10. ENVIRONMENTAL SYSTEMS

10.1 INSULATION

Accurate knowledge of the insulating properties of building materials is important to thermal comfort, energy efficiency, and fire endurance for buildings. Development of measurement methods for the properties of thermal insulation has been an early and continuing concern for NBS and NIST. This section describes the work conducted in CBT and BFRL from 1975 through 2000 based substantially on accounts prepared by Robert Zarr who has led CBT/BFRL's work since the mid 1980s [1, 2].

The energy crisis of the 70s made economical insulations much thicker than the 25 mm thickness that could be measured by then-available standard apparatuses. Because of the complexity of heat flow through insulating materials, involving conduction, convection and radiation, heat flow varies with orientation and non-linearly with thickness. Because heat flow is small through large thicknesses of high-quality insulations, it is very challenging to measure the heat actually flowing through and not that flowing around the specimen. Fortunately, Henry Robinson, leader of NBS's insulation metrology research in the 50s and 60s, had developed an innovative measurement approach applicable to large thickness [3] - the line heat source guarded hotplate. A prototype apparatus was completed in 1978 and determined to perform as predicted [4].

By the mid 70s the Federal Trade Commission (FTC) was pressing the insulation industry to justify its labeling of the insulation value of thick insulations. Frank Powell represented CBT effectively in interactions with industry, FTC, and the Department of Energy (DOE), and led the planning of development of a One Meter Line-Heat-Source apparatus capable of direct measurements of insulating value at arbitrary orientations and thickness up to 380 mm [5]. With encouragement from industry, FTC and DOE, CBT organized a team led by Robert Jones, who was appreciated for his ability to achieve team results on schedule and within budget, to construct the apparatus, which was put into service in 1980. Mahn-Hee Hahn, who also had guided the early design of the prototype apparatus a decade earlier, championed the techni-

Robert Zarr, research mechanical engineer inserting an insulation sample in NIST's Line Heat Source Guarded Hot Plate, a large-capacity device for measuring the thermal resistance of insulation and other low-density materials up to 380 mm thick and 1 m in diameter. The Hot Plate provides calibrated specimens for guarded hot plates in other laboratories.

cal design and construction for the apparatus. The apparatus immediately was used to supply reference samples for calibration of industry's heat flow meters to allow industry to comply with the FTC's order for performing insulation measurements at representative thickness [6]. Jones received the Department of Commerce Bronze Medal Award and the NBS Measurement Service Award in 1981 for his efforts and those of his team. This effective response of CBT to an important national need was very valuable when the elimination of CBT was proposed by the President in 1983. Representatives of the U.S. Chamber of Commerce testified to Congress [7] that the improved insulation measurements made possible by the one meter apparatus saved U.S. consumers $90 million annually in insulation costs. The apparatus continues to provide NIST-traceable standards to industry through the development of thermal insulation NIST Standard Reference Materials (SRMs).

Heat transfer measurements also were needed on complex, compound walls to verify computational models. Reese Achenbach, in a final performance of his long, significant career at NBS, led in the design and construction of a large, calibrated hot box capable of measuring heat, air and moisture transfer for room-sized (3 m by 4.5 m) specimens for transient heat, moisture and pressure conditions on both sides (to represent internal and external conditions) [8]. The design and construction of the calibrated hot box was funded by the DOE through its Oak Ridge National Laboratory. Significant tests were conducted of super-insulated wood framed walls [9], and innovative masonry walls [10].

In the 90s, attention turned to measurement needs for advanced insulation technologies being developed to reduce the energy consumption associated with refrigerators, freezers, and the transport of refrigerated products. Among the insulation concepts being explored are powder, foam, glass-fiber-filled evacuated panels, and low-conductivity gas-filled panels. These advanced insulation panels offer the potential for significant reductions in energy consumption and greater flexibility in product design. Unfortunately, the equipment used to determine the thermal resistance of traditional building insulation materials was not well suited for measuring the thermal resistance of advanced insulation panels. A team led by Hunter Fanney developed a calorimetric apparatus and computational procedures to measure the thermal resistance of advanced insulation materials [11]. The procedures used to determine the thermal resistance of advanced insulation panels from calorimetric results were verified by measurements with the guarded hot plate for extruded polystyrene specimens. The measurements agreed to within 3 percent over a mean temperature range of 280 K to 295 K.

In the 90s, requests from the American Society of Heating, Refrigerating, and Air Conditioning (ASHRAE) prompted BFRL to address missing references for the thermal and vapor transmission data in their handbook. Over the decades, BFRL had accumulated a valuable and comprehensive collection of guarded hot plate data on a variety of insulating and building materials. In response, BFRL and NIST's Office of Standard Reference Data developed a new online database [12] that contained over 2000 of the NBS guarded hot plate measurements from 1932 to 1983. The database reconstructs one of the original reference authorities for the handbook data on design heat transmission coefficients for insulating and building materials, and currently receives about 5000 requests a month from the public.

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10.2 WEATHERIZATION

Between 1975 and 1982, NBS undertook three significant efforts in support of Congressional mandates to assist home owners in making their houses more energy efficient. These mandates were driven by the realization that residences consumed approximately 22 percent of total U.S. Energy use , that, for the foreseeable future, much of the current residential stock will remain occupied. Weatherization applied the results of building energy conservation research to support other agencies in their mandate to assist in the cost effective weatherization of homes. Weatherization also provided the energy conservation in buildings program with feedback and identified research needs and opportunities that would not have been recognized otherwise. Heinz Trechsel led the Weatherization Program for NBS with outstanding attention to high quality, timely and useful results, responsiveness to sponsors and external collaborators, and interdisciplinary teamwork.

The three components of Weatherization were:

1. Criteria for Retrofit Materials and Products for Weatherization of Residences.
2. CSA Weatherization Demonstration - Optimal Weatherization of Low-Income Housing In The USA
3. Criteria for the Installation of Energy Conservation Measures

10.2.1 CRITERIA FOR RETROFIT MATERIALS AND PRODUCTS FOR WEATHERIZATION OF RESIDENCES

Although started in anticipation of energy conservation tax credits, this work was completed in support of the Department of Energy's program to assist low income home owners. The intent was to establish guidelines for the selection of materials that can be expected to provide energy savings when correctly installed in residences. The first goal was to establish the types of measures that would provide significant energy savings. Materials that provide primarily other benefits, such as a more pleasing interior (such as carpets) or enhanced privacy (such as curtains and drapes) were excluded, although it was recognized that such measures also might provide energy savings. The second effort was to develop specific criteria to be met by each of the generic measures. The measures selected were: thermal insulation, storm windows and doors, caulks and sealants, weatherstripping, vapor barriers, and clock thermostats. The recommended criteria were based on thermal performance, fire safety, structural integrity, durability, quality, conformance to building codes, and ease of installation. Specific criteria included conformance to Nationally recognized standards, such as Federal Standards and standards promulgated by voluntary consensus organizations, such as ASTM International. For some products, where recognized standards did not exist, it was determined that simple availability of commercial products was a sufficient requirement. The criteria developed by this effort [1,2,3] also were used as a basis for selecting retrofit measures to be included in the CSA Weatherization Demonstration.

10.2.2 CSA WEATHERIZATION DEMONSTRATION

In 1976, the Community Services Administration approached NBS with a request for assistance in determining the optimal cost savings achievable through weatherization of low income housing to better allocate its resources. The goal was to determine which weatherization measures are the most cost effective, and what level of funding for each residence would provide an optimal rate of return in terms of energy savings.

In response, NBS developed an experimental and demonstration plan for conducting field measurements before and after retrofit of selected housing units. A pilot plan was tested in a Portland, Maine. After finalizing the plan, the demonstration/experiment was carried out in 16 locations covering all major climatic areas of the USA, of which 12 submitted data: Tacoma, WA; Oakland, CA; Colorado Springs, CO; Fargo, ND; Minneapolis, MN; Chicago, IL; St Louis, MO; Atlanta, GA; Charleston, SC; Washington, DC; Easton, PA; and Portland, ME.

In each location, from four (Washington, DC) to 19 (St. Louis, MO) houses were included in the sample, for a total of 183 houses, of which 141 were experimentally retrofitted for optimal weatherization, and 41 served as control houses. The houses ranged in age from 10 years to 80 years, with a median age of about 45 years. The sample included detached and row-type attached one to three story frame and masonry houses. To qualify, all houses had to be in reasonably good repair.

The weatherization measures considered were: sealing of cracks and holes, window and door treatments, roof and wall insulation, basement wall and floor insulation, and mechanical options, heating and hot water systems improvements. The measures were selected for each house based on economic cost/benefit analysis.

The installation of the various measures was done either by contractor's personnel or by persons trained under the Comprehensive Employment and Training Act (CETA). All metering and data collection was done by local Community Action Agency (CAA) personnel trained by NBS for the purpose. Overall, an average of $1,610 was expended for each house. Payback periods through fuel savings averaged 8 years and savings in fuel consumption averaged 31 percent.

The project leader was Richard Crenshaw. In addition to the authors of the publications referenced, Scheryle Schroyer, Judy Calabrese, and Lawrence Kaetzel were computer consultants to the project. Steve Weber, Kimberly Barnes, Barbara Lippiatt, Michael Boehm, Ann Hillstrom, and Phil Chen assisted with economic analysis. Richard Grot received the Bronze Medal Award of the Department of Commerce in 1980 for development of the field measurement techniques.

The project spawned some 15 technical reports on demonstration planning, results, economic analysis, and on field measurement techniques. References [4,5,6] provide a broad overview of the project, its planning, and its results.

10.2.3 CRITERIA FOR THE INSTALLATION OF ENERGY CONSERVATION MEASURES

In 1979, in response to the National Energy Conservation and Policy Act (NECPA), the Department of Energy established the Residential Conservation Service program (RCS). RCS required large utility companies and participating heating oil suppliers to offer auditing services to their residential customers to encourage the installation of energy conserving and renewable resource measures, to assist their customers in selecting appropriate cost-effective energy conservation measures, and to aid in contracting for the procurement and installation of selected measures. NECPA also provided for DOE to establish material and installation standards to assure the effective and safe installation of energy conservation measures. NBS assisted DOE in the development of the required installation standards.

NBS had primary responsible for preparing the installation standards for thermal insulations, caulks and sealants, storm windows and doors. Installation standards for insulating domestic hot water heaters, replacement of oil burners, automatic vent dampers, and intermittent pilot ignition systems were prepared by others. In developing the installation standards, NBS needed to address several technical and safety issues, primarily control of condensation in walls and attics retrofitted with insulation and potential fire hazards from electrical wiring surrounded by thermal insulation and from recessed and surface mounted lighting fixtures.

As format, DOE and NBS chose that of ASTM standards. Not only did this provide a proven format, but it also eased the eventual conversion of the standards into voluntary consensus standards. This was determined to be desirable as a long-term strategy; DOE would hardly want to be in the business of periodic updating the standards, as would be required for them to remain current. Some of the standards originally established for the RCS program and included in the publications listed below were withdrawn by DOE in 1981, but it is a measure of success that many RCS Installation Standards for thermal insulation and those for storm windows and doors eventually were converted into ASTM standards by the respective committees, mostly with only minor changes.

The ASTM Standards based on the RCS Installation Standards were:

C 1015	Installation of Cellulosic and Mineral Fiber Loose-Fill Thermal Insulation;
C 1049	Installation of Granular Loose-Fill Thermal Insulation;
C 1320	Installation of Mineral Fiber Batt and Blanket Thermal Insulation for Light Frame Construction;
C 1158	Installation and use of Radiant Barrier Systems (RBS) in Building Construction.

The project leader was Heinz Trechsel. He received the Bronze Medal Award of the Department of Commerce in 1981 for these and other contributions to residential energy conservation. In addition to the authors of the publications referenced [7, 8], the following contributed significantly to the development of installation practices:

- Robert Hastings contributed much in the area of replacement thermal windows and storm windows,
- Reece Achenbach, Frank Powell, Bradley Peavy, and Doug Burch in the area of thermal insulations,
- Larry Galowin and Robert Beausoliel provided expertise on the effect of thermal insulation on electrical wiring.

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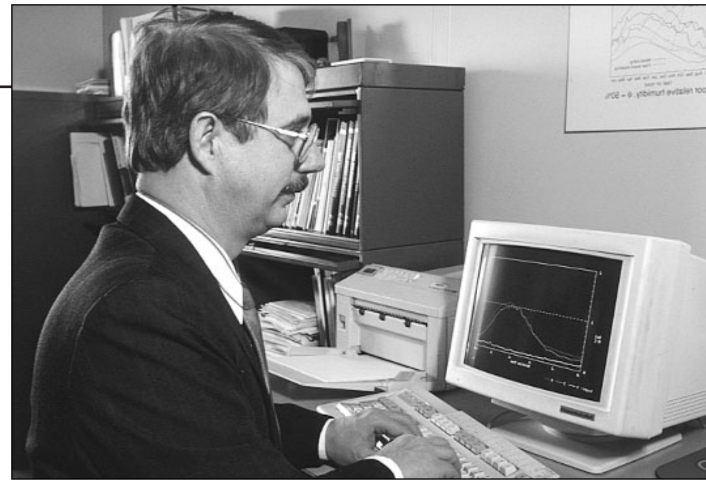

Douglas Burch, mechanical engineer, co-developer of the CBT MOIST Program, with William Thomas of Virginia Polytechnic Institute and State University testing the software to predict moisture accumulation in walls and ceilings.

