POTENTIAL SPACE-HEATING ENERGY EFFICIENCY IMPROVEMENTS IN DISTRICT-HEATED RUSSIAN APARTMENT BUILDINGS

by

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ABSTRACT

Moscow's stock of apartment buildings was analyzed as a case study for assessing potential energy savings from space-heating energy efficiency improvements in district-heated Russian apartment buildings. The analysis focused on three key areas: identifying end-use energy savings in a single building, identifying the corresponding primary fuel savings, and extrapolating savings from a single building to other buildings. End-use savings were determined by analyzing the results of a Russian field experiment, and by surveying the characteristics of apartment building thermal envelopes. Primary savings and extrapolated savings were determined by examining the characteristics of heating equipment in three domains: apartment buildings, the district-heating distribution system, and central heat stations.

Space-heating energy efficiency in Moscow's buildings was found to be poor compared to apartment buildings in the US. Improving the control of heat delivered to Russian apartment buildings offers the largest and most easily achieved energy savings—an estimated 12-14% of seasonal end-use space-heating energy could be saved in Moscow's apartment buildings by improving heating control systems. Control improvements are also required in order to save any energy through thermal envelope improvements.

Diversity in Russian apartment buildings and district heating system designs was found to be substantial. As a result, many district heating systems will be unable to save fuel in response to lower space-heating energy requirements in buildings because of impediments in either the distribution network or the central heat stations. Further, extrapolations of end-use savings from a single building to other buildings should be limited to a narrow group of similar buildings in a single city, and extrapolations of primary fuel savings from a single building to other buildings should be limited to buildings connected to similar kinds of district heating systems.

The systemic view—examining system characteristics from the points of energy service back to the points of primary fuel consumption—is critical in assessing energy savings in Russian apartment buildings. Future efforts at designing conservation programs in the Russian urban housing sector must also adopt a systemic view in order to be most effective. Since the best energy-saving strategies are largely defined by the quality of estimates of energy savings, retrofit cost, and retrofit feasibility, the results of this analysis could aid in the design of such strategies.

Thesis Advisor: Leslie K. Norford, Associate Professor

To the truth-seekers of the world, who may, from time to time, lose themselves in a jungle of misleading perceptions, confused motivations, and conflicting values, this work is dedicated. Don't give up!

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Last, but not least, I extend my heartfelt thanks to Mom for making it all possible. Mom, without your support near the end I would not have made it!

Mike Opitz

> “One may bask at the warm fire of faith or choose to live in the bleak uncertainty of reason—but one cannot have both.”
>
> Robert A. Heinlein
> Friday

CHAPTER I: INTRODUCTION

The past several decades have seen the lives of people the world over become linked in exceedingly complex, often poorly understood ways. The period has been characterized by accelerating technological change, rapid population growth, and large-scale industrialization. Nations once buffered from each other by oceans, mountains, and other natural obstacles are becoming an interconnected global civilization made possible by instantaneous communication, nearly immediate transportation, and an increasingly integrated world trade system and capital market. Yet greater interdependence breeds greater sensitivity to events in remote areas. The world's major economies are presently so closely tied that individual nations' domestic policies often have significant consequences for other countries around the world. These developments have changed the very context within which relations among nations occur.

The requirements of the recent period of resource-intensive industrialization have created a series of global issues concerning resource interdependence. Since reserves of critical economic resources—energy and minerals—are unequally distributed among the nations of the world, countries lacking such resources face problems of national security when they seek to maintain their supplies. The unequal distribution makes these resources potential weapons in confrontations between nations who have them and nations who need them. The dynamic characteristics of the global economic system only complicate matters, as the system must continually adjust to changing circumstances. Two oil crises, a raw materials and food crisis, and rampant global inflation and debt are but a few recent examples of sudden, serious shocks to the world economy.

Natural Resources, Energy, and Externalities

The global ecosystem provides many conventional resources that support human economic activity. The most important examples are air, water, food, minerals, and energy. Some resources are renewable; others, e.g. fossil fuels, are non-renewable and will eventually be depleted. Partially renewable resources, such as the waste disposal capability of the land, air, and water, are often neglected in assessments of resource adequacy [Pirages]. If the capacities of partially renewable resources are not exceeded, they can continue to serve human needs indefinitely; if their capacities are exceeded, however, they become overloaded and unable to function as effectively. Opinions vary with regard to the capacities of partially renewable resources, when depletion of non-renewables will occur, and the severity of the consequences of depletion [Meadows; Simon]. One thing is certain, however: continued resource use from a finite supply guarantees that depletion will eventually occur. The longer transitions to alternative sources are delayed, the more difficult these transitions will be.

Energy is an especially critical resource. Energy is closely linked to all economic activity, but has been used mainly as a substitute for labor in constructing, installing, and operating systems and devices.

Derived mostly from non-renewable fossil fuels, energy powered the industrialization drives of Western Europe, the United States, and the former Soviet Union. Today the health of these economies is still founded on energy. Further, developing nations have found economic transition difficult without securing fossil fuel supplies, as no readily available, inexpensive substitutes yet exist on a large scale. Stable energy supplies are therefore essential for global economic health.

Rapidly changing energy prices disrupt economic activity in market economies as price shocks are passed through to consumer goods. Energy producers and consumers both prefer price stability because it allows them to plan more confidently for the future. Thus, stable world energy prices are also necessary for economic prosperity. Yet because of growing global interdependence the domestic and foreign policies of various nations have an enormous effect on energy prices worldwide. Oil prices have been particularly sensitive, as oil was a critical element in both World Wars, in Cold War anti-expansion policies of the US, and in political turmoil in the Middle East [Yergin].

Modern society depends on energy. But many of the indirect costs of providing energy from fossil fuels are external—energy costs society billions of dollars more than consumers pay directly for oil, coal, gas, or electricity—leading to artificially low energy prices and unnecessarily high energy consumption. External costs include security subsidies, tax credits for energy production, various kinds of environmental degradation, and higher health care expenditures. Estimates of the total external cost of energy provision for the US alone range between $100 billion and $300 billion *per year* [Hubbard]. External energy costs place an enormous, though obscured, burden on the economy, and distort the choices of consumers, producers, and policymakers by providing misleading information on the societal costs of energy use.

Internalizing external costs, while still providing the energy required to fuel a growing global economy, will become a formidable challenge in coming decades as population and development pressures from the less-developed countries are felt in the industrial world. Unfortunately, calculating the actual cost of energy is a complex affair. Determinations of the nature and amount of energy's hidden costs depend as much on social values as they do on analytical solutions to well-defined problems. Nevertheless, forcing consumer energy prices to better reflect the total societal costs of energy provision would provide strong incentives for a transition to more sustainable energy use. Until this is done on a large scale, artificially high energy consumption will continue unnecessarily to aggravate many global problems.

Energy Efficiency

Energy efficiency improvements offer a medium-term solution to the problem of excessive global energy use. By reducing the energy needed to perform economic tasks, higher energy efficiency buys more time to develop alternative energy sources. Implementing energy efficiency improvements requires a radical rethinking of the management of energy supply and demand, however. Traditional remedies, especially in the USSR, have focused on the supply side of the problem by increasing energy production. The alternative, reducing energy demand, has enjoyed great success in many Western economies since the mid-1970s. Energy demand can be curtailed in three basic ways: by reducing the overall production of goods and services, by shifting the structure of production to less energy-intensive products, or by reducing the amount of energy required to produce at given levels. The third approach, increasing energy efficiency, is generally preferable because it allows the benefits of reduced energy use to be obtained without penalizing standard of living.

Energy is not an end in itself; it is a means of accomplishing other ends. Its useful characteristic is its potential to perform economic tasks. Concern should thus lie specifically with the provision of goods and services, rather than in the provision of energy per se [Lovins]. Energy varies in its quality, or ability to perform useful tasks; in order to achieve maximum energy efficiency, the quality of the energy source should be matched with the minimum quality needed for each kind of end use. Since industrialized economies generally use far more energy than the minimum amount required to provide a given standard of living, it makes sense to ask how much energy is actually *needed* by an economy.

One way to analyze the question of minimum energy requirements is in terms of the *technical* energy requirement. This is the minimum amount of energy needed, assuming the most energy-efficient available technologies are used in all economic sectors. A more common approach in the West examines the extent of profitable efficiency improvements, or the energy required if the most *cost-effective* energy technologies are in place. This sort of analysis weighs the benefits of reduced energy use over the lifetime of new energy-efficient equipment against its higher capital cost. Generally, in a given economy many cost-effective energy-efficiency improvements are possible. Total energy consumption—all energy needed to produce, deliver, install, and operate the equipment and energy used for providing energy services—is the relevant quantity in analyses of minimum energy requirements. Alternatives therefore deserve careful scrutiny: even if more energy-efficient equipment is available, its total energy requirement may actually be higher than equipment with higher operating energy efficiency.

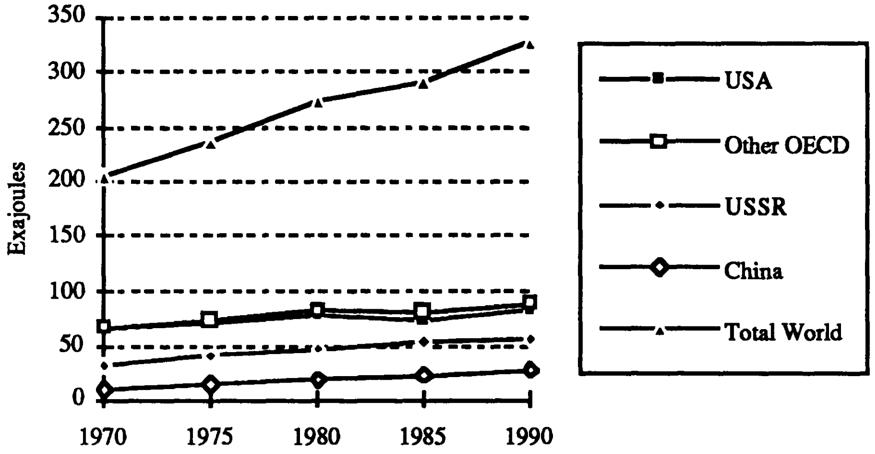
Energy inefficiency arises out of ignorance, apathy, or faulty economics. It has been well established that a number of market failures inhibit efficiency improvements. The most important ones stem from a lack of information about the consequences of energy choices, and different time horizons among decision-makers—the average consumer's payback time is much less than that of a company executive or government policy-maker. The US has demonstrated that under the proper circumstances large scale energy efficiency improvements are possible, however: although US real GNP increased by 35% between 1973 and 1986, total primary energy consumption at the two times was roughly equal [DOE a]. Part of this effect was due to a shift to less energy-intensive goods, but part of it arose from energy efficiency improvements.

Higher energy efficiency offers many benefits to societies, encompassing many time horizons. In the short term it strengthens the security of energy-importing nations by stretching supplies of nonrenewable resources, and by cushioning economies against future fuel shortages or price hikes. In the environmental domain higher energy efficiency reduces damages due to acid deposition, airborne particulates, and chemical contamination of groundwater. These problems often arise in regions surrounding areas of concentrated fossil fuel extraction, transportation, conversion, and end use. In the medium term higher energy efficiency smooths economic adjustments driven by unstable energy supplies and prices, and provides more time to develop alternative energy sources. Finally, in the long run energy efficiency hedges against the risks of global climate change and rapid resource depletion. Supply-side remedies cannot provide benefits in all these areas.

Energy in the Commonwealth of Independent States

The former Soviet Union was a prominent player in world affairs. The country was involved in several major political and economic conflicts, and for four decades was viewed by many as the single largest threat to global security. The threat was backed up by a highly industrial, rapidly expanding economy that consumed enormous amounts of energy: for over 20 years the Soviet Union was the second largest single consumer of energy in the world, after the United States (Figure 1.1). It is widely believed, both in the successor to the former USSR—the Commonwealth of Independent States (CIS)—and in the West, that Soviet economic, social, and energy pricing policies led to an energy-inefficient economy [Hewett; Gustafson]. Aggregate efficiency indicators in many economic sectors in the CIS are relatively low compared to those for developed Western economies [Cooper & Schipper 1991]. An examination of global energy overconsumption motivated by excessive external costs should therefore include the CIS.

Figure 1.1: World Primary Energy Consumption[1]
[BP; UFFA]



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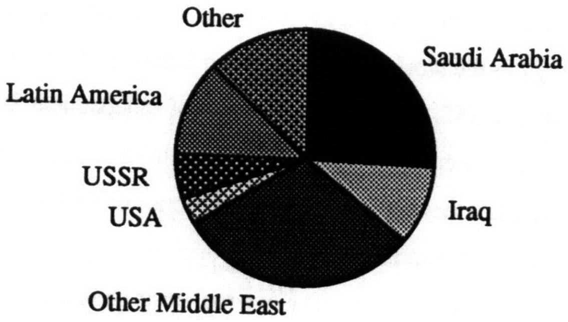
[1] several different energy units will be used in this report. 1 exajoule (EJ) ≅ 0.95 quads, where 1 quad = 10^{15} BTU. The Russians use "tonnes of standard fuel", or TSF (also abbreviated as tce, tonnes of coal equivalent, in the West), where 1 TSF = 29.3 Gigajoules (GJ)

For decades the USSR's reserves of oil, natural gas, and coal were among the world's largest—energy was so abundant that Soviet planners were able to meet rapidly expanding domestic needs, enabling them to build up one of the world's largest economies. Figure 1.2 displays the USSR's share of known world energy reserves at the end of 1991.

Figure 1.2: Distribution of Proven World Energy Reserves, 1991
[BP]

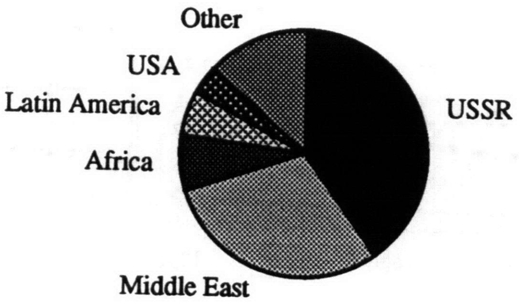
a) Oil

(total = 10^{12} barrels)



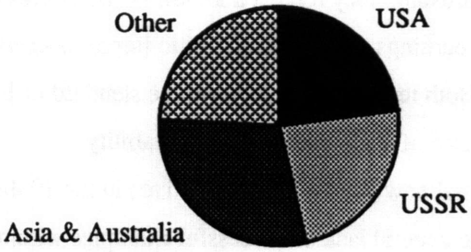
b) Natural Gas

(total = $124 * 10^{12}$ m^3)



c) Coal

(total = 10^{12} tonnes)



Energy has been a key component in Soviet economic, political, and military power during the 20th century. For nearly two decades the USSR has been the world's number one oil producer; for the past 10 years it has also been the largest producer of natural gas [UFFA]. Such high energy production allowed the USSR to export large amounts of energy to Eastern Europe, Cuba, and the West. In exchange the Soviet Union received hard currency, used to purchase food, capital goods, and other products. From its client states, the USSR received the less tangible but equally important benefits of economic and political cooperation.

The Soviet economic system was designed to combine cheap natural resources with cheap labor to produce high national income growth rates. Resource abundance, combined with a centrally planned economy, encouraged a supply-side approach to domestic energy policy that has prevailed for the past 50 years. Put simply, the Soviets set energy production targets to meet expected demand. They followed this policy with little change regardless of events in the rest of the world. Events at home began to change the Soviets' energy situation in the 1980s, however, as their cheapest, most accessible reserves became depleted. Development of new energy sources became much more costly[2].

The supply-side approach has as least one important advantage: decision-makers in the CIS know how to implement it. Yet the republics of the CIS are now experiencing the legacy of past supply-side policies: overly energy-intensive economies, capital drains to the energy sector in order to maintain high energy production, growing scarcity of accessible energy resources, and environmental problems associated with energy use. Further, recent political and economic developments suggest that the major fossil fuel industries in the CIS are in deep crisis and near collapse. Thus, even if supply-side solutions were desired, many CIS experts and Western analysts doubt whether they could succeed [McCann; Gustafson].

Despite recent difficulties bringing new energy supplies on line, energy consumption in the USSR has remained high since 1970, accounting for a significant share of worldwide consumption (Fig. 1.1). Continued consumption growth caused an imbalance between energy supply and demand in the past decade

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[2] because new supplies were located in more remote locations, and because the Soviet energy production industry was extremely inefficient by Western standards

that Soviet planners found increasingly difficult to rectify. As a result, energy shortages in regional and local economies became commonplace [Hewett; Gustafson]. Recent political and economic turmoil has worsened the imbalances. Because of the strong links between energy and the economy of the CIS, energy shortages cause major economic hardship: they force a trade-off between lower export earnings and lower economic growth. Smaller export earnings reduce the ability to import needed goods[3]; lower growth weakens the domestic economy. Both tend to lower the average standard of living for the population. Such economic hardship is often the source of strife and political instability.

Soviet leaders began several new conservation initiatives in the 1980s intended to ease energy imbalances in the economy, but the general lack of successful examples within the USSR made relying on such programs quite risky. Conservation programs represented unfamiliar territory to the Soviets: with a few exceptions, the available evidence indicates that efficient use of resources was simply unimportant to most Soviet administrators, bureaucrats, and firm managers [Gregory & Stuart; Campbell 1983]. As a result, the programs were generally less successful than energy-saving programs in the West.

The ramifications of energy policy in the CIS will be felt beyond the country's borders. The republics are extremely economically interdependent[4]; good relations will be necessary for their future survival. Energy problems will likely have a substantial impact on these relations, and on economic reforms within the republics. Because of concern over the region's political stability, and because of the sheer size of the CIS's energy reserves, energy production capacity, and economic activity, energy-related developments in the CIS will continue to garner the attention of leaders around the world. Two separate groups of political leaders thus have good, though different, reasons to address the same problem: policy-makers in the CIS wish to reduce domestic energy demand without sacrificing standard of living, and Western policy-makers wish to politically stabilize the CIS, ensure intelligent management of fossil fuel resources, and reduce the environmental impacts of fossil fuel use. These issues present strong motivations to cooperatively assess potential energy efficiency improvements in the former Soviet Union.

Structure of the Energy Sector

Relatively little is known in the West about the structure and efficiency of energy use in the CIS economy. The breakdown according to sectoral end use is shown in Figure 1.3. The large share of the industrial sector and the small shares of the transportation and buildings sectors distinguish the CIS economy from developed Western economies. The buildings sector, representing only 22% of primary energy use in the CIS, typically constitutes 30-40% of demand in Western economies.

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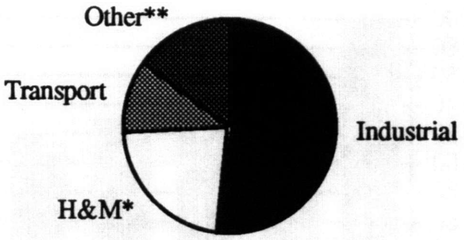
[3] an especially critical issue, given the economic chaos now being experienced in the former Soviet republics

[4] in ten of them, over 50% of the goods produced are sold to other republics, and frequently raw materials and the makers of finished products are located in different republics

Figure 1.3: Structure of Primary Energy Use in the CIS in 1985
[Tretyakova & Sagers]



* housing & municipal; includes all non-industrial buildings
** includes agriculture and construction

Within the housing and municipal (i.e., buildings) sector, Cooper and Schipper estimate that 15% of the energy is used in residential buildings, with the remaining 7% used in the municipal sector. The residential buildings sector is further broken down by end use: space heating, water heating, cooking, and other electricity. The best available estimates place the size of the residential space-heating sector at 11% of national primary energy consumption[5].

The available economic literature suggests that the Soviet economy has historically been input-oriented, increasing outputs by corresponding increases in factor inputs to production. This led to an industrial economy much less resource-efficient than developed Western economies [Gregory & Stuart; Hewett]. One recent study concluded that on average the CIS economy is also comparatively inefficient with regard to energy [Cooper & Schipper 1992]. The severity of energy inefficiency varies among economic sectors, however: some sectors are about as efficient as those of Western nations. International comparison suggests that the greatest energy inefficiencies in the CIS appear in the residential space-heating sector. The energy intensity (the inverse of efficiency) of this sector is shown in Figure 1.4 for several nations, normalized to the size of the housing stock and the average severity of the winter climate[6]. Since the residential space-heating sector may be one of the least efficient sectors in the CIS economy, it appears to be an important area needing further analysis.

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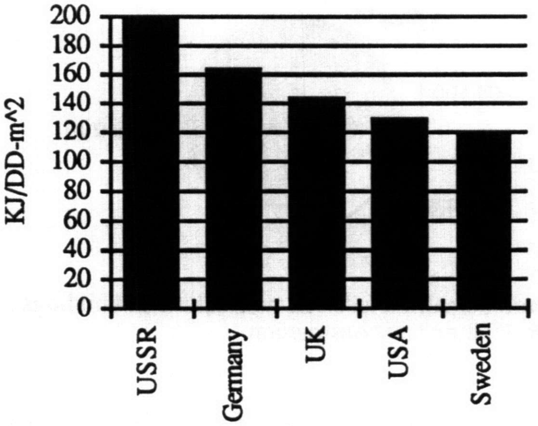
[5] this estimate is derived in Chapter 2

[6] energy intensity is measured in Figure 1.3 by the average amount of energy required to heat 1 m^2 of floor space in residential buildings, per heating degree-day. The authors made many assumptions with respect to floor areas, conversion efficiencies, and computation of degree-days in deriving this estimate, but stated that, if anything, they may have underestimated the energy intensity of the USSR.

Figure 1.4: Residential Space Heating Energy Intensity, 1985*
[Cooper & Schipper 1992]



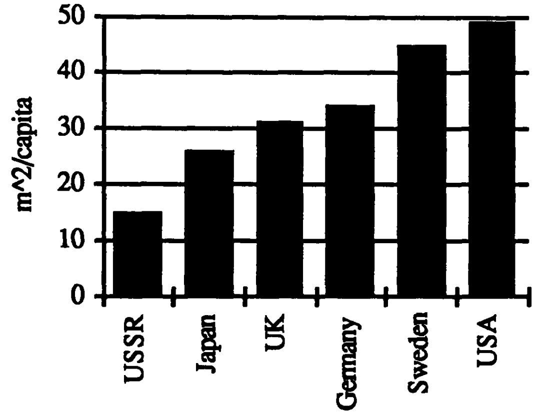
*average values, representing many kinds of housing

The Public Urban Housing Sector

In 1989 the population of the Soviet Union was 289 million. About 66% of the population lived in urban areas; of the urban population, over 40% lived in cities with populations exceeding 100,000. In 1989 about 50% (by floor area) of the national housing stock was state-owned housing in urban areas [UFFA]. Such housing is composed mainly of high-rise, multi-family dwellings with five or more stories, mass produced over the past 35 years using standardized designs. These apartment buildings are all quite similar in appearance. The uniformity suggests that potential energy savings, once identified in a few buildings, may apply to much of the national housing stock. The large portion of the CIS population housed by such structures adds to their importance—improving indoor thermal comfort and reducing energy use will benefit many persons.

Economic activity is low in the CIS residential buildings sector compared to Western nations. Figure 1.5 displays total living area per capita in several countries. Increasing energy efficiency in the CIS will reduce energy consumption in the housing sector, but these gains could be offset in the near future by rapidly expanding living space [Cooper & Schipper 1991]. A growing housing sector would represent an opportunity to put energy-efficient technologies in place, however, significantly boosting future energy efficiency.

Figure 1.5: Living Area per Capita, 1985*
[Cooper & Schipper 1992]



*average values, representing many kinds of housing

District Heating

Approximately 87% of public urban housing (by floor area) in the CIS is served by district heating systems—city-wide networks providing space heat and hot water from centralized sources[7]. The district heating sector accounts for about 10% of national primary energy consumption. Since about 40% of the energy supplied in district heating systems goes to residential buildings, the district-heated housing sector consumes about 4% of national primary energy. Because of the size of the CIS energy economy, this is a substantial amount of energy: 2.2 EJ in 1985 (2.1 quads, or 76 mn TSF).

District heating systems in the CIS have three main components: central heat stations, transmission/distribution networks, and end users. The central heat stations (either dedicated heating plants or combined heat & power plants) convert primary fuels into usable forms of heat. A network of pipes transports and distributes the thermal energy in the form of steam or hot water to end users in buildings, where it is used for space heating, hot tap water, or industrial processes.

District heating offers a number of benefits under the proper conditions: cheaper heat, improved energy efficiency (with all of its attendant benefits), and more operational flexibility. Cost and energy savings accrue from economies of scale in heat production equipment, and the ability to use inexpensive heat sources (e.g., from the burning of solid waste) [Diamant & Kut]. Most savings increase with the scale of the system; savings increase further if cogeneration of heat and electricity is used. Because of the widespread penetration of district heating in Western Europe, many nations there are now enjoying its benefits. The CIS probably also enjoys these benefits to some degree, but district heating systems in the CIS are plagued by inefficiencies in heat production, transport, distribution, and end use.

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[7] this estimate is derived in Chapter 3

Description of Thesis

This thesis will investigate three separate but closely related subjects: the size of potential end-use energy savings from space-heating energy efficiency improvements in Russian district-heated apartment buildings, the most promising specific areas for improvement, and the major impediments to accurately predicting and achieving primary fuel savings from these improvements. These three subjects center on a common theme, which forms the basic question that this work will attempt to answer:

Thesis Question: Do energy savings from space-heating energy efficiency improvements in district-heated Russian apartment buildings, once quantified for one building, apply to a significant portion of the housing stocks of Russia or the CIS?

The analysis will focus on investigating the diversity of Russian apartment buildings and district heating systems, and on determining the impact of constraints in district heating systems on achieving primary fuel savings. An apartment building in Moscow will be considered as a case study for assessing potential end-use energy savings[8].

There are many motivations for studying this topic. Most have already been discussed to some degree, but they will be repeated here:

- many persons in the CIS are currently interested in saving energy through efficiency improvements
- aggregate efficiency indicators, although highly uncertain, suggest that potential space-heating energy savings in the CIS's apartment buildings are enormous
- higher energy efficiency provides a specific set of important economic and environmental benefits
- heating energy efficiency is closely linked with thermal comfort in homes; efficiency improvements will thus benefit many persons
- apparent uniformity in the apartment building stock and in centralized district heating systems could greatly simplify heating energy analysis
- little is known about this subject in the West

Assessing current energy efficiency and potential efficiency improvements are interdisciplinary problems: technical, economic, and socio-political issues all intersected to determine the evolution of the housing stock and the district heating systems now in place in the CIS. A complete understanding of these systems requires knowledge of the objectives of their designers and builders, and the decision-making context within which system planners and managers operated. By conducting an analysis across these sets

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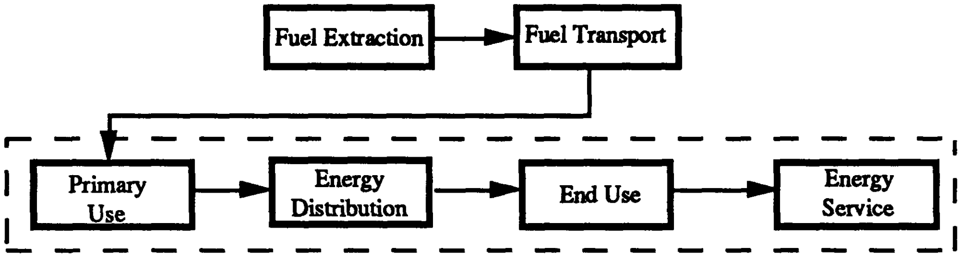
[8] studying a building in Moscow is both a blessing and a curse: although any new developments appearing in the USSR were likely to have showed up in Moscow first, many new developments in Moscow appeared nowhere else in the country.

of issues, this work will attempt to cross traditional disciplinary boundaries, illuminating not only the *extent* of present inefficiency, but also the *causes* of inefficiency.

The Analysis

A balanced view toward improving energy efficiency must address all points in the system providing the energy service, from fuel extraction all the way to the actual energy service. The objective of this study is to gain an understanding of part of this system—the portion enclosed within the dashed box in Fig. 1.6—ranging from points of primary fuel consumption (central heat stations) to the points where the energy service is provided (rooms in apartment buildings). Here, the energy service is a comfortable indoor air temperature in the buildings. The first set of questions must therefore center on whether this service has been satisfactorily provided. Namely, have the proper temperatures been maintained consistently? If not, the causes must be identified, as this will likely illuminate potential causes of energy inefficiency.

Figure 1.6: Conceptualization of the District Heating Energy Provision System



End-use energy requirements are quantified by asking how much energy is needed to provide the desired indoor air temperature. Such an analysis introduces many complications, as actual conditions can vary significantly from design conditions. For example, the quality of construction may be poor, heating equipment controls may malfunction, and building occupants may behave in unexpected ways. Design conditions themselves often vary as well: different buildings have different thermal characteristics, depending on the type of construction, and buildings in different locations face different climates. Furthermore, end-use energy requirements vary over time as climatic conditions change. Comparing design energy requirements to actual energy provided under real conditions yields an indication of the relative end-use energy efficiency of actual systems.

Although an analysis of end-use energy requirements is necessary to identify potential energy savings, ultimately savings at the points of primary fuel consumption are most important. In district heating systems primary fuel is consumed at central heat stations. The analysis must therefore continue back along the path of energy delivery to include the distribution system and the energy production system. The same sorts of questions must be asked: how much thermal energy is needed under various conditions in order to satisfy the end-use requirements of the apartment buildings? How effectively does the system provide this energy?

The technical analysis described above will provide estimates of potential energy savings in Russian apartment buildings. It is equally important to determine the causes of inefficiency, and to determine whether and to what degree energy savings are achievable under real-world conditions. In other words, the *impediments* to energy efficiency must also be closely examined. Technical impediments include heating system characteristics causing inefficient energy use, and the uncertainty of extrapolating energy savings from a single apartment building to a larger group of buildings. Economic impediments take two main forms: a lack of efficient consumer behavior, either because consumers have no choices or because they lack incentives to behave efficiently, and institutional barriers either preventing the production of energy-efficient housing and district heating systems, or preventing end-use energy savings from being realized as primary fuel savings.

Methods of Analysis

The first task of the technical analysis is to identify the size and structure of the district-heated apartment building stocks of Moscow, Russia, and the CIS. Since the chief technical impediment to assessing current energy efficiency and to predicting potential end-use efficiency improvements arises from diversity in building envelope characteristics and building heating systems, the first portion of the analysis will focus on the existing diversity in these systems. Building codes will be discussed extensively, in order to understand whether designers planned heating requirements accurately, and to identify the relative importance of each portion of building envelopes in determining heat losses. When possible, the translation of designs into actual buildings will be addressed, suggesting whether proper indoor temperatures are maintained and whether actual heat losses exceed design losses.

The characteristics of district heating systems determine whether the proper amount of heat is actually delivered to all apartment buildings under all conditions, and whether primary fuel savings are realized in response to upgrades in building systems. Diversity in district heating system designs complicates predicting primary fuel savings. This study will investigate the differences in the design and operation of Russian district heating systems, including the measurement, monitoring, and control of heat delivery in room heating elements, building connections to the district heating system, the district heating distribution system, and central heating stations.

The end-use energy analysis will be conducted by comparing calculated energy requirements with experimentally measured heat delivered in an apartment building in Moscow. This will provide an estimate of actual space-heating energy efficiency in one building, and will permit the estimation of potential end-use energy savings in the experimental building and in other similar buildings. Potential end-use and primary energy savings will be extrapolated to other buildings to the degree such extrapolations are warranted.

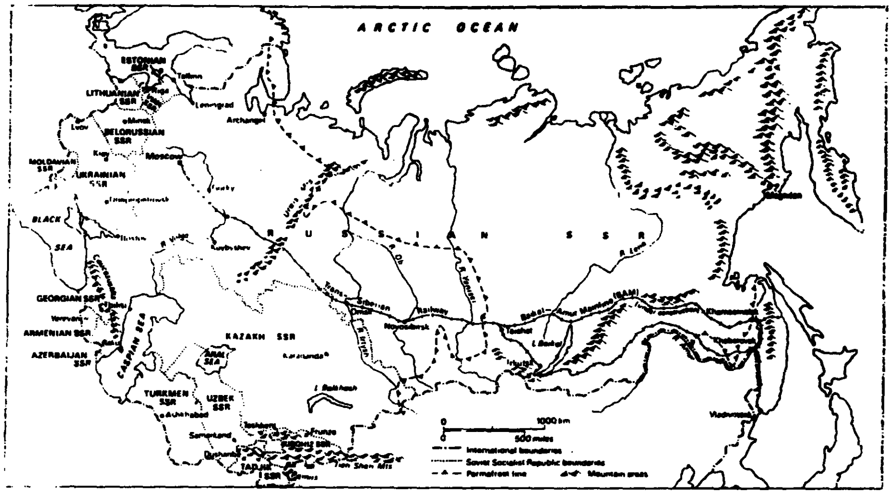
The economic and institutional analyses will focus on the ownership, control, and administration of housing, past Soviet energy pricing policies, the operation of the district heating system, and the political and economic choices and constraints that drove the development of apartment building designs and building codes. Future-oriented analyses are presently meaningless because of the highly variable, rapidly changing, sometimes inconsistent economic and institutional settings within the former Soviet republics.

This report is organized into six chapters. Chapter 2 describes Soviet housing and energy policy since World War II. Chapter 3 discusses the characteristics of Russian apartment building envelopes and heating systems. Chapter 4 addresses Russian district heating systems, focusing on the design and operation of central heating plants and the heat distribution system. Chapter 5 describes and analyzes the results of a Russian field experiment performed on an apartment building in Moscow that measured space-heating energy consumption. Chapter 6 concludes the report.

CHAPTER II. SOVIET HOUSING AND ENERGY POLICY

The Soviet Union was a large, populous nation with three times the land area of the continental US (Fig. 2.1). The country was diverse in many respects: its republics varied greatly in size, resource availability, climate, topography, population size and density, economic development, and ethnic composition. The USSR's vast resources allowed it to develop its industrial base quickly, but its diversity has led to political and economic turmoil since the fall of the union government in 1991.

Figure 2.1: The Former Soviet Union



The Commonwealth of Independent States (CIS) is the successor political and military organization to the Soviet Union. Russia, Belarus, and Ukraine agreed to form the CIS in December, 1991. Their goal was to ensure single control over the strategic armed forces of the former USSR. The founding members invited the other former Soviet republics to join the CIS; all have done so except the three Baltic states and Georgia[9]. As a political entity the CIS central government has little authority; republic leaders simply hoped that a loose confederation would promote cooperation among the former Soviet states. But Russia's commanding economic position has been increasingly destabilizing—a few republics have threatened to leave the CIS because they fear Russian domination.

After a brief overview of the Soviet economic system, this chapter will discuss the Soviet housing and energy sectors in detail, describing the size and basic structure of the housing stock and energy economies of Russia and the former USSR. This chapter provides the context for later, detailed analyses of Russian apartment buildings and district heating systems.

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[9] although strictly this means that "former Soviet Union" and "CIS" have different definitions, the two terms will be used interchangeably in this report to refer to all former Soviet republics, except the three Baltic states

THE SOVIET ECONOMIC SYSTEM[10]

The modern Soviet economic system, which existed intact until the breakup of the USSR, was the product of experimentation with market- and command-style allocation of resources that can be traced back to the 1930s. These experiments embodied both private and public ownership and control of resources in various sectors of the economy. Emphasis throughout the period was on state ownership and centralized control—since the 1930s the national government has owned the means of production and controlled resource allocation through an extensive bureaucracy directed centrally from Moscow. Virtually all Soviet economic output was allocated administratively; by comparison only about 25% of US output is allocated administratively. Authority in the Soviet government flowed from the top down in several stages, from the central union government to the republics, then to provincial governments, and finally to districts or towns.

Central Planning

The USSR's economy was centrally planned: bureaucratic institutions provided the direction and control exerted by the market in capitalist economies. In the USSR the political bureaucratic apparatus handled affairs of state, and the planning apparatus managed all economic activity. Although the two entities were officially separate, in practice they often intertwined. The Supreme Soviet was the highest authority in the planning system. The Council of Ministers, which actually oversaw the planning process, was elected by the Supreme Soviet. Both bodies received directives from the Communist Party of the Soviet Union (CPSU, or the Party), organized separately in a structure parallel to that of the planning system. The important policy-making body in the CPSU was the *Politburo*, chaired by the general secretary. The principal function of the Party in the economic system was the direct control of all operations. The CPSU achieved control through a system of nomination for all important posts in the state bureaucracy, industry (e.g., firm managers), and the armed forces.

Each individual industrial enterprise (i.e., factory) in the Soviet Union belonged to a certain administrative branch of the economy—a ministry. Three kinds of ministries were common in the Soviet system: all-union, controlled from Moscow only, which tended to be key industrial branches; union-republican, controlled from Moscow and republic capitals, which usually oversaw production concentrated in only a few republics; and republican, controlled from republic capitals only, which usually managed firms producing for local economies. The heads of the ministries, along with a few other high-level officials, constituted the Council of Ministers. The ministry system was created in 1932 with 3 ministries; by 1982 the number had grown to 64.

Ministries were usually defined sectorally. In the energy sector, instead of a single energy ministry, separate ministries controlled the production of gas, coal, oil, and electricity. Still other ministries developed basic infrastructure, produced capital equipment, and supplied capital equipment to the energy

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[10] except when cited otherwise, this section was taken mostly from Gregory & Stuart and from Hewett

ministries. All ministries concerned with energy addressed the supply side of the energy economy; notably absent was a ministry responsible for energy savings. The most important energy ministry in the residential heating sector was *Minenergo*, the Ministry of Power and Electrification. *Minenergo* was responsible for the construction and operation of thermal power plants, the electricity transmission and distribution grid, and the district heat supply networks that originated from cogeneration plants[11]. Responsibility for construction activity was divided regionally; several Ministries of Construction—*Minstroii*—coexisted, each in a different part of the USSR.

Ministries managed activity in specific economic sectors, but state committees formed national economic plans. The most important agency in the planning system was *Gosplan*, the State Planning Committee. *Gosplan* coordinated activities among all ministries. This was a formidable job, as the ministry system was quite fragmented. The All-Union Scientific Research Institute of Comprehensive Fuel and Energy Problems (VNIIKTEP), one of *Gosplan's* many advisory organs, forecasted future energy production and consumption. Another state committee planned construction activity: *Gosstroi*, the State Committee on Construction. *Gosstroi's* attention centered on construction in industry; the agency directly responsible for planning housing construction was *Gosgrazhdanstroi*, the State Committee on Civil Construction and Architecture. *Gosgrazhdanstroi* was subsidiary to *Gosstroi*. The Research Institute for Building Physics (NIISF), also subsidiary to *Gosstroi*, developed official state standards for construction in the area of building physics (e.g., heat engineering, climatology, noise control, etc.).

Economic output targets in the USSR were drawn up in terms of successive five-year plans (5YPs), each of which outlined the general economic development strategy for the forthcoming period. The first 5YP began in 1928; the 13th began in 1990. Each 5YP was further divided into five annual plans. The annual plans specified resource allocation in more detail than did 5YPs. Annual plan development was an extremely complex process—an entire year was spent developing each one. In principle the annual plans were guided by the 5YPs, but in practice this was rarely true beyond the first years that a 5YP was in effect. The 5YPs sometimes contained as much hope as they did hard projection; changing circumstances often required extensive 5YP revision. Occasionally, consensus was not reached on 5YP targets until after the beginning of the period to which they applied!

Breakdowns in incentives operating between different levels of the bureaucracy, known in economics as the principal/agent problem, were common among and within Soviet ministries, committees, and enterprises. The principal/agent problem arises when *agents*, or subservient workers, fail to perform as *principals*, or supervisors, intend them to perform. Differing goals are almost always the cause. The principal/agent problem has been cited as a major obstacle to Soviet economic plan fulfillment. Principals can deal with the problem in two ways: either by expending resources to monitor agents' activity, or by

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[11] municipal heat stations, the other main source of district heat, operated their own heating networks

devising incentive schemes that induce agents to fulfill principals' wishes. Elements of both methods were used in the Soviet system, but neither was widely effective.

Resource Allocation

Resource allocation in the USSR was defined in the annual plans by a series of balances of consumer and industrial goods, capital, labor, raw materials, and credit. In a given annual plan the CPSU established priorities for output targets, and *Gosplan* formed control figures for various economic sectors based on Party directives. *Gosplan* had little direct interaction with enterprises—ministries divided *Gosplan's* aggregated sectoral plan figures into specific targets for individual firms, and allocated supplies among the firms. Typically, the firms then relayed objections to parts of the plan back to ministries, which then negotiated with *Gosplan* to change critical targets. Finally, *Gosplan* checked the consistency of the revised plan, ensuring that all key balances were maintained.

Gosplan operated the Soviet economy at the upper limit of its production capacity: the agency repeatedly set output targets at the highest possible levels. Supplies of economic inputs were thus extremely tight. Since interdependencies between economic sectors were strong, annual plans were doomed whenever any one major indicator fell short of the mark. The USSR suffered from this problem chronically; the country experienced widespread shortages of consumer and industrial goods.

A key economic sector in the Soviet economy was the fuel sector. Theoretically, *Gosplan* accounted for all relevant aspects of fuel supply and demand when planning fuel supplies, including total planned fuel production, planned production levels in other economic sectors, norms for fuel consumption rates, and fuel savings from planned efficiency improvements. Yet another state committee—*Gossnab*, the State Committee for Material-Technical Supply—allocated fuel to ministries and other organizations based on *Gosplan's* guidelines. In practice, because of *Gosplan's* taut planning philosophy, *Gossnab* was guided more by actual conditions than by *Gosplan's* instructions: fuel deliveries stipulated by *Gosplan* were virtually never achieved [Yudzon].

Capital investment was a major determinant of Soviet economic growth. *Gosplan* allocated capital *among* ministries, but allocation *within* ministries was handled by research and development (R&D) organizations. Such organizations were external to industrial enterprises; they operated under contracts with ministries. Two R&D organizations were important in the energy sector: the State Committee for Science and Technology (GKNT), and the USSR Academy of Sciences (ANSSSR). Together, GKNT, ANSSSR, and *Gosplan* defined the scientific problems that were to be addressed during forthcoming plans, and assigned these problems to specific ministries. Most of the problems were complex, in that their solution required cooperative work among many ministries.

The R&D organizations' main job was determining which investment projects would increase firm output by the amount specified in annual plans. Interest rates were largely ignored in such decisions until 1967, when a 6% capital tax was imposed on all firms. This rate later declined, and was even eliminated in some sectors. The 6% rate was restored in 1982, but was too low to accurately reflect the shortage of capital in the Soviet economy. Thus, like most goods in the Soviet economy, capital was scarce.

Design Norms

Three kinds of documents were used in the Russian[12] planning system to establish technical requirements for equipment: GOSTs (state standards), SNiPs (norms and codes), and SNiP Manuals. Before 1980 the precise types of material permitted in GOSTs and SNiPs was explicitly defined. GOSTs and SNiPs both contained norms and codes; SNiP Manuals provided explanations of material appearing in specific SNiPs. GOSTs superseded SNiPs: text within GOSTs could not refer to SNiPs, but SNiPs referred to GOSTs. This practice has since changed; now no rigid rules govern the contents of either document. The current Russian approach is more like US practice, in which distinguishing between laws, codes, standards, and regulations is often difficult.

Coordination among designers of technical equipment was difficult in Russia. Requirements for a specific type of work, such as building construction, were separately listed in different documents, each published by a different organization. For example, three critical sets of building requirements—envelope thermal characteristics, floor plans, and indoor climate conditions—each appeared in different SNiPs. Furthermore, SNiPs changed frequently. Every month the central government published the "Bulletin of Construction Technology," which listed the new changes in all SNiPs. All designers were officially required to be aware of its contents.

Of the three main kinds of documents, SNiPs were by far the most common. All designers and builders were required to follow the mandatory codes listed in the main text of SNiPs. Appendices contained either requirements, recommendations, or general information. Of these only the requirements were mandatory; the others contained suggestions for designers and builders who needed guidelines on various topics. Designers and builders were free to use information from other SNiPs, or even from their own calculations, for any purpose not specifically covered by SNiP requirements [Matrosov]. In practice this led to widespread use of varying and inconsistent methodologies. Sometimes SNiP requirements conflicted, either directly, when different norms existed for a single parameter, or indirectly, when norms regarding different aspects of an item's production (e.g., output, quality, or efficiency), were impossible to meet simultaneously in practice.

Prices

Relative resource scarcities determine the allocation of goods and services in market economies. Prices are the mechanisms that communicate information about resource scarcity to decision-makers. In the

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[12] although this chapter chiefly addresses the former Soviet Union, specific analyses in later chapters will focus more narrowly on Russia and Moscow. Therefore, "Russian" systems will also occasionally be addressed in this chapter. Often, statements made about Russia also apply to the USSR or CIS.

Soviet economy, however, the CPSU's preferences were the most important allocative guide; resource allocation was usually not linked with prices. The Soviet price system had two other distinguishing features: all prices were set administratively by the state, and many different prices were often used for the same product. Pricing responsibilities have been shared by different central authorities over time; the most important of these was the State Price Committee.

In market economies prices have a second role: measurement and control. By providing valuations for goods and services produced, prices provide decision-makers with indicators of the relative importance of different kinds of economic activity. Measurement and control was the chief function of prices in the Soviet economy because prices provided a means of enforcement—valuations of goods produced were used in assessing the performance of enterprise managers. In market economies prices constantly change in response to changing circumstances, and economic actors generally react to the changes. In the USSR, prices remained constant until central authorities changed them. Here the planners faced a dilemma: measurement and control were easier to carry out if prices were stable, yet constant prices reflected rising costs less and less over time. Free prices would improve allocation efficiency if they reflected resource scarcities, yet they would further complicate an already cumbersome central planning system. In practice prices were revised periodically and occasionally reformed, but the intervals between revisions were variable, and sometimes over 10 years long.

Incentives and Soviet Firms

Soviet firm managers were required to achieve plan directives as laid out by *Gosplan* and ministries. All plans contained multiple targets and constraints. Although targets were never clearly ranked in priority, the critical one was almost always gross annual production. When all plan targets could not be simultaneously achieved, indicators not directly related to output—profit, quality, and timeliness—were of secondary importance. Use of a single success indicator, gross output, led to two problems in the Soviet economy. First, economic distortions arose as managers discovered ways to artificially inflate output statistics. Second, managers faced a significant disincentive from the "ratchet effect," in which they were penalized for meeting annual targets by receiving higher targets in the future.

Most managers' difficulties centered on inadequate supplies: achieving production targets depended on obtaining sufficient inputs, yet deliveries of inputs were unreliable because of *Gosplan's* taut planning and ministries' poor plan implementation. To combat shortages managers tended to stockpile critical supplies, but this only aggravated the existing shortages. Shortages were especially common in the fuels sector; firm managers in the fuels sector went to great lengths to obtain favorable fuel quotas. Their efforts fell into four main categories: 1) inflating reported fuel consumption requirements, 2) influencing *Gosplan* and *Gossnab* through ministries and local party and municipal officials, 3) artificially shifting some fuel consumption to unregulated areas, and 4) citing artificially low efficiency for equipment not regulated by SNiPs. The third and fourth methods were usually more effective, because planners lacked the means to verify firm managers' claims in specialized technical areas [Yudzon]. Other economic sectors experienced the same problems. This example illustrates a few sources of the pervasive misinformation that led to inefficiency in the Soviet economic system.

Economic Restructuring

The economies of the former Soviet republics have suffered greatly since 1991. Production in nearly every sector has fallen, and the republics' combined national income has declined by 10-40% [REFFA]. Most of the blame lies with the collapse of the old system and the partial impact of free market reforms. Even so, real economic reform in most of the republics has only begun.

State domination of the economy has continued in many republics. Although all republics seek stability and reform of their political and economic systems, no consensus has emerged concerning how reform is to take place. The main economic issue is the transformation of command economies to market systems. The issue has many facets: the scope and pace of change, specific reform techniques, and the degree of inter-republic cooperation. Particular controversy surrounds the collapse of production, price decontrol, the benefits and costs of separate national currencies, and privatization of state assets. Other disputes focus on control of the military and energy reserves, and on taxing and regulatory authority.

An unfortunate consequence of widespread political and economic turmoil in the CIS is uncertainty. The structures of the labor, resource, and capital markets are unstable, and sometimes even undefined. The legal and regulatory systems in the areas of workers' rights, wages, contracts, and property ownership are in varying degrees of disarray. Since it is impossible to predict the future course of economic developments, prospects for foreign organizations to get involved in economic activity in the CIS, either cooperatively or otherwise, are risky.

Data Problems

Western researchers have long been forced to deal with the difficulties in finding and interpreting statistical information concerning the Soviet economy. The central government's desire to conceal important production and financial facts meant that clarity and consistency in published statistics were rare, and that much interesting information was simply unavailable to the general population. Further, since information was equivalent to power within the bureaucracy, even lower officials were reluctant to reveal their secrets without good reason.

Official statistical reports were published in several forms by *Goskomstat*, the State Committee on Statistics. These reports were incomplete and often inconsistent—accounting methods and definitions varied among sources, and even within the same source in different years. The data almost seem designed to confuse. Additionally, ministries and state committees tended to use their own internal information except when the use of standard data was required.

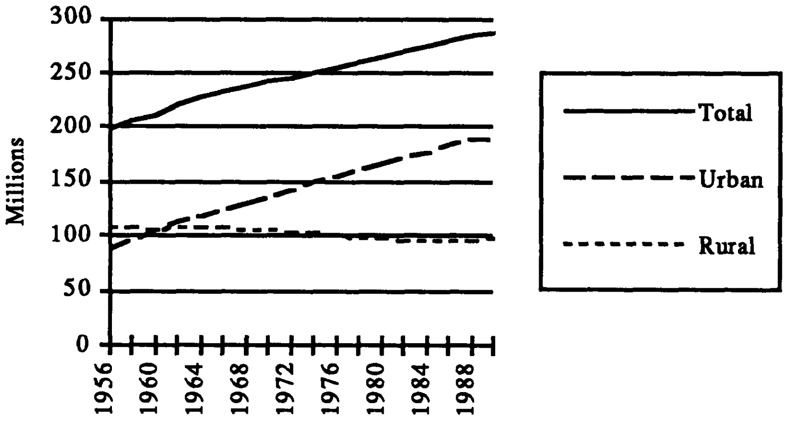
Much of the information presented in this report was drawn either directly from Soviet sources or from Western authors who cite Soviet sources. Consistency was checked when possible, but most data suffer from the consistency and definitional problems cited above. Any specific additional difficulties encountered will be described as necessary.

THE HOUSING SECTOR

The size and structure of the CIS housing stock are the result of six decades of choices made by Soviet planners, the constraints under which they made their choices, and the Soviet economic system's implementation of those choices. This section will describe the basic economic characteristics of the housing stock[13], the main influences on its evolution, and the administration of Soviet urban housing.

The USSR had the world's third largest population, after China and India, with 287 million people in 1989. After World War II the Soviet population became increasingly urban—by 1989 the urban population represented 66% of the total population (Fig. 2.2). Urbanization of the Soviet population took three forms: the definition of urban areas changed over time[14]; many new towns were founded, usually near new factory sites; and most existing towns grew substantially. As an example of the latter, the number of towns with populations of over 500,000 increased from 22 to 32 between 1959 and 1988; the total population of these towns grew from 24 million to 65 million over the same period [UFFA].

Figure 2.2: USSR Population
[Clarke; UFFA]



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[13] the technical characteristics of the housing stock will be addressed in Chapter 3

[14] the "urban population" was defined by the type of work performed by the majority of inhabitants of a populated area (whether agricultural or industrial), not by town size. The Soviets used three broad categories to classify populated areas: cities & towns, urban-type settlements, and rural-type settlements; the urban population comprised all residents within the first two categories.

A basic tenant of Marxist-Leninist philosophy is that differences between town and country should be eliminated, allowing people, the production of goods, and the provision of social services to be equally distributed throughout the nation. The Soviets believed this would provide greater economic efficiency due to reduced transportation costs, since production and consumption activities would be physically closer together. The placement of new Soviet towns since the 1930s has reflected this desire to evenly distribute the nation's economic wealth [Underhill].

The Soviet labor force has been much larger than that of the US: 92% of able-bodied Soviet citizens worked, and women constituted half the workforce [Kudryavtsev]. Even so, labor shortages were a chronic problem in Soviet cities, particularly in the construction industry. Rural inhabitants were increasingly drawn to urban areas, and to large towns in particular, to help ameliorate the shortages. The growing urban population caused rapid growth in the demand for urban housing.

