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Protection of turbine halls of power plants from exposure to high temperatures in fire conditions

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Abstract. There are numerous cases when fires in power plant turbine halls causes the collapse of roof metal structures. The use of conventional firefighting equipment in high-bay facilities has proved to be ineffective or unacceptable. In this situation fire robots are the most feasible option. Today the best variant is a fire robot that is based on a traditional fire monitor and equipped with infrared fire seat detectors. Some specific advantages of fire robots include their ability to operate under low visibility with high smoke generation conditions that are typical of a fire in a turbine hall. The program of roof structures cooling down is designed and tested in advance so that fire robots can perform their functions in automatic mode. Fire robots can be included into permanent-type fire safety systems that are designed taking into account specific construction features of a facility and temperature conditions in case of a fire. Such composite system is a multifunctional complex that is able to perform versatile fire protection functions. The most appropriate fire robot types to be used in such complex fire protection system are fire robots based on conventional fire monitors, as they have some notable advantages compared with mobile robots or androids. One of them is their ability to protect big areas starting from 5 and up to 15 thousand square meters with fire suppressing media flow rate range just 20-60 l/sec correspondingly. Water or foam can be delivered via air exactly to the fire seat instead of spraying over the total designed area. Moreover, wetting intensity can be maintained at a level that corresponds to fire seat intensity.

1. Introduction

High fire hazard in the turbine halls of conventional and nuclear power plants is related with the presence of such risky factors as insulation of power supplying and control cable; short-circuit events in power cables; oil spillage onto hot equipment areas; human errors during maintenance activities and test runs; the use of flammable materials in electrical devices and instruments. Flammable waste that results from maintenance activities on equipment components or lubrication lines may also present a serious fire hazard [1-4].

Statistically fires at nuclear power plants occurred in the main plant facilities (47% of the total number of fire events), in auxiliary facilities (21%), in storage facilities and open production plants (16% each), i.e. in the areas that have vital importance for a nuclear power plant performance. The majority of fire events were caused by a failure in the production equipment – 48%; lack of responsible care in fire hazard activities – 24%; violation of fire safety rules during hot works – 8%; violation of equipment operation regulations – 15%; and some other causes - 5% [5].

Turbine halls are the areas with the highest fire risks because of flammable oils used in turbo generator oil systems and flammable highly explosive hydrogen used in the turbo generator cooling system.

The structure of fire events at nuclear power plants is as follows, in %: electrical equipment – 7; switch-yard gear – 21; reactor department – 28; turbine halls – 30 [1].

One of the most frequent causes of fire in the turbine hall is a failure in the turbo generator set [6]. For example, about 70% of fires in turbine halls were caused by a mechanical break of a turbo generator component. Such event may occur with a gush of burning oil, hydrogen jet fire or burning of oil spillage covering a significant floor area. About 18% of events had hydrogen leaks with subsequent combustion and explosion that resulted in disastrous consequences and personnel casualties [2].

According to statistical data within 25 years period, 97 accidents including 31 fires, 2 explosions and 2 explosions followed by a fire occurred in turbine halls of nuclear and fossil-fuel power plants that had turbo-generator installations of 50 MW and more capacity in the USSR and abroad. In 22 events the roofs of turbine halls failed, which is 21% of the total accident number in that period. In 2005-2011 136 fires occurred at Russian fossil-fuel power plants including the events with turbine hall ceiling collapse [5].

2. Some fire cases in the turbine halls

On December 31, 1078, during the first decade of Beloyarsk nuclear power plant (NPP) operation (Russia), an accident occurred at the turbo-generator installation No 2 with turbine oil combustion and a fire in power supplying and control cables. The fire was caused by the loss of integrity in the oil line with oil burst and subsequent oil spontaneous ignition due to its spillage onto hot turbine equipment and steam line surfaces. Before the fire brigades arrived at the site, the turbine hall ceiling had collapsed with failed roof area exceeding 960 m^2.

On October 15, 1982 fire occurred at Armyanskaya NPP (Medzamor, USSR). The fire was caused by explosion of the generator at Unit 1. The fire destroyed the cables on the area of about 400 m^2 and caused serious equipment damage in the turbine hall on the area of about 300 m^2.

