space heating boilers which also heat domestic hot water and central heat pumps that provide domestic hot water through the use of waste heat.

Residential Plumbing Standards

Problem. Because of the growing constraints of land use and development for watersheds, water shortages and drought, costly urban infrastructure replacement financing, and environmental constraints on ground/water/land use and river water extraction limitations and waste water treatment discharge limits, the Department of Housing and Urban Development (HUD) and other Agencies requested BFRL to provide research on water conservation in buildings. These findings are now being used in NIST's plumbing laboratory accreditation program.

Approach. For more than 6 decades, BFRL studied demands for plumbing services and the hydraulic performance of plumbing fixtures and design/sizing of plumbing water supply, waste water drains, and vents.

Findings. Results included: (1) a computer-based design procedure for the drain-waste-vent system that accurately solves the transient transport of liquids and solids, (2) plumbing standards flow rate recommendations input for water savings fixtures; (3) drain sizing for simultaneous and nonsimultaneous discharge loads with water saving fixtures; (4) test procedures for plumbing standards updates and replacement with data derived from laboratory test measurements, and analytical derivations for water savings fixtures performance; and (5) rational methods for sizing vents.

Delivery Method. The Department of Defense, the National Association of Homebuilders and HUD have transferred BFRL's plumbing technologies into building codes and standards.

Impact. These results permit safe and serviceable water-conserving residential plumbing systems, and substantially reduce previous requirements for the sizes of water supply and drainage piping. Results of BFRL's plumbing research continue to be incorporated into plumbing standards. The American National Standards Institute (ANSI) standards revisions for water-conserving fixtures continue to incorporate BFRL's recommendations for test procedures and include recommendations for test procedures for adequate transport of wastes through the total plumbing system. BFRL's recommendations for water supply and sizing of venting were incorporated in 1983 and 1984 changes to the model plumbing code of the Building Official and Code Administrators, International. The 1986 One and Two Family Dwelling Code of the Council of American Building Officials, which applies to one and two family housing, adopted BFRL's findings for drainage loads and methods for sizing water supply, drain and vent piping. The National Association of Home Builders' economic assessment of the revised provisions indicated savings of about $500 per home in plumbing system costs. This amounts to an annual savings of $500 million in an ordinary year of new home construction. Further savings to the home owner will accrue from annual savings in water used, and urban development will be less constrained by our limited water resources.

Computer Image Evaluation of Building Materials

Problem. The behavior of a construction material reflects its chemical composition, internal structure, and surface condition. Qualitative and quantitative information about its structure is often obtained by human observation using a microscope following careful sample preparation, a tedious and time-consuming task. As a result, potentially important information may not be obtained.

Approach. To overcome barriers to routine analysis of images of building materials by direct human observation, BFRL has shown that computers can be used to perform quantitative analysis of images of building materials obtained with a microscope or other instrument. A computer analyzes infrared images to detect corrosion products under a coating before they become visible to the naked eye and determines the extent of the corroded area. This has important implications for increasing research productivity. For example, BFRL researchers have shown that computer image analysis can be used to determine: 1. the surface roughness of a metal; 2. the area of corrosion under paint on a metal surface; 3. a contaminated area of rubber roofing material which could interfere with proper adhesive bonding; and 4. the area of peeling paint on the surface of a large building. The development of the method for determining the surface roughness of a metal resulted in an IR 100 Award to the BFRL research team.

Findings. BFRL's research demonstrated that image analysis is a powerful and practical tool for coatings research laboratories to quantify changes in condition of a painted surface with time. To quote from a reference to BFRL's work in a report for EPA, "The critical point is that the definition of failure was clear and unambiguous.... We found no other example in which the definition of failure was so clearly stated."

Delivery Method. BFRL's image analysis techniques were disseminated through: many technical publications; talks to scientific conferences; and conversations with researchers of coatings companies, trade associations, and federal agencies.

Impact. BFRL researchers developed technologies that helped several major paint manufacturers speed up their evaluation of the durability of new coating formulations. This research provided paint manufacturers with technology to understand the mechanisms that affect the performance of paints and coatings in the protection of steel against corrosion and helped manufacturers respond to changing environmental regulations. These technologies provide coatings research laboratories with knowledge to change the basis for their observations of degradation of paint on laboratory test specimens from subjective judgment to quantitative measurement. These techniques have been used extensively in developing laboratory data for demonstrating how to predict the potential service life of coatings in different environments. BFRL's reliability approach has been adopted in many coatings laboratories in the United States and overseas, e.g., the Belgium Coatings Research Institute. The Atlas Company is now forming a consortium to help the coatings industry apply the NIST-developed techniques.

Corrosion-Protection for Reinforcing Steel

Problem. The deterioration of concrete bridge decks in the 1970's was a national problem. The Federal Highway Administration estimated $25 billion was needed over the next decade to repair these failing decks. However, only about $500 million per year is actually spent in the United States to replace concrete bridge decks that failed prematurely because deicing salts corrode the reinforcing steel. The expected life of bridge decks was only 5-10 years in the northern states where deicing salts are used.

Approach. BFRL developed performance criteria and test methods for organic coatings to protect reinforcing bars from corrosion for assuring durability and effective structural performance and to determine the structural performance of coated reinforcing bars embedded in concrete. This research was in response to a Federal Highway Administration (FHWA) request.

Findings. The research showed that only four of 48 coatings evaluated performed well in tests of corrosion protection and structural performance. All four were spray-applied powdered epoxy resins. The research results formed the basis for standards for use in selecting effective epoxy coatings for steel reinforcing bars.

Delivery Method. The results of this work were adopted in: ASTM Standards; American Association of State Highway and Transportation Official Standards; and a Concrete Reinforcing Steel Institute (CRSI) Specification for epoxy-coated steel reinforcing bars.

Impact. In 1990, over 300,000 tons of coated reinforcing bars were used in the United States, about 5 1/2 % of the total of all reinforcing bars. Epoxy-coated reinforcing bars have been extended from bridge decks to parking garages, pavements, waste water treatment plants, marine construction, and other structures. Their use has increased considerably over the last 18 years. Forty-four states use coated reinforcing bars in bridge deck construction.

A new industry was created to coordinate the new technologies; it was represented by the Fusion-Bonded Coaters Association (trade association of coaters of reinforcing bars). Findings from FHWA indicate coated reinforcing bars increase expected life of a bridge deck to more than 40 years (from 5 to 10 without coating). The cost of coated bars is about 25 percent more than uncoated bars and is insignificant in the total materials and labor cost of a bridge deck. Considering only the current annual $500 million expenditure for bridge deck repairs, an extension of service life from 10 to 40 years will, at a discount rate of 7.6 percent (3.8 percent real interest rates on 30-year treasury notes and bonds and a projected inflation rate of 3.7 percent) result in a present-value savings over 40 years of $745 million. These savings would be repeated annually for every $500 million repair expenditure.

