MEANS FOR MEASURING THE THERMAL QUANTITIES

MATERIAL TEST AND RESULTS ESTIMATION BY SAFETY INDEXES

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Abstract. In the article, both the test method features and the test results of research of thermal behavior of steel fragment were analyzed. Two types of test conditions for steel construction material were considered. The definition and main features of measurement techniques were presented. Fire retardant material test results for steel plates with hydrogen combustion shown the limit of fire resistance of the tested samples is more than 30 min. The main advantages and disadvantages of the test were determined. The positive and negative aspects of this approach were analyzed. These techniques' effective thermal condition is in an environment of uncertainty and has no limited resources was established. Concepts and principles for establishing validity, and frameworks and methods for validating test methods and their results are important elements of safety systems. The article considers the safety of the technical component of a complex organizational and technical system with the study of the functional relationship between the safety elements parameters: temperature, time, fire retardant – by hydrogen participation.

Key words: Validation; Hydrogen fire temperature; Measurement method; Quality control; Metrological support.

1. Introduction

According to statistics, for the period from 1965 to the present (including the disaster in Japan at the Fukushima-1 nuclear power plant (NPP) around the world in the engine rooms with turbogenerators with a capacity of more than 50 MW, more than 110 emergencies were recorded. Of these, 40 were fires, 7 explosions, and 9 fire explosions [1–3]. In 26 cases, fires were accompanied by the collapse of the roof of the engine room, injuries to service personnel, firefighters and damage to processing equipment.

Energy facilities: NPPs, refineries, power lines, pipelines, etc. – are an example of a complex organizational and technical system, which consists of interconnected material objects (technical means and personnel that ensure their operation). That is a hierarchical human-machine complex that functions with purpose, realizing its properties to achieve the goal. There are several high-risks in this important sector of any country's economy. The article considers the safety of the technical component of a complex organizational and technical system by studying the functional relationship between the safety elements parameters: temperature, time, fire retardant – by hydrogen participation. The rapid spread of other hydrogen energy technologies (fuel cells, hybrid engines, energy storage, etc.) is forecast, the submitted research results will also be relevant for them.

The main source of fire hazards in the engine rooms of power plants is the hydrogen cooling system of the generator stator and the generator lubrication system. The engine rooms of power plants are one-story buildings. There are two rooms stacked on top of each other: turbines are installed in the upper one, condensers, drainage and other pumps and auxiliary equipment are placed in the lower one. Pumps, electric cables, and other communication lines are placed under the floor in the basement 3–4 m deep. Turbo units in the engine room are arranged on an “island” principle. There are platforms around the turbogenerators, which are interconnected by passages along the walls of the engine room. The transverse dimensions of the hall range from 28 to 54 m depending on the type of turbogenerator, longitudinal – up to 300 m. The distance from the floor to the rafters of the floor is 21–39.5 m. The load-bearing structures are columns and trusses of the floor, steel solid folding columns of I-beam sections made of steel 16G2AF and 10G2S1, 12–30 mm thick. [4].

The explosive properties of hydrogen mixed with air are listed in most referenced books [5]. However, bear in mind that later studies have found that large amounts of hydrogen can be explosive even at lower concentrations. The larger its volume, the lower the concentration of hydrogen becomes dangerous. The source of this widespread misconception is that explosives have been studied in laboratories on small scales. Since the reaction of hydrogen with oxygen is a chain chemical reaction that takes place by a free radical mechanism, the “death” of free radicals on the walls (or, say, the surface of dust particles) is critical for the continuation of the chain. In cases where it is possible to create “limit” concentrations in large volumes (premises, hangars, shops), note that the actual explosive concentration may differ from 4 % in both larger and smaller directions.

Consider the explosive characteristics of hydrogen mixed with air and oxygen. The process of hydrogen diffusion was investigated in the instantly releasing from sphere shell and mixing with air [6–8]. Based on the obtained data, the concentration limits are calculated (Fig. 1). The maximum amount of hydrogen that can take part in the detonation is 0.42 of the initial amount of hydrogen (for air) and 0.72 – for oxygen.