Economic Policy

In the Soviet Union housing was officially considered a basic right of all citizens. Most urban housing was provided by the state, either directly or through industrial enterprises[15]. To justify the policy of state-owned housing, the state declared that private ownership made rational urban planning impossible. Although freedom of choice was desirable, the state maintained, it supposedly led to inefficient town layouts. Contrary to official goals of equity and fairness for all citizens, however, urban housing was often treated as an incentive—a reward for good work. Housing was typically used by factories to attract and to keep good workers. In practice, urban housing was rarely a public service to which all citizens had a right [DiMaio].

Although official dialogue also called for steady improvement in housing conditions, in reality many citizens' living conditions were harsh. Housing, like other essential consumer needs, has always competed with other, higher priority economic sectors in the Soviet Union. During the 1930s rapid population growth and urbanization combined with the high priority of industrial development[16] to turn an existing housing shortage into an epidemic housing crisis. Communal living became widespread, with multiple families and multiple generations often sharing a single apartment. Per capita dwelling space was abysmally low compared to European nations [Sosnovy]. The disruptions and destruction of World War II only worsened these problems.

After Stalin's death in 1953, a vicious power struggle ensued among top Soviet leaders. Housing, which leaders had neglected for 20 years, suddenly rose to the top of political agendas, as satisfying the needs of a long-ignored general population was necessary to get widespread public support. When Khrushchev emerged as the new head of state, he initiated an intense housing construction drive with the

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[15] as will be seen, this was not true in rural areas

[16] Stalin's rapid-industrialization policy reflected his desire to match the industrial outputs of Western Europe and the United States as quickly as possible

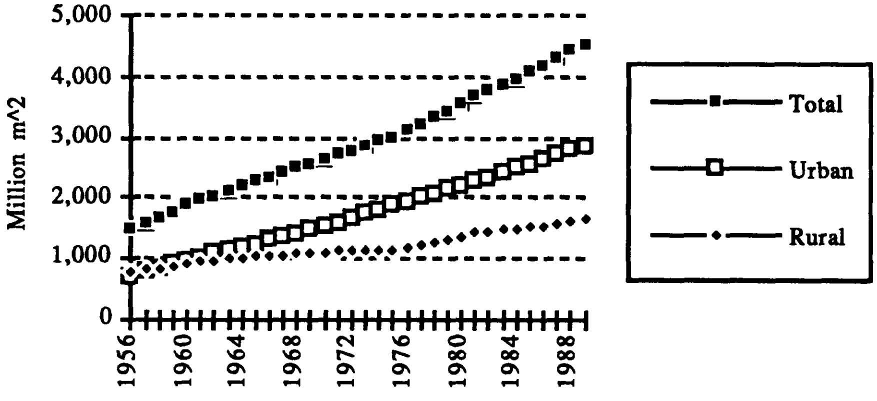
publicly stated (and Party-supported) goal of providing an apartment for each Soviet family within 12 years.

Khrushchev saw the industrialization of the housing construction industry as the long-awaited answer to the housing crisis. He initiated a transformation of the industry along three lines: 1) increased standardization of finished housing projects, 2) greater use of prefabricated construction techniques, and 3) increased mechanization within both the factories that produced construction elements and at construction sites. These changes were to occur between 1959 and 1965. In the new scheme nearly everything was prefabricated in factories: walls, floor and ceiling sections, windows, stairways, and landings. Gross output, or the area of new dwelling space completed, became the sole success indicator for construction firms and ministries, which led to the economic distortions discussed previously. Production could not wait for new architectural developments or advancing construction technology; anything that immediately increased the rate or lowered the cost of production was done[17].

Soviet housing construction rates since the late 1950s have been high: an average of 2.1 million dwelling units were built each year between 1957 and 1985. Achievements in floor area constructed were equally impressive: construction growth rates doubled in 1955-56, and the total USSR housing stock tripled in size between 1956 and 1989 (Fig. 2.3a). Growth rates in Russia and Moscow were indicative of this national trend (Figs. 2.3b-c). New urban housing was constructed at very high densities. Planners offered the ability to use cheaper, centralized heating systems as one justification for the high housing density [Underhill].

Figure 2.3: Housing Stocks (useful area[18])
[UFFA; *Nar. Khoz.*; *SSSR v Tsifrakh*]

a) USSR



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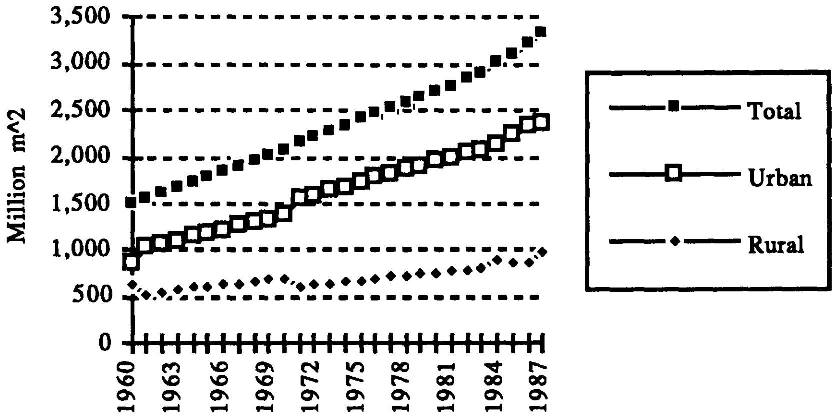
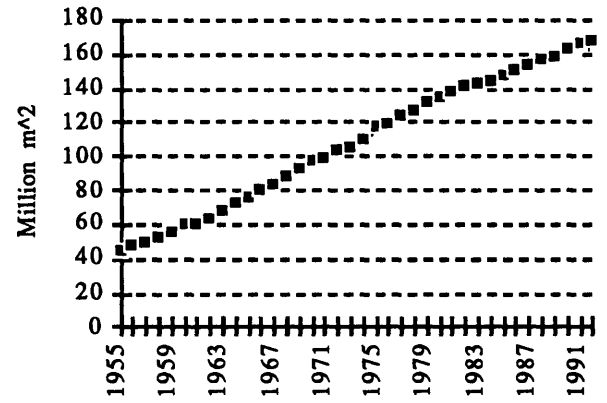
[17] a more detailed discussion of construction methods appears in Chapter 3

[18] includes bedrooms, living rooms, kitchens, baths, interior halls, and closets; living area, conversely, includes only living rooms and bedrooms

b) Russia[19]



c) Moscow[20]



The Soviet housing drive of the 1950s unquestionably improved living conditions for most urban citizens, and rent has averaged a mere 4-5% of a working family's budget since the 1930s [Kudryavtsev]. Yet substantial problems persisted. First, average per capita living space was still extremely low in the 1980s compared to Western nations (Fig. 1.5). The average citizen was entitled to only the minimum amount of floor space specified by design norms: 9.3 m^2 per person. Persons within some privileged groups received extra space, but usually a high fee was charged for having living space higher than the norm. Second, an estimated 30% of urban households still lived communally or in factory dormitories in 1980 [Morton]. Millions of people were waiting to receive new housing at any given time; as apartments became available they were allocated using waiting lists. The average waiting period was 1-3 years, but

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[19] Russian stocks were approximated using 5YP construction data, converted from living area to useful area
[20] Moscow data include estimates of annual housing demolition

ranged up to 10 years for some persons. If citizens lost favor with the Party or performed poorly on the job, they were moved lower on waiting lists, or dropped from them completely. Third, some degree of housing segregation by income existed in the USSR[21]. Greater disparities showed up at the republic level—the Baltics generally had more housing per capita and a larger share of apartment buildings, but the Middle Asian republics had less of both [Underhill].

Quality

The planning of Soviet housing was generally good, but the translation of plans into actual buildings was poor. Apartment buildings suffered from low quality of construction: many buildings were either erected with defects or opened to occupants before they were finished, causing them to need repairs sooner than expected [Sosnovy]. Quality improved dramatically during the 1960s, however: the focus of most tenants' complaints shifted from basic structural faults (leaking roofs, cracked walls, warped window frames) in 1960 to shoddy appearance and the lack of building maintenance by 1970. Even today, however, Soviet estimates show that many apartment buildings lack basic amenities (Table 2-I).

Table 2-I: Apartment Buildings Lacking Amenities (by area) [UFFA]

a) USSR	1970	1980	1987
No Central Heat	26%	13%	10%
No Hot Water	66%	43%	26%
No Gas	35%	21%	22%
b) Moscow			
No Central Heat	4%	0%	0%
No Hot Water	38%	14%	5%
No Gas	2%	19%	31%

Western and Soviet analysts have identified several causes of low quality in apartment buildings. The main reason was the low priority accorded to housing quality by central planners—despite the Soviet leadership's rhetoric, quality was unimportant in evaluations of construction enterprises [DiMaio; Underhill; Ikonnikov]. Firms in the housing construction industry, like those in most other Soviet industries, were driven by the necessity of meeting plan output targets, as speed of construction was all that mattered. Similarly, although there were many different kinds of housing inspection agencies, they often lacked the authority to affect the construction process. Underhill suggests that the method of housing administration further distorted incentives: in enterprise-owned housing, factory managers resisted diverting extensive resources from production activities to produce high-quality dwellings. Furthermore, since workers were often on long housing waiting lists, they were in no position to bargain for better housing

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[21] although it was less extreme than income segregation in Western countries

conditions. The state's essential urban housing monopoly left it with no incentive to provide high-quality housing, or even reliable maintenance and repair.

The highly centralized control of design and construction initiated by Khrushchev led to uniformity in the urban housing stock. Of almost 800 standard designs available to architects and city planners for apartment buildings, scarcely 10% have been used [Kudryavtsev]. The state emphasized rapid construction and equality in housing conditions; it made little effort to provide choices to meet the diversity of human needs or desires. More diversity meant more complexity, which required more time and resources to plan and build. In summary, although Soviet citizens were less crowded in the 1980s than they were in the 1950s, they did not necessarily *like* their new dwellings.

Ownership and Control

Even though the ideological roots of the Soviet economic system were in the principle of state ownership, the structure of housing ownership and management changed substantially over time. Most urban housing was owned and managed by the state, but at various times throughout Soviet history individual and collective ownership have been legalized, outlawed, and legalized again as central planners struggled to improve housing conditions for Soviet citizens [Sosnovy]. The forms of housing ownership and management determined the existence and nature of consumers' choices in the housing sector, the strength of consumers' incentives, and consumers' relative priorities[22] when seeking housing.

The urban housing stock was divided into four administrative categories: departmental, municipal, cooperative, and individual. Within each category different organizations were responsible for constructing, allocating, and managing the housing. Departmental and municipal housing were both state-owned, but were managed differently: departmental housing included all housing controlled by bureaucratic departments within ministries, industrial enterprises, or other central organizations, but municipal housing was administered by local city *Soviets* (political offices), each of which had a Department of the Municipal Economy handling all housing-related issues[23]. Larger cities were divided into districts, with housing in each district handled by district *Soviets*. Although this suggests that city-level authorities in the local *Soviets* controlled housing, in fact they had little or no autonomy—local *Soviets* were closely tied to the central organs of power [Sosnovy]. In fact, local government in the Western sense was virtually non-existent in the USSR. In 1970 about a third of state housing was municipal, and about two-thirds was departmental [DiMaio].

Conflicting interests led to tension between enterprises and local *Soviets*: Some officials called for more unity in each city's housing stock through greater control of urban housing by the local *Soviets*, but

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[22] the organization of the housing construction industry will be discussed in Chapter 3; this section will focus on the management of housing units after their construction

[23] municipal housing, as a separate administrative category, originated as all housing owned by corporations or individuals before the revolution in 1917, when it was confiscated and redistributed by the state because all forms of private ownership had been outlawed

enterprises resisted all suggestions that the *Soviets* could better manage the housing stocks. The promise of receiving good housing was a powerful incentive for enterprises' workers; the enterprises were reluctant to give up control of housing. As a result, any one city's housing stock was sometimes divided among hundreds of different management organizations [DiMaio].

Individual housing comprised all housing owned by private citizens, and was most common in rural areas. Cooperative housing was fairly common in urban areas, however. Semi-autonomous house-leasing cooperative organizations, *Zhakti*, were created in the 1920s in an effort to better administrate the municipal housing stock. The *Zhakti* were spontaneously formed committees of tenants that rented municipal housing from local Soviets on a long term basis, collected rents, conducted voluntary repairs, and distributed living space. Within a few years it became clear that *Zhakti* provided much better housing maintenance than local *Soviets* or central departments [Sosnovy]. After 15 years of moderate success, however, cooperatives were struck down in 1937, and ownership of most cooperative units was transferred back to the state. The official explanation for this sudden, radical action was that cooperatives managed housing poorly, causing a decline in housing conditions. In truth, this was exactly the opposite of what really happened. One Soviet author maintained that the real reason cooperatives were banned was political, not economic: the concept of an organization acting with any degree of independence was incompatible with the new totalitarian government of the time—in Stalin's view, citizens had to be completely dependent on the state [Sosnovy].

The first few years of the post-Stalin period saw the emergence of a fresh search for new solutions to lingering problems. Housing cooperatives were revived in the late 1950s in a different form, but unlike the *Zhakti* of the 1930s, the new organizations were simply assistants to the existing house management, auditing resource expenditures and training tenants in the proper maintenance of their flats [DiMaio]. Through the 1960s and 1970s the Soviet government actively encouraged the formation of cooperatives by relaxing its supervision over them, and by making state loans available for new cooperative housing construction (private builders had been taking advantage of these incentives for many years). In this period cooperative housing construction came to be officially favored over private construction, as the concept of individual ownership again became less palatable to the Soviet leadership.

After 1937 the house management was the chief administrative organization in the departmental and municipal housing sectors. Each apartment building had its own house management; the house manager was appointed either by the local *Soviet*, for municipal housing, or by the head of the controlling organization for departmental housing. House managements were gradually given more power over time. Some of their responsibilities were police-like: managers and janitors were required to observe the activities of all residents, reporting any "suspicious" activity to the Party, and house managers were fined if residents' official papers were out of order. As a result, tenants tended to avoid house management personnel in order to prevent attracting undue attention [Sosnovy]. Notably, effective building maintenance requires exactly the opposite kind of relationship. The confrontational setting that developed during the

Stalin period formed a precedent for the relationship between tenants and house management that lasted for many years.

Housing management had a low priority in the state. House managers were appointed haphazardly, with little regard for their qualifications. They often disliked their work: the chronic housing shortage, combined with constant squabbles among tenants, made their jobs miserable. Furthermore, house managers, often Party members, had little time available to manage the house effectively [Sosnovy]. House managements were replaced in 1959-60 by new organizations—Housing Operations Offices—that helped to unify the administration of cities' housing stocks, but the new offices still suffered from the problems that had plagued house managements [DiMaio].

Two kinds of housing repair work were defined by the republic ministries: current repairs, entailing daily operations and regular maintenance, and capital repairs, or major renovation work. Each kind of repair work was managed, financed, and performed separately [Sosnovy]. Part of tenants' rent was earmarked for funding repair work, but usually the revenues covered only 35-40% of building operation and maintenance costs [Underhill; DiMaio]. Tenants were responsible for basic current repairs; house management handled more complex current repairs and all capital repairs. The city housing administration decided which houses received capital repairs. Tenants tried to influence this decision, and tried to get permission to do some repair work themselves, but were rarely successful.

Building envelope and heating system repairs were typically classified as capital repairs. Capital repair costs were quite high, sometimes exceeding the cost of an equivalent amount of new housing [DiMaio]. In municipal and departmental housing, the money allocated for capital repairs was often spent ineffectively, either spread out over many different projects or diverted locally by the city *Soviet* for new construction or other projects unrelated to repair work. These problems were aggravated by the lack of relocation quarters for tenants.

In summary, coordination between a multitude of organizations, agencies, and ministries and the local *Soviets* was a fundamental problem in almost all phases of the planning, financing, and construction of Soviet urban housing. The chief difficulties were overlapping authorities, conflicts over the right to control any single stage of housing operations, and a reluctance of central leadership to give local governments the real power they needed to fulfill their responsibilities. The local *Soviets* were overworked and lacked authority, yet they had to contend with many powerful departments and ministries with different interests in order to produce and manage urban housing effectively. As a result, heating systems in the apartment buildings were usually poorly maintained.

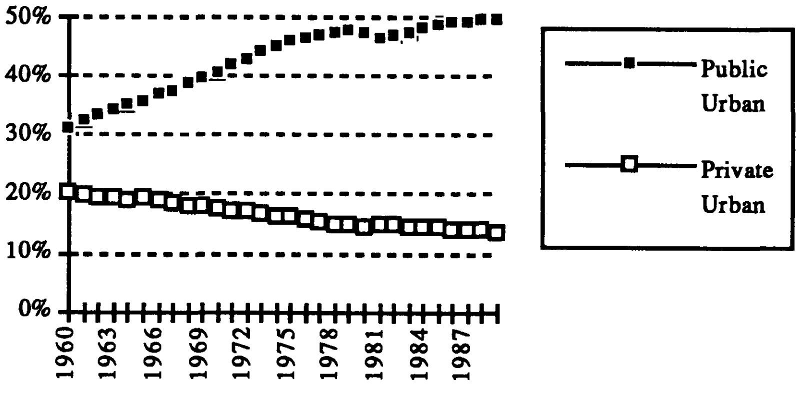
The Housing Stock

This report classifies the CIS housing stock in two ways: urban-rural, and public-private. Urban housing consists of all housing in urban areas; all other housing is considered rural. Public housing comprises housing units constructed by the state through either direct political organs or industrial enterprises, plus those constructed by housing cooperatives. All other housing is considered private. These definitions correspond roughly with Russian terminology.

The district-heated stocks of residential apartment buildings in the USSR, Russia, and Moscow are the focus of this study. Unfortunately, little information is available concerning the precise amount of floor area within these stocks. Their size can be approximated with available information, however. Apartment buildings were only constructed in urban areas, and all such buildings were publicly owned. Thus, combining the urban-rural and public-private classifications allows the total apartment building floor area to be approximated by examining the ***public urban*** housing stock (the district-heated component will be approximated in Chapter 3). The public urban stock is likely to be an upper bound for the total stock of apartment buildings, since some public urban housing may be individually owned homes. Figures 2.4-5 display estimates of the structure of the USSR and Russian housing stocks. The Soviet emphasis on urbanization and state ownership is apparent—the fraction of public urban housing increased from 30% to 50% between 1959 and 1989 nationwide, and from 37% to 55% between 1965 and 1980 in Russia.

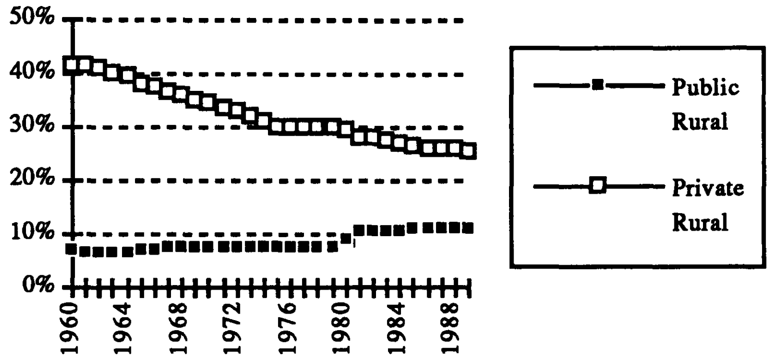
Figure 2.4: Structure of USSR Housing Stock, by useful area*
[UFFA; *Nar. Khoz.*; *SSSR v Tsifrakh*]

a) Urban Housing



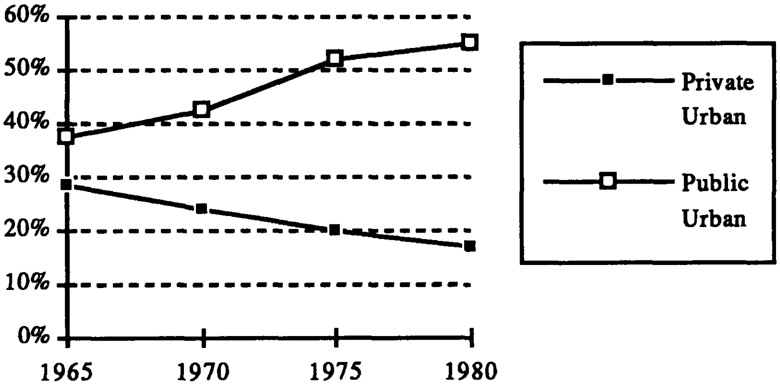
(percentages sum to total urban percentage)

b) Rural Housing



(percentages sum to total rural percentage)
**Dachas*, or private summer houses, were not included in Soviet housing stock statistics

Figure 2.5: Structure of Russia's Urban Housing Stock, by useful area [UFFA]



(percentages sum to total urban percentage)

The information presented in Figures 2.4 and 2.5 should be treated with caution. First, data were collected from many Soviet sources, which generally suffered from the consistency and definitional problems described in the previous section. Second, a mixture of housing stock data and annual housing construction data was used in the analysis. Information concerning annual housing demolition was not available; its magnitude was estimated for the USSR stock by comparing annual construction information with published values for annual housing stock in some years.

THE ENERGY SECTOR

Chapter 1 described the CIS energy economy in broad terms. This section will elaborate on several specific elements of that economy—its structure, past supply-side energy policies, energy conservation efforts, and achievements in energy efficiency—and compare CIS experience in some sectors with US experience.

Energy Supply Problems

Growth rates between 1960 and 1975 indicate the strength of the Soviet energy supply sector—over the entire period energy production grew at an average rate of about 5% per year. In the same period net energy exports increased at an average rate of nearly 9% per year. This very impressive performance caused optimistic views among Soviet planners about future energy prospects [Hewett].

In the 1980s signs of strain emerged in Soviet energy supplies. Coal and oil production in 1980 fell short of the 10th 5YP (1976-80) targets by 10% and 6%, respectively. Plans to expand nuclear power production in the late 1970s were also underfulfilled. The 11th 5YP electricity generation target for 1985 was almost achieved, but at the cost of excessive operation of thermal stations and continued generation from obsolete, inefficient sites. The 12th 5YP saw coal and oil production decrease in 1987 for the first time in 25 years; a few years later natural gas followed suit [UFFA; BP].

Capital investments in the fuel industries consistently accounted for about 40% of the *total* investment in industry between 1930 and 1975; in the 11th 5YP the energy sector still absorbed 30-35% of total investment [Yudzon]. Yet recently fuel production has become a steadily growing burden on the economy: from 1970-1990, about 60% of the *growth* in capital investment in industry went to the energy sector [UFFA]; in the 1980s alone this figure may be as high as 80-90% [Tretyakova & Sagers]. Development of fuel production also required investment in industries that supply the fuel industries (with drilling, transport, and other equipment); therefore, the energy supply sector has indirectly claimed an even larger share of investment. Some Soviet experts realized the magnitude of this crisis in the 1970s and 1980s; they feared that maintaining such high investment in energy-producing industries would ruin the economy.

Growing capital investment requirements in the energy sector were symptoms of a more basic problem: the share of energy used within the Soviet energy supply industry was about 13% of primary energy consumption in 1975, compared to 6% in the US and Western Europe [Campbell 1980]. The share of internal use reached 16% by 1980. One Soviet energy expert estimated that internal use would grow to 17% by 1990, and possibly to 19-21% by 2010 [Gustafson]. There are several causes for the high level of own-use: inhospitable environments in production regions, use of low-grade fuels, energy-intensive extractive methods, and problems in the energy transportation sector. Of these, transport problems may be most significant. Most energy demand originated in the western USSR, as it contained 75-80% of the population, industrial base, and social infrastructure. In contrast, the eastern USSR contained less than 10%

of the population, but almost 90% of the country's energy resources. As energy production in the western USSR faltered, the needs of the economy were increasingly met by eastern fuels, which had to be transported thousands of kilometers. Traditionally, the Soviet government was extremely reluctant to expand transport capacity; transportation services were provided only when and to the degree absolutely necessary [Sagers & Green]. Thus, in the early 1980s transport capacity became a limiting factor on the growth in Soviet energy production.

Energy Prices

Historically, it is clear that increases in relative energy prices (i.e., when energy prices rise faster than other prices in an economy) lead to higher energy efficiencies in developed market economies. This results from substitution of other economic inputs for energy: labor in the short run; capital in the long run. It is also clear, however, that many of these adjustments require years to take effect. It is generally assumed that market mechanisms provide the link between energy efficiency and prices. In the USSR most of these mechanisms were absent: all prices were set administratively.

Energy prices in the Soviet Union were extremely complicated. At least five different prices for each form of energy were used, each with a particular function. First was the *enterprise wholesale price*; the price paid to energy producers. Second, the *industry wholesale price* was paid by industrial and agricultural energy consumers (e.g., a power plant or a heating plant). This price was equal to the enterprise wholesale price, plus a markup that accounted for an excise tax (the "turnover tax"), profits to branch sales organizations, and transport charges. Third, the *consumer price* was charged to individuals for energy used for home heating and various other needs. These three kinds of prices differ from those in market economies not because of their existence, but because Soviet prices did not fully reflect market conditions. Although prices were typically based on production costs plus a profit markup, they bore no relation to demand or to relative scarcity.

The fourth energy price was the *planning price*. This price was not used in transactions; planners used it as one consideration in their decisions concerning investments involving energy inputs. All four internal energy prices were set by the State Price Committee. Internal prices for a single fuel often varied among different end uses. Finally, the Soviets had an *export price*, which bore no relation to any internal energy prices. Energy exported for hard currency was sold at the world market price; all profits accrued directly to the state.

Past enterprise wholesale energy prices were far below production costs, so low that energy was often considered too cheap to meter. These pricing practices—originating in 1967, and designed to encourage switching to centralized sources of electricity and heat—were common until 1982, when wholesale prices were revised throughout the Soviet economy. Energy prices were raised the most: although the average enterprise wholesale price hike throughout all industry was only 11%, prices for coal and gas rose by 44% and 28%, respectively, and the price for oil extraction rose by a whopping 123%

[Bornstein]. Yet the impact of the revisions on industry wholesale prices is unknown, as they were not published. An offset appears to have occurred for petroleum products in the form of reduced turnover taxes, because, according to one source, industry wholesale prices for petroleum products increased by only 12% in 1982. Energy price hikes thus might not have been fully passed on to industrial and agricultural consumers.

Some sectors of the Soviet economy might have been price-sensitive, however: evidence indicates that some administrators and firm managers did respond to internal price increases when they occurred [Kelly 1978; Campbell 1983], and some investment decisions appear to have been shaped by the evolution of planners' prices [Hewett]. But the specific mechanisms linking Soviet energy prices and energy demand are poorly understood, and there is dispute in the West concerning how important prices were in influencing decisions about energy use in the USSR. For example, Campbell suggests that pricing was not the prime motivation for energy savings in electric power plants [Campbell 1983].

Most consumer goods and services were sold at prices below market-clearing levels in the USSR. This caused persistent and widespread shortages and wasteful use of the goods. For example, heat consumption in apartment building flats was unmetered—consumers simply paid a flat rate, calculated proportionally according to each tenant's rent [DiMaio]. The heating charge was rarely permitted to exceed 40% of a tenant's rent, and it remained stable over time even if wholesale energy prices increased.

The insulation of internal Soviet energy prices from fluctuations on the world market had important consequences in the Soviet economy. Although world oil prices rose drastically in the 1970s, they remained constant for Soviet oil-producing enterprises, as did the potential payoffs to oil exploration teams. Any idea that the value of oil had increased in the world only came to oil drillers and explorers through plan documents and occasional newspaper articles [Gustafson]. Further, energy prices generally fell below increasing production and transportation costs, thus reducing the profitability of energy supply industries. Planning prices, even if they reflected marginal costs of supply, only affected choices concerning technologies, locations, and capital intensity of large new energy projects; they did not assess whether the energy was needed in the first place. Finally, consumer prices, constant over time and usually unrelated to consumption levels, promoted inefficient energy end use.

Planned Conservation Efforts

Soviet planners began paying attention to energy conservation possibilities in the 1970s—annual plans since that time have contained conservation targets. In many ways, though, the Russians treated energy conservation targets as just another form of regulation: without focused attention from enforcement agencies conservation programs had little chance for success. Even the plans themselves sometimes made little sense. As an example, many factories have been required by their ministries to record energy efficiency improvements of 2% per year, *every year since 1961*, regardless of the real need for or feasibility of efficiency improvements in specific sectors. Strict fulfillment of this plan implies a 38% reduction in the energy intensity of productive activity in 1985, compared to 1961 levels—a ludicrous suggestion. In these situations emphasis shifted from achieving improvements to simply recording them; the reports of some heating stations recorded efficiency coefficients exceeding 100% [Yudzon].

In 1982 a commission of Soviet experts in energy, science, and technology, the Alexandrov Commission[24], recommended large-scale efforts at energy conservation. The commission foresaw many of the problems in the fuel production sector, and proposed several strategies to reduce the risks of shifting from a supply-oriented to a demand-oriented energy policy. The commission suggested dividing the transformation into two phases. First, the preparation phase called for stabilizing oil output, developing gas and nuclear resources, improving energy consumption metering, and developing new efficiency incentives. The second phase would follow, in which new investment would shift to the demand side and obsolete equipment would be retired. Proper execution of the first step would make the second much easier, and thus less risky.

In principle these two strategies are complementary—the first substitutes labor for energy, the latter capital for energy. Both are typically employed in market economies, and they tend to blur together. In the USSR, however, they were separate programs: the first was considered a monitoring and enforcement problem and handled locally, but the second was managed like all other major capital investments—through the central planning system. Coordination of these two strategies was exceedingly difficult [OTA].

The Alexandrov Commission's report inspired some top Soviet leaders to incorporate conservation into the planning and administrative system. Initial efforts were intense: *Gosplan* prepared tighter norms for energy consumption and tried to form a more rational basis for energy efficiency targets; firms were required to prepare energy-saving plans; energy efficiency was included in the product rating system; and agencies were established to coordinate efforts, monitor progress, and enforce fuel allocations. Although these were significant policy changes, conservation still lacked the broad-based political support it needed: although some top leaders pushed for conservation, others rejected it and actively fought its introduction. Those who opposed conservation managed to curtail public discussion of the subject by weakening the Alexandrov Commission's report—the published version was vague, and de-emphasized the rapidly rising oil costs that were the authors' main concern [Gustafson].

Results of initial broad-based conservation efforts showed up in the 11th and 12th 5YPs (beginning in 1980 and 1985, respectively), which both mandated incremental total energy savings of about 2% of national energy consumption. The plans called for a large number of small gains in the production, transport, and use of energy. Of these, the combined housing and agriculture sectors were expected to contribute about 25% of the total. Further, the Soviets developed specific measures, the Long-Range Energy Programs, in an effort to plan and coordinate national energy policy. The most recent program covered the years 1986-2010, and included substantial targets for energy conservation (Table 2-II). Under

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[24] appointed by Brezhnev in the late 1970s

the plan the current high energy production levels were to be maintained, but the energy was to support a much higher level of economic activity. Unfortunately, these programs lacked real reform; they simply called for incremental changes within the confines of existing technologies, and expanded the scope of command and control methods into a new area [Hewett].

Table 2-II: Planned Soviet Energy Savings under the Latest Long-Range Energy Program, million TSF
[Tretyakova & Sagers]

	1986-90	1991-95	1996-2000	2000-2010
Technological Factors	150	150	125	200
Structural Change	50	200	350	800

Implementation of Soviet conservation plans suffered from the usual problems associated with the use of norms. First, artificial energy savings were easily achieved by firm managers merely by increasing the reported energy requirements for producing goods. Since hardly any energy was metered, *Gosplan* had difficulty verifying such "norm inflation."[25] Second, achieving the most cost-effective savings required using many norms, yet norms were impossible to enforce if they became too numerous. Third, enterprise managers had no incentive to improve energy efficiency beyond minimum requirements. Because of these problems, many firms didn't bother to prepare their energy-saving plans or adhere to new energy consumption norms. Ministries, rather than pressuring the firms, usually supported them, leaving *Gosplan* alone to enforce the norms. Since energy efficiency norms held no special status among the much larger set of economic norms, they often went unenforced.

The economic system's incentives, based on cheap energy, also needed reform as part of the demand-side scheme, but the impacts of systemic changes were unpredictable. Soviet leaders were well aware of the inertia and rigidity of their system, and hesitated to shift energy policy radically. Widespread energy shortages in the early 1980s because of tightening fuel supplies illustrated the riskiness of Soviet demand-side energy strategies: planned conservation programs had had insufficient time to take effect, and *Gosplan* officials had not yet evaluated and improved the existing programs. A dilemma was apparent: supply-side policies demanded only a steadily steepening slope of cost and risk; demand-side strategies offered a better long-term solution, yet were initially no cheaper, and were much more risky because their returns were uncertain [Gustafson].

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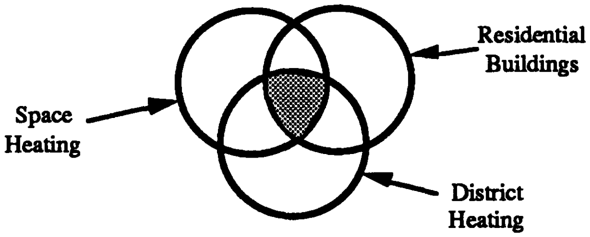
[25] sometimes this problem was so severe that planners were forced to negotiate to set energy conservation targets

Structure of the Energy Sector

The CIS energy economy can be divided for analysis in several ways. One common approach breaks it down by economic sector: industrial, transportation, and commercial/residential buildings. Alternatively, energy consumption can be divided by end-use, or the type of service the energy provides, such as space heating, light, transport, or powering electronic equipment. The relevant sector of the energy economy in this report is the district-heated residential space heating sector, defined as the intersection of three different but overlapping components of the energy economy (Fig. 2.6).

Figure 2.6: Intersection of Three Subsectors of the CIS Energy Economy



Russian sources split heat consumption statistics into two categories: centralized and decentralized. Exact definitions vary among sources, but Wilson and Dienes both adopted the definition that follows. Centralized systems provide heat to homes, offices, and factories from one of three sources: heat and power (cogeneration) plants, large municipal and industrial boilers, or local boilers (serving single buildings) with capacities exceeding 20 G-cal/hr (23 MW). The larger local boilers are included in centralized heat even though they contribute no heat to city-wide heating networks. All other systems providing heat are "decentralized." In this report, district heat, when referring to thermal energy, matches the Russian definition of centralized heat. The district heating (DH) system, however, refers to the system that produces and delivers thermal energy from heat and power plants and large municipal and industrial boilers to consumers through city-wide networks (i.e., all individual building boilers are excluded).

Table 2-III presents the structure of Soviet energy consumption by economic sector in 1985. Table 2-IIIa describes the combined disposition of all energy; Table 2-IIIb considers electric power as a separate sector. All sectors shown in the table have recently been stable—most sectoral shares have varied by less than 2 percentage points since 1970.

Table 2-III: USSR Primary Energy Consumption by Sector in 1985
[Tretyakova & Sagers]

a)

Total Primary Energy*	1850 mn TSF (54 EJ)
Industry	52%
Housing & Municipal	22%
Transportation	11%
Other**	15%

b)

Electric Power	28%
Industry	39%
Housing & Municipal	14%
Transportation	9%
Other*	10%

* by comparison, the US consumed 74 EJ of primary energy in 1985 [BP]
** includes agriculture and construction

Industry has dominated Soviet energy consumption for over 20 years. This is chiefly a consequence of the emphasis Soviet planners placed on industrialization—the low share of the housing and municipal sector reflects its low priority. Technically, three elements of the structure of Soviet energy consumption account for the low share of energy in non-industrial sectors: the small stock of privately owned cars, the low use of trucks in the transport sector, and the widespread use of district heating [OTA]. Industry's large share of energy use has caused most energy-saving efforts to be focused in the industrial sector.

The kinds of general sectoral divisions presented above are published in various Russian sources. Detailed information concerning the composition of individual sectors, however, is harder to find. Russian sources usually combine the residential and municipal sectors, and breakdowns by the type of end use (the energy service) are particularly rare. Russian statistics concerning centralized heat allocation are listed as secondary energy rather than primary energy, where secondary energy refers to the heat output of all centralized heat-producing plants. Table 2-IV presents Cooper & Schipper's estimate of the allocation of Soviet district heat among economic sectors based on estimates of the amount of built floor area in each.

Table 2-IV: USSR Secondary District Heating Thermal Energy by Sector in 1985
[Cooper & Schipper 1991]

Secondary District Heat Consumption	154 mn TSF (4.5 EJ)
Industry	50%
Residential	39%
Municipal	11%
Therefore, Secondary Residential District Heat	60 mn TSF (1.8 EJ)

In homes district heat provides two services: space heat and hot water for consumption. On average, about 20% of residential district heat energy in the USSR provided for domestic hot water, and 80% was used for space heat [Zinger & Malafeev; Zinger, Burd, & Kravitskii]. These estimates were used to calculate the energy consumed for space heating in district-heated residential buildings in the USSR. The results are presented in Table 2-V, with similar estimates for Russia[26].

Table 2-V: USSR Estimated Residential Space-Heating Energy Consumption from District Heating

	USSR: 1985	Russia: 1980
Secondary Residential District Heat	60 mn TSF (1.8 EJ)	51 mn TSF (1.5 EJ)
Estimated Secondary Residential Space Heat from District Heating	48 mn TSF (1.4 EJ); 2.6 % of USSR primary energy use	41 mn TSF (1.2 EJ); ≈ 3.9 % of Russian primary energy use
Estimated Primary Residential Space Heat from District Heating*	61 mn TSF (2.0 EJ); 3.3 % of USSR primary energy use	50 mn TSF (1.5 EJ); ≈ 4.8 % of Russian primary energy use

* assumes a heat conversion efficiency of 79% at central heat stations, the average value in the USSR in 1985 [*Nar. Khoz.*]

Although the figures in Table 2-V refer to a specific sub-sector in the energy economy, in fact they mask a considerable amount of diversity. Characteristics of apartment buildings, district heating systems, and space-heating technologies all vary widely among the former republics and within individual cities. Evaluating these differences, and their relative importance in the structure of energy consumption and in achieving energy savings, is the main objective of this study. The main systemic variations and their significance will be explored in greater detail in Chapters 3 & 4.

Energy Efficiency of the CIS Economy

Two different questions may be asked when evaluating the energy efficiency of the CIS. First, is the economy energy efficient when compared to Western developed economies? This kind of comparison is problematic because of differences between countries that complicate the analysis[27], but it can offer fresh views on energy consumption patterns. Second, one could ask how efficient the CIS economy is in an absolute sense. That is, energy efficiency could be judged relative to consumption levels if certain technologies, behavioral incentives, and management programs were in place[28]. This kind of analysis avoids the complications that often arise in international comparisons.

Several Western authors have performed analyses of the first kind. Even a cursory examination of aggregate economic indicators suggests the relative energy inefficiency of the CIS economy—it did not curb

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[26] the estimates for Russia are somewhat cruder than the USSR estimates, as some Russian sectoral data were unavailable

[27] mainly because of the informational problems mentioned previously, but also because of the radically different structure of energy use in the CIS

[28] according to either the technical or cost-effective energy-saving potential, as discussed in Chapter 1

its energy appetite in response to the oil price shocks of 1973 and 1979. For example, according to Western estimates, in 1985 the USSR's ratio of primary energy use to GNP was about 37% higher than the US ratio, a situation that has not changed since 1975 [Tretyakova & Sagers; Campbell 1983].

Table 2-VI presents a few comparisons of the structure of energy use in the USSR and in the US. The difference in per capita energy use between the USSR and the US is partly due to different levels of economic activity, and partly due to differing energy efficiencies. The housing sector presents a good example of how lower economic activity affects energy consumption: per capita floor area in the USSR is less than a third of US levels (Fig. 1.5; Table 2-VI). Recall from Figure 1.4 that in 1985 residential space heating in the USSR required about 60% more primary energy on average than the same end use in the US (these figures are repeated in Table 2-VI). The USSR's residential space-heating sector therefore represents a significant opportunity for saving energy.

Table 2-VI: Primary Energy Use in the USSR and the US, 1985
[DOE a]

	USSR	US
per capita energy use, GJ/capita		
Total	195	320
Residential	34	40
residential energy use, GJ/m^2 of useful floor area	2.3	0.73
residential space-heating energy use, climate-corrected, KJ/DD-m^2	200	130

Cooper and Schipper conducted a detailed comparison across different economic sectors by examining energy use per unit of economic activity, thus avoiding complexities and ambiguities caused by monetary valuations. Their analysis suggests that CIS sectoral energy efficiencies vary, with some roughly equivalent to those of Western countries, others substantially less [Cooper & Schipper 1992]. Campbell also cites specific examples of Soviet energy inefficiency in industry, agriculture, and transport [Campbell 1983].

Examining past Soviet efficiency improvements provides a useful way to approach the second kind of comparison. Most Soviet energy conservation programs in national plans were ineffective, as the broad energy conservation targets in the 11th and 12th 5YPs were unfulfilled. Some sectors have shown substantial improvements, however. Most energy savings in the USSR since 1960 were achieved in indirect systems, at points of primary energy conversion into electricity or heat.

The Soviets have enjoyed large energy savings in power generation: the average energy efficiency of Soviet power plants has improved dramatically since World War II, and now exceeds the US average

(Table 2-VII). Efficiency was improved by setting norms for the heat rate—the amount of fuel required to produce a unit of electricity. Yet Campbell pointed out that such comparisons should be cautious because the Russian definition of heat rate differs from the US definition[29] [Campbell 1980]; because of this the Russian heat rates should be adjusted upward by about 6%. Further, the computation of Soviet heat rates included secondary heat recovery at cogeneration plants, and cogeneration is much more widespread in the former USSR. As Campbell and others have noted, however, all forms of secondary heat use are not equally efficient, and there is disagreement about how to perform efficiency calculations when secondary heat is fully or partially used. If secondary heat recovery is ignored, the average efficiency of Soviet power plants in 1975 was only about 25%.

Table 2-VII: Published National Average Heat Rates in the USSR and the US since 1965
[Campbell 1980; Wilson; DOE b]

	1965	1975	1985
Heat Rate, grams SF / kWh	415	340	328
Equivalent Energy Efficiency	29%	36%	37%
US	33%	32%	32%

Past Soviet energy efficiency improvements are attributable to high priorities in resource allocation, close supervision by high-ranking Party officials, and the existence of central programs that concentrated resources and managerial attention on particular projects easily identified and controlled by the central planning apparatus. The electric power sector fit well within this framework: its output is homogeneous, its quality and quantity are relatively easy to measure, and it has a single, critical input—fuel. This simplicity allowed planners to focus on minimizing the cost of providing electric power[30], and to determine easily whether plan targets were being met. Improved heat rates in the USSR can be attributed mainly to the penetration of cogeneration, technological improvements in steam turbines, use of larger generating units, and the switch from coal to oil and natural gas fuels. These areas offer little potential for future efficiency improvements [OTA; Gustafson].

Soviet planners' focus on a single indicator of performance, the heat rate, might have led them to invest excessively in energy-saving in the form of too much cogeneration capacity [Campbell 1980]. For example, in the USSR cogeneration plants were sometimes installed without careful examination of local conditions. If the area lacked sufficient demand for either heat or power, the cogeneration plant was run solely as a condensing station (i.e., producing electric power only) or solely as a heating plant, both of

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[29] this difference arises because the Russians use the lower heating value of the fuel, whereas the US method uses the higher heating value. Even after correcting for this difference, however, Russian heat rates are still below those in the US.

[30] that is, the *fuel cost*, normally the largest component of the variable cost; capital (fixed) costs were a different matter

which are less efficient than producing with dedicated units[31]. Focus on heat rate norms also led to excessive fuel switching from coal to oil and gas[32].

Although improvements in conversion efficiency are important, the more fundamental issue of end-use energy savings received relatively little attention in the USSR: past end-use savings in the Soviet economy have been negligible. Soviet analysts blamed short-sightedness for this, asserting that in the 1960s planners assumed cheap oil and gas would be available indefinitely. As a result, old equipment was not upgraded[33], and consumption-related research and development slowed. Soviet and Western analysts agree that future energy conservation efforts should be focused on end uses.

SUMMARY

The USSR's economic system had some unique characteristics that distinguished it from Western market economies. One author described the Soviet system as having an ability to concentrate great scientific effort, funding, and material support on single, specific projects. Each project is then implemented against all odds, regardless of economic realities. The development of the Soviet atomic and hydrogen bombs, nuclear icebreakers and submarines, and nuclear power plants provide a few examples. In the USSR, even economically poor decisions did not lead to bankruptcy or failure. Rather, as the Russian saying goes, "We create our own difficulties which we then successfully overcome" [Rosengaus].

Periodic energy shortages caused Soviet energy policy in the past 15 years to be unbalanced, unstable, and ridden with conflict—short-term concerns predominated, precluding the development of sustained, rational policy. How should energy shortages in the CIS be mitigated? Both supply- and demand-side strategies require substantial new capital investment. The supply-side approach offers two main advantages: the Russians know how to implement it, and its costs, although high, are fairly certain. Conversely, on the demand side the Soviets had few successes—the link between energy consumption and most economic activity in the former Soviet Union remains strong. Furthermore, estimates of the capital costs of energy conservation measures range from 33% to 100% of the cost of equivalent energy supply [Hewett; Gustafson; Matrosov & Butovsky 1993]. This comparison is based on the direct costs of supplying energy, which ignores the even less certain costs of externalities.

The best available estimates of the energy efficiency of the CIS economy place it below Western levels, and below its own technical potential. Broadly speaking, CIS energy inefficiency is a consequence of the historic preference of Soviet planners for an input-oriented strategy of expanding economic output, artificially low energy prices, and the systemic problems of the command economy itself. Western and Russian authors agree that substantial energy efficiency improvements are possible in the CIS, but most

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[31] a more detailed discussion appear in Chapter 4

[32] oil and gas are high-grade fuels; using them increases the efficiency of conversion equipment

[33] for instance, during the transition from coal to oil in the 1970s little new plant was built—most equipment was simply converted

admit that quantifying these savings is difficult. Cooper and Schipper estimated that efficiency improvements of 10-35% are achievable in various CIS economic sectors if performance in these sectors improves to match average energy efficiencies in the West [Cooper & Schipper 1991]. Matrosov and Butovsky assert that the current standard of living with the CIS can be maintained with 30% less energy consumption, and that through renovation energy consumption in residential and public buildings can be reduced by 20% in the near future [Matrosov & Butovsky 1990; 1993].

The question of potential energy efficiency improvements, considered alone, is irrelevant—almost any economy could be more efficient. The real issue is, are energy efficiency improvements desirable? That is, are they cheap enough and certain enough? Can energy service levels in important sectors be maintained? Can improvements be achieved by using appropriate means? Do they benefit the right people, and in the right ways? Introducing these questions makes energy analysis less concrete and more complex, but such issues cannot be ignored—they form the basis of all important policy decisions.

CHAPTER III: THERMAL CHARACTERISTICS OF RUSSIAN APARTMENT BUILDINGS

Methods of providing heat to residential buildings vary among nations, and among regions within nations. An entire spectrum of approaches is possible, ranging from heat sources in individual buildings to city-wide networks providing heat to hundreds of buildings. Individual systems can provide more control over environmental conditions and thus greater comfort under the proper conditions, but centralized systems are often less costly to build and install. Yet even when many designs are available, their popularity depends on cost, availability of required materials and construction expertise, and owners' tastes.

In the US, single-family homes have their own heating systems, and multi-family apartment buildings (MFBs) have either dedicated units for individual apartments or building-wide centralized heat. District heating, in which many buildings are connected into a common heating system, generally appears only in dense urban areas, and most existing systems in the US were built in the late 19th century. Single-family homes in the CIS also generally have their own heating systems. Individual apartment heating units are virtually unknown, however. Some buildings have their own centralized systems with boilers providing the heat, but most MFBs are connected to the city's district heating network. These buildings are the focus of this study.

The district heating sector in Russian cities can be usefully divided into two main subsectors. First is the heat production and distribution subsector, defined in Chapter 2 as the "district heating system," or DH system, which generates heat and transports it through the city to individual buildings. Second is the buildings subsector, consisting of the stock of buildings (residential, public, and industrial) receiving heat from the DH system and distributing it to individual apartments and rooms. This chapter focuses on the residential buildings subsector; the next chapter will address the DH system.

This chapter will identify design energy service levels (indoor air temperatures), the basis for calculating end-use energy requirements for Russian residential buildings (as depicted in Fig. 1.6), and the actual systems providing the energy service in practice. After presenting background material on general building science, hot water heating systems, and climate conditions in Moscow in the first two sections, the third section describes the classification, composition, and construction of the MFB stocks of Moscow, Russia, and the CIS. Most of the material in the third section has not been previously published in detail in the West.

HEATING BUILDINGS

Broadly speaking, building heating systems should reliably provide a comfortable thermal environment for occupants at low cost. While vague, this statement captures the basic objectives of heating system designers, builders, and operators. Specific goals can vary, however, and the constraints in any given situation limit choices and force trade-offs to be made.

Building heating is one part of the broader issue of indoor climate control. Energy requirements for climate control depend on many sets of variables—desired indoor conditions, existing ambient conditions, the characteristics of the building shell, the effectiveness of the heating system, and the behavior of the occupants—which, when combined, determine indoor comfort levels and the energy required to maintain them. Understanding how these factors and their interactions come into play in building heating system design, construction, and operation can explain why energy is needed in certain forms and amounts, clarify how energy is used, and illuminate the most promising areas for efficiency improvements.

The Building Environment

At the most detailed level, the important path of heat flow in evaluating indoor comfort levels starts with the human body. The rate of heat transfer between the human body and the environment governs our sensations of thermal comfort and determines our bodies' reactions to the thermal environment. Ideally, this heat flow would be controlled directly. In practice, however, heat flow from the body is controlled indirectly by controlling the properties of the room air. The internal heat generation within human bodies varies among people, and varies with activity level for each individual. In practice climate systems cannot account for such variations—they are simply designed to provide standard environmental conditions that are comfortable to most people in an average sense. The measurable, controllable properties of room environments, such as air temperature, wall surface temperature, air motion, and humidity can, within limits depending on specific designs, be changed at will to suit different circumstances and different people.

Although air temperature is important in determining the rate of heat transfer from the body, other conditions also come into play. These include the characteristics of both transfer media (skin and environment), their surface conditions, and the area available for transfer. This means that dry air temperature is an imperfect technical measure of thermal comfort—radiative and convective effects must be included in order to accurately measure the rate of heat flow from the body. However, in terms of the analysis of Russian apartment buildings offered here, air temperature will be the most important consideration because it plays the largest role in determining the heating energy consumption in Russian MFBs. The other thermal comfort issues will be considered only peripherally, to the degree that they affect the heating energy needs of buildings.

Heat can take a number of paths from warm indoor air to cold outside air—all three modes of heat transfer normally come into play. Several climatic variables are important in determining the heat flow through a building envelope. Outside air temperature is most important for convection and radiation from the building envelope. The ground temperature determines conduction from the building into the surrounding soil, but for large MFBs this component is normally small. Humidity affects the moisture content of many building materials, which in turn can dramatically affect their material properties. Evaporation, condensation, and vapor flow within building components present additional difficulties. Freeze-thaw cycles can damage materials (and thus the integrity of the building envelope), which may lead to higher heating requirements. Latitude and relative cloud cover determine the amount of heat absorbed from solar radiation. Atmospheric pressure and wind speed affect the film coefficient at the outer surface of the building, and the flow of air through the building. All of these parameters can cause even greater difficulties if they are highly variable [AHoF].

Indoor climate conditions also affect heat flow through buildings. Air temperature, the most important variable, drives conduction through the building shell. Humidity levels determine the heat-carrying capacity of the air, and latent moisture represents a significant source of heat. Ventilation is required to maintain a clean supply of air, but causes cold air to be introduced into the building; this air must be heated to the temperature of the indoor air. The same problem occurs with infiltration, or air leaks through and around building components. Infiltration may be magnified in some parts of the building by outdoor wind speed. In tall buildings, the stack effect (or chimney effect) can be significant, in which warm building air rises relative to cold, dense outdoor air, increasing the flow of air through the building.

Finally, the behavior of the building occupants can affect heating energy requirements [Jennings]. Certain activities, like cooking and bathing, can add substantially to heat and moisture levels in individual apartments. Even more important are the actions occupants take to regulate indoor conditions. This could range from the use (or misuse) of any existing heating controls, to opening windows in overheated or underventilated apartments. Occupant behavior is notoriously unpredictable; designers must simply strive to understand possible behavioral motivations.