Prediction of the Service Lives of Building Materials

Problem. Although building and construction materials are often expected to have service lives of several decades, methods have not been available to reliably predict such long service lives from short-term tests. The lack of methods for service life prediction is a technical barrier to the effective selection, use, and maintenance of building and construction materials and has been cited as an important contributing factor to premature failures. Hence, the need for reliable predictive methods for assessing the service lives of potentially beneficial, innovative materials without decades of testing under actual service conditions led to BFRL's research program to develop reliable methods for service life prediction.

Approach. BFRL developed a systematic methodology for predicting service lives of building and other materials. The method involves identifying the mechanisms of degradation in the service environment, characterizing the influences of environmental parameters, identifying valid accelerated methods of testing, modeling the degradation process, and using the model for predicting the service life in field conditions.

Findings. BFRL demonstrated the application of reliability theory and life analysis to problems of building and construction materials durability. It also demonstrated the development of stochastic models for predicting the synergistic effects of multiple environmental factors in degrading organic building materials, including solar energy system components and materials, plastics, protective coatings and single-ply roofing membranes.

Delivery Method. BFRL's recommendations were accepted by ASTM as the basis for its standard E-632, Standard Practice for Developing Accelerated Tests to Aid Prediction of the Service Life of Building Components and Materials, which was issued in 1978. ASTM E-632 became, in time, the basis for a Technical Recommendation published by RILEM in 1984 which is now being proposed as a European Standard.

Impact. This research provided the basis upon which service life prediction problems are being addressed in the United States by the Steel Structures Painting Council (SSPC), the National Acid Precipitation Program (NAPAP), and several ASTM committees. Internationally, the research stimulated the 1984 NATO Advanced Research Workshop on Problems in the Prediction of the Service Life of Building Construction Materials; led to the establishment by the International Union of Research and Testing Laboratories for Materials and Structures (RILEM) and the International Council for Building Research, Studies and Documentation (CIB) of a joint working commission on service life prediction; and provided the technical basis for research by the Norwegian Institute for Air Research. In its research on methods for predicting the service life of protective coatings for steel, BFRL has made significant advances in methods for quantitatively and nondestructively assessing the performance and properties of coatings. Methods and associated computer image processing capabilities have been developed which enable the early detection and quantification of degradation at the steel/coating interface. As a result of BFRL's leadership, ASTM has set up a new subcommittee specifically to develop service life prediction standards for all types of materials and systems.

Quality of Construction Materials Laboratory Testing

Problem. The U.S. is dependent on the quality of construction materials for rebuilding its infrastructure which is vital to remaining competitive in the global marketplace. An important component of quality is accuracy in the testing of materials. Inadequate testing may lead to the rejection of good materials, the acceptance of poor materials, construction delays due to poor intermediate test results, and structural failures due to inaccurate predictions of the performance of materials.

Approach. BFRL through its Construction Materials Reference Laboratories (CMRL) operates two Research Associate Programs. CMEL provides laboratory services to the construction materials testing community directed to improve quality of testing. CMRL's Programs are the Cement and Concrete Reference Laboratory (CCRL) sponsored by ASTM, and the AASHTO Materials Reference Laboratory (AMRL) sponsored by the American Association of State Highway and Transportation Officials. Materials covered by these organizations are soils, bituminous materials, plastic pipe, metals, portland cement, blended cement, masonry cement and portland cement concrete. Services provided by CMRL are on-site inspection of laboratories and distribution of proficiency test samples. The inspection program includes an evaluation of a laboratory's equipment, procedures and quality system compared against ASTM and AASHTO standards. Proficiency samples are distributed once or twice a year with instructions for testing using the appropriate standards.

Findings. Laboratories participating in the inspection program receive a written report of findings shortly after the inspection. CMRL does not follow-up on correction of deficiencies, but the results of the inspection are often used by accrediting bodies and other specifying organizations in their evaluation of laboratory performance. Laboratories are provided the overall results of the proficiency sample testing program from which they may determine their performance relative to other laboratories in the program.

Delivery Method. In addition to sending results to the individual laboratories participating in its programs, CMRL provides summary results to ASTM and AASHTO committees for use in standards development such as precision statement preparation. CMRL also works with RILEM Committees (International Union of Testing and Research Laboratories for Materials and Structures) in addressing common concerns about quality tests.

Impact. CMRL programs are provided to over 1000 laboratories in North America and in 15 other countries. CMRL program area used by the three major accrediters of construction materials testing laboratories in the United States AASHTO Accreditation Program (AAP), American Association for Laboratory Accreditation (A2LA) and NIST's National Voluntary Laboratory Accreditation Program (NVLAP). Over $14 billion worth of Federal-aid supported highways are constructed annually by state transportation agencies who use CMRL programs as part of their quality management system.

Roofing Standards

Problem. About $12 billion is spent each year in the United States on the installation and repair of low-slope roofing. Low-slope roofing continues to lead the list of problems in building performance.

Approach. BFRL conducted laboratory and field research to develop the technical basis for increasing the performance and durability of low-slope roofing materials and systems that lead to test methods and selection criteria suitable for incorporation into building standards.

Findings. BFRL researchers developed test methods for built-up roofing materials which helped the National Roofing Contractors Association (trade association of over 3000 roofing contractor and roofing manufacturing organizations) improve the performance of waterproofing membranes used on low sloped roofing which covers about one-third of the roof area of U.S. buildings. In parallel research, BFRL developed data on the performance of single-ply membranes.

Delivery Method. BFRL research results are described in BFRL published technical reports and professional journals that are widely distributed to the industry, and are reprinted in publications such as *Professional Roofing*, *RSI*, and *Contractor's Guide*. Presentations are made at technical meetings including NIST/NRCA's National and International Conferences on Roofing Technology, and national seminar programs such as the Midwest Roofing Contractor Association and the Roof Consultants Institute annual meetings. Results also are provided to standards-writing and related organizations, such as ASTM Committee D08 on Roofing, Waterproofing, and Bituminous Materials and the CIB/RILEM Committee on Membrane Roofing Systems.

Impact. The National Roofing Contractors Association (NRCA) adopted BFRL's technologies on roofing asphalts and built-up roofing (BUR) membranes. BFRL research results are referenced in the *NRCA Roofing and Waterproofing Manual*, the most widely used source in the United States for roofing design and application procedures. In addition, NRCA cites BFRL's roofing results in its *Roofing Materials Guide* as the reference for characterizing the properties of BUR membranes. This guide is widely used by architects and engineers for selecting low-slope roofing materials. ASTM produced several standards under BFRL leadership for single-ply roofing materials, including standards for poly(vinyl chloride), vulcanized elastomers, and nonvulcanized polymeric sheets.

Simulating Fires with Computers

Problem. Through the 1980's fire professionals lacked the ability to predict fire and smoke transport through a building to understand the behavior and movement of the building's occupants and the resulting effect of smoke and toxic gas on the occupants. Fire professionals needed well-developed methods based on science to make sound judgments about selecting appropriate materials for fire safety.

Approach. BFRL pioneered efforts to translate the growing field of fire science into engineering calculations using computers. Through the work of staff and grantees at major U.S. Universities, the first fire models were developed and applied to problems of national and international interest. As personal computers brought the hardware to most engineers and fire professionals, the use of and demand for these analytical tools grew.

