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ASSURANCE FIRE SAFETY OF POWER FACILITIES DUE TO DEVELOPMENT AND APPLICATION OF FIRE EXTINGUISHING MOBILE ROBOTICS

As a result of statistical data analysis on fires and accidents that occurred on power facilities, specific features have been identified for suppressing such fires. One of them is exposure of persons participating in firefighting to hazardous factors and associated events. This results in interruption of fire suppression, as people and equipment have to be removed to a safe area. In order to ensure fire suppression in a hazardous environment, it is proposed to use mobile fire suppression robots that are capable of operating under the conditions considered. Technical specifications of mobile robots, that largely determine their operational efficiency, have been evaluated and substantiated. Technical requirements have been specified and used as the basis for developing a prototype of the mobile robotic fire suppression unit designed for application at power facilities. Robotic fire suppression unit tactical capabilities have been assessed under the given conditions, with a favorable result.

Keywords: fire suppression robots; power facilities; firefighting robot functionality; fire-extinguishing agents; remote controlled fire turntable monitor; fire-extinguishing agent supply range.

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Introduction

Suppression of various fire types is essentially a set of measures aimed at providing conditions that prevent the fire from spreading further, eliminate the hazard for human health and life, and create all the prerequisites required for complete elimination of the fire. Fires occurring at various facilities are different in terms of their nature and, therefore, will require different suppression tactics. This is mainly related to the facility specific features and the fire load located at the facility. As far as fires at power facilities are concerned, it should be noted that besides the fire hazards that affect the persons who participate in firefighting, events resulting in collapse of building structures, exposure to radioactive radiation (nuclear power facilities), explosions of pressure vessels, electric shock, etc. may occur.

A well-known example of such events is the major industrial disaster at Chernobyl nuclear power plant (NPP) that took place on April 26th, 1984 (Fig. 1). Suppression of fire that followed the explosion was complicated by exposure to extremely powerful ionizing radiation, as well as by over 30 fire areas emerging at different plant elevations. Electrical equipment was on

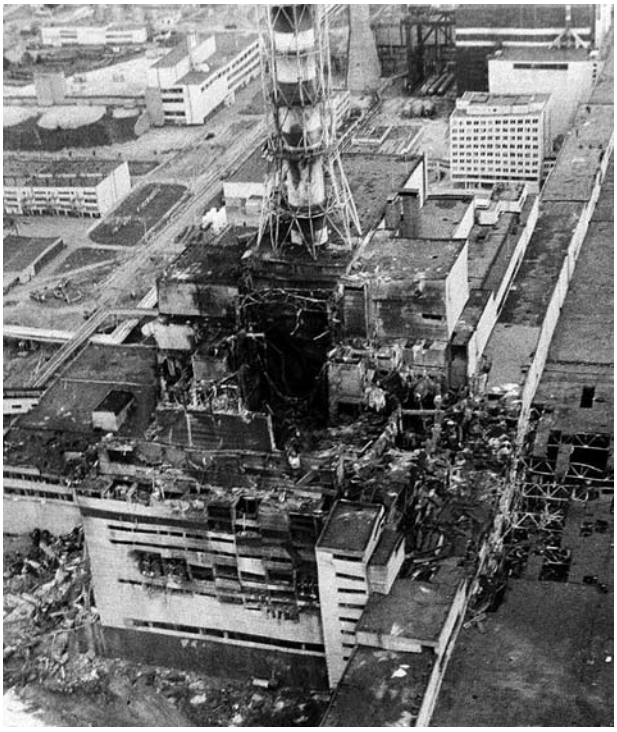

Fig. 1. Explosion and fire consequences at Chernobyl NPP

fire, the machine hall roofing collapsed and damaged oil pipelines that subsequently ignited, etc. [1, 2].

Fire departments and plant personnel acted with resolve, eliminating the fire and preventing even more disastrous consequences. Everyone who participated in fire suppression received high radiation doses. Operations had to be carried out under heavy smoke conditions, with exposure to high temperatures and open flames, and the hazards of electric shock and building structures collapse. For many of those who was fighting fire in the first hours of the accident, the radiation dose received proved to be lethal.

