# Building Energy Analysis and Retrofit Selection for Russian Multi-Family Housing

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This paper describes a building analysis model for Russian multi-family housing, an array of possible retrofits, and the energy analyses for these buildings. It also describes the Russian retrofit project that will use these analyses to specify more than $300M of retrofits across six cities. The research was done under the Enterprise Housing Divestiture Project, a Government of Russia project with partial financing from the World Bank.

A special version of the Facility Energy Decision System [FEDS] model was developed for use on Russian multi-family buildings. FEDS is a user-friendly, Windows-based, menu-driven software program for assessing the energy efficiency resources for a single building, large installation, or city. Detailed energy simulation and optimization submodels estimate the potential for energy retrofits in buildings, explicitly considering all system interactive effects.

FEDS was modified for Russian multi-family buildings. Specific characteristics peculiar to these buildings include natural draft ventilation, central plant radiator heating with no building-level flow control, and recirculating domestic hot water (which provides significant heating). Twenty-four individual building designs are considered, ranging from one-story duplexes to 16-story high-risers. About thirty retrofit measures are being evaluated including:

- insulation of attics, roofs, floors, and walls;
- caulking and weather stripping of doors, windows, and wall panels;
- repair/replacement of windows and doors, including addition of vestibule doors;
- building- and apartment-level heating controls, radiator reflectors, and in-building boilers;
- conversion to forced ventilation, or user control of natural draft ventilation;
- low-flow shower heads and faucet aerators, and in-building domestic hot water generation; and
- lighting.

## INTRODUCTION

Russian enterprises operated classic "company towns" during the Soviet era. The enterprise provided housing, schools, health care, and recreational facilities for the workers. Housing services (rent and utilities) were essentially free. In transition to a market economy, these social "assets" are significant financial liabilities for the enterprises, and they discourage foreign private investment.

In 1992 the process of enterprise privatization started to spread rapidly throughout Russia due to governmental edict. As part of this process, ownership of the enterprise housing stock is being "divested" to municipal governments, with the ultimate goal being private ownership. However, the cities are generally in poor financial condition, and despite divestiture, many enterprises remain responsible for financing and managing their former housing stock. Currently, about 20 percent of Russia's housing continues to be financed, maintained, and operated by enterprises. Enterprises have little incentive to invest resources in housing stock since (1) they no longer own it, and (2) generally their employees constitute less than 50% of the building occupants. This lack of incentive is reflected in the deteriorating condition of the buildings.

The financial problem is exacerbated by rapid rise in energy and water tariffs. Historically, tenants have paid less than

5% of the production cost of these services, with the rest subsidized from government sources. However, the federal Government (with its own financial problems) has ended subsidization of utility services, and now energy and water tariffs are rising rapidly. The tariff level now accounts for about 40% of total production costs (including capital replacement), and is expected to reach full production cost within two years. However, few occupants have the ability or the will to pay these increasing tariffs, and so the costs fall back upon the building owner. This creates an even greater incentive for the enterprises to divest the housing to municipalities. But, of course, the municipalities are not eager to accept these financial problems.

Because of these events, the Russian Government requested that the World Bank investigate the possibility of providing financial assistance to ease the housing burden of the municipal governments, and to help design a program to make it attractive for tenant ownership. The World Bank agreed to assess the feasibility of such a project under the "Enterprise Housing Divestiture Project" [EHDP] in summer 1994. (The formal approval for the World Bank EHDP loan was granted in May, 1996.) The focus of the financial assistance elements of the project is retrofit of building-level energy and water systems to reduce the overall cost of building ownership and operation.

In the fall of 1994, the World Bank conducted a cursory assessment of the likely energy savings from energy and water efficiency retrofits in Russian buildings. It requested assistance from the U.S. Department of Energy to review the assessment, and to provide national laboratory support for a fact finding trip to Russia. Staff from the Pacific Northwest National Laboratory [PNNL] verified the World Bank assessment, and one staff member accompanied the World Bank team to Russia. The result of the trip was a working agreement between PNNL and the Russian government in support of the EHDP.