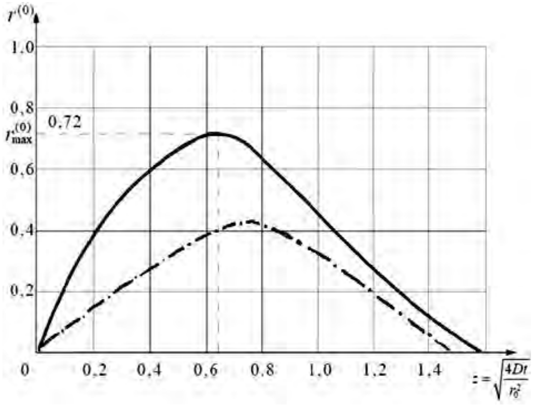


Fig. 1. The dependence of the ratio of the explosive mass of hydrogen to the initial mass from $z=\sqrt{4Dt/r_0^2}$) at the instantaneous release of hydrogen: into oxygen (line), into the air (-. -. -)

Heat exchange by radiation during fires in the engine rooms of power plants is about 40 % of the heat flux that falls on the bearing steel structures of the hall, the rest is convective heat transfer [3].

2. Drawbacks

The normative and technical base for methods of thermophysical characteristics research and tests for fire resistance are developed in [4, 9]. The calculated modes of fires express the relationship between the distribution of temperature indoors and time. By the standards of testing the limit of fire resistance the temperature curve (called "standard") is described by the expression:

$$T_s=345\cdot lg(8\tau+1)+20; \qquad (1)$$

where τ is the time counted from the beginning of the test, min; T_s is the temperature, ºC, which corresponds to time τ (average volume temperature of combustion products in the room).

The standard temperature mode reflects the conditional model is used to assess the behavior of products under the influence of a fully developed fire. The specified temperature does not reflect the real mode of fire, which significantly depends on such factors, such as the type of combustible material, airflow, ignition area. This temperature-time curve is a simplified representation of the thermal action of fire.

Although the standard (cellulose) curve has been used for many years, the values of the combustion temperature of some materials, such as gasoline, fuel oil, gas, etc., significantly exceed those values. Therefore, there is a need for alternative exposure for the petrochemical industry. For this purpose, we proposed standardized hydrocarbon curves, shown in Fig. 3, and described by the expressions:

$$T_{car}=1080(1-0,325\cdot e^{-0.167\tau}-0.675\cdot e^{-2.5\tau})+20 \qquad (2)$$

$$T_{carm}=1300(1-0.325\cdot e^{-0.167\tau}-0.675\cdot e^{-2.5\tau})+20 \qquad (3)$$

For extreme fire scenarios (e.g. transport tunnels, NPPs, etc.), stricter conditional temperature regimes can be set. These studies are performed in existing or abandoned tunnels and the laboratory. The result of the tests is a series of graphical temperature-time curves for different exposures, which do not have an analytical record yet but were obtained experimentally.

A way to stop the spread of flame through the material is to create a thermal barrier (solid phase) between the combustible and non-combustible parts. Fire-retardant coatings are often used; their role is to convert the polymer surface into coal, which separates the flame from the material and protects heat transfer to unburned parts. Non-halogenated inorganic and organic phosphate flame retardants usually act by this mechanism, forming a polymer layer of carbonated phosphoric acid [10].

3. Goal

Investigation of the behavior of fire-retardant coating under the thermal mode of hydrogen combustion as non-standard to update the limit of construction fire resistance definition and state building code requirements.

4. Assembling research method

Based on the application of a standardized method of testing the fire resistance of structural materials, it is necessary to determine the integrated values of test temperature parameters, as well as test error margins. In particular, the flame retardant is considered [11–17].

The problem of combustible gases in energy facilities is inextricably linked with the need for a study of gas-dynamic and thermophysical processes on surrounding structures [8, 18, 19].

This problem becomes relevant with the development of the concept of "acceptable risk" [20, 21]. At the same time, the issue of scientific validity and adequacy of calculation methods is one of the key issues for people.