When evaluating the modern state of power facilities in terms of fire safety, it must be noted that even with the state-of-the-art safety level they are still exposed to risk of fires. When suppressing these fires, firefighters and facility personnel will have to face exposure to hazardous factors, including hazards related to radioactive or chemical exposure. This is also confirmed in the papers of our foreign colleagues who refer to a comprehensive approach as far as safety assurance is concerned [3–5].

After the accident at Chernobyl NPP, great efforts were made to determine the limitations in power facilities safety assurance. Appropriate conclusions were made regarding tactical and technical improvement of measures aimed at higher efficiency of fire suppression and better assurance of firefighters safety. Using mobile robots was one of the above-mentioned technical solutions. In general, the Chernobyl accident became a starting point for developing and applying mobile robots in special operations. To contain the accident, a lot of mobile robotic systems were designed within record-breaking schedules. These robots were mainly used for area decontamination, removing radioactive debris from the power plant roofing, situational monitoring and many other tasks. The total deployed number of various mobile robots, including from foreign countries, was around 40. Applying robots in the specific conditions helped avoid using humans in many operation areas, helping save dozens of lives [6].

Using mobile robotic systems for fire suppression has not been overlooked either. For example, A. K. Mikeev in [7] devoted as much as a whole section to the problem of fire robots development and application. The section focuses on main design prospects, and provides information about how this concept is being implemented in foreign countries. And this was already in the early 90s.

Today, robotic systems are applied almost in all branches of activity. They play a special part in tackling the objectives assigned to units of the Russian Emergency Ministry, employed for a range of operations from situational monitoring to bomb disposal and fire suppression.

At present, the use of fixed robotic fire suppression units to ensure fire safety of electric power plant machine halls has become quite common. These units are capable of automatically detecting and eliminating fire areas [8]. However, power facilities have a rather high number of areas with potential fire hazard, where flammable materials are concentrated. These areas are situated in hard-to-reach and cluttered locations where using fixed systems is inefficient. In such a case it is more feasible to apply mobile firefighting robotic systems that are capable of maneuvering in space and providing access to hard-to-reach and cluttered areas.

If we consider the issue of using mobile firefighting robots at power facilities, it should be pointed out that, in general, this concept has not been fully implemented. Not enough attention has been given to developing and using mobile firefighting robots, although the need to develop them was evident. Therefore, this paper is mainly aimed at justifying the design requirements for a mobile robotic fire suppression vehicle (RV) developed for power facilities taking into account the specific fire suppression tactics at those facilities. To achieve the above-mentioned aim, the following objectives had to be met:

- determine robotic vehicle functionality and select the technical equipment for its implementation;
- carry out a study of the robotic fire suppression vehicle tactical capabilities;
- specify technical requirements to robotic vehicle design intended for use at power facilities and manufacture its prototype.

Determination of robotic vehicle functionality and selection of technical equipment for its implementation

The first step certainly consists in determining the robotic vehicle functionality. This means that its design must include the necessary set of actuating mechanisms required for field tasks based on the accumulated experience of their application to contain various types of fires.

Analysis of fires and accidents occurring at power facilities over a range of time reveals that the specific tactical fire suppression techniques is related, firstly, to presence of large flammable load consisting of solid and liquid flammable substances and materials, and secondly, to electrical equipment running under high voltage.

Due to large quantities of flammable load, emerging fires spread across significant areas, therefore a large amount of fire extinguishing agents (FEA) must be supplied in order to contain them. This is confirmed by reference data, specifying the required rate of fire extinguishing agent supply for suppression of fires in electric power plant machine halls at 0,2 $l/(m^2 \cdot sec)$ [9].