Findings. Today, there are more than 50 fire models and related software tools developed in more than a dozen countries, most of which can trace their origins directly to BFRL models. For example, BFRL produced the fire hazard evaluation methodology called HAZARD I. The PC compatible fire hazard assessment tool evaluates the fire safety of buildings and determines the number of fatalities and cause of death for each. These complex fire models address combustion characteristics of the burning items and building components, the influence of building geometry and ventilation, and the physiological and psychological aspects of the human victims of fire. This software helps improve design and construction practices, provides fire fighter's training, and quickly provides product manufacturers with information about the fire hazard of their products. It is used for fire reconstruction, building design and code equivalency analysis, and industrial risk management.

Delivery Method. The methodology was disseminated to the fire community and professional societies. In the nearly 2 years since its introduction, over 400 copies of HAZARD I have been purchased worldwide (international sales account for nearly 25% of total sales).

Impact. This software helps improve design and construction practices, provides fire fighter's training, and quickly provides product manufacturers with information about the fire hazard of their products. It is used for fire reconstruction, building design and code equivalency analysis, and industrial risk management. The software predicts the fire induced environment, the reaction time of building occupants to evacuation, and the impact of exposure to heat, smoke, and gases during the evacuation process. A sampling of the HAZARD I software uses include: a Canadian firm evaluated equivalencies to the Canadian National Building Code; a Swedish government researcher studied passenger safety on large ferry boats; an Australian engineer analyzed a fatal hotel fire and testified at a Coroner's Inquest; various U.S. forensic firms studied major fires in conjunction with litigation; a number of U.S. and foreign fire departments are conducting both post-incident analyses and pre-planning of tactics for potential incidents; manufacturers of fire safe products are analyzing the potential benefits of performance improvements in their products and assisting marketing efforts by justifying the extra cost, quantifying the benefits of that performance to the end user; architects and building designers have justified requests for variance with building code provisions based on equivalent safety performance of innovative materials or arrangements.

Fire Safety Evaluation System

Problem. The National Fire Protection Association's Life Safety Code is a model code designed to provide a reasonable level of safety by reducing the probability of injury and loss of life from the effects of fire. It is used in many jurisdictions in the United States. The code contains numerous specific provisions for new and existing buildings under various occupancy classes such as health care, apartment buildings, etc. To provide some building design flexibility in meeting the requirements of the code, the term "or equivalent" is used. The problem facing designers and regulators was to decide when a design provides equivalent fire safety.

Approach. For each occupancy, the parameters that affect life safety, e.g., construction, interior finish, detection and alarm systems, automatic sprinklers and evacuation routes were identified. Using Delphi panels of experts in building fire safety, a numerical value was assigned to various available designs or material classes for each parameter. A system of summing the numerical values appropriate to containment safety, fire control, people movement safety and general safety was developed and tested with the Delphi panels. Each Fire Safety Evaluation System was tailored to the special safety concerns of the occupancy class.

Findings. Fire safety professionals agreed on using sets of parameter values that provide a measure of equivalent fire safety. The Fire Safety Evaluation Systems are designed for use by building designers and those responsible for approving the fire safety design of constructed facilities.

Delivery Method. BFRL staff were members of the NFPA Committee on Safety to Life and the subcommittees responsible for different occupancy classes, and chaired the Subcommittee on Alternate Approaches to Life Safety. Prototype fire safety evaluation systems for specific occupancy classes were developed, tested, presented to the subcommittees, and refined within the committee's structure. Normal balloting procedures of NFPA were used to adopt the fire safety evaluation systems.

Impact. Fire safety evaluation systems for health care, detection and correction, board and care homes, and business occupancies are now part of the NFPA Life Safety Code as NFPA 101M Alternative Approaches to Life Safety and are used in many parts of the country to assess the fire safety of existing and newly designed buildings. At a time when the use of board and care homes was expanding through the conversion of older buildings, the application of the system by building code officials and the Health Care Finance Administration led to dramatic reductions in fire deaths in these homes. The flexibility that the system provides avoids unnecessary duplication of requirements and consequently reduces the cost of providing adequate life safety protection against fire.

Fire Investigations

Problem. Knowledge of the causes and impact oflarge fires, particularly those that result in death, provide guidance on the need to change the requirements of fire codes.

Approach. BFRL responds to requests by state fire marshals and Federal agencies to assist in the technical investigation of high impact fires. Recent fires in which BFRL has played a major part in the investigation include the Dupont Plaza Hotel in Puerto Rico, the First Interstate Bank Building in Los Angeles, a three-bedroom duplex in Sharon, Pa., the Hillhaven nursing home fire in Norfolk, Va., the Happyland Social Club in New York and a board and care facility in Colorado Springs , Co. In the DuPont Plaza Hotel fire BFRL engineers worked with the National Response Team of the Bureau of Alcohol Tobacco and Firearms, the U. S. Fire Administration, and the National Fire Protection Association during the on site investigation, and the exchange of technical information. Based on BFRL site observations and test samples obtained at the scene the BFRL team analyzed the growth and spread of the fire from the ballroom complex where the fire originated, the foyer that connected the ballroom complex to the lobby and casino areas where most of the deaths occurred. BFRL's analysis involved the use of fire growth models, engineering formulae addressing mass burning rate, rate of heat release, smoke temperature, smoke layer depth, velocity of smoke/flame front, oxygen concentration in the smoke layer, sprinkler and smoke detector response, and fire duration.

Findings. In most cases the analyses show the most likely path, and extent of the fires's development at different times, sometimes indicate whether accellerants could have been involved, and usually point to aspects of the building design, furnishings or peoples actions that contributed to the fire development. In the case of the DuPont Plaza Hotel, although there were no sprinklers or smoke detectors present, the analysis predicted when in the course of the fire they would have actuated, and the additional evacuation time that could have been provided.

Delivery Method. An engineering analysis report is supplied to the local authority or Federal agency and published as an NIST report. Sometimes depositions are given. In most cases the findings are also presented at technical society meetings such as those of the Society of Fire Protection Engineers and the National Fire Protection Association. In the case of the DuPont Plaza fire a member of the BFRL staff served on a fire code task force in Puerto Rico to recommend changes to the local fire code.

Impact. The results of the analysis at the DuPont Plaza Hotel fire were presented at a Congressional hearing on hotel fire safety, and were used in the writing of the Hotel/Motel Fire Safety Act of 1990, Public Law 101-391. The fire codes in Puerto Rico have been updated to address most of the findings of the analysis. This and other analyses have been used by others in addressing various aspects of fires under litigation and is used as examples in demonstrating the application of analytical methods to fire investigation. HHS, GSA, the Postal Service, the Architect of the Capitol, and other Federal agencies have used the results of our analyses to upgrade facilities and practices.

Soot Formation and Evolution

Problem. Unwanted fires cause many thousands of deaths and billions of dollars of property damages each year in the United States. Once a fire is larger than about 0.03 m^3, radiation from soot dominates energy transfer. Soot formation processes control the amount of smoke and toxic gases, such as CO, which are emitted from fires, and visual obscuration from smoke hinders escape from fires.

