Infiltration and Ventilation in Russian Multi-Family Buildings

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Equivalent leakage areas (ELAs) of 50 Russian apartments were measured under three conditions: 1) as found, 2) exhaust vents sealed, and 3) vents, electric boxes and windows sealed, in 12 buildings of similar construction. Distributions of ELA per unit of apartment volume are presented for the three conditions. Apartment ELAs were found to vary slightly with floor, indicating that the level of occupant-applied weatherstripping is a function of occupants' perception of infiltration rates and that lower floor occupants perceive larger infiltration rates than upper floor occupants. This is consistent with the infiltration simulation results. Simplified models for overall infiltration as a function of indoor-outdoor temperature difference, wind speed and forced ventilation rate are developed. The FEDS discrete retrofit optimization program is described and preliminary results of its application to Russian multi-family buildings are presented.

INTRODUCTION

The Enterprise Housing Divestiture Project (EHDP) aims to identify cost-effective energy efficiency and conservation measures for Russian apartment buildings and to implement these measures in the entire stock of buildings undergoing divestiture in each of several selected cities.[1] On the order of half a million Russian dwelling units are expected to obtain EHDP retrofits (Whittle 1996). With so large an investment it is important to employ the most cost-effective technologies applicable to Russian building types and conditions (Opitz, 1994).

To properly select retrofit measures it is first necessary to understand energy use and the conditions that affect energy use in the buildings. The EHDP uses all four common methods of determining energy use: hand calculation, simulation, and short- and long-term energy monitoring. Selection of measures involves hand calculation and building simulation to estimate energy use, and sometimes involves short-term testing, as well, to determine the existing building characteristics. Evaluation involves long-term monitoring, results of which will be fed back into successive implementation cycles in order to refine the process.

Computer simulation is needed when weather, occupant activity, and plant response characteristics interact. The primary simulation tool used for this purpose in the EHDP is FEDS (Dirks 1996) which has the additional capability of finding the optimal retrofit package given an extensive list of discrete candidate retrofit measures. The pre- and post-retrofit building parameters needed as simulation input include many simple parameters, such as window, wall and roof areas, as well as some parameters that are less easily obtained, such as wall thermal conductances and the infiltration characteristics of building envelope and ventilation system components.

Short-term measurements of infiltration and exterior wall heat-loss coefficient were made and long-term monitoring equipment was installed in the pilot[2] city of Zhukovskiy in April 1995. The results of these measurements have been used to assess energy efficiency retrofits in a variety of apartment buildings in all of the candidate cities[3] (Whittle 1995, Dirks 1996). This paper describes our efforts to characterize infiltration and model the effects of infiltration and ventilation measures. The construction features of Russian panel buildings are described. The blower-door test procedures are documented and results of the data analysis are reported. The characteristics data used to model whole-building infiltration and air movement are documented. The simulation results and their application to retrofit optimization are presented. The impact of retrofits on indoor air quality and heat control are also discussed.

BUILDING DESCRIPTIONS

Three occupied, pre-cast concrete panel structures were selected for testing in Zhukovskiy: a 5-story, 6-section building at Klubnaya 8, a 9-story, 4-section building at Keldisha 7, and a 14-story, 2-section building at Markievskaya 15/3[4]. The buildings were all constructed between 1975 and 1985 of concrete panels cast locally at the same factory in Zhukovskiy. Construction quality is generally poor and maintenance, beyond what is provided by tenants to their own flats, is abysmal in the current economic climate of the FSU states. Many stairwell and elevator lobby windows and doors have broken or missing glass and the units often won't close properly.

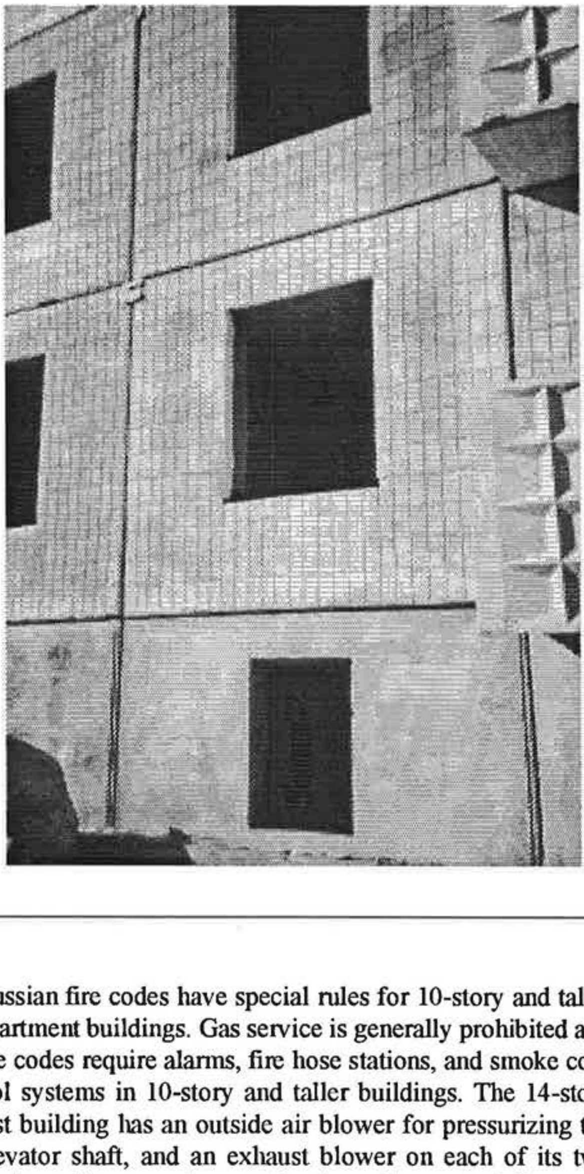
The test buildings all have 35-cm thick exterior panels and 1.5-m high by 2-m wide window units each containing three double-glazed operable sash panels of nominal 1.5 × 1.5, 1 × 0.5 and 0.5 × 0.5 meter size. Buildings typical of the type, including Keldisha 7 on the far right, are shown in Figure 1.

Panels are attached by welding metal tabs that protrude at standard locations along their edges. A typical exterior panel wall is shown before grouting in Figure 2. After welding, the panel joints are filled with grout which is sometimes covered with mastic or a similar sealant. The result of grouting at a 4-panel corner intersection is shown in Figure 3.

Each apartment has a balcony accessed from the main room by a partly or fully double-glazed door. The main room has an additional window in some cases. All other rooms, including the kitchen but excepting the bathroom (bathrooms are never situated on an exterior wall), have a single standard window unit. There is a hot water radiator under each window. None of the buildings has an attic. Except for the double glazing of windows and the reported use of light aggregates in exterior panels, the test building envelopes are uninsulated. A *one-room apartment* has a kitchen, bathroom, and one main room and a floor area of 30–35 m^2; a *two-room apartment* has one additional room and a floor area of 48–54 m^2; and a *three-room apartment* has one additional room and a floor area of 67–73 m^2.

