MODERN TECHNIQUES FOR COMPREHENSIVE THERMOVISION CONTROL OF ENERGY EFFICIENCY AND QUALITY OF CONSTRUCTION AND INDUSTRIAL FACILITIES

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This paper is dedicated to issues of development and practical application of comprehensive technical diagnostic techniques on the basis of the temperature fields analysis to ensure a safe operation and improvement of energy efficiency of construction and industrial facilities.

Currently the main focus in the field of thermal non-destructive testing (TNdT) and diagnostics is the development of equipment, including thermal imagers, methods and software for processing video images of temperature fields , monitoring systems on the basis of direct application of thermal imager devices, etc.

There are practically no studies and know-how developments available for conducting and metrological certification of the thermal control.

The increase in numbers and sophistication of technical devices, as well as a wider incidence of emergencies, the necessity of ensuring their safe operation, the identification of hazards, the ever growing power consumption – all that considerably enhances the urgency of development and implementation of new versatile know-hows for the evaluation of the technical condition and power efficiency of facilities.

In November, 2003 the Government of Russia approved the "**Energy strategy of Russia for the period up to 2030".**

One of the main objectives of the state in this area is a rigid and unconditional requirement for attainment of the planned strategic goals of ever improving energy efficiency, setting of ever more stringent requirements for energy-saving, power consumption supervision, adoption of power consumption standards and energy losses limits, as well as mandatory certification of energy-consuming installations.

The support of special businesses in the field of energy-saving, who are underdeveloped in Russia yet, thus enabling the foundation of economic agents (energy service and energy saving companies) that implement the optimal scientific, production engineering and industrial solutions focused on the decrease of energy intensity of products and services becomes an important goal of the national policy.

One of the key tendencies of energy-saving is the provision of a high quality for the thermal insulation of outside walling and observance of the regulations concerning energy losses, as well as energy efficiency during the project design, construction and upkeep of buildings. Following the research results, about 40% of the energy used for heating of buildings makes up excess losses above the rated limit for this particular reason.

The key thermotechnical quality parameters in the building industry are the value **of reduced resistance to heat transfer of walling of a building** (for example, for walls of a building the norm for the reduced resistance depending on the required specific heat consumption is within 2,3 … 3,7m^2□C/W), **the dew-point temperature, the positions of the frost penetration front, a period, during which the building functioning after an emergency heat supply cutoff is still possible, etc**.

Currently these characteristics are determined, as a rule, at the design stage of the facility by means of calculation. However, the very great inaccuracy is inherent in these results, which do not reflect the actual performance properties of a building structure, as they do not consider the most important stage between its projection and use, which is the construction phase. During this phase the design parameters of a construction project can be essentially changed for the better or for the worse. According to a long-term experience and practical work of the **Technological Institute for energy research, diagnostics and non-destructive testing "VEMO"** using the thermovision diagnostics in evaluation of buildings and building structures [1-6], at least half of the completed and commissioned construction facilities do not comply with the existing energy-saving norms. The design projects of all construction facilities have undergone all necessary mandatory examinations and correspond to building standards at that. It happens because during the construction phase there are deviations from the design documentation, changes in the construction methods, replacements of building materials, etc.

For the assessment of the **actual** characteristics of the construction facilities, the Technological Institute "VEMO" developed and implemented techniques based on thermovision for comprehensive diagnostics of buildings and construction facilities in their real maintenance conditions (both in summer- and wintertime) with the determination of their characteristics, including:

- energy diagnostic studies of building structures (with determination of the reduced resistance to heat transfer on walls and windows);

- determination of the dew-point temperature and the coordinates of the frost penetration plane;

- air cool-down time period inside a building in emergency situations,

- recommended thickness of the heat insulation material in areas of excess heat loss above the rated limit.

The variety of practical challenges by the development of the comprehensive thermal diagnostics techniques has resulted in the following problems to be solved:

- modeling of complex multivariate thermal monitoring processes,
- development of thermal defectometry method – definition of defect characteristics and material structure,
- optimization of monitoring equipment parameters,
- detection of defects in materials and constructions without reference samples,
- implementation of a multitask principle of multivariate data acquisition and processing,
- development of a data processing software for the solution of the problems set forth above, etc.

The majority of the set tasks has been solved, which enabled to create an essentially new **hardware-software methodological product to be regarded as a technological basis for the comprehensive thermal non-destructive testing and technical diagnostics so that one would** solve the following problems:

- industrial safety assessment,
- construction assessment,
- technical diagnostics and engineering audit,

- providing safety by maintenance and improving energy efficiency for construction and industrial facilities by means of inspection using a thermovision inspection method,
- prompt development of thermovision techniques for the examination and diagnostics of new facilities,
- training and certification of experts responsible for thermal non-destructive testing and technical diagnostics.

Let's review them in detail.

In Fig. 1 there is an example of an average dependence of the influence of the resistance-to-heat-transfer value of the outside walling on its energy-saving efficiency.