The Enterprise Housing Divestiture Project has, as its major goals, the divestiture of enterprise housing to municipalities, and the privatization of that housing. It has specific goals for divestiture, for condominium formation, and for the establishment of competitive maintenance to support that housing. The EHDP financial assistance program will result in more than $300M of energy and water efficiency retrofits in former enterprise and municipal housing (and especially in condominiums), as incentives for divestiture and privatization. The retrofit activity has two phases. In Phase I, heat, hot water, and cold water meters will be installed in buildings to provide a baseline of actual consumption for measuring savings, to provide information for retrofit design, and to create a basis for the municipalities to begin billing residential customers for actual consumption. In Phase II, energy- and water-efficiency retrofits will be installed. Initial estimates are that approximately 3,000 buildings will be retrofit across the six participating Russian cities: Novocherkassk, Orenburg, Petrozavodsk, Ryazan, Vladimir, and Volkhov.

These cities have varying climates, building stocks, and costs of production for energy and water services. Since the project is largely financed from a World Bank loan that must be repaid by the Russian government (and ultimately by the cities), there are financial constraints on the retrofits. In order to provide a cash flow for loan repayment, the savings that accrue from the total retrofit package for any one building must provide for a 5-year payback, measured against each city's projected cost of providing heat, hot water, and cold water service to building occupants.

Since there are no building-level energy or water use data available in any of these cities, the FEDS model is being used to estimate current energy and water use, and to estimate the savings that will accrue from the retrofit activity. The model will be calibrated using detailed pre-retrofit and post-demonstration project metered data. FEDS will then be used to prescribe the measures for all building types to be retrofitted. The model will be transferred to one or more Russian research institutes for continued use in the six EHDP cities and to help other cities interested in replicating the EHDP.

## THE FEDS MODEL

The Facility Energy Decision System [FEDS] (Currie et al. 1991; Dirks and Wrench 1993) model contains complex energy and economic modeling capabilities that use a sophisticated optimization algorithm to determine the most life-cycle-cost-effective energy resource/utilization configuration for facilities ranging from a single building to a large multi-building installation, or a city. The FEDS approach allows estimation of single building and installation-wide energy and peak demand.

FEDS was designed for two major purposes:

- estimating current energy consumption for all building energy systems where there is no metered data, and
- determining the minimum life-cycle-cost (LCC) retrofits for systems within a single building and within all buildings on a multi-building installation (considering all system interactive effects). This includes estimating the pre- and post-retrofit consumption, first cost of the retrofits, recurring O&M costs for the retrofits, the value of the change in annual energy consumption and annual O&M requirements, and the net present value of the investments. The LCC optimization can be constrained to user-specified payback and saving to investment (SIR) inputs.

FEDS can employ general user-supplied information to generate default prototypes for each building type selected for analysis. This is useful when it is necessary to estimate the likely aggregate level of investment for a city or large service area. Inferred building characteristics values are mostly from (1) NBECS (Energy Information Administration 1986a, 1986b) and RECS (Energy Information Administration 1987a, 1987b) building characteristics data, (2) ELCAP (Taylor and Pratt 1989; Pratt et al. 1990; Pratt et al. 1989) commercial and residential end-use load and building characteristics data, and (3) ASHRAE (American Society of Heating, Refrigerating, and Air Conditioning Engineers 1989, 1987) standard design and construction practices.

However, it is not necessary to use inferences when interested in accurately modeling single buildings, single building prototypes, or many buildings. The user has control over nearly all the parameters used in the energy consumption calculations. While the current set of inferences is of great value in modeling domestic buildings, most are of little value in modeling Russian buildings. As such, nearly all inferred values are replaced with Russian-specific values for the analysis of Russian buildings. For a single building analysis there are approximately 500 possible inputs in the FEDS model as configured for Russia: 75 inputs are of an economic nature and the remaining are building-specific. Once Russian inferences are developed for each building type, fewer than 10% of the variables will need to be changed within a city in order to conduct the required analyses.