Figure 1. *View from Markievskaya 15/3 of typical apartment buildings, including Keldisha 7, on the right; the small central building with four first-floor windows and a high-bay wall visible above and behind is the heat point serving Keldisha 7, Markievskaya 15/3, and nine other 9- and 14-story buildings.*

Figure 2. *Exterior of an apartment building under construction showing panel joints before grouting.*



Russian fire codes have special rules for 10-story and taller apartment buildings. Gas service is generally prohibited and the codes require alarms, fire hose stations, and smoke control systems in 10-story and taller buildings. The 14-story test building has an outside air blower for pressurizing the elevator shaft, and an exhaust blower on each of its two sections for removing smoke from the central "security halls" through which the apartments of each section are accessed. The 14-story building has a single service core that contains a fire-rated stairwell, two elevators, and a standpipe with a fire-alarm and fire hose station on each floor. However, for modelling purposes it is convenient to consider it a two-section building since the two wings are nearly identical in footprint and wall and window areas.

Adjacent sections in the 5- and 9-story buildings share a common wall but are otherwise isolated. Each section has one or two electrical risers and there is a breaker and meter panel at each floor along the riser that typically serves two apartments. The stairwell in each section extends from the front wall back to about the transverse center line. The stairs

Figure 3. Detail of corner joint after grouting.

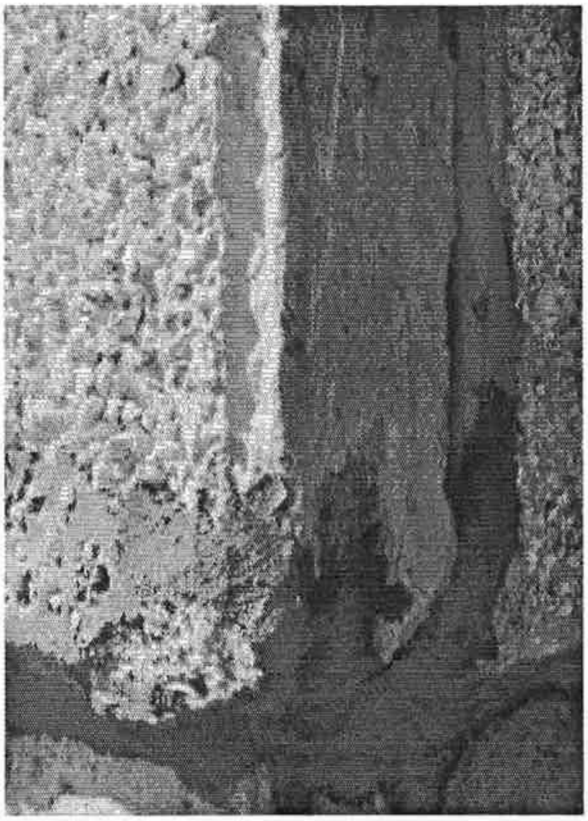
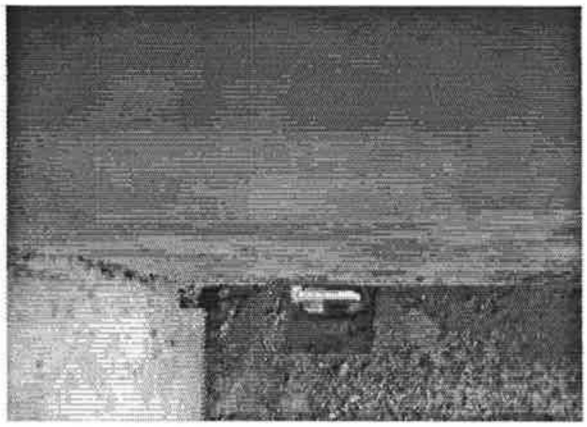


Figure 4. Typical floor penetrations for radiator pipes; note also grouted notch to the left.



progress up in half flights with main landings central to the section and mid-story landings on the front wall. The main door is typically at ground level, one-half story below the first floor, and there is a large double-glazed window at each mid-story landing. One or two apartments open off each side (left and right) of the stairwell. The 9-story building has an elevator to the left of the stairs in each section. The 5-story building has no elevators. Many (possibly a majority of) Russian multi-family panel buildings have a so-called *technical attic*[5], but the Zhukovskiy buildings described here do not.

The basements are not divided into sections, but are typically designed with a transverse hall through which heat and service water mains are routed. Heat, service, and waste water riser pipes are exposed in the apartments as they traverse the vertical extent of the building. Typical floor penetrations are shown in Figure 4; these are generally well grouted after the installation of pipes. Electrical risers, on the other hand, pass through a chase and the treatment of floor penetrations varies. Electrical wiring is not found in exterior walls. Doors and windows, passive ventilation channels, smoke control channels, electrical chases, and stair and elevator shafts appear to be the main paths available for air movement into, out of, and through the building.

BLOWER DOOR TESTS

Blower door testing is routinely carried out in occupied single-family dwellings. It is relatively easy to ensure that all windows and doors are shut and to pressurize[6] the entire volume of the structure to obtain an equivalent leakage area (ELA) for the entire building envelope. However, it is difficult to uniformly pressurize an entire occupied apartment building while ensuring that all windows and doors are shut (Shaw 1973). It is easy to test a single apartment but the resulting ELA includes leaks to adjacent apartments and common spaces as well as to the exterior.

Procedure

Consideration of the foregoing difficulties led to the use of a procedure in which envelope components are incrementally sealed (DeCicco 1995, 235). In the incremental approach, a sequence of blower door tests is run and between each test a selected component or set of components is sealed. Each change in ELA is attributed to the corresponding set of components that were sealed. In Zhukovskiy we ran three tests (i.e. a test at each of three conditions) per apartment; the kitchen and bathroom exhaust grilles were sealed between the first and second tests and the windows, balcony doors, and other major leaks were sealed between the 2nd and 3rd tests. The blower door was mounted in each apartment's main entry door and the stairwell windows on the same floor (or landings just above and below) were opened so that the pressure on the outside of the blower door would be as close as possible to the pressure on the exterior walls of the apartment under test.

It was difficult to recruit a large number of volunteers from any one building. Tests were therefore conducted in fifty apartments located in twelve buildings. Three building types are represented in the sample: Nizhegorodskaya 33 is a 14-story building identical in size and construction to Markievskaya 15/3; Latskova 4, Chkelov 11, Zuchova 1, and Gagarina 81 are 9-story buildings identical to Keldisha 7; and Luch 5, Michurina 5, and Chipaev 3 and 9 are 5-story buildings identical to Klubnaya 8. Three two-person teams, each provided with a blower door apparatus and sealing materials, were deployed to complete the tests in 8 working days. Incomplete data from three of the tests were not useable. Tenants were present except during the testing of one vacant apartment.

Field Test Results

The tests give several points on an apartment's flow versus pressure curve at each condition. An equation of the form $Q = Cp^n$ is fit to the points (ASHRAE 1993). The values of C and n resulting from each fit are presented for each test condition of each apartment in Table 1. The regression coefficient,[7] r^2, was greater than 0.99 for most of the curves. The exponent, n, has a theoretical range from 0.5, for fully turbulent flow, to 1.0, for purely laminar flow (ASHRAE 1993). The values of n obtained from the test data range from 0.50 to 0.78. The values change systematically with condition as indicated in Figure 5. The sense of this variation with condition is consistent with theory: flows tend to be most turbulent in a wide channel, like the vent stack, and least turbulent in a narrow channel, such as a wall joint, crack, or pore. The pressure-flow exponents tend to increase during the incremental sealing process because wide-channel leaks (vents, windows, and electric boxes) are sealed first, leaving mainly narrow-channel leaks (wall cracks and pores) that have a pressure-flow exponent closer to one.

