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Standards for heating energy use in Russian buildings: a review and a report of recent progress

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Abstract

A knowledge of Russian building thermal-energy codes in effect in the post-World War II era is necessary for estimating the thermal performance of the existing building stock, quantifying the impact of energy conservation retrofits, and estimating the benefits of more stringent codes. This paper begins with a thorough review of the prescriptive-based national codes that applied to heated buildings constructed in the Soviet era. The codes defined all envelope thermal performance requirements for space heating. The paper then describes two recent developments in Russian codes: (i) a novel municipal code for Moscow, in effect since 1994, that increases thermal performance levels in some buildings and unifies elements of formerly distinct codes; (ii) a revised national code, approved in 1995, that increases thermal performance levels of all buildings relative to the previous national code. Prescriptive thermal requirements established in the Moscow and new national codes are comparable to those in effect in the current version of ASHRAE Standard 90, used throughout the US. The paper concludes by describing a proposed new direction for the Russian national code that includes, for the first time, a performance requirement limiting buildings' normalized annual heating energy use.

Keywords: Residential buildings; Envelope construction; Russian building codes; Thermal protection

1. Introduction

Russia claims an important role in the world's energy economy because of the magnitude of its energy use and greenhouse-gas emissions. Russian apartment buildings are substantially less energy-efficient than Western counterparts, as noted by Russian and Western analysts [1] and described in the companion to this paper. Russian building thermal-energy codes have shaped building space-heating energy use over nearly five decades; a knowledge of the codes is necessary to estimate energy use in the existing building stock and to provide a rational basis for quantifying the impact of proposed conservation retrofits, as presented for apartment buildings in the companion paper. Recent efforts to make the codes more stringent, promoting energy conservation while preserving or enhancing thermal comfort, will exert a major influence over the construction industry and building heating energy use in coming years.

The first section of this paper, developed by the American authors and based on a more extensive recent report [2], describes the historical evolution of Soviet-era building thermal-energy codes. These prescriptive national codes focused on individual envelope construction elements. The codes documented the required minimum thermal performance levels (*norms*) and defined methodologies that determined the performance of actual wall components and windows (*calculation procedures*). Component designers first computed the thermal properties of a given wall section or window, then compared the calculated properties to the norms to determine whether the norms were being satisfied. The minimum required performance of external walls and roofs was, until 1972, driven by concerns about condensation on inside wall surfaces and led to markedly low levels of thermal insulation. Later versions of the code included a prescribed economic optimization of external wall and roof insulation levels based on life-cycle cost principles. Because the optimization was performed for each type of envelope construction, it led to substantially higher thermal resistance for insulated wall panels but permitted the continued use of uninsulated panels as well as brick and block construction. Furthermore, even for insulated panels, the technique's complexity severely limited its effectiveness.

The second section of the paper, developed by the Russian authors, focuses on recent innovations in Russian building codes. First, we describe a groundbreaking municipal-level energy code applying to residential and public buildings in

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the Moscow region that went into effect in Aug. 1994. The new Moscow code augments higher element-by-element requirements with limits on the thermal conductivity of the building envelope as a whole — revisions intended to reduce building energy use by 30% when fully implemented. The Moscow code also embraces requirements for metering, space-conditioning systems, lighting and building certification, accruing further energy savings. Second, we describe the major changes made in the latest version of the national code, approved and published in 1995. The newest national code is significantly revised, eliminating the cumbersome economic optimization formulas used in previous codes. Although this code leads to theoretical energy savings of 20–30% via stricter envelope thermal performance requirements, it is still a prescriptive code. We conclude by presenting a concept for performance criteria that limits the space-heating energy consumption of the entire building, normalized for degree days and floor area, while ceding to the building designer considerable freedom in meeting these requirements. This new concept is embedded in proposed changes to the national code.

2. Soviet building thermal-energy codes: 1972–1994

Soviet building thermal-energy codes specified the norms and calculation procedures for the thermal resistance, air permeability, vapor permeability and thermal inertia of all envelope components — external walls, windows, balcony doors, attic floors and basement ceilings — in all heated buildings within the former Soviet Union. The codes covering all kinds of buildings — industrial, public, commercial, and residential — appear in the *Stroitel'nie Normi i Pravila* (Construction Norms and Regulations, abbreviated from the Russian as 'SNiP') entitled *Stroitel'naya Teplotekhnika* (Building Thermal Engineering, or 'thermal SNiP'). Soviet SNiPs were published by *Gosstroi*, the State Construction Committee. Here we focus on specific sections of the codes in Soviet thermal SNiPs: those for thermal resistance and air permeability, as defined by winter climatic conditions, for residential buildings. We limit our discussion to thermal resistance and air permeability for the sake of brevity; we consider only winter-based codes because the codes addressing cooling appeared in other SNiPs. We narrow our scope to residential buildings, and often refer within this paper to a subset, multifamily buildings (MFBs), for three reasons: (i) because the apparent inefficiency of Russian urban residential space-heating energy use, compared to Western developed nations, makes this sector particularly worthy of study; (ii) because in Russia residential buildings are more uniform in design and construction than public, commercial or industrial buildings; (iii) because during the Soviet era new residential buildings in urban areas were predominantly high-rise apartment buildings. It is worth noting that the SNiPs in this period considered all residential buildings as a single category; our reference to MFBs simply reflects the emphasis of our study.

The Soviet thermal SNiP addressed two forms of heat loss through the building envelope: transmission (conduction and convection) and infiltration (air exchange). Each of these categories was further subdivided into opaque components (walls, attic floors, basement ceilings) and fenestration (windows, balcony doors). When describing envelope properties, the SNiP generally addressed complete envelope components — a single large panel, a wall section of bricks or large blocks, a complete window assembly, etc. — normalizing the properties based on each component's area. Thus, our discussion follows the code and the term thermal resistance generally refers to *reduced* thermal resistance, which in theory accounts for multi-dimensional heat-flow paths through heterogeneous materials.

The Russians revised their thermal SNiP periodically as their approaches for defining building codes varied over time; thus the document has had several different numerical designations since the beginning of the post-World War II Soviet housing drive. We examine three versions of the thermal SNiP (published in 1972, 1979 and 1986, respectively) to provide an idea of how the codes evolved, preceding the detailed discussion with a general description of thermal SNiPs in effect before 1972. As will be seen, some codes depended on the type of construction of individual MFB envelope components, which the companion paper describes in detail.

2.1. Pre-1972

The Russians introduced an important constraint on the thermal characteristics of building envelopes in the 1950s. It is the 'sanitary-hygienic' constraint (SH constraint), developed to prevent condensation on inner wall and ceiling surfaces. In addition to being an inconvenience to building occupants, internal condensation lowers the thermal resistance of the envelope and can damage construction materials. Ref. [3] presents an extensive discussion of the philosophy behind the SH constraint; here we simply describe its manifestations in the Soviet thermal SNiPs. A formula for implementing the SH constraint appeared in SNiP II-B.3 [4], the 1954 thermal SNiP revision; it established a norm that varied for different climates and for different kinds of envelope construction. SNiP II-A.7.62 [5], published in 1963, revised the original formula, presenting the form that persisted throughout the Soviet era and is still used today. The revised formula prescribes a minimum permissible thermal resistance of opaque envelopes, based on a minimum allowed temperature of the inner envelope surface, as shown in Eqs. (1a) and (1b):

$$R \geq R^{\rm req} = \frac{nb\,\Delta T_{\rm d}}{(T_{\rm in} - T_{\rm w})\sigma h_{\rm i}} \tag{1a}$$

$$\Delta T_{\rm d} = T_{\rm in} - T_{\rm out} \tag{1b}$$

where R = calculated thermal resistance of opaque envelope structure (m^2 °C/W); $R^{\rm req}$ = minimum required therm resistance of opaque envelope structure (m^2 °C/W); n = envelope shielding coefficient; b = coefficient accounting for quality of thermal insulation (dropped in later SNiP revisions); σ = coefficient accounting for quality of brick construction; h_i = heat transfer coefficient of inner envelope surface (W/m^2 °C); ΔT_d = design indoor – outdoor air temperature difference (°C); T_{in} = design indoor air temperature (°C); T_{out} = design outdoor air temperature (°C); T_w = inner envelope surface temperature (°C).

