UDC 613; 614
DOI: 10.21668/health.risk/2023.2.04.eng

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Research article

EFFECTIVENESS OF COMPLEX PLANS FOR AIR PROTECTION ACTIVITIES AT HEAT AND POWER ENTERPRISES AS PER RISK MITIGATION AND HEALTH HARM INDICATORS

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The whole complex of air protection activities has been planned in the RF with its aim to reduce levels of ambient air pollution. It is being implemented actively now and as a result the quality of the environment should improve for more than 7 million people.

In this study, an algorithm has been suggested for assessing effectiveness of air protection activities. It includes six subsequent stages. The algorithm was tested at heat and power enterprises located in a region participating in the Clean Air Federal project. As a result, it was established that these enterprises were sources of potential public health risks; 70 % of them belonged to high risk categories. Until air protection activities are implemented, heat and power enterprises pollute ambient air in some areas in the city (up to 29.9 single maximum MPC; up to 6.9 average daily MPC; up to 19.0 average annual MPC), create unacceptable health risks (up to 25.8 HI for acute exposure, 22.7 HI for chronic exposure, CR_T is up to $3.28 \cdot 10^{-4}$), and cause more than 87 thousand additional disease cases. Implementation of air protection activities at heat and power enterprises will reduce local levels of ambient air pollution but we still expect hygienic standards to be violated for 10 chemicals up to 3–22 MPC and high health risks are likely to persist (up to 6.5–25.5 HI for acute exposure, 11.9–22.4 HI for chronic exposure, CR_T will be up to $3.28 \cdot 10^{-4}$). Effectiveness of the air protection activities planned at heat and power enterprises corresponds to the target levels of the gross pollutant emissions (reduction by 20.56 % by 2024) set within the Clean Air Federal project but it is estimated as 'unacceptable' as per the health harm indicator, which is additional disease cases associated with activities of these enterprises (< 20 %). It is necessary to implement additional air protection activities with respect to 12 pollutants (nitrogen dioxide, particulate matter, carbon (soot), carbon oxide, sulfur dioxide, dihydrosulfide, inorganic dust containing silicon dioxide in %: 70–20, dimethyl benzene, ethyl benzene, benzene, formaldehyde, and kerosene); to use the best available technologies with respect to the most hazardous chemicals; to monitor public health in areas with elevated health risks; to implement complex medical and preventive activities.

Keywords: *heat and power enterprises, emissions, ambient air quality, public health risk, fine-dispersed particles, non-carcinogenic hazard, health disorders.*

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At present, thermal power generation is a leading branch of the world power engineering. Thermal power generation accounts for 90 % of all the produced electricity worldwide. In Russia, a substantial share of electric energy (almost 40 %) is also produced by thermal power stations, which not only generate power but also participate in centralized heat supply[1] [1]. Thermal power stations are often located in close proximity to residential areas and this may have negative influence on ambient air quality and consequently on health of exposed population[2] [2].

In the Russian Federation, thermal power stations basically use coal, heavy oil or natural gas; oil, benzine, diesel oil, peat, shale or firewood is used rarer.

According to the State reports issued by the RF Ministry of Natural Resources and the Environment, fuel and energy enterprises emit approximately 3 million tons of pollutants every year. More than 50 % of these emissions are concentrated in the eastern part of the country (the Siberian and Far East Federal Districts)[3].

Apart from thermal power stations, a lot of private coal-fueled boiler houses and autonomous heat sources (AHS) function in Russia; in 2018 more than 74.8 thousand such objects were registered in the country. Private boiler houses tend to have rather low chimneys (6–8 meters high) and consequently they pollute the bottom layers of the atmosphere, that is, the layers from which people breathe air[4].

The greatest number of autonomous heat sources that use solid fuels is also located in the Siberian and Far East Federal Districts (the Krasnoyarsk region, Transbaikalia, Kemerovo region, Irkutsk region, Novosibirsk region, etc.). The basic advantage of boiler houses that use solid fuel is their high autonomy, which is a significant component in the technological process able to ensure uninterrupted heat and hot water supply to private houses and industrial facilities in harsh winter typical for Siberia and the Far East.

Combustion of solid fuel (coal) has substantial influence on ambient air quality due to high levels (about 90 %) of mineral noncombustible substances in coal. Thus, some studies have established that heat and power objects with predominant use of solid fuels emit both solid noncombustible particles (ash, soot, dust, particulate matter $PM_{2.5}$ and PM_{10} that contain various metal compounds) and various gases (carbon dioxide and monoxide, hydrocarbons, sulfur compounds, nitrogen oxides etc.) into ambient air [3–5]. When compounds of such metals as lead, mercury, chromium, zinc, copper, manganese, and some others penetrate the bottom layers of the atmosphere, they are able to have significant adverse influence on human health affecting the respiratory organs, central nervous system, liver, and kidneys; they can also produce mutagenic and carcinogenic effects. In addition, fine-dispersed particulate matter sized 2.5 μm or smaller is hazardous for human health [6].

According to the data provided by the World Health Organization (WHO), each eighth death in the world is caused by ambient air pollution. Fine-dispersed solid particles ($PM_{2.5}$) pose the greatest threat since they are able to penetrate deep into the human airways, enter the blood flow and affect the heart, cerebral vessels and the respiratory system. Black carbon (soot) is the most hazardous type of fine-dispersed particulate matter as per its chemical compositions. The international team of experts has established that if the level of such particles in ambient air grows by 0.1 $\mu m/m^3$, this leads to a 12 % growth in incidence of lung diseases. In 2013, the Inter-

[1] Bystritskii G.F., Gasangadzhiev G.G., Kozhichenkov V.S. Obshchaya energetika (Proizvodstvo teplovoi i elektricheskoi energii) [Total energy production (thermal and electric energy generation)]: manual, 2nd ed. Moscow, KNORUS, 2014, 408 p. (in Russian); Rynok elektroenergetiki Rossii i osnovnye igroki otrasli [The market for electric power engineering in Russia and the branch leaders]: Analytical report. *Analytic Research Group (ARG)*, 2018, 487 p. (in Russian).

[2] O sostoyanii i ob okhrane okruzhayushchei sredy Rossiiskoi Federatsii v 2021 godu [On the ecological situation and environmental protection in the Russian Federation in 2021]: the State Report. Moscow, The RF Ministry of Natural Resources and Environment, M.V. Lomonosov Moscow State University, 2022. Available at: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/ (April 13, 2023) (in Russian).

[3] O sostoyanii sanitarno-epidemiologicheskogo blagopoluchiya naseleniya v Rossiiskoi Federatsii v 2022 godu [On sanitary-epidemiological wellbeing of the population in the Russian Federation in 2022]: the State Report. Moscow, the Federal Service for Surveillance over Consumer Rights Protection and Human Wellbeing, 2023, 368 p. (in Russian).

[4] Teploenergetika i tsentralizovannoe teplosnabzhenie Rossii v 2014–2018 godakh [Thermal power generation and centralized heat supply in Russia in 2014–2018]: Informational-analytical report. Moscow, 2020, pp. 110 (in Russian).

national Agency for Research on Cancer (IARC) classified solid particles sized less than 10 and 2.5 μm as carcinogens able to cause lung cancer. Their levels in ambient air are also one of the most important indicators applied for assessing exposure to ambient air pollution and its influence on human health. Poor ambient air quality can have negative effects on the brain and central nervous system and double a risk of anxiety and depression. In addition, the smallest toxicant particles penetrate the airways, injure artery walls and induce chronic inflammation [7–10].

Since 2018, the experiment on setting quotas for emissions has been conducted in Russia; its main aim is to reduce levels of ambient air pollution all over the country and it is planned to be completed by 2030. The procedure for setting emission quotas involves introducing certain quotas of emissions for enterprises participating in the experiment. These quotas are introduced for priority ambient air pollutants on the basis of aggregated calculations[5] and this will make it possible to improve ambient air quality in cities with high pollution levels.

