Methods for Testing and Rating the Performance of Heating and Air Conditioning Systems

The U.S. Congress enacted the Energy Policy and Conservation Act (EPCA, Public Law 94-163) in December 1975. It was subsequently amended four times, most recently in 1992. As amended, EPCA requires:

- the U.S. Department of Energy (DOE) to establish energy conservation standards (minimum efficiency or maximum energy use) for all major energy consuming products in a residence,
- the National Bureau of Standards (NBS) to develop test procedures for the same products, and
- the U.S. Federal Trade Commission (FTC) to develop a program of labeling the products to encourage purchase of energy efficient equipment.

EPCA required NBS to develop test procedures for each product for the determination of estimated annual operating cost and at least one other useful measure of energy consumption likely to assist consumers in making purchasing decisions. An additional requirement of the law was that "any test procedures prescribed be reasonably designed to produce test results which reflect energy efficiency, energy use, or estimated annual operating cost during a representative average use cycle and not be unduly burdensome to conduct."

Beginning in 1975, NBS staff reviewed the test procedures already in use within the appliance and heating and cooling industry. By the early 1980s, test procedures were in place for all covered products. Throughout the development, NBS staff worked closely with industry representatives experienced in testing the equipment to obtain their review and recommendations, particularly on energy conservation innovations that were being considered for future products.

This review found many test procedures that could be used with minor modifications and recommended them for adoption. The industry procedures that required little change were primarily for "white" appliances, those used for cooking, cleaning, refrigerating food, etc. For them, the performance and annual cost of operation were primarily dependent on the use schedule. Therefore, NBS adopted steady-state tests plus a calculation procedure assuming a specific daily operating schedule.

In the case of residential heating and cooling systems, however, entirely new procedures had to be developed, as described in these publications [1,2]. At the time, steady-state tests were used in the industry for central heating and cooling equipment. However, the equipment cycled on and off frequently throughout most days. During the start-up and shut-down periods, most of the equipment experienced non-trivial energy losses or inefficiencies associated with warm-up, cool-down, and/or migration of refrigerant. In addition, the performance of this equipment was almost independent of the user (except for thermostat setting) and primarily dependent on the weather conditions. As a result, NBS staff developed new procedures for this type of equipment that included steady-state and cycling tests coupled with a calculation procedure that accounted for the changing weather conditions throughout the heating and cooling seasons.

Kelly and Chi published the initial procedure for central furnaces and boilers in 1978 [1]. The testing required was simple, but the estimation of yearly performance was done through an elaborate calculation procedure. They found that the performance of furnaces and boilers under part-load, on-off operation could be described by a simple "time-constant" model, and that data required to determine the time-constant could be obtained during "warm-up" and "cool-down" periods before and after a steady-state test without extensive cycling tests.

Based on the test data, five major loss terms were calculated and subtracted from 100 to obtain the value of the seasonal efficiency.

1. Latent Heat Loss, due to the presence of uncondensed water vapor in the flue gas.
2. On-Period Sensible Heat Loss, due to the heating of combustion products and excess air from room temperature up to the flue gas temperature.
3. On-Period Infiltration Loss, due to heating on-cycle combustion and relief air from the outdoor temperature up to room temperature.
4. Off-Period Sensible Heat Loss, due to the heating of the off-cycle draft air up to a temperature in excess of the indoor air temperature.

5. Off-Period Infiltration Loss, due to the heating of the off-cycle draft and relief air from the outdoor up to the indoor air temperature.

In developing the calculation procedure, Kelly and Chi found that they could evaluate the loss terms at the heating season average outdoor air temperature and obtain virtually identical results with a more complicated "bin" analysis with a separate calculation of efficiency for each "bin." In addition, the manufacturer had to calculate an annual fuel utilization efficiency (AFUE) which differed from the seasonal efficiency if there was consumption of energy by a pilot light operating during the non-heating season.

After the publication of the original test procedure, Kelly and his colleagues modified it to handle advances in furnace and boiler technology such as:

1. pulse combustion and condensing furnaces [6]
2. modulating and two-step controls on furnaces and boilers [7]
3. furnaces with inlet dampers [8]
4. furnaces with post purge design [9].

Didion and Kelly [2] used the same approach in developing the test and calculation procedure for central air conditioners and heat pumps as for furnaces and boilers. However, because of the different ways refrigerant migrated from one component to another during the off-cycle, they could not describe the performance during the off-cycle by a simple time constant model. As a result, the testing procedure was considerably more complicated and required cycling tests.

The tests for central air conditioners and heat pumps operating in the cooling mode consisted of three steady-state tests and one cycling test. In all tests, the capacity, electrical energy input, and coefficient of performance (COP) were determined. Didion and Kelly expected to develop a procedure with only two tests: one at full capacity and one at some part-load condition requiring the unit to cycle. In both tests, the indoor coil would be wet with dehumidification occurring. However, in preliminary studies, they found that a wet-coil cycling test at part-load conditions presented significant experimental problems. The capacity was determined by measuring the enthalpy increase across the indoor coil. This measurement was unreliable under periodically varying conditions. Fortunately, they found that the ratio of the COP in the cycling mode to that under steady-state conditions was the same for dry-coil and wet-coil conditions for the same part-load conditions. Consequently, two tests were conducted to determine a degradation coefficient describing the losses due to cycling under dry-coil conditions. These results were used to modify a wet-coil steady-state test where the unit would normally cycle. Manufacturers could use an assumed value of the degradation coefficient in lieu of conducting the two dry coil tests. Finally, a full-load steady-state test was conducted at a hot outdoor temperature.