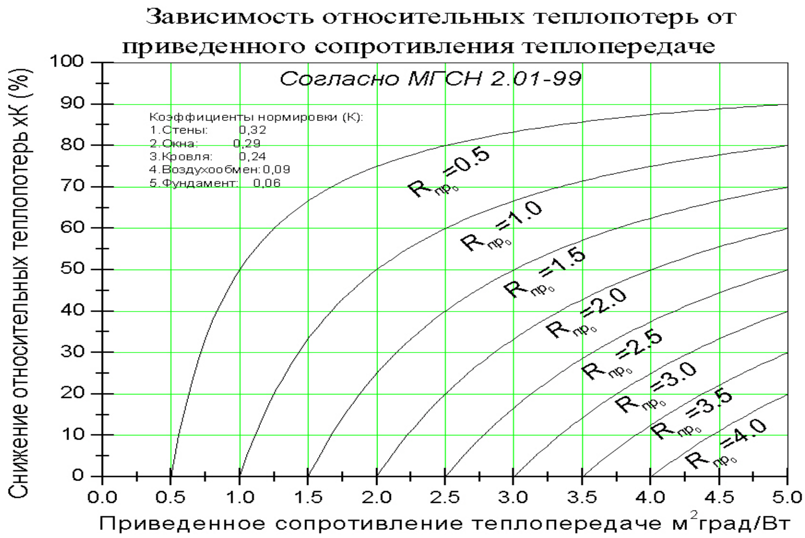


Fig. 1. Curves of dependence of heat losses on initial resistance-to-heat-transfer value.

The procedures to be named the Procedure and the Hardware-Software Complex for finding the reduced resistance to heat transfer of the outside walling of buildings and transparent structures (windows) that except the above-named disadvantages in **their actual service conditions** [3] have been developed and used for 9 years by the Technological institute “”. This procedure is based on the solution of an inverse problem of the thermal non-destructive testing in the multilayer spatial domain with subdomains simulating the defects under the conditions of a nonsteady heat transfer process.

The inverse problem of the thermal supervisory comes to the seeking extremum (minimum) of the following "likelihood functional“ (the integration is performed over a time interval (0, t)):

$$\Phi(\Theta) = \int_0^t \left(U_0(\tau) - U(\tau,\Theta)\right)^2 d\tau . \qquad (1)$$

Where

Θ - a set of parameters;

The inverse problem solution in general is based on the solution of a direct problem in the following sense: it is necessary to select the parameters of object to be tested in such a way, so that its calculated response (some function of time $U(\tau)$) comes as close as possible to the measured response U_0 (τ). The proximity is perceived in terms of vicinity in a function space (space of the functions meeting some requirements for smoothness conditions).

The actual gained value of the reduced resistance to heat transfer with corresponding initial and boundary conditions, which were identified in an experimental way by means of measurements on the tested object, underlies the method of finding the dew-point, the position of the frost penetration plane and the definition of the thermal state of a building structure in case of the emergency heat supply cutoff (with the determination of a maximum permissible cutoff interval).

The problem of the analysis of the penetration of the freezing (or thawing) front of moisture, which is contained in the outside walling of a building, as well as the coordinates of the dew- point also have a major practical importance, as they are directly related to operating life of the walling, creation of their actual heat-to-humidity ratio and their resistance to heat transfer. The latter factor determines the energy-saving efficiency of a building. Extremely adverse service conditions of materials occur in the area of the travelling frost penetration front owing to a possible alternating freezing and thawing that over time results in a structural strength reduction and ultimately in the destruction of construction.

The analysis of the frost penetration process is considered as a task, in which the change of the aggregative state (water/ice transition) occurs at a certain temperature T_k. It means that there is a distinct isothermal boundary between the areas of hardened ice and fluid.

In this case a system of two equations of the unsteady heat conduction (for the hardened and non-hardened areas) is solved, and on the surface of the object two other conditions of hardening boundary are specified in addition to the boundary conditions :

1. Heat balance:

$$\lambda_1 \frac{\partial T}{\partial x}(x = x_\kappa - 0) - \lambda_2 \frac{\partial T}{\partial x}(x = x_\kappa + 0) = L_v \frac{dx_\kappa}{dt} \qquad (2)$$

2. Temperature equality:

$$T_1(x=x_\kappa-0)=T_2(x=x_\kappa+0)=T_\kappa. \qquad (3)$$

The first term of the equation (2) expresses the density of heat flux S_1 , which is withdrawn from the boundary of phase separation through the hardened area; the second term expresses the density of the heat flux S_2 arriving at the boundary of phase separation from the non-hardened area.

In such formulation the task is named as a Stephan Problem on shift of phase separation boundary.

An example of the developed technique is given in Fig.2. There is a chart of the frost penetration front shift for a wall made of bricks and foam polystyrene. The temperature on the outside wall surface equals T_n =-20□C, the temperature on the inside wall is T_0=20□C, the moisture freezing temperature is T_k=0□C. The frost penetration process is reviewed for a period of 24 hours.