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10.3 MOISTURE

Moisture accumulation in or on building walls and roofs creates substantial problems: reduction of insulations effectiveness, mold and mildew on interior surfaces, and rotting or corrosion of wall or roof materials. Walls and roofs are complex, multi-layered systems, with differing heat and moisture storage and transfer properties for the various layers.

The energy impact associated with moisture accumulating within the building envelope is enormous. The impact associated with just low-slope roofs and residential walls is approximately $200 million per year at an assumed oil price of $20 per barrel. The total economic impact is anticipated to be much greater since the impact of moisture in crawl spaces, conventional attic, and commercial walls, is not included in this estimate.

In the mid 80s, Douglas Burch of CBT and guest researcher William Thomas, professor of Mechanical Engineering at Virginia Polytechnic Institute and State University, began to address the problem of predicting the combined flow of heat and moisture through multi-layered walls. They determined that it would be necessary to develop measurements for diffusion coefficients for various wall materials and to measure the thermal conductivity of various materials as affected by moisture content, as well as to develop and verify a computer model for heat and moisture transfer in multi-layer walls and roofs. Sponsorship for the work was provided by NBS, the Department of Energy, and the Department of Housing and Urban Development (HUD).

The computer modeling proceeded well and the MOIST program was made generally available [1], but extensive research and testing were required to define the materials properties needed for general use [2,3,4]. Version 2.0 of MOIST [5] was made available incorporating these materials properties. An immediate area of application, conducted for HUD with the Forest Products Laboratory, was to address moisture problems commonly encountered in manufactured homes in both cold and warm climates [6]. These studies led to improvements in the HUD standard for manufactured homes. The research also addressed the severe problems encountered with mold and mildew in air conditioned buildings in hot and humid climates [7] and recommended avoidance of interior vapor barriers.

Subsequent research extended MOIST to deal with transient interior temperatures and humidity, and to provide a user-friendlier program for designers, builders and investigators of moisture problems [8].

In 2001, ASTM published a document [9] that included MOIST on an accompanying CD ROM. This combination of materials offered a basic understanding of the mechanisms involved in moisture movement, condensation, and accumulation. The inclusion of MOIST allowed analysis to be conducted on building walls and roofs.

The U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy has widely disseminated the MOIST program by means of their Building Energy Software web site http://www.eren.doe.gov/buildings/tools_directory/software/moist.htm [10]. This site emphasizes the use of renewable energy and achieving energy efficiency through proper building envelope design and the judicious selection of space conditioning equipment. MOIST is included within their web site as one of the programs available to analyze the performance of building envelopes.

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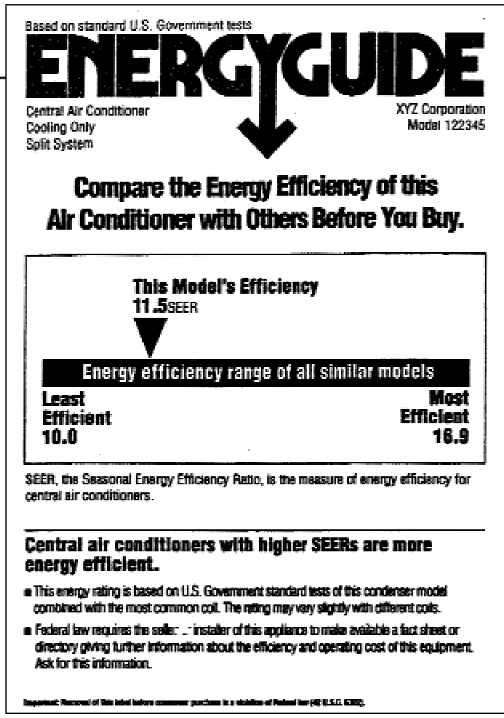
10.4 APPLIANCE TEST PROCEDURES AND LABELING

Following the nationwide gasoline shortage in the early 1970s, the U.S. Congress enacted the Energy Policy and Conservation Act (EPCA, Public Law 94-163). The energy used by household appliances was considered a major factor in the national energy conservation effort. The law was subsequently amended three times, in 1978, 1987 and 1988. The 1987 amendment, the National Appliance Energy Conservation Act of 1987 (NAECA), established the mandated energy conservation standards for the covered appliances. Under the law, DOE was required to establish energy conservation standards with respect to minimum efficiency and/or maximum energy use for all covered residential products. NBS was required to assist DOE to develop the test procedures that would be used by the appliance industries as the uniform test procedure for the measurement and reporting of the energy efficiency or energy consumption. The Federal Trade Commission (FTC) was tasked with the administration of the labeling of the energy efficiency/consumption of the covered products to provide information to and encourage consumers in the purchase the more energy efficient appliances.

At the beginning of the appliance energy efficiency program, DOE decided that providing information to consumers on the relative energy consumption of different models, would be more acceptable than direct regulation by setting maximum energy consumption for various appliances. This approach would allow competition between manufacturers on the basis of energy consumption. In addition to the development of the test methods for the covered appliances, NBS also was asked to design labels that would provide information on the annual energy consumption at the point of sale. The label was bright yellow and named the EnergyGuide. In addition to the annual cost of energy, the label showed where the particular model was positioned in the range of competitive products. Purchasers were able to make decisions on the payback time for any added cost for appliances that used less energy, and were able to compare different fuels. The FTC issued guidelines for the label in a rule promulgated in 1979. In 1994, the FTC issued a final rule that revised the EnergyGuide labels. Rather than the



NBS developed test method for appliances' energy consumption that were used by the Federal Trade Commission as Energy Guide appliance labels as illustrated for Furnace-Natural Gas appliance.

average annual operating cost that may change from year to year depending on fuel cost, the labels now contain the annual energy use (in kWh) as the main comparative indicator. The 1987 amendment requires that as the technology to improve the equipment efficiency advances, DOE periodically re-evaluate the standards, and, after public hearings, establish new minimum standards

The challenge to NBS was to develop a test method for each appliance that would measure annual energy consumption under normal use conditions and provide the information to purchasers in a meaningful way. This not only involved the development of a standard, repeatable method of measuring energy use, but also determination of normal use patterns for each specific appliance. The development of a standard test method was comparatively straightforward for the so called "white" appliances of the covered products, those used for cooking, cleaning, refrigerating food, etc. For those appliances, the performance and annual cost of operation are primarily dependent on the use pattern or schedule. Once normal use patterns/schedules were known, the existing industry steady state test method for the appliance could be combined with the specific daily use pattern/schedule to determine the performance and annual cost of operation.

Industry experts were helpful in explaining normal use patterns, but surveys were also used. In some instances it was necessary to observe people using appliances to establish use pattern. For example, most users could not say how many times they opened an oven door to check while cooking a meal, which burners they used on the range top, or which size pots they used on each burner. To solve these problems a kitchen was set up with one way mirrors in a test house known as the Bowman House, on NBS grounds, and volunteers were recruited to cook meals while being monitored by NBS staff.

At the time of the enactment of EPCA, steady state tests were used in the industry for central space heating and cooling equipment. However, in actual operation, the equipment cycles on and off frequently throughout the day. This cyclic operation causes significant energy losses or inefficiencies associated with the warm up and cool down of the heating equipment such as furnaces and boilers, or migration of refrigerant in the cooling equipment such as air-conditioner and heat pump. In addition, these appliances do not have a constant year-round daily use pattern but rather depend primarily on the outside weather conditions. Therefore, steady state tests were deemed not a sufficient procedure for the determination of the annual energy consumption. As a result, NBS staff developed new procedures to determine a seasonal (heating or cooling) efficiency for this type of equipment that includes both steady state and cycling tests coupled with calculation procedures that account for the changing weather conditions throughout the heating and cooling seasons. The resulting seasonal efficiency descriptors were the Annual Fuel Utilization Efficiency (AFUE) for furnaces and boilers, and the Seasonal Energy Efficiency Ratio (SEER) for air-conditioners and the SEER and Heating Season Performance Factor (HSPF) for heat pumps. The average annual energy consumption of these appliances on the basis of these energy efficiency descriptors was then calculated for the yellow labels.

After the initial tasks of development of the appliance test methods and labels, NBS concentrated on the improvement of the test procedures for the covered appliances to account for the advances in the energy efficiency design features spurred by the energy conservation efforts. Revised and additional test procedures were developed or under study for [1] condensing and modulating furnaces and boilers, [2] variable-speed compressor and mix-matched systems in cooling systems, [3] heat pump water heaters and improved procedure for the first hour rating of storage water heaters, [4] standardized load sample cloth and multiple load control feature in cloth washers, [5] dishwashers employing adaptive control and soil/particle sensors for performance and energy efficiency, [6] test procedures for fluorescence lamp ballast, and [7] test procedures for plumbing fixtures.

Many reports were provided to the Department of Energy including recommended label design, test methods, and the results of surveys. References [1-10] are the principal reports and publications, and [11] is a description of the outstanding technical work in the NBS/NIST Centennial Publication.

NBS provided information to DOE to enable it to hold public hearings on the test procedures, which after incorporating public comments as appropriate, were then adopted by DOE as final rules for the covered products. They were published as the federal rules in the Codes of Federal Regulations, No. 10, Part 430, Subpart B, Test Procedures, Appendix A through Appendix P. The energy efficiency and annual energy consumption values for the covered appliances were reported by the manufacturers to DOE and FTC, and listed on the appliance labels as specified in the FTC's Federal Trade Commission, Energy Guide (16 CFR Part 305).

Residential equipment accounts for 20 percent of U.S national energy consumption. The test procedures, the labeling program, and the required mandatory minimum standards stimulated competition, and have resulted in substantial improvement in equipment efficiency by manufacturers. The main impact on the public of the appliance labeling program is the visibility of the "energy labels" affixed to appliances in stores, and the fact that many purchasers are influenced by the information on the label. The American Council for an Energy Efficiency Economy (ACEEE) reported average efficiency increase from 1972 to 1987 of 96 percent for refrigerator-freezers, 35 percent for central air conditioners and heat pumps, 30 percent for room air conditioners, and 18 percent for gas furnaces. The energy cost saving makes it worthwhile to replace an old refrigerator (1970s) even though it may be working. EPCA has been amended by the Energy Policy Act of 1992, P.L. 102-486, to cover certain commercial equipment and NIST is assisting the Department of Energy to develop energy efficiency test methods for commercial water heaters, furnaces, boilers, air conditioners and heat pumps.

Initially the appliance program at NBS was lead by the Center for Consumer Product Technology (CCPT) with CBT handling the work on furnaces and central air conditioners. The human factors aspects including label design, user surveys, and cooking studies were the responsibility of the CCPT's Consumer Sciences Division headed by Mel Myerson, appliance test methods were developed by CCPT's Product Performance Engineering Division headed by Andrew Fowell, and the home heating and cooling product test methods were developed by CBT's Building Environment Division headed by Preston McNall. Key people in the early part of the program included Charles "Chuck" Howard, Ken Yee, Charles Gordon, Escher Kweller, Robert Wise, James Harris, Alan Davies, King Mon Tu, George Kelly, Joseph Chi, Walter Parken, Mark Kuklewicz, William Mulroy, and James Hill. In 1981 CCPT was disbanded and the appliance program was absorbed by CBT. Staff of CBT (now BFRL) who continued the work in the appliance program include Escher Kweller, Hunter Fanney, Brian Dougherty, Stanley Liu, William Healy, and Stuart Dols in water heaters, Esher Kweller, George Kelly, Cheol Park, Stanley Liu, and James Barnett in furnaces and boilers, David Didion, Piotr Domanski, Walter Parken, William Mulroy and Brian Dougherty in air conditioners and heat pumps, James Kao, Natascha Castro, and Andrew Persily in clothes washers, Natascha Castro in dishwashers, Steve Nabinger in Kitchen range and ovens, and Steve Treado in fluorescent lamp ballasts, plumbing fixtures and sampling procedure in performance testing and enforcement for all covered appliances.

George Kelly and David Didion received Department of Commerce Silver Medal Awards in 1978 and 1981, respectively, for their research on test methods for accurate and efficient energy labeling of heat pumps and air-conditioners. Warren Hurley received the Bronze Medal Award of the Department of Commerce in 1982 for development of data acquisition methods for appliance testing. Brian Dougherty received the Bronze Medal Award in 1999 for updating test methods for heat pumps and air-conditioners.

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10.5 TOTAL ENERGY SYSTEMS

Total Energy is a name given to the concept of recovering the waste energy from generation of electricity for use in heating and/or cooling. The best efficiency for generating electricity is about 40 percent. By using the waste energy from electricity generation to provide usable energy for heating and/or cooling, the overall efficiency typically can be 60 percent or higher, ideally as much as 85 percent.