## FEDS Energy and Retrofit Modeling

The FEDS building model estimates energy consumption for the following end uses:

- heating
- cooling
- lighting
- service hot water
- miscellaneous equipment

These are discussed below in the order in which FEDS calculates energy use. Only those aspects relevant to Russian multi-family housing are described.

FEDS models energy and water consumption on an hourly basis, using a typical day/peak day approach. Three day-types are considered: weekdays, Saturdays, and Sundays. For each month three weather days are evaluated; the hottest and coldest days are used to determine peak demand, and the average weather day is used for energy consumption calculations. Twenty-four-hour consumption profiles are generated for each day-type, and weather-day combination for each month. While Russia does not have complex time-of-day rate schedules for heat or electricity, some cities involved in this project have shown an interest in experimenting with different rate structures during this project. The hourly nature of the model makes it well suited to the proper evaluation of different time-of-day and demand-based rate schedules.

Lighting consumption is calculated using installed capacity and use for each lighting technology configuration. Capacities are multiplied by use factors for occupied and unoccupied periods to create 24-hour profiles of estimated consumption, based on the user-supplied occupancy schedule. Lighting heat-to-space is user-controllable and is an internal gain considered by the HVAC submodel. Lighting is not a significant consideration in Russian multi-family buildings. Initial analyses show that compact fluorescent lamps will be cost-effective in stairwells along with replacement of 1-2 lamps per apartment.

Miscellaneous equipment consumptions are calculated like lighting, using installed capacity and utilization for each of three types of equipment: cooking, refrigeration, and other (e.g., plug loads). Heat-to-space from each type of miscellaneous equipment is an internal gain considered by the HVAC submodel and is user-controllable. These can be important considerations in Russian multi-family buildings because ovens and ranges are often used as supplementary heating, refrigerators are very inefficient and poorly insulated, and resistance heaters are often used for supplementary heating.

Service hot water consumption is calculated using Russian "norms" and scant measured data.

The building envelope characteristics are all user-specified for the Russian buildings. Heating load calculations are based on the ASHRAE method to obtain values for solar gains, and to approximate the thermal effects of the envelope on the internal gains seen by the heating system. This approach has been augmented by the inclusion of lumped capacitance modeling to capture the thermal storage effects of the building mass on heating requirements due to changes in inside temperature (American Society of Heating Refrigerating, and Air Conditioning Engineers 1987). This method yields 24-hour profiles of the heating consumption estimates.

## FEDS HVAC System Modeling

FEDS contains three different algorithms for the calculation of heating, cooling, and ventilation loads. The heating algorithm used for the Russian buildings models heating systems that use natural convection and radiation, rather than forced air distribution. These systems are called *unlinked systems* (and there may or may not be a separate ventilation system in the building—for Russian buildings this is natural draft ventilation and is discussed later in the paper).

FEDS is initially calibrated by modeling the current energy consumption using the existing equipment and detailed end-use metered data. Then replacement or modification of the equipment is considered. These modifications include replacement with similar, but more efficient equipment (e.g., replacing existing incandescent lamps with new compact fluorescent lamps); changes to different types of equipment that provide equivalent service more efficiently (e.g., replacing an existing faucet with a low-flow faucet); and changes to more cost-effective equipment using a different fuel (e.g., fuel-switching at the building level).

When considering any equipment changes, the total effect on the building's energy consumption is considered. For example, the model determines the full impact of ventilation controls when coupled with envelope improvements and heating system changes.