Design internal air temperatures were set according to thermal comfort standards. In a given town T_{in} was constant, generally 18°C for MFB living areas. The design outdoor temperature T_{out} varied with local climate conditions and the calculated thermal inertia of the building's envelope construction (to be discussed shortly). The value of h_i depended on whether the inner envelope surface was smooth or had protruding ribs; its design value of 8.7 W/m^2 °C was uniform for all walls and floors (ribs normally appeared only in ceilings). The value of n depended on the position of the envelope component in relation to the outside air — whether walls, floors or ceilings were directly exposed, when n took the value of 1.0, or were partially shielded by unvented attics or basements, when n ranged from 0.4 to 0.9. The value of b depended on the quality of the thermal insulation used in the construction: if the insulation was compressed during its installation (e.g. on the assembly line for a prefabricated wall panel) then b was 1.2, unless the insulation material's density was less than 400 kg/m^3, when b became 1.1. Otherwise, b was 1.0. Later versions of the thermal SNiP omitted b entirely.

The constraint in Eq. (1a) is the inner wall temperature T_w. Its minimum allowed value in MFBs was equal to the design dew point, 10°C, corresponding to a design indoor relative humidity of 55%. This minimum T_w value was built into the code-specified difference ($T_{in} - T_w$), a constant 8°C for all MFBs. The mandated 8°C temperature difference was reduced by the coefficient σ, introduced before World War II to account for the poor quality of brick construction. The original value of σ was about 0.75, but it has not been changed since that time, and has since been applied to *all* kinds of wall construction. Significantly, all SNiPs containing the SH formula present the denominator of Eq. (1a) not as it is shown here, but as the product of two terms, an artificially defined temperature difference Δt (set at 6°C for external walls) and h_i, thus obscuring the existence of σ.

Early SNiPs also included a formula for computing the design thermal inertia of the external wall structure (Eq. (2)). The summation in the formula was taken over all layers of the construction, assuming the layers were thermally arranged in series (the inertia calculation ignored two-dimensional heat flows). The thermal resistance of each layer was computed using Eq. (3), and the heat absorption coefficient S_i was a tabulated material property. Early SNiPs divided buildings into four humidity zones — dry, normal, moist and wet — and the USSR into three humidity regions — dry, normal and moist. The SNiPs used these classifications to tabulate building material properties for different moisture conditions, providing a standardized way to account for some of the variations experienced by actual buildings.

$$D = \sum_i (R_i S_i) \tag{2}$$

$$R_i = \frac{\delta_i}{\lambda_i} \tag{3}$$

where D = dimensionless coefficient of thermal inertia; S_i = diurnal heat absorption coefficient of layer i of the construction element (W/m^2 °C); δ_i = thickness of layer i (m); λ_i = thermal conductivity of layer i (W/ m °C).

If the thermal inertia of a particular kind of construction (e.g. 1-layer panels made of heavy concrete) was high enough its thermal resistance requirement was relaxed, because heavy structures tended to damp extreme temperature fluctuations. The link between thermal inertia and thermal resistance occurred through the definition of T_{out} from Eq. (1b). T_{out} was defined for each town as the overall mean of the average diurnal temperatures on the coldest days of the eight coldest years in a standard 50-year design period. In SNiP II-A.7-62, if $D \leq 4$ for a particular construction component, then the Russians used the single coldest day of those 8 years to determine T_{out}. If $D \geq 7$, they used the five coldest days in the average, resulting in a milder design temperature, and thus a smaller value of ΔT_d in Eq. (1b). If $4 < D < 7$, they used the mean of the results of the first two cases.

The SH constraint also imposed a second, indirect limitation on envelope thermal resistance: it instructed designers to compute T_w to ensure that it would not fall below the design dew point. SNiP II-A.7-62 also attempted to address the problem of localized condensation by requiring additional checks on T_w in all regions of the construction containing thermal bridges — panel ribs, metal ties, joints between panels, frameworks, etc. — and included a formula to be used for performing these checks.

Through implementation of the SH constraint, the minimum design thermal resistance of envelope components depended on the climate and the type of construction — thickness, type of material, geometry, presence of insulation, etc. Based on computed thermal inertias, Table 1 shows typical design outdoor temperatures for Moscow, along with the design temperature difference. The SH constraint required very modest levels of thermal resistance, as simple substitution shows. In accordance with SNiP II-A.7-62, MFBs in the Moscow region in this period were constructed with external wall panels rated at 0.84–1.15 m^2 °C/W.

Eq. (1a) defines R^{req}, the *norm* for opaque envelope thermal resistance. Early thermal SNiPs defined the *calculated* thermal resistance, R, with Eq. (4a). The outer convection coefficient, h_o, like n in Eq. (1a), depended on the position of the envelope component in relation to the outside air; notably, h_o values were *not* differentiated by climate conditions (e.g. wind speed, air density, or humidity). The design value of h_o was 23 W/m^2 °C for all external walls and roofs directly exposed to outside air. The method of computing R_c

Table 1
Design winter outdoor air temperature, T_{out}, and indoor–outdoor temperature difference, ΔT_d, for Moscow

Thermal mass of building envelope, D	T_{out} (°C)	ΔT_d (°C)
1986 [a]		
<1.5	−35	53
1.5–4	−32	50
4–7	−29	47
>7	−26	44
1994		
1.5–4	−32	50
4–7	−30	48
>7	−28	46

[a] Design temperatures used in 1972 and 1979 were similar to those used in 1986.

depended on the geometry of the envelope construction. For single-layer designs R_c was computed using Eq. (3). For multi-layer designs with homogeneous layers arranged consecutively in series, the Russians used Eq. (4b), with the summation taken over all layers. The unventilated air layer represented by R_{air}, although commonly used in other kinds of buildings, including single-family homes, was rarely used in MFB designs.

$$R=\frac{1}{h_i}+R_c+\frac{1}{h_o} \tag{4a}$$

$$R_c=\sum_i R_i+R_{air} \tag{4b}$$

where R_c = thermal resistance to conduction through the envelope (m^2 °C/W); R_{air} = thermal resistance of an unventilated air layer within the construction (m^2 °C/W); h_o = heat transfer coefficient of outer envelope surface (W/m^2 °C).

The Russians used a more complex method of defining R_c for multi-layer constructions with heterogeneous layers (e.g. an insulated 3-layer panel with concrete ribs connecting the outer and inner concrete layers): a weighted average of two calculated one-dimensional thermal resistances, R_a and R_b, as shown in Eq. (5a). R_a, defined by Eq. (5b), assumes parallel paths of heat flow through the envelope. Conversely, R_b assumes a single series path, and was defined by Eq. (4b), replacing R_c with R_b. For both R_a and R_b, the thermal resistance of each layer R_i was computed differently, depending on whether the layer in question was homogeneous or heterogeneous. These one-dimensional series-path and parallel-path calculations yield different values for R_a and R_b in the presence of thermal bridges (i.e. the concrete ribs in the panel described above). In practice $R_a > R_b$, and the ratio indicates the degree of two-dimensional heat flow. This ratio converges for narrow thermal bridges or thin insulation layers, but in practice often diverged for the envelope designs commonly used. Early SNiPs handled divergence of R_a/R_b by requiring the use of an alternative procedure for computing R_c whenever $R_a > 1.25R_b$. The alternative procedure was based on theoretical calculations of the temperature field on the inner and outer surfaces of the envelope element.

$$R_c=\frac{R_a+2R_b}{3} \tag{5a}$$

$$R_a=\frac{\sum_i A_i}{\sum_i \frac{A_i}{R_i}} \tag{5b}$$

where R_a = 1-D thermal resistance, assuming parallel paths (m^2 °C/W); R_b = 1-D thermal resistance, assuming a single series path (m^2 °C/W); A_i = area of wall element section i, normal to heat flow (m^2).

This cumbersome calculation procedure for R_a and R_b originated in the 1950s and is still used in the newest national SNiP. The Russian authors of this paper have criticized the approach, however, because its accuracy is good only for brick construction. They have long advocated using alternative procedures for calculating R_c, based on either experiments or the theoretical calculations of temperature fields mentioned above. Full-scale experiments were rarely performed outside Moscow, but the Russian authors developed and freely distributed computer software that calculated the temperature fields automatically based on design geometries and material properties. As a result, Eqs. (5a) and (5b) have been used less frequently in recent times, in favor of the more accurate techniques.