The equivalent leakage area is defined as the area of an orifice that will give the same flow as Cp^n at a pressure of 4 Pa (ASHRAE 1993). The ELA corresponding to each (C,n) pair is given in Table 1. Another standard measure of envelope leakiness, ACH50, is also reported in the table. ACH50 is the flow rate, in air changes per hour, given by Cp^n at 50 Pa divided by apartment volume.

The sample mean of ELA across apartments varies systematically with condition. Apartment ELA is also weakly correlated with apartment volume in the as-found condition and somewhat more strongly correlated with volume in the other two conditions. The correlation of ELA with floor level (n_f/N_f where N_f is the total number of floors) is significant in the as-found condition and, to lesser extent, in the sealed conditions, indicating that lower floor tenants are more thorough at sealing leaks. The means, standard deviations, and regression coefficients pertaining to these ELA distributions and correlations are presented in Table 2. The distributions of ELA with condition are shown in Figure 6.

The per-unit-area rate at which floors and ceilings contribute to "all-sealed" ELA is assumed to be one-tenth that of interior and opaque exterior wall section rates. The resulting Effective Leakage Factor (ELF in cm^2/m^2) distributions are in reasonable agreement with the ELFs reported in the literature for a variety of buildings as compiled by Fang (1988).

Four potentially important leak paths associated with security halls are the paths leading to apartments, to the smoke exhaust shaft, to the electrical riser/meter panel, and to the elevator lobby. A test of the 14th-floor south security hall gave an ELA of 733 cm initially, an ELA of 317 cm with the opening to the smoke exhaust duct sealed. The security hall door was then sealed and the final test gave an ELA of 199 cm_2, or 66 cm_2 per apartment if we assume that this residual ELA is allocated equally among the three 14th-floor apartments served by the security hall. Future testing will involve larger samples of security halls and their associated leakage paths.

Discussion of Test Results

The pressure-flow data from this large sample of apartments in buildings of similar construction provides representative leakage path parameters that can be used to construct detailed models of air movement in these types of buildings. However, the results from individual apartments are not entirely satisfactory. The testing problems encountered, and some proposed solutions, are outlined below.

Effectiveness of sealing by blower-door teams is variable and can only be crudely estimated. The effectiveness of incremental sealing technique needs to be characterized and made more repeatable, and data interpretation methods need to be further developed, using test cells or unoccupied apartments.

With the technique of one-zone-at-a-time pressurization in tall buildings, the apartment pressure measurement is typically much less accurate than the flow measurement. Least squares should therefore be applied using flow, rather than pressure, as the independent variable. Moreover, the consistency of results would probably be improved by measuring additional pressures between the apartment under test and all zones and exterior facades that form part of its envelope. On the spot analysis of flow-pressure data would also improve the effectiveness of flow-pressure tests. In all four cases where inferred ELA reduction by window sealing (last column in Table 1) is negative the flow-pressure curves for conditions B and C are seen to intersect. This result would signal the blower door operator to repeat the tests under one or both conditions while the test equipment is still in place.

Table 1. *Leak Parameters Derived from Blower Door Test Data for Each Apartment*

Apartment Ident.		Test with Vents Sealed: C ($m^3/h@1Pa$)	n	ELA (cm^2)	ach50 (1/hr)	With Vents and Leaks Sealed: C ($m^3/h@1Pa$)	n	ELA (cm^2)	ach50 (1/hr)	Inferred Window ELA (cm^2)
14a	1	33.5	0.739	100	6.88	27.9	0.7567	86	6.16	14.19
14a	22	32.7	0.6877	92	5.5	23.4	0.7299	69	4.64	22.58
14a	29	55.8	0.6494	148	8.09	63.0	0.5733	150	6.78	−2.58
14a	31	87.2	0.7053	250	7.7	63.4	0.697	179	5.42	70.32
14a	45	147.2	0.5294	331	6.53	83.5	0.571	199	4.36	132.3
14a	57	42.0	0.6423	110	5.93	29.6	0.7175	86	5.6	23.87
14a	87	82.8	.65	220	5.89	67.5	0.6541	180	4.88	40
14a	93	171.7	0.5481	395	8.2	76.1	0.6799	210	6.08	185.2
9J	16	83.7	0.6459	221	9.8	71.4	0.6798	197	9.5	23.23
14b	5	60.5	0.5598	141	4.09	35.2	.65	94	3.4	47.74
14b	71	107.2	0.4906	228	5.54	49.2	0.6231	126	4.27	102.6
14b	74	103.6	0.5709	246	7.32	58.1	0.638	152	5.34	94.84
14b	77	102.5	0.5645	242	10.7	61.6	0.6175	156	7.9	85.81
14b	79	88.9	0.6153	225	5.52	55.6	0.6979	157	4.77	67.1
14b	96	56.8	0.6807	157	6.17	72.4	0.6005	179	5.74	−21.9
9a	3	52.1	0.7038	149	6.4	26.3	0.7304	78	3.58	70.97
9a	4	21.6	0.7669	68	2.77	21.8	0.6889	61	2.06	6.452
9a	11	158.8	0.5449	365	10.47	64.1	0.6316	166	5.93	198.7
9a	28	98.5	0.6428	259	9.5	75.9	0.6548	203	7.67	56.13
9a	21	40.3	0.681	112	5.39	34.3	0.6179	87	3.59	24.52
9a	71	118.3	0.5367	268	7.5	77.6	0.5534	180	5.3	88.39
9a	72	74.5	0.6645	202	6.39	62.5	0.6563	167	5.19	34.84
9a	76	112.1	0.5716	267	9.8	32.5	0.7489	99	5.7	168.4
9a	10	154.4	0.5557	357	10.6	45.5	0.7223	134	6.01	223.9
9a	70	46.3	0.7204	135	9.3	57.1	0.5725	135	6.41	0
9a	23	80.0	0.5907	195	6.3	40.3	0.6431	106	3.9	89.68
9a	60	127.7	0.5849	310	9.8	65.7	0.6093	165	5.56	145.2
9b	74	34.4	.65	92	5.23	24.1	.65	64	3.67	27.74
9b	93	183.2	0.555	426	10.23	135.0	0.58	325	8.32	101.3
9b	113	99.3	0.6123	250	6.8	75.5	0.626	194	5.46	56.77
9c	49	71.8	0.672	196	11.89	48.5	0.661	130	7.69	65.81
9c	50	156.5	0.6354	407	11.78	105.0	0.6439	276	8.17	131
9c	42	43.7	0.6678	119	7.12	32.3	0.6962	92	5.88	27.1
9c	26	228.5	0.5355	324	11.6	91.0	0.6255	234	6.6	90.32
9e	82	150.1	0.583	363	11.5	139.8	0.5039	303	7.86	60
5a	71	87.0	0.5984	215	7.95	102.0	0.5223	226	6.92	−11.6
5a	72	108.1	0.6378	282	9.9	82.6	0.6358	215	7.51	67.1
5a	6	166.8	0.5851	404	12.42	96.9	0.628	250	8.54	154.2
5a	13	86.7	0.6553	232	7.1	80.1	0.6241	205	5.8	26.45
5a	65	55.3	0.7295	164	8.43	55.1	0.6768	152	6.84	12.26
5a	66	110.0	0.618	279	9.33	62.1	0.669	169	6.42	110.3
5b	1	109.8	0.5896	268	6.96	54.8	0.6437	145	4.29	123.9
5c	19	99.7	0.5998	247	6.57	67.8	0.5911	166	4.32	81.29
5c	34	88.7	0.5823	214	6.79	26.1	0.725	77	3.49	137.4
5c	20	133.5	0.6	330	8.72	69.0	0.6171	175	4.82	155.5
5d	1	54.7	0.6607	147	4.55	41.3	0.6533	110	3.34	36.77
5e	49	138.3	0.5803	334	7.95	103.0	0.5893	252	6.13	81.94

Figure 5. Distributions of pressure-flow curve exponents for two of the three tested conditions: vents sealed and vents & windows sealed.