### FEDS Optimization Approach

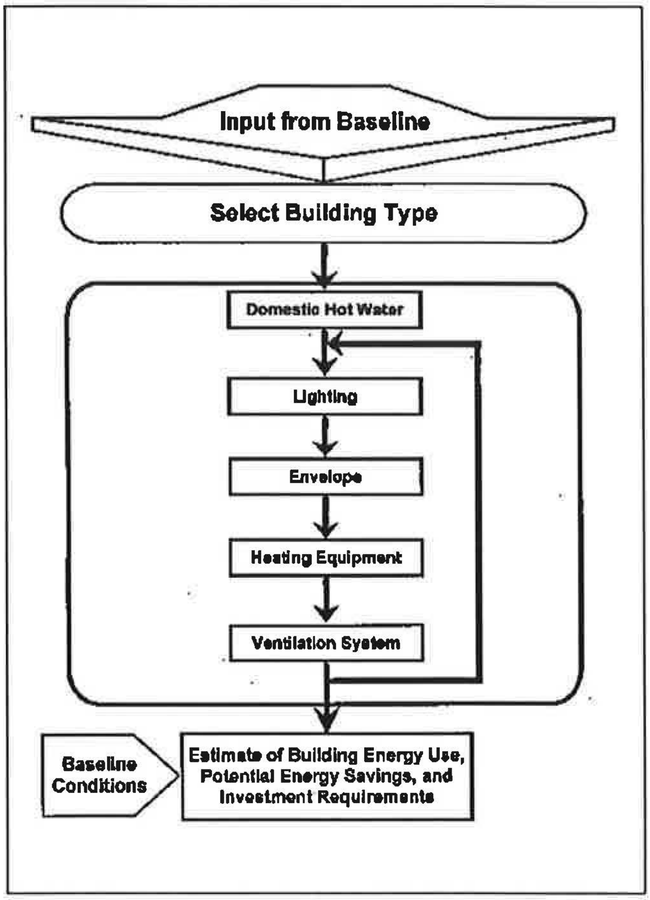
The building energy system is optimized through an iterative process as illustrated in Figure 1. The first end use is evaluated (e.g., lights) and the minimum life-cycle cost configuration for that end use is determined. When the second end use is evaluated, the model assumes that the first end use has already been changed. Once all end uses have been evaluated, the model recalculates the first end use to see if the minimum life-cycle cost configuration for that end use has changed due to changes in other end uses because of interactive effects. This process continues until the model has converged to the minimum life-cycle cost configuration for each end use in the entire building set. The model then considers the next building set and optimizes it.

## THE FEDS MODEL—RUSSIAN SPECIFIC MODIFICATION

Several modifications were made to FEDS to accurately model Russian multi-family housing and accurately determine the cost effectiveness of possible retrofits:

- natural draft ventilation,
- infiltration using ELA (equivalent leakage area) approach,
- radiator with widely varying supply temperature on outside (high U-value) walls,

*Figure 1. FEDS Iterative Optimization Process*




- recirculation of domestic hot water which provides a significant portion of the heating, and
- database of equipment cost and performance for energy and water efficient technology and material applicable to Russian buildings.

### Natural Draft Ventilation and Infiltration

Blower-door tests and ventilation chimney air flow measurements of a number of Russian multi-family housing buildings were conducted (Armstrong et al 1996). These tests were conducted with significant variation in outside temperature and wind speed. The results of these tests and measurements were used to characterize infiltration and natural draft ventilation, and to model the effects of retrofits on the infiltration and ventilation rates. The characteristics data were used to produce a natural draft ventilation/infiltration model added to the FEDS model.

The blower door approach used an incremental series of blower door tests with sequential sealing of apartment components (vents, windows, etc.). Each change in equivalent leakage area (ELA) can then be attributed to the corresponding set of components that were sealed. The following ELAs are used in the FEDS model:

*Walls*
- crack ELA per lineal meter of crack (between precast panels)
- non-crack wall ELA per square meter (porosity of wall)

*Windows (by type of window)*
- perimeter ELA per lineal meter of perimeter
- sash ELA per lineal meter of sash

*Doors (by type of door)*
- perimeter ELA per lineal meter of perimeter
- sash ELA per lineal meter of sash

*Floors*
- ELA per square meter of floor

*Roofs*
- ELA per square meter of roof

In the Russian version of FEDS, infiltration is modeled as a function of ELA, wind speed, the difference between indoor and outside temperature, and number of stories. ELA is the total leakage area for a building—the sum of the equivalent leakage areas of each sub-component listed above.