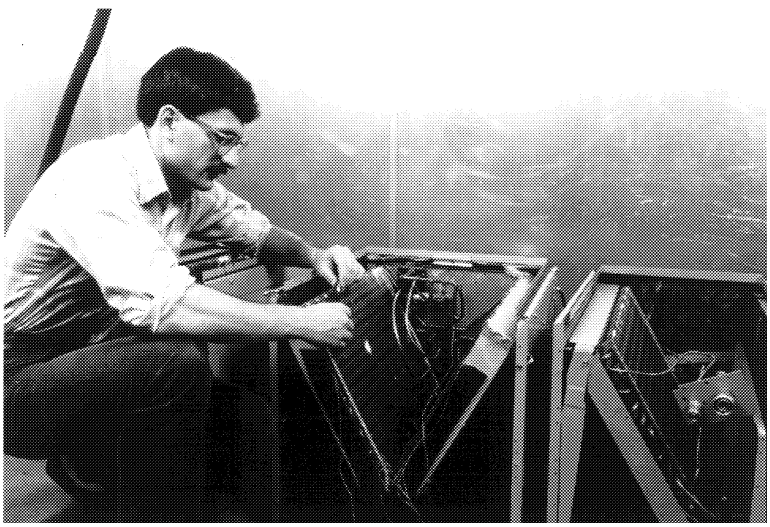

Fig. 1. Maciej Chwalowski prepares central air conditioning units for test.

As with furnaces and boilers, Didion and Kelly intended to use a bin method for calculating a seasonal energy efficiency ratio (SEER), where the performance was weighted by the number of hours the unit operates in each temperature bin. Again, they found the variation in SEER with climate for typical units to be only slight. Consequently, the SEER was calculated for a climate with a specific average operating outdoor temperature.

Four tests were also required for heat pumps operating in the heating mode: a full load steady-state test at a high outdoor temperature and one at a low temperature to determine how the capacity and power varied with temperature differences; a third test to determine cycling degradation; and a fourth to determine the effect of frosting on the outdoor coil. The calculation procedure to obtain a heating season performance factor (HSPF) was a bin method. They were not able to find a short-cut procedure as with furnaces and boilers and air conditioners operating in the cooling mode.

After the publication of the original test procedure, Didion and his colleagues modified it to handle variable-speed equipment [10]. This increased the number of mandatory tests to ten and optional tests to five. In addition, they developed procedures to rate mixed systems: those where the indoor coil of one tested system is installed with the outdoor compressor-condenser unit of another tested system [11,12].

The development of the new test procedures for central heating and cooling caused a revolution in the way industry tested such equipment. They resisted and fought the changes for several years because of the increased cost and complexity of testing. Ultimately the tests were accepted, used throughout the industry, and adopted by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) as ASHRAE Standards 103 (Central Furnaces and Boilers) and 116 (Unitary Air Conditioners and Heat Pumps).

Residential equipment accounted for 20 % of U.S. national energy consumption during the last quarter of the 20th century. The development of these test procedures, a labeling program for some of the equipment, and the threat of mandatory standards resulted in substantial increases in U.S. equipment efficiency. The American Council for an Energy Efficient Economy (ACEEE) [13] reported average efficiency increases from 1972 to 1987 of 96 % for refrigerator-freezers, 35 % for central air conditioners and heat pumps, 30 % for room air conditioners, and 18 % for gas furnaces.

George E. Kelly came to NBS in 1970 as a National Research Council/NBS Postdoctoral Research Associate. For two years, he conducted research on condensation and the theory of droplet growth in homogeneous nucleation. He joined the predecessor organization of the Building and Fire Research Laboratory (BFRL) in 1972 and began immediately working on the program of testing heating and cooling equipment for seasonal performance described above. Because of its significant impact, George received the Department of Commerce Silver Medal in 1978. He went on to establish a significant new research program on building controls beginning in 1980. Over a period of 20 years, he and his staff gained a world-wide reputation for their work. They developed an advanced dynamic building/HVAC