Approach. BFRL researchers and associated grantees have performed extensive experimental and modeling efforts which are leading to a comprehensive and integrated description of soot formation and smoke evolution in diffusion flames. When this capability is combined with appropriate descriptions of turbulent flows, which occur in real fires, then the radiation properties of fires, the production of toxic gases, and visibility conditions can be predicted.

Findings. Key contributions were made from both experimental and modeling approaches. The basic steps of soot inception, growth, and oxidation have been delineated. The most important chemical species involved in each of these steps have been identified by detailed measurements in relatively simple, laboratory size flames. These results have produced important input and tests of modeling descriptions for soot formation and destruction.

Delivery Method. The experimental and modelling investigations on soot formation processes were authored in numerous papers and archival journals, i.e., *Combustion and Flame* and *Combustion Science and Technology*, presented through invited talks and at international workshops and conferences.

Impact. BFRL's research findings have advanced the understanding of chemical structure of hydrocarbon diffusion flames and improved the characterization of optical properties of soot particles. BFRL established leadership in making quantitative concentration measurements in laminar, hydrocarbon diffusion flames and in modelling and characterizing smoke agglomerates. BFRL's database of species and temperature information is the best available for any hydrocarbon diffusion flame and provides a critical comparison for predictions of flame species concentrations. Partly as a result of these contributions, model development on soot formation processes is now active on a worldwide basis. Most worldwide investigators are incorporating BFRL's data in their descriptions. The quality and impact of this work has been well recognized by invitations to participate in international workshops and at leading universities and national laboratories, and election to chair the prestigious Gordon Research Conference on the Chemistry and Physics of Laser Diagnostics in Combustion.

Cone Calorimeter Development

Problem. Heat release rate (HRR) was identified as the single most important aspect describing hazard from building fires. Techniques for measuring HRR in a bench-scale test apparatus were under development since the 1950s. The methods available for use were troubled by serious errors and were so complex that they did not lend themselves to standardization and commercial use. Research studies during the 1980s identified that some other material fire properties, especially mass loss rate, ignitability, and smoke production rate, needed to be measured on specimens concomitant with the HRR measurement if proper use of data was to be made.

Approach. BFRL developed several prior generations of research use apparatuses for HRR measurement. Based on this experience, a development process was started whereby a HRR calorimeter would be designed which would lend itself to use by commercial testing laboratories. The engineering principle known as oxygen consumption calorimetry was explored and made practical at BFRL during the late 1970s and early 1980s. Use of this principle allowed a significant simplification to be made in instrument design, which led to the eventual concept of the Cone Calorimeter. The name here refers to the truncated-cone shape of the heating element which impresses a controlled radiant flux upon the specimen.

Findings. BFRL researchers developed the Cone Calorimeter; the primary measurement tool used by industry and testing laboratories to characterize the fire hazards of small samples (150 mm) of building materials, furniture, and other products. It proved to be a tool of much higher accuracy than the previously available methods. BFRL's work was recognized by an R&D 100 Award being granted for its development.

Delivery Method. The Cone Calorimeter was adopted by ASTM as its E1354 Standard in 1990. ISO has approved it as ISO Standard 5660 in 1991. Commercial instrument makers have fabricated over 75 of these units based on BFRL's construction drawings, and placed them into service. BFRL published a User's Guide to the Calorimeter, which constitutes the most detailed training and operator's guide ever developed for a fire test method.

Impact. The Cone Calorimeter is intended as the primary measurement tool for characterizing the fire hazards associated with building materials, furniture, and a wide variety of other products. A method was developed at NIST allowing the use of bench-scale Cone Calorimeter data to take the place of testing furniture items in full-scale. Inexpensive and high quality tests now are available to the design and construction team including the owner for a variety of building materials. This measurement method was recognized by the National Fire Protection Association as having significant advantages of reduced cost and decreased time required for testing. The tool is expected to replace many existing national tests within the European Community activities. The U.S. Navy mandated a design procedure for composites used on submarines whereby Cone Calorimeter testing is used; it is considered the most effective way available for characterizing the fire behavior of these materials. The Cone Calorimeter is being actively explored by the electric wire and cable industry, for use in characterizing flammability and corrosivity of their products. The development and widespread use of the cone calorimeter has lead to publication of over 300 scientific papers worldwide. Many of these publications are by authors from the United States.

Smoke Detector Standards

Problem. In the early 1970's, it was recognized that the widespread use of smoke detectors in residences could reduce life loss in fires by 30 - 50%. However, a barrier to widespread acceptance was the lack of standards establishing either minimum performance requirements or installation guidelines.

Approach. BFRL initiated a cooperative project with Underwriters Laboratories (UL) to develop performance requirements, including criteria and measurement apparatus. Tests were performed in houses scheduled for demolition by setting common household fires and recording the performance of detectors in different locations to establish the best recommended numbers and locations. These tests formed the basis of standards from the National Fire Protection Association (NFPA) and for many state and local laws requiring detectors in newly constructed homes and apartments. BFRL worked with IIT Research Institute and UL to develop installation guidelines and effectiveness data.

Findings. During the studies, the BFRL engineers uncovered problems with certain detectors which were quickly corrected by their manufacturers. In a few instances, this resulted in national recalls monitored by the Consumer Product Safety Commission. As a related technological development BFRL developed the first (and still only) smoke detector sensitivity tester which can make in-place quantitative measurements on any type or model of detector.

Delivery Method. The findings were published in a landmark report known as the Indiana Dunes Report, which is still the primary reference document on residential detector operation and established the installation requirements contained in the NFPA standard (NFPA 74). The results of this work formed the basis for the UL standards for residential (UL 217) and commercial (UL 268) detectors. In later years, the UL 217 standard was the basis for an International Standards Organization (ISO) standard for residential detectors. The technological advances by BFRL received frequent attention from the popular press including *Parade*, *Readers Digest*, *Popular Science*, and *Consumer Reports*; and were highlighted in a segment on the Today Show which brought 17,000 letters to BFRL from viewers.

Impact. All of the model building codes, and all Federal, state, and local laws requiring residential detectors in the United States (and some foreign countries) use the findings from this study. The publicity given to the results of this study resulted in increased demand, lower prices, legislated installations, and spectacular market developments. Annual sales of residential detectors increased from about 250,000 in 1972 to 14,000,000 in 1978. Today, approximately 80 percent of households in the United States have smoke detectors. The widespread use of smoke detectors in the United States has been a major factor in the dramatic reduction in the fire death rate in the United States, from over 60 per million population to less than 30. Interest in Europe grew in response to rapidly expanding U.S. markets. None of the European manufacturers were positioned to meet these demands; the U.S. manufacturers captured a large majority of this market, often representing the first export opportunity for these companies.

Standard for the Flammability of Children's Sleepwear

Problem. Children's sleepwear on the market during the 1970s and before, presented an unreasonable risk of death and injury under the Flammable Fabrics Act. The majority of children who were injured or killed from burning apparel were wearing nightwear. Most of this nightwear ignited easily and burned rapidly resulting in up to 300 deaths per year and thousands of injuries. The majority of burn injuries were to the face and hands causing significant disfigurement and loss of much use of the hands.