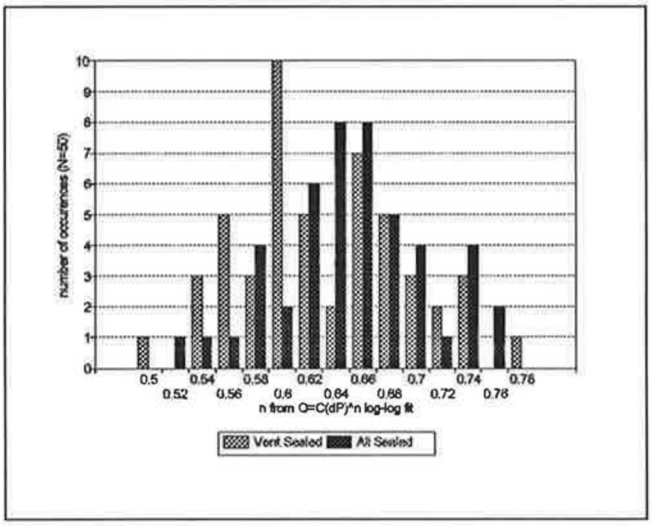


Figure 6. Distributions of apartment ELA for two of the three tested conditions: vents sealed and windows sealed.

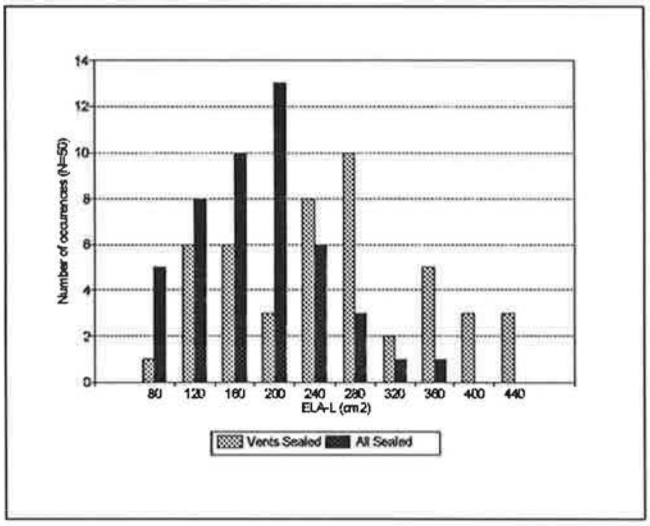


Table 2. Equivalent Leakage Area (cm^2 Per Apartment) Sample Statistics. For the regression models R1 and R2, y' denotes the regression estimate of an apartment ELA, y.

		CONDITION		
		Before Sealing	Vents Sealed	All Sealed
average (n=50)	avg(y)	348	246	168
std. deviation	s(y)	96	85	55
R1: $y' = C_0$	$s(y'-y)$	90	74	49
$+ C_1V$	r^2	0.16	0.28	0.24
	C_1	1.42	1.69	1.00
	$s(C_1)$	0.50	0.41	0.26
R2: $y' = C_0$	$s(y'-y)$	86	73	47
$+ C_1V$	r^2	0.26	0.30	0.34
$+ C_2n_f/N_f$	C_1	1.33	1.66	0.95
	$s(C_1)$	0.47	0.41	0.25
	C_2	1.14	0.41	0.62
	$s(C_2)$	0.45	0.39	0.24

Note that two of the intersecting curves are for top-floor apartments, where the pressure errors are largest, and that the inferred window leak rate at 50 Pa is substantial (5–30% of condition B) in all four cases.

Windows and patio doors represent less than one third of a typical apartment's "vents-sealed" ELA. Additional incremental sealing of leaks to common spaces and to apartments above, below, and to either side of the tested apartment would provide estimates of some of the remaining leak paths' parameters. This procedural extension would also allow use of a more realistic model that accounts for non-uniform pressure outside the envelope of the tested apartment. Blower door equipment that feeds the data directly to a computer will make the collection and analysis of more points and multiple pressure differences feasible.

Additional Tests

To more accurately model air movement and infiltration heating loads, the characteristics of leak paths associated with a building's common areas and utility spaces are needed. Based on our visual inspections for potential leak paths, and modeling of overall air movement, the following incremental sealing sequences are being adopted in the Ryazan fan-pressurization test plans.

Security halls: smoke exhaust shaft penetration; partition and door to stairway or elevator lobby; apartment doors; electrical riser at floor and ceiling penetrations; electrical conduits (and associated wall and ceiling penetrations) from panel to apartments; panel joints and cracks in apartment panels; joints and cracks in floor & ceiling decks.

Stairwells: elevator pressurization and smoke exhaust ducts (if present); main entry door and partition; landing windows; garbage chute (top and bottom); machine room door and floor penetrations; basement, attic and roof doors; cracks and penetrations to basement (e.g. electric risers, fire hose standpipe, and roof drain penetrations), attic, elevator machine room, and roof; cracks, joints, and penetrations to facade, e.g. gas service entrance; cracks and joints to apartments. On completion of this sequence, inaccessible leaks in the elevator shaft and apartment doors (characterized in the security hall tests) will comprise most of the residual ELA.

Ventilation shafts. Each channel in the array is first pressurized individually; all are then pressurized together. After testing in the as-found condition, the kitchen and bathroom grilles on all floors must be sealed. When pressurizing individual channels in this sealed condition the flows in adjacent channels can be measured so that the division of test channel ELA between (1) apartments and (2) other channels, can be estimated.

Technical attic. Sanitary vents, exhaust stacks, electrical chases, and radiator risers typically penetrate the attic floor. The purpose of this test is to determine typical floor penetration ELAs, typical ELA per unit length of various types of panel joints, and typical floor deck, roof deck, and wall panel ELFs. Apartment exhaust stacks, smoke control ducts, and access doors (including passages to other attic sections) are sealed prior to all testing. The pressurization fan is installed in the main exhaust shaft at the roof line. The sealing sequence is: electrical chases; heat risers; sanitary vents; other discrete leak sites; joints; cracks.

Basement. wall vents; wall penetrations; access door, stairwell floor penetrations; security hall floor penetrations; apartment floor penetrations; wall joints and cracks; floor joints and cracks. Open sewer cleanouts must be capped before the start of pressurization tests.

Exhaust flow rates and zone pressures. Velocities in the ventilation channels of Markievskaya 15/3 were measured once during mild weather. However, continuous cold-weather velocities have been monitored (Reilly 1996a) before and after envelope retrofits in the Ryazan buildings[8] in support of infiltration model validation. Zone pressures are also being recorded continuously in one of the Ryazan buildings for the same purpose.