In addition, the Clean Air Federal project has been implemented in the Russian Federation since 2018 in accordance with the RF President Order 'On State Tasks and Strategic Goals of the Russian Federation Development for the Period up to 2026'. Twelve cities participate in this project and half of them are located in Siberia. In 2023, 29 cities and urban districts with high and extremely high levels of ambient air pollution are going to be included into the experiment on setting quotas for pollutant emissions[6]. Eighty percent of these cities are located in the Siberian and Far East Federal Districts where heat and power objects are mostly fueled by coal.

The aforementioned state project, in particular the experiment on setting quotas for emission of harmful pollutants into ambient air, have one basic aim, which is to reduce the total pollutant emissions by 20 % by the end of 2024 against the levels identified in 2017; another aim is to reduce emissions of harmful pollutants from industrial facilities, including thermal power stations and AHS as well as communal and transport infrastructure, by two times by 2030 against the levels identified in 2020. Implementation of these projects is expected to improve quality of the environment for more than seven million people. According to the Complex plans of air protection activities aimed at reducing pollutant emissions into ambient air (approved within the Clean Air Federal project), a whole set of activities is to be implemented at heat and power objects that involves installing new technical and technological equipment at large thermal power stations, relocating people from dilapidated housing with stove heating, replacing ineffective coal-fueled boiler houses with heat and power provided by large thermal power stations.

All the aforementioned highlights the relevance of assessing influence exerted by heat and power objects on ambient air quality and public health.

The aim of this study was to assess sufficiency and effectiveness of air protection activities aimed at reducing emissions into ambient air by heat and power objects as per conformity with the existing hygienic standards, mitigation of health risks and health harm.

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[5] Ob utverzhdenii pravil kvotirovaniya vybrosov zagryaznyayushchikh veshchestv (za isklyucheniem radioaktivnykh veshchestv) v atmosfernyi vozdukh: Prikaz Minprirody Rossii ot 29.11.2019 № 814 [On Approval of the procedure for setting quotas of pollutant emissions (excluding radioactive substances) into ambient air: the Order by the RF Ministry of Natural Resources and Environment issued on November 29, 2019 No. 814]. *Ofitsial'nyi internet-portal pravovoi informatsii [The Official Internet-portal for legal information]*. Available at: http://publication.pravo.gov.ru/Document/View/0001201912260045 (January 15, 2023) (in Russian).

[6] Ob utverzhdenii perechnya gorodskikh poselenii i gorodskikh okrugov s vysokim i ochen' vysokim zagryazneniem atmosfernogo vozdukha, dopolnitel'no otnosyashchikhsya k territoriyam eksperimenta po kvotirovaniyu vybrosov zagryaznyayushchikh veshchestv (za isklyucheniem radioaktivnykh veshchestv) v atmosfernyi vozdukh na osnove svodnykh raschetov zagryazneniya atmosfernogo vozdukha: Rasporyazhenie Pravitel'stva RF ot 7 iyulya 2022 g. № 1852-r [On Approval of the list of urban settlements and urban districts with high and extremely high ambient air pollution that are to be added to the list of territories participating in the experiment of setting quotas for pollutant emissions (excluding radioactive substances) into ambient air on the bases of aggregated calculation of ambient air pollution: the RF Government Order issued on July 7, 2022 No. 1852-r] (the document has not come into force yet). *GARANT: information and legal portal*. Available at: https://www.garant.ru/products/ipo/prime/doc/404867269/ (April 10, 2023) (in Russian).

Materials and methods. We used exposure levels, inhalation risks and incidence associated with ambient air quality influenced by operations of heat and power objects and AHS as our initial data for assessing sufficiency and effectiveness of investment programs and the Complex plans of air protection activities.

Effectiveness of activities included into the Complex plan was estimated considering a necessary decrease in effects produced on ambient air by operating heat and power objects and AHS by 2024 against 2018; conformity with the existing hygienic standards; declining inhalation risks together with calculation of residual risks and a decrease in additional incidence associated with ambient air quality.

We have developed a methodical algorithm for assessing how effective the Complex plans of air protection activities were with respect to mitigation of health risks and health harm caused by operating heat and power objects against the background influence exerted by other sources of ambient air pollution. The algorithm consists of six sequential stages:

– analysis of a potential health risk caused by heat and power objects and analysis of complex air protection plans at these objects;

– creation of aggregated databases on all the stationary and mobile sources of ambient air pollution, identification of their parameters with spotting out fuel and energy complex (FEC) objects and AHS prior to implementation of air protection activities and after it;

– identification of spatially differentiated levels of ambient air pollution in residential areas considering contributions made to them by FEC objects and AHS prior to implementation of air protection activities and after it; assessment of conformity to the existing hygienic standards and identification of priority pollutants;

– health risk assessment, identification of risk rates prior to implementation of air protection activities at FEC objects and AHS and after it;

– calculation of associated disease cases caused by exposure to pollution created by FEC objects and AHS prior to implementation of air protection activities and after it;

– assessment of effectiveness of implemented / planned activities at FEC objects and AHS as per conformity to the existing hygienic standards, health risk and health harm indicators represented by additional incidence associated with ambient air pollution.

Residual pollutant levels, health risks (carcinogenic, acute and chronic) and associated incidence were calculated considering implementation of air protection activities. Effectiveness of these activities was identified as per the formula (23) in the Methodical Guidelines MUK 2.1.10.3675-20[7].

Approaches to assessing effectiveness of air protection activities at heat and power objects were tested on the example of the Complex plan designed for Krasnoyarsk (approved by the Deputy Head of the RF Government on December 28, 2018 (No. 11024p-P6)), a city participating in the Clean Air Federal project, and with specific focus on heat and power objects, AHS included.

Potential health risks were assessed based on data taken from the Federal Register foe Juridical Persons and Private Entrepreneurs subject to sanitary-epidemiological surveillance as of January 2021.

The current and expected exposure in the analyzed residential areas was assessed using the 2020 database covering 6411 sources of pollutant emissions into ambient air from 807 industrial enterprises and organizations (5977 sources), 263 traffic network sections, and 171 sources that could be considered AHS (residential areas with private houses). Ground concentrations of 251 pollutants, including 55 chemicals emitted by FEC objects, were calculated at 13,889 points in the analyzed residential areas (the geometric centers of residential buildings) using the Ekolog-Gorod Unified Software for

[7] MU 2.1.10.3675-20. Otsenka dostatochnosti i effektivnosti planiruemykh meropriyatii po snizheniyu vybrosov zagryaznyayushchikh veshchestv v atmosfernyi vozdukh dlya mitigatsii riskov i vreda zdorov'yu naseleniya: metodicheskie ukazaniya; utv. Glavnym gosudarstvennym sanitarnym vrachom RF 18.12.2020 [MU 2.1.10.3675-20. Assessment of sufficiency and effectiveness of planned activities aimed at reducing pollutant emissions in ambient air to mitigate health risks and health harm: methodical guidelines; approved by the RF Chief Sanitary Inspector on December 18, 2020], item 3.10.7. *KonsultantPlus*. Available at: http://www.consultant.ru/law/hotdocs/68710.html (May 12, 2023) (in Russian).