Approach. BFRL conducted flammability studies of full size garments on mannequins, tested fabric samples according to the then current ignition and flammability test procedures, surveyed the technology available for providing ignition resistance, studied the economic impact on garment manufacturers of various approaches to providing ignition resistance, developed an appropriate fire test method, and prepared a draft standard.

Findings. A Standard was approved and promulgated under the authority given to the Secretary of Commerce by the Flammable Fabrics Act as amended. This authority was later transferred to the Consumer Product Safety Commission.

Delivery Method. The BFRL procedures developed as the sleep Standard, under the Flammable Fabrics Act, was published in the Federal Register. BFRL staff regularly gave papers at meetings of trade associations (American Apparel Manufacturer's Association), standards bodies (ASTM), and fire related organizations (NFPA, Information Council on Fabric Flammability).

Impact. There have been no deaths due to the ignition and burning of children's sleepwear. Burn injuries have been treatable, usually without hospitalization and without disfigurement. This work established BFRL as the leading international authority on apparel flammability.

Smoldering Insulation Fires

Problem. As the cost of energy rose rapidly after the oil embargo of the early 1970's, there was a high demand for thermal insulation in residential buildings. One cost-effective insulation, which became widely used, is cellulosic insulation which is produced from recycled newsprint. The extensive use of this poorly-controlled product led to a rash of home fires across the country.

Approach. BFRL examined the fundamental and practical aspects of this problem, revealing that a smoldering fire could be initiated in this material if it contacted heat sources as recessed light fixtures in attic floors. This smoldering could break into flaming in the presence of light winds through the attic space.

Findings. The smolder initiation process could be eliminated through proper manufacturing, which included effective smolder and flaming retardants, and through careful installation of the insulation which assured that it did not come into contact with heat sources. Test methods were devised which could assure that the material was properly formulated so as to minimize its smoldering and flaming tendencies.

Delivery Method. The findings were delivered to the Consumer Product Safety Commission who promulgated regulations requiring that all cellulosic insulation pass the BFRL-developed test methods and that it be installed in a controlled manner.

Impact. The problem of smoldering insulation fires in residential buildings largely has been eliminated.

Wood Heating Safety Research

Problem. The energy crisis in the late 1970's led to a large increase in the use of wood as an alternate heating source. Along with this increase came a dramatic increase in the number of unwanted fires. The marked increase in the late 1970's and early 1980's is attributed to a growing number of installations and expanded use of wood burning stoves in homes throughout the United States where most homes are made of combustible construction. Standards for the safe installation and use of the appliances were based on information more than 40 years old and rarely applicable to modern appliances.

Approach. BFRL led concentrated research efforts to provide new and updated information to develop appropriate codes and standards for the modern appliances. Programs have been targeted to raise consumer awareness through education and to improve the standards and codes governing the construction, installation, and testing of appliances. Much of the supporting technical information for the standard and code changes and for consumer education has come from BFRL research. Today, much of the 40-year-old data and folklore originally used to develop the codes, standards, and public educational materials is being replaced by solid technical information.

Findings. Wood heating safety research at BFRL concentrated on several key aspects of the fire problem: clearances needed between wood burning appliances and combustible construction materials, creosote buildup and burnout, protective barriers to allow reduced clearances of appliances to combustible walls, safe methods of joining a chimney connector to a masonry chimney through a combustible wall, and theoretical prediction of appliance and wall heat transfer with arbitrary wall protection.

Delivery Method. As the research results became available in BFRL reports and journal articles, BFRL staff worked closely with building and fire code committees to develop a new generation of code requirements for wood heating appliances. Most of the current codes related to wood heating are based on BFRL research.

Impact. BFRL's research and others are responsible for improving the safety of these appliances and reversing an increasing fire incidence rate. After several years of extensive research on fire safe installation and use of solid fuel heating appliances have produced modern data and technical information that contributed to reversing a dramatically increasing fire problem. The drop in fire incidents is illustrated by the statistics of a high of more than 200,000 fire incidents per year in 1980 to less than 130,000 in 1987.

SECTION 2
PRELIMINARY IMPACTS

In-Place Testing of Concrete

Problem. Knowledge of the strength of concrete during construction is of critical importance for safety and economy. Failure to measure the in-place strength prior to initiating critical construction procedures have resulted in catastrophic failures and loss of lives. While a variety of methods have been proposed for estimating in-place strength, they have not been used extensively by the construction industry. Reasons for this include the lack of a clear understanding of the fundamental properties measured by some in-place test methods and the lack of suitable statistical methods for arriving at reliable strength estimates.

Approach. BFRL has undertaken research to establish a basic understanding of some of the in-place testing techniques. In addition, BFRL researchers in collaboration with statisticians in the Computing and Applied Mathematics Laboratory have sought to develop practical and reliable statistical procedures for evaluating in-place test results.

Findings. Based on analytical and experimental studies, BFRL researchers have established the failure mechanism for the pullout test, which is one of the more reliable techniques for estimating the in-place strength of concrete. In addition, BFRL research has established a rational procedure to implement the maturity method for estimating in-place strength of any concrete mixture. Recent work has also demonstrated that the method is applicable to "high-performance concrete," which is characterized by its very low ratio of water to cementitious materials. Finally, a relatively simple statistical procedure has been developed to evaluate in-place test results.

Delivery Method. The research results have been reported extensively in technical journals and presentations have been made at professional meetings. In addition, BFRL staff assumed leadership roles to get the research results incorporated into ASTM standards, reports of the American Concrete Institute, and technical recommendations of RILEM.

Preliminary Impact. BFRL research was instrumental in the development of ASTM Standard Practice C 1074, the first national standard on the use of the maturity method. The recommended statistical procedure is under consideration as a recommended practice by the American Concrete Institute. Publication of these standards promote widespread use of in-place testing and allow U.S. contractors to compete with their international competitors.

Communication Protocols for Building Automation and Control Systems

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

Approach. NIST staff has provided leadership and technical support for an industry-wide effort to develop a standard communication protocol which is capable of meeting the present and future needs of the building industry. NIST staff has contributed directly to the standard by writing large portions of the standard, building laboratory prototype implementations of the protocol, developing a framework for testing conformance to the standard, and making NIST facilities available to manufacturers who wish to test their own prototypes.

Findings. Under the auspices of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), NIST and its industry partners have developed and published a draft standard titled, *BACnet: A Data Communication Protocol for Building Automation and Control Networks.* The standard is usually referred to as simply "BACnet", an acronym for Building Automation and Control networks. The BACnet standard is currently undergoing public review. A reference implementation of the protocol has been developed along with a protocol analyzer which can interpret BACnet messages and display them for human interpretation. A draft suite of tests for determining conformance to the protocol has also been developed.

Delivery Method. The BACnet protocol was published as a draft standard. The standard has received wide-spread attention. Several countries have indicated an interest in adopting it as an international standard. Detailed technical analysis of portions of the protocol, along with proposed testing methodologies, have been published by NIST and presented in industry forums. Articles describing the protocol and its potential impact have been published in building trade magazines. NIST laboratory facilities have been made available to industry participants for unofficial testing of their prototype products for conformance to the standard. The experience gained from these tests is expected to be applied to developing an industry-run program to certify conformance to the BACnet protocol.