Total Energy has other names, such as cogenerated heat and power, combined heat and power, integrated energy, district energy, etc. It is not a new concept. In the early 1900s electric power plants (typically coal-fired plants producing steam to run turbine-driven generators) were smaller and usually located close to the buildings they served. It was relatively easy to pipe heat recovered from the turbine exhaust steam to nearby buildings or homes. As the utility plants grew larger and tended to locate more remotely, the piping of recovered heat was less practical so the cogeneration of heat and power by most of these utilities gradually disappeared.

In the 1960s and early 1970s, the natural gas industry promoted natural gas-engine-driven total energy systems for supplying electric power and heating to one or more buildings. 500 or more of these systems were installed by 1971. The electric capacity ranged from less than one to about 3 MWe, with most in the lower range below 2 MWe. Many of these were hastily conceived, poorly matched to site needs, and not maintained properly. As the energy crisis eased many were discontinued.

HUD in the 1970s, was in the final phase of their 'Operation Breakthrough' program (development of performance-based building design) and wanted to demonstrate that the concept of total energy, properly designed, installed and maintained, would make a valuable contribution to the reduction of energy use for multiple-building installations. HUD requested NBS/CBT to determine feasibility of installing total energy at one of the 'Operation Breakthrough' building demonstration sites. Because of its energy conservation potential, CBT had been studying total energy and, in response to HUD's request, recommended the 'Operation Breakthrough' residential apartment building project site in Jersey City, NJ - Summit Plaza - for the 'installation, evaluation, and field study for the demonstration total energy system. The site used off-site fabricated modules that were stacked to form the buildings. Heating and air conditioning utilities for the buildings were generated in a small power plant located within the apartment complex. Heat generated by the diesel engines was recovered and used to offset the energy needed to supply the apartments' heating and air conditioning needs. CBT instrumented the power plant and each apartment building to monitor energy generation and use. HUD was interested to know if the cogeneration design was energy efficient and worthy of replication.

CBT prepared the performance specification for the total energy installation at the site. Installation of the total energy plant was started in 1971 and went on line serving the site in December 1973. The plant is still operating supplying electric power, heating and cooling for Summit Plaza [1].

This Jersey City, NJ apartment building site of the mid 1970s featured use of prefabricated modules for medium-rise construction and an on-site energy cogeneration plant. NBS monitored the energy flow from the plant's electricity generated site recovery system including recovering heat from diesel generators that contributed to heating the building units. HUD was interested to know if the cogeneration design was energy efficient and worthy of replication.

CBT designed, installed and operated an extensive data acquisition and evaluation system for the total energy plant and developed the computer-based data reduction processes needed for performance analysis and reporting. Full-time automatic data acquisition and processing was on-line from April 1975 through December 1977 and selected data were collected and monitored, manually or automatically, from December 1973 through October 1978. A complete description of the Jersey City total energy plant, its functional and energy performance, and noise, emissions, and air quality performance, is presented in a NBS report authored by C. Warren Hurley, et al [1].

Concurrent with interest in total energy and its demonstration, HUD established their Modular Integrated Utility Systems (MIUS) program to study and encourage not only integration of electric power and heating/cooling to reduce construction cost and energy use in buildings and communities, but also the overall economics, institutional factors relative to integration of utilities, including in addition to alternative energy systems, potable water, liquid waste treatment and solid waste management systems.

HUD requested CBT and several other agencies, including, principally, the Energy Research and Development Administration, the Environmental Protection Agency, Oak Ridge National Laboratory, and the National Aeronautics and Space Administration, to conduct specific MIUS studies. CBT was requested to provide coordinated technical review for the reporting of all of these studies. The MIUS reports from all program participants, including those on total energy, totaled 213 publications [2, 3]. CBT produced 35 technical reports; 19 total energy-related publications and 16 reports of MIUS-related studies such as economic objectives, waste water management, institutional factors, comparison of MIUS with 5 alternative systems, evaluation and performance guidelines [4], and usage of electricity in non-industrial applications.

CBT, at the request of HUD and the Energy Research and Development Administration (ERDA), participated in the organization, in 1974, of the MIUS Study Group of the North Atlantic Treaty Organization's Committee on Challenges to Modern Society. CBT organized and conducted the international meetings of this study group, consisting of about 35 technical representatives from seven countries, in Belgium (1975), The Netherlands (1975), France (1976), Germany (1976), and Italy (1977). The study group mission was to exchange technical data on implementation of MIUS systems in the several countries and included development of an international projects 'catalog', a glossary of MIUS terms, sharing of MIUS feasibility computer programs, and several member-contributed papers [5].

Beginning in 1975 at HUD's request and subsequently supported by ERDA, and later by the Buildings and Communities Office of the Department of Energy, CBT organized and conducted monthly technical exchange meetings from 1977 to 1983 for Federal, state, county and city government agencies, city planners, investors, consultants, and contractors concerned with Integrated Energy Systems (IES). The meetings, with typical attendance of 50-75, were first held at NBS, then at the Department of Commerce, and finally at the U. S. Conference of Mayors headquarters in Washington, D. C.

When the National Engineering Laboratory was organized in 1978, the Total Energy Program was transferred with key personnel to the Center for Mechanical Engineering and Process Technology, but continued to involve many CBT staff. NBS participation in HUD's total energy program, its MIUS program and the DOE IES program, concluded in 1983. Throughout its history, NBS' Total Energy Program was led by Clinton W. Phillips whose enthusiasm and warmth achieved outstanding collaborations within NBS, nationally and internationally. Phillips began work as a technician with a CBT predecessor organization in the 40s, rose to lead work on modular, integrated utility systems for buildings, and was elected president of the American Society of Heating, Refrigerating and Air-Conditioning Engineers in 1982. He inspired colleagues with his enthusiasm for his and their work and his many charitable activities.

John Ryan received the Department of Commerce Bronze Medal Award in 1975 for his contributions to performance analysis of total energy systems.

Clinton Phillips served as President of the American Society of Heating, Refrigerating and Air-Conditioning Engineers 1982-1983.

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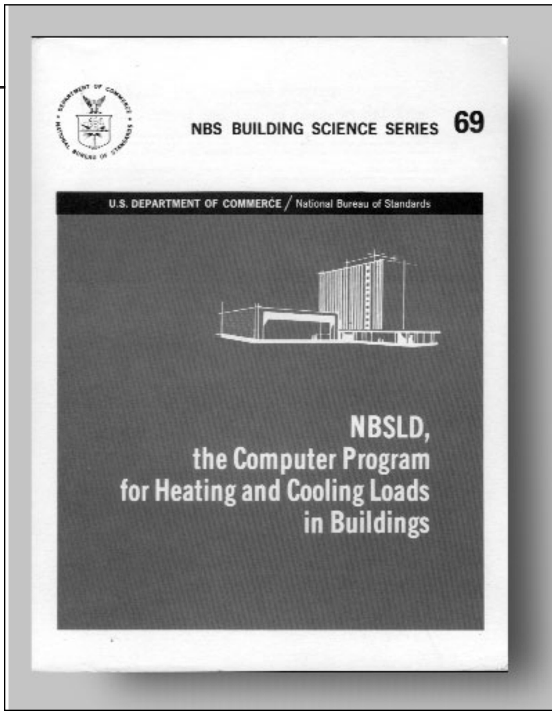
10.6 BUILDING THERMAL ENVIRONMENT ANALYSES

Before the 1970s, building environmental engineering was mostly represented by HVAC (heating, ventilating and air conditioning) engineers whose main interest was to design and select heating and cooling equipment under a set of design conditions (mainly outdoor temperature and humidity) through the so called "catalogue engineering." Very few of the HVAC engineers had any interest in, or were capable of predicting or evaluating the performance of heating and cooling equipment and systems, which they had designed or selected, under off-design conditions, which constitute a majority of the operating hours of HVAC systems and equipment. There were in fact no methodologies for estimating the performance of building indoor environment, HVAC equipment and systems under off-design conditions, since performance prediction required different and more complex mathematical approaches. Computers were also expensive and not many were found in HVAC engineers' offices.

Because of advanced computer facilities as well as the programming and mathematical talents available at NBS, some CBT researchers were very active in the use of computers for analyzing various aspects of environmental engineering for buildings, especially building heat transfer problems. Bradley Peavy [1], for example, was active in developing advanced mathematical techniques to deal with complex heat conduction problems involving the prediction of temperature in deep underground fallout shelters under the sponsorship of the Office of Civil Defense (the predecessor of FEMA). Through these activities he had developed efficient computer programs for several types of advanced computer programs involving complex Bessel functions.

Tamami Kusuda extended the fallout shelter thermal environment calculation program into an hour by hour building thermal environment calculation program in order to evaluate the performance of the Operation Breakthrough buildings of the Department of Housing and Urban Development. In this effort, he incorporated the thermal response factor method developed by Stephenson and Mitalas [2] to deal with transient heat conduction and storage in the multi-layered building envelope in lieu of finite difference calculations, which took up a large segment of the precious computer memory and involved lengthy computation time. Eventually, this computer program was expanded to include detailed heat balance calculation algorithms [3] to address the radiative heat exchange among interior surfaces of the room; the Goff and Gratch formulation of psychrometric data [4]; solar heat gain calculation procedures developed by Stephenson [5]; cloud cover modifier by Kimura/Stephenson; a comprehensive shadow program of Terry Sun [6]; an infiltration routine based on Achenbach/Coblenz equation [7] (later replaced by the Sherman/Grimsrud equation [8]); the thermal comfort equations of Fanger [9]; and ground contact heat transfer based on thermal response factors [10]. The program originally developed for a one-room building was called the NBSLD [11], the accuracy and reliability of which were validated concurrently with many different types of buildings whose thermal and energy performance were carefully measured mostly under the leadership of Frank Powell and Douglas Burch [12 - 15] (some buildings were tested inside the large environmental chamber). These measurements on test buildings included an inside-out construction (insulation placed outside of building walls), a log- cabin, a mobile home, massive masonry wall buildings, attic ventilation homes, different types of passive solar houses, houses with a whole-house fan, daylight utilization systems, thermostat setback operations, and large office buildings (e.g. the GSA Manchester demonstration building [16]). Approaches and subroutines used by NBSLD stimulated many young researchers and new research programs, and formed the starting point for the energy calculation algorithms recommended by the ASHRAE Task Group on Energy Requirements [17] as well as similar activities in many parts of the world. It laid the foundation for more sophisticated and well-known building energy simulation programs, such as DOE-2 [18], BLAST [19], TARP [20], etc., that followed. These programs played an important role in the USA when the country was developing building energy standards, during the aftermath of oil crisis of early 1970s, under the leadership of NBS, DOE, and ASHRAE.



NBS Building Science Series 69, NBSLD. Tamami Kusuda developed a dynamic computer calculation program called the National Bureau of Standards Load Determination Program (NBSLD) that provided hourly weather data covering all seasons of the year in any location and the dynamic profile of hourly energy required by a proposed building design for a full year.

Tamami Kusuda, pioneer for thermal environmental analysis.

Kusuda's contribution during this period was recognized by the 1980 Gold Medal of the Department of Commerce, the distinguished Fellow award of ASHRAE in l985, as well as by an ASHRAE symposium paper of 2000 held in Cincinnati entitled "The Role of the National Institute of Standards and Technology in Development of Energy Calculation Programs" by Professor Eugene Stamper [21] of the New Jersey Institute of Technology, who headed the ASHRAE Technical Committee on Energy Calculations.

Recognizing the need for assessing the use of computers for building environmental analyses, Achenbach and Kusuda organized the first international symposium on the use of computers for environmental engineering related to buildings [22] in1971 that attracted over 400 enthusiastic building environmental engineers from all over the world. This symposium was followed in Paris (1974), Banff (1978), Tokyo (1983), and in Seattle (1985), before it was taken over by the IBPSA (International Building Performance Simulation Association). IBPSA continues to conduct international symposia biennially ever since, and recognized Kusuda with its distinguished service award at its1993 meeting held in Adelaide, Australia. In its 1999 Kyoto, Japan, meeting of IBPSA, Kusuda was invited as the keynote speaker [23] to talk about the early history of building performance simulation activities as well as its future prospects.

In 1995, IBPSA gave its Award for Distinguished Service to Building Simulation to George Walton for his sustained contributions to the building simulation field. His work in building heat transfer and network analysis has resulted in simulation programs used worldwide including TARP, AIRNET and CONTAM. Walton received the Bronze Medal Award of the Department of Commerce in 1983 in earlier recognition of this work. Also, Douglas Burch received the Bronze Medal in 1980 for his work on attic insulation and attic ventilation.

One interesting application of NBSLD was the introduction of the predicted building habitability index (PIHI) as an integrated evaluation criterion for building performance. The PIHI concept was developed by James Hill and Tamami Kusuda in l975 [24] in which the simulated hourly energy consumption, comfort index, and system economic factors were weighted (in accordance with specific application requirements) and algebraically summed-up to arrive at an index for determining building air conditioning needs. This PIHI concept can be extended to include the energy performance of other building elements such as lighting, acoustics, moisture condensation, plumbing, etc.