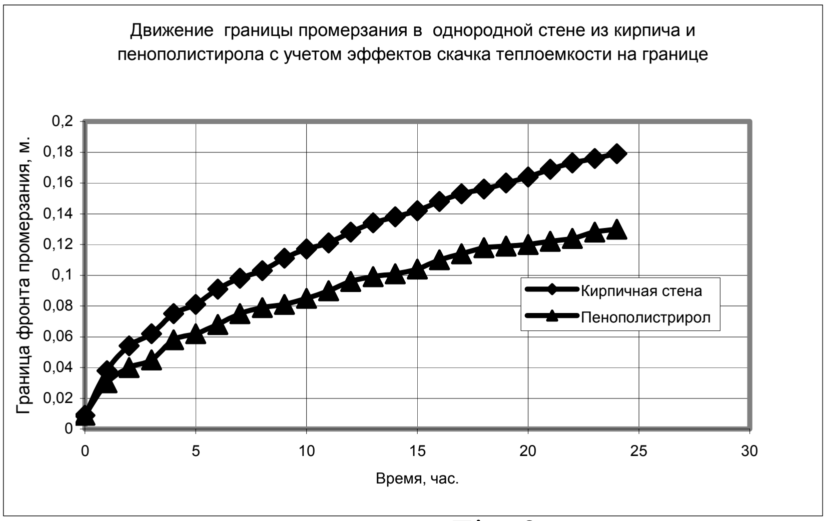


Fig. 2.

One of the extremely important parameters of residential buildings is the interval of time, during which the residential building can stay without heating, for example, in case of a heat supply system cutout due to its failure. During this period of time it is necessary to be able to perform the repair or drainage of heat consumption systems to prevent freezing of the heat carrier.

The definition of a "safe" cutout time period is based on a mathematical model describing the process of a nonsteady heat transfer in outside walling and inside lining structures, ground floor and an attic-floor room of a residential building taking into account the boundary and starting conditions and interior energy sources. In the proposed scenario the thermal condition of a residential building is determined with the help of an experiment and calculation method in case of an eventual heating system breakdown in wintertime.

The procedure includes the following: acquisition of initial data by means of instrumental measurements, including the thermovision, measurements of necessary parameters and their processing – simultaneous solution concerning the system of “n” differential equations of the transient heat conduction using partial derivatives and a system uniting them (n-1), which is made up of ordinary differential equations of the heat balance with allowance for the corresponding boundary and starting conditions.

For example, the first system of the transient heat conduction for differential equations describes a process of the temperature distribution over time in the outside walling of a building. The second system of the transient heat conduction for differential equations describes a process of the temperature change over time at the basement level of the building, etc. The dimension of the system, that is the number of the differential equations, is determined by the complexity of the building structure under research and by the required accuracy of the results to be gained.

One of the important problems, which has been ever solved for the first time by the authors, in view of the presented issues was the calculation inaccuracy for the controlled values, including the evaluation of the dependence of the value inaccuracy for the desired value (output error) on the value inaccuracy of the input data (input inaccuracy) in actual service conditions of the facilities being studied and in the conditions when the reference samples a priori were not available. The solution is based on the frequency analysis of a transient heat conduction problem and an estimation of control results using mathematical statistics methods.

With respect to all types of the above-stated diagnostic operations, a summary statement is prepared after the completed examination of the facility regarding its optimum remodeling in order to bring it into line with the valid codes and standards: an optimum heat insulation (according to the price/quality ratio) for decreasing the excess heat losses and enhancing of construction reliability, necessary repairs of the electrical equipment, etc.

Thus, the basic thermotechnical characteristics of the outside walling, as well as the transparent constructions and the inaccuracy for their determination, and the process engineering for the optimum building remodeling and repairs of the electric equipment are defined after performing of the experimental examination, including the thermovision scanning, and theoretical analysis of the acquired data gained using the developed procedures.

More details on the above outlined techniques will be presented in the following articles.

A block diagram of a comprehensive building and construction elements examination technique is given in Fig. 3.

It includes three basic steps:

Step 1. Recording of the primary information from the controlled facility in its real service conditions: temperature history of the environment and the monitored facility itself, humidity-related characteristics, etc. and their preparatory processing.

Step 2. Definition of the thermotechnical characteristics of the examined facility (the reduced resistance to heat transfer on walls and windows, the dew-points and positions of the frost penetration plane, the thermal condition of a building structure in case of emergency heat supply cutoff with the determination of a maximum permissible cutoff interval). The diagnostics of the technical condition of the electric power installations of a building is performed at this stage, as well as the calculation of the inaccuracy for finding of the above-named parameters, the detection and identification of flaws in the building structures and the development of engineering situation-oriented solutions on remodeling of the buildings.

Step 3. Preparation of reporting materials and summary statements with issuing of a free-standing insert to the energy certificate of the building.

The results of a comprehensive examination of construction and industrial facilities are given as an example in Fig. **5-10**.

In practice it is designed and built as a mobile complex of hardware (including a complete set of thermal imaging monitoring equipment), methodological means and software with a processing capacity of results according to multitask technologies (Fig. 4).

The comprehensive thermal diagnostics includes 30 unique techniques for the evaluation of the technical condition of various construction and industrial facilities.

Over 9000 construction facilities have been examined using the designed techniques.