Calculating Ambient Air Pollution, version 4.60.1. The software relies on the module MR-2017 Methods for Calculating Dispersion of Emissions of Harmful (Polluting) Substances in Ambient Air (approved by the Order of the RF Ministry of Natural Resources and Environment issued on June 06, 2017 No. 273). Based on these calculations, single maximum and average annual levels of pollutants were identified for each calculation point prior to the implementation of planned air protection activities at heat and power objects and after it. Calculated data were verified with instrumental data collected for 34 substances (including 23 chemicals typically emitted by FEC objects) at posts for monitoring of ambient air quality belonging to Rosgidromet, the territorial monitoring network, and the Center for Hygiene and Epidemiology in the Krasnoyarsk region. The instrumental data were collected within social and hygienic monitoring in 2018–2020 in accordance with methodical approaches stipulated in the Methodical guidelines MR 2.1.6.0157-19[8]. We calculated exposure levels created by all sources of ambient air pollution in the city and specifically by FEC objects and AHS and specified contributions made by the latter to the total ambient air pollution.

Public health risks caused by exposure to chemical pollution in ambient air occurring solely due to FEC objects and AHS (55 chemicals) were assessed in accordance with the Guide R 2.1.10.1920-04[9] by sequential completion of all the necessary stages. Ten carcinogenic chemicals were identified in emissions from FEC objects and AHS; in addition, 22 chemicals identified in these emissions were able to produce acute effects and 46 were able to produce chronic non-carcinogenic effects on health.

The next task was to create models of cause-effects relations within the ‘ambient air quality – incidence (as per the data provided by the Fund for Mandatory Medical Insurance)” system with the following calculation of additional associated diseases as an indicator of exposure to airborne chemicals. To do that, we took verified average annual levels of chemicals under chronic exposure established for each calculation point in residential areas on the analyzed territory. Additional diseases associated with ambient air quality were calculated according to the methodical approaches stipulated in the MR 5.1.0095-14[10].

Cause-effect relations within the ‘ambient air quality – incidence’ were established and parameterized using the following multiple regression model:

$$y_j = b_0 + \sum_i b_{1ij} \left\langle x_i - qkp_i \right\rangle ,$$

where

y_j is incidence of the j-th disease category among exposed population, cases/1000 people;

x_i is the level of the i-th pollutant, mg/m^3;

qkp_i is the derived no-effect level of the i-th indicator describing ambient air pollution, mg/m^3;

$\langle x \rangle$ are the Macaulay brackets: $\langle x \rangle = 0$ at $x < 0$ and $\langle x \rangle = x$ at $x \geq 0$;

b_0, b_{1ij} are the model parameters.

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[8] MR 2.1.6.0157-19. Formirovanie programm nablyudeniya za kachestvom atmosfernogo vozdukha i kolichestvennaya otsenka ekspozitsii naseleniya dlya zadach sotsial'no-gigienicheskogo monitoringa: Metodicheskie rekomendatsii; utv. Glavnym gosudarstvennym sanitarnym vrachom RF 02.12.2019 [MR 2.1.6.0157-19. Creation of programs for monitoring of ambient air quality and quantification of population exposure for solving tasks within social-hygienic monitoring: Methodical guidelines; approved by the RF Chief Sanitary Inspector on December 02, 2019]. *KODEKS: electronic fund for legal and reference documentation*. Available at: https://docs.cntd.ru/document/565246542 (April 03, 2023) (in Russian).

[9] Guide R 2.1.10.1920-04. Human Health Risk Assessment from Environmental Chemicals; approved and enacted by G.G. Onishchenko, the First Deputy to the RF Minister of Health and the RF Chief Sanitary Inspector on March 5, 2004. *KODEKS: electronic fund for legal and reference documentation*. Available at: https://docs.cntd.ru/document/1200037399 (April 06, 2023) (in Russian).

[10] MR 5.1.0095-14. Raschet fakticheskikh i predotvrashchennykh v rezul'tate kontrol'no-nadzornoi deyatel'nosti ekonomicheskikh poter' ot smertnosti, zabolevaemosti i invalidizatsii naseleniya, assotsiirovannykh s negativnym vozdeistviem faktorov sredy obitaniya: metodicheskie rekomendatsii; utv. rukovoditelem Federal'noi sluzhby po nadzoru v sfere zashchity prav potrebitelei i blagopoluchiya cheloveka, Glavnym gosudarstvennym sanitarnym vrachom RF A.Yu. Popovoi 23 oktyabrya 2014 goda [MR 5.1.0095-14. Calculation of actual economic losses and those prevented due to control and surveillance activities in case such losses are caused by mortality, incidence and disability among population associated with exposure to harmful environmental factors: methodical guidelines; approved by A.Yu. Popova, the Head of the Federal Service for Surveillance over Consumer Rights Protection and Human Wellbeing and the RF Chief Sanitary Inspector on October 23, 2014]. *KODEKS: electronic fund for legal and reference documentation*. Available at: https://docs.cntd.ru/document/1200129398 (April 06, 2023) (in Russian).

The derived no-effect level qkp_i was taken as equal to reference concentrations; in case such concentrations were not defined for a certain pollutant, we took average annual maximum permissible levels.

To define the list of chemicals emitted by heat and power objects more precisely, we compared ash created by operations of thermal power stations and ambient air in an area under the strongest influence of a heat and power object. The granulometric structure of ash particles and solid particles in ambient air collected on a filter was established with scanning electron microscopy (the JSM-63090LV scanning electron microscope). The chemical structure of the analyzed particles was investigated by micro-sound x-ray spectral analysis with a SEM analyzer. Image analysis involved quantitative assessment of particle size and shapes using the sphericity coefficient; it was performed with the ImageJ-Fiji software (Analyze Particles Module).

Results and discussion. The fuel and energy complex that operates on the analyzed territory consists of basic heat sources (three thermal power stations) and industrial enterprises with objects being supplied with heat. In addition, a lot of private houses using autonomous heat sources (AHS) are located in the city. According to the updated aggregated database on sources of ambient air pollution (2020), 302 enterprises out of total 807 located in the city belong to the fuel and energy complex or have some heat supply sources on their territory. The total number of emission sources that belong to heat and power objects on the analyzed territory equals 1.2 thousand; in addition, 171 emission sources are classified as AHS.

The overall town planning created a situation when heat and power objects (thermal power stations, boiler houses in city districts, and AHS) are scattered all over the city in close proximity to residential areas (Figure 1). Greatest threats for public health are posed by low emission sources of both heat supply objects and private houses (AHS); such emission sources create local elevated levels of ambient air pollution within a block or a micro-district.