Kusuda also worked on and published several papers on various subjects including the dynamic characteristics of air infiltration [25], room air convection calculations based on the numerical solution of turbulent Navier-Stokes equations [26], heat transfer of underground heat and chilled water systems [27], slab-on-grade heat transfer [28], and daylighting calculations [29]. The paper on the dynamic characteristics of air infiltration mentioned above was published jointly with James Hill and won ASHRAE's best technical paper award of 1975. The concept explored in the paper was later investigated further by John Klote [30] in his 1985 doctoral thesis at George Washington University at which Kusuda served as an adjutant professor.

The building environment simulation work started by Kusuda has been ably succeeded by other NIST researchers including George Walton, Stephen Treado, George Kelly, Cheol Park, and others in advanced building environmental simulation, the details of which are given in other sections of this report.

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10.7 SIMULATION OF MECHANICAL SYSTEMS PERFORMANCE

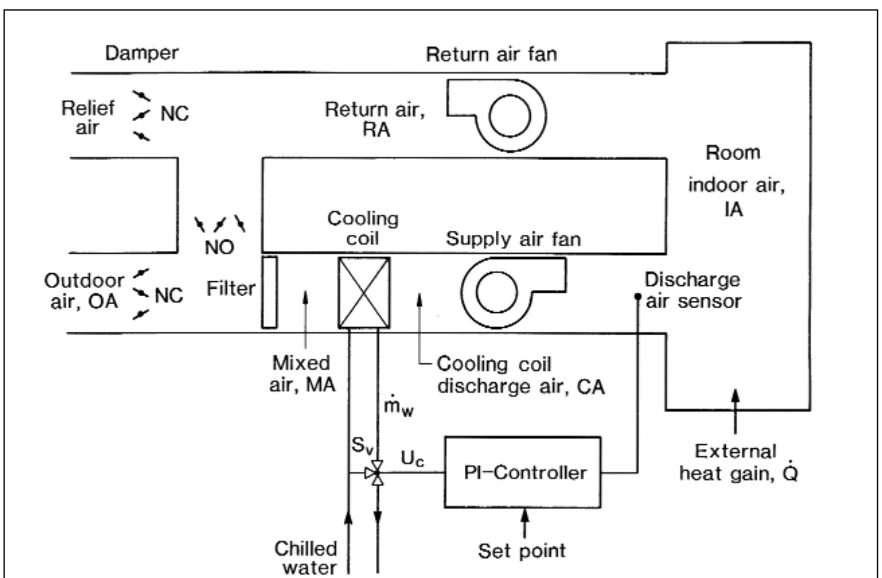
The HVAC simulation work within BFRL has focused on understanding the dynamic performance of buildings and the mechanical systems within them. These dynamics take place on a time scale on the order of seconds for control actions involving local control loops to a time scale on the order of minutes for changes in zone conditions

In an effort to understand dynamic interaction between building systems, initial development of a non-proprietary building system simulation computer program was begun at NBS in 1982. That program is called HVACSIM+, which stands for HVAC SIMulation PLUS other systems. The work built upon CBT's pioneering work in the 60s and early 70s for the National Bureau of Standards Load Determination Program [1].

HVACSIM+ [2-7] employs advanced equation solving techniques and a hierarchical, modular approach. The simulation of an entire building/HVAC/control system involves the simultaneous solution of a large number of nonlinear algebraic and differential equations over large time periods using time steps on the order of seconds or smaller. The modular approach is based upon the methodology used in the TRNSYS program. Variable time step and variable order integration techniques are also used for reducing the amount of computation time required for dynamic simulation. Stiff ordinary differential equations are solved using a solving method based upon the famous Gear algorithm.

The HVACSIM+ program consisted of a main simulation routine, a library of HVAC system component models, a building shell model, an interactive

An air-handling unit with a room simulated by HVACSIM+ program.



An air handling unit with a room simulated by HVACSIM+ program.

front end program, and post processing routines. Most of the programs were written in Fortran 77, with the Fortran 90 code used for some specific routines.

The program HVACSIM+ is intended as a tool for conducting analytical research on building systems and subsystems and not as software which can be easily used by the general public. However, the simulation techniques, equation solving routines, and component models contained in HVACSIM+ should facilitate the development of such application programs for the general public by government laboratories, universities, or the private sector.

The HVACSIM+ dynamic building/HVAC/Control systems simulation program was used in a number of projects. Some of them are briefly described below.

A large office building system, which includes the HVAC systems, building system controls, and building shell, was simulated using the HVACSIM+ program. The building used for simulation was the NIST Administration building. EMCS (Energy Management and Control System) control schemes, such as start/stop control and nighttime purging, were evaluated [8].

An advanced air-handling unit (AHU) sequencing control algorithm was also simulated (12) and evaluated. AHU controllers commonly use simple sequencing logic to determine the most economic way to use the components of the AHU to maintain the supply air temperature at a set point value. Advanced control logic was compared with a traditional approach using HVACSIM+ to simulate the AHU components and the control logic.

As a part of a joint research effort conducted by participants of the Internal Energy Agency (IEA) Annex17 committee, NIST developed an "emulator." A building emulator is analogues to a flight simulator in the aircraft industry. Just as a flight simulator simulates an airplane in real time, a building emulator simulated a building, the weather, the HVAC system, and the heating/cooling plant in real time. Real EMCS control hardware was connected to a computer via a data acquisition system. The building system was simulated using HVACSIM+. The EMCS then controlled the simulated system as if it were an actual building. The emulator also evaluated the EMCS's performance in terms of the energy consumed, degree of comfort maintained in the simulated space, and accuracy of control [9-11].

Participants of IEA Annex 25 committee for real time simulation of HVAC systems for building optimization, fault detection, and diagnosis used the HVACSIM+ program in joint exercises to evaluate their fault detection methodologies. NIST distributed the program and data for the exercises.

One of several "major products" currently under development within BFRL is called Cybernetic Building Systems (CBS). The Virtual Cybernetic Building Testbed (VCBT) is a project within CBS. Experiences obtained from previous emulator projects have been incorporated in to the VCBT work. In the VCBT, the building and the HVAC system are simulated using HVACSIM+, which communicates with actual controllers supplied by different manufacturers. A fire simulation model is used to simulate the development of fire within one of the building zones and the spread of smoke through open doorways.

Besides being used within BFRL for various projects, the HVACSIM+ program was used in the International Energy Agency (IEA) Annexes 17 and 25 and with the debugging of controller performance and control strategy development by industry. Other researchers outside of U.S. have also participated in upgrades to HVACSIM+. Many universities in different countries have used the HVACSIM+ program as a teaching tool for graduate and undergraduate students.

George Kelly conceived of the idea to develop a program for simulating building/HVAC/control system dynamics. C. Ray Hill initially developed the main part of the HVACSIM+ program while he was at NIST as a research associate. Daniel Clark developed most of the HVAC system component models. Cheol Park contributed to the building shell model development, improved the main program, and maintained and distributed HVACSIM+. Bob May developed the interactive front-end program and David Harris did most of the programming. Outside of NIST, Philip Haves, when he was at the Loughborough University in England, participated in the improvement of HVACSIM+ and on the development of the emulator described above. Many other people have also been involved in development HVACSIM+, building emulators, and experimental works on the verification of HVACSIM+ and its component models.

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10.8 CONTROLS AND CYBERNETIC BUILDING SYSTEMS

Building controls research at NIST has focused on improving and lowering the cost of buildings services by fostering the development and use of more intelligent, integrated, and optimized mechanical systems and controls. Key aspects of this effort have been the development of a standard communication protocol for exchanging information between building management and control systems and pioneering the concept of Cybernetic Building Systems for improved productivity, life-cycle cost savings, energy conservation, improved occupant satisfaction, and U.S. market leadership.

During the past twenty-five years, our understanding of buildings and how to operate them has undergone a gradual evolution involving a shift away from considering buildings as static units to considering them as dynamic, integrated, and distributed systems. During this same period, rapid advances in technology (such as inexpensive microprocessors, large scale integrated circuits, and new approaches to telecommunications) has made it possible to develop Building Control Systems that not only can account for dynamic interactions to optimize performance but promise to be extremely cost effective due to their ability to be integrated with other building services. In this rapidly changing environment, the Building Controls Program within CBT/BFRL has worked to: 1) document the current state-of-the-art in the design, control, and operation of building service systems, 2) promote improved building services through the evaluation, development, and application of advanced concepts and technologies, 3) develop system design and performance evaluation techniques, such as advanced simulation models, emulators, and test procedures, 4) promote the development of standards, protocols, and guidelines, and

5) assist in technology transfer through publications, conferences, workshops, and demonstration projects.

In the late 1970s, BFRL was involved with two field evaluation projects: the Jersey City Total Energy Site [1] and Norris Cotton Federal Office Building [2]. In 1980, the Mechanical Systems and Controls Group was formed. One of the early projects of this Group was to evaluate the energy saving potential of the most commonly employed HVAC control strategies using BLAST 2. Different control strategies were studied for a variety of HVAC systems in a small office building, a large retail store, a large office building, and an education building in different regions of the country [3].

A Building Management and Controls Laboratory was developed. It involved the design, building, and installation of a distributed Energy Management and Control System (EMCS) to control and monitor a large air handler in the CBT building, an HVAC/Controls test facility in the laboratory, and the 11-story NIST Administration Building. The Laboratory was used to study direct digital control, control dynamics, and to verify and refine dynamic models for HVAC system components. Research involved the evaluation of different building/HVAC control strategies, the verification and refinement of control algorithms, and the development of guidelines for the operation of different building systems. Research on EMCS Algorithms was centered on the development and verification of an adaptive algorithm for local loop control and various public domain application algorithms. The latter covered economizer algorithms, demand limiting algorithms, scheduled start/stop and duty cycling, optimal start/stop, and algorithms for a variety of reset control strategies. Work also involved the investigation of the performance of EMCS instrumentation, steam flow measuring systems, and hygrometers; the development of procedures and recommendations for the on?site calibration of temperature, flow and humidity measurement systems; and evaluating and documenting the effect of EMSC sensor errors on building energy consumption [4].

During the 1980s, manufacturers were developing proprietary communication protocols for their EMCS that made expansion and upgrading of these systems both difficult and expensive. As a result of these problems, ASHRAE began in January 1987 to develop an industry standard communication protocol for building automation and control systems. Standard Project Committee 135P (SPC 135P) was formed to accomplish this task and NIST played a key role in the effort [5]. The membership of SPC 135P was selected to provide a broad and balanced representation of the building control industry. The individuals came from manufacturers, consulting engineering firms, universities, and governmental agencies from Canada and the United States.

The first meeting of SPC 135P occurred in June of 1987. In August of 1991 the first public review draft of the proposed BACnet standard was published for comment [6]. A revised version of the draft standard was published for a second public review in March of 1994. Modifications were made and a third, and final, public review version was published for comment in March of 1995. The final draft version was approved for publication as an ASHRAE standard in June of 1995, eight and a half years after the formal standardization process was begun. BACnet was approved by the American National Standards Institute (ANSI) as a national standard in December, 1995. Since 1995 BACnet has been maintained and enhanced by ASHRAE Standing Standards Project Committee 135 (SSPC 135). BACnet has been translated into Chinese, Japanese, and Korean. It has been adopted as a Korean national standard and a European Community pre-standard. It has also been proposed as an ISO standard.

In 1996, the Phillip Burton Federal Building and U.S. Courthouse located at 450 Golden Gate Avenue in San Francisco was selected as the site for the world's first large-scale commercial demonstration of the BACnet standard. The site, a 22-story 130,000 m^2 office building, is the second largest office building in San Francisco and the largest Federal office building west of the Mississippi River. It was selected for this demonstration, in part,

Cover images of the English, Chinese, Japanese, and Korean versions of the BACnet Standard

because it had little pre-existing EMCS controls and recent renovations have made it comparable to typical commercial office buildings. The EMCS retrofit also represented a significant energy-efficiency opportunity for the building with projected annual utility savings of over $500,000. The project tested multiple EMCS-manufacturers' equipment in one facility and their ability to cooperatively monitor and control building systems by utilizing the BACnet standard. In addition, extensive energy monitoring instrumentation, an operator workstation network, and communications equipment were incorporated into the EMS design to facilitate future energy assessment and research activity within the building [7].

Contract awards for the first two BACnet compliant vendors were made in August 1996. Associated construction activities were completed in January 1998, and the project remained on schedule and on budget. A follow-on project involved an extensive central plant renovation and integration of the central plant controls with the existing BACnet control system. The fire alarm system was also integrated with the HVAC controls through an BACnet gateway. At the present time, the BACnet demonstration project is being expanded to include linking eleven federal office buildings located in California, Arizona, and Nevada together with a regional operations control center in the Philip Burton Federal Building. This regional operations center will be used to monitor and supervise energy conservation measures and to improve operations and maintenance activities. It will also serve as a research and demonstration platform for developing automated commissioning procedures, automated fault detection and diagnostics, and utility/building control system interactions.