The advantages of the proposed basic technology for a comprehensive mobile thermal non-destructive testing and technical diagnostics are, as follows:

- systemic, complex, multi-aspect approach to the evaluation of the technical condition of facilities and assessment of safety of their use: from engineering of technological procedures and automation of hardware and software complexes up to training and certification of specialists in corresponding fields of activity,
- identification of characteristics of defects in installation work and construction materials of different facilities, for example, electrical installations, underground railway tunnels , thermal power plants, building structures, etc. in the course of their construction and maintenance,
- possibility of diagnostics of facilities in actual conditions of their use, for example, detection of stress concentrators in metal parts of bridge cranes subjected to cyclic loads.

In coordination with the customer the following **methodological means and software** are included in the complete set of the basic modifications of the Complexes:

• procedure for identification of causes resulting in development and occurrence of defects of the outside walling of the residential and public buildings with the use of the thermal non-destructive testing method;

• procedure for identification of causes resulting in frost penetration in cladding constructions of attic-floor rooms of the residential and public buildings with the use of the thermal non-destructive testing method;

• procedure for identification of causes resulting in the frost penetration through the basements of the residential and public buildings with the use of the thermal non-destructive testing method;

• procedure for determining the concrete pile length in the foundation of the existing building with the application of a geo-radiolocating method;

• procedure for a comprehensive evaluation of the technical condition of vessels and containers for storage of liquid chemically dangerous substances with the use of non-destructive testing methods;

• procedure for the identification of causes of the development and occurrence of defects in concrete and reinforced-concrete load carrying and non-load-carrying constructions of buildings and building structures using a visual measurement method of non-destructive testing;

• procedure for the detection of causes of the development and occurrence of defects on steel load-carrying structures of the buildings and building structures using a visual measurement method of non-destructive testing;

• procedure for the detection of causes of the development and occurrence of defects on wood structures of buildings and building structures using a visual measurement method of non-destructive testing;

• procedure for a comprehensive examination of buildings and building structures using the method of non-destructive testing for the purpose of the remaining lifetime estimate;

• procedure for a comprehensive examination of tunnels with the use of non-destructive testing methods;

• procedure for carrying out measurements using the thermal imaging diagnostics (non-destructive testing of the technical condition) of the electrical equipment;

• methodological recommendations on the application of means and techniques of a non-destructive testing for the purpose of the instrumental validation of the data accuracy for the evaluation activities while making an expert examination;

• procedure for the definition of width of the layers of a road carpet with the use of a geo-radiolocating method of a non-destructive testing;

• procedure for finding the levels and depth of soil pollution as a result of oil and petroleum product spills;

• procedure for a comprehensive evaluation of the technical condition of hydraulic structures;

• procedure for the analysis of construction work contracts while conducting a construction engineering forensic examination;

• WEMO 2000 Building software for data processing after the examination of buildings and heat dissipating facilities;

• «MODEN» software for the computer simulation of heat and humidity conditions in buildings and construction facilities, etc.

All procedures are approved by the corresponding ministries and departments and certified by Gosstandart of the Russian Federation.

The accuracy and reliability of the procedures was confirmed through their use for 10 years, with over 9000 construction and industrial facilities having been examined.