In 1984 at NPP Rancho Seco (USA) hydrogen exploded in the turbo-generator cooling system, which caused fire and steam generator failure with subsequent radioactive steam release.

In 2017 the French media reported [7] an accident that took place on February 9 at Flamanville NPP. There was an explosion in Unit 3 turbine hall that caused fire. The event was caused by a short-circuit that resulted in the explosion of a fan. Because of the fire turbo-generator 1 was disconnected from the grid and Unit 1 reactor had to be shut down. Flamanville NPP is an operating nuclear power plant that is located in the North-West of France in the North Normandy Region.

On February 9, 2008 in Ulan-Ude (Russia) one of CHPP-1 turbines got on fire. At first an electrical cable caught fire, then the flame extended onto the turbine. The turbine held about 17 tons of oil. Finally, the fire area spread up to 1000 m^2. The event included a partial failure of the turbine hall roof.

On November 5, 2014 at Tomsk fossil-fuel power plant (Tomsk, Russia) a serious fire occurred in the power switchboard room. The fire was caused by oil line rupture in the area of the first turbine support. As a result, oil spilled into the switchboard room, which caused fire on the area of about 50 m^2.

On January 4, 2015 a fire occurred at Surgut power plant-2 (Surgut, Russia) that caused the collapse of two roof spans in the turbine hall of its power Unit 4 with failed area amounting 1300 m^2 (figure 1).

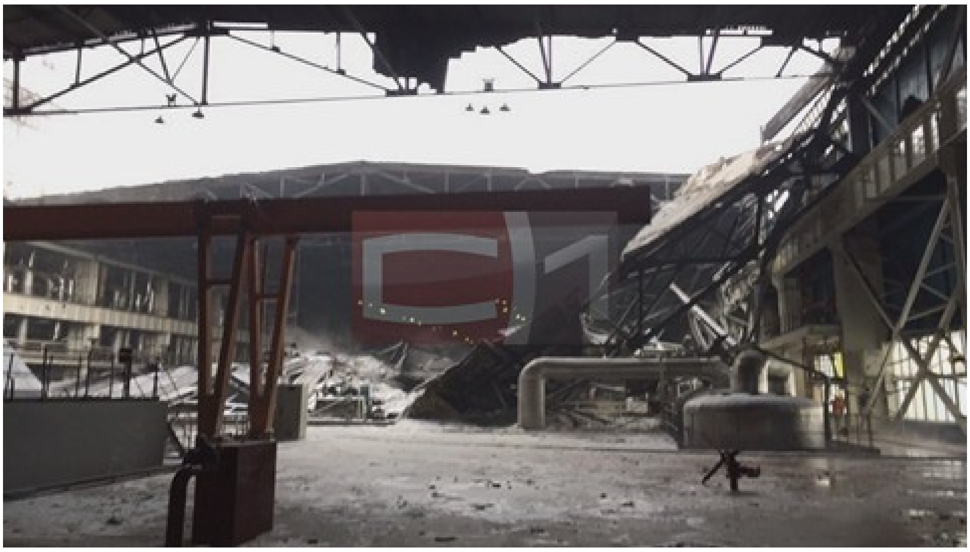

Figure 1. Failed roof of the turbine hall at Surgut power plant unit 4.

The fire was caused by ignited oil in the turbine hall close to feed water pumps. Surgut power generating plant is the biggest fossil-fuel electricity producing plant and the second one in the world. Its installed capacity is 5597.1 MW, the capacity of combined cycle power units is 797.1 MW; installed thermal capacity is 840 Gkal/h. The plant is located in Surgut, a city in Khanty-Mansi Autonomous Area. The plant utilizes associated petroleum gas and natural gas as fuel.

On December 7, 2015 a big fire occurred in the turbine hall of Vasylieostrovskaya thermal power plant (Saint-Petersburg, Russia). The fire area amounted 400 m^2. The fire was caused by a violation of equipment operating regulations, which resulted in the loss of integrity in the oil system of the fourth turbine and a complete rupture of a feeding pipe. As a result, oil under high pressure got onto the turbine hot surface and ignited to cause extensive fire. The fire flame rose at a height of 30 m causing the failure of the turbine hall roof.