Despite the researchers' attention, insufficient patterns are characterizing the parameters of the fire hazard of flammable gas emissions, especially for operating conditions of modern facilities. Thus, we developed methods for assessing primary hazards, the dynamics of development, and forecasting the consequences of emergencies related to emissions of combustible gases for individual tasks [8].

5. Calculation method adequacy justification

It is difficult to investigate fire resistance experimentally. The problem is with the overall dimensions of engineering structures or elements, placed and heated in the furnace. This method is energy-consuming and takes a long time to implement [10]. The results of structure studies cannot be applied to structures of other dimensions and materials.

Calculation and analysis of temperature field, temperature stresses, and displacements in structures of different geometric dimensions depends on the thermophysical and mechanical properties of materials (concrete, brick, metal, etc.) [22, 23]. The limit of fire resistance of unprotected steel building structures is in the range from **R** 10 to **R** 15. There are columns of the massive solid cross-section with a limit of fire resistance **R** 45. The thermal conductivity of the metal does not create a large temperature gradient inside the cross-section of the structure and causes its rapid heating.

This leads to the fact that in a fire the temperature of unprotected metal structures quickly reaches critical values (480–530 °C), at which point there is a decrease in structural strength, that leads to the structure's inability to withstand the external load applied to it, resulting in a limit state based on loss of load ability (**R**). Values of critical temperature T_{cr} of heating of various metal designs at normative operational loading are specified in Table 1 [4].

Table 1

Thermophysical characteristics of steel structures

Construction material	T_{cr}, ^oC	ρ, kg/m^3	Coefficient of thermal conductivity λ, $J/(s \cdot K \cdot m)$	Coefficient of temperature conductivity c_p, $kJ/(K \cdot kg)$
Carbon steel St3, St5	470	7850	$58 - 0.042t$	$0.47 + 2.1 \cdot 10^{-4}t$
Low-alloy steel of the 25G2S brand	550	7860	$58 - 0.041t$	$0.47 + 2.11 \cdot 10^{-4}t$
Low-alloy steel of the 30HG2S brand	500	7855	$58 - 0.042t$	$0.47 + 2.1 \cdot 10^{-4}t$

Studies of the mechanism of fire action on steel structures with fire retardant have not yet led to a sound approach to solving the problem of reliable assessment. Fire-resistance of steel depends on the distribution of temperature fields on the thickness of structures and protective materials and modes of fire action. Therefore, experiments allow substantiating such models [10, 24]. Consider the change in temperature of the flame of the combustion of hydrogen-air mixture, which is a minimum of 1800 K, depending on the concentration of hydrogen in the air. The duration of free emergency leakage of hydrogen is 3 minutes. This makes it possible to estimate the duration of combustion of the hydrogen jet and the effect of its torch on the load-bearing steel structures.

Given that the temperature of the flame torch is 1800 K and is reached in 15–20 s, the temperature of hydrogen combustion is mathematically modeled as [22]:

$$T_{fH2}=1800-(1800-T_0\cdot)\, e^{-0.315\tau}), \qquad (4)$$

where τ is the duration of the fire, s; T_0 is an initial ambient temperature, K. In Fig. 2, the standardized temperature mode of fire was compared with the modes of hydrocarbons and hydrogen combustion. Fig. 3 shows that the standardized temperature modes (curves 1–2) have lower maximum temperatures and a smaller gradient of temperature rise from possible real fires in the engine rooms of power plants (curve 3). Applying the direct method of calculating the nonstationary temperature field, we obtain the solution in the form of:

$$t(x,\tau)=\frac{\alpha_0\alpha_n}{\Delta}\times$$
$$\times\left(\psi_0(\tau)\sigma_n+\frac{\psi_n(\tau)}{\alpha_0}+\frac{\psi_0(\tau)}{\alpha_n}+(\psi_n(\tau)-\psi_0(\tau))\left(\frac{x-x_i}{\lambda_i}+\sigma_i\right)\right)+ \qquad (5)$$
$$+\sum_{k=1}^{\infty}\left[f_k\cdot e^{-\omega_k\tau}-\int_0^{\tau}e^{-\omega_k(\tau-s)}u_k(s)ds\right]\cdot X_k(x,\omega_k)$$