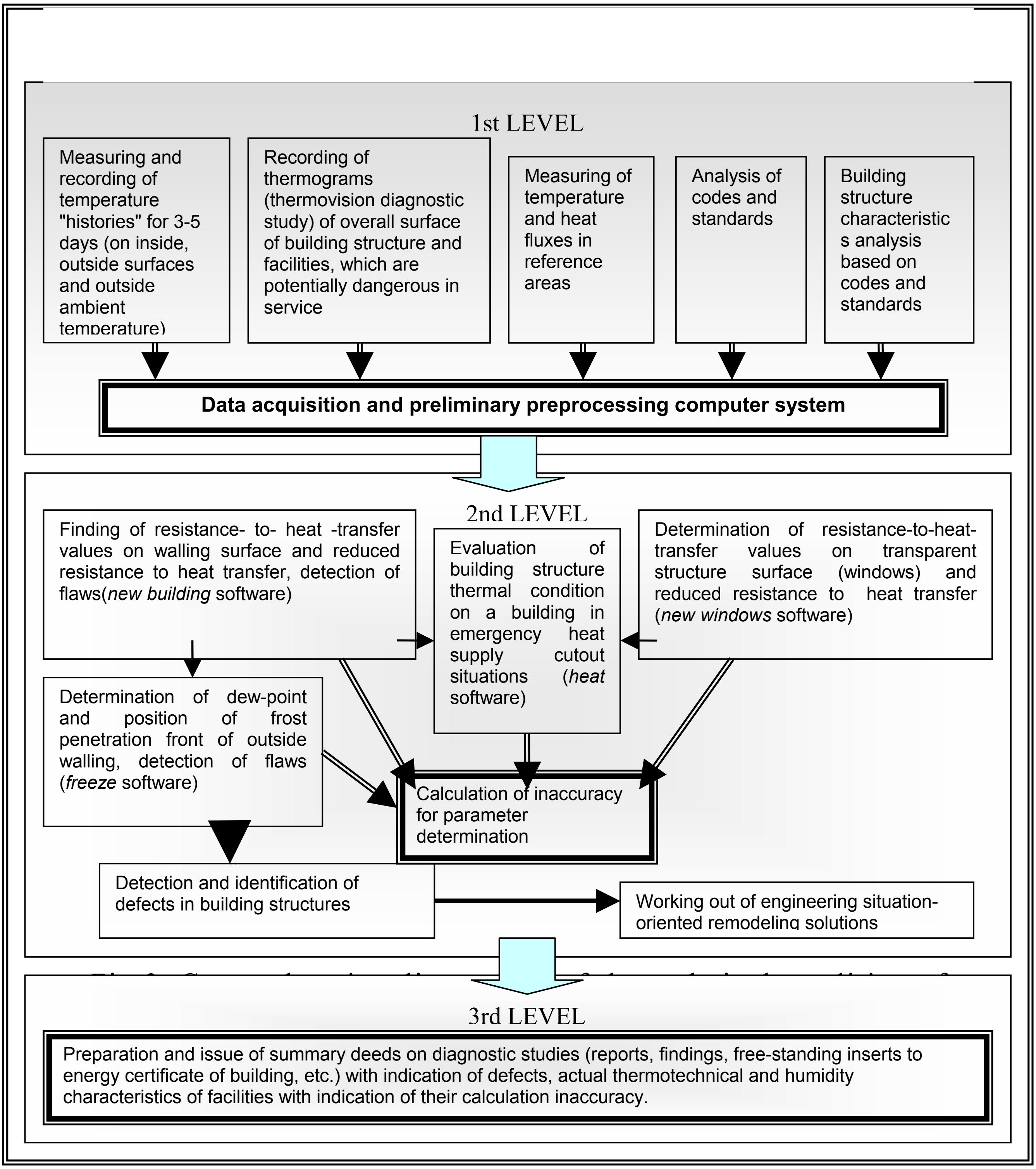
Summary

1. For the first time ever the problem of a comprehensive thermal imaging non-destructive testing and diagnostics of the technical condition of the construction facilities has been solved with the determination of the following numerical values of their thermotechnical parameters in actual conditions of their use, i.e. with allowance for the nonsteady conditions of the heat transfer through the constructions:

- value of resistance to heat transfer in each point and reduced resistance to heat transfer of walls – outside walling;
- value of reduced resistance to heat transfer of transparent constructions, i.e. windows and transparent walls;
- coordinates of the frost penetration plane in the outside walling and the dew-points;
- thermal condition of a building structure in emergency heat supply cutout situations (with the determination of the minimum cutout time interval),
- diagnostics of the technical condition of the electrical equipment,
- calculation of the inaccuracy for the determination of the thermotechnical parameters of the controlled facilities in actual conditions of their use and examination procedure,
- provision of engineering situation-oriented solutions on remodeling of the inspected facilities on the basis of the performed work.

2. Procedures and techniques of thermal non-destructive testing and engineering inspection of the construction facilities, **which have no analogs in the world,** have been developed on the basis of the solved problems**.** These procedures enable the determination of the thermotechnical and operational characteristics in actual service conditions of the facilities in different climatic zones and seasons (including winter- and summertime). The developed procedures enable the definition of the product purpose parameters with the inaccuracy of no more than 10-15%. The Russian Federation and Ministry for the Power Generating Industry of the Russian Federation consider them as a basis for the evaluation of quality of the performed construction work and energy-saving efficiency of the construction facilities.

3. All procedures are developed in the form of the corresponding technological documentation and software with use of standard measurement and calculation resources. Therefore, it would be appropriate to contribute to the realization of the **“Energy strategy of Russia for the period up to 2030”** by means of using the designed testing procedures by the inspection divisions of many industrial companies.


1st LEVEL
Measuring and recording of temperature "histories" for 3-5 days (on inside, outside surfaces and outside ambient temperature)
Recording of thermograms (thermovision diagnostic study) of overall surface of building structure and facilities, which are potentially dangerous in service
Measuring of temperature and heat fluxes in reference areas
Analysis of codes and standards
Building structure characteristic s analysis based on codes and standards
Data acquisition and preliminary preprocessing computer system
2nd LEVEL
Finding of resistance- to- heat -transfer values on walling surface and reduced resistance to heat transfer, detection of flaws(new building software)
Evaluation of building structure thermal condition on a building in emergency heat supply cutout situations (heat software)
Determination of resistance-to-heat-transfer values on transparent structure surface (windows) and reduced resistance to heat transfer (new windows software)
Determination of dew-point and position of frost penetration front of outside walling, detection of flaws (freeze software)
Calculation of inaccuracy for parameter determination
Detection and identification of defects in building structures
Working out of engineering situation-oriented remodeling solutions
3rd LEVEL
Preparation and issue of summary deeds on diagnostic studies (reports, findings, free-standing inserts to energy certificate of building, etc.) with indication of defects, actual thermotechnical and humidity characteristics of facilities with indication of their calculation inaccuracy.