Each apartment has two natural draft vents, one in the kitchen and one in the bathroom. The natural draft ventilation through the vent stacks is a strong function of the vent grill area in each apartment. Currently the occupants have no simple method for adjusting this area and controlling the ventilation rate. With a fixed ventilation damper area, the ventilation rate becomes a function of the temperature and the wind speed. This results in greatest ventilation when it is coldest outside. Two categories of ventilation retrofit were considered and included in the ventilation/infiltration model:

- occupant manually-controlled vent dampers that affect the overall building infiltration by changing the apartment apertures to the vent ducts, thereby controlling the ventilation through the stacks, and

- automatic fixed or variable-speed exhaust fans at the attic level that control the velocity of air in the ventilation ducts, thereby making the ventilation rate (and the resultant infiltration draw into the building) more constant with respect to $\Delta T$.

## Radiator on Outside Walls

Another significant variation between domestic buildings and Russian multi-family housing is the direct heat loss from the radiators to the outside. Most radiators are found on outside walls beneath windows, and the wall U-values are very high compared with buildings in similar climates elsewhere in the world (measured values of greater than 2 $W/m^{2}\text{-}^{\circ}K$ are common). According to design specifications, radiator sizes typically differ depending upon the exposure of the apartment, and where the radiator lies in the flow sequence (bigger radiators in corner apartments and at the end of heating runs when heating water is cooler). Many apartment occupants have added radiators and increased the size of existing radiators because of cold apartments.

Most radiators have no flow control, and in fact, many buildings have no easily adjustable flow control at all. The hot water supplying the radiators is supplied from a central plant or substation with constant flow (actually constant head) and variable temperature output. The plants are supposed to operate according to a "graphic" that specifies output temperature as a function of outdoor temperature and (sometimes) wind speed. Naturally, the graphic is only approximated in the best of systems, and can be almost ignored in some systems facing financial pressures. The temperature of the water that circulates within the building is typically controlled by a hydroelevator[1] at the building or building section level that mixes a fixed proportion of radiator return water with incoming water from the central plant (Figure 2). The mixing rate is set by inserting orifices of different sizes in the hydroelevators.

Since controls are virtually absent from Russian systems, there are several major impacts on modeling heating energy use. First, apartment temperatures are not uniform, either across the building or over time, which makes modeling extremely difficult. Second, the occupants moderate indoor temperature by opening and closing windows, which can result in very significant air exchange rates (for overheated apartments), even on cold winter days. FEDS inputs can be modified to account for these variables, but only to the extent to which temperature profiles and window openings can be modeled. There is virtually no information available.

***Figure 2.*** *Hydroelevator Diagram*

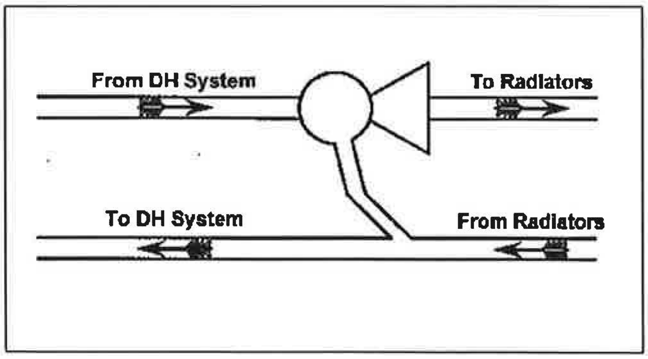
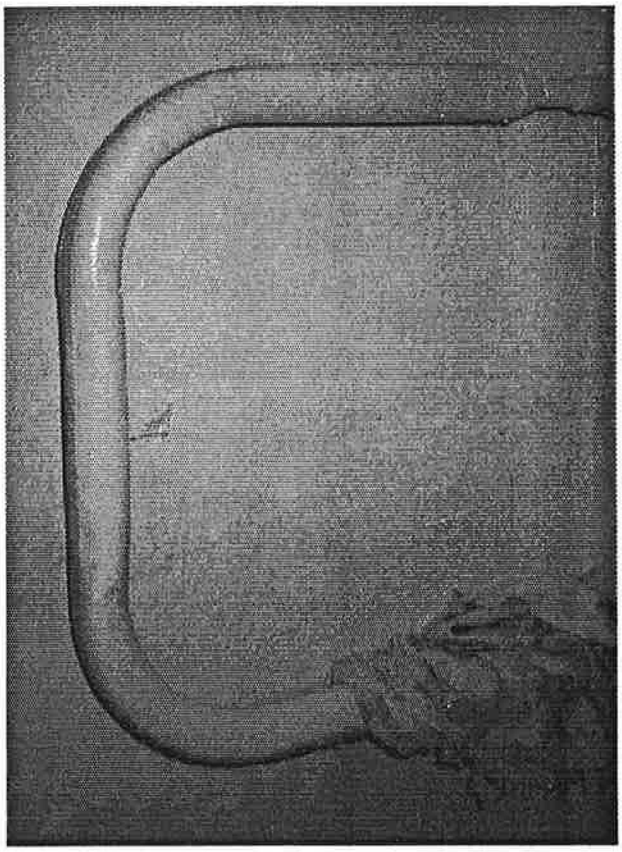