2.2. 1972–1978: SNiP II-A.7-71

2.2.1. Transmission

SNiP II-A.7-71 made several significant changes to Soviet thermal codes. The first was its introduction of new methods of determining norms for opaque element R values. For the first time since the beginning of the Stalin period, the norms required the use of explicit economic calculations incorporating both construction costs and annual heating costs. The extensive computations required to establish the norm defined an optimal value of the thermal insulation thickness, δ_{ins}, based on formulas similar to Eqs. (3)–(5) and other, more complex expressions. The thickness, related to the thermal resistance of the insulation layer by Eq. (3), was chosen to minimize the total life-cycle cost of the component, Π, defined by Eq. (6). Eq. (6) was applied to one complete opaque construction element — a wall panel or ceiling panel — not to the entire building envelope.

$$\Pi=C_d+\frac{(\mathrm{RDD})}{R^{ec}}C_T\alpha \tag{6}$$

where Π = reduced cost over the lifetime of the construction element (Rb/m^2); C_d = local initial cost of the construction element (Rb/m^2); RDD = local value of Russian degree days (°C d); C_T = local cost of heat energy (Rb/GJ) α = combined multiplicative coefficient; R^{ec} = element thermal resistance, based on insulation thickness δ_{ins} (m^2 °C/W).

In Eq. (6), RDD is analogous, although not equivalent, to the heating degree-day statistic widely used in the US (Ref. [2] explains the RDD computation in more detail). The α parameter combines three other coefficients in the calculations (unimportant in the present discussion; see Ref. [6] for a more complete description of this formula). R^{ec} is the overall thermal resistance of the construction element, depending in part on the insulation thickness δ_{ins}. SNiP II-A.7-71 instructed building designers to compute the minimum Π value for several kinds of enveloping structure, and to then choose the structure with the smallest minimum Π value. Although the procedure explains how to choose among the available options, the SNiP said nothing about *which* options had to be examined.

The new optimization procedure was widely criticized within the Soviet building industry. Designers complained that some of the formula's numerical coefficients had no apparent source, and that the formula itself was far too cumbersome to use repeatedly in practice, as the necessary data were hard to collect. Iteration was theoretically required to find the optimal value of δ_{ins}, but in practice iteration was unenforceable. The Russian authors of this paper have also criticized this approach on several grounds. First, the formula was overly restrictive because it optimizes only δ_{ins}, rather than the component's total R value. Second, the costs used in Eq. (6), like most Soviet-era prices, were set administratively, and often failed to account for real market conditions. Third, and perhaps most significantly, the formula accounts for only the heat losses through the opaque element itself, ignoring other paths of heat loss through a building's envelope. Despite these problems, the technique remained in the thermal SNiP essentially unchanged for 14 years.

Norms for opaque element R values in SNiP II-A.7-71 were still limited by the SH constraint, which this SNiP revised in several minor ways. First of all, the SNiP omitted the b coefficient in Eq. (1a), but in footnotes instructed designers to introduce a new coefficient to account for poor construction quality in large panel elements. For panels of 'uncertified quality', the value of R^{req} was increased by 10%, 20% or 30% depending on whether the panel had a single layer, three layers, or a very low thermal inertia ($D<2.5$), respectively. This SNiP also allowed compliance for brick construction if it fell within 5% of R^{req}, since the R value of a brick wall can conveniently be changed only in discrete amounts. Further, SNiP II-A.7-71 redefined the heat absorption coefficient S_i with other equations in terms of thermal conductivity, specific heat capacity, density, and the moisture contained within the material; in previous SNiPs S_i was simply a tabulated material property. SNiP II-A.7-71 also omitted the formula to be used for performing the checks on inner wall temperature T_w, instructing designers to perform their own theoretical calculations.

In SNiP II-A.7-71, norms for R values from the revised SH constraint, R^{req}, and the new economic optimization constraint, R^{ec}, each provided a lower bound for an opaque component's calculated R value. The larger of the two norms was selected to be the minimum allowable thermal resistance. In practice the economic constraint was usually binding in wall designs without thermal bridges; as a result design R values generally increased for homogeneous constructions. In walls employing thermal bridges the binding constraint on thermal resistance varied from region to region. Unfortunately, we cannot assess the overall impact of SNiP II-A.7-71 on opaque element R values because it is extremely difficult to reproduce the economic optimization calculations required by the SNiP. Instead, we will postpone this assessment until the 1986 code, which provides explicit values of thermal resistances as a starting point for the optimization. For now, we simply note that designers and builders likely had problems applying the new economic formulas properly, for the reasons discussed above and because the new approach was such a radical departure from previous techniques.

The second major change in SNiP II-A.7-71 was its integration of codes for opaque elements and fenestration in a single document; previously the codes had appeared in separate SNiPs. Norms and calculation procedures for window and balcony door (W/BD) R values in this SNiP were much simpler than those for opaque elements. *Norms* for W/BD thermal resistances were tabulated in the SNiP, ranging from 0.17 to 0.52 m^2 °C/W. For MFBs these values depended only on ΔT_d (i.e. on the local climate); for Moscow the value was 0.34 m^2 °C/W. Determining the *calculated* thermal resistance of standardized W/BD assemblies in practice was also simply a matter of looking up the values in a table. These 'actual' thermal resistances depended on the kind of W/BD construction — the number of panes, the sash material, whether the sashes were connected, etc. — and also ranged from 0.17 to 0.52 m^2 °C/W, each matching the corresponding norms precisely. Russian designers had fewer choices for window designs than for opaque wall sections, as factories produced only a few standardized assemblies.

2.2.2. *Infiltration*

SNiP II-A.7-71 defined infiltration through opaque envelope components in terms of their total resistance to air permeability, R_{op}^{inf}, a material property tabulated within the SNiP for various construction materials. The norm, an upper limit on permitted air flow, was defined by the maximum permissible air permeability G_{op}, based on laminar flow through leakage paths. This formulation ignored air flow through cracks and joints between panels, so that the specified infiltration requirements often drastically underestimated actual airflows in real buildings. G_{op} was tabulated in the SNiP for various sections of the building envelope for different kinds of buildings (the value for MFB external walls was 0.5 kg/m^2 h), and was related to R_{op}^{inf} as shown in Eq. (7). Clearly, since G_{op} is a maximum allowed air flow, for a given location Eq. (7) defines a minimum allowable value of R_{op}^{inf}. Because air flow through the envelope depends non-linearly on the indoor – outdoor pressure difference, R_{op}^{inf} is an artificially defined quantity.

$$\frac{\Delta p}{R_{op}^{inf}} \leq G_{op} \quad (7)$$

where G_{op} = maximum allowed air permeability of MFB opaque element (kg/m^2 h); Δp = design pressure difference between indoor and outdoor air (Pa); R_{op}^{inf} = calculated total air permeability resistance of opaque element (m^2 h Pa/kg).

The design pressure difference Δp was computed for each building based on building height and the design air density and average wind speed at the site (Eq. (8)). The β coefficient had one of three values — 0.6, 1.0 or 1.2 — depending on the building's location within the USSR; the value for Moscow was 0.6. The pressure difference depends on the specific weight of the air, γ, which in turn depends on local ambient air pressure and temperature. With Δp and G_{op} thus specified, compliance was checked by *calculating* values for R_{op}^{inf} as a series sum over all layers of the construction (Eq. (9)), with the value for each layer obtained from the SNiP's tables. Each value of $(R_{op}^{inf})_i$ was an average, normalized to the area of the wall element, that depended on the type and thickness of the construction. Eq. (7) was applied to the resulting total. Notably, the minimum permissible value of R_{op}^{inf} depends on Δp, and thus on the local climate, but the norm G_{op} does not. Thus, G_{op} more conveniently specifies the rate of heat loss through the envelope, and is therefore the quantity of interest here.

$$\Delta p = 0.55H(\gamma_o - \gamma_i) + 0.03\gamma_o\beta^2 v^2 \quad (8)$$

$$R_{op}^{inf} = \sum_i (R_{op}^{inf})_i \quad (9)$$

where H = height of building (m); γ_o, γ_i = specific weight of outdoor and indoor air, respectively (N/m^3); v = January average wind velocity, with a recurrence of at least 16% (m/s); β = regional coefficient; $(R_{op}^{inf})_i$ = tabulated air permeability resistance of envelope layer i (m^2 h Pa/kg).