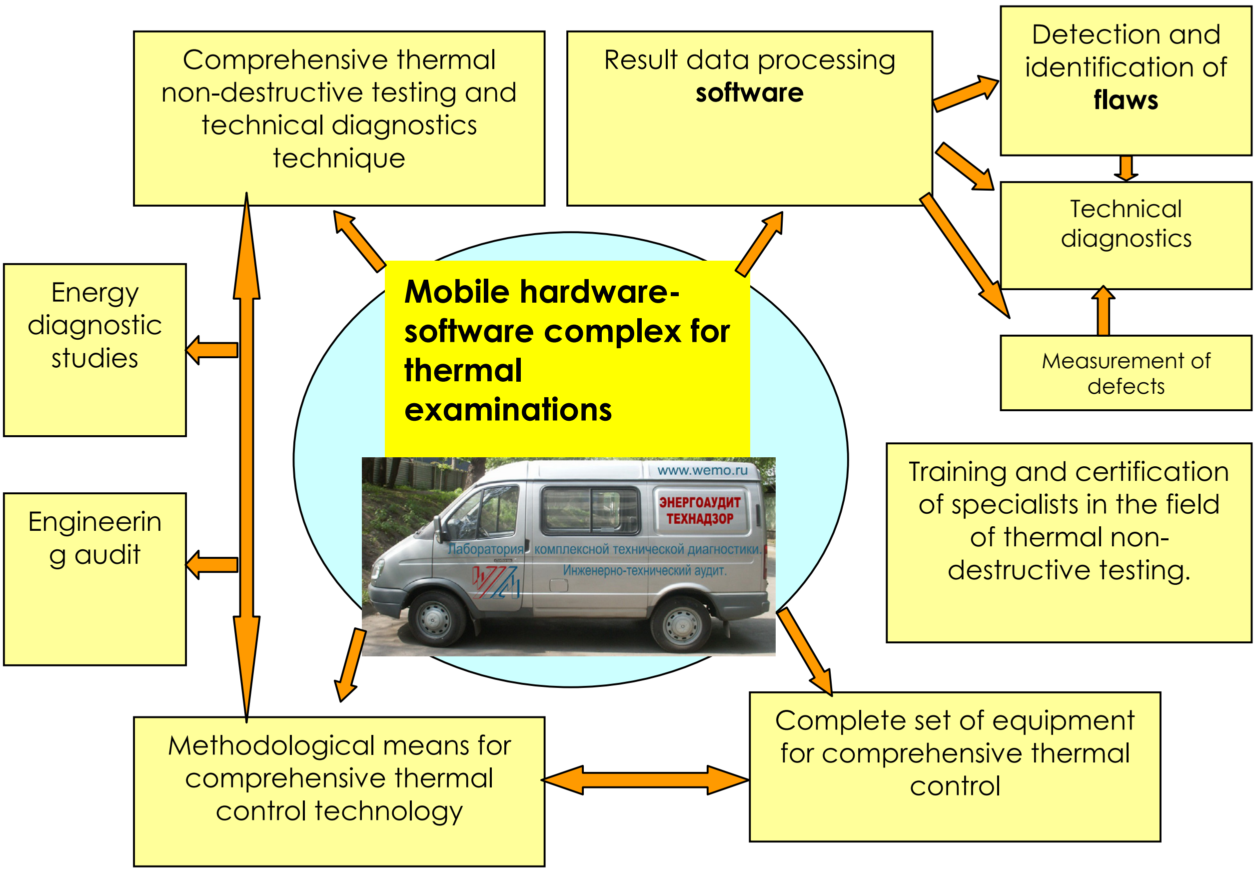


Fig. 4.

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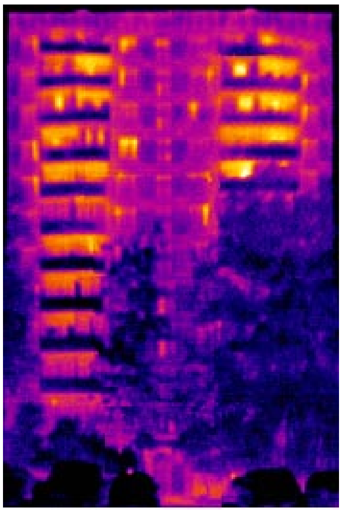
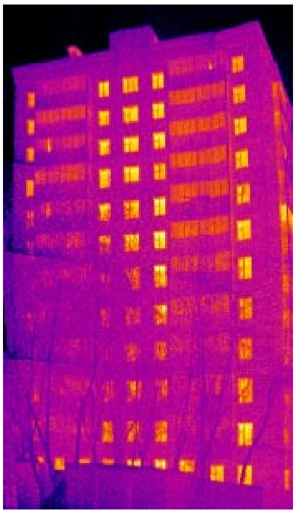


a)



b)

c)

d)

Fig.5. Reconstruction process of old housing stock following results of thermal examination.

a) before remodeling, $R_{pr} = 1{,}0m^2$□C/W. Pronounced defects are visible on the thermogram of the building structure

b) after remodeling, $R_{pr} = 3{,}0m^2$□C/W.

c) photo of a construction facility.

d) optimization example of heat insulation of a building following the thermal examination results with a view of elimination of deficiencies of heat and moisture service conditions.