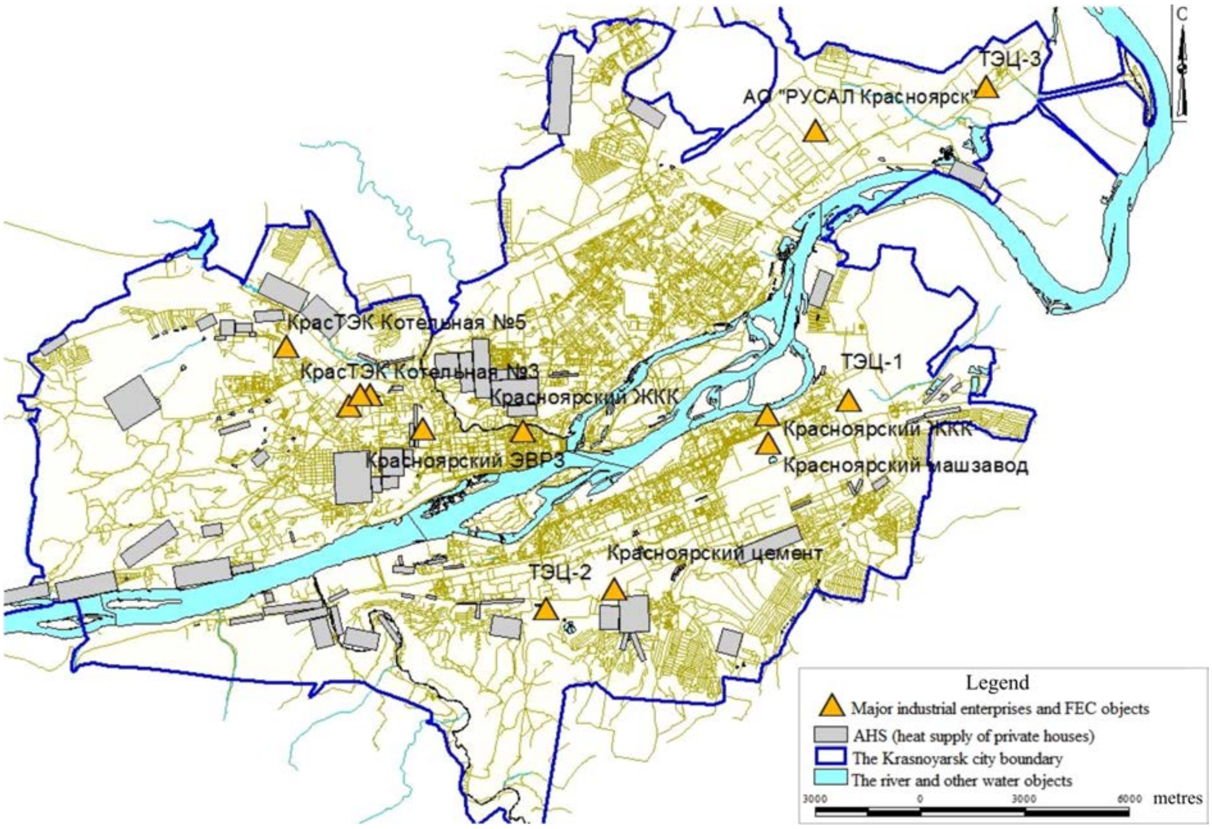

Figure 1. Spatial distribution of major heat and power objects and industrial enterprises with heat and power objects on the analyzed territory

According to the Register of Economic Entities that are subject to sanitary-epidemiologic surveillance, as of January 01, 2021, 70 % (17 units) of the economic entities dealing with 'Provision with Electric Energy, Gas and Steam; Air Conditioning' on the analyzed territory belong to extremely high or high risk category as per potential health harm (the scale of exposure is 0.226–0.518 and 0.00108–0.0065 million people accordingly, the potential health risk (R^l) exceeds $1.98 \cdot 10^{-3}$ and $7.1 \cdot 10^{-4}$–$1.2 \cdot 10^{-4}$ accordingly). The highest potential health risks among all heat and power objects are created by JSC Eniseiskaya TGK (heat generating company) and JSC Krasnoyarskkraygas, both located on the analyzed territory.

The potential health risk (R^l) created by economic entities (heat and power objects) that belong to the extremely high and high risk category is substantially higher in Krasnoyarsk city than in the Krasnoyarsk region as a whole (R^l: $1.11 \cdot 10^{-3}$–0.17 and $1.0 \cdot 10^{-4}$–$9.8 \cdot 10^{-4}$ accordingly), 7.1–50.9 times; it is also higher than potential health risks created by heat and power objects on average in the RF (R^l: $1.0 \cdot 10^{-3}$–0.101 and $1.0 \cdot 10^{-3}$–$1.0 \cdot 10^{-4}$), up to 56.0 times.

Heat and power objects emit more than 50 chemicals into ambient air in the city. Four of them belong to the first hazard category (vanadium pentoxide, lead, chromium, and benz(a)pyrene); 13 chemicals belong to the second hazard category. Only 23 chemicals of the aforementioned 50 are covered by instrumental monitoring of ambient air quality.

Contributions made by heat and power objects into ambient air pollution vary between 1 and 50 % in various areas in the city for chronic exposure and between 12 and 91 % for acute exposure.

Emissions that occur due to technological processes only at heat and power objects create substantial levels of ambient air pollution in residential areas in the analyzed city. Thus, prior to the implementation of Complex activities within the Clean Air Federal project, the existing hygienic standards are violated for acute and / or chronic exposure as per nitrogen oxide, black carbon, sulfur dioxide, dihydrosulfide, inorganic dust with silicon dioxide, in %: 70–20, dimethyl benzene, ethyl benzene, carbon oxide, benzene, formaldehyde, particulate matter and others (up to 1.5–29.9 single MPL; up to 1.4–6.9 average daily MPL; up to 1.4–19.0 average annual MPL). Levels of some chemicals were more than 5-10 times higher than their MPL (Figure 2).

Economic activities of heat supply sources create high acute non-carcinogenic health risks due to carbon oxide (up to 6.5 HQ_{ac}), formaldehyde (up to 19.05 HQ_{ac}), and particulate matter (up to 24.7 HQ_{ac}) in some areas in the city with the population more than 25 thousand people. Acute risks of respiratory diseases, diseases of the eye, disrupted development, cardiovascular diseases as well as systemic effects were ranked as 'high' on the analyzed territory (HI > 6) since the hazard index reached 6.5–25.8 HI_{ac}; the risks were ranked as 'permissible' (HI between 1 and 3) for the reproductive and immune system.

Chronic inhalation exposure creates unacceptable non-carcinogenic chronic health risks related to four chemicals: nitrogen dioxide (up to 2.1 HQ_{ch}), carbon oxide (up to 1.1 HQ_{ch}), formaldehyde (up to 19.04 HQ_{ch}), and particulate matter (up to 11.7 HQ_{ch}). Chronic health risks for respiratory diseases, diseases of the eye, and diseases of the immune system are ranked as 'high' (HI > 6) since the hazard index reaches 14.0–22.7 HI_{ch}, and this is more than 7.5 times higher than its permissible level; health risks for the hematopoietic system are ranked as 'alerting' (HI_{ch} reached 3.47, the hazard index for alerting health risks ranges between 3 and 6); health risks for the central nervous system, cardiovascular system and development processes are ranked as 'permissible' (HI_{ch} reached 1.35–1.67, the hazard index for permissible health risks ranges between 1 and 3) (Figure 3). More than 146 thousand people are exposed to elevated non-carcinogenic chronic health risks (HI > 3).

Heat and power objects, prior to the implementation of the planned air protection activities, create unacceptable carcinogenic health risks caused by exposure to formaldehyde (CR = $3.28 \cdot 10^{-4}$). The total carcinogenic health risk (TCR) ranges between $2.48 \cdot 10^{-6}$ and $3.31 \cdot 10^{-4}$ in the residential areas located on the analyzed territory.