Hot Water Heating Systems

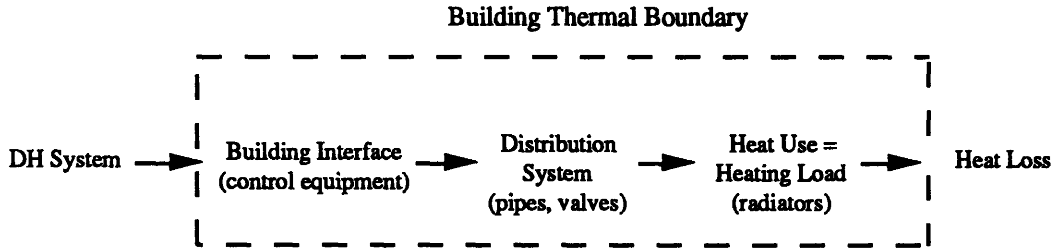
Heating systems for apartment buildings vary widely in their scope and in the method of heat delivery. For example, a system can serve each room individually or an entire building; apartments can be with or without temperature controls; the heat transfer medium can be air, water, steam, or some other fluid; heating units can be electrical resistance heaters, radiators, convectors with or without fans, or air ducts. Even though a wide variety of options exist, the heating systems in Russian MFBs are quite uniform—they use centralized heating systems, usually with radiators or convectors in individual flats. The vast majority of such systems use hot water, although a few steam systems have been installed. The space-heating system generally also provides domestic hot water for consumption.

Broadly speaking, centralized hot water heating systems within buildings can be divided into three subsystems: the heat and flow source; the heat consumption equipment at the points of end use; and the heat distribution system connecting the source to the consumption points. Even though such hot water systems represent a fairly specific form of space heating, designs for all three subsystems vary.

The heat and flow source is always a central facility. In Russian MFBs this is either a boiler and pump or a connection to the DH system. In boiler/pump systems, the water absorbs heat from the products of fossil fuel combustion in the boiler, and is circulated through the distribution system by a pump. This form of heating may be used in a significant number of Russian MFBs, but these buildings are not addressed in this study, as they are not connected to the DH system.

District-heated Russian buildings will be discussed in detail in a following section. Schematically, the disposition of heat energy delivered to district-heated MFBs is shown in Figure 3.1.

Figure 3.1: Disposition of Heat Supplied to District-Heated Russian Apartment Buildings



In Russian apartments heat is often delivered through room radiators, usually formed of cast iron. These devices, like their counterparts elsewhere, are actually misnamed since most of the heat is transferred from them via convection. Radiant output varies with radiator geometry and surface finish, but normally accounts for only 30-40% of the heat output[34] [Jennings]. Low and narrow radiators are generally more effective than tall, wide ones, and end sections transfer more heat than center sections. Fans greatly increase radiator effectiveness. Radiator location can be important too; the configuration that maximizes thermal comfort is along an outside wall below a window, to counter the effects of cold air flowing downward and of radiant exchange with the cold window surface.

In radiators of a given heat flow capacity a trade-off exists between surface area and water temperature. Lower input water temperatures require higher surface areas to transfer the required amount of heat, and vice versa. For a radiator of a given size, the difference between the average hot water temperature in the radiator and the room air temperature is most important in determining heat output [Kut]. The limiting condition for the overall thermal conductance, and therefore the effectiveness, of radiators is governed by the film conditions on the outside, or air side, of the metal.

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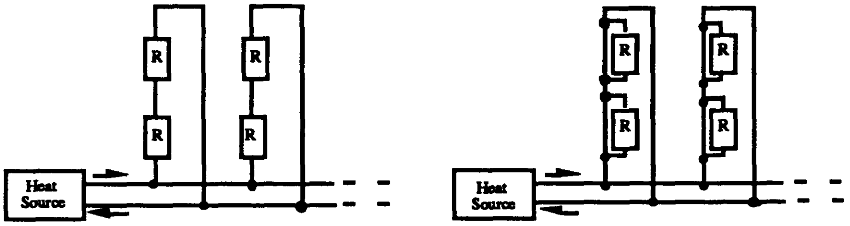
[34] an exception occurs for wide, flat radiators in which most of the transfer surface can "see" the room well, but these are uncommon in Russia

Finally, the heat distribution system consists of a pipe network that carries the hot water from the central heat source to the individual room radiators and back to the source. Understanding the design of the distribution system is important because it can affect internal temperature variations within a building. Distribution networks can use either thermal circulation, in which flow arises from density variations in the water, or forced circulation using a pump. The most common designs are the one-pipe and two-pipe systems, illustrated in Figure 3.2 [Jennings].

Figure 3.2: Pipe Layouts in Centralized Heating Systems

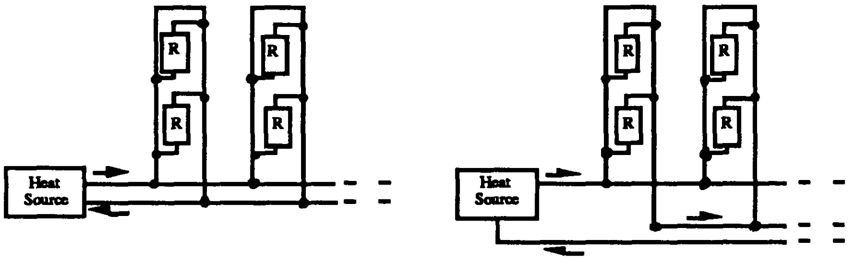
a) 1-pipe, series

b) 1-pipe, diverted



c) 2-pipe, direct return

d) 2-pipe, reversed return



In 1-pipe systems some radiators receive input water that has already flowed through one or more other radiators. One-pipe systems can be either series (a) or diverted (b). The diverted system allows individual control of each radiator; the strictly series design does not. In both cases different radiators receive input water at different temperatures. However, this effect is relatively small for systems with a small temperature difference between the hot water supply and return lines (such as 10-12 °C) [Kut]. The 1-pipe design is relatively unobtrusive to the building occupants, and balances of water flow are relatively easy to achieve. Frequently the radiators in 1-pipe systems are grouped together in separate banks, or sections. The banks are typically connected in parallel, as shown in Figures 3.2 a,b. Russian systems typically use 1-pipe designs (Russian systems will be discussed in detail later in this chapter).

In 2-pipe designs no two radiators are in series; all of them receive input water directly from the heat source. The 2-pipe system may be either direct (c) or reversed (d) return. In direct return systems the outflow from each radiator is sent directly back to the heat source. Since different water paths have different lengths, obtaining proper flow balances through each circuit is difficult. In the reversed return system output water flows from radiators to a common return main, which then runs back to the heat source. However, this system is more costly to build than the direct return system. Two-pipe designs are generally more costly than 1-pipe systems, and require more effort to balance water flows. Their main advantage is a more uniform and more controllable heating pattern within the building.

THE RUSSIAN CLIMATE

The local climate is the main determinant of the annual space-heating energy consumption in buildings; the most effective technical design for an indoor climate control system is defined by the climate. For instance, the effectiveness of active and passive solar heating, natural and artificial ventilation, and humidification systems all depend strongly on climatic conditions. About 67% of the CIS's major industrial centers lie in harsh climatic zones, with early frosts and low winter temperatures. A basic understanding of the Russian climate, particularly in Moscow, is the first step in evaluating MFB heating loads and technical designs.

Temperatures in Russia are relatively cool, with large variations with time and location. The northeast regions of Russia experience some of the most severe winter temperatures on Earth, with January mean temperatures in the range of -45 to -50 °C. Winter temperatures are much milder in the Western regions, roughly comparable to temperatures in the northern Midwest of the United States. The January distribution of temperature in Russia prevails through much of the period from November to March. In March a wave of warmth begins in the southwestern region and sweeps across the country during April. For the southern and western regions, there is little difference between mean temperatures in October and April [Lydolph].

Table 3-I provides data useful for building design in Moscow. The mean of annual minimum temperature is an average value, taken over many years. The temperatures in the columns labeled 99% and 97.5% represent values exceeded 99% and 97.5% of the time, respectively. These design conditions are widely used for various buildings in the US and Canada. The effective minimum temperature in Table 3-I is based on temperature and wind conditions; it is essentially a wind chill factor. More detailed monthly information (taken from Lydolph), useful for estimating space-heating energy requirements, is listed in Appendix A, Table A-I, for Moscow's winter season.

Table 3-I: Average-Year Winter Climate Data for Moscow
[AHoF; Lydolph]

Temperature, °C Mean of Annual Minimum	99%*	97.5%*	Fraction of Time January Temperature is Below: 0 °C	-18 °C
-28	-24	-21	93%	17%

* for the months of December, January, and February

Mean Annual Wind Speed, m/s	Maximum Annual Wind Speed, m/s	Effective Minimum Temperature, °C**
4.5	16-18	-46

** this condition has a probability of occurring once per year

Design Temperatures

Russian building designers use a specifically defined "design outdoor air temperature," T_{out}, in their calculations for building envelope characteristics. This temperature is simply an average of certain temperatures during the 8 coldest winters in a given location over the 50-year design period from 1925 to 1975. The temperatures are taken from either the one coldest day or the 5 coldest days in the design period, depending on the type of external wall construction used in the particular building. This approach provides a design temperature exceeded for 92-98% of the winter heating season (the variance depends on the thermal inertia of the structure, and will be explained later in this chapter) [Matrosov & Butovsky 1990][35]. This contrasts with Western practice, in which designers typically select a 97.5% temperature for residences (as shown in Table 3-I above). The lowest value of T_{out} used in Russia was -60 °C.

Some Russian calculations of annual space-heating energy consumption are based on the "average heating season outdoor temperature," or T_{ht}, defined as the average daily outdoor temperature over the entire heating season. The planned heating season for MFBs began on specific dates in each city, but in practice the heating season generally started during the week the mean outdoor air temperature fell below 8 °C, and ended during the week the mean temperature rose above 8 °C[36]. Usually if the average temperature fell below 8 °C for 3-5 consecutive days, the heating season was begun. Design calculations, however, were based on data from the 50-year design period. The length of the design heating season is represented as Z_{ht}, and is measured in days.

Internal room temperatures were set according to thermal comfort standards. They were designated for various kinds of rooms and buildings. For living areas within MFBs, the design indoor temperature,

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[35] methods of defining T_{out}, and thus its values for a given type of construction, varied over time

[36] this rule apparently was not rigid, and in any case was not strictly enforced; often the heating season started when power plant operators decided it should, as they controlled the provision of heat from DH systems

T_{in}, was generally 18 °C throughout Russia. The only exception occurred in regions in which T_{out} was below -31 °C, when the standard for T_{in} was increased to 20 °C to account for the increased radiative exchange between room occupants and the cold building envelope [SNiP 2.08.01-85]. Theoretically, building components and heating systems were designed to maintain T_{in} at all times.

In Russian practice the various design temperatures are sometimes combined to form standard temperature differences. The design temperature difference, ΔT_d, is defined as T_{in} - T_{out}. The heating temperature difference, ΔT_{ht}, is defined as T_{in} - T_{ht}.

Russian building designers use the product $\Delta T_{ht} * Z_{ht}$, hereafter called "Russian degree-days," or RDD, as an indication of the severity of the heating season. It is analogous, although not equivalent, to the heating degree days statistic widely used in the West. The RDD computation assumes the actual ambient temperature is T_{ht} throughout the entire heating season, and uses the previously described, somewhat arbitrary criterion to define Z_{ht}. Russian degree days would match Western degree days if T_{ht} were defined properly, but the Russian definition of T_{ht}, and thus the accuracy of the RDD method, is unknown. Values of RDD range from 2083 days- °C in mild regions to 11,667 days- °C in the coldest regions in Russia [Drozdov].

Highly variable Russian climatic conditions caused buildings in different regions to be designed according to different constraints. Table 3-II lists the chief Russian MFB design parameters presently used for Moscow.

Table 3-II: Current Design Parameters for Moscow MFBs
[NIISF]

T_{in}, °C	T_{out}, °C	T_{ht}, °C	Z_{ht}, days	RDD, days-°C
18	-26 to -35*	-2.7	220	4554

* depending on the type of construction

RUSSIAN APARTMENT BUILDINGS

Recall from Chapter 1 that one of the motivations for this study was the analytical simplicity arising from the apparent uniformity in the structure of the Russian MFB stock. Indeed, casual observation leaves one with the impression that the housing units are nearly identical—all large Russian cities contain mile after mile of high-rise, rectangular, concrete-walled apartment buildings (Appx. D, Fig. D.1). Internal similarities are also striking: all MFBs have centralized heating, and most are connected to district heating systems. The extent of these similarities determines the degree to which estimates of energy consumption and energy savings can be accurately extrapolated from a single building to other buildings. This section focuses on exploring the diversity of thermal characteristics in Russian apartment buildings, describing the various designs used for building envelope components and heating systems, the historical development of building codes since the beginning of the housing drive, and the main problems that surfaced in envelope heating system designs after their widespread use.

Understanding space-heating energy consumption patterns in Russian MFBs is a prerequisite to determining potential energy savings and the major impediments to achieving those savings, as establishing consumption patterns establishes a baseline against which to measure efficiency improvements. The first step in analyzing energy use is determining the desired indoor conditions—the proper energy service levels. Here the energy service is simple and clearly identifiable: maintaining an indoor air temperature of 18 °C in all living areas at all times. Providing this service, however, is much more complicated: air constantly flows through all buildings at varying rates, and under winter conditions heat is constantly lost from indoor air, also at varying rates.

The end-use space-heating energy requirement is the net flow of heat energy needed to maintain the desired indoor conditions in a building; it is also known as the *heating load*. The heating load is the difference between the total rate of heat loss from the building and the total rate of heat gain (from internal sources and from incident solar radiation). Thermal energy equal to the heating load should be supplied by the building's heating system.

Heating loads, both design and actual, are determined by the characteristics and by the use of all equipment that causes changes in indoor air temperature: heat provision systems, air exchange systems, and building envelopes. The actual heating load is governed by existing climatic and indoor conditions, thermal properties of real buildings, and the behavior of building occupants. The best way to determine the actual heating load is to measure it experimentally under known conditions. Unfortunately, such experiments were rare in the USSR. One recent Russian field experiment on a modern apartment building in Moscow produced useful results, however; this experiment will be discussed extensively in Chapter 5. The design heating load is determined by assumed climatic and indoor conditions and theoretical calculations of building envelope characteristics. Design thermal properties of building envelopes were defined in SNiPs published by *Gosstroi*.

The remainder of this chapter addresses design and actual heating loads in Russian MFBs. The first section describes existing design variations in MFB envelopes and heating systems, and the reasons for these variations when they are known. The second section describes the evolution of Russian building codes. The third section presents estimates of the structural composition of the Moscow, Russian, and CIS housing stocks. Finally, the chapter concludes with a discussion of how design and actual operating conditions affected the provision of proper indoor temperatures and annual space-heating energy consumption.

Building Characteristics

Architecture and Systems of Standardization[37]

This section will describe the various systems of standardization used by Russian architects in designing apartment buildings. The discussion builds on the contextual material in Chapter 2, illustrating how constraints unrelated to the provision of comfortable indoor air temperatures affected space-heating energy consumption, and exploring the diversity of building designs actually used in practice. Apartment building designs, generally highly standardized, were prepared by local state design institutes, usually controlled by local *Soviets*.

Russian architectural philosophy evolved over time, driven by the will of planners and the mood of the populace. Both were affected profoundly by changing circumstances. Before World War II many Russian buildings retained the traditions of the past, with ornately decorated exteriors and finely detailed finishing. The dramatic housing shortage of the post-war period left Russian architects with new and very different requirements, however: apartments had to be erected as quickly as possible, and they had to utilize the USSR's most available building material—concrete. This led to the widespread standardization of building components and procedures, and large-scale use of prefabricated elements. Building design came to be determined solely by the requirements of rapid construction techniques. Yet this too changed with time as the Russian people grew weary of the endlessly repetitive housing blocks that resulted.

During the first post-war years the shortage of building materials, mechanisms and skilled workers limited new building heights to 1-2 stories. Yet this approach could not be used to meet the enormous demand for new dwellings because large numbers of such buildings would have been a waste of valuable urban territory. Soon a changeover to building multi-story houses began in all cities. Early experiments demonstrated that realizing the full potential of prefabrication methods required producing only a small number of standard designs. However, the standards needed to be flexible enough to ensure a diversity of structures to meet different aesthetic and functional demands.

At first the Soviets adopted the simplest and most effective approach to prefabrication: standardized finished projects, or the "standard house." All buildings had a rectangular shape, and were limited to 5 stories in height (Appx. D, Fig. D.2). Standard windows were designed to fit within standard wall components, which fit together in standard ways. This allowed greater productivity of labor in construction, permitted the use of less qualified engineers for design work, and provided a way for production to continue in bad weather. The Soviets believed this system would be much faster than less standardized approaches [Ramsey]. By 1958, 77% of all new MFBs in the USSR conformed to standard designs, and by 1965 fully 95% had conformed to them [Kudryavtsev].

Although the standard house denied flexibility to Russian architects, it initially won public approval, largely because housing construction rates increased quickly in the late 1950s (Fig. 2.3). Further,

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[37] except where cited otherwise, the material in this section was taken from Ikonnikov

the image of regularity of the new style was, in the minds of many, linked with the associations of the space age that was just beginning. The buildings were clearly ordered, seeming to meet a criterion of truthfulness. This contrasted sharply with the "untruthfulness" of the decorative forms of the late 1940s. Yet the similarity of buildings and whole districts in different cities began to make itself felt—uniformity and unrelieved monotony became an increasing source of irritation for Soviet citizens. The impact of this objection was probably lost on central planners—according to Kudryavtsev, a popular view among planners held that "better a monotony of comfort than a diversity of discomfort." Nevertheless, during the 1960s architects strove for more originality in housing designs.

Economic criteria still dominated new housing designs in the 1960s. Use of prefabricated components was growing: in 1962, 15% of the volume of state-owned new housing was prefabricated nationwide; by 1965 this proportion had reached 30%. In Moscow alone, 65% of new housing was prefabricated in 1963 [Dykhovichnyi]. Sometimes architectural designs were affected by available construction systems: standard designs for flats had multiple variants to account for different kinds of wall construction[38]. In the 1960s diversity was achieved by combining buildings in a mixed construction pattern, allowing complexes containing buildings of different types and heights[39]. Contrasts between low oblong volumes and vertical towers were an apparent solution to monotonous skylines, but an excessive fascination with such contrasts proved self-defeating: the multiple repetition of these groups became monotonous itself.

The 1970s saw a transition from the standard house to more elementary units of standardization. Experiments had shown that diverse housing units could be constructed using a small set of standard construction elements. This led to the development of two new techniques: the block-sectional approach, and the open-ended system. The block-sectional approach was the first to develop. It was based on the use of different sets of flats, building heights, and building section configurations. By dividing buildings into separate "blocks", or groups of flats, buildings could be assembled of virtually any length or shape. In one example of block-sectional construction, the main street of a residential area was lined with 16-story tower houses, while the neighborhoods contained 9-story oblong block-sectional buildings complemented with sections connected by triangular inserts. The outline of such buildings resembles a hockey stick.

The second method is in principle more radical: a completely open-ended system of standardization. Here the primary unit is a basic construction element (wall panel, window, door, etc.), which is part of a universal set. From such a set one can assemble buildings with radically different external shapes and interior layouts. With only slight modification, all modular components are interchangeable between different building types, allowing many combinations to be formed from a few basic components. Theoretically, while preserving all the advantages of prefabrication, this method would

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[38] namely, 1-module and 2-module wall panels, to be defined shortly

[39] for example, 10-12 story towers were often surrounded by clusters of 5-8 story buildings

allow a return to customized building design. Yet the Russians found the open-ended system difficult to implement on a large scale.

The change to more flexible standardization systems made new housing much more diverse than the standard houses. According to Kudryavtsev, before 1970 only four major kinds of apartment building were widely built in Russian cities. During the 1970s hundreds of new designs became available, yet only about 10% of them have been widely used since that time. Administrative problems (coordination of different designs, resistance to change, etc.) likely explain why the remaining 90% were not used.

Apartment building designs varied throughout Russia; by the 1970s differences between building designs in Leningrad and Moscow became clearly established. Moscow architects developed housing as separate residential districts, but Leningrad architects focused more on the urban context—the immediate surroundings of the complex and the image of the city as a whole. Since architects and planners in other cities looked to Moscow and Leningrad for examples, the stylistic differences between apartment houses in the two cities profoundly influences the evolution of the Russian and Soviet housing stocks.

Heating Systems

Heating systems in Russian district-heated MFBs consist of three basic components: the heat source and its associated control equipment (at the interface between the building and the DH system), an internal heat distribution system (pipes, valves, etc.), and end-use heat delivery equipment (e.g., radiators and convectors). In Figure 3.1 these correspond to the three leftmost items within the thermal boundary of the building. Each of these systems affects the delivery of heat to living spaces: control equipment determines whether the heat delivered to a building matches the actual heating load; distribution equipment affects the proportion of heat delivered to each flat; end-use equipment determines the amount of heat transfer into living areas.

Heat Sources

The heat source is a direct connection to the DH system. The connection itself consists of either one, two, or four pressurized hot water or steam pipes[40] passing through the building envelope, usually in the basement (as most systems are hot water, the remaining discussion will focus on hot water systems). The properties of the incoming DH water (e.g., temperature, flow rate) are set by operators of central DH heat stations, and sometimes modified by control equipment in the DH distribution system (i.e., by equipment external to MFBs). Ideally, the DH system should provide heating supply water at precisely the right temperature and flow rate to meet the bulk space-heating load of each building. Heat measurement and control equipment normally ensure proper heat delivery, but in Russian MFBs such equipment is rare. Heat meters are essentially non-existent, and control equipment varies in scope and effectiveness. Most district-

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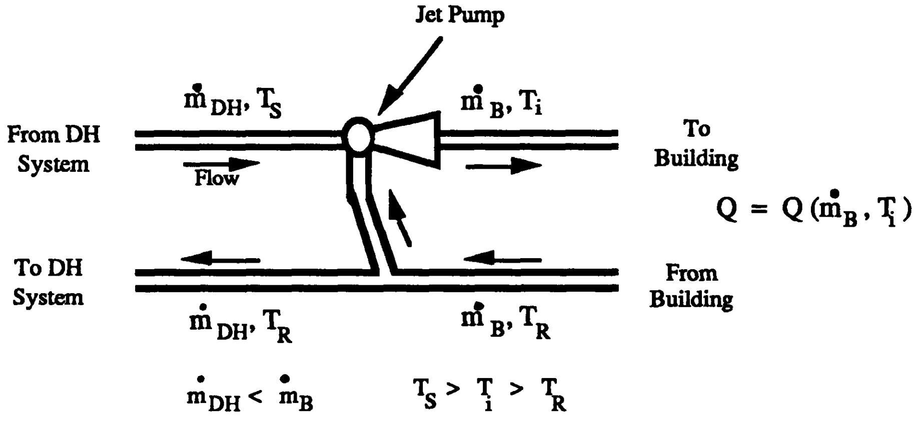
[40] depending on the precise type of DH distribution system being used

heated MFBs on hot-water heating systems also receive domestic hot water for consumption from the same system (Chapter 4 will describe the design and operation of the DH system).

Most Russian MFBs have one of two kinds of DH interface: 1) a heat exchanger, with a separate water circuit within the building, or 2) a jet pump. The jet pump is the most common approach [Matrosov; *Therm. Engr.*]. A diagram of the jet pump (also called an elevator pump, ejector pump, or variable-speed pump) appears in Figure 3.3, and Figure D.3 in Appx. D displays a photograph of a jet pump in a modern apartment building in Moscow. The jet pump operates between connections to the DH supply and return lines, recirculating part of the building's relatively cool return water, mixing it with hot DH supply water. The mixture emerging from the jet pump, with a lower temperature and higher flow rate than the DH supply water, then enters the building's heating system.

Figure 3.3: Diagram of Building Jet Pump



Jet pumps are not pumps in a literal sense. Each jet pump contains a nozzle operating on the venturi principle—the amount of return water recirculated through the jet pump depends on the flow rate of the DH supply water. The ratio of the recirculated return water flow rate to the flow rate of DH supply water is the ***mixture coefficient*** of the jet pump. The mixture coefficient is the jet pump's control parameter, set manually during system installation. The jet pump is a passive device: once the mixture coefficient is set, it remains constant unless manually reset. Usually adjustments were only made during maintenance inspections—once every few years—or sometimes at the beginning of each heating season[41]. Thus, since $\dot{m}_{DH}$ is essentially constant throughout the heating season, $\dot{m}_B$ is constant.

Heat flow into buildings is controlled by varying the temperature of the DH supply water, T_S. As ambient temperatures drop, T_S is increased (via actions taken by DH system operators), which in turn raises T_i, the temperature of the water mixture flowing into the building (because the jet pump mixture coefficient remains constant; see Fig. 3.3 above). District heating system operators set T_S according to a predetermined design temperature schedule: the ***grafik***. A standard ***grafik*** format is used in all cities, listing DH water

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[41] although jet pumps within buildings housing high-ranking officials were apparently adjusted more often

temperatures (T_S, T_i, & T_R) as a function of ambient temperature. The tabulated values within the *grafiks* vary with climate conditions—different cities have different schedules. A detailed discussion of DH *grafiks* and control procedures appears in Chapter 4; a sample *grafik* is shown in Fig. 4.8.

Jet pumps are instrumental in implementing the DH system's *grafiks*, as they allow partial control over the properties of the water mixture entering the building. Increasing the mixture coefficient (via manual adjustment) increases the flow of recirculated return water, which lowers the supply (T_i) and return (T_R) water temperatures in the building's flow circuit, which lowers the rate of heat transfer into the building. A higher mixture coefficient also <u>reduces</u> the flow of DH water into the jet pump because it increases the hydraulic resistance of the flow circuit (the pressure difference across the DH supply and return lines is constant by design).

Jet pumps were generally set to meet the building's heating needs at the design condition, i.e., during the coldest weather. Thus, even if jet pumps are properly set, they may deliver improper amounts of heat during mild winter weather. A second, more effective kind of jet pump was introduced in Russia in about 1985, but has not become widespread. It provided feedback control, automatically varying its mixture coefficient based on outdoor and indoor air temperatures. Russian experiments showed that these jet pumps reduced overheating of apartment buildings [Zinger 1983].

Distribution

Newer MFBs, or most of those constructed since the start of the housing drive, contain a number of clearly defined, separate building sections—groups of vertical columns of flats, all accessible from a single stairwell. The heating elements of all flats within each individual building section are interconnected, with a common link to the DH supply line in the basement. Each building section often has its own jet pump, separately connected to the DH supply line. The building sections were apparently connected in parallel. Some buildings, however, had a single jet pump serving the entire building. This is especially true in 5-story buildings constructed in the late 1950s.

Within building sections, the heating elements are generally grouped in separate risers, or vertical columns. The number of risers per building section varies, depending on specific designs (e.g., flat designs and arrangements). Apparently, the heating elements within an individual flat are not necessarily grouped together: different radiators within a flat may be connected to different risers. The pipe layout within most building sections is the 1-pipe design, with either series or diverted connections to heating elements (Fig. 3.2). A few buildings constructed before 1960 used 2-pipe systems, but they are believed to be far less common [Matrosov; RCG]. The 1-pipe system was the preferred design, because its initial costs were 7-10% lower than 2-pipe systems, and the labor intensity of their construction was 75% lower [Dykhovichnyi]. It is not known whether the supply water is consistently passed to lower or upper floors first; the designs probably vary. Apparently internal distribution pipes were rarely, if ever, insulated, although the DH supply pipes entering buildings generally *were* insulated upstream of the jet pump.

End-use

Before 1960, radiators were the most common heating elements in flats. Because of radiators' high metal content and high labor requirements during assembly, and because of the difficulty of industrializing their installation, other heating technologies were sought by Russian building designers. The first widely used alternative—requiring 60% less metal to make, and 32% less labor to install compared to radiators—was introduced in 1955: heated wall panels [Dykhovichnyi]. In the panel system the hot water is circulated in pipes embedded within prefabricated internal or external wall sections. The water thus directly heats the walls, which in turn heat the room air. Unfortunately, without adequate exterior insulation the walls also tend to heat the outside air. Panel heating is also employed in other countries, but the heating coils normally appear in the floor or ceiling panels[42].

A second innovation of the 1960s was the development of convectors, consisting of two parts: a steel tube circulating the heat-carrying medium, and steel ribs to transfer heat into the room. In the mid-1960s, 15 different kinds of convector were used, with varying tube diameters, tube lengths, rib sizes, and rib spacing [Dykhovichnyi]. Compared to radiators, convector production was simpler and easier to industrialize, the units used less metal, and labor costs were 40% lower. According to Dykhovichnyi, convectors also provide more uniform room heating because their heating surfaces are longer. Some convectors had adjustable dampers permitting partial control of air flow through the units. Photographs of radiators and convectors in Russian MFBs appear in Appx. D, Fig. D.4 - 5.

Radiators and convectors are heat exchangers: the heat delivered to the room air from a given unit depends on the temperature and flow rate of the room air, and on the temperature and flow rate of the water in the heating system, controlled by the DH system and the building's jet pump. The number of heating elements in each flat varies, depending on flat designs. In rooms with windows, the heating element is usually properly placed under the window. Heating elements were connected in either the series or diverted piping arrangement. Most heating elements were designed with no controls for regulating heat output, but some radiators in diverted 1-pipe systems did have manually-operated valves, and apparently some heated wall panels had control valves. The purpose of the valves is unknown, however; they might have been used simply to balance the flow through the system.

Envelope Construction

Building envelopes are made up of several elements: walls, windows, doors, attics, and basements. The composition of these elements, and the ways the elements fit together, affect the rate of heat loss from buildings (in Fig. 3.1, the rightmost component, partially within the building thermal boundary). A few general comments are in order before describing the construction systems used in Russian MFBs in detail.

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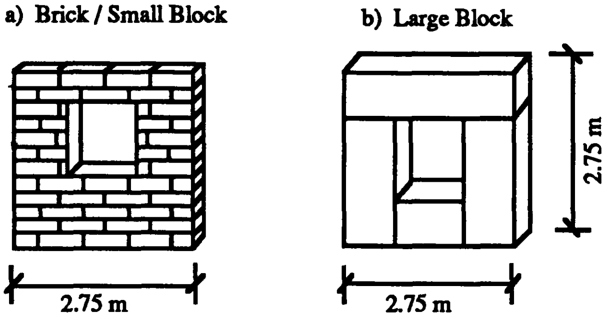
[42] generally the "reversed heat loss," or heat flow through the wrong side of the panel, is about 10% for ceiling panels and 25% for floor panels [Kut]. This loss is probably higher for wall panels. These figures apply to US and Western European systems; thus, they are probably different for Russian panels.

First, nearly all construction systems used the USSR's most available building material: concrete. At least four major varieties of concrete were common: high-strength concrete, reinforced concrete (both of which are considered "heavy concrete"), lightweight concrete, and *keramzit*. Within each major category, density, thermal conductivity, and other properties varied further depending on which materials were locally available. *Keramzit* was formed from expanded clay aggregate, providing very light weight and relatively high thermal resistance; its use was preferred in many designs when it was available. Second, in most Russian MFBs the wall elements themselves bear the building's structural loads. Some systems have exterior load-bearing walls, others interior; some have longitudinal load-bearing walls, others transverse. Internal load-bearing walls allowed either lightweight concrete or *keramzit* to be used in external walls. Third, in spite of the broad commitment to precast concrete, the Russians used at least two industrialized housing systems employing site-cast concrete: monolithic, and panel-framework (these will be described shortly). Fourth, types of wall construction must be distinguished from methods of building assembly. Wall construction refers to the composition of individual wall sections, but building assembly refers to the ways entire rooms and building stories were assembled out of individual components. Only four basic kinds of wall construction and three kinds of building assembly were used in Russian MFBs (again, these will be described shortly). Finally, design trade-offs limited the use of some kinds of construction in some areas. For example, if certain materials, factories, or construction equipment were not available locally, builders were sometimes unable to use the most effective building designs. For example, many regions lacked the resources needed to produce highly preferred *keramzit* in sufficient quantities [Matrosov].

External Walls

The four major kinds of wall construction will be described in roughly chronological order of development. Two kinds of wall construction have been used in MFBs since the 1930s: brick/small-block, and monolithic [Matrosov]. In monolithic wall construction the concrete walls are cast on-site by erecting temporary molds. When the first-story walls have hardened, molds are moved up one level, and the walls for the next story are poured. The process is continued until the top floor is completed. Monolithic construction is relatively uncommon in MFBs. Brick construction, and its close relative, small-block construction, were widely used in MFBs before the start of the housing drive. Since then, however, they tended to be used only for residences of the privileged (e.g., high-ranking party officials). The bricks (or blocks) are small; their dimensions range from several centimeters (bricks) to about half a meter (small blocks; see Fig. 3.4a).

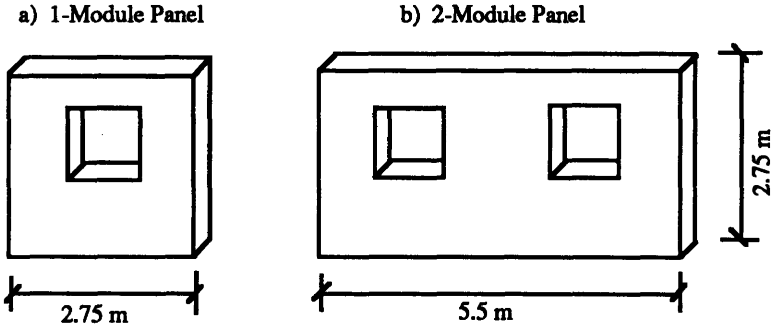
Figure 3.4: Two Kinds of Block Construction



The third major kind of wall construction consists of the assembly of large precast concrete rectangular blocks (Fig. 3.4b) [Ikonnikov; Matrosov]. The blocks are larger than bricks, yet smaller than complete wall panels—their dimensions range from about 0.25-3 m. Most large blocks were solid throughout, cast of concrete. A second type was also used, in which the large blocks were prefabricated out of bricks, but these were uncommon. Hollow versions of both large blocks and bricks were produced, but apparently were rarely used [Savchenko].

The large-block technique was favored by architects in Leningrad. In Moscow, on the other hand, the quest for a specific architecture using prefabrication principles resulted in experiments with large-panel buildings. Large-panel wall construction is made up of precast entire wall sections, including window openings. The large-panel system was less labor-intensive, and offered more flexibility and faster construction: labor per house dropped by 35-40%, and construction time per house dropped by 33-50% compared to block-based techniques [Dykhovichnyi]. Two panel sizes were used: the 1-module panel and the 2-module panel (Fig. 3.5). The 2-module panel was about twice the size of 1-module panels, enclosing two rooms in the building instead of one. The 1-module panel evolved first, but the Russians hoped 2-module panels would allow even faster construction times and reduce infiltration losses because they required fewer joints.

Figure 3.5: Two Large Panel Designs



The composition of large panels varied tremendously: many different kinds of panel were developed, made of different materials, with different internal configurations, all with different thermal properties [Matrosov; Matrosov & Butovsky 1989; Dykhovichnyi]. The first design widely used had three layers, consisting of concrete, thermal insulation (either mineral wool or foam plastic—{polystyrene}), and concrete, respectively. The two concrete layers, designated as "shells," were connected with small-diameter metal ties (Fig. 3.6c). The inner concrete layer bore the structural loads; the outer layer protected the assembly from the elements, and was free to deform with changes in temperature. Although the two concrete layers had very different functions, in initial designs they were formed identically from heavy concrete. The metal ties connecting the shells in these panels suffered from corrosion, as initially stainless steel was unavailable [Dykhovichnyi].

A second 3-layer large panel design connected the concrete layers with internal, lightweight concrete ribs instead of metal ties (Fig. 3.6d). Several varieties were used, each with different thermal properties. For example, the ribs could either pass entirely through the panel, or stop midway through it, crossing with perpendicular ribs in the center. Sometimes ribs were used around window frames; if so, they were absent elsewhere in the panel. If highly flammable and toxic foam plastic was used for the internal insulation layer, ribs were always included around the panel edges. Rib width and spacing varied: one highly industrialized design used 2-cm wide ribs, spaced roughly every 20 cm in a grid along the inside of each concrete panel shell, giving the shell the appearance of a waffle. Ribbed panels were simpler to make than 3-layer panels with metal ties, and avoided the metal corrosion problems. Because the ribs formed significant thermal bridges between the concrete shells[43], however, ribbed panels were less thermally efficient than tied panels [Matrosov & Butovsky 1989]. Finally, some 3-layer panels employed both metal ties and ribs[44].

Single-layer large panels were also widely used. The panels were cast of solid heavy, lightweight, or *keramzit* concrete, depending on which was locally available (Fig. 3.6a). Panel thickness depended on whether the panel was used in an internal or external wall; 1-layer panels were generally thicker than 3-layer panels in order to satisfy thermal norms. Some 1-layer panel designs might have included rectangular blocks of mineral wool or foam plastic insulation inside the panels. Although this provided such panels with the features of a multi-layer design, apparently the panels were still classified as 1-layer panels [Matrosov]. Single-layer panels were generally preferred because of their lower costs and simplicity of manufacture, but the thermal performance of *keramzit* panels, potentially the most effective design, was highly sensitive to the quality of both the clay aggregate and production methods [Dykhovichnyi].

Finally, the third basic panel design was the 2-layer panel, consisting of an inner, heavy concrete layer bonded to an outer layer of either lightweight concrete or *keramzit* (Fig. 3.6b). Sometimes the layers were connected with metal ties.

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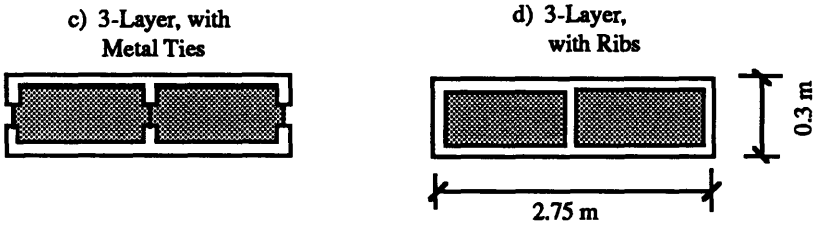
[43] the effect of these ribs on the thermal performance of the panels will be discussed later in this chapter

[44] ribs were often added to provide better fire protection in panels employing flammable insulation material

Figure 3.6: Cross-Sections of Four Large-Panel Wall Sections (viewed from top)

a) 1-Layer

b) 2-Layer



c) 3-Layer, with Metal Ties

d) 3-Layer, with Ribs

Building Assembly

Three basic methods of building assembly were used in Russian MFBs: direct, panel framework, and volume block [Matrosov; Dykhovichnyi]. Direct assembly was most common, in which load-bearing wall sections comprised of bricks, large blocks, or large panels were individually assembled into complete structural units.

The other two kinds of building assembly were both based on large panels. First, in panel-framework construction, load-bearing columns were erected on site. Floor slabs were then cast in a stack around the columns at ground level, and jacked into place when they were strong enough. With the columns and floors in place, standard structural large panels were used to enclose the flats (Fig. 3.7a). Technically the structural panels were not needed since the columns bore the loads, but in early designs non-structural panels were unavailable[45]. Different kinds of large panels were used in panel-framework construction, depending on the design, and on what was locally available. There were three kinds of panel framework building: 1) pure framework, in which the frame bore all loads; 2) combined loading, in which wind loads and structural loads were both shared by wall panels and the framework; 3) partial wall loading, in which the walls bore wind loads, and the framework bore structural loads [Dykhovichnyi]. The second method was preferred; it required less steel, yet still provided adequate structural rigidity. Unfortunately, the columns tended to form significant thermal bridges through the building envelope.

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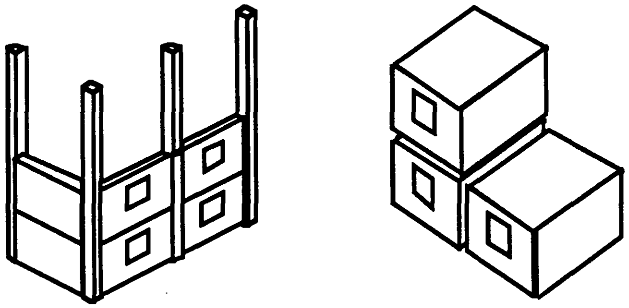
[45] because of the time and labor needed to gear up new factories

Figure 3.7: Two Building Assembly Methods



a) Panel Framework

b) Volume Block

Second, in volume-block construction, the walls and ceiling of enclosed blocks (rectangular boxes) were prefabricated as a unit. At the construction site the blocks were jacked up and stacked to form a building (Fig. 3.7b). This approach allowed very fast construction times. Different kinds of large panel were also used in the volume-block approach.

Joints between wall panels—butt-joints—must be sealed during building assembly in the direct and panel framework assembly methods. Older Russian butt-joint designs (in the late 1950s to early 1960s) were seriously flawed: adjacent construction elements simply rested side-by-side, with the gaps sealed with pliable compounds. Even if perfectly built, their protection against moisture penetration and heat flow was inadequate, as gaps led to rapid corrosion of metal ties, and heat losses through infiltration. Monolithic joints, using interlocking construction elements, were developed in the 1960s, in which the entire length of all interlocking zones was sealed with heavy concrete. Further, hermetic sealant provided an external water-tight film, preventing moisture diffusion and reducing infiltration by 66-75% compared to non-monolithic butt-joints [Dykhovichnyi].

Windows and Balcony Doors

Window designs in Russian MFBs are nearly as varied as kinds of external wall construction. In most MFBs the windows fit within standardized openings in wall sections. Windows are generally grouped together to form compound units, with panes of different sizes separated by sashes. Single, double, and triple-glazed windows were all used, depending on the requirements of building codes in a given region. Most windows in MFBs are double-glazed; triple-glazed units were used only in towns with the coldest weather, and single-glazed units were used only in mild regions. Window sashes were generally made of wood or aluminum, and the sashes were either coupled, as a single unit, or uncoupled. Some window units had casements; others did not. Window area in MFBs was restricted to about 15% of the external wall area of the living rooms and kitchen [Matrosov].

In most MFBs a balcony was connected to the living room of each flat. The balcony door was generally about 2.5 m in height, but much narrower than flat entry doors (Appx. D, Fig. D.6). Balcony doors are integrated with the window units in the living room: the upper two-thirds of the door is normally glazed. This suggests that balcony door designs may be as varied as window designs.

Data on the penetration of various window designs are scarce. Russian authors estimate that throughout the CIS about 5-7% of windows are single-glazed, 67-70% are double-glazed, and 20-23% are triple glazed, most with wooden sashes [Matrosov & Butovsky 1993; Dykhovichnyi]. Of all double-glazed windows, about two thirds have coupled sashes, and about one third have separate sashes. Apparently very few windows were treated with coatings or separated by high-R gases [Cooper & Schipper 1992], and about 90% of MFB windows lack weatherstripping [Yudzon; Savchenko]. Even when weatherstripping is present, it is usually of low quality [Matrosov].

Attics and Basements

There were two kinds of roof construction used in Russian MFBs: those with attics, and those without attics. In the non-attic approach, a slightly sloping roof was built above the top floor's ceiling, with an apex of about 0.5 m in the center. Some ceilings had multi-layer composite construction, others were 1-layer concrete panels. Non-attic roofs were either ventilated, permitting inflow of outside air, or non-ventilated, completely sealed from outside air. In non-ventilated designs, moisture diffusing up from the building interior collected within the roof insulation, lowering the roof's thermal resistance and potentially damaging its construction. Ventilated roofs, conversely, dried quickly. Most roofs built before 1965 lacked attics, because their construction required less material and labor.

Roofs with attics also came in two varieties: warm-attic and cold-attic. The warm-attic technique reduced conduction losses by venting warm room air to the attic[46] before releasing it to the atmosphere; cold attics lacked this feature. Warm attics have drawbacks, however: exhaust air is sometimes recirculated back into the flats in windy weather and during summer months, and the attic air is more humid, which can degrade the performance of insulation materials. The warm-attic was used mainly in Moscow [Matrosov].

Cellar designs varied with regional conditions. Two kinds of cellar were used in Russian MFBs: warm and cold. In warm cellars, heat losses from the building's hydronic pipes warm the cellar air, thus reducing conduction losses from the ground floor to the cellar compared to the cold cellar design. Cold cellars contained either insulated pipes or separate chambers housing the pipes.

The warm-attic technique increased the equivalent reduced thermal resistance[47] of the top of the building by up to a factor of 5 compared to the cold-attic approach (from R=1 to R=5 {m^2°C/W}). Similarly, the design reduced thermal resistance of warm cellars was triple that of cold cellars (R=3, vs R=1 {m^2°C/W}) [Matrosov]. Apparently *net* energy savings were unimportant; higher losses from the DH pipes might have cancelled the energy savings in warm cellars in practice.

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[46] flowing upward from interconnected vertical columns of flats

[47] defined with respect to the total heat flow through the ceiling; the definition accounts for the higher air temperature in the attic

Ventilation

Unlike other building systems, ventilation systems in Russian MFBs are fairly uniform. Apartment buildings universally depend on natural, or density-driven, circulation for their fresh air flow; none have forced-air ventilation systems. The natural air circulation is driven by the stack effect, and occurs via infiltration through building envelopes. The only significant variance in ventilation systems is in the degree of central connection within the building: in modern MFBs vertical columns of flats are connected by a common air shaft, in which each flat's exhaust air travels up to the building attic, where it is either deposited to the attic (warm-attic technique) or discharged to the environment. In older, 5 to 9-story MFBs ventilation air was exhausted directly from each flat.

Building Classifications

Russian apartment buildings are classified by "series number." Each building series represents a specific building design. The designs are distinguished by assembly methods, types of wall and floor construction, placement of load-bearing walls, total building height, flat designs, and so on. These traits address overall building performance, not only thermal performance; therefore, series numbers do not classify buildings exclusively in terms of their envelope thermal properties. Yet, since construction and assembly methods largely determine envelope thermal properties, the series designations are important. Table 3-III presents a sample (not a complete list) of the building designs used in Moscow near the beginning of the housing drive (design thermal properties of the buildings will be discussed later in this chapter).

Table 3-III: Five Kinds of New Prefabricated Apartment Buildings in Moscow, 1956-1965
[Dykhovichnyi]

a) General Characteristics*

Series	Load-Carrying Component	External Wall Construction	Internal Wall Construction	Attic
1-515	Longitudinal Walls	1-Lyr. Panel	1-Lyr. Panel	Cold
1605	Longitudinal & Transverse Walls	3-Lyr. Panel	1-Lyr. Panel	None
K-7	Transverse Wall Girders	3-Lyr. Panel	Wall Girders	None
II-35	Transverse Walls	3-Lyr. Panel	3-Lyr. Panel	N.A.
II-32	Transverse Walls	3-Lyr. Panel	1-Lyr. Panel	N.A.

* N.A. = not available

b) Wall Panel Construction**

Series	Longitudinal	Transverse
1-515	Int: heavy, 20 cm (thickness) Ext: *keramzit*, 40 cm	Int: ferro-concrete, 14 cm Ext: same as longitudinal
1605	Int.: N.A. Ext: ferro-concrete / insulation / ferro-concrete, 4 cm / 13 cm / 4 cm	Int: ferro-concrete, 12 cm Ext: same as longitudinal
K-7	Int: N.A. Ext: cement / insulation / cement, 3 cm / 10 cm / 3 cm	Int: girders Ext: girders
II-35	Int: 2 shells Ext: shell / insulation / shell	Int: 2 back-to-back shells Ext: same as longitudinal
II-32	Int: N.A. Ext: insulation / inlaid brick / ceramic tile, 1.5 cm / 12 cm / 0.5 cm	Int: inlaid brick, 12 cm Ext: same as longitudinal

** Int. = internal walls; Ext. = external walls

Table 3-III emphasizes the potential diversity of MFB structures: all building series listed were "standard houses," but different series used different kinds of wall construction. The table suggests that walls within single buildings also varied; even *external* walls within a single building varied in some cases[48]. Only a few building series (1-515, 1605, others in later years) were widely used; others were only short-lived experiments (K-7, II-35, II-32). Experimental building series often contained new types of structural members (e.g., wall girders, double-shell panels, inlaid brick). The series designation is still used today in Russian MFBs; sample large-panel series numbers from recent years include P44, KOPE (both 3-layer), P3, P30, P46, and P55 (all 1-layer).

In practice, then, the general large panel designs described previously each comprise a rich diversity of specific designs. The diversity is the result of continuous experimentation with industrialized construction methods, in a constant effort to produce housing faster and less labor-intensively. Panel production techniques, internal geometries, and material composition varied through time because of the experiments, and among regions depending on locally available materials.

Summary of Possible Building Envelope Characteristics

Table 3-IV presents a summary of the space-heating-related building systems described in this chapter. The chief design variations are listed, along with the approximate times of their widespread introduction into new housing construction.

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[48] see chapter 5 for an example of a building that has external walls with varying thermal properties

Table 3-IV: Major Kinds of Heating-Related Apartment Building Components

Building Component	Year of Introduction	Building Component	Year of Introduction
Walls		**Windows**	
Large Panel:		Sash Type:	
Assembly Methods:		Coupled	N.A.
Direct	1957	Separate	N.A.
Panel Framework	1949	Sash Material:	
Volume Block	≈ 1975	Wood	N.A.
Panel Size:		Aluminum	N.A.
1-module	1957	Plastic	N.A.
2-module	≈ 1972	Glazing:	
Panel Construction:		Single	≈ 1956
3-layer:		Double	"
Metal Ties	1957	Triple	"
Concrete Ribs	1970	Casement:	
1-layer:		With	N.A.
Solid	≈ 1965	Without	N.A.
Insulation Inserts	≈ 1980		
2-layer	"	**Balcony Doors**	
		Door Material:	N.A.
Brick:		N.A.	
Direct	pre-1950	Window Glazing:	N.A.
Panel Framework	1955	N.A.	
Large Block	1956	**Ventilation**	
Monolithic	pre-1950	centrally connected flats	≈ 1965
		separate flats	pre-1965
Roof			
With Attic		**Heating System**	
Warm	≈ 1980	Radiators:	
Cold	≈ 1960	With Valves	N.A.
Without Attic		Without Valves	≈ 1956
Ventilated	≈ 1956	Wall Panels	≈ 1956
Non-Ventilated	"	Internal	≈ 1960
		External	"
Cellar		Convectors:	
Warm	≈ 1980	With Dampers	≈ 1975
Cold	≈ 1956	Without Dampers	≈ 1965

Evolution of Russian Building Codes

This section will describe the historical evolution of Soviet building codes pertaining to space-heating energy consumption in apartment buildings, as defined by winter conditions. Other authors have described some aspects of Russian building codes, especially recent codes [Matrosov & Butovsky 1989, 1990; Drozdov], but a detailed discussion of the evolution of the codes has not previously been published in the West. The codes specified the norms and calculation procedures for the thermal resistance and air permeability of building envelope components: walls, windows, ceilings below roofs, and floors above basements. The codes for all buildings (i.e., industrial, public, and residential) appear in the SNiP entitled *Stroitelnaya Teplotekhnika* (Building Thermal Engineering). This SNiP was revised periodically as approaches for defining the codes varied; it has had different designations since the beginning of the housing drive. Three versions were examined in some detail to provide an idea of how the codes evolved over time. The following discussion will thus address four historical periods, corresponding to the dates on which the three SNiP versions took effect: pre-1972, 1972-1979, 1979-1986, and post-1986. Formulas and definitions were taken directly from the SNiPs.

Pre-1972

Between 1930 and 1956 most new buildings in the USSR were constructed of brick, and heated with individual room stoves. In order to help heat buildings between periods of intermittent stove operation, much research was performed during this period on the thermal inertia of building materials. Initially, brick wall sections were installed near stoves to provide extra thermal mass, but soon thereafter the building codes accounted for the thermal inertia of the building structure, eliminating the need for the extra brick walls. All building codes published since this time have accounted for the building's thermal inertia in specifying requirements for envelope components.

An important constraint on the thermal characteristics of building envelopes was introduced in 1947. It is the "sanitary-hygienic" constraint (SH constraint), developed to prevent condensation on inner envelope surfaces. In addition to being an inconvenience to building occupants, internal condensation lowers the thermal resistance of the envelope, and can damage some construction materials. Apparently no formulas were provided in the building codes of this time, however, only text stating that condensation must not occur. A formula for the SH constraint appeared in the SNiP II-B.3, the thermal SNiP published in 1954, which defined the minimum external wall thermal resistance required to prevent condensation (the formula was similar to Eqn. 3.1, to be discussed shortly).

1972-1979 [SNiP II-A.7-71]

This SNiP specified two important sets of codes: norms for building envelope components, and procedures used to calculate the properties of actual components. Designers compared the calculated properties to the norms to determine whether the norms were satisfied. The 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, floors, roofs) and fenestration (windows, balcony doors). When describing envelope properties, the SNiP generally addressed complete envelope components (e.g., a single large panel, a wall section of bricks or large blocks, a complete window assembly, etc.). Thus, in the discussion, the term thermal resistance generally refers to *reduced* thermal resistance.