Preliminary Impact. Many buildings do not use DDC technology because standards do not yet exist. In other buildings the technology is used, but not to its full potential. Adoption of the BACnet protocol will result in greatly increasing the use and effectiveness of DDC technology resulting in significant energy savings, reduced maintenance costs, improved occupant comfort, and increased productivity. Adoption of the standard also permits the concept of an "intelligent building," where HVAC, fire, security, lighting, and other building control systems are integrated. This allows building owners to optimize the interactions between systems and streamline management of the systems. The scale of benefits is broad, potentially affecting all commercial buildings in the world.

Computer Simulation of the Properties of Concrete and Other Porous Materials

Problem. Concrete is a complex, environmentally sensitive, porous material about which it is difficult to learn from experiment. It would be desirable to be able to predict the properties of concrete, particularly those that are difficult to measure, from the properties and proportions of its constituents, and the conditions of mixing, curing, and use. The results would be valuable for guiding engineers in the design of concrete for specific purposes and for educating new generations of engineers.

Approach. BFRL is developing computer models to simulate the microstructure development during the setting and hardening of cement, and to simulate the transport properties of the hardened porous mass. Models already developed show the relationship between degree of hydration of a cement and the pore structure for a given water/cement ratio, the microstructure of cement paste close to the surface of an aggregate particle for pastes both with and without a mineral admixture such as fly ash or silica fume, and the diffusivity of the capillary pore system in the structure formed.

Findings. The results of the calculations have given insights into the diffusivity of cement pastes that could not have been obtained without extensive and costly long-term experiments. They also have been used to aid the interpretation of recent data from Purdue University on the pore structures of a series of cement pastes and mortars.

Delivery Method. The results of the BFRL work are published in journals intended to be read by potential users on several different levels. The results also are shared with the research community through seminars, talks at scientific meetings, and at an annual one-week workshop held at NIST each summer. Since a portion of the work is supported by the NSF Center for Advanced Cement-Based Materials, progress is shared with researchers in the Center's four participating universities -- Northwestern, Illinois, Purdue and Michigan -- through semiannual presentations and research collaborations; the results are also shared with the Center's 13 Industrial Affiliates. Delivery to the standards community is taking place through the Research Subcommittee in ASTM C-1 on Cement, and the Subcommittee on Mathematical Modeling of Cement Hydration in ACI 225 on Hydraulic Cements

Preliminary Impact. The BFRL work has received national and international attention. It has been reported in *Engineering News Record*, ASTM's *Standardization News*, *Oilfield Review*, and in *Cray Channels*, the house publication of the Cray Computer Company. The international impact of the work is recognized by the award to BFRL's principal investigator, Edward Garboczi, of the Robert 1992 L'Hermite Medal from RILEM, the International Union of Testing and Research Laboratories for Materials and Structures.

Cigarette-Induced Furniture Fires

Problem. The national fire incidence statistics continue to reveal that cigarette-initiated fires in upholstered furniture are the leading causes of fire deaths in the United States. A voluntary furniture industry program which seeks to limit smolder-prone materials has had a limited impact on the problem.

Approach. Congress has mandated that an alternative approach be assessed, that of modifying cigarettes to lessen or eliminate their tendency to cause smoldering fires when they come into contact with soft furnishings. This has the potential advantage of being able to impact the problem almost immediately instead of over a period approaching 2 decades which would be required to replace existing furniture.

Findings. In the first part of this research, BFRL established the technical feasibility of cigarettes which will not ignite soft furnishings, even if the cigarette continues to burn while in contact with them. BFRL has now developed a standard test method to rate the furniture ignition propensity of cigarettes. The method is currently in round robin testing among nine laboratories across the country.

Delivery Method. The results of the BFRL studies are being delivered to the Consumer Product Safety Commission who convey them to Congress for possible action.

Preliminary Impact. The potential impact is immense. Should less fire-prone cigarettes become commercial, up to 1200 fire deaths could be avoided annually (1/4 of the current national total). Additional yearly benefits could include elimination of over 3000 serious injuries and $0.5 billion in residential property losses alone.

Carbon Monoxide Formation in Enclosure Fires

Problem. Roughly two thirds of all fire deaths (3000 deaths per year in the United States) are attributed to smoke inhalation. The component of smoke which is responsible for the vast majority of these deaths is carbon monoxide which is generated at high concentrations by enclosure fires. Despite the importance of the problem, very little was known concerning the generation of CO by fires. An understanding of the formation of this dangerous gas by fires is necessary so that models of the process can be formulated and possible means for limiting its formation by fires developed.

Approach. A workshop of fire researchers was convened in which the understanding of CO formation in fires was assessed and recommendations were made for a long-range research plan to address the problem. This led to the generation of a long-range research plan which has guided research in this area for the past 4 years. The research plan combines engineering approaches designed to characterize the amount of CO formed in enclosure fires and the parameters which control the amount generated and more fundamental components designed to provide insights based on the physics and chemistry responsible for fire behavior. Research is being performed by BFRL researchers as well as by academic workers who receive BFRL grants. The ultimate objective is to provide sufficient understanding to allow quantitative prediction of CO levels by BFRL models designed to predict fire hazard.

Findings. Work thus far has demonstrated that high CO levels are the result of under-ventilated burning and that vitiation of combustion gases seems to play a minor role. The results have confirmed an earlier hypothesis that fires burning within enclosures having two well-defined layers generate CO by quenching the flame gases in a rich, high-temperature upper layer. Recent research has shown that CO also can be generated by the direct introduction of air into the upper layer resulting from under-ventilated burning. A third mechanism, which can lead to the generation of very high concen-

trations of CO, has been identified. This formation mechanism is the result of pyrolysis of oxygenated organic polymers (such as wood) in a high-temperature, highly vitiated upper layer. The latter two mechanisms have been identified for the first time during this project.

Delivery Method. The results of this work are made available to the fire research community by a series of NIST reports and journal publications. Additionally, the results are being incorporated into fire models under development within BFRL to predict fire hazard. These models ultimately will be used to design buildings with improved fire safety.

Preliminary Impact. The results of this work are leading to an improved understanding of CO formation during enclosure fires and are being incorporated into fire models. Ultimately, the models will be used to improve fire codes so enclosure fires will be less likely to generate and transport the levels of CO responsible for the majority of fire deaths.

Halon Alternative Fire Extinguishing Agents

Problem. The search for chemicals to replace halon fire extinguishing agents is proceeding too slowly for the implementation of alternatives before current supplies of halons become depleted. None of the alternatives proposed to date have both a low potential for ozone depletion and a high fire suppression efficiency. Halon 1301 is used in a multitude of aircraft applications with little understanding of the phenomena which control the extinguishment process. Deadlines imposed for ceasing production of halons have intensified the need for the fire suppression industry and end-users to identify the best alternatives for maintaining safe operation of aircraft without further damage to the ozone layer.