The Russians handled infiltration through fenestration assemblies slightly differently. *Norms* were again defined in terms of a maximum allowable air permeability, $G_{W/BD}$ (Eq. (10a)), but unlike G_{op}, the norms for $G_{W/BD}$ were tabulated for different regions depending on T_{out}. The norms ranged from 25 kg/m^2 h for mild regions to 8 kg/m^2 h in severe regions (the value for Moscow was 13 kg/m^2 h). Air permeability was *calculated* for W/BD assemblies by taking the larger root of the quadratic equation in G shown in Eq. (10b). As with R_{op}^{inf} for opaque elements, G represented an average value, normalized to the area of the W/BD assembly. The design pressure difference is the same Δp defined in Eq. (8). The parameters A and B were tabulated in the SNiP, depending on the type of W/BD construction and on the amount and type of weather-stripping used.

$$G \leq G_{W/BD} \quad (10a)$$

$$BG^2 + AG = \Delta p \quad (10b)$$

where G = calculated air permeability of W/BD assembly (kg/m^2 h); $G_{W/BD}$ = maximum allowed air permeability of W/BD assembly (kg/m^2 h); A, B = empirical coefficients.

2.3. 1979–1986: SNiP II-3-79

2.3.1. Transmission

In SNiP II-3-79, the essence of the previous approach for opaque envelope elements remained unchanged: the SNiP limited the minimum permissible R value with both the SH constraint and the economic optimization formula. SNiP II-3-79 further revised the SH constraint. First, the values for the heat absorption coefficient, S from Eq. (2), were no longer computed using complicated auxiliary formulas; now S was simply tabulated with other material properties as it had been in older thermal SNiPs. Second, the calculated thermal inertia of the envelope, D from Eq. (2) (used for computing T_{out}), was now divided into four categories instead of three: if $D \leq 1.5$, the Russians used the *absolute* minimum temperature (rather than the diurnal average temperature) of the coldest day for T_{out}. This potentially provided better thermal protection for buildings of very lightweight construction.

Two further revisions increased the impact of the SH constraint, compared to SNiP II-A.7-71. First, SNiP II-3-79 provided a rearranged version of Eq. (1a) for checking the inner envelope surface temperature, T_w, but without the hidden fudge factor σ. Second, the SNiP provided a separate formula for checking T_w near thermal bridges that included an extra term, κ, to correct for the presence of the thermal bridges (Eq. (11)). The value of κ depended on the thermal resistances of the construction both with and without the thermal bridge, and on the geometry of the thermal bridge itself. Because κ always exceeded unity, envelopes with thermal bridges had lower calculated values of T_w, and were thus theoretically held to a higher standard of thermal performance. Eq. (11) resembles the formula that had appeared in SNiP II-A.7-62 for similar purposes, but which SNiP II-A.7-71 had dropped.

$$T_w = T_{in} - \frac{\Delta T_d}{R^{hom} h_i}\kappa \quad (11)$$

where R^{hom} = thermal resistance (R, from Eq. (4)) assuming no thermal bridge is present (m^2 °C/W); κ = heterogeneity correction coefficient.

Calculation methods for opaque elements also changed in SNiP II-3-79. The SNiP provided an alternative to the cumbersome calculations of Eq. (5) for computing the thermal resistance of prefabricated external wall panels in MFBs (Eq. (12)). The designer could base the r value on either theoretical calculations or experimental data; typical calculated values for 3-layer panels ranged from 0.40 for panels with 50 mm wide ribs to 0.70 for panels with 8 mm diameter metal ties [7]. Potentially, this approach left much latitude for building designers in computing R.

$$R = R^{hom} r \quad (12)$$

where r = coefficient of homogeneity.

The *norms and calculation procedures* for window and balcony door R values did not change in SNiP II-3-79, but designers had many more choices of W/BD assemblies than they had in SNiP II-A.7-71.

2.3.2. Infiltration

Norms for infiltration through opaque elements changed in SNiP II-3-79: the β coefficient in Eq. (8) was removed, thus altering the computation of Δp (Eq. (13)). In Moscow MFBs, this increased the value of Δp, and thus increased the minimum permissible air permeability resistance R_{op}^{inf}, as Eq. (7) demonstrates. Notably, this had no effect on G_{op}, the norm we emphasize here, because it is independent of Δp. The method of *calculating* R_{op}^{inf} for the elements did not change in SNiP II-3-79.

$$\Delta p = 0.55H(\gamma_o - \gamma_i) + 0.03\gamma_o v^2 \tag{13}$$

For fenestration, both the *norms* and the *calculation procedures* changed. Previous fenestration *norms* were tabulated based on T_{out}, but in this SNiP the required resistance to air permeability was defined by Eq. (14), using the revised Δp shown in Eq. (13). Like G_{op}, the air permeability $G_{W/BD}$ was now listed as a fixed value of 10 kg/m^2 h for all MFB fenestration. The Russian authors of this paper have criticized Eq. (14) as it is shown here, as it led to nonsense units in $R_{W/BD}^{inf}$ and lacked a meaningful reference pressure for Δp. Furthermore, we believe that the specified value of 10 kg/m^2 h for $G_{W/BD}$ is itself overly optimistic, as the air flow through real building envelopes may be as much as 30–40 kg/m^2 h.

$$\frac{\Delta p^{2/3}}{R_{W/BD}^{inf}} \leq G_{W/BD} \tag{14}$$

where $R_{W/BD}^{inf}$ = tabulated air permeability resistance of fenestration (m^2 h (Pa)$^{2/3}$/kg).

Calculating $R_{W/BD}^{inf}$ became simpler in SNiP II-3-79: designers simply consulted tabulated values of the air permeability resistance for various kinds of W/BD construction. Some of the sophistication of the previous approach disappeared in this SNiP: the tabulated values no longer varied for different weather-stripping materials.

*2.4. 1987–1994: SNiP II-3-79***

2.4.1. Transmission

SNiP II-3-79** [10] was the last version of the USSR's codes on building thermal engineering published before the breakup of the Soviet Union, and it changed the *norms* for opaque envelope components yet again. This SNiP improved the economic optimization of envelope performance: rather than optimizing the insulation thickness, the reduced thermal resistance of the envelope was optimized. That is, a value of R was chosen, R^{ec}, that minimized the total reduced cost Π in Eq. (6). This approach was more general than the method introduced in 1972, because now wall sections could be made thicker or thinner, or with varying amounts of insulation material, or with different geometries or materials, etc. The revised method also avoided some computational difficulties associated with the formulation presented in SNiP II-A.7-71. The formula still required some fairly cumbersome calculations, covering 8–10 types of construction in each of about 200 climatic zones, leading us to suspect that in practice even the new formulas were rarely used.

SNiP II-3-79** also greatly simplified the optimization procedure by providing initial values of R for the calculations, $(R^{ec})_i$, based on the local value of R^{req} from the SH constraint (Eq. (1a)) and on the tabulated coefficient ϕ (Eq. (15)). The coefficient ϕ varied for different types of wall construction, as shown in Table 2. This approach had its own problems, however, as ϕ depended strongly on local conditions, and the recommended values for ϕ were not necessarily based on rigorous technical and economic analysis.

$$(R^{ec})_i = R^{req}\phi \tag{15}$$

where $(R^{ec})_i$ = initial value of economic thermal resistance (m^2 °C/W); ϕ = tabulated thermal resistance multiplier.

Russian experience showed that optimal R values often differed little from the initial value given by Eq. (15); this might have led some designers and builders to simply stop the optimization procedure after computing the initial value. Even if Russian specialists widely exercised this shortcut, in theory the economic optimization substantially boosted the required thermal resistance of the widely used 3-layer panel assemblies — the optimization influenced thermal resistance requirements much more than did thermal inertia through its very limited impact on the SH constraint.

SNiP II-3-79** further revised the SH constraint by introducing a second correction formula for checking the value of T_w near thermal bridges. The previously used formula (from SNiP II-3-79), originally applying to all thermal bridges, was now restricted to only non-metallic bridges; the new formula in this SNiP addressed metallic bridges. Tabulations for the correction coefficients in these two equations were now much more complex, each accounting for roughly 60 possible thermal bridge geometries. The revised equations imposed higher limits on the local thermal resistance of the envelope than the corresponding equation in SNiP II-3-79.

SNiP II-3-79** also further developed the alternative, simplified *calculation procedure* for MFB panel walls introduced in SNiP II-3-79 (Eq. (12)). This SNiP included an appendix

Table 2
Thermal resistance multipliers applied to the SH constraint, SNiP II-3-79** (1986)

Wall type	ϕ coefficient
Single-layer panel made of porous aggregate; brick and block	1.1
Single-layer panel, made of cellular concrete	1.3
Three-layer panel, with mineral wool or rigid foam insulation	1.8
Three-layer panel as above, with sheathing	2.0
Other	1.1

[redacted]

that provided values for the coefficient of homogeneity, r, for those MFBs with 3-layer panels using concrete ribs or metal ties. For panels with metal ties, r was tabulated as a function of the tie diameter, the relative spacing between the ties, and the concrete density; its values ranged from 0.70 to 0.98. For ribbed panels, r depended on the rib area and the density of the rib material, and ranged from 0.50 to 0.90. These standardized correction factors provided more predictable results than allowing designers free reign with Eq. (12), yet still preserved the relative simplicity of the approach (in contrast to Eq. (5) and their accompanying formulas).