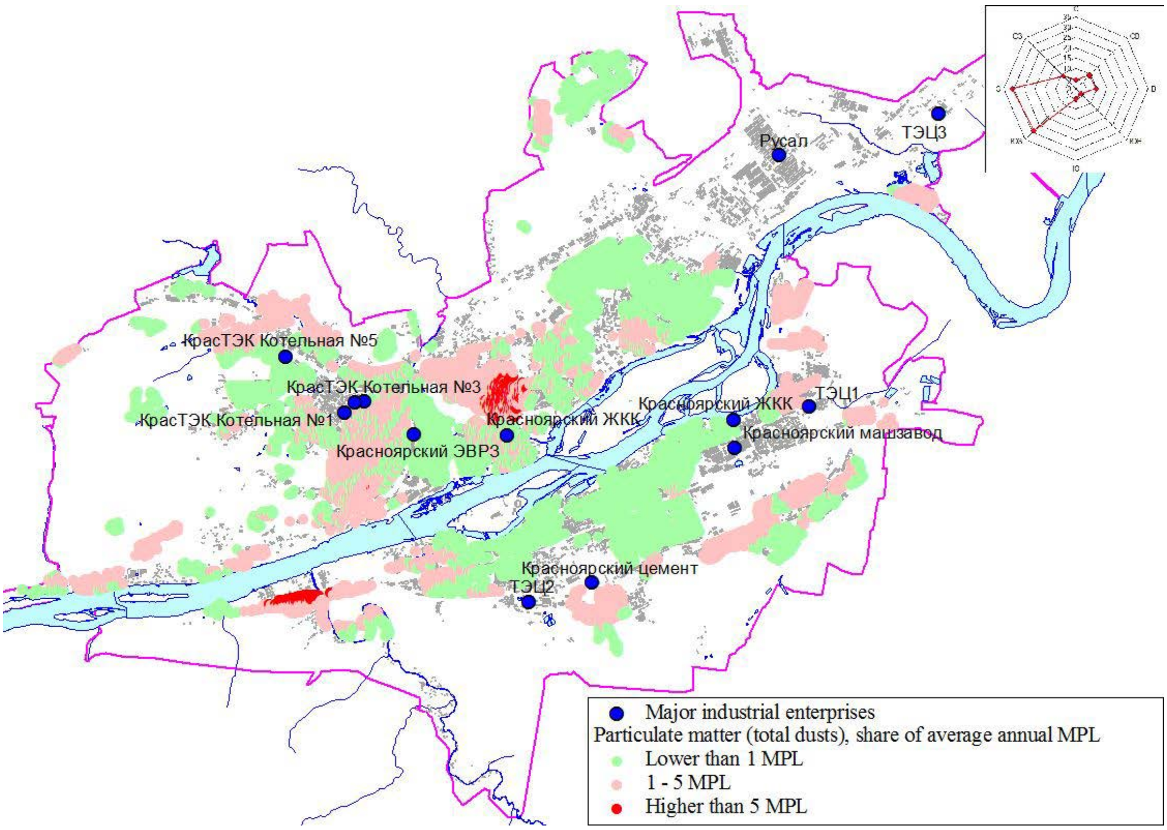

Figure 2. The analyzed territory divided into specific zones as per levels of ambient air pollution with particulate matter (total dusts) created by heat supply sources

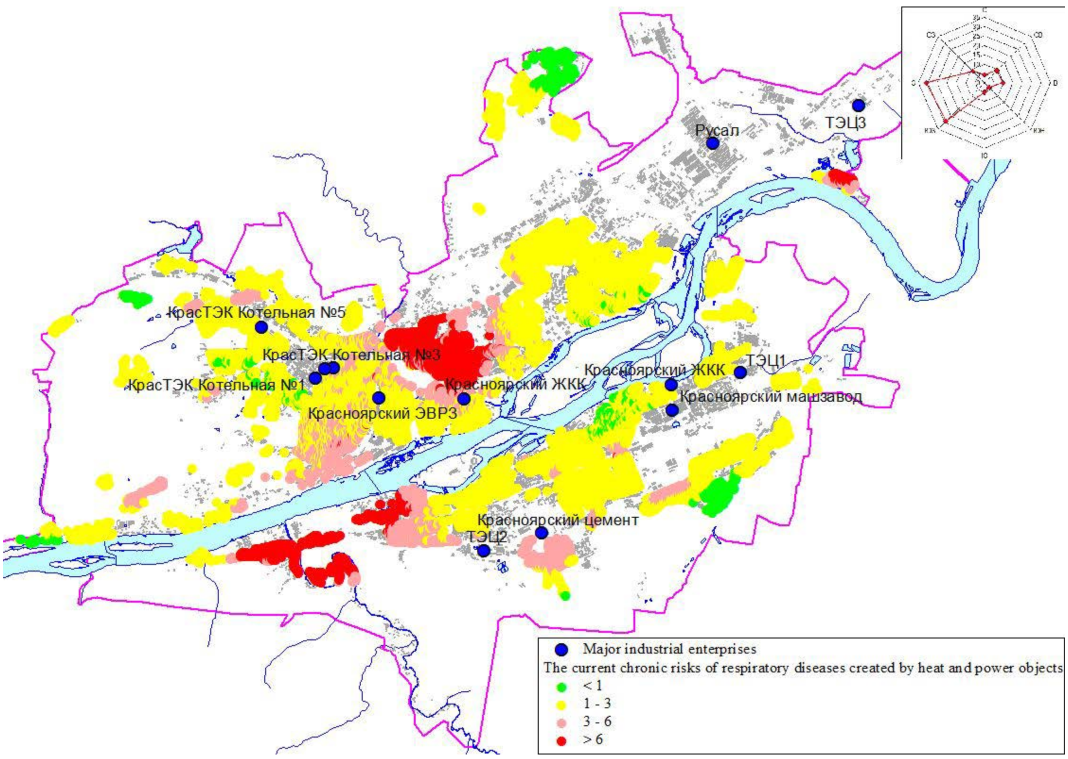

Figure 3. The analyzed territory divided into specific zones as per levels of chronic non-carcinogenic risks of respiratory diseases due to ambient air pollution created by heat supply sources

Table

Example parameters of the cause-effect relations within the 'ambient air quality (chemical levels), mg/m^3 – child incidence, $^{0}/_{00}$' system, ($p \leq 0.05$)

Disease	Parameter	The coefficient b_i value	*F*
Diseases of the eye and adnexa	Absolute term	2.61E+04	15.24
	Dimethyl benzene (xylene)	2.29E+05	
	Formaldehyde	1.11E+05	
Diseases of the musculoskeletal system and connective tissue	Absolute term	1.16E+04	24.23
	Gaseous fluorides	6.66E+05	
Diseases of the blood and blood-forming organs and certain disorders involving the immune mechanism	Absolute term	1.06E+03	34.66
	Dihydrosulfide	2.04E+05	
Diseases of the genitourinary system	Absolute term	6.93E+03	29.49
	Lead and its inorganic compounds	1.56E+08	
	Dimethyl benzene (xylene)	4.82E+03	
	Tetrachloroethylene	8.95E+04	
Diseases of the nervous system	Absolute term	1.47E+04	39.91
	Lead and its inorganic compounds	1.52E+08	
	Methyl benzene (toluene)	1.07E+05	
	Tetrachloroethylene	4.51E+05	
Diseases of the respiratory system	Absolute term	2.31E+05	41.94
	Dialuminum trioxide	9.01E+07	
	Ozone	3.67E+06	
	Sulfur dioxide	3.27E+06	
	Dihydrosulfide	5.13E+06	
	Dimethyl benzene (xylene)	1.09E+06	
	Tetrachloroethylene	5.41E+05	
	Prop-2-enenitrile	5.39E+06	
	Diiron trioxide	9.50E+07	
Diseases of the digestive system	Absolute term	6.73E+04	38.34
	Dimethyl benzene (xylene)	6.95E+05	
	Trichloroethylene	4.10E+04	
	Hydroxybenzene (Phenol)	1.82E+07	
	Kerosene	8.01E+06	
Diseases of the circulatory system	Absolute term	5.93E+03	41.45
	Benzene	8.29E+03	
	Hydroxybenzene (Phenol)	2.84E+06	
Congenital malformations, deformations and chromosomal abnormalities	Absolute term	3.12E+03	19.17
	Tetrachloroethylene	8.09E+04	
	Lead and its inorganic compounds	8.26E+06	

Having modeled the cause-effect relations within the 'ambient air quality – incidence (according to the data provided by the Fund for Mandatory Medical Insurance)', we built 31 authentic models of such relations that parameterized adverse effects produced by 35 chemicals (Table).

Ambient air pollution in Krasnoyarsk due to heat and power objects prior to the implementation of the air protection activities (2020) causes more than 87.5 thousand additional diseases (94.7 cases per 1000 people). More than 44.8 % of these additional diseases occur among children (more than 39 thousand additional diseases or 223.8 cases per 1000 children). Diseases of the respiratory system account for the major part in this additional incidence, namely, for 80.03 % (more than 69 thousand diseases or 7.2 % of the actual incidence of respiratory diseases). They are followed by diseases of the digestive system, 17.9 %; diseases of the eye and adnexa, 1.1 %. Additional child incidence has a similar structure: 80.8 %, 17.9 %, and 1.2 % accordingly.