*Figure 3. Typical Russian Residential Towel Warmer*



### Domestic Hot Water Recirculation

In many buildings the domestic hot water [DHW] is continuously recirculated. Depending on the type of supply, the DHW temperature can vary with the heating hot water or can be relatively constant in temperature. The pipes within the building that supply the domestic hot water are exposed (i.e., not within the interior walls). In the bathroom the pipe is often formed in a horizontal U used as a towel rack/towel warmer (Figure 3). In some cases, it is estimated that the domestic hot water system supplies up to 30% of the heating requirement.

## DATABASE OF EQUIPMENT COST AND PERFORMANCE FOR ANALYSIS OF RUSSIAN BUILDINGS

To determine the cost effectiveness of retrofits in Russia, reasonably accurate cost and performance data for possible retrofits need to be obtained. Cost data was obtained by contracting with Hanscomb Associates in Chicago, which maintains an office in Moscow. Hanscomb provided the project with cost estimates for thirty different retrofits, broken down by purchase and delivery costs, and installation cost. Installation cost was estimated as a function of either Western, Russian, and mixed labor rates and productivity rates.

Following is a partial list of the retrofits being considered. These retrofits are intended to reduce the amount of and/or cost of energy and water consumption. Some retrofits have multiple effects. For example, spray on exterior polyurethane foam decreases the ELA of the panel crack and wall porosity, decreases the U-value of the wall, and decreases the U-value of the wall behind the radiator. All impacts associated with a retrofit are accounted for within the model.

- building piping insulation—unconditioned spaces with adequate physical access
- attic insulation—for buildings with cold air attics
- roof insulation—for building with no attics
- basement ceiling insulation—for buildings with crawl spaces or basements
- caulking/sealing—around fixed windows, window frames, doors, and between precast panels
- weatherstripping—around movable windows, interior doors, and exterior doors to reduce the infiltration of outside air
- external wall insulation—alternative insulation types and thicknesses that could be applied to the exterior of building walls
- space heating supply control—at the heat point serving several buildings, at the building, or on each radiator in a building to reduce or eliminate building overheating
- radiator reflector—installed behind radiators on exterior walls to reduce heat loss through the wall
- riser balancing—adjust hot water flow through parallel flow paths within building to achieve more uniform apartment temperatures and reduce or eliminate overheating
- DHW optimization—optimize recirculation system
- low-flow shower heads—reduce domestic hot water and cold water consumption

- faucet aerators—reduce domestic hot water and cold water consumption.
- faucet repair—reduce domestic hot water and cold water consumption
- replace faucets—replaced with new faucets that will accept aerators or low-flow faucets reducing domestic hot water and cold water consumption
- gas-fired hot water generators—gas-fired water heaters could be installed at the heat point or building level to avoid energy charges associated with the district heating system
- new toilet flush mechanism—eliminated water wasted via leaks
- reduction of toilet closet volume—reduce water consumption per flush
- compact fluorescent lights—reduce electricity consumption
- high-efficiency refrigerators—reduce electricity consumption
- variable aperture vent damper—reduce infiltration by reducing natural draft
- fixed or variable speed exhaust fan—reduce infiltration in cold weather, increase ventilation in warmer weather