The method of determining fenestration *norms* and *calculation procedures* did not change (i.e. both were still tabulated). Some of the norms themselves increased by about 20%, however.

2.4.2. *Infiltration*

Norms and *calculation procedures* for infiltration through opaque construction elements were unchanged in SNiP II-3-79**. The SNiP improved fenestration *norms* for $R^{\text{inf}}_{\text{W/BD}}$, thanks to the efforts of the Russian authors: the Δp term in Eq. (14) was divided by a reference pressure of 10 Pa before being exponentiated, improving the accuracy of the formula and eliminating the nonsense units. As in the revision of opaque infiltration norms in SNiP II-3-79 (discussed in the text preceding Eq. (13)), however, this had no effect on $G_{\text{W/BD}}$, the norm of main interest here. Choosing the *calculated* value of air permeability resistance for a given fenestration assembly became more complicated in SNiP II-3-79**: like the parameters from the quadratic equation in SNiP II-A.7-71, it depended on the type of W/BD construction and the amount and type of weather-stripping used.

2.5. *Application*

We used the Soviet building codes to estimate the thermal performance of Moscow's apartment buildings (Table 3(a)–(d)). From 1972–93 the norms were taken from the three SNiPs discussed in detail above [8–10]; from 1954–71 norms were taken from the two preceding thermal SNiPs

Table 3
Estimated thermal norms for MFB envelope components in Moscow

(a) Transmission through opaque walls (reduced thermal resistance, m² °C/W)

Type of wall construction	1954–62	1963–71	1972–78
$D<4$	0.97	1.06–1.15	0.96
$4<D<7$	0.93	0.90	0.90
$7<D$	0.84	0.84	0.84
	1979–86	1987–93	
Three-layer panel	1.4	1.7–1.9	
Brick/large block	0.90	0.90	
Single-layer panel	0.93	0.92–1.1	

Notes: all localized constraints on inner wall temperature were omitted in the computation of transmission norms for opaque walls from the SH constraint; the listed norms apply only to external walls — norms for attic floors and cellar ceilings ranged from 40–100% of the values for walls.

(b) Transmission through fenestration (reduced thermal resistance, m² °C/W)

	1972–78	1979–86	1987–93
All construction types	0.34	0.34	0.39

Note: the increase in fenestration norms in 1986 is deceptive, because the rated R value of window assemblies was increased by the same amount.

(c) Infiltration through opaque walls (air permeability, kg/m² h)

Type of wall construction	1954–62	1963–71	1972–78	1979–86	1987–93
$D<4$	0.82	0.80	0.50	0.50	0.50
$4<D<7$	0.86	1.0	0.05	0.05	0.05
$7<D$	0.95	1.1	0.05	0.05	0.05

Notes: infiltration calculations ignore gaps between wall panels and any cracks or openings; before 1972, an average pressure difference was calculated based on the building heights most commonly constructed in each period, and on a design wind speed of 5 m/s, the mean value for Moscow in January.

(d) Infiltration through fenestration (air permeability, kg/m² h)

	1972–78	1979–86	1987–93
All construction types	13	10	10
Equivalent average air exchange rate from values in (c) and (d): 0.4–0.6 ACH (for a typical building)			

Notes: fenestration values were all normalized to the fenestration area.

covering opaque elements [4,5]. Fenestration norms for periods before 1972 are missing because they appeared in other SNiPs, and were unavailable for this study. Two complications arise for estimating transmission norms for opaque walls. First, the classification scheme for different kinds of construction shifts in 1972. Before 1972 the norms were defined solely in terms of the SH constraint, but after 1972 they also theoretically depended on the results of economic optimization formulas. Recall that the SH constraint groups types of wall construction according to their calculated thermal inertia, *D*, but that initial values for the economic optimizations used in SNiP II-3-79** (1986) were grouped according to the type of construction (1-layer panels, 3-layer panels, etc.). Table 3(a) reflects this difference. Second, the optimization formulas used from 1972–86 included no initial values, and we could find no reliable information on prices applying in this period. We therefore assumed that the optimization formulas had no significant effect on the norms during the first period in which they applied (1972–1978), and estimated the norms for the following period (1979–1986) as the mean of the norms applying in 1978 and 1987, respectively. Note that infiltration norms (Table 3(c) and (d)) are listed as air leakage rates rather than equivalent thermal resistances.

Table 3(a)–(d) suggests that, despite *Gosstroi's* efforts to incorporate annual heating costs in the design of building envelopes, code-specified minimum *R* values for MFBs were generally stable for 40 years. Three-layer panel constructions provide the single exception, as Table 3(a) shows. This may have helped save heating energy in Moscow, since 3-layer wall panels were widely used there, but it had a smaller impact on the USSR's MFB stock (see the companion paper for details). Part of the problem is undoubtedly *Gosstroi's* decision to focus its economic optimization efforts solely on opaque element *R* values, rather than including heat losses through fenestration and infiltration as well. Theoretical infiltration norms for opaque elements more than doubled in 1972 (Table 3(c)), then remained constant through 1994. As mentioned earlier, however, we are skeptical of their effect in real buildings. Much more information is needed in order to properly and precisely specify the norms over all five SNiP periods, but we believe we have provided a useful first look at the norms' evolution. We emphasize that Table 3(a)–(d) describes only *design* envelope performance; *actual* performance may differ considerably for a variety of technical, economic and socio-political reasons.

Overall, the thermal design of envelopes in Russian MFBs appears to have focused on meeting worst-case weather conditions, with relatively little attention paid to providing the proper indoor air temperatures for all residents under all conditions. The lack of any consideration of annual heating costs in the building codes until 1972 suggests that operating efficiency was unimportant to central planners until that time. Such design practices appear to cause widespread improper indoor temperatures and heat supply to buildings, as well as rampant energy waste, supporting Western suspicions that dramatic space-heating energy efficiency improvements are possible in existing Russian apartment buildings.

3. New municipal and national codes

The national code established in 1986 suffered from two failings. First, the required thermal resistances were lower than those required in some Western countries. ASHRAE Standard 90 [11], for a climate similar to Moscow's, requires thermal resistances of 2.3–2.6 m^2 °C/W, compared to a maximum of about 1.7 m^2 °C/W in the Russian code. Second, the code failed to address building form and whole-building energy consumption: any shape and any amount of glass were permitted, as long as components met requirements. New codes for Moscow and for Russia in its entirety both increase the required thermal resistance of building elements. The Moscow code takes the first step in considering whole-building performance by including prescriptive requirements for the building envelope as a whole. A proposed new direction for the national code goes further by introducing, for the first time in Russia, performance requirements that limit the annual heat-energy use of a building, adjusted for degree days and floor area [12]. This paper will discuss both of the new codes and the proposed future directions, all of which have been developed by the Russian authors of this paper [13].

3.1. Moscow code

The 1992–1995 energy conservation plan for Moscow provided for the development of Russia's first municipal energy-conservation code, taking advantage of a provision for municipal and regional codes in SNiP 10-01-93 [14]. The Moscow code [15,16] was prepared by the Moscow Research Institute for Typical and Experimental Design (MNIITEP) and the Research Institute for Building Physics (NIISF) with the assistance of the Moscow Committee on Architecture, the Moscow Center for Energy Efficiency (CENEf), and the Natural Resources Defense Council (USA). The new standard took effect in Aug. 1994; since then it has become binding for all Moscow organizations involved in design of new residential and public buildings and refurbishment of existing buildings. Application of the code is mandated for all organizations and corporations irrespective of ownership or affiliation and for all persons practicing on an individual basis or undertaking any private construction, including foreign firms or individuals working independently or with Russian partners in joint ventures.

Two important provisions have been formulated in the new code: achievement of higher thermal comfort than mandated in previous codes, and reduction of energy consumption in buildings by at least 30% relative to the 1986 national code. In practice, of course, a level of thermal performance higher than the mandated minimum requirements can be demanded by a particular customer. The Moscow code consists of four sections:

1. *Thermal Performance of Buildings.* Thermal performance requirements will ensure a 20% reduction of energy consumption in newly erected buildings in the first stage of code implementation and another 10% in the second stage, to follow in three years.