In 1993, a BACnet Interoperability Testing Consortium was formed to develop test methods and software tools to automate the compliance testing of BACnet systems [8]. Originally consisting of 12 members, it grew to 23 members before being replaced by the BACnet Manufacturers Association (BMA) in 2000. The BMA is an industry run organization whose purpose is to encourage the successful use of BACnet in building automation and control systems through interoperability testing, educational programs, and promotional activities.

While BACnet was being developed, the Mechanical Systems and Controls Group was also involved in three successive International Energy Agency (IEA) Annexes. Annex 17, which was entitled "Building Energy Management Systems (BEMS) Evaluation and Emulation Techniques," ran from February 1988 until February 1993 [9]. It focused on the use of simulation and emulation for evaluating BEMS performance. Subtask A used simulation to assess the "a priori" energy savings achievable through the use of building energy management systems (BEMS). Subtask B involved experiments on heating and cooling coils to develop and validate dynamic coil models. Other work has included experimental validation of a methodology for determining control strategies for a heating system. Subtask C, which was led by Finland and the United Kingdom, involved the analysis and development of Emulators for BEMS. The concept of BEMS Emulators was based upon research conducted at NIST several years previously. This Subtask involved construction of actual emulators by the participating countries, carrying out various emulation exercises, and developing a BEMS testing methodology using Emulators and

Steven Bushby, leader, Mechanical Systems and Control Group, checks wiring connections for controllers in the BACnetTM Virtual Building.

completing a "round robin" testing program using different Emulators and BEMS systems. Emulators were developed by the U.S., United Kingdom, Belgium, Finland, The Netherlands, and France and exercises involving commercially available BEMS were conducted in each country. Guidelines for selecting and evaluating BEMS and for building emulators were also developed based upon experience and knowledge gained from the joint exercises.

Annex 25, entitled Real Time Simulation of HVAC-systems for Building Optimization, Fault Detection, and Diagnostics (BOFD), ran from April 1991 until April 1996. Its objectives were to evaluate alternative model identification methods, determining which real time simulation models are most suitable for BOFD-systems, performing qualitative availability analyses on various HVAC systems to determine the likelihood of different faults, developing a database on the most important problems and diagnostic procedures, and demonstrating the implementation of BOFD concepts through joint exercises. NIST led the Annex activities related to air-handling units and performed detailed comparison of techniques for classifying AHU operations (i.e., normal, faulty, and type of fault).

Annex 34, Computer-aided Evaluation of HVAC System Performance: The Practical Application of Fault Detection and Diagnosis Techniques In Real Buildings, ran from September 1996 until September 2000. The main objective of this Annex was to work with control manufacturers, industrial partners, and/or building owners and operators to demonstrate the benefits of fault detection and diagnostics in real building applications. The fault detection and diagnostic (FDD) methods developed in Annex 25 were combined into robust FDD systems and incorporated into either stand-alone PC based supervisors or into outstations of a future generation of "smart" building control systems. NIST activities in Annex 34 were primarily focused on field tests of a rule-based tool for detecting faults in AHUs that underscored the prevalence of control performance problems in buildings.

In the fall of 1998, several of the projects in the Mechanical Systems and Controls Group, along with two projects in the Fire Safety and Fire Science Divisions, were combined in to a Major Product called Cybernetic Building Systems (CBS). The objectives of this Major Product were to develop, test, integrate, and demonstrate open Cybernetic Building Systems for improved productivity, life cycle cost savings, energy conservation, improved occupant satisfaction, and market leadership. This work was to be carried out in close cooperation with the U.S. building industry, industrial partners, building owners/operators, and newly developing service companies.

The word "cybernetics" comes from the Greek work "steersman" and is defined as the science of control and communication of complex systems. Unlike the field of artificial intelligence, AI, which tends to focus on how information is stored and manipulated, cybernetics takes the "constructivist" point of view that information (and intelligence) is the attribute of system interactions (communications) and is not a commodity that is stored in a computer. In the field of cybernetics, "intelligence" is determined by the "observed conversations" (i.e., interactions) among the various components making up the (cybernetic) system. In other words, if a complex system "looks, acts, and is observed communicating intelligent information" it is "intelligent," regardless of how the information is stored and manipulated internally.

A Cybernetic Building System involves energy management, fire detection, security, and transport systems, energy providers, one or more utilities, an aggregator, and numerous service providers, and information handling and complex control at many different levels.

The BFRL is currently working with industry, building professionals, ASHRAE and Trade Organizations, university researchers, and other government agencies to develop and demonstrate CBS. The work involves the following tasks and will include a full scale demonstration of one or more Cybernetic Building Systems:

1. Develop standard communication protocols which facilitate the open exchange of information among energy providers, utilities, EMCS, fire detection and smoke control systems, security systems, elevator controls, building operators, building occupants, and (newly developing) service provider companies;
2. Develop enabling technologies, such as fault detection and diagnostic (FDD) methods, a hierarchical framework for control decision making, advanced operating strategies for single and aggregated buildings, automated commissioning, and the application of fire modeling to a cybernetic building response to fires;
3. Develop advanced measurement technologies, including smart multi-functional sensors.
4. Develop performance evaluation tools for protocol compliance testing, real time monitoring, and the evaluation and documentation of interactions among cybernetic building systems;
5. Develop a standard-based program infrastructure supporting the design, analysis, specification, procurement, installation, operation, and maintenance or heating, ventilation, air-conditioning, and refrigeration (HVAC/R) systems;
6. Construct a Virtual Cybernetic Building System in the laboratory to facilitate the development and evaluation of new products and systems by manufacturers (including BACnet speaking EMCS, stand alone/integrated FDD systems, intelligent fire panels, and smart sensors) and external service providers;
7. Develop a CBS Product Data Model (PDM) capable of accurately describing, in a standard format, a building(s), its mechanical systems and controls, the desired operating strategies, and the internal/external services provided.
8. Conduct basic research on the dynamic interactions of a fire, HVAC/distribution, and the zones of a commercial building through utilization of existing and new simulation models and validate this new simulation program through both laboratory and field studies.
9. Develop a Consortium consisting of manufacturers and service providers interested in producing, testing, demonstrating, and selling Cybernetic Building Systems; and
10. Conduct a full scale demonstration of a Cybernetic Building System in a government owned office building complex consisting of five or more buildings in the southwest region of the country. This will involve the integration of energy management, fire detection, smoke control, smart fire panels, multi-functional sensors, building transport, fault detection and diagnosis, aggregation of multiple building loads, and real time communication with energy providers, the utility, an aggregator, and numerous service providers.

Work conducted under the Cybernetic Building Systems Program will improve productivity, life cycle cost savings, energy conservation, occupant satisfaction, and will increase U.S. market leadership through the commercial application of tested, integrated, and open Cybernetic Building Systems and concepts. Based upon an very conservative FY 99 impact assessment done by BFRL's Office of Applied Economics [10], this work is expected to result in a nationwide present value cost savings of $1.1 billion and a return-on-investment benefit of $7.90 for each $1 spent on BFRL's CBS-related research.

C. Warren Hurley, William Rippey, Robert May and others were involved in the Jersey City Total Energy Site and the Norris Cotton Federal Office Building studies, respectively. George Kelly became the first Leader of the Mechanical Systems and Controls Group in the summer of 1980. James Kao and Walter Parken used BLAST to study different control strategies in four commercial buildings. Robert May, C. Warren Hurley, and Bent Borresen from the University of Trondheim, Norway developed and used the Building Management and Controls Laboratory.

Steven Bushby evaluated the application of direct digital control in NIST's eleven story Administration Building. James Kao developed design criteria and guidelines for direct digital control based building automation systems. Alexander David, Robert May, and Cheol Park developed public domain algorithms for adaptive control and various energy management strategies. James Kao and Warren Hurley defined the characteristics and expected performance of EMCS Sensors. James Kao did a study on the effect of EMCS sensor errors on building energy consumption. From 1987 on, Steven Bushby single handedly led the effort to develop the BACnet communication protocol. He was secretary of ASHRAE SPC 135 committee that developed the BACnet standard and later Chairman of the SSPC 135 committee that was formed to maintain the standard after it was adopted. He also created the BACnet Interoperability Testing Consortium and was instrumental in the creation of the BACnet Manufacturers Association.

George Kelly was the leader of the U.S. teams that participated in IEA Annexes 17 and 25, while John House was the U.S. team leader in Annex 34. George Kelly, Robert May, Cheol Park, and Gaylon Decious developed the building/HVAC emulator concept and participated in the "round robin" emulator exercises conducted by Annex 17 participants. Won-Yong Lee from the Korean Institute of Energy Research, John House, Cheol Park, and George Kelly were involved in the development and evaluation of different fault detection and diagnostic (FDD) methods in Annex 25. John House, Natascha Castro, and John Seem from Johnson Controls, Inc. demonstrated the application of different FDD methods in real building applications as a part of the Annex 34 activities.

In the fall of 1998, George Kelly proposed the CBS concept as a Major Product within BFRL. People who have worked on the CBS Major Project include George Kelly, Steven Bushby, John House, Natascha Castro, Jeanne Palmer, Cheol Park, and Mike Galler from the Building Environment Division; William Davis and Glenn Forney from the Fire Safety Engineering Division; Bill Grosshandler and Tom Cleary from the Fire Science Division; and Robert Chapman from BFRL's Office of Applied Economics. In February 1999, Steven Bushby became the new Leader of the Mechanical Systems and Controls Group, while George Kelly became the Chief of the Building Environment Division and continued as Project Manager of the CBS Major Product development effort.

Steven Bushby received the Department of Commerce Bronze Medal Award in 1992, and the NIST Slichter Award in 1996 for his contributions to BACnet. Steven Bushby and other project team members received the Vice Presidents "Hammer Award" for the 450 Golden Gate Project.

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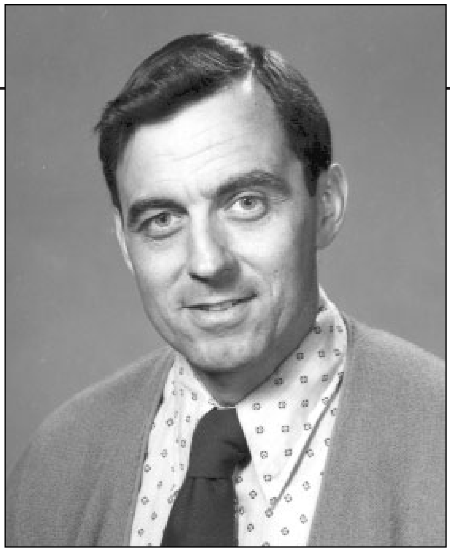
10.9 ALTERNATIVE REFRIGERANTS

The NIST refrigerants program began in 1981 as an outgrowth of the Thermal Machinery Group's research into methods of improving residential heat pump performance. For the previous five years the Group's main programmatic focus was on a U.S. Department of Energy sponsored effort to develop performance test procedures for residential heating and cooling appliances. Since energy conservation was still a national priority, heat pumps were selected, from among all residential heating systems because their current production model performance was furthest from ideal and they appeared to have the largest market growth. Coincidentally at this time the relatively new industrial agency, The Electric Power Research Institute (EPRI), was inviting proposals for advanced energy conservation concepts.

David Didion, the group leader, thought that an appropriate program would have to be both fundamental and practical. The first because it was in keeping with Laboratory's mission to lead the industry into new areas without competing with their own research organizations. The second because any success would have to be reasonably close to current system designs, if the industry was to accept it. The idea of using refrigerant mixtures as a working fluid was not new. The original idea was conceived by Lorentz, in 1894, and ever since Europeans had written about its theoretical advantages and performed an occasional experiment in one machine or another. Also, in 1981, General Electric was researching the use of mixture in home refrigerators and DuPont was also exploring candidate zeotropic (a.k.a. nonazeotropic) mixtures with an appropriate temperature glide for use in air conditioners. However, there was no record of any systematic quantitative study as to the potential improvement that mixtures could do for refrigeration systems.

Even at the proposal writing stage, it was obvious that the success of such a program would depend strongly on our knowledge of the thermodynamic properties of possible mixtures. For this reason a physical chemist, Graham Morrison, from the NIST's Thermophysics Division was asked to join the program for the purpose of


David Didion, leader, Thermal Machinery Group and world leader for environmentally benign refrigeration technology.

selecting an appropriate equation-of-state that could be used in the modification of the Group's vapor compression cycle model. This model had been under development by Piotr Domanski for the DoE efficiency labeling program. The fact that this model was based on first principles, as opposed to the Industrial type which is usually an empirically based component performance model, made it amendable to such a radical conversion. It was also obvious that a parallel study into the convection coefficient degradation, that mixtures were known to have, would have to be conducted. This was because the possibility existed that the theoretical thermodynamic benefits that the Lorentz cycle offered would be offset by the poorer heat transfer in the mixture two phase flow.