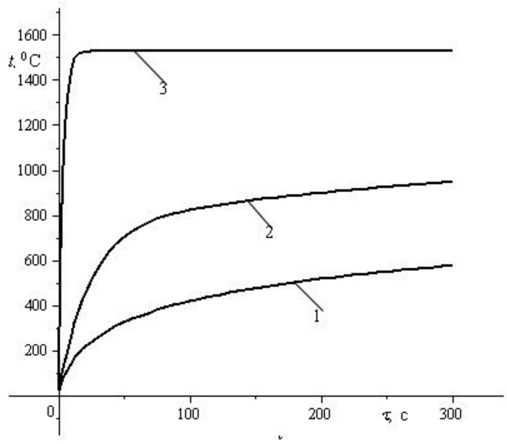


Fig. 2. Temperature modes of fire: 1 – "standard"; 2 – "hydrocarbon "; 3 – "hydrogen"

The characteristics of the main means of fire retardants at nuclear power plants in Ukraine are given in Table 2.

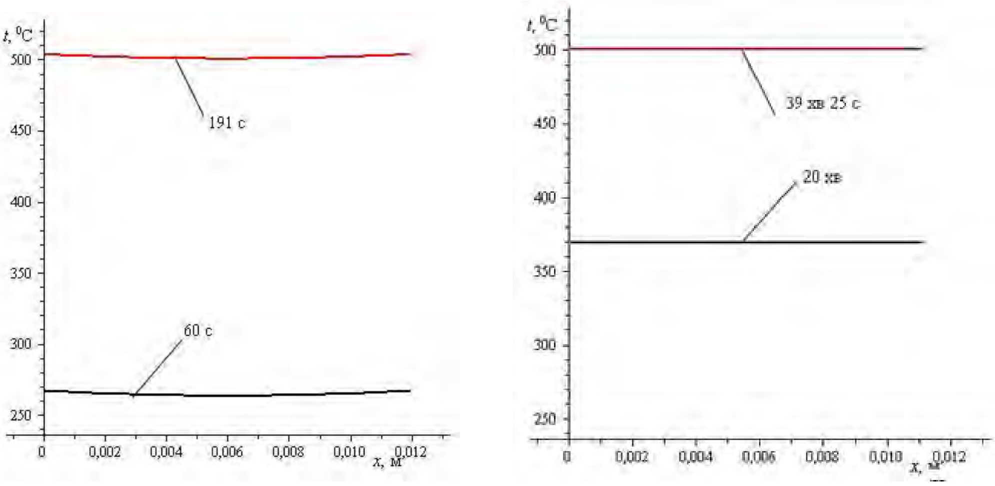
All these means certification tests were received on the standard mode of the fire (maximum temperature – 1520 K). As the flame temperature of the torch combustion reaches more than 1800 K, the effectiveness of the fire protection measures is questionable.

According to equation (5), the research of the temperature field through the thickness of the rafter truss was carried out. The initial temperature was taken 22 °C. The studies were performed for the temperature of the medium, which varies according to the hydrogen temperature mode (4) and different intensities of heat exchange between the fire flame and the structure. The results of the calculation are shown in Fig. 3. Its analysis reveals losing the fire resistance of unprotected load-bearing steel trusses for 60–191 s.

Table 2

Coefficient of thermal conductivity of fire-retardant coatings for steel structures

No	Means of fire protection	Producer	Coefficient of thermal conductivity, *J/(m·s·K)*
1	"Siloterm EP-6"	CJSC Elox-Prom (RF)	0.17
2	Metallax VM graphite 15 %, liquid glass 80 %, sodium silicon fluoride 5 %	BC Proxima (RF)	0.436 (unblown) 0.132 (burst)
3	"OFP-NV (Escalibur)" is a mixture of mineral fiber and an organic binder	Escalibur (RF)	0.075 at 2000 K
4	Paint "Endotherm 210104"	Specmaterials Group (Ukraine)	0.15
5	Paint "Interchar 963"	(Sweden)	0.2 – 0.4 (in the range 20 – 1500 °C experimental data)
6	"Unitherm ASR"	Unitherm (Germany)	0.15
7	Solvent-based Polylack-A	"Dunamenti Tűzvédelem Zrt" (Hungary)	0.5 (unblown) 0.05 (burst)
8	"Pyro-Safe Flammoplast SP-A2"	"St. Brandschutz "(Germany)	0.89 (unblown) 0.09 (burst)



a *b*

Fig. 3. Temperature field distribution of unprotected (a) and protected (b) rafter truss