AIR FLOW SIMULATION

Direct methods for calculating infiltration rate given ELA have not been developed for multi-zone buildings (ASHRAE 1993). Interaction of internal and envelope air flow resistances and the complex ways in which spatial distribution of envelope leaks affect infiltration rate make simulation a virtual necessity. A multi-zone building can be realistically modelled as a network, i.e. as a collection of nodes (or zones) connected by flow paths (Cross 1934, Walton 1984, Walton 1989). Computer program CONTAM (Walton 1994, 1995) was used to provide a modelling framework and run the simulations. The central service shaft and south block of apartments of Markievskaya 15/3 was chosen as the first simulation exercise. The measured and estimated leak characteristics were used to simulate the building under various wind and outdoor temperature conditions. A schematic zone and flow path plan of the 11th floor of Markievskaya 15/3 is shown in Figure 7.

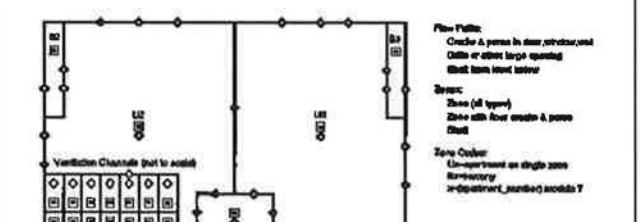
Model Description

Each apartment is modelled as a single zone because the blower door and temperature logger deployment teams observed that most of the interior doors were left open. A floor panel leakage path is shown in each zone. An exterior wall panel leakage path is provided for each exterior wall orientation that exists for each apartment. A path is provided for each window unit. An interior wall panel leakage path and an apartment door path are provided between each apartment and its associated security hall. Apartments that share a common interior wall are connected by an interior wall panel leakage path. Panel leakage is assumed proportional to the interior and exterior wall areas associated with each apartment as determined from the original building plans.

Each apartment has a balcony, about 75% of which have been closed in with window sash units to create a small sun room. Window/door unit and exterior panel leakage paths are shown between each apartment and its balcony. A single, relatively low-resistance path, representing aggregate sash-edge leakage, is shown between each balcony and ambient.

The ventilation chimney system has been simplified by combining each apartment's kitchen and bathroom exhaust grilles into a single orifice leading to a single ventilation channel. The channels in each of the three ventilation arrays

Figure 7. *Schematic zone and flow path plan of the eleventh floor of Markievskaya 15/3, Zhukovskiy (not to scale).*



are assigned to floor levels from left to right as follows: channel 1 serves floors 1–3, channel 2 serves floors 4–6, channel 3 serves floors 7–8, channel 4 serves floors 9–10, channel 5 serves floors 11–12, channel 6 serves floor 13 and channel 7 serves floor 14.

The security hall has interior wall panel and apartment door paths to each apartment, as previously mentioned. In addition, there is leakage to the elevator lobby via the security door and door panel[9] and leakage to the smoke exhaust duct via a normally-closed motorized damper.

CONTAM represents the system by a pressure-flow relation for each flow path and a mass balance equation for each node. The resulting sparse system of nonlinear equations is solved by a constrained Newton-Raphson (NR) procedure. A system of linear equations is constructed from the partial derivative of each nonlinear equation with respect to each variable. The matrix of partials must be evaluated, and the system of equations solved, at each NR iteration. Floating-point operations are minimized by expressing the derivatives analytically. Upon convergence of zone pressures the flow path equations are evaluated individually to obtain all flow rates. For the 14-story building, with about 500 zones and 1000 paths, the procedure typically converged on a solution in about 10 iterations with no wind and 15 iterations with wind.

A total of 29 leak types are defined in the as-found model of Markievskaya 15/3. A given leak type may be referenced any number of times, e.g., the balcony window/door leak type is referenced once for each apartment in Markievskaya 15/3. Each reference to a leak type includes additional parameters such as relative leak site elevation, multiplier, and positive flow direction indicator.

Simulation Results

A test grid was defined with wind speeds of 0 and 2 to 32 m/s in factor-of-two increments and with outdoor temperatures of 18°, 15°, and 10° to −40°C in 10K increments. The results for no wind, an indoor temperature of 18°C and an outdoor temperature of 0°C are shown in Figures 8 through 10. Figure 8 shows window, wall, and apartment door leak rates for first-floor units. Figure 9 shows window, wall, and apartment door leak rates for fourteenth-floor units. Figure 10 shows smoke exhaust shaft, elevator shaft, and garbage chute effects, as well as the general variation of apartment infiltration with vertical position.

The overall infiltration rate to apartments is obtained from the CONTAM output file (flow report) by a post-processing program. The results for all the base case (building as found) runs are plotted in Figure 11.

Figure 8. *Flow rates (m^3/h) through window (W), wall pore (P), door/window unit (U), and door (D) leaks on the first floor for no wind, an indoor temperature of 18°C and an outdoor temperature of 0°C.*

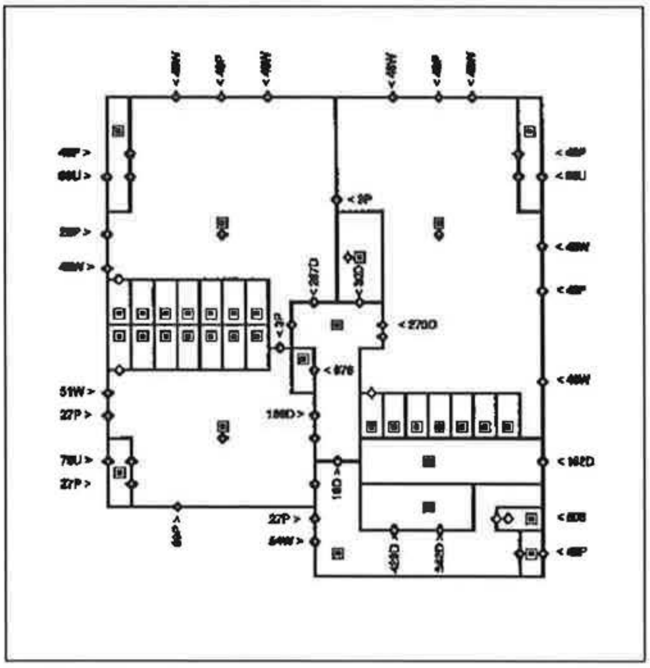


Figure 9. *Flow rates (m^3/h) through window (W), wall pore (P), door/window unit (U), and door (D) leaks on the fourteenth floor for no wind, an indoor temperature of 18°C and an outdoor temperature of 0°C.*