The EPRI proposal constituted the initiation of the NIST refrigeration program. It stated that based on the NIST expertise in heat pump evaluation and thermodynamic equations-of-state, along with its laboratory facilities supporting both, that NIST would begin to investigate the potential of the

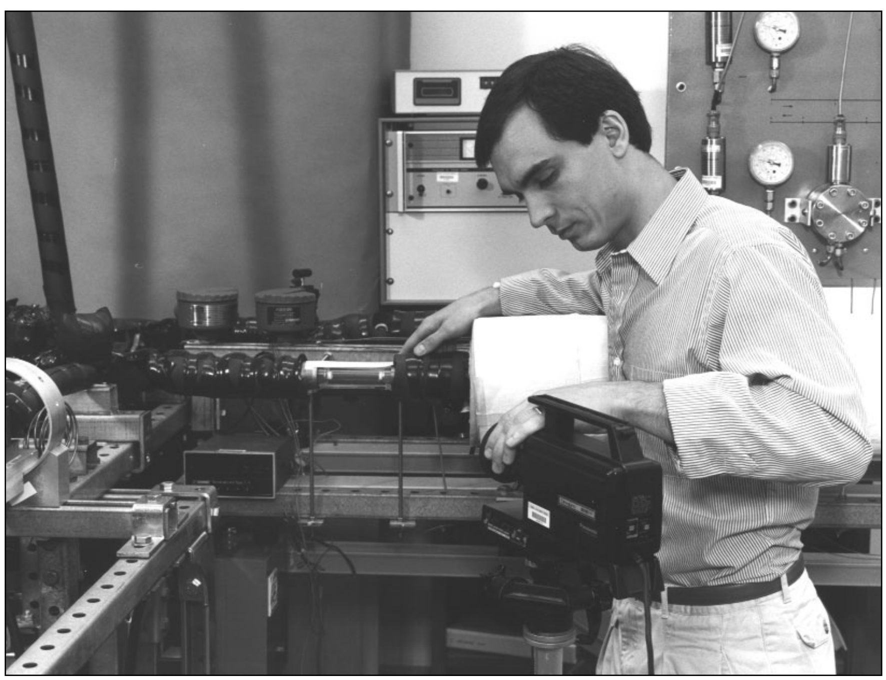
Lorentz concept for improving heat pump performance. NIST would share equally in the funding of the effort and take the most fundamental approach possible; that is, to attribute causes of system performance differences back to fluid and/or cycle properties, wherever possible.

Selecting a zeotropic mixture whose temperature glide (i.e., the difference between its dew and bubble points) can match the sensible fluids temperature gradient is the very essence of the Lorentz Cycle's performance merits. In order to determine the maximum system performance benefits it was necessary to construct heat exchangers that were grossly oversized and purely counter-flow. This experimental work was done in the first of several newly constructed vapor compression rigs called breadboard heat pumps because the four thermally important components (i.e., evaporator, compressor, condenser, expansion device) were spread out so that instrumentation accuracy was not compromised.

Tests of different mixtures soon began to demonstrate that the binary zeotropes' temperature gradients were typically nonlinear. About this time Mark McLinden, a Chemical Engineer, joined the Group. He provided a quantitative explanation that the enthalpy of phase change was a function of composition, which of course was changing during the evaporation and condensation processes. And that the degree of non-linearity was somewhat a function of the differences in normal boiling points of the components [1]. The practical ramification of this non-linearity was a pinch-point between the refrigerant mixture and the secondary heat transfer fluid in either the evaporator or the condenser was likely to occur with insignificant heat transfer down stream of the pinch point. A solution to this problem was determined to be the interjection of a third component whose normal boiling point is between the other two.

In parallel with the above thermodynamic work, a two phase heat transfer laboratory was created and developed for the specific purpose of explaining and quantifying the degradation of the zeotrope's heat transfer coefficient relative to the weighted average of the components' coefficients. The degradation was caused by a lack of the higher pressure component at the two phase interface, whether it be at a nucleate bubble or the liquid-vapor boundary of annular flow. Although the number of different mixtures measured was limited, Morrison concluded that the magnitude of the degradation may be a function of the difference in molecular size of the components. This evaporative flow work was taken over by a new full-time addition to the Group, Mark Kedzierski, at about the time the entire program was to change its objective due to the advent of the ozone crisis. One of his first assignments was to review the past two phase flow work

Mark Kedzierski, mechanical engineer, investigating the fundamental properties of pool boiling of alternative refrigerants.



we had been doing and make qualitative conclusions [2].

Early in the program a third laboratory path was initiated. Zeotropic mixture drop-in tests were conducted in several commercial heat pumps. It was realized that it was unlikely that the full performance benefits could be seen in a unit, since the Lorentz cycle's smaller average temperature difference between the refrigerant and the secondary heat transfer fluid necessarily requires a larger heat exchanger surface. So the indoor coil was replaced with one that had several banks of coils to approximate a cross-counter flow condition between the zeotropic phase change glide and that of the moist air stream. Although the efficiency never reached that for the original refrigerant, this work did provide some practical estimates of component sizes needed, particularly for cooling and dehumidification purposes. Included in this phase of the program was an investigation to explore the possibility of improving performance through the use of multistage distillation. This work showed the cost effectiveness of developing a heat pump that could essentially operate on one composition in the cooling mode and a significantly different one in the heating mode.

Not since the 1930s, when the halogens were introduced to the industry as a stable, safe (i.e., nonflammable and nontoxic) efficient family of refrigerants, had there been proposed such a widespread change in the industry's working fluids as that which resulted from the acknowledgement that chlorine was degrading the earth's ozone layer. Very little was known about chlorine-free refrigerants because the CFCs were the most stable and the best performers. By 1987, NIST researchers were in a truly unique position in their knowledge of how fluid properties effect the basic refrigeration cycle performance. Realizing the need for the industry's engineers to understand the fundamentals of using different refrigerants, McLinden and Didion wrote a seminal paper on the halogen family refrigerants [3]. This paper established NIST as an authority on the subject and paved the way for a decade of funding from government and industry.

ASHRAE immediately recognized the impact of this ozone/refrigerants issue and offered to play an important central role, as did ARI, for inter-industry communication. A series of special conferences were held with NIST and the Herrick Labs of Purdue University, in alternate years. The first was at NIST where the Building Environment Division hosted an invited speakers conference of thirteen papers on the alternative refrigerants. It was titled "CFCS: Today's Options - Tomorrows Solutions." Its was subtitled ASHRAE's 1989 CFC Technology Conference indicating how intimately CFCs were intertwined with the very concept of a refrigerant. The second ASHRAE/NIST refrigerants conference, in 1993, was "R-22/R-502 Alternatives." This subject was in response to the 1992 revisions to the Montreal Protocol, which called for the eventual phase out of all HCFCs. The 1997 conference was entitled Refrigerants for the 21st Century, and over half of the sixteen invited papers were on the natural refrigerants; that is, ammonia. carbon dioxide, air, water, hydrocarbons.

One of the most significant accomplishments during this phase of the program was that of Piotr Domanski's continuing modifications to the computer simulation model (CYCLE-11) to handle the ever-changing data-base [4] that NIST's Thermophysics Division was developing in the form that is now called REFPROP [5]. As these developments occurred the model was shared with selected industries. This enabled NIST to have a better understanding of industry needs while not having the huge burden of support documentation and making it user-friendly in a Windows format. However, due to public requests, a simplified version called CYCLE D was developed in a Windows format and issued for sale through NIST's Standard Reference Database 49 [6]. This program enables the user to compare fundamental cycle performances among virtually any working fluid, single component or mixture, that is contained within REFPROP. Further developments to CYCLE-11 allowed simulations with counter-flow, cross-flow and parallel-flow heat exchangers with consideration of the refrigerant circuitry design and its impact on pressure drop and heat transfer coefficient.

Flammable HFCs were being introduced into different zeotropes. It was necessary to mix non-flammable refrigerants with them such that the mixture was non-flammable under all feasible conditions. All of these developments were taking place at the same time ASHRAE was wrestling with how to determine flammability. McLinden and Didion worked with ASHRAE SSPC34 to determine how to measure flammability and to define the most flammable composition likely to occur in the field. The committee decided that would be a series of five slow leaks of 20 percent of the original quantity with subsequent recharges of the original composition. Establishing this composition experimentally turned out to be a procedure that took several days. Realizing REFPROP's ability to predict the composition of a mixture at any given thermodynamic state, NIST developed a quasi-steady state computer simulation procedure to act as an alternative to the tedious experimental procedure. The result was NIST Standard Reference Database 73 REFLEAK [7] that can predict the composition change of any mixture that can be created in REFPROP up to five recharge cycles and for either isothermal (slow) or adiabatic (fast) leaks.

Another critical need of industry was to understand and measure the heat transfer characteristics of alternative and mixed refrigerants with lubricants. Mark Kedzierski, soon after his arrival, began simultaneous construction on a pool boiling and on a convective boiling/condensation rig to meet these needs. These were both significant undertakings due to the unique rig designs and consequently required several years to build. An existing quartz tube rig was modified and operated so that some experimental results could be made available to industry while construction was underway. High-speed films at 6000 frames per second were taken of the low quality refrigerant flowing in the tube. The refrigerant/lubricant boiling was dramatically different from the pure refrigerant boiling [8]. Rather than relatively large discrete bubbles characterized by pure refrigerants, the refrigerant/lubricant boiled in a misty cloud of micro bubbles. The lubricant caused the bubbles to be much smaller and more numerous than the pure refrigerant bubbles. The lubricant effect on bubble size, bubble frequency, and the site density were quantified with the high-speed films. These data not only helped industry to redesign surfaces for the new refrigerants, but also were indispensable for the understanding of the influence of lubricant on boiling.

The uniqueness of the pool-boiling rig was that it was designed specifically to obtain measurements with low uncertainties with fluid heating. For example, the rig had the unique capability of using either electric heating or fluid heating for the same test section independent of the data acquisition method. A comparison of several enhancements showed that the heat flux obtained by fluid heating can be as much as 30 percent greater than that as obtained by electric heating. This casts a shadow on the use of electric heating as a valid test method for boiling. Kedzierski parametrically investigated the influence of lubricant viscosity, miscibility and composition with specially designed lubricant. A model was derived to predict the influence of each lubricant property on the heat transfer performance [9]. In general, it is possible to attain 100 percent enhancement relative to the pure refrigerant heat flux with a small quantity of high viscosity lubricant that is partially miscible in the refrigerant.

The profound contributions of this work to the world's knowledge of refrigeration technology, protection of the environment, and competitiveness of U.S. industry have been recognized by use of the results by industry and by numerous awards. These include the Department of Commerce Gold Medal for Didion in 1987, NIST Condon Award for Didion and McLinden in 1988, the NIST Applied Research Award for Didion in 1987, the Department of Commerce Bronze Medal Award for Domanski in 1991, the NIST Slichter Award for Didion, Kedzierski and Domanski in 1995, the Department of Commerce Bronze Medal Award for Kedzierski in 1995, the first Lorentzen Prize of the International Institute of Refrigeration for Didion in 1999, and the Hall Gold Medal from the United Kingdom's Institute of Refrigeration for Didion in 2001.

It is difficult to note all of the contributors who were involved in the program over twenty years. However there are a few who made especially significant contributions through dedicated service, unusual talent or both. Two were full time employees, William Mulroy and Peter Rothfleisch, and one was a guest worker from Seoul National University, Min Soo Kim.

This summary of CBT and BFRL work in alternative refrigerants has been excerpted from more comprehensive papers published by ASHRAE [10, 11].

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10.10 INDOOR AIR QUALITY

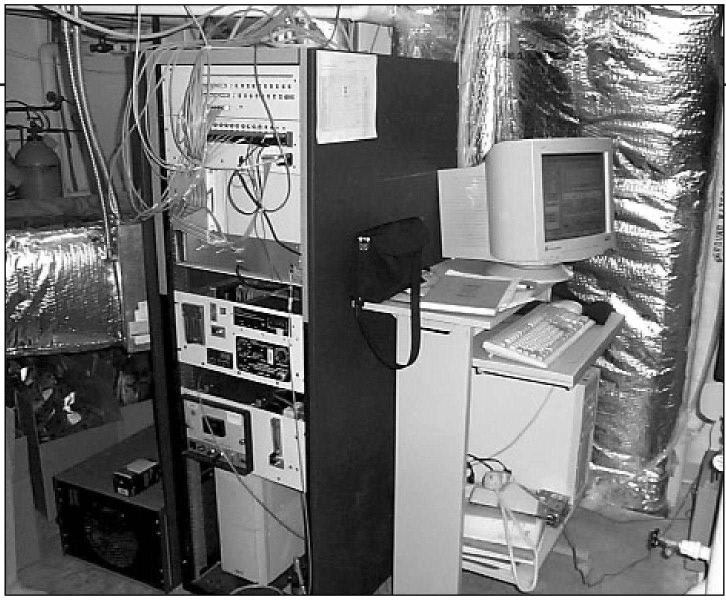
About the same time that energy efficiency research and demonstration projects were advancing in the mid-1970s, concerns about indoor air pollution were also increasing. These concerns were based upon energy efficiency measures of increased envelope air-tightness, leading to reduced infiltration rates, along with reductions in outdoor air ventilation rates. In combination with new materials being used indoors, these measures could increase indoor contaminant levels to the point that occupant health and comfort may be compromised.