Transmission

Transmission losses through opaque envelope components were governed by the SH constraint introduced in 1947. This SNiP provided a formula for the minimum permissible thermal resistance, based on a minimum temperature of the inner envelope surface (Eqn. 3.1)[49,50]. The design temperature difference ΔT_d varies with local climatic conditions and the thermal inertia of the construction. The value of ΔT_d is the only parameter in Eqn. 3.1 that varied for different buildings. The permitted values of h_i and *n* were tabulated in the SNiP—h_i depended on whether the inner envelope surface was smooth or had protruding ribs; its design value for all walls and floors was uniform (ribs normally appeared only in ceilings). The value of *n* depended only on the position of the envelope component in relation to the outside air—whether walls, floors, or ceilings were directly exposed or were partially shielded by other structures (e.g., ceilings below non-ventilated attics and warm attics were not fully exposed). The constraint in Eqn. 3.1 is T_w. The design dew point was assumed to be 10 °C for MFBs in this SNiP, corresponding to a design indoor relative humidity of 55%[51]. The difference between T_w and T_{in}, 8 °C, was a constant for all MFBs. This value was reduced by the coefficient σ—introduced before World War II—developed to account for the poor quality of brick construction. The value of σ originally used was about 0.75, but it has not been changed since that time, and apparently has since been applied to <u>all</u> types of wall construction. Significantly, all SNiPs containing the SH formula present the denominator of Eqn. 3.1 not as it is shown here, but as the product of two terms, an artificially defined temperature difference ΔT and h_i, thus obscuring the existence of σ[52].

$$R \geq R^{req} = \frac{n\,\Delta T_d}{(T_{in} - T_w)\,\sigma\, h_i} \qquad (3.1)$$

R = calculated thermal resistance of building structure [m^2 °C/W]
R^{req} = minimum required thermal resistance [m^2 °C/W]
n = building geometry coefficient
T_w = inner envelope surface temperature [°C]
σ = coefficient accounting for quality of brick construction
h_i = heat transfer coefficient of inner envelope surface [W/m^2 °C]

This SNiP also included a formula for computing the design thermal inertia of the external wall structure (Eqn. 3.2). The summation in the formula was taken over all layers of the construction, assuming the layers were thermally connected in series (apparently the inertia calculation ignored 2-dimensional heat flows). The thermal resistance of each layer was computed using Eqn. 3.3a; values of S_i were defined in the SNiP by other equations in terms of thermal conductivity, specific heat capacity, density, and the moisture contained within the material (Eqn. 3.3b).

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[49] in fact, much of this material was introduced in 1954 in SNiP II-B.3 and repeated in 1963 in SNiP II-A.7-62, the predecessors to SNiP II-A.7-71

[50] in this SNiP these equations did not use SI units; they were converted to SI by the author

[51] although this SNiP said nothing about the design relative humidity of MFBs being 55%, the next SNiP in this series stated this assumption explicitly

[52] the existence of σ was revealed by Matrosov; see Matrosov & Butovsky 1990 for a more extensive discussion of the SH constraint

$$D = \Sigma (R_i S_i) \tag{3.2}$$

$$R_i = \frac{\delta_i}{\lambda_i} \tag{3.3a}$$

$$S_i = S_i(\delta, \text{material properties, moisture content}) \tag{3.3b}$$

D = dimensionless coefficient of thermal inertia
S_i = coefficient of heat absorption 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 was high enough its thermal resistance requirement was relaxed, because heavy structures tended to damp extreme temperature fluctuations. The total thermal inertia, D, was used to define the design outdoor air temperature, T_{out}. Recall that T_{out} is the overall mean of the temperatures on the coldest days of the eight coldest years in a standard 50-year design period. In this SNiP, if $D \leq 4$ for a particular construction component, then the single coldest day of those 8 years was used. If $D \geq 7$, then the five coldest days were used, resulting in a milder design temperature, and thus a smaller value of ΔT_d in Eqn. 3.1. If $4 < D < 7$, the mean of the results of the first two cases was used. In this way, the minimum design thermal resistance of envelope components depended on the type of construction (thickness, type of material, presence of insulation, etc.)[53].

The calculated thermal resistance of opaque construction elements, to be used for computing R in Eqn. 3.1, was defined by Eqn. 3.4. The outer convection coefficient, h_o, like *n* in Eqn. 3.1, depended on the position of the envelope component in relation to the outside air; notably, h_o values were <u>not</u> differentiated by climate conditions (e.g., local mean humidity levels or wind conditions)[54]. The method of computing R_c varied, depending on the geometry of the envelope construction. For example, for either single-layer designs or multi-layer designs with the layers connected in series, R_c was computed using Eqn. 3.3a, summing values over several layers if necessary. For multi-layer constructions with layers not strictly connected in series (i.e., for constructions in which 2-dimensional effects were important), a weighted average of two calculated auxiliary thermal resistances, R_a and R_b, was used as shown in Eqn. 3.5a. The significance of these auxiliary R-values is unclear, but apparently they represent two different ways of computing the same thing—the reduced thermal resistance of the wall element. The R_a value was computed by dividing the element into layers thermally connected in parallel between the inner and outer surfaces (Eqn. 3.5b); the R_b calculation assumed the layers were connected in series (Eqn. 3.5c)[55].

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[53] in previous SNiPs the SH constraint included an extra coefficient in the numerator of Eqn. 3.1 to account for the thermal inertia of the construction, and values of T_{out} were invariant

[54] Matrosov suggested that the wind effect was usually small

[55] the calculation procedure shown in Eqns. 3.4 & 3.5 was also used in SNiPs II-B.3 and II-A.7-62

$$R = \frac{1}{h_i} + R_c + \frac{1}{h_o} \tag{3.4}$$

$$R_c = \frac{R_a + 2\,R_b}{3} \tag{3.5a}$$

$$R_a = \frac{\Sigma\,A_i}{\Sigma\,\frac{A_i}{R_i}} \tag{3.5b}$$

$$R_b = \Sigma\,R_i \tag{3.5c}$$

R_c = thermal resistance to conduction through the envelope [m^2 °C/W]
R_a = auxiliary thermal resistance, assuming layers in parallel [m^2 °C/W]
R_b = auxiliary thermal resistance, assuming layers in series [m^2 °C/W]
h_o = heat transfer coefficient of outer envelope surface [W/m^2 °C]

Norms and calculation procedures for transmission losses through windows and balcony doors (W/BD) were much simpler than those for opaque envelope sections. Norms for W/BD thermal resistances were tabulated in the SNiP, and for MFBs depended only on the design temperature difference, ΔT_d. The norms ranged from 0.17 - 0.52 m^2 °C/W. Calculating the thermal resistance of actual standardized W/BD assemblies in practice was also simply a matter of looking up the values in a table. The thermal resistance of W/BD assemblies depended on their construction—the number of panes, the sash material, whether the sashes were connected, etc. The tabulated values of design thermal resistances also ranged from 0.17 - 0.52 m^2 °C/W; they matched the norms precisely. Window designs were less flexible than opaque wall sections, as only a few standardized assemblies were produced.

This SNiP also included economic optimizations that, if used, conserved construction materials. The technique had been developed during World War II, but was not widely known within the USSR until the mid-1960s[56]. Designers and builders of the period were free to use the economic formulas if they wished, but were not required to use them.

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[56] one reason for this obscurity may be because of its resemblance to capitalist approaches to economic allocation, which Stalin abhorred

Infiltration

Infiltration through opaque envelope components was defined in terms of the resistance to air permeability, R_{inf}, a material property tabulated in the SNiP. The upper limit on permitted air flow was defined by the air permeability G_{op}, related to R_{inf} as shown in Eqn. 3.6. The design pressure difference Δp was computed for each building based on building height, design air density, and design average wind speed (Eqn. 3.7). 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, given by Eqn. 3.8. Actual values for R_{inf} were computed as a series sum of all layers of the construction; each value was an average, normalized to the area of the wall element.

$$\frac{\Delta p}{R_{inf}} \leq G_{op} = 0.5 \tag{3.6}$$

$$\Delta p = 0.55\, H\, (\gamma_o - \gamma_i) + 0.03\, \gamma_o\, \beta^2 v^2 \tag{3.7}$$

$$\gamma = \frac{3463}{273 + t} \tag{3.8}$$

Δp = design pressure difference between indoor and outdoor air [Pa]
R_{inf} = tabulated air permeability resistance of actual wall section [m^2 h Pa/kg]
G_{op} = norm for air permeability of wall section [kg/h m^2]
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
t = air temperature [°C]

Infiltration around W/BD assemblies was handled slightly differently. Norms were again defined in terms of a maximum allowable air permeability, G_{inf}, but here the norms for G_{inf} were tabulated, depending only 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 computed for W/BD assemblies by taking the larger root of the quadratic equation in G shown in Eqn. 3.9; again, the G value was an average, normalized to the area of the W/BD assembly. The design pressure difference is the same Δp defined above in Eqn. 3.7. The parameters A and B were tabulated in the SNiP; they depended on the type of W/BD construction and on the amount and type of weatherstripping used.

$$B\, G^2 + A\, G = \Delta p \tag{3.9}$$

G = calculated air permeability of W/BD assembly [kg/m^2 h]
A, B = empirical coefficients

1979-1986 [SNiP II-3-79]

Transmission

In 1979 *Gosstroi* introduced many new requirements and procedures in SNiP II-3-79. For instance, design window areas were now related to the amount of available natural lighting, and all joints between construction elements were now supposed to be sealed during construction to reduce infiltration. The codes also explicitly called for the rational and effective use of materials. The most important changes were in the norms and calculations for thermal resistance of opaque envelope components. For the first time since the beginning of the Stalinist period, explicit economic calculations incorporating both construction costs and heating costs were used to constrain thermal characteristics. The new calculation defined an optimal thickness of the building envelope construction element, based on extensive calculations using equations similar to Eqns. 3.3-3.5, and other, more complex expressions. The δ value was chosen to minimize the total cost, P, of the component, given by Eqn. 3.10; δ and P were linked through the thermal resistance R (from Eqn. 3.3a). In the formula, α combines three other coefficients in the calculations (these are unimportant in the present discussion; see Drozdov for a more complete description of this expression)[57].

$$P = C_d + \frac{(RDD)}{R} C_T \alpha \tag{3.10}$$

P = 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-days]
C_T = local cost of heat energy [Rb/GJ]
α = combined multiplicative coefficient

Equation 3.10 was applied to one complete construction element, such as a wall panel or ceiling panel; not to the entire building envelope. Since local conditions often permitted efficient construction of only a few types, the new procedure was intended to provide more flexibility for building designers—the envelope thickness was a relatively easy parameter to adjust for most kinds of construction. The SNiP instructed building designers to compare several kinds of enveloping structure and to choose the one with the smallest reduced cost. 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 fell under criticism within the Soviet building industry. Many designers realized the formula is overly restrictive because it optimizes only the thickness of the construction. Further, some of the numerical coefficients had no apparent source. Many designers resisted using the new procedure, as it was quite complicated, and the required data were hard to collect. Iteration was typically required to find the optimal thermal resistance, although in practice iteration was

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[57] in this SNiP these equations did not use SI units; they were converted to SI by the author

unenforceable. Despite these problems, for 7 years the formula was not revised because its author was a high-ranking official within *Gosstroi* [Matrosov].

Two changes in this SNiP increased the impact of the SH constraint[58]. First, instead of simply using a minimum thermal resistance according to Eqn. 3.1, designers now had to explicitly compute the inner envelope surface temperature to ensure that it would not fall below the dew point. This SNiP provided a rearranged version of Eqn. 3.1 for this calculation, but without the hidden fudge factor σ[59]. The SNiP mandated a design relative humidity in all MFBs of 55%—resulting in a dew point of 10 °C—which had already been used for nearly 20 years. Second, this SNiP also addressed the problem of localized condensation by requiring additional checks on T_w in all regions of the construction containing thermal bridges—regions of lower thermal resistance arising because of panel ribs, metal ties, monolithic butt-joints, frameworks, etc. The SNiP provided a second formula for checking T_w in these regions that included an extra term, κ, to correct for the presence of the thermal bridges (Eqn. 3.11a). The κ value depended on the thermal resistances of the construction both with and without the thermal bridge, and on the geometry of the thermal bridge.

$$T_w = T_{in} - \frac{\Delta T_d}{R^* h_i}\kappa \qquad (3.11a)$$

R^* = thermal resistance, assuming no thermal bridge is present [m^2 °C/W]
κ = correction coefficient

In the new formulation the SH constraint and the new economic optimization constraint each provided lower bounds for the thermal resistance of opaque envelope components. The larger of the two values was then selected for use as the minimum thermal resistance. In practice the economic constraint was usually binding in wall designs without thermal bridges; as a result R-values were increased, and thus design heat transmission losses through opaque sections were reduced. In walls employing thermal bridges the binding constraint on thermal resistance varied.

Calculation methods for opaque elements were also changed in the SNiP of 1979. First, the values for S from Eqn. 3.2 were no longer computed using auxiliary formulas as in Eqn. 3.3b; now they were simply tabulated with other material properties in the SNiP for various materials. This SNiP also divided buildings into humidity zones, and the USSR into humidity regions. These classifications were used to determine design properties of building materials, providing a cruder, yet more standardized way to account for actual moisture conditions. Second, the calculated thermal inertia of the envelope, D (Eqn. 3.2), used for computing T_{out}, was now divided into four categories instead of three: if $D \leq 1.5$, the <u>absolute</u> minimum temperature of the coldest day was used. This potentially provided better thermal protection for buildings

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[58] SNiP II-A.7-62 also incorporated these changes, but, curiously, they were abandoned in SNiP II-A.7-71
[59] effectively eliminating the influence of σ in Eqn. 3.1, if in fact designers performed these extra calculations

of very lightweight construction. Third, the SNiP provided an alternative to Eqn. 3.4 for calculating the thermal resistance of external wall panels in MFBs (Eqn. 3.11b). The designer could base the *r* value on either theoretical calculations or experimental data. Potentially, this left much latitude for building designers in computing R.

$$R = R^{hom}\, r \tag{3.11b}$$

R^{hom} = thermal resistance of the construction (R, from Eqn. 3.4) assuming no thermal bridge is present [$m^2\,°C/W$]
r = coefficient of homogeneity

The norms for transmission losses through windows and balcony doors did not change in this SNiP, but designers could choose from among many more kinds of W/BD assemblies than they could in 1972.

Infiltration

Norms for infiltration through opaque elements remained unchanged in this SNiP. The calculation procedure changed, however, as the β coefficient in Eqn. 3.7 was removed (Eqn. 3.12a). Also, previous fenestration norms were tabulated based on T_{out}, but in this SNiP the required resistance to air permeability was defined by Eqn. 3.12b. The air permeability, $G_{W/BD}$, was tabulated in the SNiP for different envelope components. Like G_{op}, $G_{W/BD}$ was simply an upper limit on permitted air flow.

$$\Delta p = 0.55\,H\,(\gamma_o - \gamma_i) + 0.03\,\gamma_o v^2 \tag{3.12a}$$

$$\frac{\Delta p^{2/3}}{R_{inf}} \leq G_{W/BD} = 10 \tag{3.12b}$$

The calculation procedure for infiltration through W/BD also changed in 1979. Instead of solving a quadratic equation, now building designers simply consulted tabulated values of R_{inf} 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 weatherstripping materials.

Post-1986 [SNiP II-3-79**]

Transmission

This SNiP was the last version of the USSR's building codes on building thermal engineering published before the breakup of the Soviet Union. The norms for opaque envelope components were changed yet again. This SNiP improved the economic optimization of the envelope thermal resistance:

rather than optimizing the thickness of the envelope, the reduced thermal resistance itself was optimized. That is, a value of R was chosen, R^{ec}, that minimized the total reduced cost P in Eqn. 3.10. This approach was more general than the method introduced in 1979, 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 computational difficulties encountered with the previous formulation. The formula still required some fairly cumbersome calculations[60], yet this SNiP simplified the task by providing initial values of R for the economic optimization, based on the local value of R^{req} from the SH constraint (from Eqn. 3.1) and on the tabulated coefficient ϕ, which varied for different types of wall construction (Eqn. 3.13a). Russian experience had shown that often optimal R-values differed little from the initial value; this might have led some designers to simply stop the procedure after computing the initial value [Matrosov].

$$R_{opt} = R^{req}\,\phi \qquad (3.13a)$$

R_{opt} = initial value of economically optimal thermal resistance [m^2 °C/W]
ϕ = tabulated wall construction coefficient

This SNiP expanded on two calculation methods introduced in the previous SNiP. First, a second correction formula was introduced for checking the value of T_w to prevent internal condensation near regions containing thermal bridges. The previously used formula was now restricted to only non-metallic thermal bridges; the new formula in this SNiP addressed metallic thermal bridges. Tabulations for the correction coefficients in these two equations were now much more complex, each accounting for roughly 60 possible thermal bridge geometries. Further, the revised equations imposed higher limits on the local thermal resistance of the envelope than the corresponding equation in the previous SNiP.

Second, the alternative, simplified calculation procedure for MFB panel walls shown in Eqn. 3.11b was further developed. This SNiP included an appendix 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, depending on the tie diameter and the relative spacing between the ties within the panel. For ribbed panels, *r* was defined in terms of two other parameters, as shown in Eqn. 13b. These standardized correction factors provided better accuracy than Eqn. 3.11b, yet still preserved the relative simplicity of the approach (in contrast to Eqn. 3.5 and its accompanying formulas).

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[60] nationwide, about 2000 separate computations were required: 8-10 types of construction in each of about 200 climatic zones

$$r = r_1 * r_2 \qquad (3.13b)$$

r_1 = coefficient accounting for relative rib area
r_2 = coefficient accounting for density of rib material

The method of determining fenestration norms did not change (i.e., they were still tabulated), but some of the norm magnitudes for MFBs did increase by about 20%. The method of specifying actual W/BD thermal resistances remained unchanged.

Infiltration

Norms and calculation procedures for infiltration through opaque construction elements remained unchanged. The method of computing the required value of R_{inf} changed slightly for fenestration: the Δp term in Eqn. 3.12b was divided by a reference pressure of 10 Pa before being exponentiated. This had no effect on the norms, but since tabulated numerical values of R_{inf} were unchanged, the net effect was to permit more widespread use of more permeable W/BD assemblies. Specifying the actual R_{inf} values became more complicated in this SNiP: like the parameters from the quadratic equation in the SNiP of 1972, determining actual values for R_{inf} depended on the type of W/BD construction and the amount and type of weatherstripping used.

Summary

This section has described the evolution of Russian building codes—norms and calculation procedures—based on winter design conditions[61]. The codes have varied over time since the beginning of the 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. Significantly, the codes never addressed the whole building as a single energy system, although future codes will do so [Matrosov & Butovsky 1993]. Throughout the period, 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 operating conditions.

The information presented in this section permits the estimation of the norms governing transmission and infiltration losses for MFBs in Moscow. From 1956 - 79 the thermal resistance of opaque

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[61] building codes based on summer design conditions influenced MFB properties in some regions if July temperatures were high enough, but the extent of these effects is unclear

elements were determined by the SH constraint. The economically optimal norms used after 1979 depended on prices, which were unavailable in this study; R-values in this period were estimated here as the mean of the R-values used before 1979 and after 1986, respectively. R-values for opaque wall elements after 1986 were estimated using the initial value from the optimization procedure, provided by Eqn. 3.13a. Recall that the SH constraint groups types of wall construction according to their thermal inertia, which depends on wall geometry and material properties. Thus, the thermal inertia of all four major kinds of wall construction (3-layer panel, 1-layer panel, large block, and brick) could vary substantially. It is not generally known whether walls with a few typical values for thermal inertia constitute most of the housing stock, but some crude approximations were made in this analysis. Specifically, all 1-layer panels were assumed to be in the lightest possible category in each period (either $D < 1.5$ or $D < 4$); all brick and large-block walls were assumed to be in the heaviest category ($D > 7$); and all 3-layer panels were assumed to be in a medium category ($4 < D < 7$). Much more information is needed in order to properly classify wall construction designs.

Table 3-V provides estimates of thermal norms for Moscow MFBs built since the beginning of the housing drive in 1956. Infiltration norms are equivalent R-values, derived by assuming a constant design pressure difference, Δp, for all buildings in a given period when necessary, and by dividing air permeability norms by the specific heat capacity of air to relate air mass flows to heating requirements. The results presented in Table 3-V, although only approximate, have not previously been published in the West; they form a key part of forthcoming analyses in this chapter and in Chapter 5. Some typical current ASHRAE standards for new buildings in the US are also listed.

Table 3-V: Estimated Thermal Resistances of MFB Envelopes in Moscow

a) Transmission Through Opaque Walls (reduced thermal resistance, m^2 °C/W)

Type of Wall Construction	1956-62	1963-72	1973-79	1980-86	Post-1986
3-Layer Panel	0.97	0.94	0.94	1.30	1.66
1-Layer Panel	1.01	0.99	0.99	1.12	1.25
Brick/Large Block	0.88	0.88	0.88	0.90	0.92

b) Transmission Through Fenestration (reduced thermal resistance, m^2 °C/W)

	1956-62	1963-72	1973-79	1980-86	Post-1986
All Construction Types	0.30	0.30	0.34	0.34	0.39

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 ceilings below roofs and floors above basements ranged from 40-100% of the values for walls; the increase in fenestration norms in 1986 is deceptive, because the rated R-value of window assemblies was increased by the same amount; fenestration values before 1972 are the author's guesses.

c) Infiltration Through Opaque Walls (equivalent reduced thermal resistance, m^2 °C/W)

Type of Wall Construction	1956-62	1963-72	1973-79	1980-86	Post-1986
3-Layer Panel	4.68	2.77	7.17	7.17	7.17
1-Layer Panel	4.86	2.90	"	"	"
Brick/Large Block	4.24	2.59	"	"	"

d) Infiltration Through Fenestration (equivalent reduced thermal resistance, m^2 °C/W)

	1956-62	1963-72	1973-79	1980-86	Post-1986
All Construction Types	0.24	0.24	0.28	0.36	0.36

Equivalent average air exchange rate from values in Tables c&d: 0.4 - 0.6 ACH (for a typical building)

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 [Lydolph] (the value used by the Russians was unavailable); fenestration values were all normalized to the fenestration area; fenestration values before 1972 are the author's guesses.

e) Standards for New Buildings in the US (for a climate similar to Moscow's)
[ASHRAE Standard 90]

Reduced Thermal Resistance (transmission), m^2 °C/W

Opaque Walls	Fenestration (double-glazed)
2.3 - 2.6	0.4 - 0.6

Typical minimum air exchange rate: 0.6 ACH (to maintain fresh air supply)

The estimates in Table 3-V suggest that most Russian MFB thermal norms tended to increase over time, and that norms governing transmission losses through opaque walls were consistently below US standards of 1989. Since transmission losses through opaque walls represent a large part of a building's total heat losses, part of the poor space-heating energy inefficiency of Russian MFBs is attributable to relatively low performance standards. Other norms—for transmission losses through fenestration, and overall infiltration rates—were comparable to current US standards, however, suggesting that some causes of poor Russian MFB energy performance lie in other areas (norm calculation procedures, norm enforcement, quality of component manufacture, quality of building construction, etc.).

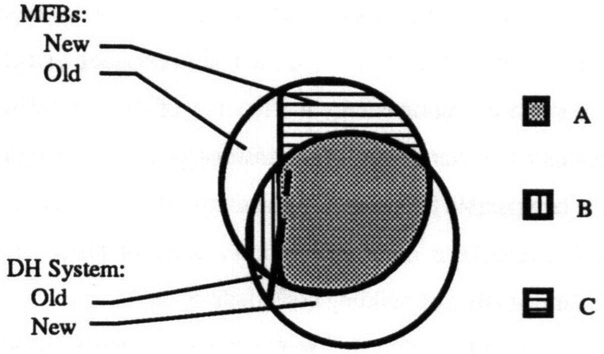
It must be emphasized that even if Table 3-V were complete, it would specify only design building thermal properties. Envelope characteristics were not always constrained by thermal norms: as discussed in the previous section, structural designs of buildings with different series numbers varied, so that the thermal resistance of a given wall section may exceed the lower bound provided by the norms. In such cases, higher norms for thermal resistance have no effect on new buildings. Thus, classifying buildings by their series numbers would provide a more effective way to organize a list of thermal properties in Moscow's MFBs. Unfortunately, such detailed information was unavailable for this study.

The District-Heated Housing Stocks of Moscow, Russia, and the CIS

Estimating the Stock Size

The portion of the CIS apartment building stock served by district heating systems is not generally known. Here, it is assumed that the floor area of the CIS's district-heated MFB stock is equal to the floor area of *all* MFBs built after 1955. The difference between these two quantities is displayed in Figure 3.8. The figure depicts the overlap between the MFB sector and the total district-heated buildings sector (i.e., housing, industrial, and commercial buildings). Each sector is divided into old and new components: *old* represents construction (either of housing or of district-heated buildings) that began before 1955; *new* consists of all buildings erected since 1955. District-heated MFBs (the quantity needed) are represented by the intersection of the two circles—the sum of areas A and B. New MFBs are represented by the sum of areas A and C. The accuracy of the approximation used here thus depends on how closely areas B and C match.

Figure 3.8: The CIS Apartment Building and District Heating Buildings Sectors



Area B represents old apartment buildings connected to the old DH system[62]. The size of this sector is not known, but it is likely to be relatively small because of the evolution of the DH system: although district heating was introduced in the USSR in 1924, it did not grow substantially until 1955. The onset of rapid growth in the district heating coincides with the beginning of the housing drive[63]. Since the aggregate size of the USSR's DH system in 1955 was less than 10% of its size in 1985 (Table 3-VI), the "old" DH system is therefore small compared to the "new" system. As a result, area B is likely to be small compared to area A.

Table 3-VI: Evolution of District Heating in the USSR
[Sokolov & Zinger]

	1955	1970	1985
Heat Output of Cogeneration Plants, billion GJ/year	0.4	2.7	5.5
Length of Main Pipelines of DH Networks, thousand km	2	13	27

Area C represents new MFBs not connected to the DH system (i.e., buildings with individual heating systems[64]). The size of this sector is unknown as well, but it is also likely to be relatively small because of the emphasis Soviet planners placed on city-wide centralized heating systems. Since areas B and C are both likely to be small compared to area A, the floor area of <u>new</u> MFBs should be a reasonable estimate of the floor area of <u>district-heated</u> MFBs.

Although the available data only support approximating district-heated MFBs with new MFBs for the CIS, the same assumption will be made for Russia and Moscow. Unfortunately, the size of the new MFB stock is not known with precision either. The new MFB stock is approximated by <u>all</u> new housing

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[62] strictly, a small part of area B represents old MFBs connected to the new DH system, as shown in the figure. Given the high costs of retrofitting the heating systems of existing MFBs, however, the size of this sector is very likely to be insignificant.

[63] this makes sense because district heating systems are most cost-effective when they are built at the same time as new buildings

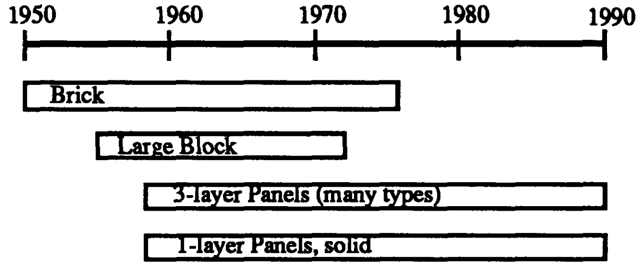
[64] recall that heating systems in such buildings fall within the Russian definition of "centralized heat supply" if their capacities exceed 20 G-cal/hr

construction since 1955 in Moscow, and by new public urban[65] housing construction in Russia and the CIS. This analysis assumes the definition of "housing stock" used in Russian statistics did not change over time.

General Structural Divisions

The remainder of this section will attempt to quantify the amount of housing with each major kind of opaque wall construction. As will be seen shortly, of all possible kinds of wall construction, only a few were widely used in apartment buildings in practice. Figure 3.9 displays the approximate periods during which the most common types were widely employed in the USSR. In the late 1940s the walls of new houses generally consisted of bricks or small blocks, and the ceilings consisted of reinforced concrete panels. After 1950, brick and small-block construction became far less common in MFBs. The first prefabricated MFBs, built in Moscow in 1949, were panel framework with large-panel walls, but large-panel buildings were uncommon until the late 1950s. The panel categories are intentionally broad: 3-layer panels include single-module panels, 2-module panels, and all specific kinds of 3-layer design. All categories except large block include some panel-framework construction, and each panel category may also include some volume-block construction.

Figure 3.9: Main Wall Construction Types Used in New Apartment Buildings in the USSR
[Ikonnikov; Dykhovichnyi; Matrosov]



Sometimes the thermal characteristics of external walls in Russian MFB can be identified simply by knowing the number of floors in the building. For example, most MFBs with 9 stories contain 3-layer panel walls. Nearly all buildings with 12 or more stories have large-panel walls—some 1-layer and some 3-layer. Large blocks, bricks, and small blocks were used only in buildings with fewer than 15 stories, and mostly in buildings with less than 12 stories [Matrosov]. Correlations also exist between heating system design and building height. Apartment buildings constructed in the 1950s and 1960s, mostly with 5- and 9-stories, have radiators or heated wall panels. Most 12-story buildings that emerged in the 1970s used heated wall panels. Convectors were used in modern 17-story and 22-story buildings. These kinds of

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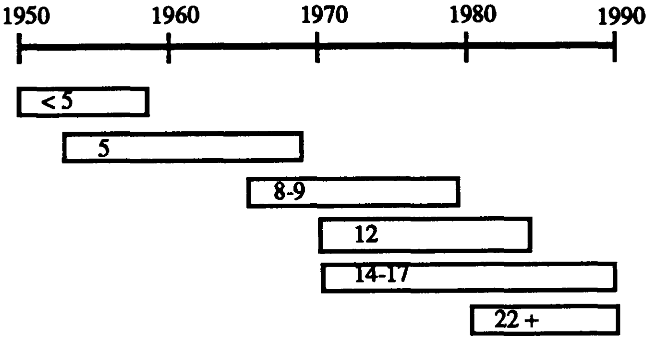
[65] as defined in Chapter 2

correlations help estimate the composition of the national housing stock. Although these relationships are general guidelines and not strict rules, it is still useful to examine the structure of new housing construction by the number of stories. The heights of the CIS's MFBs range from 1 to 32 stories, but not all heights were common. Figure 3.10 shows the approximate evolution of building heights in new MFB construction in the USSR. All transitions were gradual—construction of 5-story buildings did not suddenly cease in 1968; it tapered off over several years.

Figure 3.10: Common Heights of New Apartment Buildings in the USSR
[Ikonnikov]

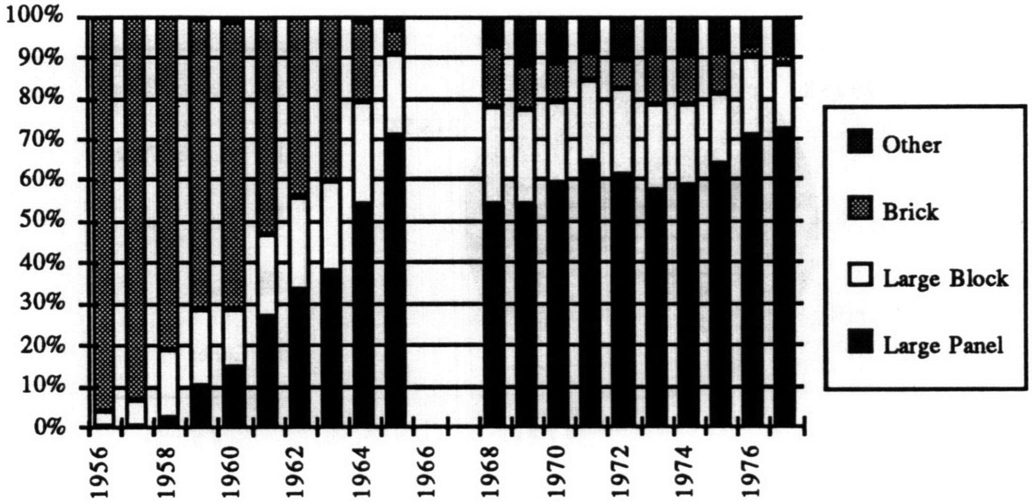


Size and Structure of Moscow's Stock

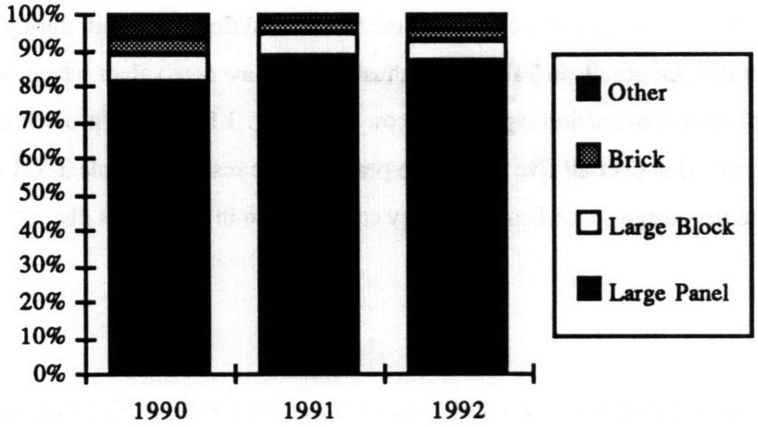
A complete classification of Moscow's housing stock requires a breakdown of total floor area built each year within each building series category. Unfortunately, these data were unavailable in most years, and available data are less specific: they may refer only to prefabricated construction, or they may lump more than one kind of construction into a single category. Varying area definitions were handled by converting raw area data into percentages of total construction. Figure 3.11 displays estimates of the structure of Moscow's new MFB construction in some years. It must be stressed that numbers in Fig. 3.11 are only estimates: consistency and definitional problems plagued attempts to combine data from more than one source (see Appendix B for a more detailed description of this analysis).

Figure 3.11: Structure of New Apartment Building Construction in Moscow, by area

a)1956-65, & 1968-77 [Dykhovychnyi]



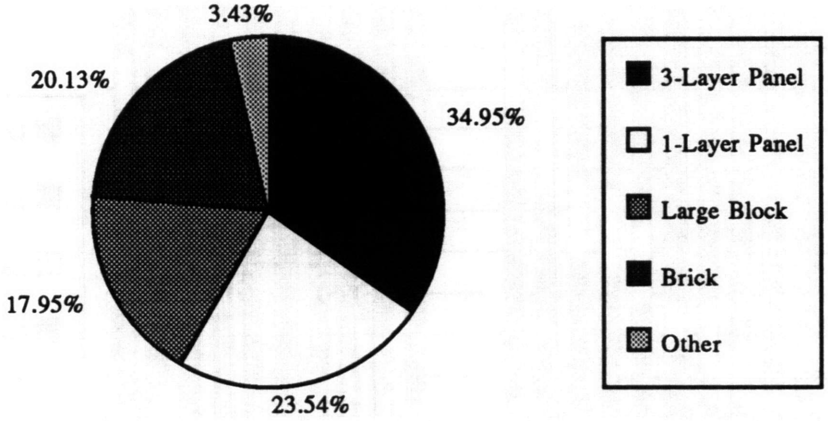
b) 1990-92 [Matrosov]



After combining the information from Figure 3.11 with data on total new construction in Moscow, interpolating the structural composition figures when data were absent, and incorporating information on the building heights constructed since 1960 (again, see Appendix B for details), it became clear that Moscow's district-heated MFB stock is dominated by large-panel walls (Figure 3.12).

Figure 3.12: Estimated Structure of Moscow's District-Heated MFB Stock in 1992

Total Useful Floor Area: 152 million m^2



The results presented in Figure 3.12 may be combined with the estimates for thermal norms presented in Table 3-V to define a set of equivalent design thermal resistances applying to Moscow's MFB stock (Table 3-VII). The thermal resistances applying to each kind of wall construction in each time period (taken from Table 3-V) were weighted according to the total useful floor area built during the period in which each norm applied; the results in Table 3-VII thus represent average values which, when applied to the total floor area of each construction type in Moscow (from Fig. 3.12 above), provide the same total heat consumption as a summation over all five SNiP time periods. The results in Table 3-VII will be used in Chapter 5 to estimate the design space-heating energy consumption in Moscow's district-heated MFB stock.

Table 3-VII: Estimated Equivalent R-Values of Moscow's District-Heated MFB Stock (m^2 °C/W)

Type of Wall Construction	Transmission		Infiltration	
	Opaque	Fenestration	Opaque	Fenestration
3-Layer Panel	1.05	0.32	4.56	0.27
1-Layer Panel	1.07	"	5.30	"
Brick/Large Block	0.88	"	3.94	"

Size and Structure of the Stocks of Russia and the CIS

Less information was available on the structure of the CIS's housing stock (none for Russia alone). Specific breakdowns in new construction can be estimated for some years (Fig. 3.13), but published data consist mainly of scattered references and vague comments. Some authors have provided a few pieces of the puzzle, however (again, see Appendix B for details). Combining the available sources with the figures in Fig. 3.13 yielded an estimate of the composition of the CIS's district-heated MFB stock (Fig. 3.14). Again, the emphasis on large panels is clear, but in this case 1-layer panels account for a substantially greater portion of the stock.

Figure 3.13: Estimated Structure of New MFBs in the USSR, by area
[Broner]

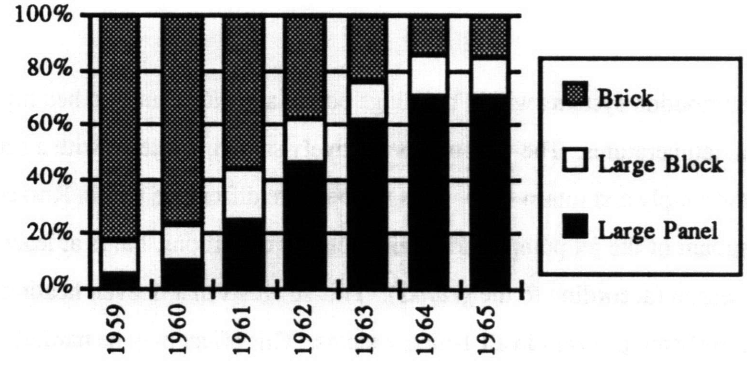
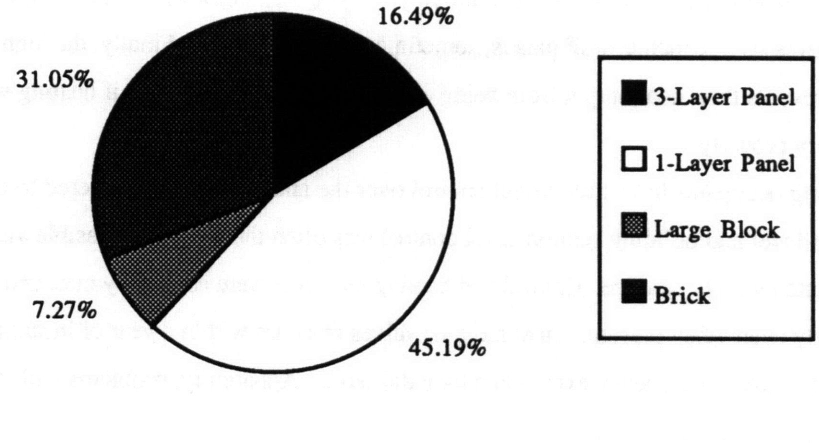


Figure 3.14: Estimated Structure of the USSR's District-Heated MFB Stock in 1989
Total Useful Floor Area: 2076 million m^2
(Russia = 1075 million m^2)



System Design and Actual Conditions

Most evidence for heating effectiveness in flats is anecdotal; the diversity in MFB envelopes and heating systems complicates generalizing from a few examples. The only consistent picture that emerges is that some apartments are overheated, some are underheated, and some are heated properly. According to one Russian author, every winter there are countless complaints of cold apartments in large cities [Yudzon], probably most commonly during severe weather. Complaints from overheated apartments are common near the beginning and end of the official heating season, when outdoor temperatures are mild [Cooper & Schipper 1992; RCG]. The Russian literature notes that actual heat losses in buildings exceed design heat losses by 25-40% in MFBs, and by 40-50% in public buildings [Yudzon], indicating significant problems in heating systems, building envelopes, or both.

Heating Systems

One-pipe distribution systems within buildings potentially cause uneven heating because of varying radiator input temperatures. The variation is relatively small in systems with a small temperature difference between the supply and return lines. This temperature difference within Russian building sections (i.e., downstream of the jet pump) varies with outdoor conditions, but is at least 15 °C throughout most of the heating season (according to the *grafiks*). This suggests that uneven heating within building sections could be a significant problem in all 1-pipe systems. This effect may be partially offset, however, by rising warm air in systems that feed lower floors first. Uneven heating within buildings is less important if heat flows across internal walls are relatively high.

The wall-panel heating system, although cheaper to fabricate, was generally less effective and less efficient than radiator or convector systems. Wall panels lose about 60% of their heat through radiation, and 40% through convection[66] [Jennings; Kut]. The high radiative component caused comfort conditions within panel-heated rooms to differ from those in radiator-heated rooms. Heated panels, when installed in partition walls, lead to less uniform indoor temperatures, as the heating elements are unable to counter cold air currents moving along external walls. Additionally, varying heating water supply temperatures cause cyclic thermal stresses in concrete wall panels, sometimes damaging them. Finally, the high thermal inertia of the panels prevents their heat output from being easily varied with time, even if heating water temperatures vary properly.

Building occupants have little direct control over the amount of heat delivered to their flats. Partial building-level and building section-level control was often theoretically possible via jet pumps, but rarely implemented well in practice. Controls on heating elements were especially rare, and failed to function properly even when present: most radiator valves froze up within a year of installation, becoming unusable, and the valves were leaky even when they did work. Apparently, problems with radiator valves

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[66] recall that the opposite trend holds for radiators

were rooted in their manufacture: they were often fashioned from incorrect materials [Minsk]. Some convectors had dampers, permitting heated air flow to be varied, but the dampers were difficult to move, and, like radiator valves, often froze up. As a result, one of the most widely used methods of temperature control in Russian flats has been the windows: they were simply opened when flats were overheated. Underheating presented more of a challenge, but there are many stories of residents filling their bathtubs and sinks with hot water, and of firing up the kitchen stove in an effort to stay warm [Yudzon; Dykhovichnyi].

Building Envelopes

Condensation is a common problem on the inner surfaces of MFB external walls, especially in the corners of walls and floors. Condensation occurred either because norms for envelope thermal properties were unsatisfied, or because of actual conditions not anticipated by designers. As an example of the latter, a significant amount of moisture is generated in MFBs from baths, showers, and kitchens, sometimes raising indoor relative humidity to 80%, which in turn raises the dew point to 15-18 °C. Additionally, new wall panels contain high moisture levels due to the panel manufacturing process [Savchenko]. In practice, rooms in new buildings are overheated (to 20-22 °C) and overventilated during their first heating season (sometimes during the first two heating seasons) to reduce the moisture contained in the walls [Dykhovichnyi; Matrosov].

Thermal bridges in 3-layer wall panels caused significant additional heat losses: they decreased the reduced thermal resistance of the panels by 30-60% in various panel designs (Table 3-VIII). The values in Table 3-VIII are based on theoretical calculations performed by NIISF; in the table, the "ideal R-value" is the reduced R-value of the panel assuming no thermal bridges are present. As discussed previously, some calculation procedures in the building codes attempted to account for thermal bridges in 3-layer wall panels (Eqns. 3.5, 3.11b, & 3.13b), but the accuracy of these formulas is not generally known.

Table 3-VIII: Effects of Thermal Bridges on Thermal Performance in 3-Layer Wall Panels
[Matrosov & Butovsky 1989]

Type of Thermal Bridge	Actual R-Value / Ideal R-Value
Concrete Ribs (50 mm thick)	0.40
Metal Ties	
8 mm Diameter	0.70
20 mm Diameter	0.64
8 mm Ties and 20 mm Ribs	0.63

Relatively little is known about actual properties of existing construction elements—Russian field experiments assessing actual building performance were rare. Overall, thermal resistances of real wall sections in Russian MFBs are generally believed to be below code-specified requirements—some estimates place the difference at about 10%, but it may be even higher [NIISF; Savchenko]. In all multi-layer large panel designs the thickness of thermal insulation sections and of concrete layers were poorly controlled in the manufacturing process. For 3-layer panels with metal ties, two factors explain most of the difference between design R-values and actual R-values. First, the metal ties cause gaps to appear between the two separate sheets of thermal insulation inserted during manufacture. This leads to two problems: design calculations assume no gap is present, and concrete sometimes flows into the gap during manufacture and forms a thermal bridge. Second, improper materials are often used on site: the actual density of concrete may be up to 15% higher than the design density, and the actual thermal conductivity may exceed the design value by up to 45% [NIISF]. As discussed previously, many kinds of concrete were used in Russia, and often substitutions were necessary to finish projects on time and below cost.

Butt-joints in MFB large-panel external walls are subject to constant reversible (temperature-induced) and irreversible (structural) deformations. The deformations lead to gaps between construction elements in non-monolithic butt-joints, most severe when different wall sections are made of different materials. Gaps of 1-3 mm are common, but up to 10 mm-wide gaps have been reported in some 5-story buildings. Air gaps between construction elements increased infiltration losses beyond design levels [Dykhovichnyi; Matrosov]. Buildings using volume-block construction had a similar problem: air gaps between the blocks permitted high infiltration rates, and served as an excellent home for insects, rodents, and leaves.

Other envelope components can also cause heating problems. Most windows fit poorly or close improperly, and all sashes tend to leak either because of rot or poor construction. Dampness often causes wooden door and window frames to warp, forming cracks and leading to higher infiltration. Further, window panes were sometimes widely spaced, allowing significant convection currents to form between the panes. Corner sections of older buildings lost so much heat that they sometimes froze through, allowing ice to form on the *inner* envelope surface. Sometimes extra insulation was added to corner sections to prevent this problem; in other cases a heating pipe was installed[67] [Dykhovichnyi]. Corrosion of metal ties because of cracks in outer shells was also a serious problem, especially around window openings.

ORGANIZATION OF THE MFB CONSTRUCTION INDUSTRY

A significant source of uncertainty in MFB thermal properties was the quality of construction labor and management. Other sections of this report, in this chapter and in Chapter 2, have described the poor quality of construction in Russian MFBs. This section will address some of the causes of poor quality. Construction planning was handled by *Gosstroi* USSR and *Gosstroi* of the Union Republics. Housing construction was managed through republic ministries.

Construction work, which included all on-site tasks from ground excavation to component assembly, was performed either by industrial enterprises or by dedicated construction organizations

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[67] it is not known how common these heating pipes were, or whether they were connected to the district heating system

[Omarov]. The former method was sometimes used when an enterprise needed a building for its own use (e.g., housing). In this case the firm set up its own construction organization, acquired the necessary equipment, and hired construction workers. Upon completing its work this organization was usually dissolved, and the construction workers moved on to other construction sites.

In the second approach work was conducted by construction organizations under a contract with their customers—usually local *Soviets*. The permanent labor force of these construction agencies accumulated construction experience and was generally much more proficient in construction work than the smaller groups set up by enterprises. The cost of contracted work was often much lower than if it had been handled by enterprise construction organizations [Omarov]. This method was thus preferred, and became predominant by 1970.

Sometimes house-building cooperatives were the customers of construction organizations. In house-building cooperatives, a group of persons pooled their resources and hired an organization to build their home. The state offered loans and credits to induce people to join the cooperatives, but even so only the rich could afford to join. Cooperative apartment buildings generally have higher quality of construction, but they have not become widespread: since 1965, cooperative houses have averaged only 5-6% of new floor area constructed nationwide.

Sosnovy concluded that apartment building construction was adversely affected by the proliferation of construction organizations, each under contract with a particular department or ministry. It was common in the 1950s and 1960s to see several construction organizations clustered together in the same area, or even on the same construction site, using different sources of material supply and different transportation facilities. This led to dramatic labor and resource inefficiencies. Furthermore, there was a lack of specialized skills and high turnover rates in the labor force because of the strenuous work and relatively low wages.

In the early 1950s housing construction was reorganized in terms of "House-Building Combines," or DSKs, drastically simplifying construction administration [Dykhovichnyi]. In DSKs, responsibility for housing construction extended from securing resources to presenting finished houses; the DSKs controlled the output of all component-producing factories, the transport of all components to building sites, and building erection. A major development of DSKs was the continuous flow process, in which building components were loaded onto transport vehicles at the factory, shipped to construction sites, and assembled on-site as they were unloaded, thus eliminating the need for storage. Although DSKs were apparently quite successful, they did not totally replace the many smaller construction organizations. And, like the smaller organizations, DSKs often were still subject to many masters.

Historically, maintaining adequate supplies was the most serious problem for the Soviet construction industry. Because of great demand and a poorly functioning distribution system, construction materials were chronically in short supply or simply unobtainable. Yet managers were faced with considerable pressure to meet output targets, so they tended to either hoard supplies or substitute other, inferior materials (e.g., a different type of brick or concrete) when necessary rather than permit delays. According to Matrosov, SNiP enforcement was another significant problem: enforcement agencies were disorganized, many inspectors lacked authority, and sometimes thermal requirements were relaxed if the local central heating plant had enough excess heating capacity to make up for the extra heating load.

SUMMARY

In district-heated Russian MFBs hot water flows into each building through the DH connection at an essentially constant flow rate. Water supply temperature, theoretically determined by standard schedules, is in practice determined by DH heat plant operators and the quality of DH system controlling equipment. After entering the building the water is allocated to each building section, where it passes through a jet pump and the internal distribution system—generally 1-pipe diverted (usually without valves) in older buildings, and 1-pipe series in newer buildings—and on to the radiators, convectors, or wall panels, where heat is transferred from the water to the room air and building structure. Radiator output water flows through other radiators and back to the building's basement—where part of the water is recirculated through the jet pump—and back to the DH system. Heat consumption is unmeasured, and the heat output of radiators is generally uncontrollable.

The heat supplied from the heating system, along with heat from internal and solar gains, is lost from the building to the environment through direct transmission and infiltration. Transmission occurs through external walls, basements, and roofs, generally of large-panel design, and through windows and balcony doors, generally double-glazed, with casements and coupled wooden sashes. Infiltration occurs through external walls, basements, and roofs (all are air permeable), through gaps between envelope components (panels, windows, sashes, and balcony doors), and through cracks in these components.

Three major conclusions relevant to this study can be drawn from the discussion in this chapter. First, although casual observation suggests that a great degree of uniformity exists in the Russian MFB stock, in fact designs for nearly all heating-related building systems—envelope configurations, construction materials, building assembly methods, and heat delivery systems—vary considerably. Considering the national stock (of Russia or the CIS) as a whole, MFB characteristics vary with climate, not surprisingly, leading to substantial regional diversity. Further regional differences in industrialization levels and in material availability—disparities that casual observation fails to illuminate—also affected the quality of housing construction. Focusing on a single city eliminates regional climate and economic disparities, yet introduces other variations depending on the design of buildings. This is mildly surprising; as a first guess one might assume that in a highly standardized, centrally planned economy with a cold climate, design thermal properties would be uniform in all buildings in a given location. Finally, limiting consideration to a single building design—in the CIS, a single building series number—yet more diversity can show up among specific buildings. Diversity within building series, surprising in its extent, arises because of possible differences in the way building designers chose to meet various design constraints, local management of construction activity, local availability of proper materials when the buildings were constructed, and, finally, because of differences in the form of building ownership. Taken together, the potential structural variations in the Russian and CIS MFB stocks suggest that generalizing thermal properties from any single building to a larger group of buildings is at best shaky, and at worst meaningless.

Second, the design of heating-related systems in Russian MFBs appears to have focused on meeting worst-case weather conditions, with relatively little attention paid to providing the proper amounts of heat to all consumers under all conditions. This is evidenced by the sanitary-hygienic constraint for building envelopes, norms for transmission and infiltration losses through windows, the lack of individual heating controls, and the infrequent adjustment of building-level controls. The lack of heating controls, of high-quality building construction, or of any consideration of heating costs in the building codes until 1979 suggest that operating efficiency was unimportant; these shortcomings are consistent with the Soviet goal of providing new housing as quickly as possible. The result of Russian MFB design practices appears to be widespread improper heating levels and energy waste, supporting Western suspicions that dramatic space-heating energy efficiency improvements are possible.