2. *Heat and Water Supply of Residential Areas and Buildings.* Section 2 contains requirements, intended to further reduce energy consumption in buildings, for decentralization of heat and water supply systems, introduction of thermostatic control of convective and radiant heating devices, and application of heat and water meters. For buildings connected to district-heating systems, the new code calls for design of local heat-supply substations in every building instead of connection to central heat-supply substations. The local substations are to be equipped with heat meters and with automatic control of water as a function of outdoor temperature.

3. *Power Supply and Electrical Equipment for Buildings.* Requirements are presented for installation of modern electric meters.

4. *Artificial Lighting of Buildings.* This section establishes standard requirements for illumination systems and light control methods.

The Moscow code considers the thermal performance of both individual building components and the building in its entirety. Components must comply with the following thermal performance requirements.

(i) Minimum permissible reduced thermal resistance of opaque envelopes, as given in Table 4, and of windows and balcony doors, specified as 0.55 m^2 °C/W for uncoated glass and 0.48 m^2 °C/W for double-glass units with low-emissivity coatings. These requirements are set to meet comfort requirements for the indoor environment. The first stage of the Moscow code mandates resistance values that are at least 25% higher than values derived from the 1986 national code (SNiP II-3-79**) for the Moscow region, as can be seen by comparing Tables 3 and 4. Second-stage requirements exceed those mandated by Ref. [11] for a comparable climate in the US: wall thermal resistance of 2.5–3.0 m^2 °C/W in Moscow, with the higher value for lighter construction, compared to 1.8–2.8 m^2 °C/W for Minneapolis, MN.

Table 4
Thermal resistance of exterior walls, R^{req}, required by Moscow code

Thermal mass of building envelope, D	Moscow code thermal resistance (m^2 °C/W)	
	Stage I [a]	Stage II
1.5–4	2.2	3.0
4–7	2.1/1.3	2.8/1.7
>7	2.0/1.3	2.5

[a] Stage I applies from 1994–1997, when Stage II requirements go into effect. When thermal resistances appear in pairs, the first entry corresponds to walls with efficient thermal insulation, primarily three-layer large panels, while the second entry refers to masonry, small block, and single-layer large panel construction made of porous-aggregate and cellular concretes.

(ii) Minimum permissible temperatures of inner surfaces of exterior walls, unchanged from earlier codes and therefore not lower than the dew-point temperature at a design relative air humidity of 55% and design outdoor air temperatures as given in Table 1.

(iii) Maximum permissible air permeabilities of envelope elements as presented in Table 5, based on an outdoor temperature of −28°C and a wind velocity of 4.9 m/s. The first stage requirements match those of SNiP II-3-79** for high-rise multi-family buildings and add comparable requirements for low-rise and single-family structures, while the second phase tightens requirements for roofs, doors and windows.

The assembly of all exterior envelopes (exterior walls, fenestration, attic ceilings and ground floors) should meet the overall heat-transfer coefficient, K_m^{req}, requirement presented in Table 6 and the overall air permeability, G_m^{req}, requirement given in Table 7. These requirements were not included in the 1986 or earlier national codes. The thermal conductivity requirement effectively limits the amount of glass: the element thermal conductivities fall below the requirement for the envelope as a whole except for glazing elements. To further control excessive application of glass a

Table 5
Air permeabilities of building envelope elements, G^{req}, required by Moscow code

Enveloping structure	Air permeability, G^{req} (kg/m^2 h)	
	Stage I	Stage II
1. Exterior walls, including butt joints:		
in one- and two-storied buildings	0.7	0.7
in three-storied and high-rise buildings	0.5	0.5
2. Roofing constructions and floors for ground floor and first floor above ground	0.5	0.3
3. Apartment entrance doors	1.5	1.5
4. Entrance doors of single-family houses	1.5	1.0
5. Windows and balcony doors [a]	10	8

[a] The required air permeabilities for windows and balcony doors have been set at a pressure difference of 10 Pa.

Table 6
Overall heat-transfer coefficients, K_m^{req}, required by Moscow code

Building type and number of stories	Overall heat-transfer coefficient, K_m^{req} (W/m^2 °C)	
	Stage I	Stage II
Multi-storied		
8 and higher	0.7	0.6
4–7 stories	0.65/0.85	0.55
Low-rise		
3-storied	0.67/0.85	0.55
2-storied	0.6/0.85	0.5
Cottages (with attic) and 1- and 2-storied row houses	0.6/0.85	0.5

Table 7
Overall air permeabilities, G_m^{req}, required by Moscow code

Building type and number of stories	Overall air permeability coefficient, G_m^{req} (kg m^2/h)	
	Stage I	Stage II
Multi-storied		
10 and higher	2.5	2.1
6–9	2.4	2.0
2–5 stories	2.2	1.8
Single-family houses, including cottages and row houses		
1-storied	1.7	1.3
2-storied	2.1	1.7

limit of 18% has been set for the fenestration area in relation to the total envelope area.

The limit of 0.7 W/m^2 °C on overall envelope thermal conductivity is of comparable severity to the combination of the explicit glass limit and the element thermal conductivities. For example, a high-rise building with envelope area dominated by walls and windows will, in the limit of a vanishingly small percentage of envelope area due to the roof and ground floor, have an overall conductivity of 0.73 W/m^2 °C, based on a wall thermal resistance of 2.0 m^2 °C/W, a window resistance of 0.55 m^2 °C/W and an 18% window-area fraction. The conductivity will decrease when roof and ground-floor elements are included.

Energy efficiency of buildings is influenced by the thermal performance level of all building envelopes, air tightness of envelope components and the joints between them, and availability of heating control systems to maintain indoor air temperature at an assigned level. Energy efficiency can be specified at the time of design and subsequently tested by measuring energy use and influencing variables. To document the energy performance of new or renovated buildings, the new Moscow code includes an energy passport. This certificate aims to specify the energy-efficiency level of a building design and indicate its full compliance with the new code requirements. It includes:

(i) *general construction* data on building geometry, dimensions and orientation, volume, number of stories, area of exterior envelope, and heated floor area;

(ii) data on the *thermal performance* of the building and energy parameters, including reduced total thermal and air permeability resistances of both individual envelope components and the entire building, cumulative energy parameters of the building such as the specific energy consumption and maximum specific heat consumption for heating the building in the heating season, and information on the heating system and the heat-supply substation;

(iii) conclusions on building certification and classification regarding its thermal performance made in the course of heat engineering tests of the building after one year's operation. Upon certification, the building is assigned a certain energy efficiency category.

The energy certificate is intended to provide economic stimulation for energy conservation via favorable taxation, credits and subsidies, and an unprejudiced estimation of energy consumption as an element of the market price of the real estate.

Adoption of the new standards has created a market for new domestic and foreign energy conservation technologies and new construction materials. The Moscow Administration has mandated that Moscow industries produce technologies required by code provisions, including more efficient three-layer exterior wall panels, windows and balcony doors with triple panes, metering and control devices for gas, heat and electricity, variable-speed motor drives, and highly efficient light sources for public and housing services. Further, Moscow's energy-conservation program envisages introduction of multi-level tariffs for the use of heat and power as well as penalties for wasteful and unreasonable consumption of energy, and incentives to some municipal organizations for more efficient delivery of heat.

Early experience with the Moscow code suggests that it is achieving the desired results. Code writers have given many lectures about the code. The Moscow Department of Construction has indicated that all design organizations are working in compliance with the code. Three of the four factories in the city that manufacture wall panels have altered production processes to meet the tighter thermal-resistance requirements, and triple-pane windows are now being produced for the Moscow market.

3.2. New National Code: SNiP II-3-79 (1995 edition)*

In 1995 Russian Federation's Ministry of Construction (*Minstroi*) adopted amendments to SNiP II-3-79** which provide for a considerably higher level of thermal performance in new and renovated buildings and also improve the thermal comfort of building occupants. The amended standard, denoted SNiP II-3-79* (1995 edition), was developed by specialists from the Research Institute for Building Physics and Minstroi's Department of Codes and Standards (*Glavtekhnormirovaniye*) [17] with regard for proposals from the Central Research Institute of Experimental Design of Residential Buildings (*TsNIIEPzhilishcha*) and the Central Research and Design Institute of Industrial Buildings (*TsNIIPromzdanij*). Current practice in the USA, Canada, Sweden and other countries was made available by CENEf and the Natural Resources Defense Council.