6. Test quality indicators

Fire hazard indicators and test methods for construction, finishing, and installation materials are set in international, regional, and national standards and state building codes. Both for manufacturers and regulatory authorities, the implementation of such tests in full is problematic. Combining the efforts of different laboratories to ensure compliance with the requirements of technical regulation and, consequently, enhance fire safety is possible provided that their test results are accurate and consistent [25].

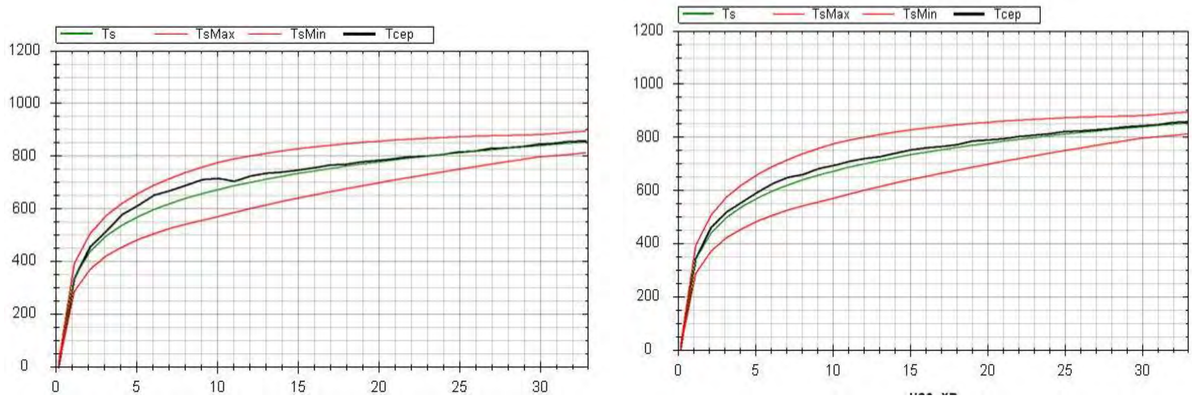
The ability to maintain operation under fire conditions is determined by IEC 60331. In Ukraine, it is assessed during testing of steel structural materials for fire resistance according to DSTU B V.1.1–11:2005 in a furnace, according to DSTU B V. 1.1-4-98*. The oven is designed to create a standard temperature (1). The limit state of fire resistance is the loss of functionality (sign *R*). During the tests, the excess pressure in the furnace must be (10 ± 3) Pa, starting from the 5th minute of the test. The environmental conditions in the laboratory must comply with DSTU B B.1.1-4-98*. The test result is the limit of fire resistance, determined by the equation:

$$t_{fr} = t_{mes} - \Delta t, \qquad (6)$$

where t_{fr} is the limit of fire resistance of the structure, min.; t_{mes} is the lowest value of time from the beginning of the test to reach the limit state of fire resistance, which is determined by the results of tests of the same samples, min; Δt is the test error, min. The error value t is determined according to Annex D [3] by the equation:

$$\Delta t = (0{,}015 t_{mes} + 3)(A_s - A_f)/(A_s - A_{\min}) \qquad (7)$$

where A_s, A_f, A_{min} are integral values (areas under the curves) of the standard temperature, the average temperature in the furnace, and the minimum allowable temperature in the furnace, respectively, °C×min. If $A_f > A_s$, then $t = 0$.



a *b*

Fig. 4. The temperature on the samples of steel plates with (a) and without (b) fire-retardant