Heat and power objects and AHS are sources of several harmful environmental factors creating the highest health losses due to additional incidence among the city population. These factors include black carbon, sulfur dioxide, nitrogen oxides, xylene and other aromatic hydrocarbons, formaldehyde, particulate matter and some other chemicals; their contributions range between 1.1 and 95.2 %. The greatest contributions to health losses among children are made by sulfur dioxide (79.3 %), kerosene (17.5 %), xylene (1 %), and formaldehyde (1 %).

Additional incidence of respiratory diseases among the whole population, which is associated with ambient air pollution created by heat and power objects, is distributed over the whole analyzed territory. Its local peaks are identified in areas influenced by heat and power objects with low or middle-height chimneys (10–50 meters) and AHS (6–8 meters) (Figure 4). Large thermal power stations usually have chimneys 180–270 meters high; they create relatively even ambient air pollution and, consequently, relatively even distribution of additional diseases over the whole city territory.

According to the Complex plan[11] aimed at reducing pollutant emissions into ambient air on the analyzed territory, the total emission volume created by heat and power objects and AHS is expected to fall by 20.56 % against its level identified in 2017. In particular, several activities are to be accomplished at heat and power objects: 25 municipal coal-fueled boiler houses are to be switched to centralized heat supply; a large thermal power station is to be modernized with a new chimney higher than 270 meters to be installed there, a boiler with an electric filter to be reconstructed, ineffective turbines to be removed and new turbines and a new cooling system to be put into

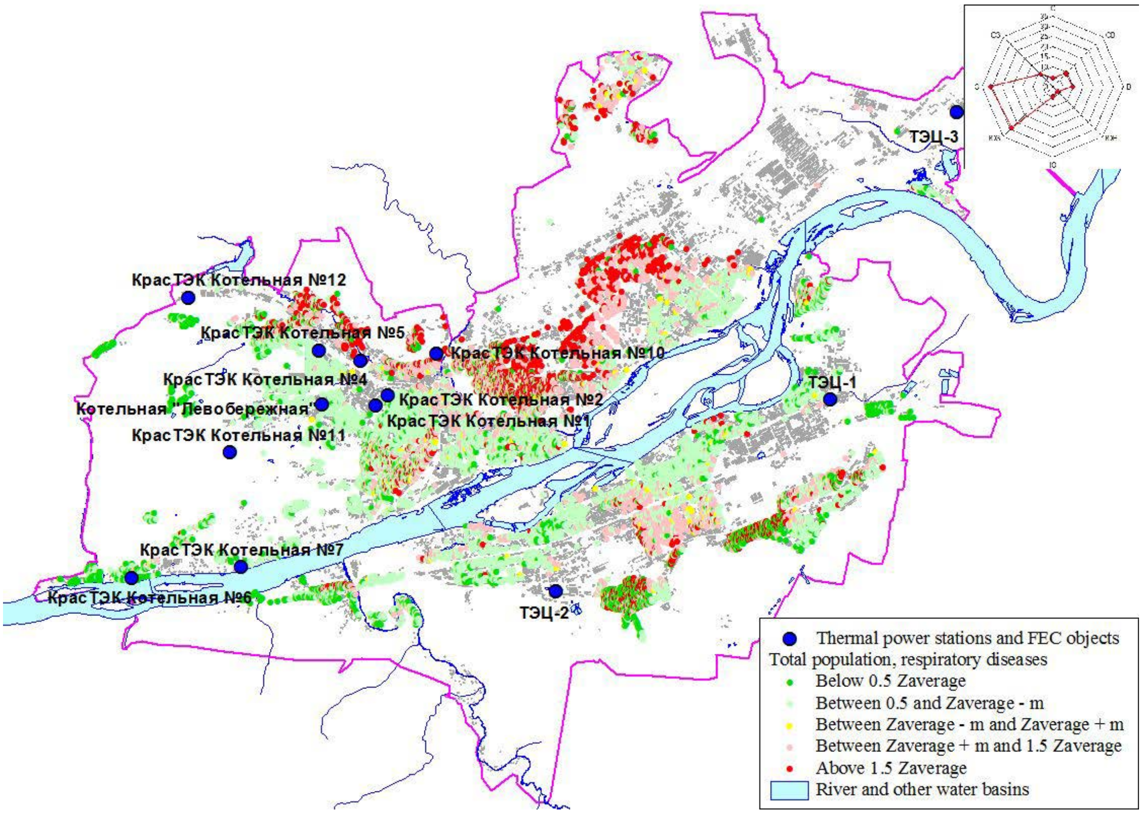

Figure 4. Spatial distribution of additional incidence of respiratory diseases associated with ambient air quality among the total population as a result of activities by heat and power objects, $^{o}/_{oo}$

[11] Kompleksnyi plan meropriyatii po snizheniyu vybrosov zagryaznyayushchikh veshchestv v atmosfernyi vozdukh v g. Krasnoyarske; utv. Zamestitelem Predsedatelya Pravitel'stva RF V. Abramchenko 16 noyabrya 2022 g. № 13424p-P11 [The Complex plan of activities aimed at reducing pollutant emissions into ambient air in Krasnoyarsk; approved by B. Abramchnko, the Deputy to the Head of the RF Government on November 16, 2022 No.13424p-P11]. *the RF Ministry of Natural Resources and the Environment*. Available at: https://www.mnr.gov.ru/upload/medialibrary/db3/%D0%9A%D1%80%D0%B0%D1%81%D0%BD%D0%BE%D1%8F%D1%80%D1%81%D0%BA,%20%D0%BF%D0%BB%D0%B0%D0%BD%20.pdf (April 13, 2023) (in Russian).

operation, automatic sensors for control of pollutant emissions into ambient air to be installed; 35 ineffective coal-fueled boiler houses are to be replaced with capacities of a large thermal power station (closing down ineffective coal-fueled boiler houses on the pilot territory, building new power generating units to balance heat loads related to replacement of ineffective coal-fueled boilers). Implementation of all these air protection activities will make it possible to reduce emissions from heat and power objects and AHS by 10.8 thousand tons by 2024.

Implementation of air protection activities at heat and power objects stipulated by the Complex plan will locally reduce levels of 4 out of 11 chemicals in ambient air, which are now higher than the existing hygienic standards, namely, nitrogen dioxide, carbon oxide, particulate matter, and inorganic dust with silicon dioxide, in %: 70–20, by 1.2–5.5 single MPL, by 1.1–5.8 average daily MPL, by 2.1 average annual MPL. However, hygienic standards are expected to still be violated as per some of these chemicals; thus, only FEC objects and AHS will create elevated levels of particulate matter up to 14.8 single MPL, up to 5.8 average daily MPL, and up to 11.7 average annual MPL. As for sulfur dioxide, operations of FEC objects and AHS, if taken separately, will not create levels higher than the hygienic standards in all the analyzed residential areas. The situation will remain the same for 6 chemicals (lead, ammonia, poorly soluble organic fluorides, benz(a)pyrene, hydroxybenzene, and methyl benzene); their levels will reach up to 22.3 single MPL and up to 3.03 average daily MPL.

Upon implementation of air protection activities aimed at reducing pollutant emissions into ambient air from heat and power objects, positive trends are expected such as a local reduction in acute and chronic risks of diseases of the central nervous, hematopoietic, cardiovascular, reproductive, and immune system, respiratory diseases, development processes, etc. (by 1.1–1.21 times).