The amended standard is prescriptive in nature. The thermal resistance of opaque envelope elements must equal or exceed the higher of two thermal resistance values found by considering both envelope-element and thermal-comfort requirements. An understanding of wall-panel manufacturing and the maximum thermal resistance that can be achieved for each type and thickness of wall panel served as a starting point in shaping the requirements. Resistance values were then set by assessing the impact of increased thermal resistance on annual space-heating energy, calculated for 486 locations in Russia and normalized by floor area and Russian heating degree days. Calculations were made for eight types of multi-storied and the same number of one- and two-storied buildings, with each type corresponding to a different design of the building envelope. Heating energy consumption, plotted as a histogram, revealed a distribution of values that was characterized by a single number, the consumption exceeded by only 5% of the cases. Then two reduction levels for heating-energy consumption were set, each associated with thermal resistance requirements for envelope elements.

The first stage of the new standard, now in effect, and a second stage are described in Tables 8 and 9 and correspond to the following reductions in specific energy consumption:

20% for newly constructed and 40% for renovated buildings at the first stage;

40% for all kinds of buildings at the second stage.

Note that the standard provisions listed in Tables 8 and 9 are unified for envelopes of different kind, with no differentiation by thermal mass of the envelope material. Single-layered envelopes and insulated brick walls are effectively excluded, because they are subject to the same thermal resistance requirements as three-layer panels and cannot be economically built in sufficient thickness to meet these requirements. The new code has forced a reorganization of the building industry by effectively requiring the production of multi-layered envelope panels, now in use in 70% of new construction. Both the thermal resistance values and their impact on industry are comparable to that set by the Moscow municipal code.

The standard accounts for thermal comfort by considering temperature conditions both in the central portion of a room and at its margins. Thermal comfort is influenced by the indoor air temperature and the radiant temperature, with the latter determined by the temperatures of all surfaces in a room, weighted by view factors at a particular point in the room. It was found that temperature differentials $\Delta T_{in} = T_{in} - T_w$ between the indoor air temperature and the envelope's inner surface temperature, approved in SNiP II-3-79** as guaranteeing an absence of condensation, do not ensure comfortable conditions.

Two prototype multi-storied residential buildings were used to assess thermal comfort: one building used steel convector heating units and had exterior walls made of three-layer reinforced concrete panels with expanded polystyrene as the insulating material and with steel rods connecting the inner and outer concrete layers; the second building had exterior walls made of single-layer expanded-clay concrete panels with cast-iron radiators. The thermal comfort level was determined by calculations that accounted for the surface temperatures of the radiators and convectors. SNiP II-3-79**, following earlier versions of the code, specified a temperature difference of 8°C between indoor air and the inner surface of exterior walls, effectively reduced to 6°C by application of the construction-quality coefficient σ shown in Eq. (1a). Reduced temperature differences of 4°C for ceilings below roofs and 2°C for floors at ground level were also specified.

Table 8
Thermal resistances for Stage I of amended SNiP II-3-79** (1995), effective from 1 Sept. 1995

Building type	No. of Russian degree days in the heating season (°C d)	Standard areal thermal resistances, R_o^{tp}, of envelopes (m² °C/W)				
		Walls	Roofing constructions (attics included)	Floors above building arches and over cold crawl space and basements ventilated with outdoor air	Windows and balcony doors	Skylights
Residential buildings, medical care institutions, nurseries, schools, and boarding houses	2000	1.2	1.8	1.6	0.35	0.25
	4000	1.6	2.5	2.2	0.40	0.30
	6000	2.0	3.2	2.8	0.45	0.35
	8000	2.4	3.9	3.4	0.50	0.40
	10000	2.8	4.6	4.0	0.55	0.45
	12000	3.2	5.3	4.6	0.60	0.50
Public buildings except for the above, administrative and municipal service buildings excluding premises with humid/wet air conditions	2000	1.0	1.6	1.4	0.33	0.23
	4000	1.4	2.3	2.0	0.38	0.28
	6000	1.8	3.0	2.6	0.43	0.33
	8000	2.2	3.7	3.2	0.48	0.38
	10000	2.6	4.4	3.8	0.53	0.43
	12000	3.0	5.1	4.4	0.58	0.48
Industrial buildings with dry/normal air conditions	2000	0.8	1.4	1.2	0.21	0.19
	4000	1.1	1.8	1.5	0.24	0.22
	6000	1.4	2.2	1.8	0.27	0.25
	8000	1.7	2.6	2.1	0.30	0.28
	10000	2.0	3.0	2.4	0.33	0.31
	12000	2.3	3.6	2.7	0.36	0.34

Table 9
Thermal resistances for Stage II of amended SNiP II-3-79** (1995), to be effective from 1 Jan. 2000 for new construction and 1 Jan. 1996 for renovation

Building type	No. of Russians degree days in the heating season (°C d)	Standard areal thermal resistances, R_o^{tp}, of envelopes (m² °C/W)				
		Walls	Roofing constructions (attics included)	Floors above building arches and over cold crawl space and basements ventilated with outdoor air	Windows and balcony doors	Skylights
Residential buildings, medical care institutions, nurseries, schools, and boarding houses	2000	2.1	3.2	2.8	[illegible]	0.25
	4000	2.8	4.2	3.7	[illegible]	0.30
	6000	3.5	5.2	4.6	[illegible]	0.35
	8000	4.2	6.2	5.5	[illegible]	0.40
	10000	4.9	7.2	6.4	[illegible]	0.45
	12000	5.6	8.2	7.3	[illegible]	0.50
Public buildings except for the above, administrative and municipal service buildings excluding premises with humid/wet air conditions	2000	1.6	2.4	2.0	[illegible]	0.23
	4000	2.4	3.2	2.7	[illegible]	0.28
	6000	3.0	4.0	3.4	[illegible]	0.33
	8000	3.6	4.8	4.1	[illegible]	0.38
	10000	4.2	5.6	4.8	[illegible]	0.43
	12000	4.8	6.4	5.5	[illegible]	0.48
Industrial buildings with dry/normal air conditions	2000	1.4	2.0	1.4	[illegible]	0.19
	4000	1.8	2.5	1.8	[illegible]	0.22
	6000	2.2	3.0	2.2	[illegible]	0.25
	8000	2.6	3.5	2.6	[illegible]	0.28
	10000	3.0	4.0	3.0	[illegible]	0.31
	12000	3.4	4.5	3.4	[illegible]	0.34

Calculations made for corner rooms of the top story of the two residential buildings showed that with the indoor air temperature equal to 18°C the required comfort level was not attained and with $T = 20$°C the comfort requirement was met only when the reduced ΔT_{in} was lowered to 4°C for exterior walls and to 3°C for ceilings. Table 10 presents these and other values of the temperature differential ΔT_{in}, that provide comfortable conditions in the central working space of rooms in various kinds of buildings. These temperature differentials, inserted in Eq. (1a), in turn lead to a minimum thermal resistance for envelope elements needed for thermal comfort.

Comfortable conditions in the center of room are insufficient to assure adequate comfort level in the entire working space, extending as far as 0.5 m from inner wall surfaces. Therefore, the radiant temperature asymmetry has been also calculated for these rooms, based on the requirements of SNiP II-3-79**. In all cases this temperature asymmetry varies under design conditions from 9.5 to 11.5°C at the level of a

Table 10
Maximum allowable differences in temperature between room air and wall surfaces, reduced by construction-quality coefficient, as specified by amendments to SNiP II-3-79** (1995)

Building type	Reduced temperature differential, ΔT_{in} (°C) for		
	Exterior walls	Roofing constructions (attics included)	Floors above building arches, over basements and crawl space
1. Residential buildings, medical care institutions, nurseries, schools, boarding houses	4.0	3.0	2.0
2. Public buildings except for those under item 1, administrative and municipal service buildings with humid/wet air conditions	4.5	4.0	2.5
3. Industrial buildings with dry/normal air conditions	$T_{in} - T_w$, but not more than 7	$0.8(T_{in} - T_w)$ but not more than 6	2.5 [a]
4. Industrial and other premises with humid/wet air conditions	$T_{in} - T_w$	$0.8(T_{in} - T_w)$	2.5 [a]

[a] Applies only for permanent working spaces.