Finally, the discussion helps to identify the buildings most deserving of further study. The most promising areas for saving energy in MFBs are determined by the specific causes of energy inefficiency, which generally vary among buildings. There are three basic reasons some buildings might be more preferable than others, depending on whether energy savings are more certain, larger, or easier to achieve (namely, faster or cheaper). The latter requires specific knowledge of potential building retrofits, local availability of materials and expertise, etc.; ranking buildings in this manner is generally a task of least-cost planning, and will not be further discussed here. The discussion of this chapter can offer some insight into the potential size and certainty of energy savings, however.

First, the available information suggests that some building designs may offer more predictable energy savings because either their thermal configurations are simpler or their heating systems are more effective. For example, since the actual thermal resistance of an existing 1-layer large-panel wall can be estimated with much greater accuracy than a panel of multi-layer design, present energy consumption, and thus potential savings, can be more accurately quantified. Of all 1-layer panel buildings, 2-module panels are preferable for the same reason, as these buildings have fewer seams. Additionally, a 2-pipe heating system is more likely to provide energy savings in response to radiator controls than a 1-pipe system, and, considering the whole building, one with several independent sections, each with its own jet pump, is potentially more responsive to individual controls than a building with a single jet pump (assuming all jet pumps are properly readjusted after the retrofit). In fact, one way of obtaining guaranteed savings may require only a simple readjustment of existing jet pumps in all chronically overheated buildings (as will be seen in Chapter 4, however, in some cases this may not help).

Second, some building designs are more wasteful of energy than others. For example, buildings using external wall panel space-heating systems may offer the most potential energy savings, as they waste much more heat than buildings with internal wall panel heaters, radiators, or convectors. Also, buildings lacking any provision for control of the heat delivered from the DH system, whether jet pump or heat exchanger, should be considered good candidates for some kind of building-level heating control system. The buildings may also be ranked by envelope characteristics: the most wasteful design is probably that of older buildings using non-monolithic butt-joints. Other candidates include any designs having significant thermal bridges, including multi-layer large panels or panel framework buildings, because calculated design properties for these designs were generally less accurate. These conclusions are tentative, as experimental measurements are the only means of determining which buildings are least energy efficient. Even so, they represent a significant step forward toward the goal of understanding patterns of energy use in Russian apartment buildings.

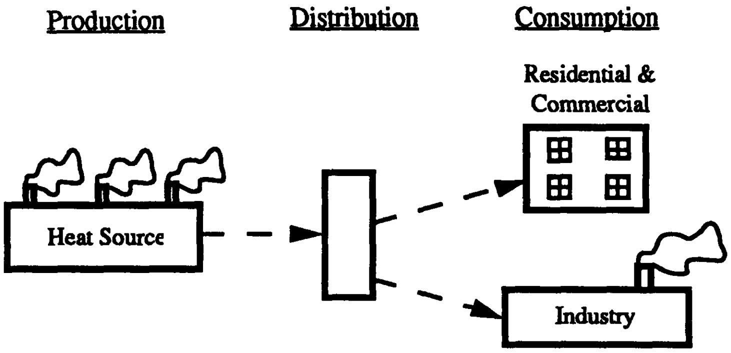
CHAPTER IV: THERMAL CHARACTERISTICS OF RUSSIAN DISTRICT HEATING SYSTEMS

Buildings are the points of end-use energy consumption in Russian district heating systems. Chapter 3 discussed the composition of the Russian apartment building stock, and the distinguishing traits of the buildings important for understanding potential space-heating energy savings. This chapter addresses the composition of the DH system itself: the heat generation stations, and the distribution network that transports heat to individual buildings. The emphasis here is on identifying characteristics of Russian DH system design and operation that could impede realizing end-use energy savings at the points of primary fuel consumption. The first section provides context for a discussion of Russian systems by reviewing the characteristics of DH systems in general; the second section describes Russian systems.

DISTRICT HEATING SYSTEMS

Modern district heating systems produce heat in central stations and transport this heat to supply the low- to medium-quality thermal needs of a community's homes, offices, or industrial establishments. Although specific designs vary, all DH systems have three main components: central heat generation plants, a thermal distribution system, and points of end-use energy consumption (Fig. 4.1). The central plants convert primary energy fuels into forms of heat that are easily transported (e.g., steam or hot water). A network of pipes then conveys and distributes the thermal energy to consumers in the buildings, who may use the heat for space heat, hot water consumption, or industrial process loads.

Figure 4.1: The District Heating Concept



District heating, in its most general sense, can be implemented on scales ranging from a single building to an entire city. Group heating, in which the heating systems of relatively few buildings are connected together, can include up to several hundred customers[68]. District heating, in the sense used here, refers to systems serving tens or hundreds of thousands of customers in hundreds of buildings scattered across large urban areas.

District heating can, under the right conditions, offer two main advantages over decentralized heating systems. First, fuel cost savings can accrue from economies of scale in heat production equipment, volume discounts on fuel purchases, using lower grades of fuel, and from better maintenance and control of heating equipment. Second, air pollution is reduced because emissions from centralized systems are more easily controlled. Unless fuel prices are extremely high, fuel cost savings in DH systems rarely outweigh the huge cost of the necessary pipe networks. Piping costs are easily overcome, however, if DH systems can take advantage of inexpensive fuel sources, such as waste heat from electric power plants and other industrial processes, or heat from the burning of solid waste [Diamant & Kut].

Some conditions help to make DH more competitive with individual heating systems. Effectiveness rises dramatically if the density of heat demand is high in the area to be heated, and short periods of extremely low outdoor air temperatures should be rare, since DH systems are generally more sluggish than individual systems in responding to rapid temperature swings. Further, the buildings to be served should be owned by only a few individuals, or at best by a single entity. This minimizes institutional problems involved with providing a common service to a large number of customers [Diamant & Kut]. One disadvantage of DH systems is a relative inflexibility to the changing needs and desires of consumers. Another drawback is initial cost, often prohibitive because of the large distribution network. Obviously, DH is best implemented as part of new construction, since this avoids complications arising from retrofitting (ripped city streets, disrupted pedestrian and automobile traffic, etc.).

Both steam and hot water have been widely used as the medium for transporting heat through DH systems. Each has advantages; selection of the proper medium depends on local circumstances. In steam systems, demand for industrial processes can be combined with demand for water or space heating. Steam can also be used to run air conditioning plants during summer months, is more easily supplied to higher elevations (whether because of terrain or tall buildings), and is easier to meter than hot water. Finally, steam systems operate at higher temperatures, reducing external corrosion of steel distribution pipes.

Hot water systems have advantages in other areas, however. First, hot water can be obtained as a by-product of power generation at a lower fuel cost because of its lower temperature. Second, both the flow rate and temperature of hot water can be varied easily, whereas controlling steam temperatures is difficult. Third, because of hot water's greater volumetric thermal storage capacity, pipes are smaller, lowering capital costs. Fourth, hot water is safer and simpler to handle than steam. Finally, hot-water systems are able to

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[68] this terminology will be used later to define group heating substations, which serve small groups of users in large Russian DH systems

service larger areas—their range can be 100 km or more, depending on relative fuel prices. In contrast, the transmission of steam becomes impractical over distances of greater than 6-8 km because of high costs and excessive pressure losses [DOE b; Diamant ; Diamant & Kut].

Existing DH Systems

District heating was first implemented in modern times in the US in the late 19th century. Steam systems were installed in several large US cities; many of these systems still operate today. Yet after several decades of successful operation DH gradually declined in the US, largely because of technical progress in the production of electricity—the cheap, plentiful steam that had been a by-product of power generation was no longer available to supply the DH system. Today most DH systems in the US serve relatively small groups of users, such as apartment complexes, universities, and industrial complexes.

Western European countries took advantage of opportunities to move in the direction of energy conservation after World War II. Ravaged by the war, the continent required massive rebuilding programs. Some national governments encouraged the development of DH systems as the best available way to meet their heating needs; this is one reason DH systems have been more successful in Europe than in the US. Following Europe's example, the governments of Canada and Japan have recently favored new DH developments.

District heating was implemented on a truly gigantic scale in the former Soviet Union. Every major urban area in the country has some form of DH in place. Unlike the situation in other countries, there were few institutional and economic barriers to DH development in the USSR—most urban residents had little choice of the method of heating their homes. In fact, in the Soviet Union DH could be viewed as an instrument of social control: centralized heat supply, combined with the lack of individual heating controls, stripped urban consumers of effective methods of controlling their environment. One justification offered by planners for the widespread use of centralized heating systems was their effectiveness for heating densely-packed housing in urban areas. As Chapter 2 noted, however, planners also justified the high density of new housing by pointing to the widespread use of centralized heating systems.

Cogeneration

When fuel is burned in large power plants only about 1/3 of the heating value of the fuel is converted into electricity. The remaining 2/3, manifested as heat, is lost because of thermodynamic inefficiencies, technological limitations, and economic constraints. Even though the waste heat represents an enormous source of low-quality heat energy, it is typically discharged to the environment. Until the 1980s there was little incentive to utilize this energy in the US. Recently, however, higher energy prices have motivated the search for ways to use the heat for water heating, space heating, or industrial processes.

Cogeneration is the simultaneous production of high-quality energy (i.e., availability, usually as electricity) and useful heat. Cogeneration systems are designed to deliver both forms of energy effectively; they offer a substantially higher fuel efficiency than combined use of systems designed to deliver either product alone. However, potential fuel savings are realized only if adequate demand for both electricity and heat exists; without it energy is unnecessarily wasted.

Since the cooling load in a typical condensing power station is about 1.7 times its electrical output, power stations rely on the local availability of large amounts of coolant (usually water). Space-heating water (in a DH system, for example) is ideally suited for extracting heat. Hot water generally needs to have a temperature of 70-120 °C to be useful in providing heating services, but efficient power plants usually generate waste heat at about 30-40 °C. Electricity generation capacity must therefore be lowered slightly to obtain higher quality heat. A sacrifice of one unit of electricity during simultaneous heat and power production yields from 5 to 10 units of heat, depending on the unit's design [Diamant & Kut; Karkheck & Powell]. For modern fossil-fired cogeneration facilities in the West, electricity output is 28% of the fuel heating value, compared to 33-35% for electric-only plants. Power plants retrofitted for cogeneration are generally less than 28% efficient at producing electricity.

Considered separately, cogeneration and district heating are each potentially energy-saving technologies. They also complement each other when used together on a large scale, providing additional energy savings. This natural partnership between the two technologies was one motivation for the widespread use of cogeneration and district heating in the USSR.

Central Plants

Heat is supplied to DH networks by one of two main methods: direct heating via boilers, or indirect heating via steam bled from condensing turbines. Boilers can be grouped into two classes: water-heating and steam-generating. Direct heating stations use water-heating boilers, which simply raise the temperature of DH circulating water, either directly or through a secondary fluid circuit. Electric power stations use steam-generating boilers, designed to produce steam at a high temperature and pressure. Modern large steam-generating boilers are over 90% efficient; by comparison, small localized boilers are about 75% efficient. Boiler complexity varies depending on the type of fuel: coal-fired units are complex, requiring many separate steps for fuel preparation and exhaust cleanup; oil- and gas-fired systems are relatively simple.

Electricity is generated by turbines, which can be classified in several ways: by the choice of working fluid (steam vs gas), by the initial operating parameters of the working fluid, or by the operational flexibility in adjusting output levels. Two basic kinds of turbines are used to generate electricity in the CIS: steam turbines and gas turbines.

Steam turbines are generally condensing turbines or back-pressure turbines operating on the Rankine cycle. In these units a boiler heats feedwater, converting it to steam at 100-250 atm, 450-550 °C, which then drives a turbine connected to an electric generator. As the steam passes through the turbine it expands, and its pressure and temperature drop drastically. The efficiency of the cycle depends on the ratio of the steam temperatures entering and exiting the turbine[69]. Since steam condenses at the lowest possible temperature under near-vacuum conditions (at about 30 °C), in condensing turbines the steam exits at a very low pressure, usually at a temperature of 35-40 °C. From there the steam is passed through a heat exchanger (the condenser), which extracts low-temperature heat from the steam, converting it back to water. In back-pressure turbines steam exits the turbine at a higher pressure and temperature, and is then used for industrial process loads, steam-based heating systems, or for other purposes. Some steam turbines operate on modified Rankine cycles, such as the Reheating Cycle or the Regenerative Cycle, which offer improved thermodynamic efficiencies [Sonntag & van Wylen].

Gas turbines operate on the Brayton cycle, relying on the expansion and cooling of very hot, gaseous combustion products. Since gas turbine exhaust has a much higher temperature than steam turbine exhaust, gas turbines provide higher-quality heat than steam turbines. Gas turbine efficiency is less sensitive to the temperature at which the heat is extracted for auxiliary heating. Some systems use regenerators, in which exhaust gases preheat intake air. Occasionally exhaust gases are used to run secondary steam turbines for power generation; this limits the usefulness of such systems for cogeneration.

To maximize efficiency, central heat or power plants should be operated only if sufficient demand for their output exists. Demand for electric power or heat in a given region varies throughout each day, and throughout the year (Fig. 4.2a). Demand curves are typically divided into three regions, according to how much of the time the demand is present: 1) baseload demand is needed 24 hours per day, year round, 2) semi-peak demand is needed only part of the year (or part of the day, depending on local use of the term), and 3) peak demand is needed only briefly—perhaps 10-20% of the time. Generation equipment must be able to follow these fluctuations to avoid surpluses or shortages. This basic design objective determines the technical characteristics of the most effective equipment: usually generating stations with low fuel costs and high capital costs are employed for baseload power, and stations with high fuel costs and low capital costs are used for peak demand. The local need for each kind of generation unit is often illustrated by a load-duration curve (Fig. 4.2b).

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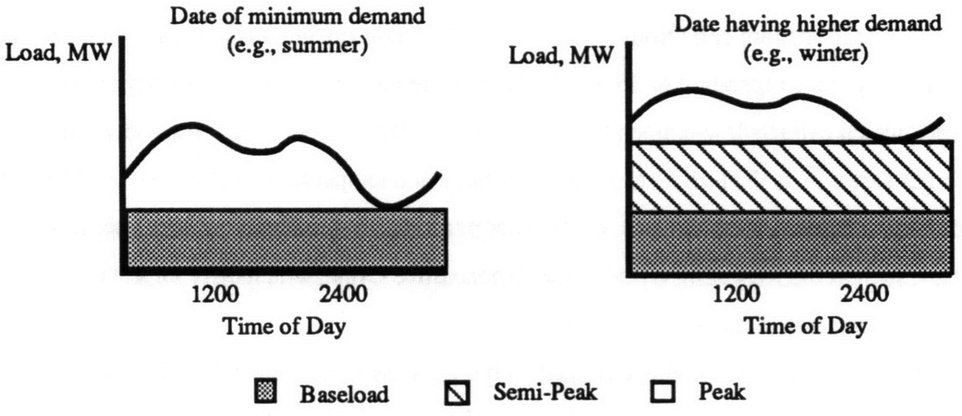
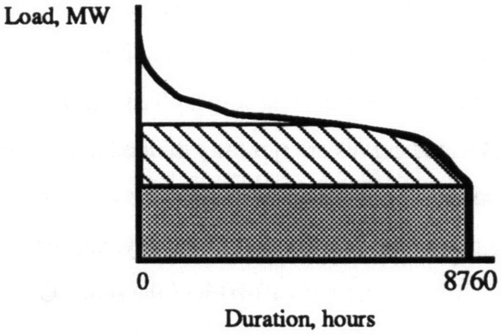
[69] because, thermodynamically, these temperatures determine the temperatures at which heat is added to and rejected from the system

Figure 4.2: Typical Load Curves for Electricity or Heat

a) Daily Load Curves (not representative; simply illustrative)

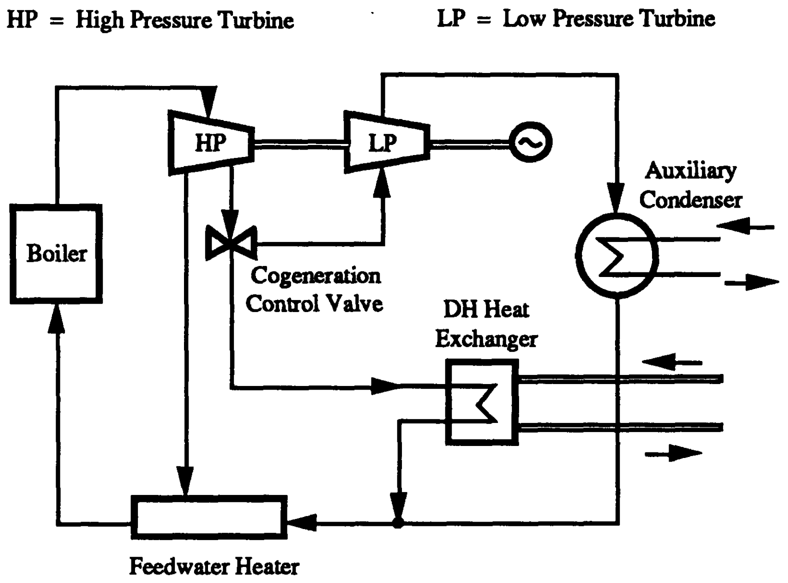


b) Annual Load-Duration Curve



A widely used technology for implementing cogeneration effectively at power stations is the intermediate take-off condensing (ITOC) turbine (Fig. 4.3) [Diamant & Kut]. In ITOC turbines, the steam exiting the boiler is fed first to a back-pressure turbine operating at high temperature and pressure. From the first turbine the steam is fed either to heat DH network water, or to generate more electricity in a second, low-pressure turbine, or to both. Steam exiting the low-pressure turbine is passed through the condenser (or to process loads, if the low-pressure turbine is a back-pressure turbine). From there the feedwater mixes with steam condensate leaving DH heat exchangers; the mixture is then pre-heated regeneratively, and sent back to the boiler. ITOC stations generally heat feedwater and DH network water using more than one stage to improve efficiency.

Figure 4.3: Layout of a Condensing ITOC Station on the Regenerative Rankine Cycle



ITOC stations are efficient because they can adjust outputs instantaneously from producing electricity only (at an efficiency nearly equal to that of dedicated electric units) to producing electricity and heat, up to the maximum possible heat output. This design permits the power plant to meet variations in demand for heat and electricity simply and efficiently, eliminating the necessity of simply dumping waste heat through the condenser or of varying the fuel input to the boiler, an inefficient and less effective procedure [Diamant & Kut]. ITOC stations also offer an effective way to reduce the total peak energy (i.e., heat plus power) loads: ITOC turbines can be used during periods of low electricity demand to heat DH circulating water, which is then stored—either in tanks or in the DH distribution system itself—and later used to meet heat demand during periods of peak power demand.

Back-pressure turbines are sometimes used in DH systems, but they are less effective than ITOC designs because their heat output cannot be adjusted to suit changing DH heating loads. Back-pressure turbines are thus best suited for baseload heating operation.

Distribution Systems

The distribution system makes up 50-70% of the initial cost of DH systems. District heating distribution networks are hydraulic systems: flows through all mains (large-diameter pipes) and branches are determined by relative pressures and hydraulic resistances. Proper design requires knowing end-use heating loads, vertical elevation, and the minimum pressure head required at all network junctions. Given this information, design pressure heads can be determined throughout the network. Hydraulic design is a complicated affair because of the large number of users, the physical complexity of hydraulic sections, and the continual addition of new loads in the network. The result of this complexity is often low hydraulic stability—hydraulic performance (i.e., maintenance of design water flow rates) at most consumer points is quite sensitive to conditions elsewhere in the network [Gromov 1976].

Heating mains are generally fabricated from either plastic or metal; in Russia they are steel pipelines, lying either above or below ground. In both cases the pipes are usually insulated to reduce heat losses. Corrosion damage is the main problem faced by metal DH pipes. Internal corrosion can be reduced by minimizing the dissolved oxygen content of the water; external corrosion is reduced by keeping moisture away from the surface of the pipes. Because of the cost of manufacturing, installing, and maintaining metal pipes, their use is widely disfavored in modern DH facilities in other countries; plastic pipes have proven more durable [Diamant & Kut].

Four different piping arrangements are generally used for the supply of hot water or steam in DH systems: the 1-pipe, 2-pipe, 3-pipe, and 4-pipe systems. The 1-pipe design is used in most steam systems, and in schemes employing very highly pressurized and superheated water. Hot fluid is supplied to the main pipelines and distributed through the network. After use the excess fluid is discharged as waste. Such networks offer several advantages when used with hot water. First, high temperature water has a higher heating capacity, and requires less intensive water treatment than water at 100 °C. Second, the much simpler distribution network can be constructed faster and more cheaply. Third, 1-pipe systems, being shorter and employing hotter, less viscous water, have lower pumping costs.

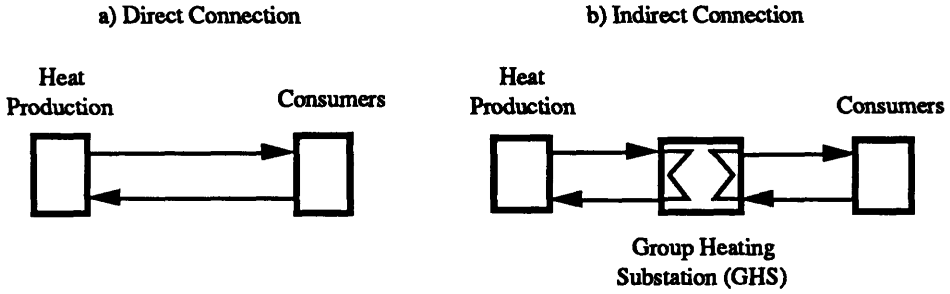
Most hot water DH systems in use today, especially in Europe and Russia, employ a 2-pipe arrangement. In this system hot water is pumped from the central heat source to the points of end use, where part of the water may be diverted for domestic hot water. Afterwards, the water is returned to the heat source via a return line. This system, while more expensive to build, offers potentially greater energy efficiency and lower water treatment costs because the water is re-used.

The 3-pipe system is even more expensive to build, but has some advantages over the 2-pipe system. Two large mains are laid to serve as the supply and return pipes. A much smaller main is added to supply hot water and space-heating demand in the summer; in the winter both the large and small supply pipes carry water. The common return line serves both supply lines. In this way heat losses are considerably reduced during the summer months. The extra line also enables heat supply to be more flexible during periods of maximum heat demand.

In the 4-pipe system domestic and space-heating hot water are circulated through two separate sets of pipes. This system is most expensive, with few real advantages to offer over 2- or 3-pipe systems; its use is generally discouraged in Western nations.

Regardless of the piping arrangement used, another way of classifying DH distribution systems refers to the number of separate water circuits existing between the heat source and consumers. In this scheme distribution systems are either direct or indirect. The two designs are depicted in Figure 4.4; they apply to DH systems for either domestic hot water consumption or space heating. The Russians use the terms *open* (direct) and *closed* (indirect) for domestic hot water systems, and the terms *dependent* (direct) and *independent* (indirect) for space-heating systems. Space-heating systems and domestic hot water systems need not use the same connection scheme in a given section of a DH network.

Figure 4.4: Direct and Indirect District Heating Distribution Networks



In the direct heat supply system (Fig. 4.4a) the DH water flows directly from the central heat station to the consumers in a single water circuit. Direct systems are simpler and cheaper to build, but they suffer from several disadvantages. First, it is generally difficult to control the hydraulic state of the network in large systems: pressures vary with location and elevation, making water flow rates highly variable. The stability of the system is low because of the large number of interconnected consumers. Second, direct systems are less flexible during emergencies (i.e., when pipes rupture). Finally, direct systems cannot heat high-lying areas without extra line pumps.

In indirect systems (Fig. 4.4b) heat is delivered through the mains to group heating substations (GHSs), which transfer heat through heat exchangers to secondary water circuits having their own pumping and distribution systems. From the substations the secondary water is sent to individual buildings for space heating and hot water supply. The supply water temperature in the secondary circuit is always lower than that of the primary circuit. Indirect systems are considerably more costly than direct systems, but overcome their main disadvantages.

RUSSIAN DISTRICT HEATING SYSTEMS

District heating was introduced in the former Soviet Union in 1924, but did not grow substantially until after the beginning of the housing drive (Table 3-IV). Since then, district heating has been implemented on a truly gigantic scale. The total length of all heat supply lines in the CIS currently exceeds 200,000 km [Gromov 1988]. The radius of an individual DH network can extend to 30 km, with thousands of connected buildings, and the diameter of the mains can reach 1.4 meters [Melent'ev & Rudenko]. The CIS distributes more heat through DH systems than do all other countries combined; the systems provide over a third of the national space-heating load. Moscow has the largest single DH network in the world, with over 2600 km of distribution pipes in use, connected to over 4000 GHSs, serving about 40,000 buildings and 400 enterprises. Nearly 70% of all residences and public buildings in the city are connected to the DH network. The system has 21 cogeneration plants—over ten of them large—which supply 75% of the city's heat demand. The remaining 25% is supplied by over 15 municipal (direct) heating stations.

This thesis investigates potential energy savings from end-use efficiency improvements in Russian MFBs. The main goal of this chapter, therefore, is not identifying potential energy savings within Russian DH systems themselves. The objectives here are determining the DH system characteristics leading to incorrect heating levels in Russian MFBs, determining whether end-use savings in buildings are passed through the DH system to central heating plants, and determining whether primary fuel savings will be realized in response to end-use savings. This requires understanding how the characteristics of the DH system affect realizing these savings, and how reduced end-use heating requirements affect the DH system's performance. Most information in this section was taken from the journal *Thermal Engineering*, the English translation of the Russian journal *Teploenergetika*. Unlike much of the material presented in Chapter 3, most of the following material has already been published in the West. The main exception is the presentation of technical impediments to energy savings presented near the end of the chapter, a significant original contribution of this thesis.

System Configuration

Heat Sources

Heat sources in Russian DH systems can be thermal or nuclear electric power plants, large municipal heat stations, industrial heat stations, or small building boilers exceeding 20 Gcal/hr in capacity. Some of these sources are insignificant in existing DH systems: although nuclear heating plants may be widely used in the future, at present only a few nuclear stations have been constructed; industrial heat stations provided less than 5% of DH heat supply in 1985; and small building boilers, although possibly significant in aggregate heat production, are not connected to DH networks. That leaves the two major kinds of heat source in DH systems: large municipal direct heating stations, or boiler houses (BHs), and thermal electric power stations. Electric power stations can be divided into two categories: condensing stations (KES), and cogeneration stations (TETs). The former category is relevant here because the Russians converted some older condensing stations to produce heat in a cogeneration mode for DH systems.

For decades cogeneration was a central part of Soviet energy policy in the area of urban power generation. For 12 years the former USSR has had the world's leading volume of cogeneration energy production, with more than 1000 stations supplying heat and electricity to about 800 cities. Cogeneration stations are the chief source of centralized urban heat: in new areas they supply 90% of DH heat; in older areas 70% [Yudzon].

Boilers and Turbines

Boiler houses consist of a number of water-heating, fossil-fuel fired boilers. Pumps force water through the boilers, where it is heated to the desired temperature. From the boilers the water is sent into the DH network. At the boiler outlet some water is diverted to heat chemically treated makeup water (from DH network leaks, and from domestic hot water consumption). Some thermal power plants also supply heat with either water-heating or steam-generating boilers. Water-heating boilers, if present, operate independently of the power production system, covering peak DH heating loads. Some steam-generating boilers operate at relatively low steam conditions; others use supercritical steam.

Boilers in BHs usually burn oil, gas, or both. Operation of oil-fired water-heating boilers has some intrinsic shortcomings, lowering their reliability: internal corrosion is highly sensitive to network water quality, and external corrosion occurs in low-temperature sections, especially when the return water temperature is too low. To combat external corrosion, some hot output water is mixed with boiler inlet water to keep its temperature higher than the dew point, normally 60 °C [Yarovoy].

Boiler houses were usually constructed to serve new town districts—because of their lower capital costs they could be brought on-line much more quickly than TETs. Most were designed for a 6-year lifetime; normally after that time a new TETs began operating. Afterwards, the BHs remained in operation either to preheat fuel oil for the TETs or to help cover heating loads during severe weather. Boiler houses produce heat for DH systems less efficiently that TETs, but their operation is relatively simple: their sole purpose is meeting heat demand.

Cogeneration plants produce heat more efficiently than boiler houses, but only when operating in a cogeneration mode. TETs supply heat to DH networks with either steam (from turbine bleeds or steam boilers), hot water (from boilers), or both. The boilers are typically used for peak heating demand, raising DH supply water to the required high temperatures during cold weather. Cogeneration only occurs when turbine-extracted steam is used for heating; boiler-supplied heat is in principle no different than producing heat in boiler houses.

The vast majority of thermal electric power stations in the CIS employ steam turbines. Gas turbines and combined-cycle plants, although recommended in the Russian literature for the future, are not common now (less than 5% of power stations employ gas turbines of any sort, and virtually no TETs currently employ them) [*Therm. Engr.*]. Some steam turbines were designed exclusively for TETs, others for KES. In KES converted to cogeneration operation the turbines were either refitted with steam bleeds or modified to operate in a back-pressure mode.

Russian TETs steam turbine designs are grouped into three basic categories: R-type, T-type, and PT-type. For this discussion, the most important distinguishing trait among these designs is the kind of secondary steam demand each turbine is designed to serve. R-type turbines are back-pressure turbines, designed to provide high-pressure, high-temperature steam for industrial processes; they have no DH steam bleeds. T-type turbines are essentially the opposite: condensing units with one or more DH steam bleeds, but no industrial process steam bleeds. PT-type turbines are a hybrid condensing turbine design, containing both kinds of bleeds. Since R-type turbines are normally used only to serve industrial consumers, they will not be discussed further here.

Many T-type and PT-type turbine designs were produced, with various power capacities and initial steam conditions. Common turbines have design power outputs ranging from 50-250 MW, and initial steam temperatures and pressures from 450-550 °C and 9-24 MPa, respectively[70]. In a typical turbine designation, such as T-250-240 or PT-80-130, the first number represents the design power capacity of the turbine in MW, and the second number is apparently the initial steam pressure in bars[71]. Some turbine designations (e.g., T-175/210-130) explicitly indicate that the turbines were designed to operate in either a combined heat and power mode or a pure condensing mode (in this case, with a design power output of 175 or 210 MW, respectively). T-type and PT-type turbines are generally equipped with more than one steam bleed, each operating at a different pressure depending on whether the steam is destined for industrial process loads or for heating DH water.

TETs and Demand Curves: Design

Cogeneration plants are constrained by two load curves. Since these curves generally differ in shape, the combined mode of operation is more complex than a pure condensing mode. A TETs' energy efficiency depends on whether the station can regulate its production of usable heat, scaling it back during periods of low heat demand to save fuel or to generate more power. Russian authors in *Teploenergetika* describe several TETs designs used in Russia; their writings suggest two meaningful ways of classifying the TETs.

First, TETs can be either flexible or inflexible. *Flexible* plants are able to easily adjust power output to follow fluctuating loads, and are used to cover semi-peak power demand. *Inflexible* plants are baseload plants, and cannot easily adjust their power output. This is not a rigid classification, as "easily adjustable power output" is a vague term; flexibility is simply a general guide for distinguishing TETs. It normally refers to the cost of making adjustments, the time required to adjust, or both. TETs flexibility depends on station size, type of fuel, and on the specific technologies used in turbines and boilers.

As mentioned previously, in a TETs heat is supplied to the DH system in one of two ways: from turbine steam bleeds or from boilers. The second TETs classification is by controllability, or the adjustability of the plant's steam-bled heat output. *Controllable* TETs are ITOC stations, able to independently and continuously vary the amount of steam bled from the turbines in response to changing

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[70] supercritical units, employing steam with $T > 374$ °C and $P > 22$ MPa, are the most energy efficient
[71] this is partially the author's guess, as Russian authors fail to explicitly define the second number

heat demand. In controllable TETs, power generation efficiency declines as more heat is supplied to the DH system from steam bleeds. Conversely, *uncontrollable* TETs cannot continuously vary the amount of steam bled from the turbines—for a fixed power production rate, any excess heat not needed by the DH system is simply dumped through the condensers. This classification scheme is also somewhat vague: some DH turbine bleeds are partially controllable, setting DH heat output in discrete steps; in other designs DH heat output is independent of power output, but depends on heat output to industrial users.

The steam bleeds in controllable TETs turbines may be less adjustable than the ITOC stations widely used in the West. If more than one DH bleed is present in a T-type or PT-type turbine, the turbine may usually use either one or both bleeds, depending on the DH heating load. In some turbines, however, the bleeds themselves may be uncontrollable. Dual-mode turbines (e.g., T-180/210-130 and the like) are generally controllable: DH heat supply through the bleeds is regulated with diaphragms by varying the pressure of the steam in the bleed. The DH bleed pressure typically has a minimum value greater than zero[72], however, preventing complete control of DH heat supply from zero up to the turbine's maximum DH bleed heating capacity [Volkov].

TETs stations often contain more than one turbine, and the turbines are often of different types. Station flexibility and controllability depend strongly on the design of each turbine within the station, but may also be affected by the specific combination of turbines used in the station.

A serious economic problem facing Russian cogeneration stations is dramatic underutilization of heating capacity. For example, in 1975 nationwide aggregate TETs heating capacity was 272,000 Gcal/hr, but aggregate peak loads were only 200,000 Gcal/hr [*Therm. Engr.*]. Campbell cites two particularly bad cases of this problem: one TETs had a heating capacity nearly three times its connected peak heat load; another had no heating network connected at all, and was not likely to get one in the near future [Campbell 1980]. Excess heating capacity forces a TETs either to operate solely as a condensing station, to waste usable heat, or to operate at below its power generation capacity. Many Russian authors call for increasing heating capacity utilization in TETs [*Therm. Engr.*].

The electric and heating capacities of TETs turbines were sized by optimizing the "district heating factor," α, the ratio of the heating capacity of the turbines to the design peak heat load connected to the station[73] [Shitsman]. The α value was chosen to minimize reduced design costs of the TETs (nothing is known about the structure of the cost formula, or about whether heating costs or power costs were more important). Optimal α values varied over time as design methods changed; they also depended on local conditions. Typical values range from $\alpha = 0.5\text{-}0.55$ for older plants, to $\alpha = 0.38$ for newer ones. Lower α values mean that less of a given district's heat demand is provided through cogeneration. The balance must be made up by peaking water-heating boilers, either in the TETs or in a BH (if the nets have sufficient

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[72] for example, in a T-180/210-130 turbine the pressure in the low-pressure DH bleed ranges from 50-150 kPa, and the pressure in the high-pressure bleed from 60-200 kPa

[73] in practice TETs operate at variable DH factors: α tends to decline over time because connected peak heating loads increase as DH networks expand

interconnections). A lower α value in an individual TETs thus increases its fuel requirements for heating, lowering its average thermal efficiency. Recently the average α value of the USSR's TETs has declined: the fraction of TETs heat output supplied via cogeneration fell from 92% in 1970 to 78% in 1980.

Lower α values also permit higher capacity utilization, however. When a TETs sets output according to local heat demand (as opposed to following power demand), higher heating capacity utilization leads to higher electricity output. This electricity often displaces power produced less efficiently in KES; the resulting fuel savings exceed the higher fuel requirements for heating [Shitsman]. Thus, under the right conditions—namely, for non-controllable TETs for which makeup power is provided by KES—lower α values lead to net fuel savings.

Heat Distribution Networks

Russian apartment buildings and DH systems were designed using the same basic approach: designers focused on meeting projected worst-case conditions, with comparatively little attention paid to optimizing operating conditions [Yudzon]. Sizing of system components (central heat plant capacities, pipe and pump sizes, etc.) and settings for distribution system equipment (jet pumps, orifices, valves, temperature schedules, etc.) were based on delivering the required amount of heat using design heating load calculations for buildings at the design outdoor air temperature.

In many Russian towns the industrial, commercial, and residential users are all connected to the same DH distribution system. Four different heating end uses are served by DH systems: space heat, domestic hot water (DHW), ventilation (public and industrial buildings), and process steam (industrial buildings). Apartment buildings have only two loads, however: space heat and DHW (in all MFBs the space-heating load is the larger load). The end users differ in their heating needs, as industrial consumers have lower indoor air temperature standards, larger internal heat gains, and predominating ventilation loads. Further, industrial DHW supply is usually heated by secondary steam from industrial processes. For this reason, DH networks sometimes separate different kinds of end users in local distribution systems, minimizing their interactions. Since most Russian DH systems serving MFBs use hot water as the transport medium, the remaining discussion will focus on hot water systems.

Heat Losses and Reliability

Reliability is the most serious problem in Russian DH nets: most breakdowns in DH systems occur in the nets, and about 90% of these failures are due to external corrosion of pipes. Heating pipes were laid either above or below ground. Pipes laid above ground failed less often, and were more easily inspected and repaired, but generally suffered from higher heat losses. Some underground pipes were laid in channels constructed of prefabricated concrete (the more common approach), others were buried directly. All designs have been unreliable. Yudzon describes an extreme example of the problem: when the hot water from one ruptured underground pipe eroded the soil beneath the earth's surface, the remaining thin layer of topsoil collapsed under the weight of a passing pedestrian.

Transmission heat losses and water leaks in Russian DH nets—nominally totaling 8-10% of heating loads—both exceeded design standards specified in SNiPs, by up to 150% in some cases [Yudzon]. Only some directly buried DH pipes were coated with insulation. As a result, underground pipes are often traceable in winter by following patterns of melted snow. This suggests that large amounts of energy could be saved if thermal insulation on DH pipes were improved. In fact, a crude analysis suggests that adding insulation to DH pipes may save substantially more energy than an equivalent amount of insulation added to external walls of apartment buildings[74]. Further, savings from improved pipe insulation are more likely to result in primary fuel savings, since many potential impediments in buildings and the DH network are avoided. Thus, potential energy savings through improved DH pipe insulation should be assessed with more precision. Since this analysis focuses on energy savings in apartment buildings, no such effort will be made here.

Network Layout

Most Russian DH networks are split into isolated districts, with different areas each served by a single central heat source. Network layouts continually changed over time as they were retrofitted with new and better equipment. Russian networks generally use 1-pipe, 2-pipe, or 4-pipe systems.

In the 1-pipe system treated water is supplied to the DH network at a high temperature (up to 200 °C) from remote central stations. In Russia it has been economical to pump hot water from heat and power stations over immense distances in 1-pipe networks [Diamant; *Therm. Engr.*]. Once the hot water reaches the urban area it is either mixed with additional hot water from boiler houses and distributed within a 2-pipe system, or supplied to consumers directly in a 1-pipe distribution system. In the latter case part of the water is passed to the consumers' heating system when it reaches buildings. Of the remaining supply water, some is then mixed with the cooler return water from the heating system. The mixture is then used for domestic hot water. Any excess water is drained off to waste.

Most Russian DH nets employ 2-pipe systems for the mains, usually including some kind of substation between the central heat source and the end users. In Russian usage substation is an ambiguous term, however: it can refer either to a group substation, serving several buildings in a local distribution network, or to an individual substation, serving a single building. Further, group substations come in two varieties: pumping substations, which simply increase the pressure of the DH water, and group heating substations (GHSs, from Fig. 4.4), allocating the DH water among different buildings and end uses. Group heating substations employ water-to-water heat exchangers for DHW or space heating. The heat exchangers

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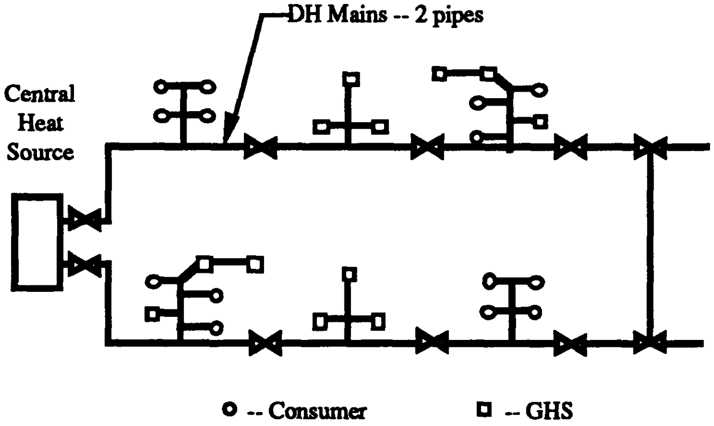
[74] improved pipe insulation may save up to 20-25 Watts per cubic meter of insulation material, whereas improved insulation on external walls saves only about 1-2 W/m^3 (author's calculations)

are usually split into several sections, each serving a small number of buildings on the secondary circuit (1-4 if high rise; 10-12 if less than 6 stories).

The layout of a DH distribution system need not be uniform throughout the network—most Russian DH networks are in fact quite varied. For example, in Russia 2-pipe systems are commonly employed between central heat stations and GHSs, with 4-pipe systems between each GHS and individual buildings. Similarly, some network sections may employ direct consumer connections (of space heat, DHW, or both), and others may connect consumers indirectly. Both direct and indirect DHW systems can be used with either direct or indirect space-heating systems. Reliability can also vary: some parts of the network may have redundant connections; others may have no such provisions for backup. Figure 4.5 displays an example of the diversity that can show up in Russian DH networks.

Figure 4.5: Layout of a Typical Russian District Heating Distribution Network
[Gromov, 1976]



Domestic Hot Water Connections

Most district-heated MFBs obtain domestic hot water from the DH system[75]. The DHW heating load typically ranges from 15-40% of the space-heating load—in Russian terminology, the *relative* DHW load is typically 0.15-0.40. Russian sanitary standards call for all DHW to be heated to at least 60 °C. As mentioned previously, DHW systems were connected to the DH network either directly or indirectly (Fig. 4.4); the Russians distinguish the two systems as *open* and *closed.*

In open systems water flows directly from the DH mains through consumers' water taps (Fig. 4.6). In some systems the DHW flows from both the supply and return mains; in others only from the return line [*Therm. Engr.*]. In open systems the DH system must provide a minimum amount of makeup water corresponding to total DHW consumption. Physically, the DHW connections are generally located in building basements.

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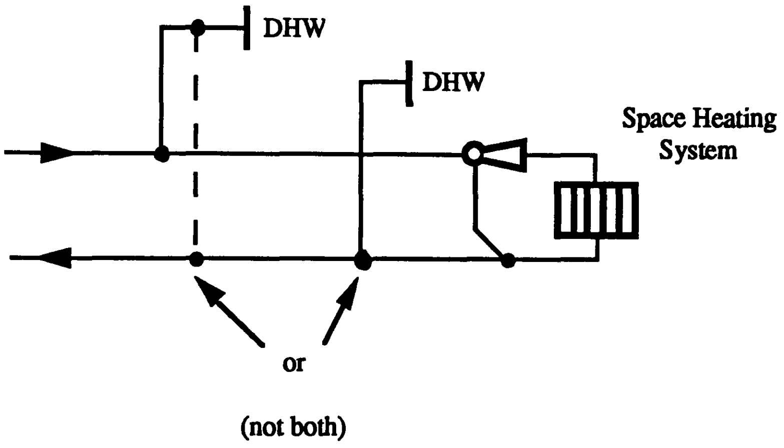
[75] a few use individual gas-fired hot water equipment

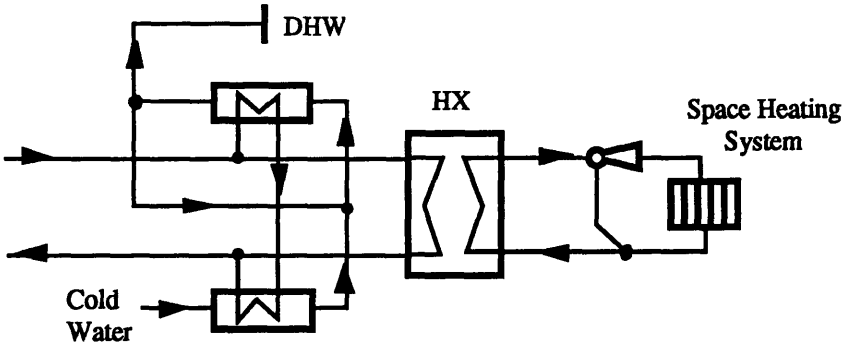
Figure 4.6: Two Possible Open DHW Systems, with Dependent Space-Heating Connection
[*Therm. Engr.*]



Open systems have a major shortcoming: hydraulic instability in the local heating network because of drastic fluctuations in water flow. The problem is especially severe in open systems with dependently connected space-heating systems (as in Figure 4.6) with part or all of the DHW water taken from the supply line. Water flow through radiators, invariant by design, in reality varies inversely with DHW loads, leading to underheated rooms when relative DHW loads are high. Some open systems may include DHW preheaters at consumers' premises, in which space-heating supply water flows through a heat exchanger, supplying heat to return water for DHW consumption [Malafeev].

In closed DHW systems cold potable water is heated with DH water separately using a 2-stage heat exchanger of either series or mixed design, depending on the size of the DHW heat load (Fig. 4.7). In the series design the first stage uses return water from the space-heating system to heat the DHW, and the second stage uses supply water. Most series systems have a device (either a throttle orifice or a flow controller) installed in the DH supply line to maintain a constant flow of DH water to the space-heating system. In the series system, the temperature of the space-heating water varies with relative DHW loads. In the mixed design, DH supply water passes through the second stage first, then is routed to the first stage, and finally to the DH return line. Mixed systems sometimes have flow controllers at the inlet of the space-heating system, but usually lack them. If no flow controller is used, water flow through the space-heating system varies with flow through the DHW heat exchangers.

Figure 4.7: A Closed DHW System (mixed design shown) with Independent Space-Heating Connection [*Therm. Engr.*]



In both open and closed DHW systems, if the space-heating system is independently connected then the city block network may use either a 2-pipe system, in which DHW is drawn off at each building, or a 4-pipe arrangement, in which DHW is drawn off at the GHS. Four-pipe closed designs maintain water circulation even when DHW loads are zero in order to circulate the water in the heat exchangers, to maintain instant supply at the required temperature at hot water taps, and for towel-dryers in the building's bathrooms. The circulation line is generally connected to the DHW line between the first and second stages of the DHW heat exchangers (Fig. 4.7), increasing the load of the second stage by an amount equal to the heat losses in the DHW circulation line. Since these loads were not included in design calculations, this is another potential cause of underheated buildings served by local 4-pipe systems [*Therm. Engr.*].

Space-Heating Connections

Space-heating systems, like hot water systems, were connected to the DH network either directly or indirectly. Here the Russians distinguished the two systems as *dependent* and *independent*. Dependent heating connections use jet pumps to directly connect space-heating systems to DH nets: a single water circuit connects central heat sources and consumers (Fig. 4.6). Some dependent systems have an intermixing pump triggered by a pressure differential relay in the local network to maintain a constant flow of water in the space-heating system.

Dependent connection was justified for small DH networks with small DHW loads, but have great shortcomings in open systems under modern conditions. Considerable pressure fluctuations occur in return lines, requiring pressure controllers to prevent radiators in tall buildings from emptying at high DHW loads. Additionally, DHW quality is adversely affected by the passage of DH water through space-heating systems. To remedy these problems, independent space-heating connections should be used in open DHW systems [Zinger & Orlov].

In independent systems, space-heating water circulates in a circuit separate from central DH supply water (Fig. 4.7). The two circuits are linked by a heat exchanger, located either in a GHS or in a consumers' building. In the 4-pipe arrangement hot DH water is delivered to the GHS, where part of it is diverted for DHW. The remaining DH supply water passes through the space-heating heat exchangers, transferring its heat to the water in the secondary heating circuit, and is then returned to the DH network. In the secondary circuit a circulating pump forces the hot water through the heat exchanger, to buildings, through their heating systems, and back to the GHS. Many systems contain flow control equipment for the secondary water circuit.

Summary of Russian DH System Configurations, and Comparisons with Western DH Systems

Russian authors suggest that most TETs are inflexible, baseload power plants—they call for increasing the range of controllability by up to 50% to help account for the inflexibility, and are now focusing much attention on the development of new, highly flexible gas turbine and combined-cycle plants [*Therm. Engr.*]. Most TETs serving residential areas employ T-type or PT-type turbines. Russian and Western authors suggest that these are usually ITOC stations, but, as indicated earlier, many may only be partially controllable. Nothing is known about the relative penetration of dual-mode turbines in Russia. Modern Russian TETs tend to have higher connected heat loads, increasing their capacity utilization. This suggests growing use of peaking water-heating boilers within TETs and in BHs. About 50% of the DH heating capacity in Moscow's TETs comprises peaking boilers, with 50% comprising turbine bleeds.

In Western Europe most DH systems employ cogeneration stations. Back-pressure turbines and ITOC stations are both common; as in Russia, the design of a given plant depends on the nature of the local heating loads. West Germany has the most effective DH systems in the West, with widespread use of ITOC cogeneration stations. Cogeneration efficiency in West German ITOC systems is driven largely by the supply temperature of the DH water, usually determined by outdoor conditions: at 80 °C 10-15 units of heat can be produced for each unit of electric power sacrificed, but at 160 °C only 4-6 units of heat per unit of power can be produced [Diamant & Kut]. As will be seen shortly, supply temperatures in Russian systems also vary with outdoor conditions, so that the cogeneration efficiency of a given station varies over time. In some regards, then, Russian and West German practices are similar.

Most Russian DH distribution networks use hot water: virtually all of Moscow's system is hot water, versus about 80% of St. Petersburg's system. In towns and large housing groups 2-pipe systems predominate (in the West, 3-pipe systems are preferred). Most Russian DH nets are isolated districts, served by a single central heat source, with interconnections only for emergencies. About half of Russian heat supply systems in cities and towns in 1986 were open systems [Varvarsky]. Most open systems employ dependent connection of space-heating loads, even though independent systems are widely regarded as superior [Zinger & Barmina]. As of the mid-1970s, only 20% of Moscow's DH network employed independent space-heating connections [McIntyre & Thornton]. Since Moscow tended to receive innovations first, this suggests that independent systems are uncommon in Russia. Most distribution systems lack temperature or flow controllers, even though Russian experts have developed and successfully tested automatic and manual control systems for space heating [Bestolchenko]. Finally, most building connection systems use jet pumps.

Heat losses in Russian distribution systems are generally believed to be higher than losses in Western systems. A typical (underground) 2-pipe hot water system in the West loses about 0.7% of the water's heat content per kilometer of pipe [Diamant & Kut], or roughly 7% losses in a 10 km network (a length typical of many Russian systems). Russian design calculations generally assumed 8-10% losses in the network, and as previously noted, network heat losses commonly reached 15% [Yudzon]. Diamant & Kut cite losses in Moscow's network of only 5.5%, crediting the high performance to highly effective external pipe insulation. Since infrastructure in Moscow was commonly of higher quality than infrastructure in other Russian cities, average Russian DH network losses almost certainly exceed 5.5%. As mentioned previously, improved pipe insulation could yield substantial energy savings.

System Operation

Heat Sources and Demand Curves: Operation

Design heat production in TETs and BHs is standardized: heat output is specified by predetermined schedules, or *grafiks*, listing the required DH supply temperature as a function of outdoor air temperature. Thus, heating plant operators' job is simply to maintain the proper flow of DH water at the proper temperature. This job is simple for boiler house operators. If adequate fuel supplies are available, BHs can easily tailor their heat production to meet heat demand. The same is true of TETs when meeting heat demand directly from boilers: their fuel inputs are easily reduced when heat loads fall.

In a typical Russian boiler house, a dispatcher informs plant operators of the required supply temperature 3-4 times per day, and the operators make the necessary adjustments. The only major constraints facing them involve equipment reliability, fuel availability, etc., problems unrelated to the demand for heat. Boiler equipment is sensitive to the temperature of the return water, however: at temperatures less than 40 °C external pipe corrosion becomes a serious problem. Boiler input water should have a temperature of at least 60°; if necessary, hot boiler output water is mixed with return water to achieve this temperature. Return water temperature constraints could affect realizing DH energy savings in BHs without such recirculation lines.

TETs' operational modes are more complex when supplying heat from turbine steam bleeds. Depending on the specific turbine design and on local conditions, TETs turbines serving MFBs may operate in one of two modes: power-generating, in which heat production is small (or even zero in some designs); or combined, in which both heat outputs and power outputs are significant. Because heat and power demand curves sometimes differ radically, TETs are sometimes unable to operate in a cogeneration mode. Thus TETs' sensitivity to end-use energy savings and TETs' effectiveness as heat sources vary, depending on specific turbine designs and operational modes.

Many Russian authors suggest that adjustable (i.e., flexible, controllable, or both) TETs usually set outputs according to local heat demand. This seems likely, since power is more easily transported over large distances than heat. But TETs constitute a significant fraction of Russia's power generation capacity; cuts in TETs power output to meet changing heating demand must be limited unless adequate KES reserve is locally available.