Some of the earliest NBS work in this area was done by Tamami Kusuda [1] in an effort to look for ways to reduce ventilation rates and the associated energy consumption while still maintaining acceptable indoor air quality through the use of occupant-generated carbon dioxide levels to control the ventilation system. Most of the other work at NBS over the next 5 to 10 years focused on the development and application of tracer gas methods to determine ventilation rates in buildings. However, a major program to develop predictive models for building airflow and contaminant levels was initiated in the early 1980s [2]. This led to the development of the CONTAM series of computer programs that have expanded in capabilities and usability since the mid-1980s into the 21st century [3-6].

Other indoor air quality research focused on measurement methods to determine formaldehyde emissions from wood products and the development of models relating these emission rates to temperature and relative humidity [7, 8]. Another area of focus was the development of test methods to evaluate the performance of gaseous air cleaning devices [9-11]. This work built on similar research in the 1970s and before on particulate filter efficiency by Charles (Max) Hunt. The gaseous efficiency test methodology has fed directly into the ASHRAE committee developing a test for gaseous air cleaning media, which will be issued as Standard 145.

Another area of NBS and subsequently NIST indoor air quality research was in the development of methods for conducting long term field studies of ventilation and indoor contaminant levels in buildings. This work built off the tracer gas research (see section 10.11) and involved the development and deployment of automated data acquisition systems to monitor carbon monoxide, carbon dioxide, particulate and other contaminant levels. These studies were performed in a number of buildings located throughout the country and greatly expanded our knowledge of actual indoor air quality performance in office buildings and the factors that impacted that performance [12-17]. Among other results, this work produced the first comprehensive database of measured ventilation rates in mechanically ventilated office buildings, that is still unique and relied upon in many analyses of indoor air quality in U.S. office buildings [18]. The other major contribution of this work has been in the area of the measurement and interpretation of indoor carbon dioxide concentrations as they relate to building ventilation rates and indoor air quality [19]. This work led to the subsequent development of an ASTM guide on that subject, Standard D6245.

Charles (Max) Hunt received the Bronze Medal Award of the Department of Commerce in 1977 for his development of tracer gas measurement techniques. Andrew Persily received the Bronze Medal Award in 1989 for advancement of measurement techniques for indoor air quality, and Persily received the 2002 Award of Appreciation from ASTM Committee D-22, Sampling and Analysis of Atmospheres, for his leadership as Chair of the Related Factors section of Subcommittee D22.05, Indoor Air, and for his contributions to the development of new standards for the sampling and analysis of indoor atmospheres.



Automated tracer gas system for measuring building air change rates.

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10.11 BUILDING ENVELOPE PERFORMANCE

Driven by energy efficiency issues in the 1970s, a major program was started at NBS to develop measurement methods to evaluate the thermal performance of the building envelopes of office buildings. Supported by the U.S. Department of Energy and the General Services Administration's Public Building Service, NBS developed measurement methods to determine envelope airtightness and infiltration rates, in-site thermal resistance of walls, and overall thermal integrity using infrared thermography. The primary effort was in the area of tracer gas methods for measuring building infiltration rates, with a focus on automated instrumentation that would determine hourly average air change rates over periods of several months in order to characterize infiltration rates as a function of weather conditions and building system operation. This work began in the late 1970s, with the first measurements made in the NBS Administration Building [1]. More buildings were studied in the 1980s, including a 26-story office building in Newark NJ [2].

A major effort was conducted in the early 1980s for GSA, in which eight federal buildings throughout the country were studied using all the measurement methods referred to earlier [3]. These buildings were generally of fairly recent vintage and were not meeting their expected energy efficiency performance. Thermal envelope problems were suspected as being part of the reason for this discrepancy, and this research effort was carried out to first refine the test procedures and then to demonstrate them in the field while increasing our understanding of the magnitude and impacts of these thermal defects. The results of this research resulted in a great advances in the measurement knowledge and our knowledge of building envelope performance [4-6]. The results of this effort contributed to numerous ASTM test methods in the area of tracer gas techniques, building pressurization methods and in-site R-value measurement. Ultimately, NIST developed design guidelines for thermal envelope integrity for GSA that have had widespread application in the design of office building envelopes in the U.S. [7].

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10.12 PERFORMANCE CRITERIA AND STANDARDS FOR SOLAR ENERGY SYSTEMS

In September 1974, the United States Government enacted the Solar Heating and Cooling Demonstration Act [1]. The purpose of this Act was to "provide for the early development and commercial demonstration of the technology of solar heating and combined solar heating and cooling systems." Various sections of the Act assigned specific responsibilities to NBS. These responsibilities included: the development of interim performance criteria for solar heating systems and dwellings within 120 days; the development of definitive performance criteria, as soon as feasible, using data obtained from the residential solar demonstration program; preparation of test procedures by which manufacturers of solar systems and components could certify their products as to compliance with the definitive performance criteria; and monitoring the performance and operation of various solar heating and cooling demonstration projects. Working with the lead Federal agencies, U.S. Department of Housing and Urban Development (HUD) and Energy Research and Development Administration (ERDA), now the Department of Energy (DoE), and other organizations in the public and private sectors, NBS had an unique and challenging opportunity during a twelve year period (1974-1986) to conduct research activities in carrying out and meeting its responsibilities.

To develop interim performance criteria, NBS staff used: a performance statement format developed by NBS for a previous HUD program on innovative and industrialized housing systems [2]; available limited published information on solar hot water, heating and cooling systems; recommendations from consultants in solar heating and cooling system design, construction, and operation; and comments and suggestions on draft performance criteria which were developed by NBS and made available for public review in November 1974. The interim performance criteria document, which dealt with the functional, mechanical, structural, safety, durability/reliability, and maintainability performance of systems and components, was published in January 1975 [3].

Under the HUD residential solar demonstration program, over 500 projects, involving 10,000 dwelling units at a cost of $19.5 million were completed. Approximately 65 percent of these projects consisted of active solar energy systems and 35 percent consisted of passive or hybrid solar systems. The HUD program, along with the DoE National Solar Data Network Program which developed instrumented thermal performance data, provided a large data base on the performance of solar heating and cooling systems which was very valuable in identifying technical problems and issues pertinent to the development of performance criteria and standards.

NBS prepared a revised interim performance criteria document in 1978 [4], and in 1981, a draft final or "definitive" performance criteria document was prepared and made available for public review and comments [5]. Following consideration of the comments received, definitive performance criteria for solar heating and cooling systems in residential buildings were published in 1982 [6].

The 1982 document served as a technical reference and resource for the solar industry, building industry and various governmental agencies concerned with assessing the design and performance of solar heating systems in buildings. Previously, the interim performance criteria documents [3, 4] served as useful resources for the development of: performance criteria for commercial solar heating and cooling systems [7, 8] and photovoltaic systems [9]; HUD standards for solar heating and hot water systems [10], and recommended requirements for building codes [11].

Members of NBS staff who participated in the preparation of performance criteria were: F. Eugene Metz, John K. Holton, Thomas H. Boone, Leopold F. Skoda, Michael F. McCabe, Elmer P. Streed, Lawrence W. Masters, Elizabeth J. Clark, Paul W. Brown, W. Douglas Walton, David Waksman, Thomas K. Faison, Belinda C. Reeder, and Robert D. Dikkers.

A plan that identified the needs and priorities for test methods and other standards (recommended practices, specifications) for solar heating and cooling applications was first published by NBS in 1976. It was later revised in 1978 [12]. This plan was prepared in cooperation with a Steering Committee established under the auspices of the American National Standards Institute (ANSI) and was useful in establishing priorities for research and standards development projects. The purposes of this Steering Committee, which was comprised of representatives from over 20 public and private-sector organizations, were to: identify needs and formulate specific tasks leading to the development of national consensus standards for the utilization of solar heating and cooling; assign standards development projects to competent standards-writing organizations; and maintain a continuous overview of these organizations' activities in order to assure an orderly and effective process which would avoid duplication of effort and conflicting standards. With financial support from ERDA and DoE, NBS established various research projects for generating draft standards that could be subsequently utilized by standards-writing organizations as a starting basis for the accelerated generation of national consensus standards.

During the eight-year period, 1974-1982, significant accomplishments were made in the development and validation of test methods and other standards relating to solar heating and cooling systems, components, and materials. With DoE support, many organizations including the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), American Society for Testing and Materials (ASTM), ANSI, and NBS contributed to the development of twenty new national consensus standards. Most of these standards, along with improved analytical procedures and design guidelines were referenced in the various evaluation sections of the 1982 definitive performance document (6).

Specifically, NBS assisted ASHRAE in the development and evaluation of test methods to measure the thermal performance of solar collectors [13-17], storage devices [14, 18-20], and domestic water heating systems [21]. The NBS method of test for solar thermal collectors allowed characterization under both outdoor environmental conditions and indoors using a solar simulator [22-26]. The test procedure developed for solar hot water systems permitted testing under outdoor conditions, indoor testing using a solar simulator, and indoor testing using a novel thermal simulation method [21, 27-35]. The Solar Rating and Certification Corporation (SRCC), an independent non-profit organization, adopted the solar collector and hot water test methods developed by NBS in the early 1980s. To date, over 1000 solar thermal collectors and 300 solar hot water systems have been SRCC certified providing much needed information to consumers contemplating the purchase of solar equipment.

Through research and the preparation of draft standards, NBS also aided ASTM in developing specifications for rubber seals and hose [36-38]; and practices for evaluating the durability of cover plates [39,40], absorptive coatings [41], thermal insulation [42], metallic and polymeric containment materials [43,44], and solar collectors [45]. Several of these standards have been referenced for use in U.S. industry certification programs for solar collectors and hot water systems. Many of the other standards were used as valuable tools in the evaluation of new materials and components for use in solar heating and cooling systems.

The U.S. Department of Energy sponsored research at NBS from 1977 through 1987 to provide experimental data to validate and improve computer

The majority of the experimental work on solar energy equipment took place at the NIST Annex (adjacent to NIST's campus, a former US Army Nike Missile site). The solar equipment, in this photograph, is being used to develop test methods for materials, solar collectors, and solar water heating systems.

simulation models used to predict the performance of solar water heating systems. In order to meet this objective, Hunter Fanney led a team consisting of Jim Allen, Donn Ebberts, Charles Terlizzi, and latter Brian Dougherty in the construction of a solar hot water test facility. The resulting facility was the only one within the U.S. that permitted the side-by-side testing of up to six solar water heaters subjected to identical environmental and load conditions. Over the years, this facility was used to test a vast array of solar water heating systems utilizing various solar collector designs, heat transfer fluids, control strategies, and storage tank configurations. The data collected from this facility greatly improved the simulation models and as a result, Hunter Fanney was asked to join and provide data to the International Energy Agency's Solar Heating and Cooling Program. His subsequent involvement provided additional exposure to NBS' solar energy activities.

In addition to providing experimental data for model validation [46-51], the research conducted within this facility led to an improved understanding of component interactions within solar water heating systems [52-55], the development of a novel measurement technique to measure the flow rate in thermosyphon solar water heating systems [56, 57], and supported the development of a testing methodology for solar water heating systems.

As interest in the direct conversion of sunlight to electricity through the use of solar photovoltaics increased during the 1980s, NBS researchers Hunter Fanney and Brian Dougherty became intrigued with the development of a solar hot water system that utilized photovoltaic panels. This work led to a prototype system and a U.S. patent was awarded to NIST in 1994 [58,59]. During the next several years, the U.S. Air Force funded NIST to deploy and measure the performance of two of these systems at the Kadena Air Force Base in Okinawa, Japan. The Tennessee Valley Authority, in concert with the National Park Service, funded the installation and monitoring of NIST's solar photovoltaic system at the Great Smoky Mountains National Park (GSMNP) [60,61]. Since 1996 this system has met the hot water needs of the main visitor's center and provided excellent visibility for NIST's efforts.

Building integrated photovoltaics, the integration of photovoltaic cells into one or more of the exterior surfaces of the building envelope, began to receive widespread interest in the late 1990s. Several factors are supporting this current interest including increased concerns over global warming, continuing declines in photovoltaic prices, legislation that requires utilities to buy excess energy generated by on-site distributed energy sources, and the fact that buildings account for 40 percent of the U.S. energy consumption. One of the barriers to the widespread proliferation of building integrated photovoltaics is the lack of performance data and validated models that will enable designers, architects, installers, and consumers to judge the merits of building integrated photovoltaics. In order to address this need Hunter Fanney, Brian Dougherty, and Mark Davis have constructed a number of experimental facilities and undertaken a multi-year project, co-funded by the California Energy Commission to provide the data needed for model validation. The facilities include a mobile, photovoltaic test facility, a building integrated photovoltaic "test bed," and

Hunter Fanney, leader, Heat Transfer and Alternative Energy Systems Group and David Block, director, Florida Solar Energy Center, shown commissioning a photovoltaic solar water heating system at the Florida Solar Energy Center.

a meteorological station [62]. Working with the solar photovoltaic industry NIST has characterized a number of photovoltaic cell technologies [63], collected long-term experimental data for a number of building integrated photovoltaic panels [64], and is currently striving to improve the computer simulation tools [65,66].