				Design requirement	Examination result data
221	Приведенное сопротивление теплопередаче СТЕН:	Rw	кв.м² С/Вт	2,85	3,4
221	Приведенное сопротивление теплопередаче ОКОН и ВИТРАЖЕЙ	RF	кв.м² С/Вт	0,56 0,45	0,53 0,5

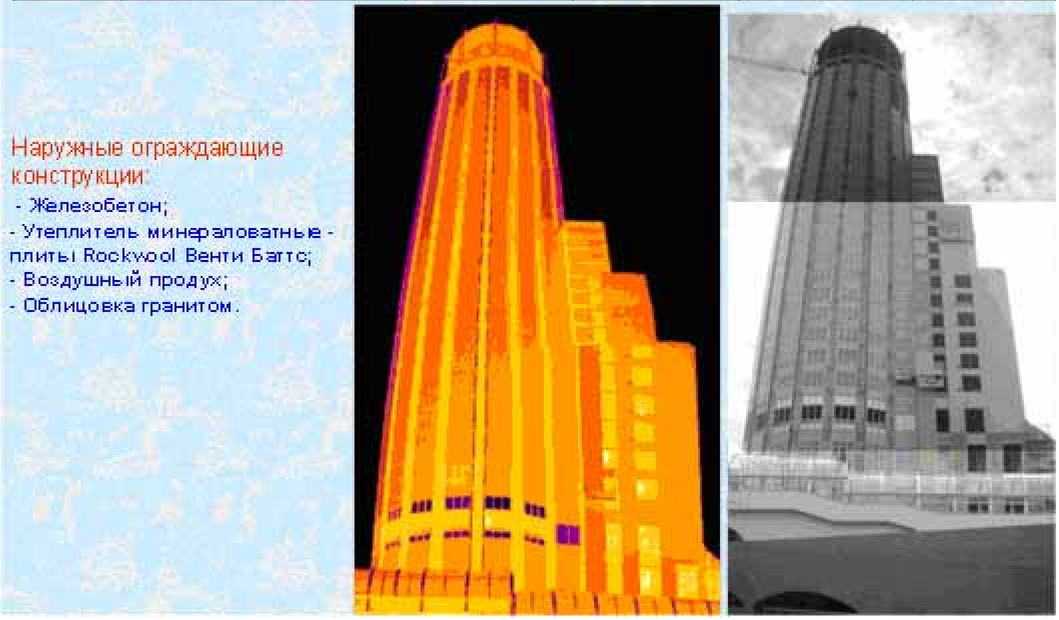


Fig. 6. Thermal examination of a high-rise hotel.

Fig. 7. Thermal quality control of boiler setting.

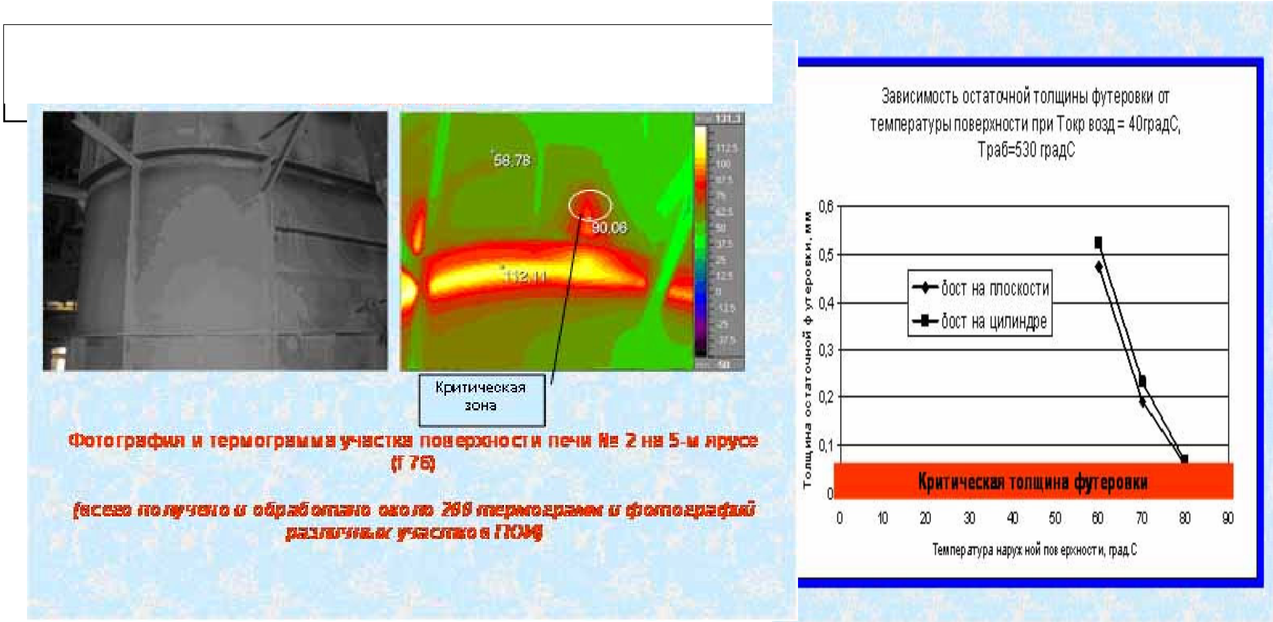


Fig. 8. Thermal control of brick-lining thickness of calcination furnace with critical area plotting.