Regardless of the type of equipment in place at a given TETs, or of the load curve being followed at a given time, TETs operators usually face one of three situations with regard to heat and power demand: either demand for both are at design levels, heat demand is below design levels, or power demand is below design levels. The first scenario is essentially a dual-baseload situation; it occurs only during the heating season, when heat demands are predictably high. In this situation the TETs is producing both heat and power at full capacity. TETs are best suited for baseload operation, with no risk of either load disappearing, because they are most efficient when the rated demand for both heat and power are present.

In the second scenario heat demand is high, but power demand is below capacity. This scenario typically occurs at night and on weekends during the heating season, but can be avoided if a neighboring KES can reduce its power output instead. Controllable TETs have no difficulty handling this situation, but in other stations turbines must be unloaded or shut down. This means that either the steam from the power-generating boiler is passed directly to the DH water heaters, or the heating load is met by water-heating boilers, either within the TETs or a neighboring boiler house. Failure to make one of these adjustments causes either a shortage of heat or a surplus of power.

In the third scenario heat demand is below TETs capacity, but power demand remains high; it occurs in mild weather and in the summer. Again, controllable stations can handle the situation easily. If the DH network is sufficiently interconnected then boiler houses are shut down during the summer months, and the TETs are fully loaded with the remaining non-space-heating DH loads. Even so, often flexible TETs in this situation must operate at low electric capacity, with makeup power coming from KES stations (many of which are obsolete). If alternative power sources are unavailable, flexible TETs follow the electric load curve, dumping the excess heat. Here, a lack of adjustability causes either a shortage of power or a surplus of heat.

Some BHs are interconnected with TETs in a common distribution network. In this situation the two plants can schedule their heat output in one of two ways: either jointly or separately. Older designs called for separate scheduling, with each plant operating during the entire heating season. Joint scheduling offers a better approach, however, because it increases the utilization of the TETs' heating capacity. In joint scheduling the TETs operates in mild weather, meeting the entire heating load up to its rated heating capacity; the BH only produces heat to meet peak demand during the coldest part of the heating season [Dubin].

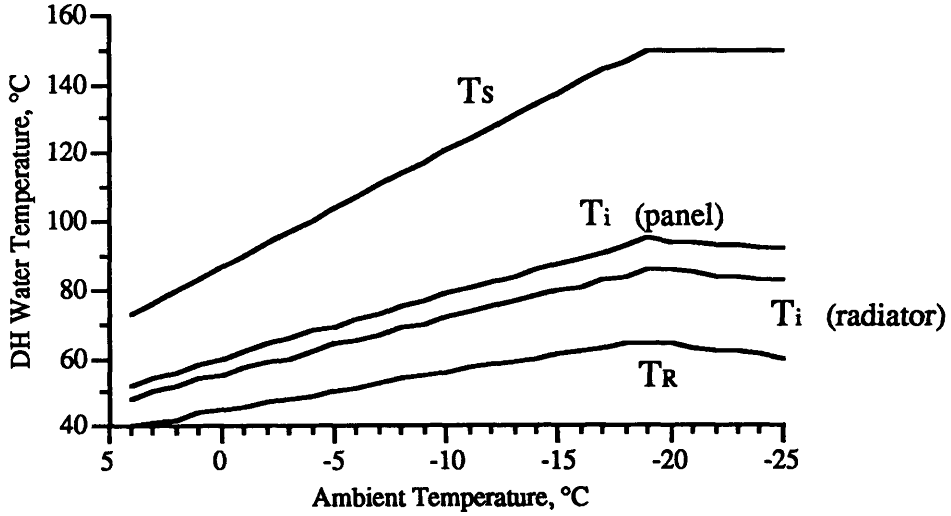
Finally, the most serious real constraint faced by all central heating plant operators is fuel shortages. These problems were discussed in some detail in Chapter 2. Fuel shortages are manifested in the DH system as reduced supply water temperatures: sometimes as much as 10-15 °C below schedule requirements [Yudzon; Minsk].

Central Heat Control

There are three general methods of controlling heat provided in a DH system: qualitative, quantitative, and qualitative-quantitative. In qualitative control the temperature of the water is varied and the flow rate is held constant; in quantitative control the reverse is true. Qualitative-quantitative control varies both temperature and flow rate. Although the Russians experimented with quantitative control, most existing Russian systems use qualitative control. Control of Russian DH systems was centralized: heat plant operators set the temperature of DH supply water according to design temperature schedules, or *grafiks.*

Grafiks were standardized: officially all heat plant operators were required to follow them (Fig. 4.8). All *grafiks* were similarly shaped, but the temperature ranges on both axes varied. In most *grafiks* the maximum value of T_S, the temperature of the DH supply water, occurs when ambient temperature falls to the design external temperature for the location. The maximum value of T_S varied from 130-170 °C, and was typically 150 °C. The minimum value of T_S occurs at the inflection point, or the highest ambient air temperature shown on the *grafik.* Using this method of heating control, the design condition of the DH space-heating system corresponds to the design condition of building thermal envelopes, allowing space-heating systems to be tailored to suit local conditions.

Figure 4.8: District-Heating Supply Water Temperature Schedules for Minsk
[Minsk]



Grafiks also specify the mixture temperature T_i for water entering buildings' heating systems, and the return water temperature T_R. *Grafiks* are usually implemented in individual buildings with jet pumps, designed to provide water at T_i for the building, given DH supply water at T_S (see Fig. 3.3 in Chapter 3). Apparently, T_R refers to the water temperature entering central heat stations, not the water temperature leaving the buildings[76]. Design values for T_i depend on the type of heating elements used within each building (whether radiators/convectors or wall panels); two separate T_i schedules were used, as shown in Fig. 4.8. The difference was implemented in practice by adjusting the mixture coefficients in jet pumps. Notably, *grafiks* took no account of varying envelope thermal characteristics among different buildings—the heating systems of all buildings in a given city with radiators were designed to receive DH water at the same temperature, regardless of the kind of wall, roof, or window construction. Control of heat supply in different building designs thus depended solely on the designs of heating elements.

It is not known how well *grafiks* were followed in practice, but some evidence indicates that supply temperatures sometimes peaked at 120-130 °C rather than 150 °C [RMA]. District heating system operators adjust T_S at regular intervals throughout each day (every 4-6 hours in some towns, 8-10 in others), but the adjustments may often have been imprecise: one Russian DH distribution system specialist bemoans the "unacceptable casualness" of central heating station operators in controlling supply water temperature, citing daily fluctuations of ±10 °C [Gromov 1988]. In some systems the maximum temperature was increased to 170-190 °C to lower flow rates through the network. Matrosov suggests that use of design *grafiks* leads to overheating, and therefore that actual *grafiks* used in practice are shifted downward. Additionally, dispatchers' ability to follow the design *grafik* depends on local fuel availability, and sometimes on the effectiveness of control systems in TETs turbines. These control systems, which govern heat supply indirectly by controlling bleed pressure, often lead to errors in DH supply temperatures far exceeding the officially permitted variation of ± 2 °C [Rabinovich].

In all design *grafiks*, DH water temperatures—and thus, heat delivered to apartment buildings—increased linearly with outdoor air temperature, as Fig. 4.8 shows. A linear design *grafik* depending only on T_{out} is imperfect, as space-heating loads are generally non-linear with T_{out}, and depend on other parameters as well (for reasons to be discussed in Chapter 5). Thus, improper heat delivery to MFBs might have resulted in some buildings even if the grafiks were properly followed in practice.

There is confusion about how return water temperatures are handled in practice: some sources say it is constant, at 70 °C; others maintain that T_R varies as shown on the *grafik*. Conceivably, both situations could occur in practice, since in some open systems DHW water is taken directly from the return line (thus providing a reason to hold return water temperature at 70°), and since some central plants may be more sensitive to corrosion than others. There is some evidence that return water temperatures were significantly higher than design [RCG].

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[76] in an ideal DH distribution system, with no heat losses, the two temperatures would be equal

Examining Figure 4.8 in the region of low ambient temperatures reveals a potential cause for incorrect heat delivery under severe climatic conditions. Assuming the maximum supply temperature of 150 °C is the proper value for an ambient temperature of -20 °C for buildings in Minsk, all buildings are underheated when ambient temperature falls below -20 °C. The constant value of T_S alone would cause underheating (since it no longer increases to counter falling outdoor temperatures), but the effect is amplified by the design of the system: the return water temperature T_R falls with falling ambient temperature if T_S is held constant. If T_R falls then T_i falls as well (because of mixing in the building's jet pump), so that at an ambient temperature of -25 °C room heating elements receive only enough heat appropriate for an ambient temperature of about -17 °C.

Grafiks were originally designed to cover the main heat load—space heating—characterized by a flat daily graph and sharply pronounced seasonal variations. Domestic hot water demand, conversely, has a flat seasonal graph with pronounced daily variations. Development of DHW supply systems has therefore led to changes in the space-heating temperature graph. Today elevated *grafiks* are sometimes employed, covering either the space-heating load, the combined space-heating and DHW load, or the total DH heating load (i.e., including ventilation in public buildings) [Yudkin]. The inflection point shifts upward in elevated *grafiks* by an amount depending on the relative load of the DHW system, but the design point remains constant. When elevated *grafiks* are used, rooms are overheated for all outside air temperatures other than the design (maximum) temperature for many consumers. Apparently modern *grafiks* also make different assumptions about the kind of DHW and space-heating systems used, and about the penetration of control equipment in the distribution system. As a result, the shape of *grafiks* used in practice are generally no longer predictable.

Network Heat Control

The design temperature of DH supply water is uniform throughout all primary main pipes in the network. In dependent systems, the supply temperature is, by design at least, uniform throughout the *entire* network, all the way to building jet pumps. In reality, however, the large size of the distribution networks and the high heat losses in DH pipes cause supply temperatures to vary considerably within the networks: consumers close to central heat stations receive water at much higher temperatures than consumers located far from the stations. In this situation the supply temperature is only proper for a limited number of consumers. Officially, heating plant operators set supply temperatures to meet the heating needs of consumers furthest from the station, but in practice supply temperatures were usually lower than the official minimum temperature [Minsk]. As a result, buildings far from central heat stations were underheated, and nearby buildings were overheated. Adjusting jet pumps helps, but causes DH water flow rates to differ from design. Flow rates can also vary in different network sections, depending on distance from the heat source, the number of buildings served by the pipe section, and so on.

In independent systems, supply temperatures in secondary circuits are usually regulated according to secondary *grafiks*. GHSs in these systems are equipped with automatic control equipment to fulfill this function, employing open-loop control, and using ambient air temperature as the control parameter; closed-loop systems were used only in small-scale experiments. Water in secondary circuits flows at a lower temperature than water in the primary circuit: the maximum supply temperature of secondary water varies depending on local needs, but is generally 120-130 °C if the peak primary supply temperature is 150 °C. Pressure in secondary circuits is maintained by secondary pumps. Sometimes the secondary lines are fitted with flow controllers.

Control Equipment

Large DH nets with significant DHW loads and many interconnections are hydraulically unstable: proper flow rates are difficult to maintain. Most systems are equipped with closed-loop temperature controllers for the DHW supply, and some DHW systems employ flow controllers in the space-heating supply line to regulate flow through building radiators. If flow controllers are lacking, then water flow and temperature in the space-heating system fluctuate with relative DHW loads. In a typical network these fluctuations are significant: during periods of average DHW demand flow increases by 6-15%; during peak DHW demand flow increases by 13-28% [*Therm. Engr.*]. Automatic controllers for space heating are virtually non-existent in Russian DH systems: space-heating systems employ units of constant hydraulic resistance—nozzles and orifice plates—which must be adjusted periodically to be effective. The adjustments are rarely made on schedule, and are often performed improperly; they are only approximately accurate even when done properly [*Therm. Engr.*].

Most premises also lack heat meters. Even central heat suppliers may not know the size of their own heat production with precision: Wilson estimates that about half of all central heat stations lack heat meters. Hot water heat flow meters are expensive, and thus economical only for large consumers (e.g., entire buildings) [Diamant & Kut]. An effective alternative is using a single heat flow meter to service one building or a block of buildings, then using smaller and cheaper water flow meters at each residence to approximate heat consumption. The amount of space heat delivered by radiators can also be measured with relatively cheap evaporation meters.

For most Russian apartment buildings, central control through the *grafik* is the only significant adjustment made in daily heat supply. Unfortunately, DH systems fail to transmit these adjustments to users quickly because of the system's thermal inertia: depending on location, a given building may not see a change in supply water temperature until 4-5 hours after the central adjustment in a nearby boiler house, or after up to 24 hours in a remote TETs. This limits the DH system's ability to respond to daily temperature fluctuations. Fortunately, the building envelopes also have high thermal inertia, and therefore absorb rapid temperature fluctuations.

Large water storage tanks are sometimes used in the nets of open systems to store water for peak heating periods. The storage tanks increase the nets' hydraulic stability, and permit storage of DH water heated by ITOC stations during periods of low power demand. Control systems are still needed, however, as they provide proper delivery of heat to consumers and allow nets to take advantage of the most efficient heat sources [Varvarsky]. The widespread lack of adjustments in DH nets leads to excessive network water flow (and therefore higher pumping costs), which causes excessive consumption of heat and consumer discomfort. Improper flow rates also cause a systematic increase in DH return water temperatures. Russian experts call for the installation of automatic controls for space heating to remedy these problems [Zinger].

DHW Systems

In some systems heat delivery to building radiators depends on the relative load in the DHW system. For example, at night reduced DHW loads cause a higher pressure differential to act across buildings' flow circuits; the corresponding increased flow rate causes building overheating [Minsk; *Therm. Engr.*]. When this happens, DH return temperatures can exceed the value specified by *grafiks* by 12-15 °C. Conversely, room temperatures often fall during periods of maximum hot water consumption. In some (but not all) closed 2-stage series systems, water flow was reduced during the periods of maximum DHW loads in order to reduce total DH network water flow; this reduced water flow through space-heating systems. Highly variable DHW loads caused large fluctuations in the return water temperature T_R in many closed systems (all of which lacked hot water storage tanks). This led to control problems in systems connected to controllable TETs turbines, because meeting the unexpectedly high heating loads excessively lowered power output. Finally, closed 4-pipe systems maintained DHW circulation at all times, with the return pipe connected between the 2 heater stages. Since this raises the DHW heating load above design levels, heat delivered to radiators falls below design levels. The magnitude of all of these interactions is driven by the relative DHW load; again, proper automation would prevent them from occurring.

In other systems, space heating irregularities depend not on relative DHW loads, but on the kind of DHW connection used. Recall that design standards call for all DHW to be heated to at least 60 °C. In open systems the DH supply temperature is maintained at a minimum of 60 °C; in closed systems 70 °C (because of losses in the 2-stage heat exchangers). In mild weather (2-8 °C, depending on location), however, the *grafiks* call for a supply temperature of less than 60 °C. In practice, heat suppliers simply cut off the lower part of the *grafik* in mild weather, maintaining supply temperatures exceeding scheduled requirements, which leads to room overheating in most buildings. This problem is chronic in all systems lacking flow controllers for the space-heating system (which comprises the vast majority of Russian systems).

TECHNICAL IMPEDIMENTS TO ENERGY SAVINGS

Because of the diversity of Russian DH systems, predicting real energy savings is difficult: even if savings are technically possible (i.e., given reduced end-use space-heating energy needs in a building) they may not show up as fuel savings at central heat plants. In order to classify the DH system designs according to their sensitivity to end-use heat savings, it must first be understood precisely how space-heating energy savings in buildings would be manifested in the DH system. Most energy-saving retrofits aim to reduce the rate of heat loss in buildings via improvements in some part of their thermal envelopes. Yet Russian MFBs lack individual heating controls; if their overall rate of heat loss declines, rooms will simply be overheated unless the building's heating system is properly adjusted. The heat delivered to a building can be reduced in several ways: by reducing supply water temperature or water flow rate (or both), or by changing the heat transfer effectiveness of the room heating elements (for example, by changing their area, geometry, or film coefficients). As has been shown, design DH network water supply temperature is uniform throughout the network according to the *grafik*, but flow rates and temperatures differ in local group networks and in individual buildings. Existing buildings will likely be retrofitted one at a time, or at best in small groups, making it impractical to adjust DH network water supply temperature uniformly at central heating stations. On the other hand, water properties are easily changed at the building level by adjusting either a jet pump or a heat exchanger.

Heat flow through a jet pump is reduced by increasing its mixture coefficient, which increases the flow of recirculated return water. This reduces the temperature of the water entering the building, T_i, in turn reducing the return water temperature T_R[77]. Because from the DH system's point of view the effect of a higher jet pump mixture coefficient is to increase the hydraulic resistance of the building's flow circuit, the net flow of DH water through the building *decreases* after the adjustment (since the pressure difference acting across the building remains constant). Thus, the effect of adjusting heat input with a jet pump is DH water with a lower flow rate <u>and</u> a lower return temperature. Because DH supply water must be heated to temperatures specified by *grafiks*, these two perturbations have opposing effects on heating requirements at central heat plants or GHSs: a lower return temperature increases heat demand; a lower flow rate decreases it. Since the net effect must be a reduced heating load, the drop in flow rate is the dominant effect.

If the adjustment is made in a heat exchanger, however (either in a building or a GHS), then the supply temperature or flow rate in the secondary circuit is changed to lower the heat transfer from the primary water circuit. Since supply temperature and flow rate in the primary circuit remain constant, the net effect in the primary circuit is a *higher* return water temperature.

Thus, end-use energy savings will be manifested in the DH system in different ways, depending on how the heating system is adjusted to account for the change. Since the vast majority of Russian MFBs

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[77] the return temperature falls because the heat transferred from building radiators is driven by the supply temperature of the heating water; if supply temperature falls, return temperature also falls, but by a smaller amount. This is the principle governing the shapes of the *grafiks*.

employ jet pumps, in most cases the end-use energy savings will show up as DH water with a lower flow rate and a lower return temperature. The question therefore becomes, will the DH system react to these changes, and if so, how will it react? The following analysis answers this question for the major kinds of Russian DH systems. Obtaining these answers is the main goal of this chapter, and is one of the significant contributions of this thesis.

The Distribution System

The first step in assessing the transmission of energy savings must focus on the DH distribution system. The issue here is whether local end-use space-heating savings due to a lower DH water temperature and flow rate are necessarily transmitted through to the mains. The disposition of potential savings depends on the layout of the distribution network serving the building, determined by the kind of DHW system and space-heating system connections used. Because of the diversity in system designs generalizations are difficult; each case must be examined separately. Figure 4.9 displays a matrix of possible distribution system designs for any individual district-heated apartment building, and a reminder of the various definitions used to classify connections to the DH system. The matrix indicates whether each combination is likely to pass building space-heating energy savings through to heat production points unimpeded: "Y" = yes, "N" = no. An "N" in the chart implies only that actual savings are either uncertain or significantly less than potential savings; it does not imply that no savings are possible under any circumstances.

Figure 4.9: Heat Savings Transmission through DH Distribution Networks

Type of Space Heating Connection		Type of DHW Connection: Open		Type of DHW Connection: Closed
		Supply	Return	
Dependent		Y	N	Y
Independent	+	Y	N	Y
Independent	-	N		N

- Open DHW systems are connected directly to the central heat source; closed DHW systems are connected indirectly, and use heat exchangers to heat domestic hot water. Open DHW systems are classified as either supply or return, depending on which DH main supplies the DHW flow.
- Dependent space-heating systems are connected directly to the central heat source; independent space-heating systems are connected indirectly, through a secondary water circuit. Among independently connected space-heating systems, those with properly adjusted, well-functioning secondary *grafik* control systems are indicated by "+"; all other independent systems are designated by "-".

Four of the eight cases examined in Figure 4.9 impede complete energy savings, but they generally do so for different reasons. Most buildings are likely to be connected to open, dependent DH systems. The figure addresses only open systems without preheaters, because these systems are more common (systems with preheaters present no serious impediments). Return-supplied open systems must maintain a minimum return water temperature of 60 °C. Thus, the lower part of the *grafik* is simply cut off in such systems for all outdoor air temperatures above the temperature at which $T_R = 60$ °C. Although a lower flow rate presents no problems, under these conditions a lower return water temperature would probably be countered by raising the supply water temperature, nullifying the energy savings. The same argument holds for independently connected systems. The problem with missing or malfunctioning secondary circuit control systems in independently connected buildings is more straightforward: if the GHS improperly regulates the flow of secondary circuit water then the secondary *grafik* is improperly followed, indoor temperatures vary, and energy savings could be nullified.

Clearly, in independently connected space-heating systems proper adjustment and operation of the GHS secondary control equipment is critical in delivering the proper amount of heat to buildings and in transmitting energy savings in the building through to central heat sources. It must be emphasized that proper operation alone is insufficient; without proper adjustment (i.e., without properly setting the secondary *grafik*) buildings will be improperly heated.

The remaining four cases appear to present no serious impediments to realizing end-use heat savings. All four do face two significant problems, however, tending to reduce actual savings. First, in mild weather (above 4 °C, for example) space-heating loads may have no effect on the amount of heat actually delivered because the system must heat DHW to its minimum temperature. Second, some of the interaction problems between the DHW system and the space-heating system described earlier will tend to become more serious because they are driven by the relative DHW load, which will tend to increase because of the lower total flow rate through the DH system after the retrofit. Systems with flow controllers are more likely to be stable, and may therefore be most attractive.

As an example of applying Figure 4.9, consider the DH system connections to a 17-story apartment building in Moscow (to be discussed extensively in the next chapter). This building uses a closed DHW system, and an independent space-heating system. Consulting Figure 4.9, these systems will transmit energy savings back to the central heat source if the secondary *grafik* control system at the group heating substation functions properly. If the control system is functioning, the flow rate through the secondary side of the heat exchanger will be reduced to prevent an excessive secondary supply temperature, in turn raising the return water temperature in the primary circuit. The central heat source will thus be faced with a lower heating load.

The discussion of this chapter also permits the identification of potential causes of overheating in the 17-story building. The independent space-heating connection allows flow and temperature variations in the primary circuit to be isolated from the secondary circuit, avoiding the highly fluctuating conditions experienced in either open or dependent systems. The control equipment at the GHS must be properly adjusted to achieve this isolation. The closed DHW system could potentially cause serious overheating in mild weather since in closed systems the DH supply water must not fall below 70 °C, but in this particular system the DHW heat exchangers are located on the *primary* side of the GHS space-heating heat exchanger. This nullifies the overheating effect if the GHS secondary *grafik* control equipment is properly adjusted.

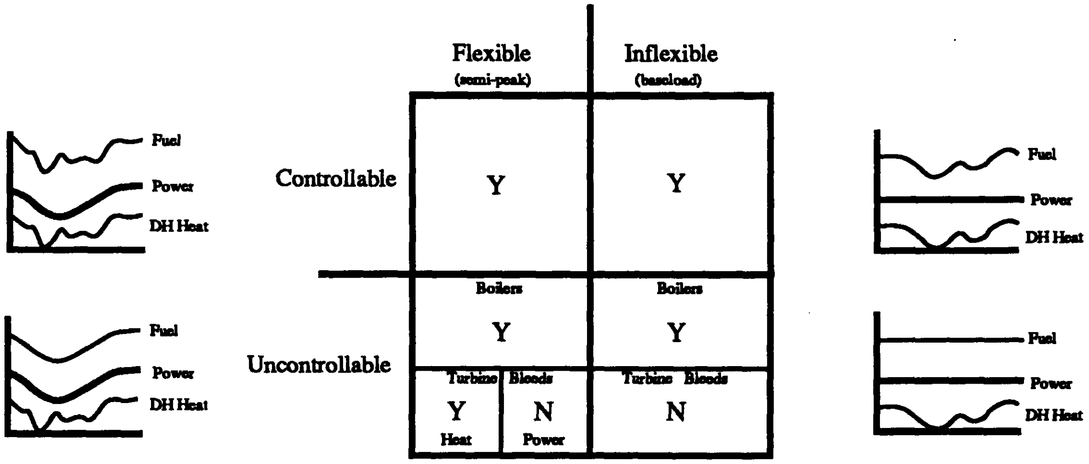
Central Heating Plants

The second step in assessing systemic impediments to energy savings focuses on heating stations. If the distribution system transmits energy savings to the central heat stations, they will be faced with a reduced heat output requirement. All kinds of heating stations can reduce the heat supplied to the DH network, but the important issue is whether the station will save fuel in response to the smaller heat load. Again, systemic diversity makes general statements impossible; the possibility of achieving real fuel savings depends on the type of heating plant serving the building.

The response of one class of central heat stations is easy to predict. Since the only function of boiler houses is heating DH water, and since they can reduce their fuel consumption to match a smaller heat load, most boiler houses present no serious systemic impediments to realizing end-use savings. Heat and power stations (both TETs and refitted KES) differ, however, because they work in a dual-purpose mode most of the time, which adds an additional set of constraints to their operation. Since a lower heat demand often leads to greater inefficiency in TETs operation, it is important to understand how each design will react to lower heating loads.

Figure 4.10 divides TETs into several categories, depending on each station's ability to adjust its inputs and outputs. Each of the four major cases is accompanied by a graph depicting an example of the adjustability of the station's fuel input, power output, and heat output to the DH system from turbine steam bleeds. The matrix columns and rows are defined by concepts discussed previously; again, the figure includes reminders of their definitions. The heat supply of a given building always falls within one of the four major boxes in the figure, but in boxes containing more than a single sub-category (i.e., all uncontrollable TETs) the placement of the building may vary with time, depending on TETs design, the policies of local operators, and the shape of the local heat demand curve.

Figure 4.10: Heat Savings Transmission through TETs



- Flexible (semi-peak) TETs are able to easily adjust their power output to match varying loads; inflexible (baseload) TETs produce electric power at a constant rate. Unlike the distribution system categories, this classification is not rigid; station designs may overlap in the figure. Large, coal-fired TETs tend to be inflexible; smaller oil- or gas-fired TETs may be flexible.

- Controllable TETs can independently and continuously vary the amount of steam bled from the turbine's DH steam bleeds within some range (i.e., they are ITOC stations); uncontrollable TETs can make this adjustment only conditionally (i.e., in discrete steps, or only in concert with some other adjustment), or are unable to adjust DH steam bleed output at all.

    - Among uncontrollable TETs, ***boilers*** means that at the time in question DH heat is being supplied from boilers within the TETs, either from peaking water-heaters or from steam bypassed from steam-generating units; ***turbine bleeds*** means the heat is being supplied by the turbine's DH steam bleeds.

        - Within the turbine bleeds sub-category, ***heat*** means the TETs sets its output according to the local heat demand; ***power*** means the TETs follows the power demand curve.

Of the nine cases presented in Figure 4.10, two present serious impediments to realizing fuel savings. As before, they generally cause problems for different reasons. First, in inflexible, non-controllable stations electrical output and rate of fuel consumption are both constant over time, precluding any opportunities to save energy from the heating system when heat is being supplied from steam bleeds. Second, flexible, uncontrollable TETs cannot save fuel from reduced heat demand if heat is supplied from the turbine bleeds and the plant is following the power demand curve. In this case the excess heat is simply dumped through the condensers. Fuel savings are possible if the plant operates on the heat demand curve, although the "savings" may show up as higher power output. As Figure 4.10 shows, since peaking boilers in TETs operate essentially like miniature boiler houses, reduced TETs boiler output provides fuel savings even in non-adjustable TETs designs.

Figure 4.10 asserts that for certain systems primary fuel savings are *possible*; it says little about whether they are necessarily ***desirable***. When fuel savings result from lower fuel inputs to boilers directly supplying DH heat, they are clearly desirable. But when savings are rooted in lower steam extractions, the value of the savings may depend on local circumstances. For example, for flexible, non-controllable TETs following the heat demand curve in this situation (thus operating at maximum steam-bled heat output), reducing heat output requires reducing power output as well, which may or may not be desirable, depending on the efficiency of local alternative power sources.

Finally, a given building may face different situations over time: heat and power demands vary daily, weekly, and seasonally, equipment breaks down, and different heat sources may serve the building depending on the severity of the weather. This can complicate predictions of the effects of reduced end-use heating loads. For example, in mild weather all of a building's space heat may be supplied by a TETs turbine bleed, but in severe weather part of the same building's space heat will probably be supplied by a peaking boiler, either in the TETs or in a boiler house. The latter is especially likely to occur in systems with a BH and a TETs both serving a common DH network. Identifying the source facing a reduced heating load is simpler for joint scheduling than for separate scheduling, because in joint scheduling the boiler house only operates during the coldest weather.

As an example of applying Figure 4.10, consider one of Moscow's TETs. One of the turbines in Moscow TETs station No. 23 is a T-250/300-240 unit. This turbine is dual-mode, with two controllable DH steam bleeds and a total DH heating capacity of about 400 MW. Since the turbine is a T-type unit, it has no industrial bleeds constraining its operation. Although the control range of the DH bleeds has a non-zero lower bound (as discussed previously in this chapter), this turbine is as controllable as any mass-produced Russian TETs turbine; it is thus classified as controllable. It must be stressed that not all T-type turbines are dual-mode, and not all have controllable DH steam bleeds; this particular turbine happens to have both qualities. The large size of the turbine (300 MW design power output) suggests that it is inflexible. As Figure 4.10 shows, the flexibility classification is irrelevant for controllable TETs, however, as either design will respond well to lower heating loads.

The discussion of this chapter also permits the identification or the elimination of potential causes of improper heating in buildings connected to TETs No. 23. Since the turbine is controllable, it should be able to properly match its heat output to DH heat demand if its control systems are functioning properly (most heating complications arise for uncontrollable turbines). As mentioned previously in this chapter, however, control of DH water supply temperature was often inaccurate because T_S was regulated indirectly by controlling the pressure in the DH bleed. This control problem would lead to a noisy DH supply temperature in the primary circuit.

Given end-use space-heating energy savings in a building, Figures 4.9-10 do not predict the appearance of primary energy savings with certainty. Rather, the figures are approximate indicators of which DH systems are *most likely* to realize end-use savings as significant primary savings. Thus, the two matrices are best viewed as a set of the right questions to ask when concerned with energy savings in buildings; they help determine which buildings are most worthy of retrofits, or of further scientific study.

INSTITUTIONAL IMPEDIMENTS TO ENERGY SAVINGS

On the surface it may appear that the setting in the USSR was ideal for district heating: Soviet planners favored large, centralized systems over smaller, decentralized systems, and, as previously discussed, urban consumers had virtually no choice of the method of heating their homes. The district heating sector, like many other Soviet economic sectors, was plagued by systemic distortions, however: inefficient resource allocation, poor coordination, and widespread mismanagement. Institutional problems in the district heating sector were typical of those in the fuels sector in general—addressed in Chapter 2—and were present in the planning, operation, and management phases of DH systems.

Minenergo was generally responsible for producing most heat in towns with populations greater than 100,000, and was the largest single producer of heat in the Soviet Union: in the late 1980s *Minenergo* owned over 360 TETs, and about 250 boiler houses [*Therm. Engr.*]. In smaller towns responsibility for heat production fell to the local branch of the Republican Ministry of Housing. In virtually all heat supply systems different parts of the DH system were managed by different organizations: TETs and DH mains were *Minenergo's* responsibility, boiler houses and distribution nets were the local *Soviets'* responsibility, and heating equipment within buildings (plus group heating substations in some systems) was handled by the district office of the Ministry of Housing. Thus, thermal energy typically changed hands at least twice—in some systems, three times—between its production and final consumption. Residential consumers were billed by the organization responsible for the building's heating systems, usually the Ministry of Housing, but sometimes the local *Soviet*. Since the billing organization was just one of many agencies involved in the provision of heat, residential consumers had great difficulties getting problems in the heating system corrected.

Consumers in the heat supply system were officially ranked in priority: Party and state agencies had top priority, followed by military establishments, research and development centers, power plants, industrial consumers, residential consumers in Moscow, residential consumers in other large cities, consumers in smaller towns, and, finally, rural consumers. Those near the top of the list were entitled to all the energy they needed, regardless of rates, quotas, or norms. Their demands were met in spite of widespread fuel shortages, usually at the expense of consumers lower on the list. Since residential consumers were ranked last, they often suffered the most [Yudzon].

The main planning indicators for fuel and heat supply were absolute and specific (per unit of output) energy consumption. As discussed in Chapter 2, both norms were specified in annual plans by *Gosplan* and *Gossnab* for all major energy consumers, including TETs and boiler houses. Consumer heating loads were determined according to technical specifications defined in SNiPs, and were defined relative to the design condition. Rates and norms in the electric power industry were the most reliable and technologically well-founded within the energy sector, because in the power industry fuel consumption and electricity output targets were based on actual measurements from past years [Hewett]. In other sectors, including the municipal heating sector (boiler houses), heat production targets were more a reflection of planners' desires than of feasible goals. Since heat delivered to residential consumers was virtually never metered, in boiler houses official plan documents were easily falsified. As a result, predicting heat production with precision was generally impossible.

Soviet leaders addressed the problems in the heating sector using typically Soviet methods: by strengthening administrative control. This control was exercised by a large network of organizations, including the Fuel Inspectorate of *Gossnab*, the Energy Inspectorate of *Minenergo*, the Central Statistical Administration of the Council of Ministers, local *Soviets'* Executive Committees, district, city, and regional Communist Party Committees, and still others. These agencies monitored fuel and power consumption at TETs and boiler houses, sometimes working together, other times verifying each others' work. Not surprisingly, the administrative confusion often caused the programs to be ineffective [Yudzon].

In 1980 a team of Soviet experts proposed introducing a new set of specific fuel consumption rates for heat production, differentiated with loads and outdoor air temperature. The new idea was denounced by the managers of virtually all TETs and BHs in the power industry, plus many managers of industrial enterprises, as politically and economically unorthodox. The managers knew the new rates would be more accurate and technically justified than the old system, but they also knew actual heat production depended more on real operating conditions than on norms and quotas. The new system would only worsen existing energy supply imbalances, and would make report falsification more difficult. The managers prevailed: the new approach was dropped, squashing a significant effort at major systemic reform [Yudzon].

Overall, planning and reporting in the heat supply system was conducted on a purely formal basis, and was not treated very seriously. The actual amount of heat supplied to a consumer depended not on the planned quotas, but on the consumer's relations with the supplier, the condition of heat production equipment, and the amount of fuel available to the supplier. All these problems suggest that even if energy savings are technically possible, other barriers may prevent actual fuel savings in any DH systems still being managed as *Minenergo* managed them. Economic and institutional arrangements in present-day systems vary widely, and are still in flux in many areas, making institutional impediments to achieving energy savings less clear.

SUMMARY

In Russian district heating systems the design emphasis was on meeting the bulk heating needs of whole heating networks at the design condition (i.e., during the coldest weather). Relatively little attention was paid to supplying the correct amount of heat to all individual consumers under all conditions. The result is a DH system in which essentially all delivered space heat is unmetered and uncontrolled. Additionally, conditions in other systems often affect heat delivery to apartment buildings: interactions between the DHW system and the space-heating system cause delivered heat to differ from planned requirements, and cause it to vary over time as conditions in the distribution network or at the central heat stations change. Further, some MFBs are affected by other kinds of buildings (e.g., public, industrial) because they are connected on a common DH network. As many Russian specialists have noted, however, most of the DH system's performance problems can be solved through use of the proper monitoring and control equipment. Unfortunately, improving the performance of district heating systems has had a low economic priority in most Russian towns.

This chapter has highlighted some of the main known variations in the design and operation of Russian district heating systems, and addressed some constraints and organizational problems in the DH system's management and operation that led to inefficient heating practices. Diversity in Russian DH systems causes widespread underheating and overheating of apartment buildings. The system diversity described, although substantial, probably fails to represent all systems and approaches currently used in Russian practice. Since the DH system generally operates independently of the actions building occupants take to regulate the temperatures in their homes, DH system diversity leads to less predictable energy consumption patterns.

Saving energy in Russian MFBs therefore requires more than effective modifications to the buildings themselves—the DH system introduces a completely separate set of critical issues. Without some knowledge of the composition of the DH system serving a building, it is uncertain whether end-use energy savings in the building would be transmitted, in part or at all, to the central heating plant, or whether lower heating requirements at the plant would necessarily result in primary fuel savings. Thus, understanding the nature of a building's linkage with the DH system, and making the proper adjustments in the DH system's equipment, are both critical steps in achieving fuel savings from end-use space-heating efficiency improvements in district-heated Russian MFBs.

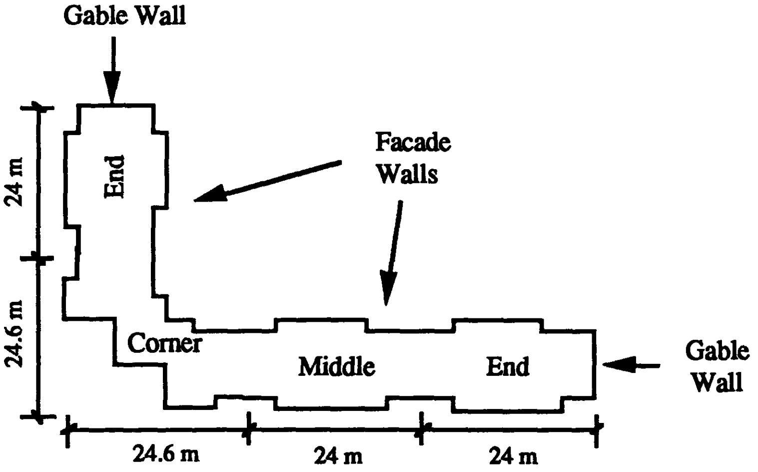
CHAPTER V: POTENTIAL END-USE ENERGY SAVINGS IN A MOSCOW APARTMENT BUILDING

Chapters 2-4 of this thesis have focused on gaining an understanding of the various systems governing space-heating energy consumption in Russia's stock of district-heated apartment buildings. The present chapter shifts the focus to energy consumption patterns in a single apartment building in Moscow. Actual calculated and measured space-heating energy consumption patterns will be described, along with estimates of potential energy savings in the building. Calculated energy use is based on a model developed by the author to simulate the daily heating loads in the apartment building; measured energy use is based on the results of a field experiment performed on the building by the Research Institute for Building Physics (NIISF), of Gosstroi USSR. The main purpose of this chapter is not to describe or criticize the field experiment in detail, but to develop a methodology for comparing the space-heating energy needed by a Russian apartment building with one of the very few available measurements of the space-heating energy delivered to the building by the district heating system under real conditions. This, in turn, will permit the calculation of rough estimates of potential space-heating energy savings in the apartment building. The results of the analysis will be extrapolated to other apartment buildings in Moscow.

Description of the Test Building

The building studied is a 17-story "P44-Series" building owned by a housing cooperative. The test building (hereafter referred to as P44) is divided into four sections: two end sections, a middle section, and a corner section (Fig. 5.1; a photograph of the building's exterior appears in Appendix D, Fig. D.7). Each section contains 64 flats, 4 on each of 16 floors, for a total of 256 flats in the building. The floor plans of the two end sections and the middle section are essentially identical, but the shape of the corner section differs. Most of the exposed perimeters of both end sections—and the entire exposed perimeter of the middle section—consist of facade walls; the exposed perimeter of the corner section consists mainly of gable walls. This kind of building—P44-Series with 17 stories—has been widely used in new housing construction in Moscow for the past 15 years; in 1992, 35% of new apartment buildings in Moscow were of this design [Matrosov, Butovsky, & Watson].

Figure 5.1: Plan View of the P44 Test Building



The external walls of P44 are 3-layer large panels with metal ties, with a foam plastic insulation layer. The facade walls and gable walls differ significantly in construction: the facade walls are normal, composed of a single wall of 3-layer panels, but the gable walls consist of two walls, an inner structural wall, and a separate external wall composed of 3-layer panels. The windows and balcony doors are double-glazed, with coupled wooden sashes and weatherstripping. The building employs a warm attic and a warm cellar. Table 5-I displays some of P44's physical characteristics.

Table 5-I: P44 Characteristics

Envelope Component	Area, m^2	Design Reduced Thermal Resistance, m^2 °C/W
Floor Above Cellar (Basement)	1067	3.00
Ceiling Below Attic (Roof)	1067	5.00
Gable Walls	2324	1.65
Facade Walls	7821	1.25
Fenestration	2360	0.39
Total Useful Floor Area:	17,072 m^2	
Total Volume:	50,619 m^3	
Air Exchange Rate:	0.4 - 0.8 ACH	
Internal Heat Gain:	0 - 12 W/m^2	
Fenestration Area / Total Wall Area:		18 %
Total Wall Area / Floor Area:		73 %
Total Envelope Area / Floor Area:		86 %

Notes: R-values assume design humidity levels according to the SNiP classification scheme; values for the warm basement and roof are design equivalent R-values, accounting for the higher indoor air temperature in the attic and cellar. R-values for the facade and gable walls were tested in some locations in the building, and corresponded with design values for those particular types of construction. The best available estimate of the norm for 3-layer large-panel R-values of this period is 1.73 m^2 °C/W (see Chapter 3). Air exchange and internal gains in the building will be discussed below.

Each of P44's sections has its own jet pump; each section's internal distribution system is 1-pipe, with lower flats connected first (i.e., upstream of upper flats), and with series-connected convectors in the flats (Appx. D, Fig. D.5). The space-heating system of P44 is independently connected to the DH system; P44 is the second of two buildings connected in series on the secondary flow circuit. The DHW system is the closed, mixed design, with the heat exchangers on the primary side of the group heating substation. The primary heating circuit is connected to a TETs.

Calculated Energy Consumption

A model was developed by the author to simulate P44's heating loads in an effort to calculate the heating energy needed by P44 during the heating season. The model is similar to the bin method, employing various theoretical calculations, empirical relationships, and estimated actual properties of the building. The model computes heat losses separately for all envelope components using equations linear in the outdoor air temperature, T_{out}, then sums the losses to obtain the total rate of heat loss. The model simulates steady-state conditions, ignoring the thermal inertia of the building envelope. The accuracy of this method depends on the accuracy of the information in Table 5-I, and on the validity of breaking down heat losses through P44's envelope into separate components corresponding to construction elements (all effects at the boundaries of construction elements were ignored). This model differs from the bin method in one important way: it uses daily values for outdoor air temperature, not hourly temperature bins.

Calculation Methodology

The building's daily heating load—the heat needed from its heating system—is computed in the model according to Eqn. 5.1. As discussed in Chapter 3, transmission includes all heat flowing via convection and conduction through all parts of the building envelope, and infiltration includes all heat loss due to air exchange. Internal gain includes all heat generated within the building from appliances, electronic equipment, human bodies, etc. Solar gain is all heat supplied by solar radiation through the building's windows.

$$Q = Q_{tr} + Q_{inf} - Q_{ig} - Q_{sol} \tag{5.1}$$

Q = heating load [kWh/day]
Q_{tr} = heat loss via transmission [kWh/day]
Q_{inf} = heat loss via infiltration [kWh/day]
Q_{ig} = internal heat gain [kWh/day]
Q_{sol} = solar gain [kWh/day]

The heat transmission term, Q_{tr}, is a theoretically calculated value based on transmission losses through five envelope components: the external facade walls, the external gable walls, the ceiling below the attic, the floor above the cellar, and the windows. Total transmission losses are computed as the sum of these five components, as shown in Eqn. 5.2. All non-uniformities arising from thermal bridges, joints, corners, and the like are ignored except when the reduced R-values themselves accounted for them[78].

$$Q_{tr} = \Sigma\, Q_{tr_i} = \Sigma\, \frac{A_i}{R_i}\, \Delta T \tag{5.2}$$

$$\Delta T = T_{in} - T_{out} \tag{5.2a}$$

T_{in} = indoor air temperature [°C]
A_i = area of envelope component [m^2]
R_i = reduced thermal resistance of envelope component [m^2 °C/W]

The infiltration term, Q_{inf}, is computed from an estimated value of P44's average rate of overall air exchange according to Eqn. 5.3. The overall air exchange rate includes air flow through walls, cracks, and gaps between construction elements; it assumes all windows and balcony doors are closed. NIISF performed experiments with a blower door to correlate the leakage rate in some of P44's flats with the pressure difference between indoor and outdoor air. The average value of this pressure difference was computed for Moscow's heating season using design climate parameters (average outdoor air temperature = 3.6 °C; average wind speed = 3.8 m/s). The data from the blower door experiments were then extrapolated to the whole building, which resulted in a calculated average ACH value of 0.41 [Matrosov, Butovsky, & Watson]. This value seems low compared to MFBs in the US, however, so a range of values was explored in this study (Table 5-I). In Eqn. 5.3, the air density and specific heat capacity are both evaluated at standard conditions.

$$Q_{inf} = (ACH)\,(V)\,\rho\, C_p\, \Delta T \tag{5.3}$$

ACH = overall building air exchange rate [air changes per hour]
V = total building volume [m^3]
ρ = air density [kg/m^3]
C_p = constant-pressure specific heat of air [KJ/kg °C]

The heat loss terms in Eqns. 5.2 - 5.3 both depend on ΔT, the temperature difference between indoor and outdoor air, defined by Eqn. 5.2a. Values for outdoor temperature are either measured values or median bin temperatures. Indoor temperatures are either constant at 18 °C or measured values. Using a constant indoor air temperature simulates design indoor conditions; using measured indoor temperatures more closely approximates actual conditions during the experiment.

Internal heat gains were modeled based on an average rate of internal heat gain per unit of floor area (Eqn. 5.4). The official Russian standard calls for an average rate of 21 W/m² in MFBs, and has done

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[78] unfortunately, it is not known precisely which of these <u>were</u> accounted for; R-values for external wall panels might account for internal thermal bridges, but effects from other non-uniformities probably were not included in design calculations

so for years [SNiP 2.04.05-91], but the source of this number is generally unknown even among the Russians, and many seem to believe it is too high. Further ambiguity exists because some Russian sources refer only to gains from electrical equipment, others to total gains. Russian planned heating loads accounted for no heat gains in MFBs, whether internal or solar [Safonov], so internal gains are likely to cause discrepancies between planned and actual energy use. Like the air exchange rate, a range of values of internal heat gains was explored in this study (Table 5-I).

$$Q_{int} = (IG)\,A_u \tag{5.4}$$

IG = average rate of internal heat gain [W/m^2]
A_u = useful floor area of building [m^2]

Simulations of heating loads should account for solar gains, both direct and diffuse. No information of any kind regarding solar heat gains in Moscow MFBs was available for this study, however. Vadon et. al. have developed simple empirical relationships that predict total incident solar radiation on surfaces of various orientations during daylight hours, based on TMY[79] climate data. The correlations are based on bin-sorted, hourly outdoor air temperatures, taken over one complete standard-weather year. Unfortunately, these data were also unavailable for Moscow. The field experiment on P44 did provide daily, measured outdoor air temperatures over part of a heating season, however. Using these data in Vadon's method likely leads to less accurate predictions of solar gains, but this was still judged to be the best method available. Assuming the methodology is sound, and that Moscow's weather is consistent with some sample locations in the TMY data set from which the correlations were derived, the Russians could easily refine the calculations by using the proper air temperature data.

The total solar gain in the test building was divided into heat gain through north-, south-, east-, and west-facing windows; each of these components consists of terms accounting for solar insolation, the average number of daylight hours, fenestration surface area, and transmission through the windows (Eqn. 5.5a). The solar insolation, I, was taken from Vadon, and is given by Eqn. 5.5b. The coefficients α and β are defined in terms of two parameters: the orientation of the wall containing the windows, and the standard deviation of the local hourly outdoor air temperature distribution taken over a period of one year. Thus, as Eqn. 5.5b shows, for a given window surface at a given location the solar insolation is a linear function of outside air temperature. The average daily fraction of sunshine, SS, was computed separately and input as a constant value; its calculation accounted for the starting and ending dates of the experiment and site latitude [Kreith]. The solar heat gain factor and shading coefficients are approximate values, accounting for the type of construction of the window assemblies, different wall orientations, the presence of drapes, etc. [AHoF]. Because of the crudeness of this estimate, and because solar gains were ignored in Russian calculations of planned energy use, this study examines a range of solar gains.

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[79] Typical Meteorological Year

$$Q_{sol} = \Sigma\, Q_{sol_i} = \Sigma\, [I_i\ SS\ WA_i\ F\ SC_i] \qquad (5.5a)$$

$$I_i = \alpha_i\, T_{out} + \beta_i \qquad (5.5b)$$

I_i = solar insolation on wall i [W/m^2]
SS = average fraction of time the sun is shining on a given day
WA_i = window area on wall i [m^2]
F = solar heat gain factor
SC_i = shading coefficient on wall i
α_i, β_i = empirical coefficients

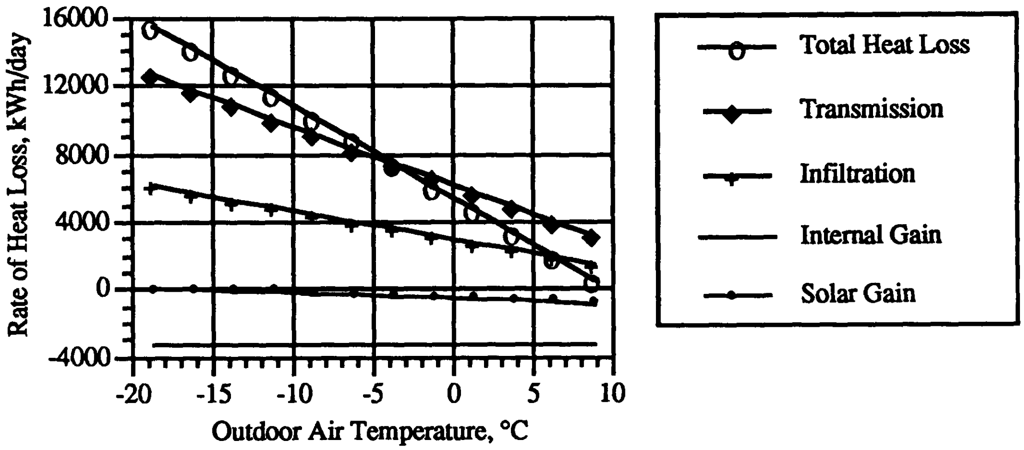
As Eqns. 5.2 - 5.5 show, only one climate parameter influences daily heating loads in the model: T_{out}. Further, the functional dependence of the heating loads on T_{out} is assumed to be linear. These assumptions inevitably lead to inaccuracies in predicting actual heating loads. First, in real buildings other climate parameters do in fact influence heating loads. For example, moisture levels affect internal and external envelope film coefficients, the latent heat content of air, and material thermal properties (especially if the moisture evaporates or freezes within the material); wind affects external film coefficients and air exchange rates; and occupant behavior affects air exchange rates and internal gains. Second, space-heating loads are generally non-linear functions of T_{out}: time-dependence arises because of thermal inertia in building envelopes; the envelopes may contain materials with thermal properties varying significantly with temperature; air exchange rates are driven non-linearly by pressure differences between indoor and outdoor air; and solar gains are only empirically correlated with T_{out}. Although errors from these sources may be significant, the accuracy of the model's methodology is believed to be consistent with the quality of the available data on Moscow's climate conditions and P44's thermal properties.

Appendix C contains a printed copy of the spreadsheet model used in this analysis.

Structure of Energy Use

The model was used to simulate space-heating energy requirements in P44 corresponding to the dates covered by the experiment performed by NIISF (which covered only part of a heating season). During the experimental period the outdoor air temperature ranged from -20 °C to +10 °C; the net rate of heat loss was calculated in the model within the same range. This temperature range was divided into 2.5 °C temperature bins because of noise in the experimental data (discussed below). The heat losses were calculated for a total of twelve outdoor air temperatures, in 2.5 °C increments, beginning at the highest median bin temperature, 8.75 °C. A constant indoor air temperature of 18 °C was assumed for the initial calculations. The results are shown in Figure 5.2, using nominal values of the overall air exchange rate (0.41), average rate of internal gain (8), and solar loads (best guess of all coefficients). This set of values for these parameters is the *baseline case*. In the figure all heat gains are shown as negative values. Under the stated assumptions, transmission losses dominate heat losses at low temperatures, solar gains are significant only at mild temperatures, and the heating load essentially vanishes at temperatures near 10 °C.