NIST's most recent activity in solar energy took place on September 14, 2001 when a 35 kW photovoltaic system located on NIST's Administration Building began supplying electrical power into the electrical grid [67]. This system provides enough electrical energy on an annual basis to meet the total electrical needs of four to five typical homes in the Gaithersburg, MD, area. In addition to saving energy and reducing peak demand charges, over a 30 year lifetime, this solar system is projected to avoid power plant emissions of an estimated 3,211 kg of nitrogen oxides, 7,470 kg of sulfur oxides, and 1,261 t of carbon dioxide. This project represents a cooperative effort between BFRL's Heat Transfer and Alternative Energy Systems Group, led by Hunter Fanney, and NIST's Plant Division, led by Douglas Elznic. This grid-connected photovoltaic system will serve as a model for the future installation of photovoltaic systems at NIST.

James Hill, who began NBS research in 1974 on measurement methods for the performance of solar collectors and storage systems, received the Department of Commerce Silver Medal Award in 1976, for contributions to the development of efficient solar energy systems. Robert D. Dikkers, who was responsible for the management and coordination of solar heating and cooling research activities being carried out for DoE and HUD from September 1974 through September 1986, was awarded the Department of Commerce Silver Medal Award in 1979 for his significant contributions to the development of national performance criteria and standards for solar energy systems. Department of Commerce Bronze Medal awards in 1980 went to: Willard Roberts for developing durability tests for solar systems materials; Elmer Streed for developing and evaluating testing standards for solar heating and cooling equipment; and David Waksman for development of performance criteria and standards for solar heating and cooling applications. Hunter Fanney, received the Department of Commerce Bronze Medal in 1988, for development of design, testing, and rating procedures for solar domestic water heating systems for buildings. In 1996 Hunter Fanney and Brian Dougherty received the Federal Laboratory's Consortium Excellence in Technology transfer Award for their outstanding work in transferring the photovoltaic solar

Photovoltaic Array installed on the NIST Administration Building that provided NIST's first on-site renewable energy on 14 September 2001.

water heating technology to the private sector. Based upon his contributions to the field of solar energy, Hunter Fanney was selected by the National Society of Professional Engineers as the Department of Commerce's "1999 Engineer of the Year." To date, the NIST team conducting solar photovoltaic research (Hunter Fanney, Brian Dougherty, and Mark Davis) has received three American Society of Mechanical Engineers' Best Paper Awards.

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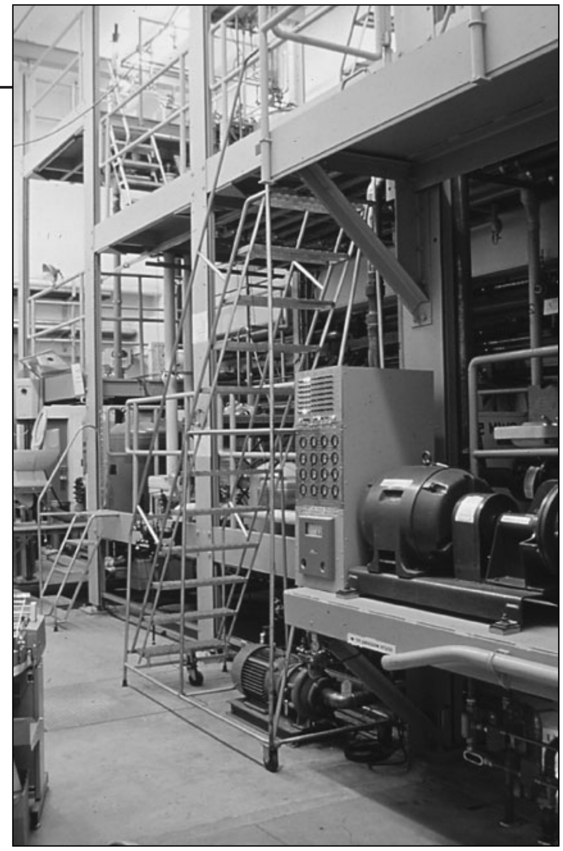
10.13 PLUMBING

In 1924 Herbert Hoover, Secretary of the Department of Commerce, reported in "Recommended Minimum Requirements for Plumbing in Dwellings and Similar Buildings," "…actual (plumbing) practice has been governed by opinions and guesswork, often involving needless costly precautions which many families could ill afford. The lack of generalized principles is responsible to a certain extent for the contradictory plumbing regulations in different localities…." NBS' Dr. Roy B. Hunter's research contributions established the basis for U.S. national plumbing codes that followed "The Hoover Codes" of 1928 and 1932 [1]. Those contributions remain in worldwide plumbing codes as adopted "Hunter Fixture Units" for design applications to full bore water supply pipe flow and partially filled pipe flow in drain-waste systems [2, 3].

FULL SCALE DYNAMIC PLUMBING TEST FACILITY - REALIZED

After NBS moved to Gaithersburg in the late 1960s the need was recognized for a plumbing test facility to investigate hydraulic phenomena of pipe networks of as-built systems. A full-scale tower installation was advocated by



CBT's seven-story plumbing tower and high-speed computerized electronic data acquisition system is used to simulate operation of full-scale plumbing systems in multistory buildings and reduced size venting and drain-waste-vent studies.

industry and code groups and constructed with the assistance of industry. Increased competence in hydraulic research event measurement was foreseen and was achieved with the introduction of computers for dynamic conditions event recording coupled with advanced instrumentation methods. The NBS plumbing test tower was constructed in 1972 in CBT under the supervision of Robert Wyly, Jack Snell, and Reece Achenbach. The facility provided capabilities for full-scale simulations of drain-waste-vent (D-W-V) plumbing systems in multi-story and town house installations.

SELECTED PLUMBING RESEARCH CONTRIBUTIONS

Several important building plumbing systems research investigations were performed using the plumbing facility in collaborations with industry and the government sectors. Working with the Copper Development Association NBS developed test procedures for test loads and measurements of a novel high rise single stack system (now the Sovent system) for U.S. applications. The work followed HUD Operation Breakthrough High Rise investigations with particularly identified research needs [4]. Installation acceptance for U.S. high rise buildings was advanced as a result of the data and information from this research; various materials are now marketed for the stacks and fittings with cost savings to contractors.

In collaboration with the National Association of Home Builders (NAHB) and DoD's Tri-Services Committee NBS developed recommendations for sizing vents at less than code specifications [5] for small residential buildings. Data were derived from test evaluations in NBS' new laboratory town house module.

With the DoD Tri-Services Committee for Building Materials, NBS supported full scale testing of a two-story townhouse configuration with reduced-size vents over a wide range of waste loading conditions in drain-waste-vent systems (D-W-V) [6]. Pipe size reductions were shown feasible without jeopardizing trap seal retention capacity. Actual air demand measurements were significantly less than assumed from current practice in plumbing codes (based on earlier NBS reports) for short stack systems with vent networks.

With the USAF, the Building Research Committee Tri-Services, and HUD, NBS determined reduced vent sizing for six new homes based on prior laboratory results. The field studies installation included automated system instrumentation (in occupied homes) for plumbing performance and user data collection for water usage [7]. NAHB encouraged their constituency of small home builders to adopt this sizing into practice by presentation of a mockup display installation. Cost savings of materials and labor indicated a potential for larger number of mortgage approvals as determined from NBS economic analyses applied to national financial minimum conditions for applicants. NAHB's economic assessment of the latter provisions indicated savings of about $500 per home in plumbing system costs. Confirmation of the sizing procedure information was submitted for plumbing code acceptance. It was not achieved primarily due to dissident opinion from sources seeking preservation of 'existing satisfactory practices'.

In a HUD sponsored research NBS performed investigation of water closet reduced consumption by control modifications of installed fixtures [8]. Laboratory testing of two-step flush control devices installed on water closets were conducted to evaluate the efficacy for water savings with reduced flush volumes. Criteria were developed for performance testing of mechanical functions and necessary performance evaluation procedures for retention of siphonic action, trap seal restoration, contaminated water exchange variability or reduction, rim wash cleansing, and adequacy of tissue extraction. Recommendations were prepared for implementation in standards.

Dynamic evaluations also were conducted in the test facility. Investigation was made of added circulation drain and vent loop modified D-W-V systems to increase system capacity in housing rehabilitation [9]. Reduced size vent applications for Veterans Administration hospitals were investigated by testing and analytical modeling for sizing [10]. Test data from dynamic measurements on multi-branch vent circuit networks were obtained for a novel installation of 'vent header' interconnects (of vertical vent stacks) in the interstitial space below the roof to avoid rain leakage from roof penetrations. Building sidewall fittings provide atmospheric pressure relief. Pressure calculations included algorithms for air pressure loss factors based on for local conditions; design sizing tables were prepared as guide to illustrate applications [10].

MODERNIZATION AND TRANSFORMATION OF PRINCIPLES

Elimination of steady flow assumptions for plumbing hydraulic phenomena became practical as the 1970s decade closed. Upgrading the test tower by Paul Kopetka, Fred Winter, and Lynn Shuman provided a unique ability to simultaneously measure time dependent phenomena and improve data precision.

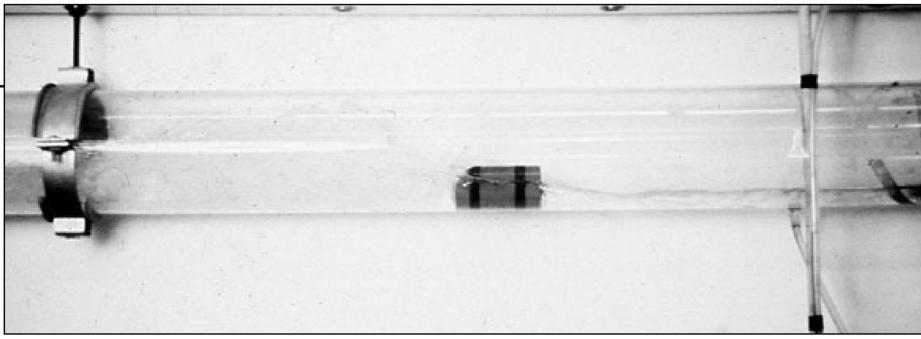
No comparable measurements in a full-scale drain-waste-vent plumbing system and fixtures had been undertaken elsewhere, or have been duplicated to date. The determination of actual transient event details became practical (water closets discharge from three to ten seconds while hydraulic jumps and flow mixing in merged flows occur within a second). Instrumentation was installed coupled with an electronic advanced sensor interface with desk top computer systems that established new competency in dynamic measurement and automated data recording with control of test events and pre-arranged loading condition sequences.

POTABLE WATER CONSERVATION PROGRAM - A COMPREHENSIVE THRUST

HUD Under Secretary Donna Shallala in 1978 approved plans for a National Potable Water Conservation program led by Lawrence Galowin with broadly inclusive participation from other participating sectors. NBS activity incorporated economics, human factors, consumer products, establishment of Stevens Institute contract, and HUD private contractor interface. Field studies of residential water demand and usage in a series of city studies on home water consumption (published by HUD) became a decade long primary resource for the American Water Works Association. The Residential Water Conservation Projects Summary Report on water conserving installations was published by HUD. It summarized three projects in Los Angeles, Denver, and the Washington areas. Robert Wyly and Lawrence Galowin assisted HUD as participants, technical advisors, and reviewers.

Results included performance of water-conserving fixtures, water supply requirements suitable for plumbing codes and consistent with water-conserving fixtures, and test procedures for the performance of water-conserving fixtures. These results permitted reliable and serviceable water-conserving residential plumbing systems with showerhead flow pressure control, user temperature requirements, pressure limiting devices and water distributions testing for performance standards [11]. Results were incorporated into the 1983 American National Standards Institute standard for water-conserving fixtures. The 1986 One and Two Family Dwelling Code of the Council of American Building Officials adopted the recommendations for drainage loads and methods for sizing water supply, drain, and vent piping. The work led to a National Potable Water Conservation Conference [12]. As a result, the American Water Works Association has encouraged water conservation.

A major result was the development (by Professor John A. Swaffield as



Horizontal solid waste drain transport for surge flow discharge

Guest Scientist at NBS) of a numerical method of characteristics solution to the governing equations for time dependent flow and waste solids transport. A computer-based engineering design procedure for the drain-waste-vent system accurately accounted for the transient transport of liquids and solids [13-20]. Fundamental theory and applications to plumbing codes were achieved which correctly reflected the hydraulics of plumbing piping systems and waste solids transport.

The dynamic modeling computer program for plumbing drainage system design has become a commercially available product in the 1990s for engineered systems and to many diverse applications for design and problem resolution. Progress continues with sustained research in doctoral degree programs in the United Kingdom that are directed by Professor Swaffield.

Larry Galowin provided enthusiastic leadership for CBT's plumbing research until it was curtailed by the cuts in CBT in the mid 80s. Galowin continued to be active in national and international plumbing research and standardization activities while assigned to other programs at NBS/NIST. As a NIST Guest Researcher he continues participation in plumbing activities. Galowin received national and international recognition for his research and recently served as a Visiting Professor and Leverhulme Fellow appointed at Heriot-Watt University, Scotland.

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