Effectiveness of air protection activities was assessed as per residual risks after their implementation. The assessment revealed that carcinogenic risks were expected to still be elevated ($CR > 1\cdot10^{-4}$) on the pilot territory for formaldehyde (up to $3.28\cdot10^{-4}$). This chemical was also expected to cause high and alerting acute risks of respiratory diseases, diseases of the eye, cardiovascular diseases, development processes, and systemic effects (up to 2.8–25.5 HI_{ac}); high and alerting chronic risks were expected with respect to respiratory diseases, diseases of the eye, diseases of the hematopoietic and immune system (3.5–22.6 HI_{ch}).

The implementation of air protection activities aimed at reducing emissions from heat and power objects should be completed on the analyzed territory by 2024 in accordance with the Complex plan (by 20.56 % against the levels identified in 2017). This will make it possible to move approximately 50 thousand people from a zone with an unacceptable acute risk (HI higher than 3) and more than 120 thousand people from a zone with an unacceptable chronic risk (HI higher than 3) into a zone where risk levels are minimal (target ones). Still, high and alerting risks under acute exposure will persist with respect to diseases of the respiratory system, diseases of the eye, cardiovascular diseases, disrupted development processes and systemic effects (up to 6.5–25.8 HI_{ac}); under chronic exposure, with respect to diseases of the respiratory system, diseases of the eye, diseases of the hematopoietic and immune system (up to 2.96–22.6 HI_{ch}).

After all the planned air protection activities are implemented at heat and power objects, the number of additional diseases associated with ambient air quality will go down by 18.8 % among the total population living on the analyzed territory (by 16.5 thousand additional diseases or 17.8 cases per 1000 people) and will be equal to 70.9 thousand additional diseases. This reduction in additional associated diseases among the total population is largely due to a decrease in incidence among working age population (by 11.8 thousand cases) and children (by 4.5 thousand cases).

The structure of incidence among the total population will remain the same after the implementation of the planned activities at heat and power objects. The first rank place will belong to diseases of the respiratory system

(75.5 %); they will be followed by diseases of the digestive system (21.9 %) and diseases of the eye and adnexa (1.3 %). Diseases of the genitourinary, nervous, and endocrine system will account for 1.2 %. As for child incidence, the first place also belongs to diseases of the respiratory system (78.4 %), which are followed by diseases of the digestive system (20.1 %) and diseases of the eye and adnexa (1.3 %).

According to the submitted inventory lists, heat and power objects emit approximately 55 chemicals with 36 % of them being solid components such as particulate matter including $PM_{2.5}$ and PM_{10}, metal compounds (aluminum, vanadium, wolfram, iron, manganese, copper and others).

Examination of solid ash particles formed as a result of solid fuel combustion (brown coal from the Borodinskoye mine in the Kansko-Achniskiy coal field) established that this ash had several solid components in its structure including sodium, magnesium, iron, silicon, aluminum, potassium, sulfur, phosphor, calcium, and strontium. They are not mentioned in the inventory lists submitted by heat and power objects but we should remember that they are hazardous toxicants able to produce a wide range of adverse effects on human health. Calcium, magnesium, iron, and silicon compounds account for a major part of emitted solid particles with their contributions ranging between 5.8 and 35.5 %.

We analyzed the dispersed structure of solid particles in ash; as a result, particles sized smaller than 10.0 µm were established to prevail in it since their share reached 63.8 % of total particles. Notably, a half of such particles were smaller than 5 µm (30–31 % of total particles) (Figure 5).

Chemical analysis of ash established that particles sized between 0 and 10 µm contained such metals as calcium, aluminum, magnesium, iron, and strontium. Calcium particles (38.9 %) as well as particles of magnesium, iron, and silicon account for the major part in ash (more than 50 %). It is noteworthy that smaller particulate matter (between 2.5 and 10 µm) are not included into the inventory lists of emitted particles by heat and power objects although they are definitely potential risk factors able to produce negative effects on human health.

Several components identified in ash emitted into ambient air by heat and power objects are not covered by monitoring either, for example, iron, silicon, aluminum, sodium, calcium, magnesium compounds and some others.

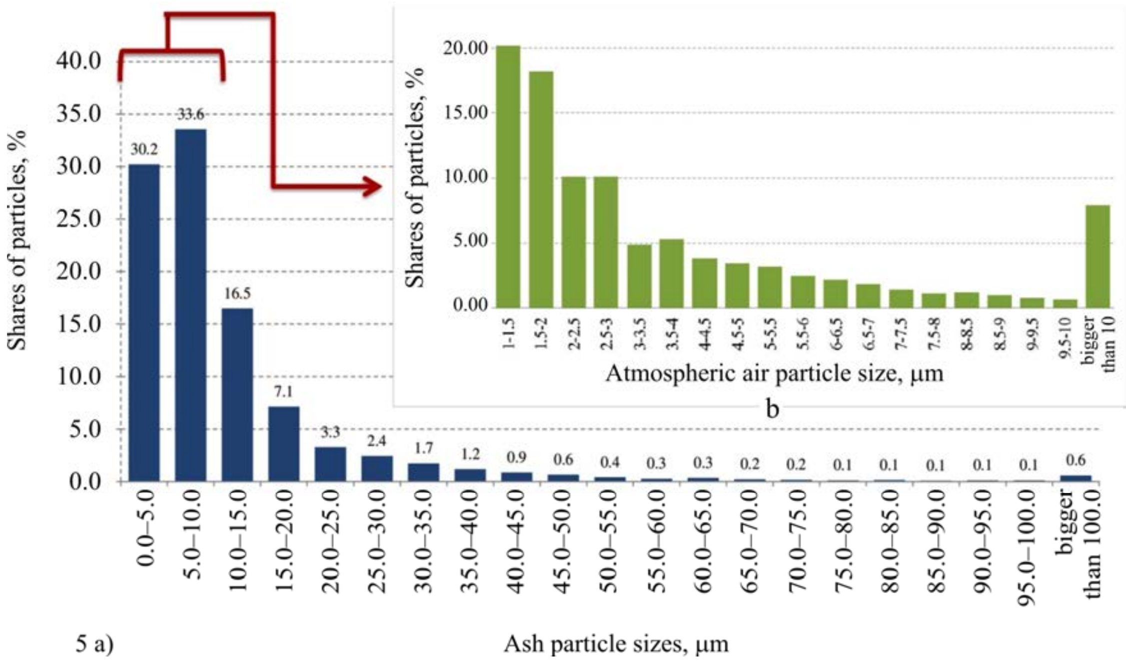

Figure 5. The dispersed structure of particulate matter in ash (5a) and in ambient air (5b) in a zone under maximum influence of FEC objects and AHS, %

It is noteworthy that the chemical structure of ambient air in areas influenced by FEC objects and AHS is similar to that of emitted ash. Sodium, iron, silicon, aluminum, potassium, sulfur, and phosphor accounted for the major part of particles (more than 65 %). The dispersed structure of particulate matter in ambient air and in ash was also quite similar with prevailing smaller particles (up to 10 μm), 88.9 % and 63.8 % accordingly (Figure 5a).

The results obtained by assessing effectiveness of the implemented air protection activities on the example of heat and power objects reveal some positive trends as regards some improvement in ambient air quality. Still, these activities are not sufficient for providing sanitary-epidemiological well-being of the population living on the analyzed territory. We expect the hygienic standards to be violated in areas influenced by heat and power objects and health risks to be higher than their permissible levels as well as resulting additional diseases associated with ambient air quality. Planned reduction in the total emission volume does not consider differentiated effects produced on human health by different chemicals. Effectiveness of the activities to be implemented at heat and power objects is ranked as 'unacceptable'[12] (below 20 %) and insufficient as per health harm mitigation, that is, substantial reduction in additional associated diseases. Technological emissions solely from heat and power objects are expected to cause approximately 70 thousand additional diseases annually.