Besides combustion of solid flammable substances, combustion of flammable liquids has occurred as well, including transformer oil contained in lubrication systems of turbines and other equipment. Hence, the robotic vehicle must be capable of supplying a significant quantity of FEA into the fire area. Besides water, it must also supply foam solution with a range of at least 30 m. This will ensure that a sizable area is covered and that building structures are cooled. In order to implement the above-mentioned measures, it is necessary to provide a remote controlled fire turntable monitor with the fire extinguishing agent flow rate of up to 20 l/sec.

However, the main feature of fire suppression at power facilities is extinguishing live electrical equipment on fire. Statistical information analysis for fires at power facilities has revealed that between 2005 and 2016 they suffered from 5066 fires. 38 % of those fires occurred directly on electrical equipment (Fig. 2) [10–13].

The task of suppressing electrical equipment fires has alway been the most critical and demanding because of electric shock hazard. However, as far as power facilities are concerned, their specifics must be taken into account, i. e. that parts of equipment cannot be deenergized even if on fire, because it is critical for the safe operation of facility.

A mobile fire suppression robot is a system capable of adapting to the actual conditions of an accident or fire, including presence of live equipment. This capability makes it an efficient fire suppression appliance. Robotic systems, as well as humans, are threatened by leakage currents flowing through the FEA jet, that can cause the RV to fail if they affect its electronics. Extinguishing electrical equipment on fire using water and water/foam compounds supplied by standard monitors is not safe because of high jet conductivity. Therefore, an auxiliary fire suppression appliance must be selected, where leakage currents through the jet are minimum, and that is most suitable for using in combination with mobile robotic systems.

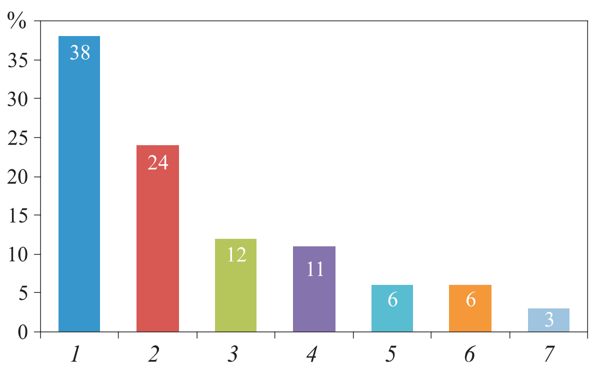

Fig. 2. Equipment with the highest risk of fire break-out: *1* — cable systems; *2* — oil pipelines; *3* — oil pumps; *4* — turbine generators; *5* — electronic equipment; *6* — transformers; *7* — ventilation systems

Assessment of fire-extinguishing compounds suitable for suppressing fires on live electrical equipment has demonstrated that finely dispersed water with an average droplet diameter below 200 μm has excellent fire extinguishing properties [14].

Water-cutting jet fire suppression unit was selected as the delivery appliance, implementing both the surface, and locally applied saturation fire extinguishing principle. The main advantage of the unit is that fire-extinguishing agents can be supplied into the volume on fire through the building structure envelope by destroying it with the mixture of water and abrasive particles. The average size of liquid droplets generated by the unit is around 170 μm [15–17].

To assess the possibility of using the systems in question for fire suppression on live electrical equipment, experimental studies were carried out. As a result, operational parameters of fire suppression units were determined when used by fire and rescue team personnel. Besides, it was found that when the units are used in combination with mobile robots, it is acceptable to suppress fires at a minimum distance of 0.5 m, if the unit monitor installed on the robot is connected to it using dielectric connectors, and if leakage current protection devices rated at 1 mA are integrated into the robot design [18].

Study on the robotic fire suppression vehicle tactical capabilities

Determination of the fire-extinguishing agent delivery maximum range

Technical capabilities of the robotic vehicle must ensure that it can be applied not only in open areas, but in many rooms of the electric power plant. To a large extent, this can be achieved by reducing the robot's overall dimensions and fully loaded weight. To meet these requirements, the RV design must have no onboard FEA reserve, but only fire suppression appliances and other equipment are to be included. Fire-extinguishing agents should be supplied to the RV via hose lines. Accordingly, conditions must be determined that define the robotic vehicle tactical capabilities.