*Figure 4. 9-Story Demonstration Building*

*Figure 5. 5-Story Demonstration Building*

## THE RYAZAN DEMONSTRATION PROJECT

As one basis for exploring the effectiveness and cost-effectiveness of potential retrofits, to produce detailed end-use data for calibrating FEDS, and to gauge city and occupant reactions to the likely mix of retrofits, six buildings in the city of Ryazan (200km outside Moscow) have been selected for a demonstration project. In this project, three 9-story and three 5-story buildings, the most common building types across the six participating cities, are being retrofit over a multi-year period (Figures 4 and 5). The retrofits are being managed by European consulting firms selected through an international competitive tender. The retrofits are being installed by a mixture of Russian and Bulgarian firms with Western oversight.

In the first year (over the 1995-96 winter), four of these buildings are being retrofit with alternative retrofits. One has a complete (best estimate) suite of retrofits designed to maximize net present value under the constraint of a 5-year payback. A second building is being used to compare alternative ventilation control strategies. A third is being used to evaluate the effectiveness of (only) modernizing the heating system using building-level and radiator thermostatic controls. A fourth is being used to evaluate a complete building tightening approach. Two buildings (one 9-story and one 5-story) remain unretrofit as controls. In future years additional retrofits will be conducted on these buildings.

Each of these buildings is being extensively monitored for energy and water consumption, and with continuous temperature recorders in basements, attics, staircases and in many apartments. Specialized ventilation measurements are being made in several buildings, and a number of before-and-after blower door tests have been conducted on apartments and in stair wells. A complete meteorological station has also been installed on the roof of a 9-story building. The data set should be one of the richest data sets available for Soviet-style apartment buildings.

## NEXT STEPS

The FEDS model will be calibrated to the metered data, including actual weather data, that has been collected since the first of the year. This includes large variations in outside temperature, weather, and occupant behavior. Once calibrated the model will be used to estimate the current energy consumption for buildings that have not yet been metered.

Data from the demonstration project buildings will be used to further calibrate the model to correctly capture the impact of the retrofits in each demonstration. Once this final calibration is complete, the model will be capable to estimating the impact on the energy consumption of any combination of retrofits.

To prepare for the large retrofit project, FEDS runs will be made for twenty-four "prototypical buildings" that cover 98% of the eligible building stock. These range from single story duplexes to 16-story high-rises, in six cities with different weather and energy costs. The result will be detailed specifications for each building type in each city, with allowances made for field level in-building deviations from the assumed conditions. Eliminating the need for analyzing each building in the field will ensure that most of the money is employed for actual retrofits, and not for studies by consultants.

The analyses will be complete by the end of 1996. The analytical result will be the optimized "final state" building configurations, under the previously stated constraints, for each building type in each city. Inspection of the current state of each building type by the municipalities, coupled with the results of the FEDS analyses, will identify the energy and water efficiency retrofit technologies to be procured and installed.

## ENDNOTES

1. The hydroelevator is a kind of jet pump commonly used in district heating systems in Eastern Europe. It functions as a balancing, tempering, and impedance matching device. As an impedance matching device, it transforms a small flow of distribution water delivered at high differential pressure to a larger (typically 1.5×) flow for delivery to the low pressure drop network of parallel radiator loops in the building. The radiator supply (mixed-water) temperature is reduced from the distribution network supply temperature in the process. The mixing ratio is adjusted by changing the size of the orifice through which the jet of distribution supply water enters the hydroelevator. Initial balancing may involve adjusting the hydroelevator orifices in all buildings served by a particular district heating system. Note that all hydroelevators on the district heat network receive power for their jet pump action from the district heating distribution pump or pumps; this is very different from the water pumping application most familiar to westerners, in which a centrifugal pump at the surface is used to power a jet pump located at the bottom of a deep well.

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