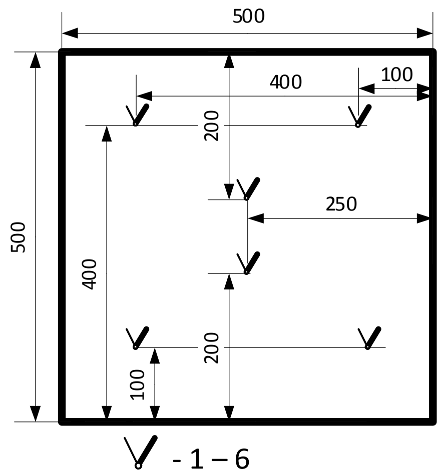


Fig. 5. Placement of thermocouples on the sample

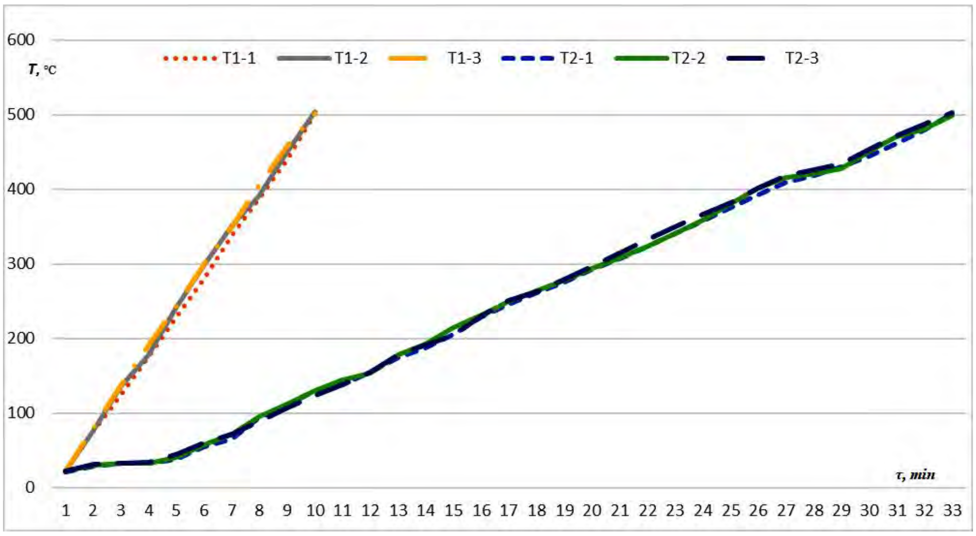
The results of temperature measurements are shown in Fig. 4. The values of A_s, A_f, A_{min} for samples of steel during the test time of 33 min were 23782; 24322.52; 21317.73 °C×min. The values of A_s, A_f, A_{min} for samples of steel with protection were 23354; 23882.23; 20910.07 °C×min. accordingly. The test error t calculated by (7) was 0 min since $A_f > A_s$.

A mixture of swellable flame retardant for steel structures was tested (solvent-based flame retardant coating "Polylack-A" – SFR-A). Samples are the prepared steel plates in the size of 500–500–14 mm with the put-on flame-retardant covering SFR-A. The sample was mounted in a horizontal position. 6 THA-10 (Type K) thermocouples are installed for each sample according to the scheme (Fig. 5).The surface of the unheated side of the plate was protected by two heat-protective layers, the first with a thickness of 10 mm, the second with a mineral plate 25 mm thick. The distance between the burner and the sample before the start of the test was lesser than 0.45 m. The test was ongoing until the temperature on the not heated plate side exceeded 500 °C.

7. Results of testing

There were conducted fire tests of 6 metal plates, three of which (samples 4, 5, 6) were with a fire-retardant coating with a thickness of 1 mm, and three plates (samples 1, 2, 3) without fire protection. After a layer of primer GF-021, 0.065 mm thick and the paint on the plates was formed a white matte surface (Fig. 6). To measure the thickness of the coating layer, a thickness gauge was used, which was used to measure the thickness at 9 points of the plate, the average layer thickness was 1 ± 0.2 mm.