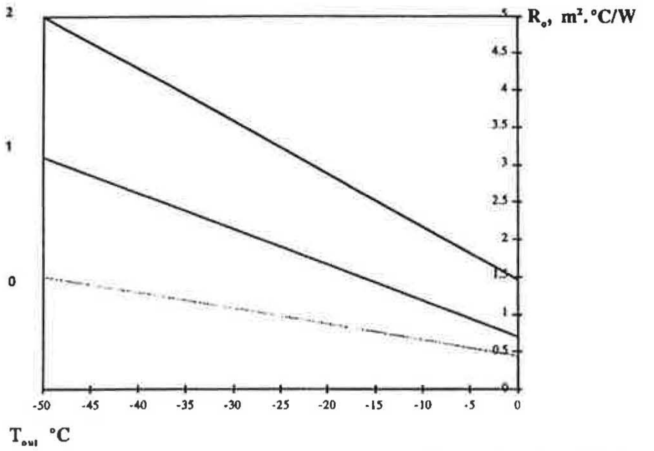

Fig. 1. Required thermal resistance of exterior walls as a function of design temperature. 2: SNIPII-3-79* (1995 edn.) Stage II; 1: SNIPII-3-79* (1995 edn.) Stage I; 0: SNIPII-3-79** (1987–1994).

human head 0.5 m from an exterior wall with a window. Substituting triple for double glazing can reduce the temperature asymmetry by 3°C, but the comfort requirement will still not be met. The new ΔT_{in} proposals, which effectively require enhanced thermal insulation, satisfy this comfort requirement.

Fig. 1 compares thermal resistance values for envelope elements as provided by SNiP II-3-79** and those introduced at the two stages of SNiP II-3-79* (1995 edition). The thermal performance level shown for SNiP II-3-79** is that for single-layer envelopes, which matches codes used in Scandinavian countries before 1980. The first-stage thermal performance approximates standard provisions already available for walls made with three-layer panels, and the second-stage correlates with current provisions in such countries as Sweden and Canada.

The reorganization of the building industry required by the code amendments will have a substantial impact on materials and costs of wall elements, as estimated for annual housing construction in Moscow of 3 million m^2:

for brick walls, 2.9 billion bricks and 1.6 million m^3 or mortar will be replaced by 0.48 million m^3 of polystyrene foam insulation or 0.64 million m^3 of fiberglass;

for lightweight concrete panels, 0.53 million m^3 of polystyrene foam insulation or 0.71 million m^3 of fiberglass will be required instead of 3.4 million m^3 of expanded-clay concrete.

Using Russian prices for materials as of Jan. 1995, converted to US dollars, the change in envelope construction will reduce the cost per m^2 of brick walls from \$68 to \$47 and reduce the cost of lightweight concrete walls from \$25 to \$18.

For windows, SNiP II-3-79* (1995 edition) limits the fenestration area to 18% of the building facade area at design outdoor temperatures higher than −31°C, if the overall thermal resistance of windows is less than or equal to 0.56 m^2 °C/W, and reduces the window area to 15% at lower design temperatures. This requirement matches the Moscow code. The maximum air permeability at a pressure differential of 10 Pa is set at 8 kg/m^2 h at design outdoor temperatures higher than −31°C and at 6 kg/m^2 h for lower design temperatures, in contrast with 10 kg/m^2 h in SNiP II-3-79**. Triple-pane windows are recommended for regions with more than 6000 Russian degree days (base 18°C). Low-emissivity coatings and heavy-gas fill between panes are also recommended.

3.3. Future directions for national codes

National codes, including SNiP II-3-79* (1995 edition), have been of a prescriptive nature, giving both code requirements and calculation methods for individual building components. Prescriptive codes limit the implementation of innovative technologies, materials and technical designs into building practice. For example, they do not permit trade-offs between higher-performance glass and the thermal resistance of walls, nor account for passive-solar designs.

To remove the limitations inherent in prescriptive codes, Gosstroi issued SNiP-10-01-94 'a system of stipulating documents in construction', which states that new regulations should give the user 'functional' or 'performance' provisions, setting the goals but not the ways of achieving them. The Russian authors of this paper have proposed a new concept of setting standards and regulations for a building's thermal performance [18] that is based on regarding a building as a single energy system. In addition, the new concept offers an opportunity to tighten code provisions with regard to thermal performance by accounting for regional or national economic conditions.

The concept is based on the following three principles [18]:

(i) setting code provisions to achieve three key goals — thermal comfort, in both the central part of a room and at the margins; no condensation on inner wall and ceiling surfaces; a certain level of heat consumption for a building;

(ii) giving the designer a free hand achieving the required thermal performance, based on measurable parameters instead of a meticulous observance of certain rules;

(iii) providing an opportunity to control and certify actual energy parameters of the building, to check that a building as constructed and operated meets the design goals.

The key point concerns an upper limit on building heating-energy consumption, replacing the component-level thermal resistance limits that formed the basis of previous national codes as well as the Moscow code. The limit was determined from a distribution of calculated values for annual heating-energy consumption. This type of distribution was used as an aid in setting prescriptive requirements for thermal resistance of envelope elements in SNiP II-3-79* (1995 edition). Now, in the proposed code, annual-energy consumption is no longer 'behind the veil' but becomes the central concept.

Heating-energy calculations were made first for a single building in six Russian climatic zones (Table 11) and then for ten apartment buildings most typical of Russia (5-, 9- and 17-stories) located in 302 Russian climatic zones. Calcula-

Table 11
Energy consumption during heating season for a typical 9-story multifamily building

Towns	Specific heat consumption	
	kWh/(m² year)	Wh/(m² °C day)
Verhoynsk	467	38
Yakutsk	393	37
Omsk	256	39
Samara	195	39
Astrahan	139	41
Krasnodar	100	40

SNiP II-3-79* (1995 edition), stage I implementation.

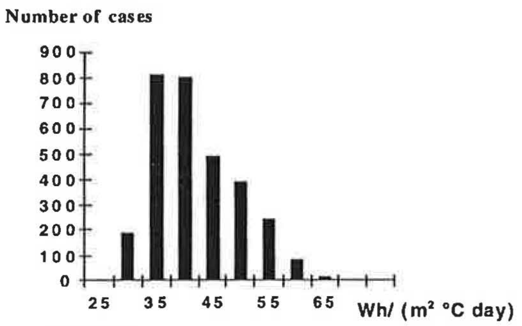

Fig. 2. Histogram of specific energy consumption.

Table 12
Maximum level for specific energy consumption of building q_o

No. of floors	1–2	3–4	5–9	10 and more
Specific energy consumption, q_o Wh/(m² °C days)	85	70	55	50

tions were based on component thermal performance required by Stage I of SNiP II-3-79* (1995 edition) (Table 11). The calculations accounted for building dimensions; rated heat transfer and air permeability resistances of walls, floors, ceilings and windows; the average indoor air temperature; duration of the heating period; and the average wind velocity and solar radiation over this period, all depending on the construction area. The histogram (Fig. 2) presents the distribution of the 3020 values of normalized annual energy consumption. Similar histograms, each confined to a subset of buildings of the same height, were then used to identify the annual energy consumption below which can be found 95% of the population in each subset. These values serve as mandated maximum energy consumptions for the proposed code, as listed in Table 12.

4. Conclusions

This paper has described the evolution of Russian codes — both norms and calculation procedures — governing space-heating energy use in buildings. The codes have been based on winter design conditions and, most recently, annual heating energy; summer design conditions, ignored in this paper, influenced building properties in some regions if July temperatures were high enough. The codes have varied over time since the beginning of the post-World War II Soviet housing drive. Diversity in Russian building codes is important, as it increases the diversity in thermal characteristics of the MFB stock. A few contrasts are significant: some codes were complex, varying substantially to suit local conditions, others were simple and were uniformly applied everywhere; early codes placed a much greater computational burden on building designers and builders, later codes used tabulated values to define key parameters; generally earlier codes were less strict than later codes; finally, in some cases designers were permitted to choose from among more than one set of codes addressing the same item. Throughout, the emphasis in the design of building thermal systems was on meeting the design condition-providing satisfactory performance during the worst weather. Comparatively little attention was paid, at least until 1979, to average operating conditions.

Recent code changes have been dramatic. The first-of-its-kind municipal code adopted in Moscow substantially stiffens component thermal resistance requirements; in the second stage of the code, wall thermal resistance requirements will be slightly higher than current US standards for a comparable climate. The Moscow code also accounts for the building as a whole for the first time in Russia by prescribing maximum values for overall thermal resistance and air permeability of the building envelope. Required values are calculated from assumed building geometries and glass areas and code-mandated thermal resistances and air permeabilities for envelope components. The 1995 national code mandates component thermal resistance values that are more stringent than previous national codes and also boost thermal comfort by increasing minimum indoor surface temperatures. Finally, a new direction for the national code proposed by the Russian authors of this paper would replace prescriptive requirements for thermal resistance and air permeability of envelope elements with a performance requirement that would limit normalized annual heating energy.

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