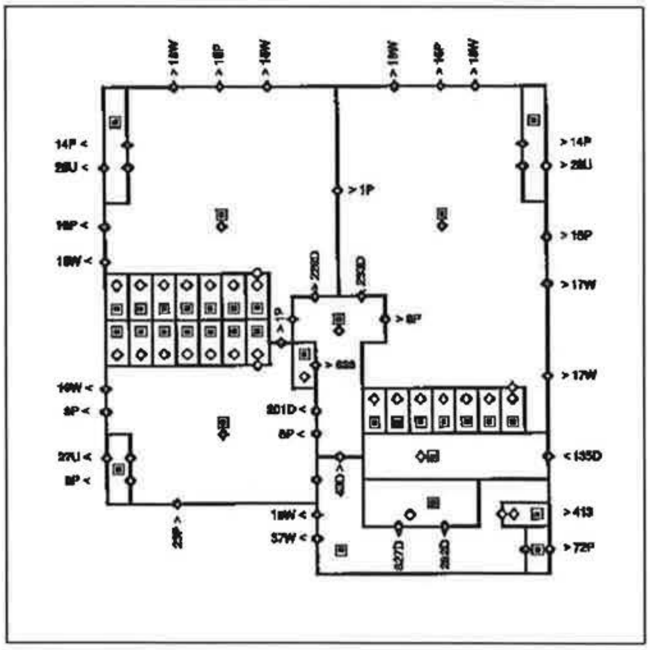
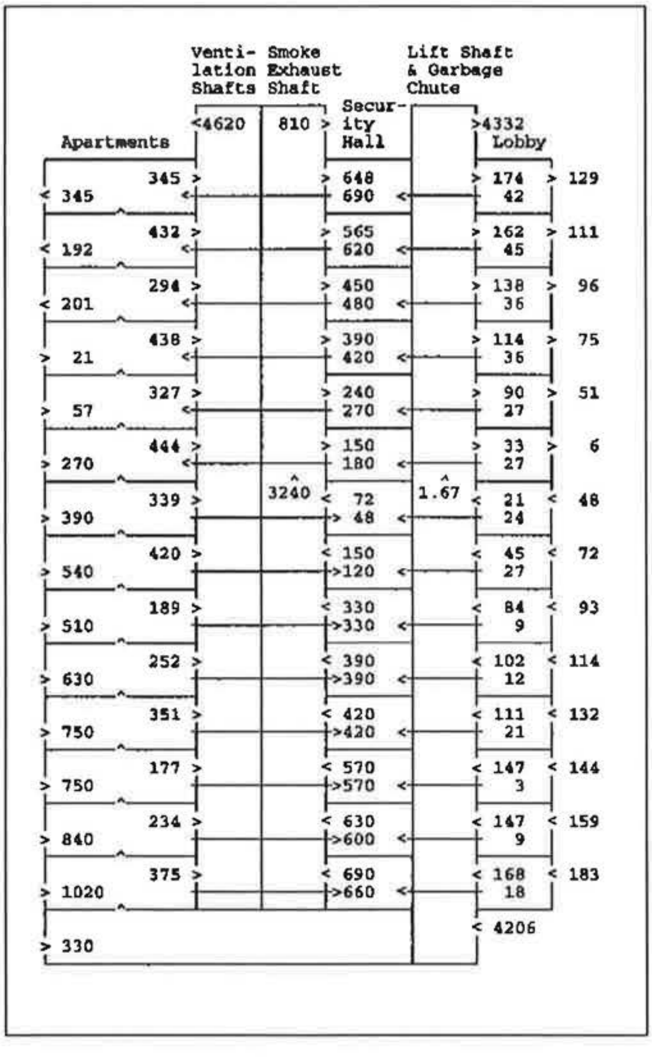


***Figure 10.** Schematic vertical section showing ventilation shaft, smoke exhaust shaft, elevator shaft, and garbage chute shaft flows in m³/h. Rate of flow between floors is only shown for top and bottom floors and point of maximum or minimum if located elsewhere.*

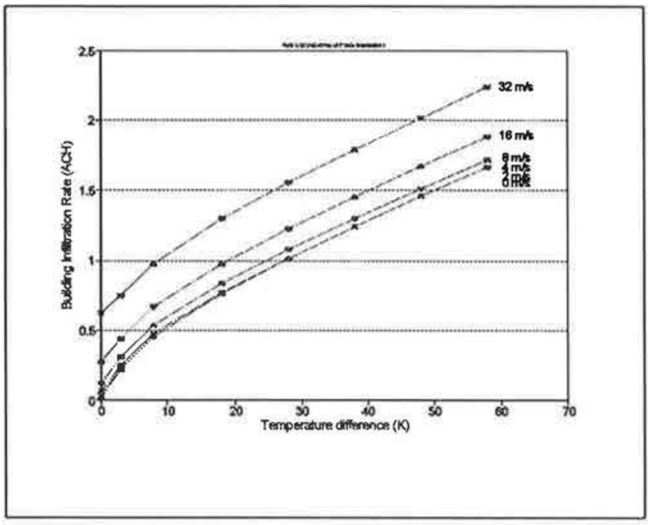


Discussion of Modeling Results

The simulation results are consistent with anecdotal data in that the cold-weather apartment-to-ambient flows are inward on the lower floors and outward on the upper floors. The results are also consistent with the small, but statistically significant, observed variation in ELA with floor level in that lower floor windows and balcony doors had less retrofit potential (i.e. were better sealed in their as-found state) than upper floor windows and balcony doors.

Simulation shows that the building has two distinct neutral planes. For the conditions that resulted in the Figure 10 flows, the common space neutral plane is on the 9th floor. This reflects air flows not intended by the designers that lead, ultimately, to the roof via leaks in the emergency smoke control system. The apartments' neutral plane is on the 11th floor; its distance above building mid-height is a consequence of the passive ventilation system providing a low-resistance path from each apartment to the roof. The passive ventilation system is well designed in terms of simplicity, providing correct *average* flow rate, and preventing cross contamination. However, overall exhaust rate is still excessive in cold weather and insufficient in mild weather.

***Figure 11.** Average infiltration rate versus temperature difference for wind speeds of 0 and 2 to 32 m/s in powers of 2.*



In the as-found condition, passive ventilation channel flow is limited by exhaust channel geometry rather than by apartment ELA. Thus the first increment of envelope tightening will reduce lower floor infiltration and upper floor exfiltration more than it affects ventilation channel flows. Conversely, a retrofit package designed only to reduce cold-weather exhaust rates will exacerbate upper floor IAQ problems[10] while providing only a moderate reduction in overall infiltration rates and the associated heat loads. These results point to the importance of treating internal leak paths that promote vertical air movement between apartments as a *prerequisite* to further envelope tightening measures.

While ACH does not vary much by floor, the heating and contaminant loads do, because air on the upper floors is replaced largely by air that has already been heated and contaminated in its passage through the lower floors. This makes control of heat and ventilation much more difficult than it would be for the same building with uniform loads across zones[11] Retrofits that reduce vertical air movement therefore have *higher value* than retrofits that mainly reduce horizontal air movement.

SIMPLIFIED MODEL

The infiltration and ventilation components of heating load must be evaluated within the FEDS program in order to reasonably approximate the complex interactions among envelope infiltration, ventilation, other heat transfer processes, heating plant operations, and occupancy effects that influence overall annual energy use.

FEDS evaluates annual building energy use for all reasonable retrofit combinations and selects from these the least-LCC mix of retrofits for a particular or typical building (Dirks 1996). This process may involve some 100,000 (product of timesteps/year and retrofit combinations) load calculations per building. Running a detailed infiltration simulation within the FEDS model would not be practical. It turns out, however, that the overall infiltration relationship depicted in Figure 11 can be represented by a few simple closed-form expressions.

Driving Component Models

The buoyancy-, wind-, and ventilation-induced components of whole-building air-change rate, when taken one at a time, are described by the following formulas.

$$X = C_T|T_i - T_o|^m$$

is stack-induced leakage with exhaust vents closed, where C_T is a constant loosely related to floor-to-floor ELA, and $|T_i - T_o|$ is the indoor-outdoor temperature difference;

$$Y = C_W W^n$$

is wind-induced infiltration in which C_W is a constant loosely related vertical envelope ELA, and Z is one of the following ventilation models:

$$Z_1 = A_G/A_V Q/V$$

is the infiltration rate induced by an idealized[12] forced ventilation system, in which Q/V = (fan flow rate)/(building volume) expressed in ACH (hr^{-1});

$$Z_2 = A_G C_G(h|T_i - T_o|)^r$$

is the infiltration induced by a passive ventilation system. A_V is the building's aggregate vent channel cross sectional area or, where user controlled gates are employed, a fraction, A_G/A_V, of the cross-sectional area which may vary with time or temperature. Note that A_V includes the vent channel cross-sectional area when passive ventilation is used but does not include the vent channel cross-sectional area when the channels when fan induced ventilation ($Z_1>0$) is used in place of ($Z_2=0$) natural ventilation.