3. Specific features of fires in turbine halls

According to fire and explosion hazard classification a fire in a power plant turbine hall belongs to the highest risk category. For example, a failure of the generator shaft oil seal may result in high temperature (over 2000°C) jet flame of burning hydrogen and oil mixture. Spreading flows of burning oil in combination with high temperature of hydrogen flame present serious threat for the integrity and load carrying capacity of metal structures, roof trusses and columns of the turbine hall. In such situation the temperature of unprotected surfaces of metal structures can reach its critical value (500°C) within one minute, which means that within this time metal trusses and roofing will fail [8].

The amount of oil leak from failed turbine control and lubrication systems can actually be about several tons because the capacity of the oil tank may reach 10 m^3 and the system of high-pressure oil pipelines is extremely branching. Within the time period starting from an oil pipe break till emergency disconnection of oil supply the oil leakage volume can become very big with much oil draining into lower elevation areas.

Traditional equipment layout makes fire conditions with burning oil even more complicated because oil tanks, oil pipelines and oil pumps are located at the zero elevation where oil spillage may catch fire and start burning, while generators and turbines with their control and instrumentation systems are located at higher elevations of + 8 … +10 m, i.e. in the zone affected by fire flames. So, there may be cases when fire begins simultaneously at different elevations: at the turbine floor and at mid-floors. In case of an oil system fire, the fire area may depend on the type of equipment damage and its location. Maximal known fire spread rate is 25 m^2/min. [9].

Oil that is burning at mid-floors or at generator floor presents significant hazard for unprotected roof trusses, because flammable products of combustion rise up to accumulate under the ceiling and heat metal trusses up.

Fire risks can be reduced by implementing fire protection measures. Turbine oil tank, turbine oil coolers, oil pumps of the generator shaft seal and hydrostatic rotor lift, oil pumps of the turbine oil supply and control system, generator and turbine surge tanks are protected by water spray systems that can be controlled both remotely and manually. However, the analysis of fire cases has shown that such measures may be either insufficient or inefficient.

4. Performance of metal structures under fire impact

In case of fire impact, the performance of building structures is characterized by the following processes:

- steel resilience and strength are reduced;
- steel becomes ductile with developing creep effects;
- as structures are heated up their inner internal stresses (such as bending and tensile stress) get redistributed;
- because structures are heated up unevenly, significant thermal stresses are developed therein, which can be compared with extra load impacts;
- eventually cross-section areas with developed limit conditions become inoperable while stresses in load-carrying elements are increasing; and
- plastic centroids are formed in the affected cross-sectional areas.

Metal trusses have an essential disadvantage as in case of fire they heat up faster, which causes their extensive destruction under weight loads at early fire stages.

As is shown in [10] theoretical and experimental studies of the performance of metal structures in fires have demonstrated that when metal trusses that are experiencing rated static loads are heated up over 500°C, they get deformed, lose their strength and collapse. That is why the temperature of 500°C is considered to be the limiting heating state. With heat source areas of 80, 50 and 35 m^2 the limiting heating state of a truss (with its subsequent deformation and collapse) is reached within 5, 9 and 16 minutes starting from the fire onset correspondingly.

Load carrying structures that have been damaged by fire may be abnormally deflected or fail completely. Considering multiple connections of building structures even a local failure can result in disastrous consequences for the building on the whole. That is why in case of fire such structures have to be cooled down. Therefore, one of immediate fire fighting measures in a turbine hall is to protect its enclosure and roofing against heat impact by discharging water from hydraulic monitors.

5. Standard methods of protecting metal structures

In engineering practice drencher or sprinkler systems are used to protect metal structures against high temperature impacts. However, they may be inefficient to use in turbine halls due to the following deficiencies [5, 11]:

- sprinkler system pipelines and sprinklers should be fixed directly on the trusses that support roof structures. It increases the loads onto the trusses and columns, especially when the system is filled with water, which may result in complete utilization of the load bearing capacity of these structures;
- sprinkler and drencher systems are usually hard to maintain and test because of their pipelines range and high positioning of piping and sprinklers;
- it is hardly possible to install a fire protection sprinkler or drencher system at existing operating power plants because it may overload the trusses beyond design based values;
- in case of fire the pipelines of sprinkler systems filled with water can be heated intensely with steam formation inside the pipeline, which may result in internal pressure growth and pipe rupture, or cause excessive actuation of sprinklers;

- both vertical and horizontal pipelines located at a significant height have low explosion resistance. In case of explosion one of main feeding or discharging lines can be easily damaged with loss of integrity, and that will disable a total section of the system.