The suggested approach to assessing effectiveness of health risk and health harm mitigation when planning and implementing air protection activities is an adequate instrument. It makes it possible to assess multicomponent harmful exposures producing multiple negative effects on health, including actual health harm, and sufficiency of implemented activities, which is also confirmed by the research results [11]. In this study, the complex assessment of negative influence exerted by economic entities relied on assessing exposure levels, identifying relationship parameters within the 'dose – effect' system, levels of acceptable and actual health risks, peculiarities of responses by the human body under combined airborne exposures, and plans of air protection activities.

Thus, when all the planned air protection activities are implemented at heat and power objects on the analyzed pilot territory (a city participating in the Clean Air Federal project), we expect some local improvement of ambient air quality, reduction in health risk levels and the number of additional incidence associated with exposure created by such economic entities.

Elevated levels of ambient air pollution created solely by heat and power objects are expected to persist and, consequently, we can expect negative health outcomes in exposed population. In this case, it is advisory to create more precise inventory lists for each source of ambient air pollution at heat and power objects; these lists should cover solid particles, including particulate matter smaller than 2 μm, and ensure conformity with the existing hygienic standards for these pollutants. Another important task is to adjust the complex plans of air protection activities considering their orientation at implementation of the best available technologies and management of priority health risk factors.

The results obtained by examining heat and power objects are comparable with the findings of other relevant studies confirming that long-term persistent pollution of the bottom layers in close proximity to residential areas creates health risks for exposed population and can lead to actual health harm. Thus, the studies [11–16] have established that fine-dispersed dust containing silicon, aluminum, copper, iron, and other metals, which is emitted, among other things, by heat and power objects, is able to produce cumulative effects. Under elevated

[12] MU 2.1.10.3675-20. Otsenka dostatochnosti i effektivnosti planiruemykh meropriyatii po snizheniyu vybrosov zagryaznyayushchikh veshchestv v atmosfernyi vozdukh dlya mitigatsii riskov i vreda zdorov'yu naseleniya: metodicheskie ukazaniya; utv. Glavnym gosudarstvennym sanitarnym vrachom RF 18.12.2020 [MU 2.1.10.3675-20. Assessment of sufficiency and effectiveness of planned activities aimed at reducing pollutant emissions in ambient air to mitigate health risks and health harm: methodical guidelines; approved by the RF Chief Sanitary Inspector on December 18, 2020]. *KonsultantPlus*. Available at: http://www.consultant.ru/law/hotdocs/68710.html (May 12, 2023) (in Russian).

chronic inhalation exposure, such dust leads to negative health outcomes such as respiratory diseases and cardiovascular diseases and influences biochemical processes in the body.

The studies [17–22] have established that any increase in levels of particulate matter smaller than 2.5 μm would have greater influence on mortality under both acute and chronic exposure than an increase in levels of PM_{10} or any other fractions. Major effects produced by micro-sized particles (PM_{10}, $PM_{2.5}$) on the human body are determined by their ability to penetrate deep into the lower airways, to injure lung tissues and to enter the blood flow through damaged cellular membranes of the lung alveoli; they can also produce various toxic effects depending on the their component structure [6–9].

At present, monitoring over ambient air quality is rather limited and does not involve analyzing dispersed structures of micro-sized particles. This requires additional research aimed at assessing effects produced on public health by solid particles with multicomponent structures.

Conclusions:

1. We have suggested an algorithm for assessing effectiveness of air protection activities. It includes six subsequent stages and makes it possible to assess their effectiveness and sufficiency as per conformity with the existing hygienic standards, health risks and actual health harm as additional incidence associated with poor quality of the environment due to activities performed by economic entities.

2. The algorithm has been tested at heat and power objects in a city that was included in the Clean Air Federal project and located in the Siberian Federal District. As a result, it has been established that potential health risks (R^l) created by heat and power objects are ranked as high and extremely high on the analyzed territory and are considerably higher than the regional levels and the national level, 7.1–50.9 times and up to 56.0 time accordingly.

3. Prior to the implementation of the planned air protection activities, heat and power objects emit certain pollutants in some areas in the city in quantities being 5–10 times higher than the maximum permissible levels (up to 29.9 single MPL; up to 6.9 average daily MPL; up to 19.0 average annual MPL). As a result, they create unacceptable (HI > 3) acute health risks (up to 25.8 HI_{ac}) for the respiratory system, eyes, the circulatory system, development processes; unacceptable chronic risks (up to 22.7 HI_{ch}) for the respiratory organs, eyes, and the immune system; unacceptable carcinogenic risks (up to $3.28 \cdot 10^{-4}$). Nitrogen dioxide, carbon oxide, benzene, formaldehyde, particulate matters and some other pollutants are the priority risk factors.

4. Prior to the implementation of the planned air protection activities, technological emissions from heat and power objectsannually cause approximately 87.5 thousand additional diseases with more than 44.8 % of them among children. Diseases of the respiratory system account for the major part in this additional incidence since their share is 80.03 %.

5. The implementation of the planned air protection activities at heat and power objects will lead to a local reduction in ambient air pollution. Levels of 10 chemicals are still expected to be higher than the existing hygienic standards; levels of 4 chemicals will decrease by 1.2–5.5 single MPL, by 1.1–5.8 average daily MPL, and by 2.1 average annual MPL; the situation will remain the same for 6 chemicals and their levels will be up to 22.3 single MPL and up to 3.03 average daily MPL higher than the hygienic standards. High and alerting levels of non-carcinogenic risks will persist for the respiratory organs, eyes, the hematopoietic, immune and cardiovascular system, development processes and systemic effects (up to 2.8–25.5 HI_{ac}, 3.5–22.6 HI_{ch}); carcinogenic risk levels will remain stable (CR up to $3.28 \cdot 10^{-4}$). The implementation of the planned air protection activities at heat and power objects will move approximately 50 thousand people from a zone with unacceptable acute health risks (above 3 HI) and more than 120 thousand people form a zone with unacceptable chronic risks.

6. Microscopy analysis of ash particles sized 0–100 μm has established their chemical structure that includes 10 various chemicals. Particles sized up to 10 μm prevail in the ana-

lyzed ash (63.8 %) and mostly contain calcium, magnesium, iron, and silicon (contributions range between 5.8 and 35.5 %). Due to them, ambient air in areas influenced by heat and power objects has a similar component structure.

7. We have assessed effectiveness of the air protection activities planned at FEC objects and AHS on the analyzed territory. As a result, we have established that the gross reduction in pollutant emissions corresponds to the target one stipulated in the Clean Air Federal project by 2024. At the same time, this planned reduction is not sufficient for achieving conformity with the existing hygienic standards, acceptable risk levels and reduction in risk-associated incidence in areas influenced by heat and power objects. Effectiveness of the planned air protection activities is ranked as ‘unacceptable’ (< 20 %) as per actual heath harm represented by additional incidence associated with influence of operating heat and power objects.

8. The results obtained by assessing effectiveness of the air protection activities planned at heat and power objects and expected ambient air quality, health risk levels and health harm after their implementation require some additional measures taken by economic entities and local authorities as well as orientation at using the best available technologies with respect to the most hazardous chemicals. Nitrogen dioxide, particulate matter, black carbon, carbon oxide, sulfur dioxide, dihydrosulfide, inorganic dust with silicon dioxide, in %: 20–70, dimethyl benzene, ethyl benzene, benzene, formaldehyde, and kerosene are the priority chemicals that should be covered by additional activities aimed at public health protection. Until proper ambient air quality is reached, according to the hygienic standards and health risk levels, it is advisable to perform systemic monitoring of public health in areas influenced by heat and power objects, to develop and implement complex medical and prevention activities.

Funding. The research was not granted any financial support.

Competing interests. The authors declare no competing interests.

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Received: 20.04.2023
Approved: 25.06.2023
Accepted for publication: 28.06.2023