Approach. A comprehensive experimental program has been established to screen promising chemicals to identify the best candidates for a subsequent full-scale aircraft fire extinguishment evaluation program. The research deals with the thermal properties and dynamics of agent dispersion, flame extinction measurements, and flame/agent chemistry. Theoretical models are being used to interpret the results, to increase our understanding of the suppression process, and to predict behavior over an expanded range of operating conditions. In particular, control of those phenomena which dominate the actual suppression process is sought, be they the chemical reactivity of the agent or the properties associated with the physical mixing of the agent into the fire.

Findings. The effectiveness of a fire suppression agent is related to its thermodynamic properties, its behavior during two-phase flow, its interaction with flame chemistry, the timing of its release and the nature of the fire. The sudden discharge of low boiling point alternative agents into the atmosphere has been recorded and numerical models developed to simulate the emptying process and the development of the super-heated spray. Details of the flow are being measured with high speed photography of the exiting spray. A number of flame extinction facilities have been devised to

experimentally simulate the behavior of the agent over the operational range of conditions expected in a full-scale aircraft fire. Chemical kinetic modeling and the results of diffusion flame measurements are being used to determine whether the dominant mechanism of suppression is chemical or physical. Additional chemicals are being theoretically designed which appear to have high flame suppression efficiency and low ozone depletion potential.

Delivery Method. The information gained by this effort is formally disseminated through reports to the sponsoring agencies, the Annual BFRL Fire Conference, and at scientific and professional meetings. Informal discussions are being held with the fire suppression industry, chemical suppliers, and other agencies concerned with finding satisfactory ozone-friendly agents.

Preliminary Impact. Research into how halons suppress a fire or how to increase delivery of the agent to the fire has lain dormant for decades because Halon 1301 has been such an effective fire-fighting agent in aircraft applications. By undertaking this research in collaboration with other government agencies, BFRL will be in a position to provide the generic information to the chemical producers and fire protection industry which is required before a new generation, environmentally benign fire suppression system can be designed. The impact of this work will be significant because it will reduce the tradeoffs necessary between crew safety and aircraft performance.

Turbulent Mixing Research

Problem. Effective models of turbulent combustion are required to allow prediction of the behavior (especially CO generation) of unwanted fires and to allow the design of practical combustion devices with improved energy efficiency and reduced pollutant emissions.

Approach. BFRL researchers initiated a long-term investigation of isothermal, variable density turbulent flows. Powerful new optical diagnostics were developed to characterize mixing in these complex flow fields. These diagnostics were applied to both momentum- and buoyancy-dominated flows. The findings were used in the generation and validation of models of turbulent mixing of variable density fluids--a fundamental requirement for modeling turbulent combustion.

Findings. Experiments have demonstrated that the largest eddies (roughly the same length as the flow) in the flow field are responsible for entrainment into turbulent free shear flows. The time-averaged mixing is therefore independent of molecular properties. The mixing behavior is highly dependent on density differences in regions of the flow field where density gradients are large. Eventually, as the flow entrains ambient fluid and the jet density approaches ambient density, the mixing behavior is determined primarily by the flow momentum. Variable-density axisymmetric jets have been shown to obey simple engineering correlations for large downstream distances where the flow density is approximately equal to the ambient density. The results also provided direct insight into the mechanisms for the stabilization of lifted turbulent jet diffusion flames which had been the subject of a great deal of speculation. The observed eddy structure indicates that stabilization will occur on the upstream edges of the large eddies where velocity and concentration gradients are low.

Delivery Method. Results of this research have appeared as a series of internal reports and archival journal articles. Findings also have been presented in numerous invited seminars

and national and international scientific meetings.

Preliminary Impact. The results of these measurements were cited numerous times in the literature and have been used for comparison with modeling studies. BFRL's approach for investigating variable density flows was adopted by the French government which has funded a National Program in Turbulent Mixing. Their research Program is an integrated experimental and theoretical effort involving numerous government and academic laboratories. The extent of the Program is evident from a recent workshop funded by the Centre National de la Recherche Scientifique in Orleans, France. William Pitts of BFRL was invited to this workshop as the only foreign participant. Much of the current French effort is built directly on BFRL's research. It is anticipated that the French program will make a significant contribution to the modeling of turbulent combustion.

Materials Fire Research

Problem. Two recent trends which have started to affect the U.S. plastics and manufacturing industries are polymer recycling and a demand for nonhalogenated flame retardants. The huge waste volume of plastics is an important problem for modern society. Landfills and incinerators are unwelcome on the periphery of cities where they are most needed. A more popular solution to the problem is recycling. But some of the same social forces which are encouraging recycling are also having an impact on acceptable retardants. Brominated flame retardants have gained a major position in the worldwide plastics industry. To meet today's requirements in the electronics and electrical equipment industries, for example, virtually every plastic requires flame retardancy, frequently with brominated compounds. Due to publicity about dioxin and furans as possible degradation products, these retardants have acquired a negative public image in Europe and soon they may be regulated. Although the overall use of halogenated flame retardants is still showing an upward trend, the preceding concerns have started a definite search for alternatives. As a result of these trends, it is possible that available selections of polymer materials and of flame retardant treatments will be more limited than in the past. Since the regulations for fire safety will not be eased in the future, this could mean that improving or even maintaining the current level of flammability performance across the U.S. plastics and manufacturing industries will become much more of a challenge.

Approach. BFRL performs research on nonhalogenated flame retardant treatments which form char during polymer burning. This treatment is ideal because carbon atoms retained in the condensed phase as char lessens the available fuel for flaming combustion even as they help insulate the polymer from the heat of the flame. A molecular dynamic model describing the behavior of polymer chains and fragments from heated polyethylene has been developed and solved numerically on a super computer to determine under what conditions the formation of crosslinks among the polymer

chains is enhanced. The model is being extended to apply to other polymers. Experimentally, electron-beam irradiation is applied to various plastics to form crosslinks and the flammability properties of the irradiated samples are being measured. This project is a cooperative study with the Technical Center, Federal Aviation Administration. In another cooperative study with GE's Corporate Research and Develop Center, the effects of silicone on the flammability properties of engineering plastics are measured and the effects of varying char structure on their flammability properties are determined.

Findings. The theoretical calculation demonstrated the possibility of the formation of crosslinks during the thermal degradation of polyethylene and determined the conditions under which this formation is enhanced. The concept of flame retardancy by the irradiative crosslinking of a polymer sample was demonstrated by the formation of a small amount of char from burning the irradiated polyethylene. The addition of silicone to polycarbonate significantly reduces the peak heat release rate, although the amount of char formed is about the same as that without silicone. It appears that there exist significant effects of the char structure on flammability properties.

Delivery Method. The results were presented at various technical meetings and seminars and published in technical journals.

Preliminary Impact. Many inquiries were received from U.S. companies seeking possible cooperative studies with BFRL to develop new type flame retardant treatments. This joint work will help U.S. industry meet the challenge described above and to maintain and enhance its competitiveness.

Furniture Flammability Testing

Problem. The California Bureau of Home Furnishings introduced a flammability test for seating furniture for consideration for use in public occupancies (hotels, prisons, nursing homes, etc.). The ignition source, crumpled newsprint, resulted in substantial variability in the test results. The variability of the ignition source was particularly critical when applied to substrates that are marginally ignitable. The problem was to develop an ignition source of similar severity but with more consistent behavior.