Fire suppression agents applied onto the surface of metal trusses can also increase weight load, because the protected area may be rather large. Moreover, it may be very difficult to apply a fire suppression agent onto the structures of an existing building of an operating facility [11].

Thus, the most feasible method of protecting metal structures in an operating turbine hall is their cooling down by means of water discharged from hydraulic monitors. In this case it is very important that each point on the metal truss should be wet down by two dense water jets. Hydraulic monitors are suitable to focus high-rate water supply on the required area with less consumption of fire extinguishants.

After analysing the possibilities of using fixed manually operated hydraulic monitors in NPP turbine halls it has been found out that they are rather limited due to the following disadvantages:

- manually operated monitors require human presence in the fire area where the operator is exposed to such hazards as open flame, high temperature, toxic combustion products and smoke, as well as to the risks of building structure collapse and even radioactive releases;
- it is rather difficult to aim water jets precisely onto metal structures, because the pointing has to be done visually under heavy smoke formation conditions considering that according to available data the combustion of just 8 kg of turbine oil reduces the reach of sight down to 3 m at the elevations above 7.4 m [11];
- as roof trusses can fail very quickly, water discharge should begin immediately after fire has been detected. However in case of fire the operators in the turbine hall must take prompt actions to protect equipment and may not be able to operate several monitors at the same time; moreover, manual operation of monitors may require additional human effort of fire fighting detachments, which means that people will have to work in extremely hazardous conditions related with open fire, high temperatures, combustion products and smoke with taking risks of enclosure collapse or radiation explosion.

6. Modern fire fighting systems and advanced methods of protecting metal structures against high temperature impacts

Since lately fire fighting robots (FR) have been developing very quickly [12, 13]. They are based on remotely operated hydraulic monitors of permanent-type (figure 2). Their use ensures effective cooling down of metal trusses and guarantees fire resistance of structures within 30 min. This time is sufficient to isolate the fire and suppress it. Practical fire fighting experience has shown that operation time of hydraulic monitors in an NPP turbine hall can range from 8 to 20 hours.

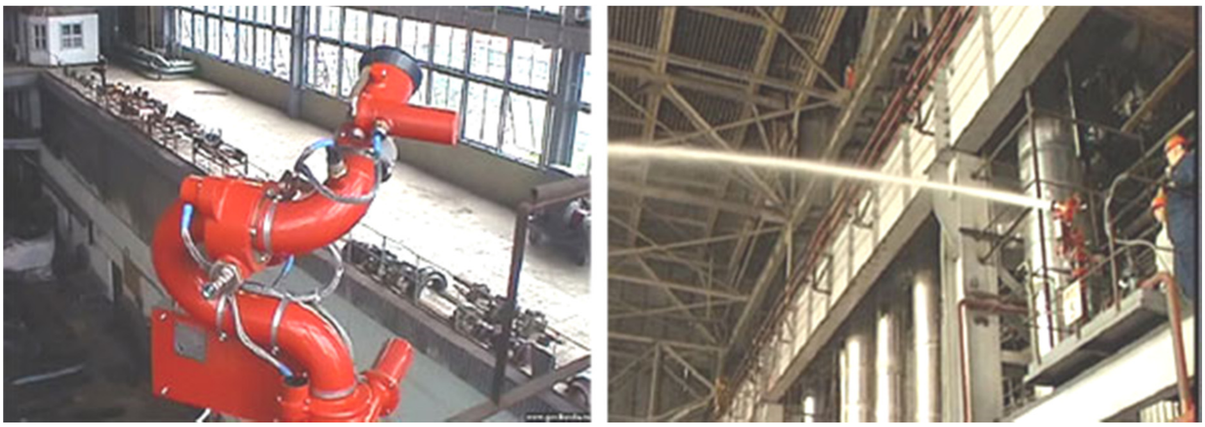

Figure 2. Fire robot (left), discharged water jet (right).