The constants, C_T, C_W, C_G, m, n, and r, in the component formulas can be determined by non-linear least squares using data generated by the detailed CONTAM model.

Model Parameters

Infiltration rates at the 6*8 = 48 wind-temperature conditions were calculated by detailed simulation. While it's not generally true (ASHRAE 1993; Blomsterberg 1979; Shaw 1977; Sherman 1992), overall infiltration rate, in this case, is proportional to the sum of the driving components. A significant, distinct term for the passive ventilation component could not be found. For the 14-story building, as found, the overall infiltration rate is given by:

$ACH = (X + Z_2) + Y$ where

$(X + Z_2) = 0.0916\,|T_i - T_o|^{0.71}$ (T in °C)

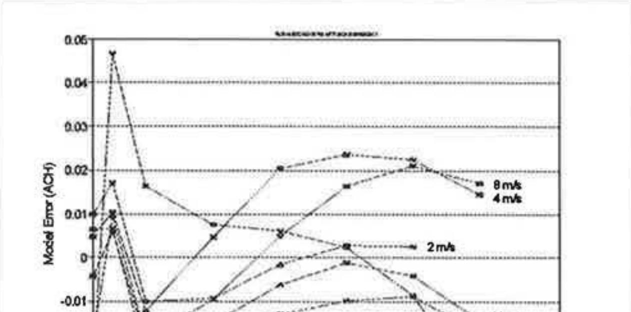
$Y = 0.0049\,W_{spd}^{1.37}$ (W_{spd} in m/s)

The residuals with respect to the CONTAM results of Figure 11 are shown in Figure 12.

RETROFIT SELECTION

Selection of a retrofit package for a particular building, climate and occupancy type is a constrained, non-linear optimization problem. The objective function is life-cycle cost, typically expressed as net present value, to own and operate a building. The optimization involves many variables, each representing the level at which a particular retrofit is applied. Most levels are constrained to be greater than or equal to zero. In addition, there are many combinations of retrofits

__Figure 12.__ Residuals of the simple model for the base case (building as found).



that "don't work" or are known from experience to be sub-optimal.

Optimization Method

The FEDS program finds optimal retrofit packages by a series of one-dimensional searches. At each iteration the level of each candidate retrofit is adjusted in a predetermined sequence. Many retrofits are inherently discrete, e.g. one has a choice of weatherstripping a window or not. Retrofits that are not inherently discrete, e.g. thickness of blow-in attic insulation, are discretized, typically to 4 or 5 levels (including always the level that corresponds to the building's existing condition). The field of candidate retrofits is constrained to valid combinations (for example, the replacement and weatherstripping of existing windows cannot both occur) by treating each minimal set in which invalid combinations occur as a single candidate retrofit whose "levels" comprise all valid combinations.

At each iteration, the objective function, an expression of marginal facility life-cycle cost, is evaluated at all admissible levels. The level corresponding to lowest LCC becomes the current level until the retrofit in question is evaluated again in the succeeding iteration. The process stops when an iteration is completed with no level changes to any of the candidate retrofits.

For each objective function evaluation, annual heating energy, the component of life-cycle cost that is of immediate interest, is evaluated by a half-hourly thermal simulation of the building or facility, its heating plant, and its heat control and distribution systems, through 108 (12 months; by 3 day types: weekday, Saturday, and Sunday; by 3 weather days: average, hot, and cold) typical days.

The simplified infiltration model has been added to the FEDS building thermal response model so that FEDS can properly account for interactions among infiltration and other building system, operations, and occupancy effects in determining the optimal mix of energy efficiency measures.

Retrofit Measures

The most straightforward way to add infiltration modelling capability to FEDS is to take advantage of its discrete optimization approach and provide a set of simplified ACH model coefficients for each feasible retrofit combination. Consider the following tightening and ventilation control measures:

(A) tighten security halls (doors, lobby door panel and perimeter, smoke damper)

(B) tighten apartment windows

(C) tighten exterior walls

(D) convert passive exhaust to fan-powered

Retrofits (A)–(C) each have two possible levels, go or no-go. Retrofit (D) has three possible levels, no-go, one-speed fan, and two-speed fan with contaminant sensor or programmable clock. This gives $2 \times 2 \times 2 \times 3 = 24$ possible combinations. However, because of the heat load and contaminant imbalance problems discussed earlier, measures (B)–(D) are not considered feasible unless measure (A) is implemented. Also, with current labor and material costs, it can be shown that wall tightening (C) is cost-effective only if window tightening (B) is cost effective. Eliminating the inadmissible combinations leaves eight infiltration and ventilation packages. Each of these packages was simulated in CONTAM for the 48 temperature and windspeed pairs defined by the conditions grids. When the equations of the simplified model were fit to the simulation results for each retrofit package the temperature term was found to be insignificant for packages with passive-to-mechanical ventilation conversion. The fitted equations are given below along with the corresponding infiltration rate evaluated at a temperature difference of 18 Kelvins and a wind speed of 4 m/s (9 mph).

Retrofit Level A	B	C	D	Eqn #	ACH equation	typ ACH
0	0	0	0	0	$0.030 + 0.0916T^{0.71} + 0.0049W^{1.37}$	0.78
1	0	0	0	1	$0.007 + 0.0692T^{0.70} + 0.0062W^{1.31}$	0.58
1	0	0	1	2	$0.390 + 0.0016T^{0.85} + 0.0049W^{1.36}$	0.47
1	0	0	2	3	$0.234 + 0.0055W^{1.34}$	0.37
1	1	0	1	4	$0.407 + 0.0041W^{1.31}$	0.43
1	1	0	2	5	$0.205 + 0.0046W^{1.29}$	0.33
1	1	1	1	6	$0.403 + 0.0030W^{1.28}$	0.42
1	1	1	2	7	$0.204 + 0.0032W^{1.26}$	0.32

Note that retrofit packages 3, 5 and 7 each involve two equations, Eqn n and Eqn $n-1$, where n is the package number. Eqn n is for low-speed exhaust fan operation and Eqn $n-1$ is for high-speed operation. The assumed schedule[13] calls for high-speed operation from 0600 to 2100 Saturday, from 0600 to 2000 Sunday, and from 0400 to 0600, 0900 to 1100, and 1400 to 2100 weekdays. The "typical ACH" column for packages 3, 5, and 7 shows the weighted average of the values given by Eqns n and $n-1$.

Preliminary Results

Retrofit package optimization outcomes are sensitive to energy and individual retrofit unit costs as well as to individual retrofit performance. Most of the retrofit unit costs can only be crudely estimated at this time.

The optimization outcome also depends on how retrofits are discretized. For example, in our first runs, the cost of scaffolding is included once for a number of exterior envelope retrofits whose installation requires scaffolding.