Also, it should be taken into account that when mobile robotic systems are used for fire suppression, the maximum range of fire extinguishing agents delivery through hose lines, including hydraulic losses, must not result in reduced intensity of agents supply into the fire area.

Head losses are divided into local and line losses. Line losses occur as a result of transported liquid friction against pipeline walls and between the walls; local losses occur as a result of flow deformation (valves, transition pieces, etc.) [19].

In general, round pipeline head losses along the line h_l (m) are calculated using the Darcy–Weisbach equation:

$$h_l = \lambda \frac{l}{d} \frac{v^2}{2g}, \qquad (1)$$

where λ is the flow friction factor;
l is pipeline length, m;
d is the wetted cross-section diameter, m;
v is the average liquid flow velocity, m/sec;
g is the gravity acceleration, m/sec^2.

The main criterion describing head losses with any given parameters of pump/hose system operation is the flow friction factor λ that depends on flow velocity and internal surface roughness. Determination of the flow friction factor is a rather challenging task. Therefore, as demonstrated by research work analysis, it should be determined empirically for specific operating conditions.

When one considers water-cutting jet fire suppression units, it should be pointed out that they operate at a pressure of 30 MPa, and the fire-extinguishing agents being transported consist of not only water, but are essentially a mixture of water and abrasive particles intended for cutting structures. Therefore, additional head losses occur during mixture transportation due to movement of abrasive particles. Head losses during mixture transportation i_{mix} (m) are determined according to the following formula:

$$i_{mix} = i_w + \Delta i, \qquad (2)$$

where i_w is specific head losses during water movement, m;
Δi is additional head losses, m.

Specific head losses during water movement can be determined using the Darcy–Weisbach equation, additional losses are calculated as follows

$$\Delta i = \delta \sqrt[4]{j^3} \sqrt{C_0^2}\ (V_{cr}/V), \qquad (3)$$

where δ is the factor to account for the effect of relative ground particle size d/D with regard to pipe diameter;
j is the factor to account for unevenness of solid particle size;
C_0 is the actual weight consistency;
V_{cr} is the critical mixture movement velocity whereby particles begin to travel along the flow, m/sec;
V is the flow velocity, m/sec.

The calculations using formulas (1) and (3) have demonstrated that head losses due to presence of hydroabrasive particles are less significant in comparison to hydraulic losses of water. However, bearing in mind that fire suppression units have a certain nondeterminism in terms of their performance, head losses of both water and cutting particles mixture and, therefore, the flow friction factor, must be determined by way of trial to ensure that accurate values are obtained. As a result of experimental studies, maximum ranges of fire-extinguishing agent delivery via hose lines were obtained for water and cutting particles mixture, which amounted to 317 and 290 m correspondingly. Besides, the flow friction factor was determined, characterizing head losses during water transportation through hoses of water-cutting jet fire suppression units, being equal to 0.019 [20].

When a fire suppression robotic system is operated in combination with a high pressure finely dispersed water fire suppression unit, the hose line (high pressure hose) is laid automatically from on-board the robot. In this case, no additional requirements are applied to the robotic system traction capabilities for laying the hose line. If the fire-extinguishing agent is supplied using the integrated, remote controlled monitor, the hose line is laid using the method of line pulling. This results in higher requirements applied to the robot's traction performance to ensure that it can travel with the hose line when approaching the FEA supply position and that it can maneuver with the hose line.

Traction force determination

To determine the traction force that the robotic vehicle must ensure, experimental studies were performed using general purpose firefighting pressure hoses. The hoses were moved on three types of surface most wide-spread at power facilities: tiles, cast-in-place floor, and asphalt. The resulting friction force was measured. The studies helped obtain the friction factors that characterize hose friction against the surfaces examined, configurations for supplying fire-extinguishing agents using RVs were evaluated, and the most feasible option for supplying agents was selected. It was found that in order to implement this option, the RV must provide a traction force of at least 1000 N [21].