After installation and fixing of the test specimens into the oven, they are subjected to a fire test until the critical temperature (500 °C). Fig. 6 shows that the coating swelled evenly in the center of the plate. The direct action of the hydrogen flame flare took place in the center of the plate. The fire-retardant paint applied to a steel plate with GF-021 primer was satisfactory adhesive strength; exfoliation of the formed expanded coating from the plate on the area was not observed. The measurement of the thickness of the expanded layer of the coating was carried out with a thickness gauge at 9 points of the plate. The average thickness of the swelled layer was 15 ± 3 mm.



Sample 5 Sample 6

Fig. 6. Experimental samples (number 5 – before testing, number 6 – after testing)

Table 3

Fire retardant material tests estimation for steel plates while hydrogen combustion

Safety index	T2-1	T2-2	T2-3	$\overline{x}$	s^2	σ
Index of the time of reaching the critical temperature averaged over 6 thermocouples, s	1912	1926	1907	1915.00	10.77778	3.28295
The temperature dependence index for a time of 30 minutes, °C	461	470	471	467.33	3.37037	1.83586

Concepts and principles for establishing validity, and frameworks and methods for validating test methods and their results are important elements for strengthening the understanding of the subject of materials behavior in emergency cases [26].

Fig. 7 – comparing the heat transfer through steel construction material and temperature change (°C) in time (minutes) on the non-heated surface of the plate, where: T1-1, T1-2, T1-3 – samples without coating, T2-1, T2-2, T2-3 – samples with coating SFR-A.

The based on experimental studies of the heating of steel structures, under conditions of hydrogen combustion, uncoated and with a fire-retardant coating SFR-A on a solvent basis, obtained results:

– the limit of fire resistance of a steel plate without a fire-retardant covering makes 9 min;

– the limit of fire resistance of a steel plate protected by a fire-retardant coating with a thickness of 1 mm – 32 min.

The disadvantages of this approach include:

– increased requirements for the qualification and experience of employees;

– difficulty in calculating the final amount of evaluation cost;

– resilience to changes, which makes impossible any changes to the material reaction to fire;

– an increase of risk – is already testing the finished product rather than its particles.

Therefore, the total value of test method compliance has to be increased [27].

Temperature change (°C) in time (s) on the non-heated surface of the plate, which is sample without and with coating SFR-A, are shown in Fig. 7.

After implementation of the material test results estimation system [28] according to safety indexes, it is received that:

– flame retardant tests have admitted several advantages and disadvantages in heat realizing or fire scenario implementation under uncertainty of measurement;

– it is necessary to provide the validation procedure by criterion validity per models of materials structure, parametrization, and behavior analysis or as the part of common quality assessing procedures;

– uncertainty of properties seems to be a feature that restricts applying of the particular type of materials which are inherent in the critical indexes of non-compliance with the technical regulation requirements;

– requirements for the high qualification and experience of the laboratory personal is necessary to constantly adapt to changes in the test technique and normative regulations.

8. Conclusions

1. The presented results of tests according to the ISO method on compliance with the requirements of fire safety standards satisfy the conditions of accuracy and convergence. The limit of fire resistance of the tested samples established by the test results is more than 30 min and the fire resistance class is *R* 30. Based on the standardized method of establishing the limit of fire resistance for building structures and engineering networks, the integral values of the temperature parameters of the test as well as the test error are determined.

2. Studies of heat fluxes accounting for the complex heat transfer of the fire flame have demonstrated that its value during hydrogen combustion in the engine rooms of NPPs is within 150–250 kW/m^2.

3. Studies of fire resistance of load-bearing columns and rafter trusses have shown that to ensure fire resistance of steel structures it is necessary to coat them with a fire retardant. The critical temperature (500 °C) of 32 (20) mm-diameter bearing column protected with the coating “SPF-A2” of 0.8 mm thickness, is not reached while the hydrogen combustion. This temperature of 5 (9) mm rafter trusses protected with 1.5 mm coating “SPF-A2”, is not reached while the hydrogen combusting.

4. According to the implementation of the system for evaluating the tests on safety indicators of the fire scenario under conditions of experiment uncertainty, a validation procedure for the certain models of materials structure, parameterization, and analysis of their behavior, is proposed.

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10. Conflict of Interest

The authors claim that there are no possible financial or other conflicts over the work.

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