Figure 5.2: Calculated Structure of P44 Heating Loads, baseline case

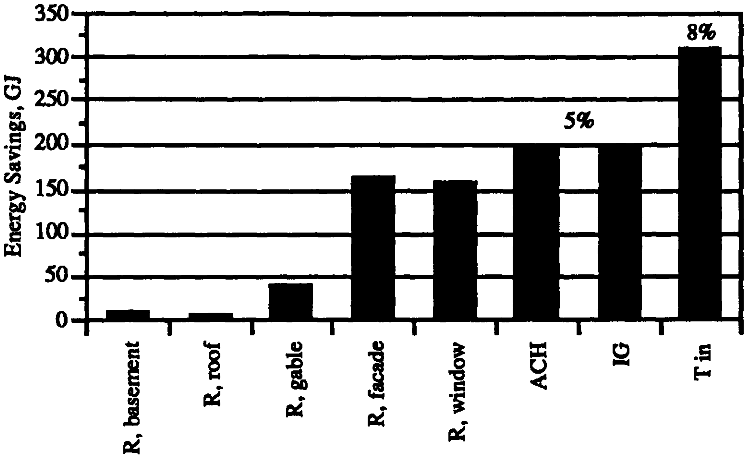


Sensitivity Analysis

The model was also used to explore the sensitivities of various parameters in the model by calculating energy savings (Fig. 5.3). The reduction in the rate of heat loss through P44's envelope was computed for all 12 bin temperatures, given adjustments to physically changeable quantities: a 10% increase in each of the five thermal resistances listed in Table 5-I or in the average rate of internal heat gains, a 10% decrease in the average air exchange rate, or a 1 °C drop in the indoor air temperature. Savings in each bin were multiplied by the bin frequency to obtain the energy savings for the duration of the experimental period (this amount will be smaller than the calculated savings over a design heating season). Figure 5.3 suggests that window and facade wall R-values are good candidates for potential retrofits, and that heat consumption is quite sensitive to the thermal resistances of facade walls and windows, the average air exchange rate, the average rate of internal heat generation, and the average indoor air temperature.

Figure 5.3: Calculated Sensitivities of Model Parameters, baseline case with constant T_{in} = 18 °C

Total Calculated Energy Consumption: 3960 GJ (135 TSF)*



* calculated savings were computed relative to this value, the total over the duration of the experiment

Measured Energy Consumption

The test building was the subject of a field experiment, performed by NIISF, designed to measure the heat for space heating delivered by the district heating system. The experiment was performed from October 1992 to April 1993; the recorded data covered the latter 167 days of that year's heating season in Moscow (recall that the design heating season is about 220 days long). Matrosov, Butovsky, and Watson describe the procedures and results of the experiment in detail, and compare measured heat delivered by the DH system with planned heat delivery. Here, the focus is on presenting the results of that experiment in a form readily compared to P44's calculated energy requirements from the model described in the previous section.

Experimental Procedure

In the experiment measurements were taken of P44's indoor air temperature, outdoor air temperature, the temperature of the supply and return water from the DH system, and the flow rate of DH water. The DH water flow rate into the building was essentially constant throughout the experiment, at 620 m^3/day. The supply and return temperatures of the DH water were measured in P44's basement, upstream of all four jet pumps; both temperatures varied significantly with ambient temperature during the heating period. Two measured indoor air temperatures were used in this analysis: in a 2nd floor unoccupied flat, and in a 9th floor occupied flat. Ambient air temperature was measured in two locations: one at the height of P44's 2nd floor, the other at the 9th floor level. Additionally, the attic and basement air temperatures were measured in order to verify the design R-values shown in Table 5-I [Matrosov, Butovsky, & Watson].

The heat delivered to P44 each day was computed from knowledge of the flow rate and supply and return temperatures of DH water using the energy balance shown in Eqn. 5.6. This equation accounts for all heat losses from the heating system to building air, including losses from convectors, distribution pipes in the heated area of the building, and main pipes in the building's basement. With a constant flow rate, the heat energy delivered to P44 from the DH system depends solely on the temperature difference between the supply and return water (temperature-driven variations in water density and specific heat capacity were insignificant). The major uncertainty in Q_{DH} arises from the inaccuracy of the flow meter used in the experiment, estimated by Matrosov to be ±15%.

$$Q_{DH} = \rho V_{DH} C_p \Delta T_{DH} \tag{5.6}$$

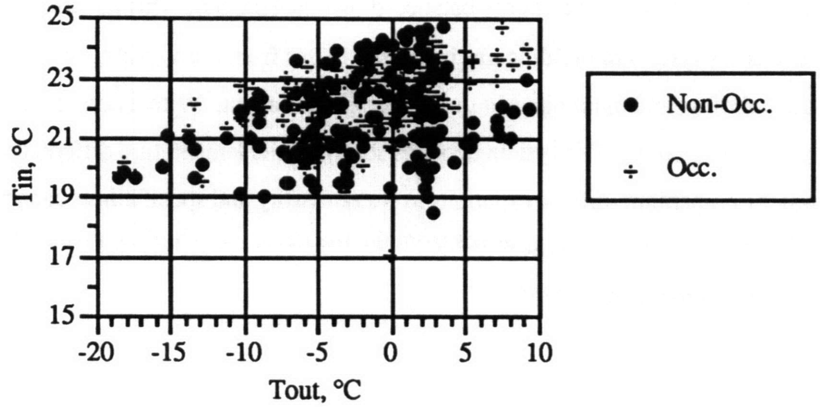
Q_{DH} = measured heat delivered to P44 from DH system [kWh/day]
ρ = density of DH water [kg/m^3]
V_{DH} = volume flow rate of DH water [m^3/day]
C_p = specific heat capacity of DH water [kWh/kg °C]
ΔT_{DH} = temperature difference between DH supply and return water [°C]

Experimental Results

The results of NIISF's experiment relevant to this study are presented in Figure 5.4. Most of the data in both figures lie within an outdoor temperature range of $-10\ ^\circ C < T_{out} < +5\ ^\circ C$ (recall that Moscow's design heating season begins when outdoor temperatures drop below 8 °C). Figure 5.4a plots the indoor air temperature in the non-occupied and in the occupied flats as a function of outdoor air temperature. The data, ranging from 19 - 25 °C, show substantial variation with outdoor temperature. The figure also displays some disparity between the temperatures in the two flats. Figure 5.4b displays the daily heat delivered to P44 by the DH system, Q_{DH}. Again, the data show substantial scatter: the heat delivered should be the same for all days with a given value of T_{out}, but measured values vary by ± 15%. The noise could be due to inaccurate measurements, inaccurate water properties delivered by the DH system, or both. The range of the scatter matches the estimated uncertainty in the flow measurements very well, however, suggesting that proper data reduction could improve the usefulness of the results.

Figure 5.4: Results of NIISF Experiment on P44

a) Indoor Air Temperature vs Outdoor Air Temperature



b) DH Heat Delivered vs Outdoor Air Temperature

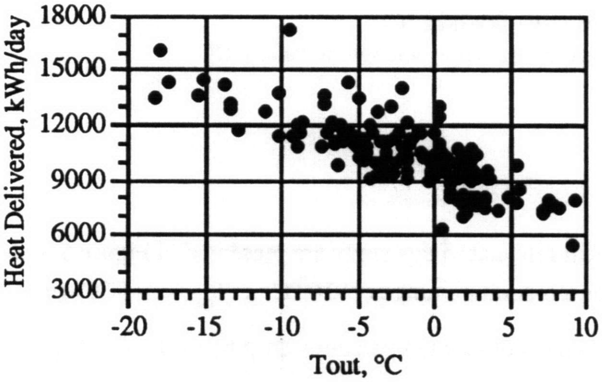


Figure 5.5 displays the same data after sorting them into 2.5 °C temperature bins. All values within common bins were averaged together. The indoor air temperatures now show a roughly linear correlation with T_{out} (Fig. 5.5a), indicating that flats tend to be cooler in cold weather. The drop in the indoor temperature of the unoccupied flat during mild weather is puzzling; there are many potential causes for the drop, but no information was available regarding which are likely to be most important. Further, the unoccupied flat was consistently cooler than the occupied flat. Supply temperature variations in the 1-pipe distribution system do not explain this discrepancy: since the unoccupied flat was on the second floor, it received DH supply water at a higher temperature than the occupied flat on the ninth floor[80], suggesting that the convector in the unoccupied flat delivered more heat than the convector in the occupied flat, which in turn suggests that the unoccupied flat should have been warmer. Since the experimental data do not

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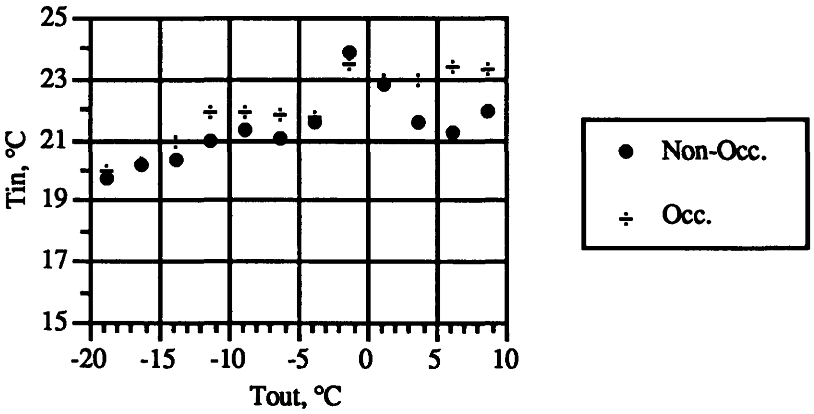
[80] according to Matrosov, a typical supply water temperature in the unoccupied flat was 59 °C, compared to 53 °C for the occupied flat

suggest this conclusion, conditions in the two flats were different in some way. As will be discussed shortly, internal heat gains are one likely cause of the difference.

The bin-sorted delivered heat data (Fig. 5.5b) show an excellent linear correlation with T_{out}, and indicate a temperature difference between the DH supply and return lines that varies linearly with T_{out} (since the flow rate was essentially constant). The total heat consumption measured over the duration of the experiment was 1743 MWh (6275 GJ).

Figure 5.5: Bin-Sorted Results of NIISF Experiment on P44

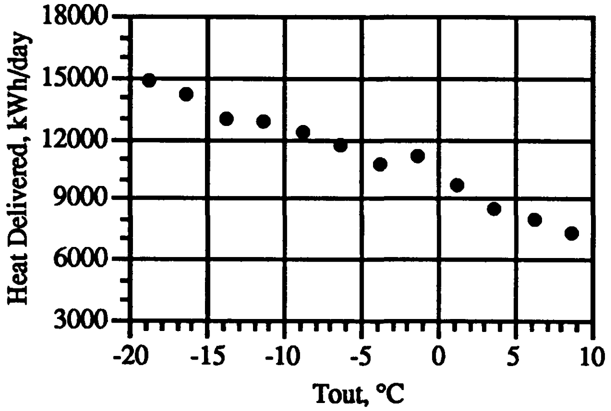
a) Indoor Air Temperature vs Outdoor Air Temperature



Seasonal Mean Measured Temperatures:

Non-Occupied	21.8 °C
Occupied	22.3 °C
Overall	22.0 °C

b) DH Heat Delivered vs Outdoor Air Temperature



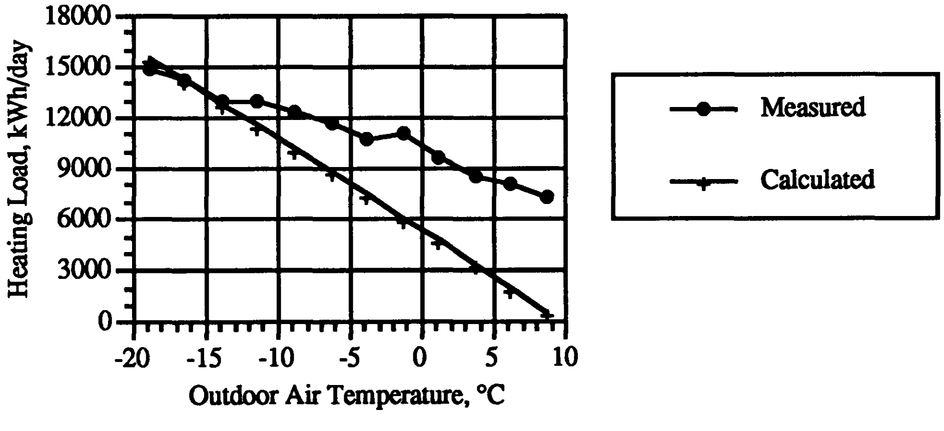
Comparing Calculated and Measured Energy Consumption

For convenience in the following discussion, the ***seasonal heating ratio*** (SHR) is defined as the ratio of aggregate measured heat consumption to aggregate calculated heat consumption over the duration of the experiment. The SHR indicates relative agreement between measured heat consumption and calculated values under various assumptions. The name is a slight misnomer since the experiment failed to cover the entire heating season, but it emphasizes that the comparisons are between values of total energy consumption, rather than between daily heating loads.

Adjustments in Well-Known Quantities

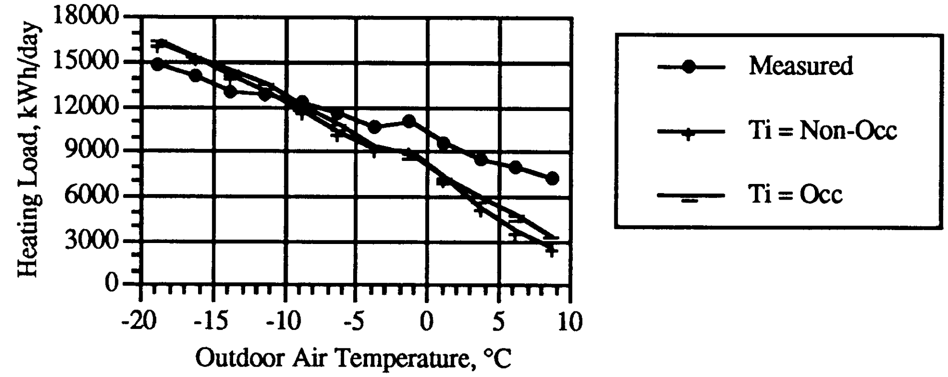
The first step in assessing the performance of P44's heating system is comparing measured heat to calculated heat under the assumptions of the baseline case with a constant indoor temperature of 18 °C, as this case represents the best available estimate of P44's design heating needs (Fig. 5.6). The figure clearly shows substantial disagreement between measured and calculated heating loads for most temperatures, with higher discrepancies in warmer weather. The seasonal heating ratio in this case was 163%.

Figure 5.6: Measured and Calculated Heating Loads, baseline case



The next step is beginning an investigation into the possible causes of the large discrepancies displayed in Fig. 5.6. Figure 5.3 suggests that the calculated heating load is quite sensitive to the indoor air temperature T_i; any deviations from 18 °C could therefore profoundly influence heating loads. Figure 5.7 displays another comparison between measured and calculated energy, assuming the entire building has an indoor temperature equal to either the temperature measured in the non-occupied flat, or that of the occupied flat. The SHR values for these two cases were 123% and 119%, respectively. Using measured indoor temperatures causes two effects: an upward shift of the calculated curves of about 1000 kWh/day, and slightly shallower slopes. In Fig. 5.7 the calculated curves overpredict DH heat delivery in severe weather, not surprising since flats are supposedly underheated in the coldest weather. Yet indoor temperatures, although lower than those under milder conditions, were still above design levels even during severe weather (Fig. 5.5a). This suggests either experimental error or inaccuracies in the model at low outdoor air temperatures. As in Fig. 5.6, the model drastically underpredicts heat supply in mild weather.

Figure 5.7: Measured and Calculated Heating Loads, measured indoor temperatures



The calculated curve for the occupied flat appears to match the measured curve slightly better than that for the non-occupied flat. Because this difference is small, however, a third calculated curve corresponding to the average of the two bin-sorted measured indoor temperatures will be used in the remaining comparisons; its heating load graph essentially matches those depicted in Fig. 5.7, and its SHR is 121%.

Higher actual indoor air temperatures in P44 lead to substantially higher aggregate heat consumption over the course of a heating season. As previously mentioned, the SHR value was 121% using measured T_i values, but 163% for $T_i = 18$ °C. Thus, 35% more end-use heating energy was required by P44 to maintain T_i at the measured values compared to maintaining a constant T_i at 18 °C, suggesting that actual heating energy consumption exceeded planned consumption. Higher end-use heat consumption alone may not be a problem, however: as the discussion in Chapter 4 demonstrated, this might not have led to higher primary fuel consumption at the TETs, because operating constraints (either at the TETs or within the DH distribution system) may force fuel consumption in the TETs to exceed the minimum required to provide heating services. Further, the building occupants were likely more comfortable at 22-23 °C (71-73 °F) than they would have been at 18 °C (65 °F), as most persons would consider 18 °C a chilly indoor temperature.

A likely explanation for the higher measured indoor air temperatures is the lack of consideration of any heat gains in MFBs in the Russians' planned heat consumption calculations. Figure 5.2 showed that internal gains are significant in P44 under baseline case assumptions. Internal heat gains cause a building's indoor air temperature to rise if other influences on the heating load remain constant. This temperature difference can be calculated, given the size of the internal gains and the properties of the building envelope.

Specifically, if Q_{tr} is replaced by Q_{int} in Eqn. 5.2, and if the summation on the right-hand side is taken over the entire building envelope, including an equivalent term for infiltration losses, then the expression can be solved for ΔT, representing the difference between the initial and final indoor air temperatures. When this is done for P44, the final air temperature is about 24 °C for the baseline case (with a constant initial air temperature of 18 °C). As Fig. 5.5a shows, this is fairly close to the average measured T_i in the experiment, 22 °C. The temperature increase due to internal gains depends strongly on the average rate of air exchange, however, and is thus only approximate.

Adjustments in Poorly Known Quantities

Further investigation of the discrepancies between measured and actual energy consumption is largely speculative, as the problem is underdetermined: several quantities in the analysis could affect the calculated energy requirements. The three main poorly known quantities here are solar gains, the average rate of air exchange, and the average rate of internal heat gain. None of these are known for P44 with precision, but, as the discussion in the first section of this chapter indicated, some of them can be bounded. Specifically, the baseline case values likely underestimate solar gains and the average air exchange rate.

Two major questions can be asked when exploring the effects of these three parameters. First, how sensitive is the total calculated energy consumption to variations in the parameters? This question addresses seasonal heating energy requirements of buildings, and is important for planning fuel supplies and for calculations of aggregate energy demand. Second, how sensitive are P44's heating loads to these parameters at different outdoor air temperatures? This question evaluates the agreement between the model and the experiment more specifically by indicating how well the delivered heat matched the calculated heating load under varying climate conditions.

The sensitivity of seasonal heating energy consumption can be addressed by examining the variation in the previously defined seasonal heating ratio (Table 5-II). Recall that a SHR of 100% indicates perfect agreement between measured and calculated end-use space-heating energy consumption. Table 5-II shows that the SHR is relatively insensitive to variations in the solar calculation, moderately sensitive to the air exchange rate, and highly sensitive to the rate of internal heat gains. The table shows that an increase in ACH of 50% provides good agreement between measured and calculated total energy consumption. Similarly, dropping the average rate of internal gains by 50% also provides good agreement. Two conclusions can be drawn from these observations. First, air exchange rates and internal gains are both important enough to warrant more careful observation in future experiments on P44-Series buildings. Second, if Russian planned heat consumption calculations improperly accounted for air exchange rates or internal gains—either by using incorrect values (air exchange) or by ignoring them completely (internal gains)—then actual heating consumption would vary considerably from planned consumption.

Table 5-II: Sensitivity of the Seasonal Heating Ratio

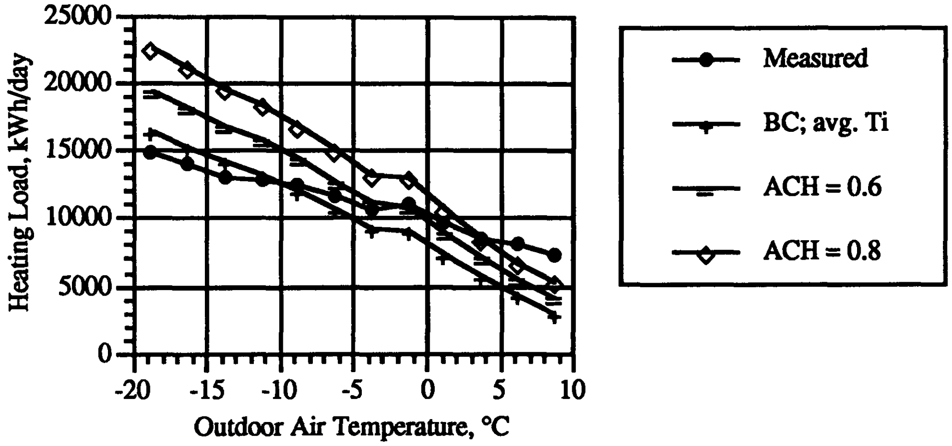
Adjustment to Sensitivity Parameter	SHR, %
Baseline Case, using curve of average measured T_i:	121
Solar:	
↑ 50%*	131
↑ 100%*	140
Infiltration:	
ACH = 0.6 (↑ 50%)	100
ACH = 0.8 (↑ 100%)	84
Internal Gains (W/m^2):	
IG = 16 (↑ 100%)	196
IG = 12 (↑ 50%)	150
IG = 4 (↓ 50%)	102
IG = 0 (↓ 100%)	88

*manifested as a 50% increase in the standard deviation of the temperature distribution used to calculate the two empirical coefficients in the equation for solar insolation (see Eqn. 5.5b)

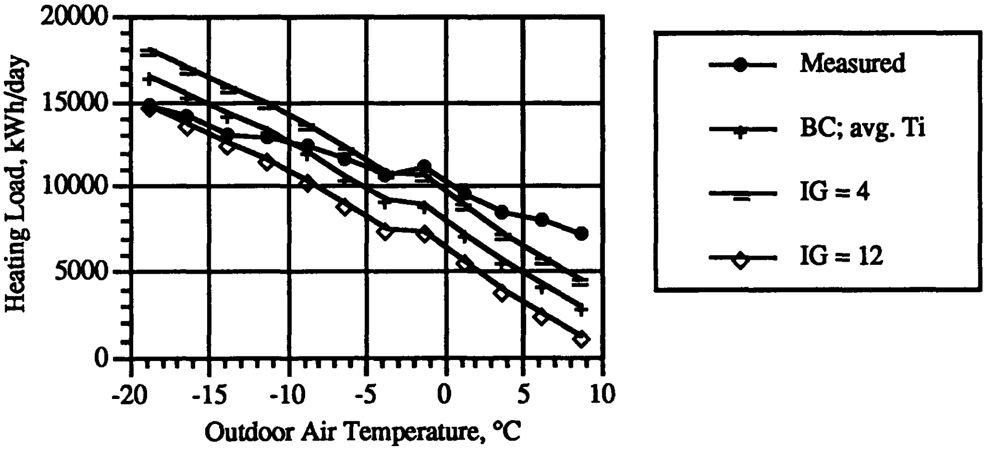
The sensitivity of P44's heating loads can be addressed by examining graphs of measured and calculated heating loads for other values of ACH and IG (Fig. 5.8). The effects of solar variations on the heating load were small, and were confined to the lower part of the graph where outdoor temperatures are mild; they will not be discussed further here. In Figure 5.8 the baseline case (BC) curves use the average of the two measured indoor air temperature curves (as in Table 5-II above). Increasing infiltration loads leads to poorer agreement between measured and calculated heating loads at low outdoor temperatures, but improves agreement at mild temperatures (Fig. 5.8a). The same is true if the rate of internal gains falls (Fig. 5.8b). Increasing internal gains has the opposite effect. These results suggest the same two conclusions as the analysis of the variation in SHR described above.

Figure 5.8: Sensitivities of P44's Heating Loads

a) Variations in air exchange rate ACH



b) Variations in rate of internal gains IG



The results displayed in Figure 5.8 suggest two additional conclusions, however. First, the figure provides more evidence that apartments in Russian MFBs are overheated[81] in mild weather (at $T_{out} > 0$ °C) under a wide range of assumptions about the characteristics of the buildings. The discussion following Fig. 5.7 suggested that internal heat gains caused overheating in P44. If this hypothesis is correct, the small measured temperature difference between the occupied (9th floor) and non-occupied (2nd floor) flats (about 0.5 °C on average; see Fig. 5.5a) suggests that in the occupied flat the internal gains exceeded any

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[81] i.e., that heat delivered exceeds heat needed; comparing heat delivered with planned energy use is a separate issue

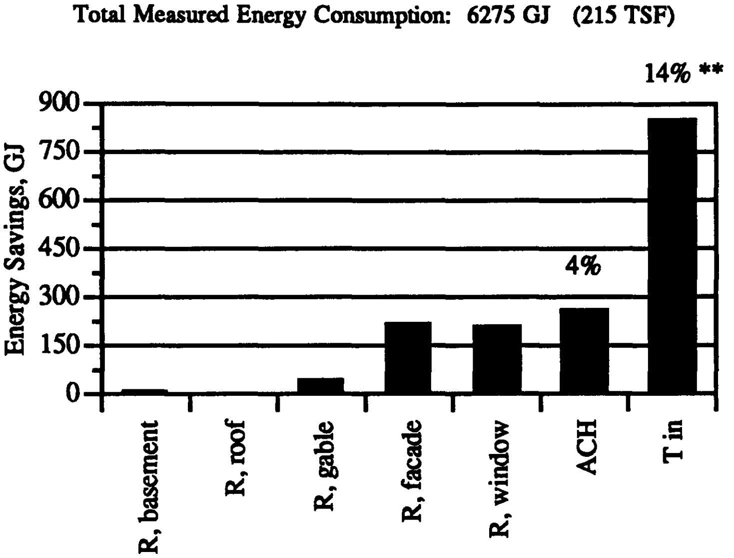
possible lower heat delivery due to the flat's position near the middle of the 1-pipe building distribution system (although indoor air temperatures might have been lower in a 17th floor flat). Second, since indoor temperatures in the occupied flat remained roughly constant even when the building was overheated (Fig. 5.5a), occupants probably controlled the temperature in their flats by opening their windows. Further, the discussion following Fig. 5.7 suggested that, all else equal, internal gains would have raised the average indoor temperature from 18 °C to about 24 °C. If windows were gradually opened as outdoor temperatures rose, higher air exchange during milder weather would have resulted, in turn leading to a higher heating load during mild weather and a flatter measured curve. Since temperatures are mild during a substantial part of the heating season (Fig. 5.4a), apartment overheating, if widespread, causes enormous amounts of energy to be wasted.

The small temperature difference between the occupied and non-occupied flats also suggests that heat flow across internal building walls may be significant. Such heat flows, driven by a temperature difference between two adjacent flats, could have a number of causes. First, internal gains could differ between the two flats because of differences in occupancies, in the number and types of appliances in the flats, and in occupant behavior (amount of cooking, hot water use, appliance use, etc.). Second, flats with different floor plans (and thus with different numbers of radiators) might have received significantly different amounts of heat from the heating system. Third, the flats would have lost heat to outdoor air at different rates if occupants opened their windows by different amounts. All three of these influences can potentially cause an indoor air temperature difference between two adjacent flats; the resulting heat flow across the internal walls separating the two flats depends on the thermal properties of those walls (R-values, air tightness). Unfortunately, little is known about these properties. High heat flows across internal walls are consistent with the results displayed in Figs. 5.8 and 5.5a, however. If internal heat flows are in fact high, any sort of improved control of room heating systems may have only a limited effect on indoor air temperatures, and thus on heating energy consumption.

Potential Energy Savings

Comparisons between measured and calculated energy consumption permit calculation of revised seasonal energy savings estimates. Figure 5.3 presented calculated savings based on the baseline case and on a constant indoor air temperature, given improvements in various quantities influencing P44's heating loads. Figure 5.9 provides similar estimates, with three major differences: in Fig. 5.9 the calculations used the average measured indoor air temperature instead of a constant temperature; savings from improved temperature control were computed relative to a constant value (20 °C, as shown below the figure) instead of a constant change (-1 °C, as shown in Fig. 5.3); and, finally, the results were scaled up by 21% (according to the baseline case SHR) for the sake of comparing the results with the total measured energy consumption in the experiment.

Figure 5.9: Revised Potential End-Use Heating Energy Savings in the P44 Experimental Building*



Given:

a 10% increase in various thermal resistances, or
a 10% decrease in infiltration, or
a perfectly controlled indoor air temperature at 20 °C

* the results are calculated estimates, and represent aggregate savings over the entire period of the P44 experiment

** higher energy savings (29%) would result if indoor air temperatures were perfectly controlled at the design level of 18 °C instead of 20 °C

The results shown in Figure 5.9 provide improved estimates of potential savings under actual operating conditions. Compared to the results of Fig. 5.3, the absolute size of estimated savings shown in Fig. 5.9 increased considerably. Figure 5.9 also reemphasizes that improvements in indoor air temperature control, infiltration, facade walls, and windows will likely provide the most energy savings. It must be stressed, however, that the results displayed in Figure 5.9 depend strongly on the initial R-values—if assumptions about P44's R-values (as listed in Table 5-I) are inaccurate, then the structure of potential energy savings could differ from the results shown in Figure 5.9 (e.g., if window R-values are actually less than 0.39 m^2 °C/W, window improvements would offer more energy savings than Fig. 5.9 indicates).

Assessing primary energy savings is difficult because of the diversity of DH system designs, as discussed in Chapter 4. Recall that P44 employs a closed hot water system and an independent space-heating system. Assuming the control equipment in the secondary DH water circuit functions properly, then potential heating energy savings of 280-1100 GJ would show up at the TETs[82]. Unfortunately, nothing is

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[82] 225-850 GJ (from Fig. 5.9) divided by 0.79, the national average efficiency of DH heat conversion, discussed in Chapter 2. This amount would differ, of course, if the efficiency of DH conversion in P44's connected DH system differs from the national average.

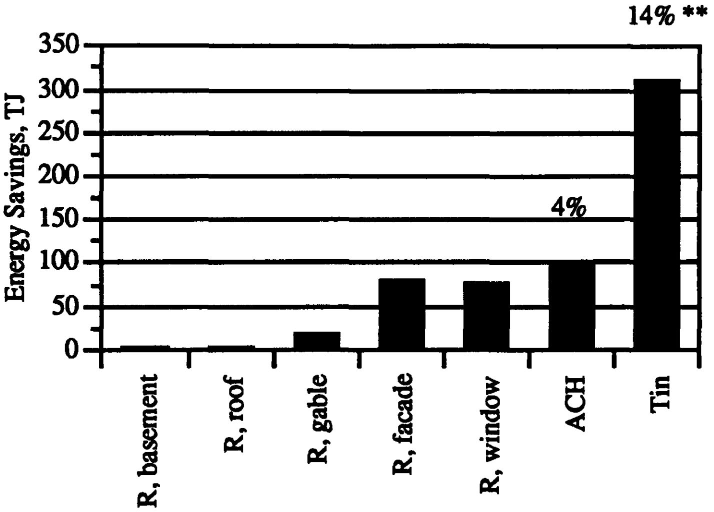
known about the design of the TETs serving the P44 experimental building, so the potential primary fuel savings could remain partially or fully unrealized.

Extrapolating Energy Savings

This thesis has focused on investigating the validity of extrapolating end-use and primary energy savings from a single building to a larger group of buildings. The first step in this process is extrapolating end-use savings from P44 to other similar buildings in the same location: other P44-Series buildings in Moscow. The size of Moscow's stock of P44-Series buildings is not known precisely, but it can be estimated from available data. Total new P44 construction from 1990-92 in Moscow amounted to about 2.5 million m^2 of useful floor area [Matrosov]. Since the P44 series is fairly new, the first buildings of this design might have appeared in about 1980. Starting in 1980, and assuming 25% of total new construction in 1990-92 was built during the first 3 years, 50% of this value in the second 3 years, and 75% in the third 3 years, the total stock is currently about 6.3 million m^2. The useful floor area of the P44 building studied in this analysis is 17,072 m^2 (Table 5-I). Dividing the results presented in Fig. 5.9 by this area, and then multiplying by 6.3 million m^2 provides crude estimates of energy consumption and energy savings in all P44-Series buildings in Moscow (Fig. 5.10). The structure of the savings estimates are identical to that displayed in Fig. 5.10.

Figure 5.10: Estimates of Potential End-Use Heating Energy Savings in Moscow's Stock of P44-Series Apartment Buildings

Estimated Total Energy Consumption: 2300 TJ (78,500 TSF)



Given:
- a 10% increase in various thermal resistances, or
- a 10% decrease in infiltration, or
- a perfectly controlled indoor air temperature at 20 °C

* again, the results are calculated estimates, and represent aggregate savings over the entire period of the P44 experiment

** higher energy savings (29%) would result if indoor air temperatures were perfectly controlled at the design level of 18 °C instead of 20 °C

Many assumptions are implicit in the results displayed in Figure 5.10. In addition to uncertainties in the energy savings estimates of Fig. 5.9 and the crudeness of the P44-Series stock estimate, the results of Fig. 5.10 assume the envelope characteristics of all P44-Series buildings in Moscow are similar to the building addressed in this study. This is far from certain! First, all P44-Series buildings may not share the physical layout of the P44-Series building studied in this analysis (as depicted in Figure 5.1)—the number of sections in buildings and their patterns of combination might have varied, leading to different relative proportions of facade wall, gable wall, and window areas. Second, even assuming all the buildings are identically shaped, further local variations in building characteristics are possible depending on who constructed the building (i.e., the state or a cooperative), the organization of the state-owned firms that constructed the building, the availability of the proper materials when the building was constructed, etc.—problems described at length in Chapters 2 & 3. Further uncertainties arise because of possible differences in building occupancy rates, in occupant behavior, and in characteristics of the DH system connections. Unfortunately, there is no way to quantify any of these uncertainties without more information. The results shown in Fig. 5.10 should therefore be treated as approximate.

Extrapolating end-use energy savings beyond Moscow's P44-Series stock is even more problematic, but crude estimates of design seasonal energy consumption in buildings with different kinds of wall construction in Moscow are possible. These estimates are founded on the analysis of total floor area constructed and average thermal resistance of the major kinds of wall construction presented in Chapter 3 (Table 3-VII); the design estimates derived here thus depend on all assumptions of the previous analysis. The calculation methodology described in this chapter was used to estimate space-heating energy consumption in the apartment buildings. For the sake of comparison, the calculations used the same measured indoor and outdoor air temperature data from the P44 experiment. Transmission losses, internal gains, and solar gains were computed using the same method applied to P44. Design infiltration losses, however, were estimated for opaque wall components and for fenestration based on the estimates in Table 3-VII.

Several further assumptions about envelope areas were necessary in order to calculate the design energy traits in Moscow's apartment buildings. First, the entire housing stock using each of the three major kinds of wall construction in Table 3-VII (3-layer panel, 1-layer panel, and Brick/Large Block) was modelled as a single building. Second, the average ratio of external wall area to useful floor area is unknown; all buildings built after 1979 were assumed to have the same value of this ratio as P44: 73%. For buildings built between 1956 and 1979, this ratio was increased by 10% (to 80%) in an attempt to account for the smaller floor area in older buildings. Third, the average ratio of fenestration area to total external wall area is also unknown; this ratio for all buildings was assumed to match P44's value of 18%. Finally, since heat losses through the basement and roof were relatively small in P44, they were ignored in the design calculations for other apartment buildings.

The results of the extrapolation are presented in Table 5-III. The first column suggests that MFBs constructed of bricks and large blocks, taken together, consume more space-heating energy than any other kind of apartment building in Moscow. This is not surprising, since such buildings constitute more of the district-heated stock than large-panel buildings (Fig. 3.12, Chapter 3). The second column suggests that on average all buildings respond similarly to better control of indoor air temperature (the heating system improvement offering the highest potential energy savings), and that on average they respond almost as well as P44 responds. The slight difference in the energy savings estimates (12% savings vs 14% savings) arises because various R-values and envelope areas were in different proportions for the P44 experimental building than for the stocks in aggregate.

Table 5-III: Estimated Design Energy Characteristics of Moscow's District-Heated MFB Stock

	Space-heating Energy Consumption, TJ	Energy Savings, TJ*	Relative Energy Intensity, MJ/m^2
1-Layer Panel	15,300	1800 (12%)	440
3-Layer Panel	24,700	3000 "	450
Brick/Large Block	29,000	3500 "	500
P44 Experimental Building	6.3	0.85 (14%)	300

*assuming the indoor air temperature is perfectly maintained at 20 °C

Total Estimated Savings from Improved Indoor Temperature Control:

8300 TJ (285,000 TSF), about 12% of seasonal consumption

The third column of the table suggests two major conclusions. First, since some of the energy intensities differ significantly, design energy efficiency in Moscow's MFBs is apparently somewhat correlated with the type of wall construction. Further, since all three values differ significantly from the design energy intensity obtained for the P44 experimental building using the same procedure, the results support Chapter 3's contention that structural differences among different building series are important. The diversity suggested by the results in the third column is rooted in the R-values of opaque walls (both transmission and infiltration), since fenestration norms and assumed area ratios were invariant among the three cases. Second, brick and large-block buildings are the least energy efficient of the major kinds of wall construction. Most of these buildings were constructed early in the housing drive, when norms were less stringent and construction quality poorer than in later years. Since these buildings represent a significant fraction of total estimated design energy consumption, they should be targeted for further study.

The estimates shown in Table 5-III are quite crude, and should be treated as such. They are based on a limited amount of information, and represent only the first step in analyzing the design energy consumption characteristics of Moscow's MFB stock. Detailed statistical surveys would yield a more solid foundation for making extrapolations by providing better estimates of the average ratio of fenestration area to wall area, the average ratio of wall area to useful floor area, average design R-values, etc. A complete classification of Moscow's MFB stock by building series, along with complete definitions and descriptions of each series, may be the best way to obtain the necessary information. Such a classification would also determine which building series make up most of Moscow's apartment buildings. Even this analysis would be incomplete, however, as it would only provide *design* information. *Actual* building characteristics likely vary even further, and must be measured individually for each building series. Field experiments designed to measure R-values, infiltration rates, and internal gains thus offer another promising area for follow-up work. The analysis in this chapter suggests that solar gains are small in the buildings, and therefore that further investigation of solar gains should have a relatively low priority.

As Chapters 3 & 4 emphasized, additional difficulties are encountered with further extrapolations. First, extrapolating end-use savings to buildings in other cities is difficult because building characteristics varied regionally with climate and economic conditions. Second, the likelihood of achieving primary fuel savings requires knowledge of local operating conditions, such as the state of repair of control equipment, the demand for power and heat, and TETs' flexibility and controllability. Because of these difficulties additional extrapolations will not be attempted here.

Improving Space-Heating System Controls

The results of the Russian field experiment suggest that heat delivery from the DH system to the P44 apartment building was poorly controlled, a conclusion consistent with general observations made by Western researchers and with the reports of Russian district heating specialists [*Therm. Engr.*]. Control of the heat delivered to buildings is, in many ways, a fundamental issue. First, improving control over heat delivery may offer the largest potential energy savings in overheated apartment buildings in Moscow—up to 29%, depending on the desired indoor air temperature. In many cases these savings will also be the easiest to achieve. Second, improvements in building envelopes, while reducing heating loads, will save less energy (or at worst, will save no energy) without improving control over heat delivery. Finally, improving heating control generally leads to improved thermal comfort in the buildings, ultimately the goal of any space-heating system.

General Control Problems

Chapter 4 discussed the design, effectiveness, and diversity of existing control systems in Russian DH networks in detail. Generally, breakdowns in heating control can occur anywhere in the DH system between central heat sources and building heating elements. All district-heated buildings are subject to at least two potential control problems: improper heat supply at central heat sources (relative to the primary *grafik*), and hydraulic instability in the DH distribution network due to either the requirements of other consumers or malfunctioning pressure control equipment. For a given building, however, the number of additional control problems—and the nature of those problems—depends on the design of the DH system serving the building.

Recall that the DH system serving the P44 experimental building has a closed DHW design and an independent space-heating design . Potential problems in the independent design center on the effectiveness of the open-loop space-heating control system at the group heating substation (GHS). If the control equipment functioned properly, and if it responded quickly enough, then fluctuations in the primary DH water circuit would have been damped, allowing secondary water temperatures to be provided according to the secondary *grafik*. This would effectively solve many potential control problems in the building's heating system[83]. If, however, DH control at the GHS was inadequate, then the heat supply to P44's space-heating system would have exceeded design levels significantly in mild weather because of control problems in TETs, network hydraulic instability, or the high supply water temperatures necessary to operate the closed DHW system (which, as the discussion in Chapter 4 pointed out, exceed the design space-heating supply water temperatures in mild weather).

Conditions within the secondary DH heating circuit could also have affected heat delivery to P44. Since P44 is the second of two buildings connected in series on the circuit, operating conditions in the first building affected the properties of the DH water supplied to P44. Heat delivery to P44's heating systems also depended on the mixture coefficients of the building's jet pumps: if they were set improperly[84] then the actual heat delivered could have differed significantly from design calculations. Even if the jet pump was properly set, actual heat delivery could differ from planned heat delivery in mild weather because mixture coefficients were usually set to provide the proper amount of heat only during design weather.

Operating conditions within individual flats could also have affected P44's heating energy consumption. Since building occupants have little direct control over the heating system, however, occupant behavior plays a minor role in determining the amount of heat delivered from the space-heating system[85]. The lack of controls on individual heating elements does influence the amount of heat delivered, but only if heat flow through internal walls is relatively small. As discussed earlier, the results of the field experiment performed on P44 suggest that heat flow through internal walls may be high.

Identifying Specific Control Problems

Determining the most important specific causes of overheating in the P44 experiment (and therefore the best remedies to overheating problems) is difficult. The two most likely causes of building-level control problems in the DH system are faulty GHS equipment and improper mixture coefficients in the building's jet pumps. Unfortunately, maladjustments in both systems cause similar effects on the temperature of the heating water delivered to P44's convectors (T_i, from the *grafik* displayed in Fig. 4.8), and thus on P44's actual heating load curves (from Fig. 5.7): a vertical shift in the actual heating load curve, and a change in the curve's slope[86]. Thus, in the results of the Russian field experiment, the effects of faulty GHS equipment cannot be distinguished from the effects of poorly adjusted jet pumps[87].

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[83] although it would not address the planning issue of whether the secondary *grafik* itself was defined properly

[84] i.e., if the ratio of recirculated water flow rate to DH supply water flow rate was improper, given the actual hydraulic conditions in the local DH network

[85] the major heating-related control action of building occupants was opening windows to prevent excessive indoor temperatures; this does provide lower indoor air temperatures, but it also tends to increase heat delivered from room heating elements (because of the higher ΔT between the radiator and the room air). This contrasts sharply with reducing delivered heat, a more efficient response to room overheating.

[86] intuitively, adjusting a jet pump might be expected to produce only a vertical shift in the heating load curve, but in fact a change in slope results as well, because the temperature of the water exiting the jet pump (T_i) is a non-linear function of the jet pump's mixture coefficient

[87] this may be due to insufficient knowledge of how GHS control equipment actually works in practice—perhaps better knowledge of the equipment would allow the two effects to be distinguished

Given the available information, the control equipment in the GHS is most suspect because of its importance in regulating the hydraulic conditions in the secondary flow circuit, and because measured DH water supply and return temperatures (T_S and T_R, from the *grafik* displayed in Fig. 4.8) in the P44 experiment apparently differed from design temperatures [Matrosov, Butovsky, & Watson]. Measured temperatures were below design, which is the opposite of what one would expect if buildings were overheated, yet since design *grafiks* often caused overheating [*Therm. Engr.*], an actual *grafik* shifted downward (perhaps including a slope change as well) might have been appropriate under real operating conditions. Unfortunately, there is no way to judge the proper size of this downward adjustment without better knowledge of Russian design heating calculations in the secondary flow circuit. If the actual downward shift were less than the shift required to provide proper heating, then actual DH water supply and return temperatures could have been below design and still caused overheating.

Clearly, repair or adjustment of GHS control equipment or jet pumps could provide easily obtainable, significant energy savings in the P44 experimental building. If GHS and jet pump designs are fairly uniform, and if many apartment buildings are in fact overheated in mild weather, then similar adjustments may readily save large amounts of energy in other buildings as well. Such adjustments must be made with care, however, as adjusting a jet pump to reduce heat delivery during mild weather will also reduce heat delivery during severe weather; the effects of adjusting GHS control equipment may be similar. Adjustments could thus lead to excessively cool indoor air temperatures during severe weather, already a problem in many apartment buildings.

Other improvements in DH heating control are possible, but they are either less effective than adjustments in the GHS or jet pump[88], or are ineffective without these adjustments. For example, improved room heater controls of many kinds are available, ranging from simple insulated radiator covers that limit the heat transfer to the room air to sophisticated automatic closed-loop controlling valves. Although effective individual room heating controls are desirable, refitting existing Russian MFBs with individual heating controls may offer only limited improvements in heating system performance. First, because most Russian MFBs employ 1-pipe internal distribution systems, improving individual heater controls in one flat will lead to a less stable internal hydronic system, and thus to less controllable heaters in other flats. Second, the effect of such controls on reducing heat delivery to individual flats will be limited if heat flow through internal building walls is significant. Since the impact of improved individual heating controls on saving energy is uncertain, devoting extensive resources to providing them could be wasted effort.

Regardless of any adjustments made in space-heating system controls, primary fuel savings at central heat stations will still depend on operating conditions there, as discussed in Chapter 4.

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[88] because their results are less certain

Summary

The results of a Russian experiment measuring space-heating energy consumption in an apartment building in Moscow were compared to calculated energy requirements of the building using a model developed by the author. There were three major uncertain quantities in the analysis: solar heat gains, internal heat gains, and the total air exchange rate. Solar gains made up a small component of P44's calculated heating load, but internal gains and infiltration were both significant. The analysis described in this chapter led to three major conclusions:

- significant discrepancies between measured and calculated space-heating energy use are apparent—on both daily and seasonal bases—under a wide range of assumptions about uncertain quantities in the analysis
- indoor air temperatures in P44 were consistently higher than the design indoor temperature, possibly because design heating loads took no account of internal heat gains
- P44 was substantially overheated during mild weather, again under a wide range of assumptions about uncertain quantities; occupants probably controlled the temperature in their flats by opening their windows

These conclusions are tentative, as uncertainties remain large, but they are consistent with the best available information. Further experimental work is needed to confirm them. Although the conclusions may be no surprise to some Western readers, they represent a significant step toward improving understanding of the heating characteristics of Russian MFBs.

Patterns of Energy Use in Moscow's District-Heated MFB Stock

Results from the analysis of P44's heating characteristics were extrapolated to other buildings. As discussed earlier in the chapter, all of these extrapolations contain large uncertainties (perhaps on the order of ± 50-75%); the results should thus be treated as approximate.

- Moscow's stock of district-heated P44-Series apartment buildings seasonally consumes about 2300 TJ (78,500 TSF) of end-use space-heating energy
- Moscow's entire district-heated MFB stock consumes about 69,000 TJ (2.3 million TSF) of seasonal end-use space-heating energy, roughly 6% of Russia's total seasonal end-use space-heating energy supply from district heating systems (see Chapter 2). Brick and large-block buildings consume the most space-heating energy (42%) in aggregate, followed by 3-layer panel buildings (36%) and 1-layer panel buildings (22%).
- The space-heating energy efficiencies of buildings using different types of wall construction differ significantly, supporting Chapter 3's contention that structural differences within the MFB stock are important determinants of energy efficiency. Further, older buildings appear to be significantly less energy-efficient than newer buildings.

Causes of Improper Heating

The systemic view of space-heating energy analysis was found to be extremely important for identifying causes of improper heating levels. Insufficient control of indoor air temperatures was the main cause of overheating in the P44 experimental building, which in turn was caused by insufficient control of heat delivery to the building. Room-level effects (1-pipe distribution system irregularities, occupant behavior, the lack of controls on individual heating elements) on heating energy consumption might have been small because of high heat flows across internal walls. Building-level control problems were likely rooted in either of two potential causes, either of which could have led to the observed discrepancies in actual heating loads:

- maladjusted or malfunctioning equipment in the group heating substation of the district heating system (more likely)
- maladjusted or malfunctioning jet pumps in the P44 experimental building

Thus, the first efforts at improving space-heating system controls should focus on equipment in GHSs and on building jet pumps. Widespread installation of room-level heating controls is not recommended without further investigation of the effectiveness of such controls. It must be stressed that control problems in the district heating system are no surprise to Russian district heating specialists. Such problems may not be well-known in the Russian buildings community, however, and thus may offer some fresh insights into analyses of space-heating energy consumption.

Potential Efficiency Improvements

The systemic view was also important for assessing potential energy savings. The most promising areas for improvements are in indoor air temperature control, infiltration, and transmission losses through windows and facade walls:

- an estimated 310 TJ (10,600 TSF) of end-use space-heating energy (14% of consumption during the heating season) could be saved in Moscow's stock of district-heated P44-Series apartment buildings if indoor air temperatures were properly controlled at 20 °C; 29% savings would result from lowering actual indoor air temperatures to 18 °C
- an estimated 100 TJ (3200 TSF) of heating energy (4% of seasonal consumption) could be saved if overall air exchange rates were reduced by 10%
- an estimated 75 TJ (2600 TSF) of heating energy (3% of seasonal consumption) could be saved if the thermal resistance of either facade walls or windows were increased by 10%
- an estimated 8300 TJ (285,000 TSF) of end-use space-heating energy (about 12% of consumption during the heating season) could be saved in Moscow's entire district-heated MFB stock by properly controlling indoor air temperatures at 20 °C

Improving control of indoor air temperatures (and thus of heat delivered from the heating system) is the key issue: it offers the largest, most easily achieved savings, and is a prerequisite for realizing energy savings from all improvements in building thermal envelopes. All methods of improving building heating system controls offer only end-use energy savings, however; as Chapter 4 emphasized, realizing primary fuel savings depends on conditions at the central heat stations in the DH system.

Recommendations for Future Work

Further analysis of space-heating energy consumption patterns in Russian MFBs should focus on four areas: improving understanding of consumption patterns in a single apartment building; improving the accuracy of extrapolations from a single building to other buildings in the same city; improving the accuracy of extrapolating end-use savings in buildings to primary fuel savings at central heat stations; and further exploring the validity of extrapolations from buildings in one region (e.g., Moscow) to buildings in another region (e.g., Minsk or St. Petersburg).

The two important uncertain quantities in the analysis described in this chapter—internal gains and infiltration—should both be studied further to determine their impacts on heating energy consumption patterns in a single building with more precision. Better knowledge is also needed of actual transmission R-values of entire envelope sections (i.e., the sum of all facade wall sections, the aggregate of all fenestration), as opposed to design R-values of individual envelope components (i.e., a single large panel or window). Fenestration should be especially targeted for further study, as the thermal properties of actual window and balcony door assemblies are presently poorly understood. Finally, the thermal properties of internal walls should be investigated to determine whether internal heat flows between adjacent flats are significant.

As mentioned earlier, detailed statistical surveys would yield a more solid foundation for making extrapolations of end-use savings by providing better estimates of the average ratio of fenestration area to wall area, the average ratio of wall area to useful floor area, average design R-values, etc. A complete classification of Moscow's MFB stock by building series, along with complete definitions and descriptions of each series, may be the best way to obtain the necessary information. Such a classification would also determine which building series make up most of Moscow's apartment buildings. Further investigation of the composition of the housing stock in other regions (by building series) or of district heating systems (by the type of distribution system, and by the type of TETs) would permit reasonably accurate extrapolations of end-use and primary energy savings, and should also be considered for potential follow-up studies.

CHAPTER VI: CONCLUSION

Chapter 1 presented the basic, central question that this work would attempt to answer. The Thesis Question will now be repeated here:

Thesis Question: Do energy savings from space-heating energy efficiency improvements in Russian district-heated apartment buildings, once quantified for one building, apply to a significant portion of the housing stocks of Russia or the CIS?

This study has shown that accurately extrapolating end-use or primary energy savings from a single building to any larger group of buildings is difficult because of the diversity in the characteristics of Russian apartment buildings and district heating systems. This conclusion has profound policy implications, as the best energy-saving programs are often defined by the quality of estimates of the programs' effectiveness, cost, and feasibility.

This study yielded several further conclusions about space-heating energy efficiency and the scope for efficiency improvements in Russian apartment buildings, falling into two main areas. The first addresses the current state of the buildings: whether they are properly heated, the chief causes of incorrect heating levels, and the energy efficiency of the heating systems. The second addresses potential improvements in the heating systems: the size of potential energy savings, the difficulty of predicting the savings, and major impediments to achieving the savings. A specific methodology was also developed for selecting which apartment buildings are best suited for further study.

The systemic view was found to be important throughout the analysis, as indoor climate conditions, heating system efficiency, and potential energy savings were determined not only by building characteristics and the actions taken by building occupants, but also by the characteristics of the district heating system and the behavior of central heat station operators. Thus, future efforts at institutional reform in the urban housing sector should account for <u>all</u> major causes of space-heating energy inefficiency. In other words, programs providing economic incentives for building occupants to improve energy efficiency may be ineffective if the programs focus only on improving building envelopes—such programs should include incentives for improving control of heating systems, parts of which are beyond the control of building residents.

It must be stressed that although most of the following discussion focuses on Russian buildings, it largely applies to apartment buildings throughout the CIS.