FEDS runs using these preliminary retrofit dicretization assumptions and cost and efficacy data show that all of the candidate infiltration and ventilation packages are cost effective. The most aggressive package, consisting of measures (A) through (D) at their highest levels, yields the lowest life-cycle cost. The average heating season infiltration rate with this package is 0.32 ACH, compared to 0.97 ACH for the existing building. The corresponding annual infiltration heating loads are 88 $MJ\cdot m^{-2}y^{-1}$ (21 $Mcal\cdot m^{-2}y^{-1}$) after retrofit and 284 $MJ\cdot m^{-2}y^{-1}$ (68 $Mcal\cdot m^{-2}y^{-1}$) before.

Pkg #	Infiltration rate (ACH)	EUI MJ/m2 − y
0	0.971	284
1	0.713	209
2	0.441	123
3	0.350	97
4	0.432	120
5	0.328	91
6	0.415	116
7	0.316	88

Based on the results reported here and elsewhere (Whittle 1996), four demonstration buildings in Ryazan have received retrofits and are currently being monitored in detail. More comprehensive FEDS runs will be made upon completion of the Ryazan demonstration and analysis of actual costs and energy savings. In addition to monitoring heat, domestic hot and cold water, electrical energy, and apartment temperatures every hour, the Ryazan buildings have been subjected to additional blower door tests, including stairwells and security halls as well as apartments. Hourly ventilation flow rates and air quality have also been measured during the 1995–1996 heating season.

CONCLUSIONS

The housing sector of the Russian economy faces a serious dilemma: while many tenants cannot bear the full cost of heating, building owners are likewise unable to finance energy efficiency improvements. Owners and lending institutions need technical assurance that energy retrofits make good financial sense. Considerable effort is needed to find and demonstrate near-LCC-optimal retrofit packages. However, the required effort is justified by the large potential savings locked up in the hundreds of thousands of mass-produced apartment units that will benefit from EHDP retrofits.

The problem of finding optimal infiltration and ventilation retrofit packages for tall buildings can be solved by careful characterization of existing buildings and by decomposing the synthesis activity into detailed and simplified modelling tasks. Using this approach, infiltration and ventilation improvements that represent a significant savings potential have been identified for typical Russian high-rise apartments of panel construction.

Preliminary results, based on \$22.80/Gcal heating water at the building service entrance, indicate the potential to reduce average heating season infiltration rates by about half an ACH, saving 1.07 $\$/m^2$ annually. The investment cost is about $\$2.50/m^2$ giving a simple payback of less than 2.5 years for the infiltration and ventilation measures.

More complete pre- and post-retrofit characterization of component leaks is needed and planned so the process of retrofit selection can be refined as better cost data are obtained. Detailed models of additional building types have been constructed and will eventually number over twenty. Validation of five- and nine-story Ryazan building models using continuous exhaust flow and zone pressure and zone temperature measurements is underway and needs to be augmented with tracer gas measurements.

One of the biggest challenges presented by these buildings is control of vertical air movement. Vertical air movement complicates control by causing heating and infiltration loads to vary non-linearly with floor position and indoor-outdoor temperature difference. Leak paths in apartment floor decks, apartment-stairwell, and apartment-security hall walls must be identified and low-cost procedures developed to reduce these ELA's to a specified level. Once sealing has significantly reduced vertical air movement through apartments, the relatively easy tasks of tightening the exterior envelope and controlling ventilation can begin.

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ENDNOTES

1. The project demonstration cities are Novocherkask, Orenburg, Petrozavodsk, Ryazan, Vladimir, Volkhov; Cherepovets may become a project city; other cities that responded to the city survey include Zhukovskiy, Efremov, Kraznoyarsk, Kulebaki, and Yaroslavl.

2. The purpose of pre-demonstration (pilot) phase testing was to determine building characteristics upon which an

initial estimate of cost-effective energy savings potential could be based. Three buildings (5-, 9-, and 14-story) were selected in Zhukovskiy for these tests.

3. See note 1 for list of city survey responders.

4. The buildings are referenced by street name and building number. Russian addressing convention uses "building numbers" which are sequential but, in contrast to U.S. street numbers, bear little or no relation to distance from an origin or location on any particular city block.

5. The technical attic is the upper terminating point for electrical risers, hot-water radiator risers, and exhaust ducts from individual apartments. It is also the place where sanitary vent pipes collect into a single roof vent, where air is bled from DHW recirculation loops and radiator circuits, and where homeless people sometimes shelter in winter. The technical attic usually has a single large exhaust chimney up through the roof that serves as a collector for exhausts from all of the apartments in the corresponding building section. Some technical attics have sidewall openings which presumably function to prevent condensation by admitting dry air.

6. The term "pressurize" is used throughout the paper to mean "induce a positive *or* negative pressure across the envelope"; because the exhaust channels are not equipped with back-draft dampers, the results of blower door tests run at positive and negative pressures were found to differ very little.

7. The domain of r^2 is from 0 to 1 with 0 indicating no correlation between ln(Q) and ln(p) and 1 indicating a perfect correlation.

8. Pre- and post-retrofit velocities in the ventilation channels that serve a kitchen or bathroom in each of 1 to 4 vertically aligned apartments, and in the large single-channel collector stacks that serve the 15 to 36 apartments found in a typical building section, have been monitored continuously in one of the EHDP retrofit demonstration buildings located in Ryazan; velocities are being measured in the collector stacks (not present in the Zhukovskiy buildings) only on the roof of this and two other Ryazan demonstration buildings.

9. The wall at the head of the "security" hall is, ironically, a rather flimsy wooden panel affair. Pre- and post-retrofit ELAs of doors and walls of this type are being measured in the Ryazan demonstration buildings.

10. Radon was the only contaminant measured in Zhukovskiy, and the purpose was only to determine whether or not a potential radon problem existed. The radon concentrations nevertheless gave a qualitative confirmation of the vertical air movement problem. In Markievskaya 15/3, concentrations 1.3 and 1.8 pCi/l were measured in the north and south basements, <0.2 in a first floor apartment and first floor electrical room and 0.6 in a fifth floor apartment. In Keldisha 7 concentrations were <0.2 in a first floor, and 0.3 in a third floor apartment. These observations are consistent with detailed modelling which predicts that, in a building with strong vertical air movement, first floor apartments can have lower concentrations than higher apartments in spite of being closer to the contaminant source.

11. Thermostat (a form of feedback) control is rarely used in Russian buildings; outdoor reset (a form of feedforward control) is used instead. The issue of heat control leads us directly into the thorniest of questions about two of the most occupant-behavior dependent retrofits: thermostats and apartment level metering. A number of different retrofit packages are being applied to the intensively monitored buildings in Ryazan to learn more about this.

12. It is expedient to retain the existing passive ventilation ducts when converting to mechanical ventilation. However, this will result in passive ventilation forces interacting with the fan curve to prevent a truly fixed ventilation rate; i.e. exhaust rates will still vary somewhat with indoor-outdoor temperature difference in any practical, cost-effective mechanical ventilation design. For example, a 14-story air column at $-40°C$ exerts a pressure at its base about 100 Pa greater than the pressure exerted by a 14-story air column at 18°C. This pressure difference is comparable to that developed by axial-flow exhaust fans and such a variation in external pressure will result in significant flow variation through the fan. Seasonal adjustment, automatic reset of balancing valves, or variable speed fan control is therefore needed to approach the ideal of uniform, temperature-independent ventilation rates for all apartments.

13. based on weekly cooking gas demand, electric demand, and contaminant generation profiles measured between 25 Jan and 3 Mar 1996 in six Ryazan apartment buildings (Reilly 1996a).

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