Approach. The ignition source of five sheets of crumpled newspaper was first characterized by testing it on an inert mock-up. Video observations were made of the flame extension and the area of impact. An infrared camera was used to make quantitative measurements of the two dimensional surface temperature patterns, and a computer based image analysis system was used to identify optimum locations for more accurate heat flux measurements. A gas burner, an inherently more reproducible heat source, was then designed to replace the original source. The characteristics of the new burner were carefully measured.

Findings. By improving the nature of the ignition source and by making it possible to quantify the rate of heat release from the furniture item in the test, BFRL brought the test method into the mainstream of modern fire protection technology. The original ignition source proved to be subject to appreciable variability in its affects on the side arms of the chair, and the level and duration of heat flux on the seat back. The gas burner produced a more reproducible flame and was preferred as an ignition source.

Delivery Method. BFRL researchers collaborated with staff of the California Bureau of Home Furnishings (CBHF) during the study. BFRL researchers developed source characterization measurements and CBHF researchers performed full scale room burn tests. The results of the collaborative study were published in NIST research reports and presented at techni-

cal meetings. The new test method is being introduced to ASTM for adoption as a standard test.

Preliminary Impact. The new ignition source has been included in the California test and is being used in several private testing and product development laboratories. A number of other States have pending legislation to adopt the California test for public occupancy furniture. Most public occupancy furniture manufacturers nationwide are making furniture to meet the CBHF test.

Standard for the Cigarette Ignition Resistance of Mattresses

Problem. Cigarette ignition of mattresses and upholstered furniture is the leading cause of fire deaths in the United States. Smoldering combustion is a slow, insidious form of combustion, very difficult to extinguish and may go unnoticed for up to an hour after the cigarette is dropped. Smoldering often progresses to open flaming in mattresses and upholstered furniture. Victims typically die from smoke inhalation.

Approach. BFRL conducted ignition studies of full-scale retail mattresses. Methods for improving the ignition resistance were developed and evaluated. Commercially available cigarettes were studied for their ignition performance on mattresses. The potential impact on the mattress industry of a mattress ignition standard was studied.

Findings. A cigarette ignition test method for mattresses was developed and a draft standard was prepared and recommended. The Consumer Product Safety Commission published the final standard after the responsibilities under the Flammable Fabrics Act were transferred to them.

Delivery Method. The procedures developed under the Flammable Fabrics Act require three distinct steps, all published in the Federal Register. In addition, BFRL staff regularly gave papers at meetings of trade associations, e.g., National Association of Bedding Manufacturers, standards bodies, e.g., ASTM, and others. A major effort was made to provide the mattress industry with viable means to comply with the standard through their trade associations and trade publications.

Preliminary Impact. The effect of the mattress ignition standard has shown that the incidence of cigarette ignition of mattresses is reducing rapidly.

Support of Navy Firefighter Trainer Program

Problem. Ships are lost due to fire. It is essential that each seaman receive "Hot Fire" training to control and extinguish fires that may occur accidently, or as a result of enemy action. The Navy is developing and building 33 propane-fired trainers, that will be located at Naval Stations on the continental United States, Hawaii, and Japan. The trainers must provide safe and realistic training without causing unnecessary pollution of the environment.

Approach. Since 1986, BFRL has served as a technical resource to this Navy program. Activities include:
a. measuring the environment within the trainer for safety and realism -- air temperatures, temperatures of equipment that the trainees may contact, radiant heat flux, gas composition (breathability), smoke density, and other characteristics,
b. solving trainer development problems, using such NIST capabilities as computational fluid mechanics and electron microscopic examination, and
c. helping to satisfy State and Local Air Pollution Control personnel, at the sites where trainers are built, about trainer emissions.

Findings. Calculations made on prototype designs showed the need for additional ventilation to avoid hazardous conditions and for increased separation of components to avoid undue thermal exposure to structural elements of the trainers. Computational fluid mechanics was used to evaluate various designs of wind screens to stabilize the fire in the open deck fire simulator. Measurements on samples of simulated smoke from the trainers and technical information on the toxicity of those products showed that trainers can be operated within state air pollution guidelines. Research showed that the ceramic insulation used in some trainers to protect the concrete walls was satisfactory despite the fact that it separated explosively from the concrete.

Delivery Method. This information is disseminated in official NIST "Reports of Tests" to the sponsor, presentations to the Fleet Project Team, discussions with the Navy "Device" contractors and operating personnel, and discussions with Navy and State Air Pollution Regulators.

Preliminary Impact. Two of the Navy Device Contractors are using Navy technology to develop and sell trainers for civilian fire fighter training. Although expensive, trainers with various scenarios are being purchased by major civilian fire departments, and consortia of departments for safe, realistic training of their personnel. The evaluation of the new wind screen using new computational techniques rather than full scale testing saved time and funding by the Navy in solving flame stabilization problems.

Using Fire to Clean Up Oil Spills

Problem. Subsequent to the major oil spill in Alaska from the grounded tanker Exxon Valdez, national attention has been focused on the development of new technology for oil spill response. As part of a research program funded by the Minerals Management Service, the capabilities and impacts of in-situ burning have been measured to assess the technology and provide responders with technical information needed for spill response decisions.

Approach. Laboratory and mesoscale experiments have been used by BFRL to measure the burning rate removal efficiencies, combustion products, and smoke plume trajectories of oil spill fires. Measurements have been performed using standard fire and environmental instrumentation and new exploratory methods of assessing fire characteristics. Computer modeling has been used extensively to understand the dynamics of local smoke plume motion and downwind smoke particulate deposition.

Findings. Burning has been shown to be a rapid and cost effective method of removing oil spills from the surface of the water. In mesoscale experiments, 13 m^3 of crude oil was burned in a 15 m square pan in 20 minutes leaving only 1 percent of the original oil mass as residue. Measurements have shown that the surface regression rate of burning crude oil is 0.055 mm/s. During burning, most of the oil is converted to the complete combustion products of carbon dioxide and water vapor. About 10 percent of the oil is converted to smoke particulates. Although a concern in the immediate area of the burning, the smoke produced from burning dissipates quickly downwind of the burn site. In order to predict the downwind trajectory and deposition of smoke particulate, a Large Eddy Simulation (LES Model) has been developed. This model represents a new technology for assessment of the local impact of large fire events. Interest has been expressed in using this modeling technology as the logical successor to an existing gaussian dispersion model used extensively by U.S. industry and government agencies to assess pollution and hazardous material exposures.

Delivery Method. Results of this research have been presented to Regional Oil Spill Response Teams meeting throughout the United States and at specialized technical meetings.

Preliminary Impact. In-situ burning of oil spills offers oil spill response professionals an additional choice to the existing mechanical recovery and dispersant methods. Burning requires a minimum of specialized equipment and has been shown to be a cost effective response method. In the arctic area, it is often the old viable method of oil spill response. BFRL is the only source of measurements and modeling applicable to in-situ burning of crude oil spills in the United States.

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