A fire robot generates water or foam jet and discharges it directly into the fire hot spot located at a significant distance. FR arm tool is a branch-pipe with a nozzle; water pressure is controlled

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automatically at a rate from 8 to 80 l/sec, which ensures the most optimal jet parameters. The robot can generate different jet types starting from a direct continuous jet and finishing with water screen. Water leaves the nozzle in the form of finely dispersed particles, so called Jet Fog (JF), with particle sizes ranging from 50 to 400 mcm. Due to high kinetic energy of big droplets the jet is able to reach a burning surface directly through the fire flame and deliver finely dispersed water particles that have high heat radiation absorption ability into the fire seat. Dosed water supply guarantees desired wetting intensity. Thanks to this performance feature the robot can respond to different fire development scenarios and ensure maximal capacity of feeding fire suppressing agents to the fire hot spot at an early fire stage.

FR is designed to vary the jet direction horizontally in 360° range and vertically in 180° range, thus covering the total space in its operation area. Jet angle can also be changed from 0 to 90°, so that different jet profiles are generated. One robot with water flow rate capacity of 20 to 100 l/sec can protect an area of 5000 - 15000 m^2. For example, a small-size fire robot operating at a water flow rate 20 l/sec with jet supply distance 50 m is able to protected an area over 7500 m^2 ($\pi R^2 = \pi 50^2$). The total amount of fire suppressing agent can be fed into the fire hot spot with wetting rate of about 1.2 l/ ($sec \times m^2$) on an area of 12 m^2, which ensures quick fire suppression at an early development stage. Thanks to dosed feed the wetting strength corresponds the heat rate of the fire hot spot.

To supply water to fire equipment only one main pipeline is used; it has no distribution network that is typical of sprinkler and drencher systems.

All parameters of the fire robot meet the requirements to automated firefighting equipment: it has a feature of automatic fire alarm; is able to fix hot spot coordinates and can be actuated automatically to start fire suppression either with water or with foam, if needed; it can also be used to cool down metal structures.

Compared with remotely operated hydraulic monitors, FR has machine vision function that is realized by an IR sensor with a scanner and a TV camera, and machine intelligence that corresponds to the level of performed tasks, including object recognition, target location and pointing, etc.
Fire hot spot detection sensitivity is 0.1 m^2 at a distance of 20 m; response time is several seconds and this time is enough to determine the fire size in 3D coordinate system.

A specific feature of fire robots is their ability to function under heavy smoke conditions with low visibility, which is a typical fire situation in turbine halls. Sophisticated trusted program of cooling the enclosure structures down is developed and tested in advance. Fire robots have wide operation range and high positioning precision. For example, the program can set up complex paths of the monitor nozzle motion and the patterns of water jet travel along the roof trusses of the turbine hall taking into consideration ballistic laws.

As the time period before trusses can fail is rather small, water discharge should start immediately after fire has been detected. Considering this requirement it is advisable to use fire robots united into a robotic firefighting system (RFS) controlled by a common software system [12, 14, 15].

RFS also comprises fire alarm system and TV monitoring system that are used to detect fires and send alarm signal to the security control room (fire point) and generate the signal to actuate fire suppression equipment and on-line monitoring of the situation in the fire hot spot area. Fire robots are connected via mains with network controllers and control devices. All information on firefighting progress is registered by means of TV cameras and the protocol of action development succession. During on-duty period the system operates in self-testing mode and informs operators about any adjustment needs by using a pre-set address, thus maintaining its functional readiness.

RFS is a multifunctional system that is able to accomplish different fire safety and fire protection tasks, such as fire detection and suppression with synchronous sending fire alarm signal and data on the current status of equipment to the plant security station (fire point room). RFS with water cooling unit can be used to cool down load bearing construction elements and protected equipment components that are located close to the fire hot spot.

Fire alarm system and TV monitoring system make a part of RFS and are meant to detect fires at early stage, generate fire alarms and fire fighting equipment actuation signals. They are also used for on-line monitoring of fire development conditions.

In the stand-by mode (alert mode) RFS water pipe system is filled with water up to the disk valves of FRs. The water is supplied either from fire suppression pump station or from utility-firefighting water pipeline under design pressure of 650 kPa. Foam maker pipeline is filled up to solenoid valves.