As the vehicle base, a unified electromechanically driven tracked chassis was chosen that will ensure RV application in minor debris and heavy smoke environments. To supply fire-extinguishing agents, it can be equipped with a remote controlled fire turntable monitor or a nozzle for supplying high pressure finely dispersed water or water-cutting jet.

Technical requirements to the robotic vehicle design for application at power facilities

As a result of studying the tactical specifics of mobile robot application for fire suppression at power facilities, the following technical requirements to robotic vehicle design were determined (see Table).

For practical implementation of the specified technical requirements, it is feasible to use a unified remote controlled vehicle platform that is equipped with specific firefighting tools depending on the objective to be tackled.

Technical requirements to RV design

No.	Parameter	Parameter value
1	Intended application	1. Fireground reconnaissance, data acquisition and situational monitoring. 2. Fire suppression, emergency rescue operations (ERO)
2	Application environment	Land
3	Functionality degree	Multifunctional (versatile)
4	Fire suppression and emergency rescue operations (ERO) equipment installed	1. Remote controlled fire turntable monitor with FEA flow rate 15 to 20 l/sec. 2. Fire suppression unit nozzle with water-cutting jet. 3. Robotic manipulator arm
5	Used fire-extinguishing compounds	1. Water, water/foam solution. 2. Finely dispersed water (170 μm). 3. Water/abrasive particle cutting mixture
6	Drive type	Electromechanical
7	Base vehicle propulsion type	Track
8	Traction force	No less than 100 kg
9	RV type	Light-weight
10	RV class	1
11	RV weight	Over 100 to 300 kg included. Subclass, 101 to 150 kg included
12	Overall dimensions	Not more than 1500×900×1900 mm
13	Continuous operation time	No less than 4 h

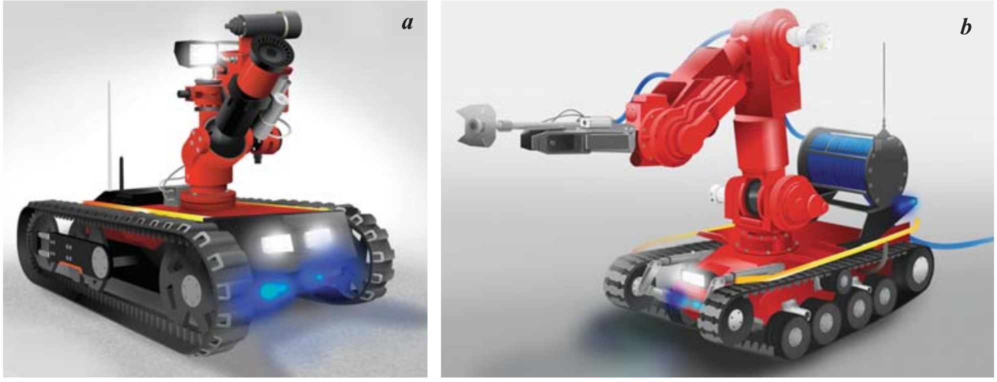

Fig. 3. A system consisting of first (*a*) and second (*b*) versions of robotic vehicle model