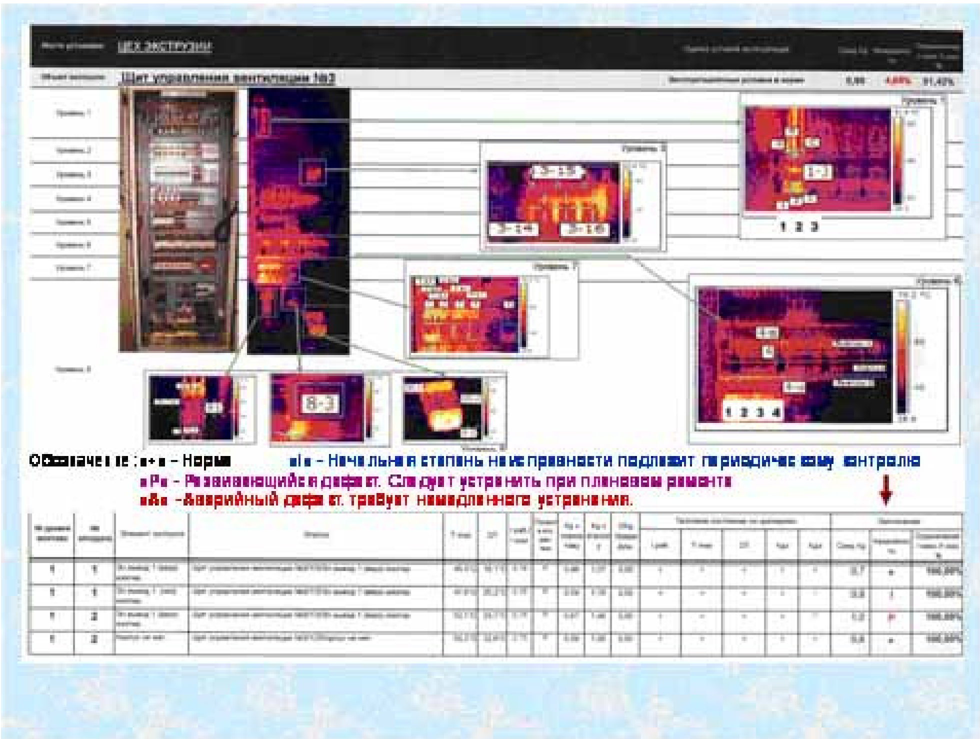


Fig. 9. Thermal control and diagnostics of technical condition of electrical equipment.

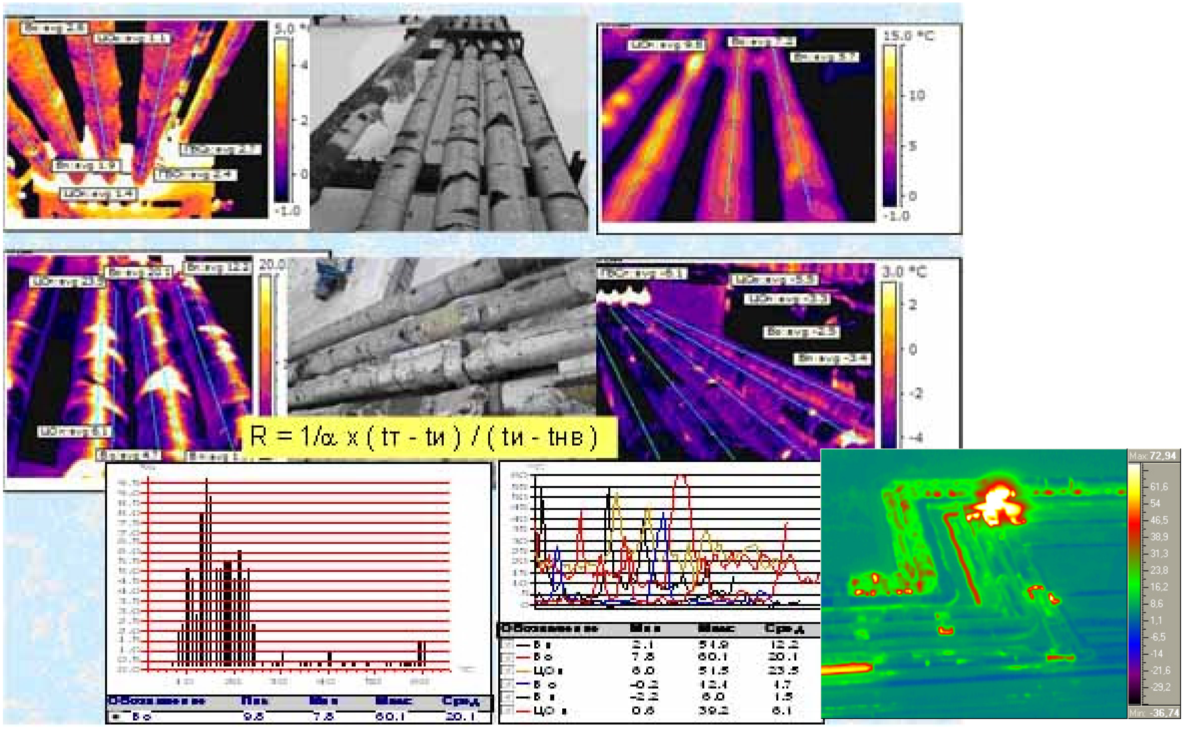


Fig.10. Thermal control and diagnostics of technical condition of heating mains.