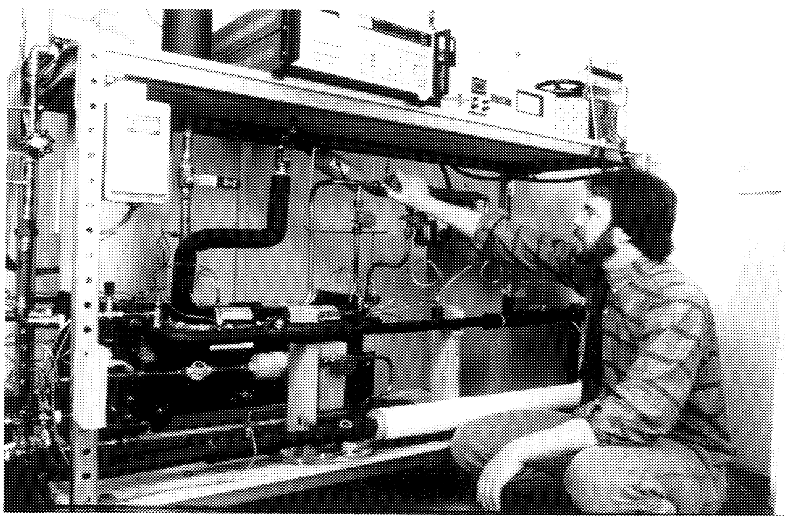

Fig. 2. David Aaron adjusts flow conditions in refrigeration loop where flow restrictors are evaluated.

Fig. 3. Brian Dougherty prepares super-efficient heat pump for tests.

control simulation program HVACSIM+, pioneered an innovative method for testing and evaluating computerized control systems using a building emulator, and developed a standard communication protocol for building controls, BACnet, which was adopted nationally as ASHRAE Standard 135, adopted internationally by ISO, and named by Engineering News Record in 1999 as one of the 100 top innovations of the 20th century in the construction industry. For his work, George was named the Department of Commerce Engineer of the Year in 1992. He was promoted to Chief of the Building Environment Division of BFRL in 1999.

David A. Didion came to NBS in 1971 and immediately began working on the performance of heating and cooling equipment. He too received the Department of Commerce Silver Medal in 1981 for his work. In 1980, Dave and his staff began an intense research program on refrigeration machinery and the use of refrigerant mixtures to improve their performance. When ozone depletion in the stratosphere was recognized as an international environmental crisis and the first international protocol/regulation was established in 1987, chlorofluorocarbons (CFC) were phased out of use in refrigeration equipment. Dave's research team was ideally poised to lead the national effort in identifying refrigerant mixtures that ultimately replaced the CFCs. For this work he was recognized with numerous awards; among them the Department of Commerce Gold Medal (1987), the NIST Applied Research Award (1987), the Edward Uhler Condon Award (1988), the William P. Slichter Award (1995), and the first Gustov Lorenzen Prize from the International Institute of Refrigeration (1999). He was elevated to NIST Fellow in 1995.

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Bibliography

[1] Joseph Chi and George E. Kelly, A Method for Estimating the Seasonal Performance of Residential Gas and Oil-Fired Heating Systems, *ASHRAE Trans.* **84**, Part 1, 405-421 (1978).

[2] David A. Didion and George E. Kelly, New Testing and Rating Procedures for Seasonal Performance of Heat Pumps, *ASHRAE J.* **21** (9), 40-44 (1979).

[3] George E. Kelly, Joseph Chi and Mark E. Kuklewicz, *Recommended Testing and Calculation Procedures for Determining the Seasonal Performance of Residential Central Furnaces and Boilers,* NBSIR 78-1543, National Bureau of Standards, Washington, DC, September 1978.

[4] G. E. Kelly and W. H. Parken, Jr., *Method of Testing, Rating, and Estimating the Seasonal Performance of Central Air-Conditioners and Heat Pumps Operating in the Cooling Mode,* NBSIR 77-1271, National Bureau of Standards, Washington, DC, April 1978.

[5] Walter H. Parken, George E. Kelly, and David A. Didion, *Method of Testing, Rating, and Estimating the Heating Seasonal Performance of Heat Pumps,* NBSIR 80-2002, National Bureau of Standards, Washington, DC, April 1980.

[6] George E. Kelly and Mark E. Kuklewicz, *Recommended Testing and Calculation Procedures for Estimating the Seasonal Performance of Residential Condensing Furnaces and Boilers,* NBSIR 80-2110, National Bureau of Standards, Washington, DC, April 1981.

[7] Esher Kweller and Robert L. Palla, Jr., *A Test Method and Calculation Procedure for Determining Annual Efficiency for Vented Household Heaters and Furnaces Equipped with Modulating-Type Controls,* NBSIR 82-2497, National Bureau of Standards, Washington, DC, May 1982.

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

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

[10] Piotr A. Domanski, *Recommended Procedure for Rating and Testing of Variable Speed Air Source Unitary Air Conditioners and Heat Pumps,* NISTIR 88-3781, National Institute of Standards and Technology, Gaithersburg, MD, May 1988.

[11] Piotr A. Domanski, *Rating Procedure for Mixed Air-Source Unitary Air Conditioners and Heat Pumps Operating in the Cooling Mode—Revision 1,* NISTIR 89-4071, National Institute of Standards and Technology, Gaithersburg, MD, May 1989.

[12] Piotr A. Domanski, *Rating Procedure for Mixed Air-Source Unitary Heat Pumps Operating in the Heating Mode,* NISTIR 90-4298, National Institute of Standards and Technology, Gaithersburg, MD, May 1990.

[13] Howard S. Geller, *Residential Equipment Efficiency: 1988 Update,* American Council for an Energy-Efficient Economy, Washington, DC, August 1988.