Fig. 4. Mobile robotic fire suppression unit

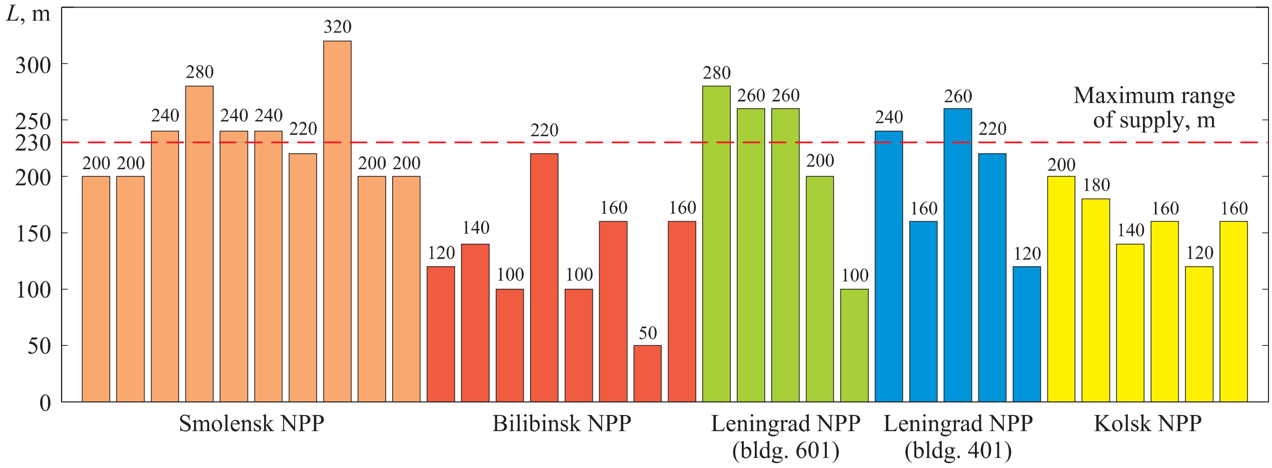

Fig. 5. Maximum range *L* of fire-extinguishing agent supply by means of MRFSU equipped with fire turntable monitor

The first RV version is a remote controlled track chassis platform with electromechanical drive, carrying a remote controlled fire turntable monitor with FEA flow rate of 15 to 20 l/sec, equipped with a robotic vision system, lights, infrared imager to locate fire areas, and a set of equipment required to ensure RV operation (Fig. 3,*a*).

The second version of robotic vehicle is a remote controlled track chassis platform with electromechanical drive, carrying a robotic manipulator arm with a gripper, having five degrees of freedom, and a fire suppression unit nozzle with water-cutting jet. The robotic manipulator will be used for tactical firefighting techniques with the fire suppression unit nozzle, as well as for dismantling and transporting structures and equipment during emergency rescue operations (Fig. 3,*b*).

At the moment, a prototype of RV version 1 has been developed. It carries a remote controlled fire turntable monitor with the water/foam fire-extinguishing agent flow rate of 20 l/sec (Fig. 4). The vehicle has been named as “mobile robotic fire suppression unit” (MRFSU).

A feature of MRFSU is that it can operate in gamma radiation environments with the strength of up to 10 Sv/h. To verify this condition, experimental studies have been carried out. These studies involved exposing the MRFSU to gamma radiation with the above-mentioned strength for the period of 4 h. The study results confirmed that MRFSU can be used for operations under gamma radiation of up to 10 Sv/h.

For evaluating MRFSU tactical capabilities, premises of operational nuclear power plants were considered as an example (Fig. 5). The benchmark applied was the effective range (penetration depth) of the robotic vehicle that depends on the distance of water supply through the hose at initial pressure of 10 atm provided by the fire truck tank located at the water source. As a result, it was found that fire-extinguishing agents will be supplied to rooms that are considered as protected assets in 75 % of cases.

MRFSU tactical capabilities that confirm its efficiency were evaluated for the considered conditions of nuclear power plants. To increase efficiency and promptness of MRFSU application, tactical techniques are to be worked out for each specific facility individually, taking into account location of water sources, facility layout, and location of rooms and equipment with the highest fire hazard.

Conclusion

Using mobile robots for suppressing fires at power facilities is a challenging operation. The need to apply mobile robots is not present at every fire or accident, but in certain cases it is the only option to ensure that firefighting action continues with the hazards that emerge. This helps replace humans and, therefore, save people’s lives and health.

The model of mobile robotic fire suppression unit that has been developed combines the features of a highly maneuverable vehicle, applicable for reconnaissance and fire suppression. When it is used along the fire and rescue department personnel, it can increase fire suppression efficiency and ensure safety of participating persons.

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