THE CURRENT STATE OF BUILDING HEATING SYSTEMS

The first objective of this study was to gain a basic understanding of all systems in Russian apartment buildings affecting indoor temperature levels and space-heating energy requirements. This report has continually emphasized that a complete understanding of the system requires not only technical knowledge of envelope constructions and heating systems used in various building designs, but also knowledge of the goals of central planners and building designers, and of the constraints under which they operated.

The Evolution of the Russian Apartment Building Stock

At the end of World War II the Soviet people were faced with an immense housing shortage; in the mid-1950s Soviet leaders instituted a mass housing construction drive to ameliorate the shortage. Most housing built since that time has been owned, built, managed, and maintained by the state. In this period apartment buildings were designed to be erected as quickly and as cheaply as possible, using the bare minimum amount of materials and the minimum amount of labor for construction. Early in the housing drive, building designs were highly standardized, production and construction methods were highly industrialized, and high building operating and maintenance costs were ignored in housing planning decisions. The quality of construction and repair of Russian apartment buildings was also extremely poor: thermal resistances of envelope components were often below standards; doors and windows often fit poorly; large gaps sometimes appeared between wall panels; and condensation on inner wall surfaces was common. Most of these buildings remained in poor condition for many years—repairs were usually performed behind schedule, causing needless building deterioration and eventually requiring even more extensive and costly work because of the delays. This period set the precedent for designers and builders of Russian apartment buildings for many years.

External walls in the CIS's district-heated apartment building stock are dominated by large-panel construction: large panels constitute about 60% of the walls (by building floor area). Of the remaining wall area, about 30% is composed of bricks and small blocks, with about 10% composed of large blocks. The structure of Moscow's stock is similar: large panels constitute about 60% of all external walls, large blocks constitute about 20%, and bricks and small blocks constitute about 20%. Estimates of the structure of these housing stocks have not previously been published in the West.

Thermal properties of Russian apartment buildings are determined by the building design; various designs were designated by "building series" numbers. Different building series were distinguished by the type of wall and attic construction, the placement and composition of load-bearing members, the heating system design, flat designs, building heights, and so on. In some designs thermal properties of building envelopes were driven by thermal building codes, in others, by constraints unrelated to the codes. The building series designs changed often over time, resulting in the widespread use of a large number of designs in Russia since the beginning of the housing drive.

Norms and calculation procedures for thermal properties of Russian apartment building envelopes were revised at 6-8 year intervals. Space-heating energy consumption was relatively unimportant in thermal building codes until the late 1970s, when energy shortages became widespread in the Soviet economy: in 1979 the codes included annual fuel costs as a constraint on the design of opaque envelope components for the first time. Yet this was only the first step: stricter standards for other envelope components and for building heating systems lagged behind these improvements.

Typical values of design minimum thermal resistances are likely for each of the three major kinds of wall construction in a given city. Differences among these constructions may be substantial, however: a crude analysis of Moscow's district-heated apartment building stock suggests that design space-heating energy use per unit floor area varies up to 12% among the three building stocks on average, and possibly up to 65% for individual buildings. The type of wall construction also influences the accuracy of code-specified calculations for computing actual R-values: indirect evidence suggests that actual R-values in Russian apartment buildings are substantially lower than values specified in Russian norms. Because of these discrepancies, and because of diversity among building series designs—surprising in its extent—the thermal resistance of external walls in a given building may differ considerably from the minimum design value. These insights on Russian building codes have not previously been published in the West.

Heating System Effectiveness

Knowledge of energy service levels (i.e., indoor air temperatures) helps to identify potential causes of energy inefficiency. The question of whether energy service levels were proper centers on whether flats in Russian apartment buildings were properly heated. Most available evidence is anecdotal, consisting of scattered references to typical complaints of building occupants. Most such references suggest that many buildings are overheated during mild weather. The results of one field experiment performed on an apartment building in Moscow corroborate the anecdotal evidence. There is some anecdotal evidence that many flats are also underheated in severe weather, but the results of the field experiment provide no support for this conclusion. Widespread improper heating in older buildings is not surprising, given the original goals of housing planners and the constraints of building designers, but it is mildly surprising that the Russians have failed to correct the problem even in modern systems.

Potential causes of improper heating levels can be divided into two basic areas, according to the systemic view used throughout this analysis: problems in buildings (excessive heat loss), and problems in district heating systems (excessive or insufficient heat delivery).

Problems in Building Systems

The thermal performance of Russian apartment building envelopes is generally below design specifications: norms for thermal resistance were often unsatisfied because of difficulties in accurately calculating the thermal properties of complex construction geometries, or because inferior materials were used in building construction. As mentioned above, many older buildings were designed and built so poorly that actual infiltration rates far exceed design levels.

Individual flats within buildings generally lack any sort of heating control equipment. If flats were overheated occupants opened their windows; if flats were underheated occupants often found other ways to heat their homes (e.g., by filling containers with hot water, or by firing up the kitchen stove). Manual building-level heating controls—jet pumps—were only adjusted about once per year, if that often, and usually failed to account properly for hydraulic conditions in the local district-heating network.

Russian apartment buildings were designed for satisfactory operation at the design condition—during the lowest outdoor air temperatures. For building envelopes, "satisfactory operation" was defined as preventing condensation on inner envelope surfaces, not as maintaining comfortable indoor air temperatures. Similarly, the jet pumps were set to provide proper heat delivery at the design outdoor air temperature; all building heating systems relied on the district heating system to make any further adjustments as outdoor air temperatures changed. Realizing that Russian designers focused mainly on worst-case conditions is one of the fresh insights of this study.

Problems in District Heating Systems

Essentially all Russian district heating systems shared several common problems. Like the apartment buildings, the district heating systems were designed for satisfactory operation during the coldest weather; most equipment was sized and adjusted accordingly. Virtually all control of the heating of apartment buildings was centralized: in all systems the planned district heating supply water temperature varied linearly with outdoor air temperature to provide variable amounts of heat to the buildings. Like the heating equipment, design temperature schedules were set relative to design conditions. The linear design schedules themselves were imperfect, as space-heating needs are generally non-linear, and in practice actual temperature schedules differed significantly from design schedules. Central heating control, although feasible in theory, was difficult to implement in practice.

Conditions in Russian district heating networks vary widely; the diversity is caused by networks' large size, differing constraints at central heat stations, the different kinds of network designs, and the different kinds of connected consumer loads. Thermal inertia in the networks is the source of much variance in large systems. At central heat stations supply water temperatures are often updated infrequently, and the control of the supply temperatures is often noisy; these practices contribute to the discrepancies. Other variations arise because of interactions with domestic hot water systems. In some systems water temperatures are higher than the proper temperature for space heating; in other designs the water flow through the space-heating system depends on the size of domestic hot water loads. Finally, virtually all networks lack closed-loop automatic space-heating control equipment. As a result, the networks are generally unable to provide the proper amount of heat to all consumers under all conditions, suggesting that central space-heating control, as practiced by the Russians, is ineffective. This conclusion is somewhat surprising, since district heating has the potential to provide highly effective heating services.

Energy Efficiency

The final step in evaluating the present state of Russian apartment building space-heating systems is examining their energy efficiency. The results of a field experiment performed on one apartment building in Moscow suggest that the space-heating heat delivered to the building substantially exceeded its space-heating requirements, under a wide range of assumptions. Excess consumption tended to occur during mild weather, when flats in buildings were typically overheated. This conclusion is not new, but experimental evidence supporting it has been unavailable until now. In the experimental building, the heating system control problems were most likely rooted in either of two potential causes: faulty equipment in the group heating substation of the district heating system, or faulty jet pumps in the building itself. Maladjustments in either system would have caused the observed discrepancies in actual heating loads.

Generally, energy inefficiency in Russian apartment buildings can have many other causes as well. This study produced crude estimates of average design thermal resistances for Moscow's stock of district-heated apartment buildings. The estimates suggest that R-values generally increased in all three SNiP revisions occurring after 1963, but most of the increases were relatively small. Norms for transmission R-values through opaque walls built during the past 35 years were only 35-70% of the values taken from similar US standards for new buildings in 1989, but norms for the overall air exchange rate (i.e., infiltration plus ventilation) and for transmission losses through fenestration in apartment buildings in Moscow and the US have been similar. Since most Russian apartment buildings were built during the early part of the housing drive, when thermal norms were relatively low, much of the present housing stock is energy inefficient by design. Crude estimates of the design space-heating energy consumption per unit floor area support this conclusion, as on average Moscow's district-heated apartment building stock consumes from 45-65% more space-heating energy per unit floor area than the relatively new P44 building studied in the field experiment. As mentioned previously, however, the poor quality of construction of Russian buildings, especially older ones, means that actual heat losses often far exceed design losses.

POTENTIAL IMPROVEMENTS IN BUILDING HEATING SYSTEMS

Assessment of current energy efficiency lays the foundation for the second important set of issues: the scope for potential efficiency improvements, and the difficulty of predicting and achieving energy savings from these improvements.

Potential End-Use Energy Savings

Based on an analysis of the results of the Russian field experiment discussed above, an estimated 14% of seasonal end-use space-heating energy could be saved in Moscow's stock of district-heated P44-Series apartment buildings if indoor air temperatures were perfectly controlled at 20 °C. Roughly 3-4% savings could be achieved given either a 10% increase in the thermal resistance of facade walls or windows, or a 10% decrease in the total air exchange rate. Further extrapolations to other kinds of apartment buildings are less certain because of the diversity of the housing stock. A crude analysis based on the available information suggests that 12% savings could be achieved in Moscow's entire district-heated apartment building stock by perfectly controlling indoor air temperatures at 20 °C. These energy savings estimates are presently the most technically well-founded estimates of their kind available in the West.

End-use savings are only part of the story, however. Energy efficiency improvements may not improve occupant thermal comfort, as indoor air temperatures will still vary with outdoor conditions in many systems. Further, end-use savings may not show up as primary fuel savings in central heat stations, for any of several reasons. First, in all buildings a manual readjustment of the jet pump or heat exchanger in the building's heating system is required to transmit a lower heating load to the district heating system—without the adjustment the buildings will simply be overheated. Second, building-level savings may not be transmitted to central heating plants because of barriers in the distribution network. Finally, central heating plants may be unable to provide fuel savings in response to lower heating requirements. The importance of systemic constraints in quantifying potential energy savings in Russian apartment buildings is quite surprising, and has not previously been emphasized in the West.

Diversity in District-Heated Russian Apartment Buildings

Initially the diversity in Russian apartment building heating systems was believed to be small—differences among buildings seemed insignificant, and the district heating system serving the buildings appeared to be uniform. This apparent uniformity suggested that the analysis of heating energy requirements in apartment buildings might have been relatively simple, and that centralized heating systems might have responded to lower heating requirements better than individual consumers, especially in an economy in which individuals have had no incentive for efficient energy use. This study has definitively shown that diversity in the apartment buildings and district heating systems is actually substantial, dashing all hopes of analytical simplicity. Further, as will be seen shortly, because of this diversity many heating systems will be unable to respond to lower end-use space-heating energy requirements at all. This diversity is quite surprising; its implications for achieving energy savings in Russian apartment buildings had not previously been explored in the West.

Diversity in Russian apartment buildings and district heating systems has four critical consequences in this analysis:

1) the effectiveness and energy efficiency of space-heating systems vary significantly among different buildings, complicating the prediction of energy consumption patterns
2) extrapolating potential end-use space-heating energy savings from a single building to a larger group of buildings must be done with extreme care—extrapolations should be limited to a narrow group of similar buildings in a single city in order to preserve maximum accuracy
3) extrapolating primary energy savings from a single building to other buildings is also problematic—extrapolations should be limited to buildings connected to similar kinds of district heating systems
4) analysis of the structural diversity allows a filtering process to be used, identifying major causes of energy inefficiency, as well as which buildings are most worthy of further study

The fourth item, the "buildings filter" concept, is one of the key insights of this study: it permits a ranking of buildings according to the size of potential primary energy savings they can offer, either because they offer the highest end-use energy savings, or because end-use savings in the buildings are most likely to lead to primary fuel savings.

Complications arising from building diversity can be grouped around three sets of issues: characteristics of buildings, characteristics of district-heating distribution systems, and characteristics of district-heating central heat stations. These areas also provide an effective way to divide the buildings filter.

Building Characteristics

The chief cause of energy inefficiency is likely to be poor control of indoor air temperatures. Improved building-level control is the recommended solution to this problem, through either better adjustments of building jet pumps (which may lead to building underheating during severe weather) or replacing the passive jet pumps with active controllers (either open-loop or closed-loop). In some buildings, the same effect can be achieved by adjusting equipment in the district heating system (see Filter #2 below). The impact of internal control devices (e.g., multiple jet pumps, individual radiator controls) depends on the relative size of heat flows across internal building walls, which is unknown. If internal heat flows are high, then improved internal heating controls may be useless.

Russian calculations for planned space-heating energy use in apartment buildings seem to overestimate actual energy consumption, probably because such calculations ignored internal heat gains.

The most promising areas for improvement in building envelopes are reducing infiltration rates, and reducing transmission losses through windows and facade walls. In order to obtain energy savings from these improvements the heating system must be adjusted; without any adjustments (in jet pumps or in the district heating distribution system) the amount of heat supplied by the system will remain constant, and the potential energy savings will be wasted.

The first filter highlights apartment buildings with especially poor space-heating efficiencies.

Filter #1: Building Characteristics

- The joints between wall panels in most large-panel buildings constructed before 1965 are non-monolithic (i.e., the joints lack poured concrete), and are thus very leaky.
- Buildings employing envelopes with relatively large numbers of thermal bridges (e.g., 3-layer large panels, panel framework construction) are likely to suffer from higher heat losses because of potentially inaccurate design calculations or sloppy component manufacture or assembly.
- Buildings with relatively more seams in external walls (e.g., brick/small block, 1-module large panels) probably suffer from higher heat losses because thermal norms ignored the effects of seams between construction elements.
- Buildings employing external wall-panel heating are less energy efficient than buildings using radiators or convectors.

District Heating Distribution System Characteristics

Distribution systems employing open domestic hot water systems and dependent space-heating systems are least hydraulically stable, and cause the most unpredictable fluctuations in space-heating energy delivery to buildings. Independent space-heating systems control heat delivery to buildings effectively if the control equipment in group heating substations functions properly.

Building-level heating system control in buildings connected to independent systems may be improved either by adjusting jet pumps (as discussed in Filter #1 above) or by adjusting equipment in the group heating substation; building-level control improvements in buildings connected to dependent systems may be performed only by adjusting jet pumps.

The second filter highlights buildings connected to district heating distribution systems most likely to transmit end-use energy savings (whether arising from improved heating system control or building envelope improvements) to central heating stations.

Filter #2: District Heating Distribution System Characteristics

- District heating networks employing closed, dependent systems cause the most severe overheating in Russian apartment buildings, and should be targeted for improved building-level control. Further, such systems are most responsive to end-use energy savings.
- Closed, independent systems will also transmit savings effectively if control equipment at group heating substations is working properly.
- Adjusting control equipment at group heating substations is the recommended approach for improving heating system control in buildings connected to independent systems.

District Heating Central Heat Station Characteristics

The third and final filter highlights buildings connected to central heat stations most likely to save primary fuel when faced with a lower heating load in the district heating network.

Filter #3: District Heating Central Heat Station Characteristics

- Boiler houses and controllable cogeneration stations (TETs) are most likely to respond to lower heating loads, and least likely to supply district-heating water at improper temperatures. A controllable TETs is especially effective if it is operating in a peaking mode (i.e., supplying heat directly via boilers).
- In uncontrollable TETs (or refitted condensing stations), the sensitivity to changes in heating loads is time-dependent. If the station is operating in a peaking mode, then it can easily respond to lower heating loads. If the station is providing heat through turbine steam bleeds, the question of achieving fuel savings becomes even more complex:

    a) if the TETs is inflexible, a reduced heating load will have no effect on primary fuel consumption.

    b) if the TETs is flexible, fuel savings will be realized only if output is set according to the local demand for heat. If the plant follows local power demand instead, a lower heating load will provide no fuel savings.

The Most Promising Areas for Efficiency Improvements

Applying any one of the three buildings filters increases potential primary fuel savings in response to upgraded space-heating systems or building envelopes; applying all three filters provides maximum savings. Therefore, the energy-saving retrofits most likely to provide maximum benefits in Russian apartment buildings are those that:

- improve control of space-heating equipment, reduce total infiltration losses, or reduce transmission losses through windows or facade walls

within

- older buildings with faulty joints between wall panels, or within any buildings employing either multi-layer wall panels or external wall panel heating systems

using

- closed domestic hot water systems and dependent space-heating systems, or independent space-heating systems with properly functioning control equipment,

connected to

- a boiler house or a controllable TETs

The order of applying the filters is important if complete information about a given building is unavailable. As listed—starting from buildings and working up to central heat stations—the first filter focuses attention on the least energy-efficient buildings, regardless of whether energy savings are transmitted through to central heat stations. This approach emphasizes providing better conditions for building occupants. In the reverse order—starting from central heat sources and working down to buildings—the first filter focuses attention on buildings for which achieving significant primary fuels savings is most likely. This approach emphasizes achieving real energy savings.

LAST WORD

Economic conditions, central planners' lack of priority on providing effective, efficient heating systems, and sloppy implementation in building construction and repair have led to poor space-heating system performance and high space-heating energy requirements in district-heated apartment buildings throughout Russia and the former USSR. This work has illuminated some of the causes of energy inefficiency in these buildings, provided a framework for evaluating the effectiveness and efficiency of space-heating systems in the buildings, and developed a methodology for selecting the buildings best suited for further study. The analysis has demonstrated that the systemic view—examining system characteristics from the points of energy service back to the points of primary fuel consumption—is critical in assessing potential space-heating energy efficiency improvements in the buildings. Future efforts at designing conservation programs in the Russian urban housing sector must also adopt a systemic view in order to be most effective.

Potential follow-up studies to this work can be grouped into two categories: statistical research, and field experiments. First, apartment building wall construction systems, building series designs, district heating distribution systems, and central heat stations in the CIS should be surveyed in detail in order to: 1) determine the extent of existing diversity in these systems with more precision, 2) group the systems according to the framework presented in this study, and 3) determine if any correlations exist among the different systems (i.e., to determine whether certain apartment building series were usually connected to certain kinds of district heating distribution systems, etc.). Such investigations will allow more accurate extrapolations of end-use energy savings from a single building to other buildings, as well as of end-use savings in a building to primary fuel savings at the central heat station.

Second, future experimental work (or, perhaps, the analysis of the results of Russian experiments currently unknown in the West) should focus on measuring a number of quantities within several different building series designs: thermal properties of entire building envelopes, total air infiltration rates, rates of internal heat gain, and rates of heat flow across internal walls. Such investigations will improve our understanding of space-heating energy consumption patterns in individual apartment buildings, and permit more accurate estimates of end-use energy savings in the buildings.

Fade to Purple

APPENDIX A

Climate Data for Moscow

Table A-I [Lydolph]

	Temperature, °C		Mean Wind Speed, m/s	Number of Days of:	
	Mean	Minimum		Snow Cover	Cloud Cover
October	4.1	-20	4.7		18.3
November	-2.3	-33	4.9	4	20.9
December	-8.0	-39	4.7	31	23.4
January	-10.3	-42	5.0	31	19.5
February	-9.7	-40	4.9	28	16.7
March	-5.0	-32	5.2	31	14.3
April	3.7	-19	4.7	6	11.5

APPENDIX B

Structural Analysis of Moscow, Russia, and USSR District-Heated Apartment Building Stocks

As explained in Chapter 3, the district-heated MFB stocks of Moscow, Russia, and the CIS were approximated in this study with the new MFB stocks—all MFB floor area constructed since 1956. Chapter 3 presented estimates of the structural composition of these stocks, according to the type of construction of the external walls of the buildings. This appendix will explain how those estimates were derived.

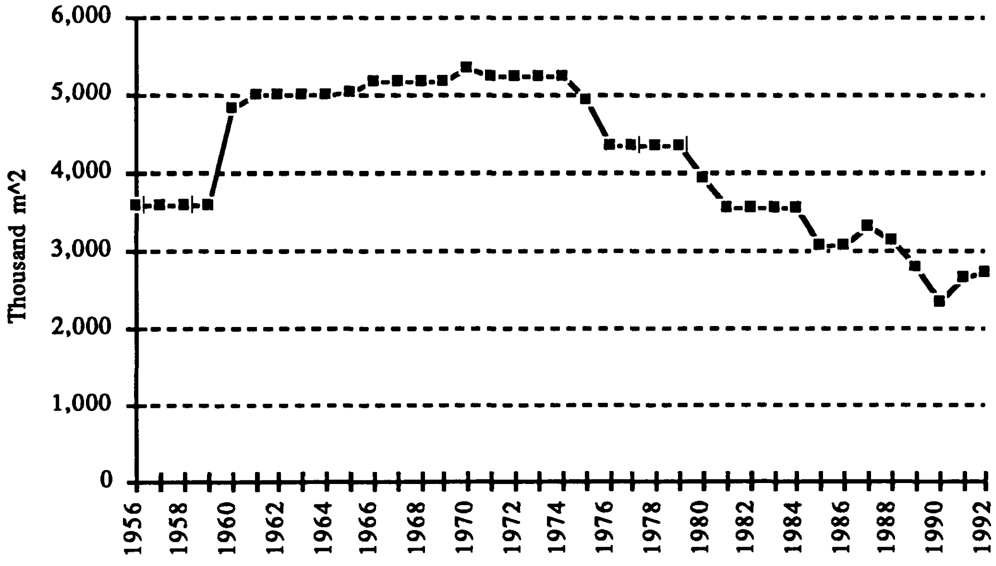
Moscow

The composition of Moscow's district-heated MFB stock in 1992 was estimated by summing the total new MFB construction within each wall category (3-layer panels, 1-layer panels, large blocks, brick, and other, with all panel-framework buildings combined with panel buildings) each year from 1956-1992. The amount of new construction within each wall category was estimated by combining total new MFB construction in Moscow each year with calculated proportions of new construction within each wall category. The analysis can thus be broken down into two components: estimating total new MFB construction, and estimating the proportions of new MFB construction in each wall category.

Total Construction

Usually data on new housing construction is listed in Russian sources as the total useful floor area commissioned during 5YP periods, with the fifth year of the plan listed separately. Useful floor area is defined as the sum of the areas of all bedrooms, living areas, kitchens, baths, interior halls (i.e., within flats), and closets. If other years are not separately listed (as is often the case), construction in the first four years of each 5YP period must be estimated based on the 5YP totals. New construction figures from 1956 to 1989 were taken from *Moskva v Tsifrakh* (Moscow in Figures); for 1990-92, Yurij Matrosov provided the totals. The data are shown in Figure B.1. This part of the analysis is straightforward; the main issue is the accuracy of the information in *Moskva v Tsifrakh.*

Figure B.1: New Housing Construction in Moscow, useful area



Structure

The structural analysis, however, suffered from less complete available information and ambiguous, conflicting definitions among different sources. Structural information was available in only some years since 1956, requiring interpolation in other years. When available, the data referred to either useful area or living area (the sum of bedroom, living room, and dining area), or failed to specify which area was being described. This problem was addressed in this analysis by forming ratios of the structural breakdown of the data (i.e., new construction in each category, divided by the total new construction provided by that source)—this procedure should increase the compatibility of the data. The data generally failed to split large-panel construction into 1-layer and 3-layer categories. Finally, some data listed actual floor space commissioned, others merely represented annual plans.

The first segment of available structural data cover the years 1956-1965 (Chapter 3, Fig. 3.11a). The data were taken from Dykhovichnyi, and represent prefabricated housing construction in Moscow, based on living area. The data from 1956-63 represent housing commissioned; those for 1964-65 are planned figures. Dykhovichnyi divided new prefabricated housing construction according to the building series numbers (discussed in Chapter 3), each defined in some detail within the text. These data were readily split into the appropriate categories; the ratios were computed based on living area. Total living area of prefabricated construction was then converted to useful area (using a conversion coefficient of 0.667, apparently the value the Russians use for urban housing), and the residual—estimated non-prefabricated construction—was all assumed to be brick.

The second segment of available structural data cover the years 1968-1977 (Chapter 3, Fig. 3.11a). These data were provided by Matrosov, and listed total new housing construction in four categories: large panel, large block, brick, and other. The area definition used in the source was unclear, and the totals differed from useful area and living area totals available in those years from other sources. Ratios of structural composition were computed here as well.

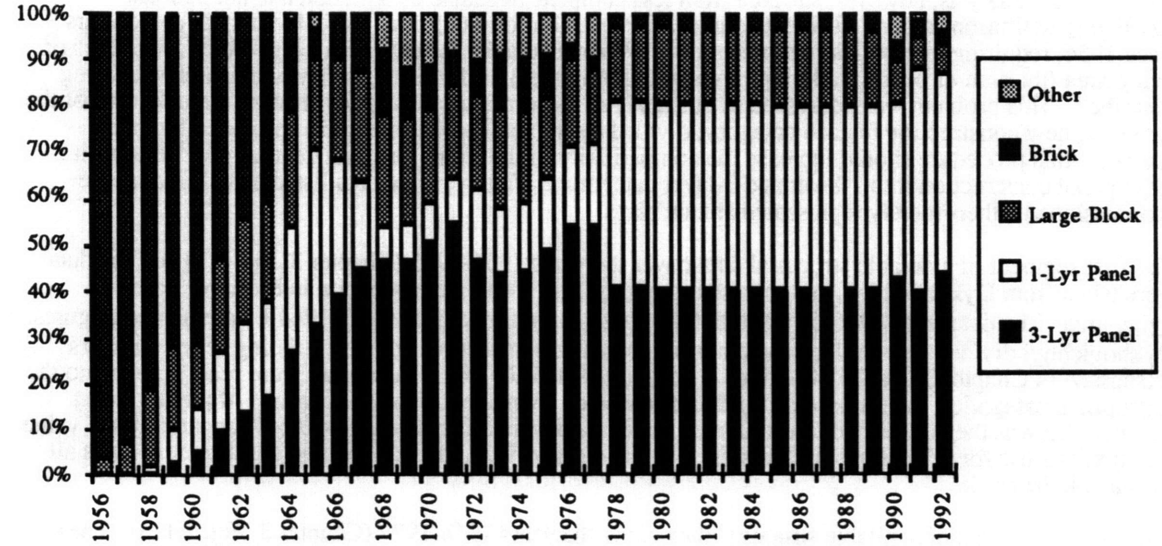
Finally, the third segment of available structural data cover the years 1990-1992 (Chapter 3, Fig. 3.11b). These data were also provided by Matrosov; they described new housing construction by building series number, similar to Dykhovichnyi, except that in this case all new housing was included (not only prefabricated housing). These data were based on useful area. Matrosov described which building series used 1-layer panels, and which used 3-layer panels.

Approximations

All missing information was approximated, based mainly on trends from available data in other years. For the years 1966-67 and 1978-89, in which no structural information at all were available, all categories were interpolated between years for which estimates were available. Between 1968 and 1977, the composition of the large-panel category was split into 1-layer and 3-layer categories based on trends in the heights of new buildings constructed in that period (and on rough correlations between the type of external walls and building height provided by Matrosov), and based on scattered references to the composition of new housing construction from various other sources. From 1968-71, the assumed split was 85% 3-layer, 15% 1-layer; from 1972-77, 75% 3-layer, 25% 1-layer.

The results of the structural analysis—estimates of the fraction of new housing construction in Moscow within each external wall construction category—are displayed in Figure B.2.

Figure B.2: Estimated Structure of New Housing Construction in Moscow



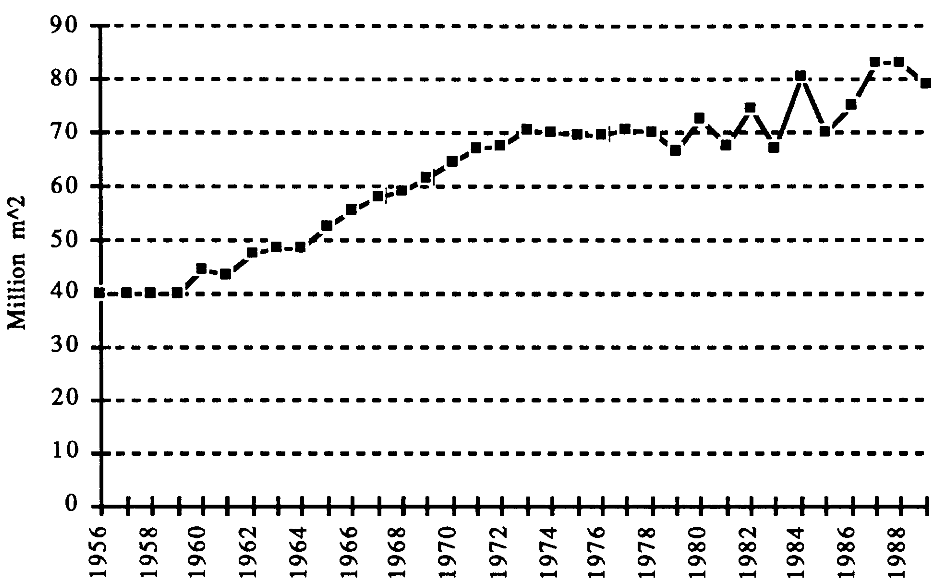
USSR & Russia

The structures of the district-heated MFB stocks of Russia and the USSR were estimated using the same general methodology described above. Unfortunately, far fewer data were available on both total MFB construction and the structure of new construction. Total construction was only available up to 1989. Reliable structural data for the USSR were only available for 1959-1965; no structural data at all were available for Russia. As a result, total construction was estimated separately for Russia and the USSR, but the structural composition of the Russian MFB stock was assumed to match that of the USSR's stock.

Total Construction

The MFB stocks of the USSR and Russia were approximated by the public urban housing stock, as defined in Chapter 2. Again, available data represented a mixture of living area and useful area, and of commissioned housing and planned housing construction. For some years public urban construction was known explicitly; in other years it was computed as a residual from data describing the total urban stock and the private urban stock. Even these data were missing explicitly in some years: the urban stock was sometimes computed as a residual from the total stock and the rural stock, and the private urban stock from other breakdowns of the total stock. Despite these difficulties, the data seemed to form a fairly consistent representation of the public urban housing stock. The results of this analysis are shown in Figure B.3. Data were taken from UFFA and Clarke, who cite the Russian sources *Narodnoe Khoziaistvo* and *SSSR v Tsifrakh* (various years).

Figure B.3: New Public Urban Housing Construction in the USSR, useful area



Structure

The problems cited above in the analysis for Moscow also apply to this analysis, but to an even greater degree: the analysis for the USSR includes many more guesses and much more interpolation than the analysis for Moscow. A consistent structural breakdown was only available for the years 1959-1965 (Chapter 3, Fig. 3.13), and these data failed to subdivide the large-panel category.

For the years 1959-65, Broner lists the structure of all (i.e., urban plus rural) new public housing constructed nationwide. Broner used five categories: large panel, large block, brick, small block, and other (stone, wood). Two categories, small block and other, were excluded in an attempt to approximate the urban portion of Broner's data. Some brick construction was likely rural, but since there is no way of knowing exactly how much, it was all assumed to be urban for simplicity. This error is partially compensated by completely omitting small block construction, some of which was urban. Broner does not clearly define the area basis of his data; structural ratios were thus computed as in the analysis for Moscow. Finally, the breakdown of the large-panel category was set at 25% 3-layer panels, 75% 1-layer panels, again based on scattered hints of the structure of new apartment buildings in various periods.

Approximations

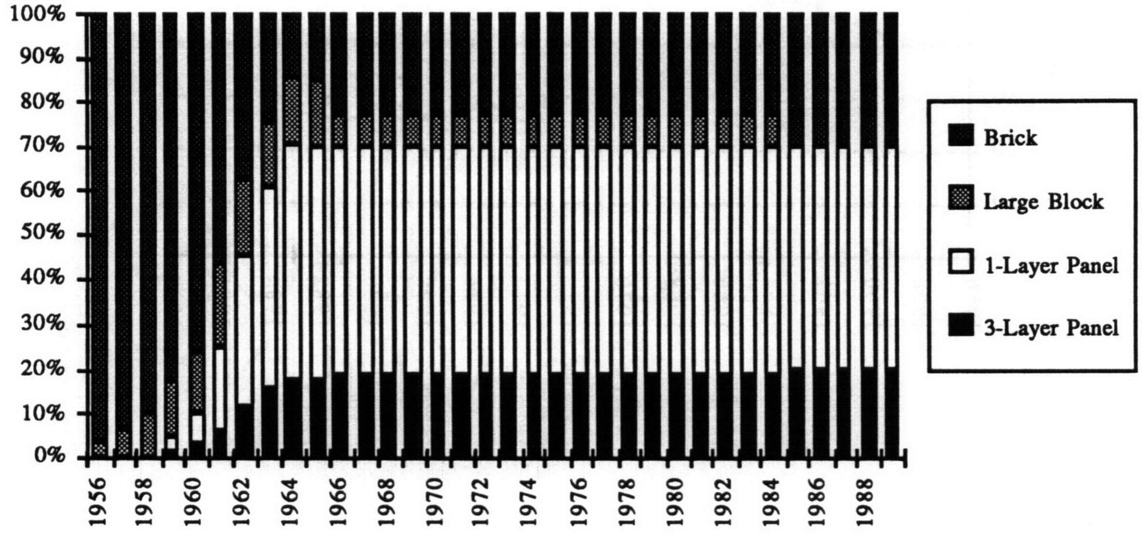
From 1956-58, all large-panel construction was assumed to be zero. This is consistent with data from Broner and from the Moscow analysis. Large-block construction was interpolated between a value of zero in 1955 and the value provided by Broner in 1959. All remaining construction was assumed to be brick.

Data on the stock's structure from 1966-1984 were unavailable; these values were interpolated between the values in 1965 and 1985.

From 1985 to 1989, large-block construction was set at zero, brick construction at 30%, and large-panel construction at 70% of the total. Of the large panels, 30% were assumed to be 3-layer, 70% 1-layer. Again, these estimates are based on collected pieces of the structural puzzle provided by various authors: Drozdov suggests that as of the mid-1980s 70% of the walls of new MFBs were built of large panels, with 30% of brick, and that about 70% of large-panel walls were 1-layer panels. Meanwhile, Yudzon suggests that at the same time 80% of all MFB walls were 1-layer, but unfortunately fails to specify whether he refers only to large panels or to all forms of wall construction, or whether he refers to new MFBs or existing MFBs.

Figure B.4 displays the results of the structural analysis for the USSR. The results shown in the figure were also applied to Russia.

Figure B.4: Estimated Structure of New MFB Construction in the USSR



APPENDIX C

Spreadsheet Model Used in the End-Use Energy Analysis

Russian P44 Apartment Building Energy Calculations										
		(baseline case)					**UA-VALUES:**			
AREAS:			**R-VALUES:**				Infiltration	6,946	*W/°C*	
Bsmt	1,067	*m^2*	Bsmt	3.00	*m^2-°C/W*		Bsmt	356	*W/°C*	
Roof	1,067	*m^2*	Roof	5.00	*m^2-°C/W*		Roof	213	*W/°C*	
Gable Wall	2,324	*m^2*	Gable Wall	1.65	*m^2-°C/W*		Gable Wall	1,408	*W/°C*	
Facade Wall	7,821	*m^2*	Facade Wall	1.25	*m^2-°C/W*		Facade Wall	6,257	*W/°C*	
Window	2,360	*m^2*	Window	0.39	*m^2-°C/W*		Window	6,051	*W/°C*	
							UA equiv.	21,231	*W/°C*	
OTHER BUILDING PARAMETERS:										
Int. Gain	8.00	*W/m^2*	Floor Area	17,072	*m^2*		I.G. Gain	136,576	*W*	
Avg. I.G.	3,278	*kWh/day*	Volume	50,619	*m^3*		Tin - Tbal	6.43	℃	
			Infiltration	0.41	*ACH*					
			(minimum value)							
Tin, °C	Tout, °C	Tout, °F	Tin - Tout	**HEAT LOSSES THROUGH:**						
	(bin)	(for solar)	℃	'------------------- *Transmission* -------------------'					**Total**	**Infil-**
				Facade	**Gable**	**Bsmt**	**Roof**	**Windows**	**Transm.**	**tration**
22.71	8.75	47.75	13.96	2,096	472	119	71	2,027	4,786	2,327
22.36	6.25	43.25	16.11	2,419	545	138	83	2,340	5,523	2,685
22.36	3.75	38.75	18.61	2,794	629	159	95	2,702	6,379	3,101
22.97	1.25	34.25	21.72	3,262	734	185	111	3,154	7,447	3,621
23.73	-1.25	29.75	24.98	3,751	844	213	128	3,628	8,564	4,164
21.54	-3.75	25.25	25.29	3,798	855	216	130	3,673	8,671	4,216
21.47	-6.25	20.75	27.72	4,163	937	237	142	4,026	9,504	4,621
21.66	-8.75	16.25	30.41	4,566	1,028	260	156	4,416	10,426	5,069
21.47	-11.25	11.75	32.72	4,914	1,106	279	168	4,752	11,219	5,455
20.68	-13.75	7.25	34.43	5,170	1,164	294	176	5,000	11,804	5,739
20.30	-16.25	2.75	36.55	5,489	1,236	312	187	5,309	12,533	6,093
19.92	-18.75	-1.75	38.67	5,807	1,307	330	198	5,617	13,259	6,447

SOLAR CALCULATIONS:				Sqrt. SD	3.11	℉			
North Windows:		A	7.42		East Windows:		A	6.46	
787	m^2	B	-1.25		393	m^2	B	-1.21	
Alpha	1.14	C	-580.20		Alpha	0.87	C	-528.30	
Beta	-45.46	D	141.10		Beta	0.53	D	170.40	
South Windows:		A	12.91		West Windows:		A	14.76	
787	m^2	B	-2.95		393	m^2	B	-2.16	
Alpha	1.20	C	-1024.50		Alpha	2.59	C	-1192.90	
Beta	-10.52	D	318.90		Beta	-119.27	D	264.30	
					SC n	0.26			
Average Daylight Fraction (SS):			0.4		SC e,w	0.51			
Solar Heat Gain Factor (F):			0.87		SC s	0.56			
Solar Insolation (through windows)				Solar Heat Gains				**HEAT GAINS:**	
									Total
Solar (N)	*Solar (S)*	*Solar (E)*	*Solar (W)*	North	South	East	West	**Internal**	**Solar**
211	1,114	499	53	48	543	221	23	3,278	835
89	986	452	0	20	480	201	0	3,278	701
0	857	406	0	0	417	180	0	3,278	598
0	728	359	0	0	355	159	0	3,278	514
0	600	313	0	0	292	139	0	3,278	431
0	471	267	0	0	229	118	0	3,278	348
0	342	220	0	0	167	98	0	3,278	265
0	214	174	0	0	104	77	0	3,278	181
0	85	127	0	0	42	57	0	3,278	98
0	0	81	0	0	0	36	0	3,278	36
0	0	35	0	0	0	15	0	3,278	15
0	0	0	0	0	0	0	0	3,278	0

Tout, °C	Bin	Calc.	Meas.		Calculated Seasonal		Measured Seasonal
(bin)	Freq.	Heat Use	Heat Use		Heat Use		Heat Use
		kWh/day	*kWh/day*				
8.75	2.99%	3,000	7,281		1436 MWh		1743 MWh
6.25	3.59%	4,230	8,013		5170 GJ		6275 GJ
3.75	13.17%	5,605	8,503				
1.25	24.55%	7,275	9,660				
-1.25	13.77%	9,019	11,095				
-3.75	16.17%	9,262	10,739				
-6.25	13.77%	10,583	11,638				
-8.75	4.19%	12,035	12,397				
-11.25	2.40%	13,298	12,887				
-13.75	2.40%	14,230	12,984				
-16.25	1.80%	15,333	14,138				
-18.75	1.20%	16,428	14,817				

APPENDIX D

Photographs of Russian Apartment Buildings and Heating Equipment

Figure D.1: Apartment Buildings in Moscow

Figure D.2: A 5-story Standard House

Figure D.3: A Jet Pump in the P44 Experimental Building

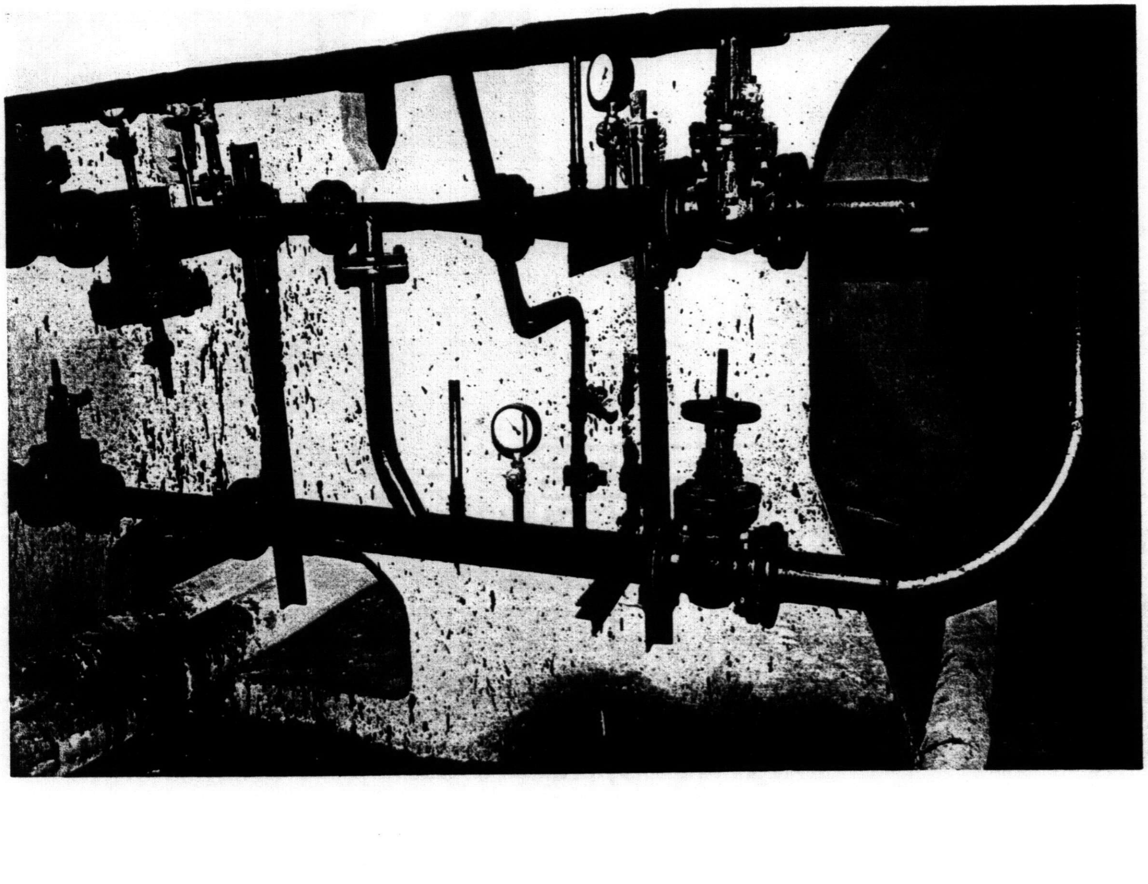


Figure D.4: A Radiator in a Russian Apartment Building

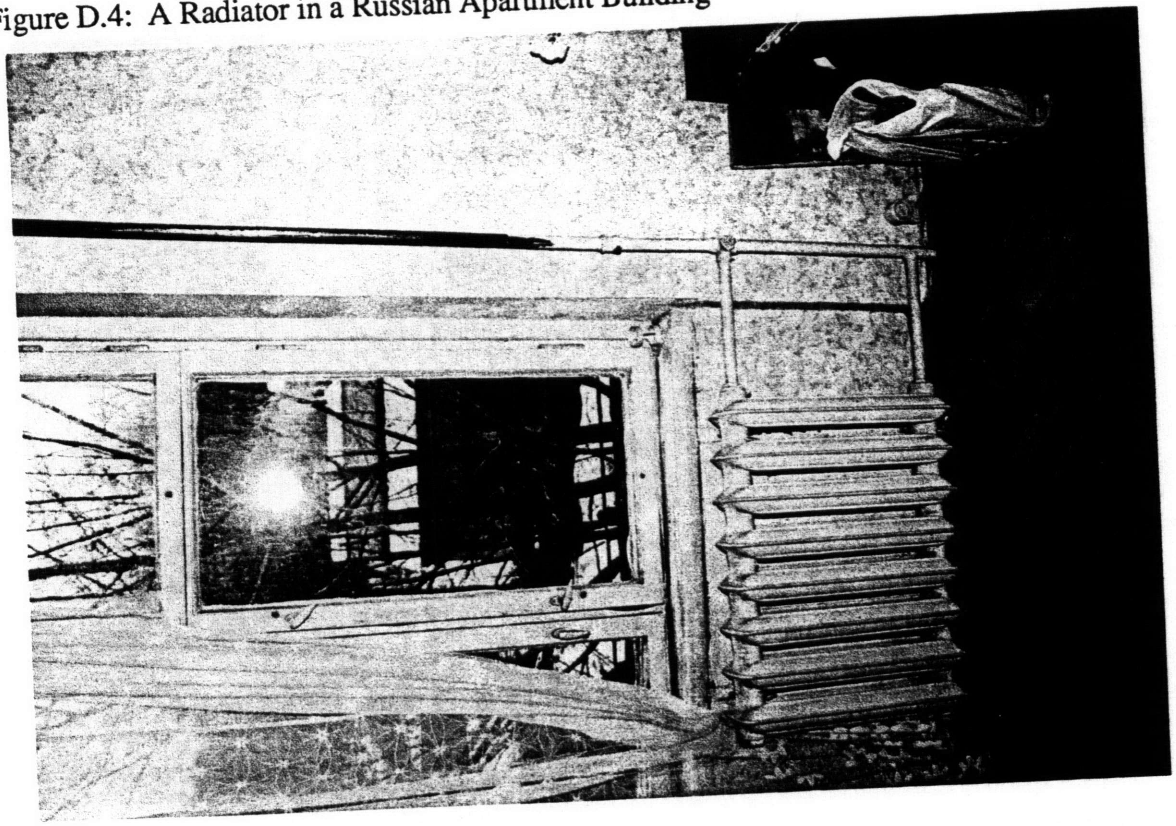


Figure D.5: A Convector in the P44 Experimental Building

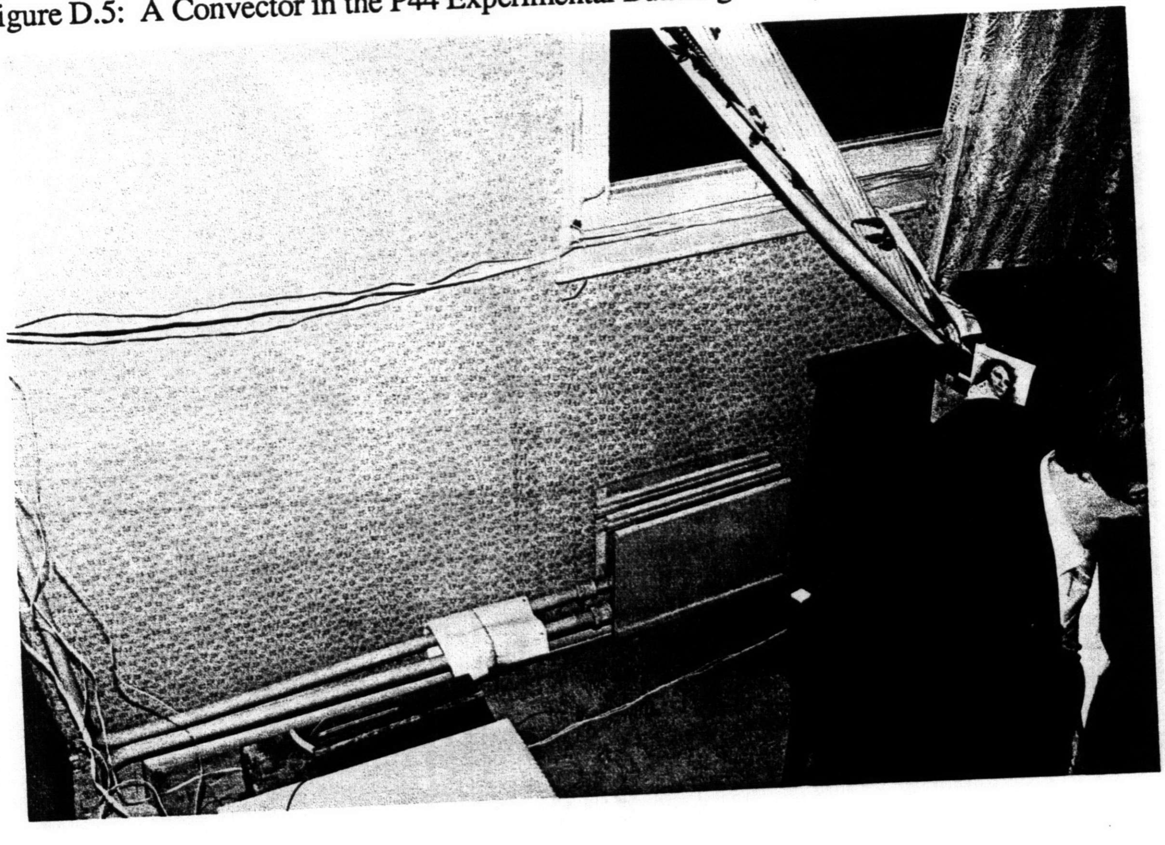


Figure D.6: A Balcony Door in a Russian Apartment Building

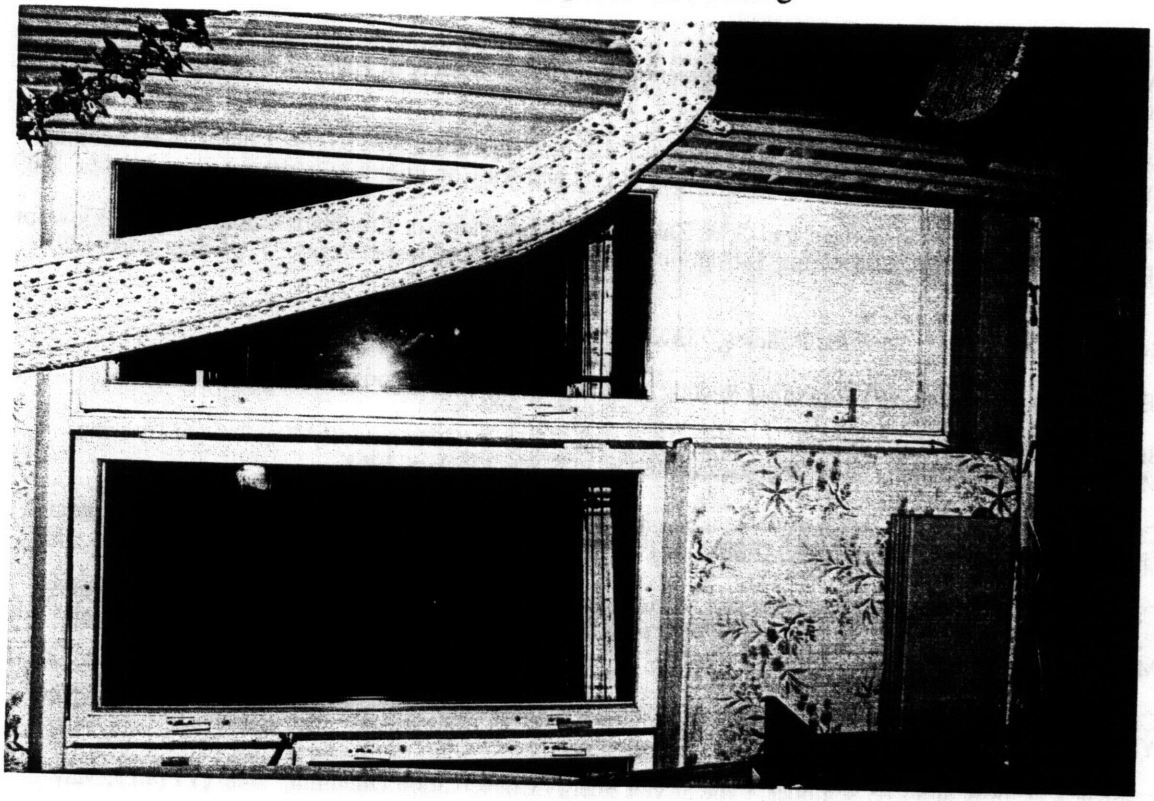


Figure D.7: The Exterior of the P44 Experimental Building

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