If addressable fire detectors of flame or addressable loop failure (in case of short-circuit or wire rupture) get actuated, light alarm window will be actuated on the control device with loop number identification and simultaneous actuation of internal audible alarm. Audible fire alarm and loop failure alarms have different sound tones. Multiple interface units will generate fire alarm and forward it to the RFS interface unit to launch fire fighting program. Following a preset program the RFS interface unit selects fire robots to be actuated, specifies fire hot spot angular coordinates and chooses fire suppression media with its discharge mode.

RFS has three operation modes:

- remote;
- self-acting;
- automated.

The first variant can be combined with the second or the third modes, in which case the operator can adjust RFS operation pattern so that to increase its fire fighting efficiency and ensure better cooling of building structures.

The second mode should be used for fire protection purposes in the absence of duty personnel.

As distinct from the second mode in the third one such RFS operations as searching the fire seat, opening disk valves and actuation of RFS interface terminals should be authorized by the operator. This mode is recommended as a regular method of the system operation in duty personnel’s presence.

If needed the fire fighting system can also be operated manually.

To cool down the building structures that are located close to the fire seat maximum two fire robots should be activated.

6.1. Remote mode of RFS operation.

The system is operated remotely from the control board (RCB) that is connected either with FR connection box or with RFS interface terminal, or radio control unit (RCU) that is operating within a radio signal range. In this mode the system can perform the following commands:

- select FR(-s);
- open/close disk and solenoid valves;
- point FR (control its horizontal and vertical motion);
- set FR travel speed (8 rates);
- change the jet angle;
- set up program mode (spherical rectangle line-by-line scanning) and register program mode parameters in the FR non-volatile memory – 8 programs;
- start up/stop the program mode; and
- set up FR motion limits in vertical and horizontal planes.

The following information on the current state of the controlled FR is displayed either at RCB or RCU:

- set up FR speed;
- current magnitude of the operating electrical drive;
- water pressure;
- operating data of electrical drives;
- current state of disk valves (open/closed);
- emergency alarms.

6.2. Self-acting mode of RFS operation.

The decision about RFS operation in automatic mode shall be taken by the duty operator at the permanently manned control centre. If within 5 minutes after receiving a fire alarm the operator issues no control signal, fire suppression will start automatically.

Visual control is performed by means of a TV camera that is installed on the fire robot and can be pointed at the fire seat together with the FR to transmit video data on the current situation in the protected area to the operator’s display. RFS program ensures the following mode of automatic operation of a FR with fire seat detection function:

- at addressable fire indicator actuation the control-and-indicating unit sends the signal “Fire” to the RFS interface with identifying the number of the actuated indicator;
- upon this signal the RFS interface generates control signals to point minimum two respective fire robots at the identified zone;
- upon entering the identified zone, the fire seat searching program is launched and fire detectors send seat location coordinates to RFS interface;
- upon receiving the signals from two FR the RFS interface determines fire seat coordinates in 3D system and forms fire suppression program;
- at RFS start up for fire suppression the RSF interface forms the following instructions:
  - to disconnect production and electric equipment (if needed), disable ventilation and actuate public fire alarm system;
  - for the pump control cabinet to start up pumps according to a specially designed program;
  - to open disk valves and solenoid valves of the relevant fir robots;
  - to start up FR;
- FR control unit controls the pressure in the RF at the designed level by controlling disk valve position;
- minimum two fire monitors start fire seat suppression.

When the distance to the fire seat is relatively small (up to 15 m) the fire is suppressed by water spraying at a preset angle; at a bigger distance line jets are applied airy.

7. Conclusion

Fire robots have enjoyed extensive use since early 2000-ties. They are one of the most reliable firefighting means, because this equipment is started following actual conditions in the protected area and are able to suppress fire without human involvement. Today fire robots are widely used in different industrial and agricultural spheres. For example, fire robots are used to protect turbine hall of fossil-fuel power plants, for instance, they have been on duty at Petrozavodsk thermal power plant since 1997. Automated stations based on robotic fire suppression systems have already been implemented to protect high-bay building structures at dozens of facilities in different Russian cities and outdoor facilities, examples are sports and concert centres, wood processing factories, refineries and chemical plants, plane docks and major oil storage sites.

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