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# Route Optimization Methods for Response to Radiological Emergency Situations

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**Abstract.** The work actualizes the need for regional authorities to be ready to respond to possible radiological emergencies due to the ever-expanding use of radiation sources in various fields of activity (besides nuclear reactors) to ensure the safety of sustainable development of cities, territories and regions taking into account the human factor. Described are the developed routing optimization algorithms using mathematical modelling methods to minimize the radiological impact on emergency formations personnel while eliminating possible radiological emergencies. Presented are the results of computational experiments to assess the reduction of personnel exposure during route optimization of work in radiation-hazardous conditions. The recommendations on the use of the developed algorithms during the operation and decommissioning of nuclear facilities are formulated.

## 1. Introduction

Any industrial technology, including energy technology, has a certain danger, i.e. the possibility of harmful effects on humans and the environment, poses a threat to the health and life of operating personnel and the public. Nuclear technologies, along with the dangers inherent in other technologies, have a specific hazard (radiation) associated with exposure to ionizing radiation. Thus nuclear technologies determine a special approach to ensuring the safety of its use [1].

The use of radiation sources in various fields of activity, in addition to nuclear reactors, is expanding every day. Despite the precautionary measures envisaged, accidents involving sources of radiation occur more frequently than at nuclear reactors. Such accidents usually affect a small number of people. However, for these people the consequences of the accident can be quite serious.

Currently, international guidelines developed (for example, [2]) contain general response instructions designed to protect the public and emergency workers in various types of radiological accidents, including accidents involving closed and open sources and nuclear power generators, as well as accidents involving transport. The main objectives of emergency response are to reduce the risk or mitigate the consequences of an accident at the place of its occurrence, prevent the development of deterministic medical effects and reduce the risk of stochastic ones by taking protective measures, and also by keeping individual doses received by the public and emergency workers at a level not exceeding the threshold which is set in regulatory documents.

In many radiation accidents that are not related to nuclear reactors, the danger due to radiation is often less than the danger caused by other factors (for example, fire, hazardous chemicals). Therefore, priority should almost always be given to the non-radiological aspect of a radiation accident: saving lives, treating injuries, fighting fire, protecting essential equipment and ensuring personnel safety. As



soon as the overall situation is stabilized, immediate actions should be taken to reduce the risk of radiation damage to the population, emergency workers and the environment [2].

Accidents with radioactive sources or material are a broad category, including detected radioactive material, contaminated areas or objects, missing or lost sources of radiation, unprotected sources, accidents in laboratories, in industrial or scientific facilities, transport accident.

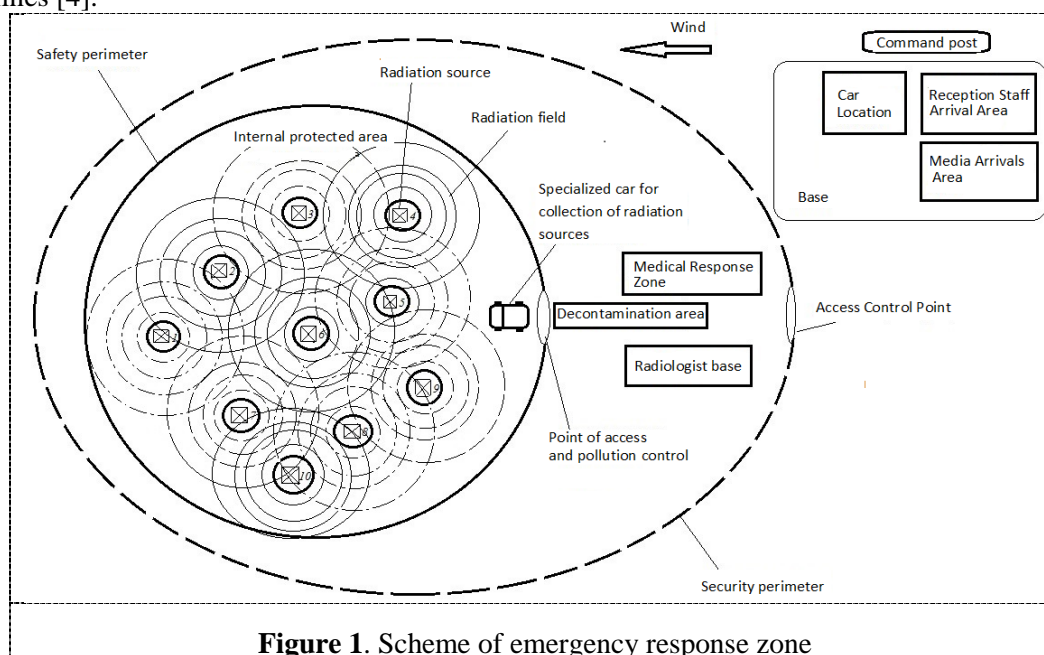
Radioactive materials in the form of hermetically sealed sources are used in industry, medicine, scientific research, as well as in the manufacture of many consumer goods intended for sale to the public. They are used for radiography, sterilization, radiation therapy and nuclear medicine; for well logging, in sensors recording the surface level, thickness, density and humidity; in antistatic devices, lightning arresters, smoke detectors. In their activity, all these sources are extremely diverse.

Thousands of transport operations involving the use of radiation and radioactive materials take place all over the world every day. All types of transport are involved in this process to varying degrees – road, rail, air and sea. The main problem in planning a response to a traffic accident is the fact that they can happen anywhere. Therefore, adequate means of emergency response are required, acting mobile within the entire state. A feature of transport accidents is that, in addition to drivers of vehicles, people around are also at great risk. Transportation of radioactive material is governed by strict regulations designed to provide protection in accordance with the danger that the contents of the containers present in the event of an accident. The higher the potential hazard, the more substantial the protection required by the instructions.

In its present form, the fundamental international safety principles, including the provision of radiation safety, are detailed in the “IAEA Requirements and Recommendations. Fundamentals of Safety” №SF-1, 2007 (10 principles in total).

The principles of radiation safety (justification, rationing, optimization, protection of future generations and the environment) are most widely known, since they concern all citizens, not just professionals.

The main provisions of the Recommendations of the International Commission on Radiation Protection (ICRP) of 2007 (Publication 103) include further use of the fundamental principles of justifying and optimizing protection against all controlled exposure situations, which are characterized as planned exposure situations, emergencies and existing exposure situations [3]. Strengthening the principle of optimization of radiation protection, which should equally be applied to all exposure situations, subject to individual dose limitations and radiation risks, is also provided for in national guidelines [4].



## 2. Methods and means

The first important stage of emergency response is the establishment of boundaries of safety and security, as well as control over the access of personnel and unauthorized persons to the danger zone. At the same time, it is necessary to constantly monitor the prevalence of pollution, the necessary perimeters of safety and security, protective measures for emergency workers, restrictions on the time they are in the danger zone, protective measures for the public with the help of radiologists.

The best way to control access is to establish physical barriers based on local conditions and the extent to which the risk of exposure can be reduced. Entrance and exit from the protected area should be made through the established control points. These points serve as a gathering place for emergency personnel, as well as radiological monitoring points (Fig. 1).

Dose exposure of personnel during radiation hazardous work is reduced by reducing the residence time in radiation fields, increasing the distance from the radiation source to the person, exposure to the radiation parameter (shielding, deactivation, etc.) [5], [6], [7]. An effective way to reduce personnel dose costs (by 25–40%), which do not require significant material costs, is routing optimization of work in non-stationary radiation fields [8], [9].

The main goal of solving route optimization problems is to find the minimum of the quality functional — the total dose of radiation when performing a complex of works in non-stationary radiation fields:

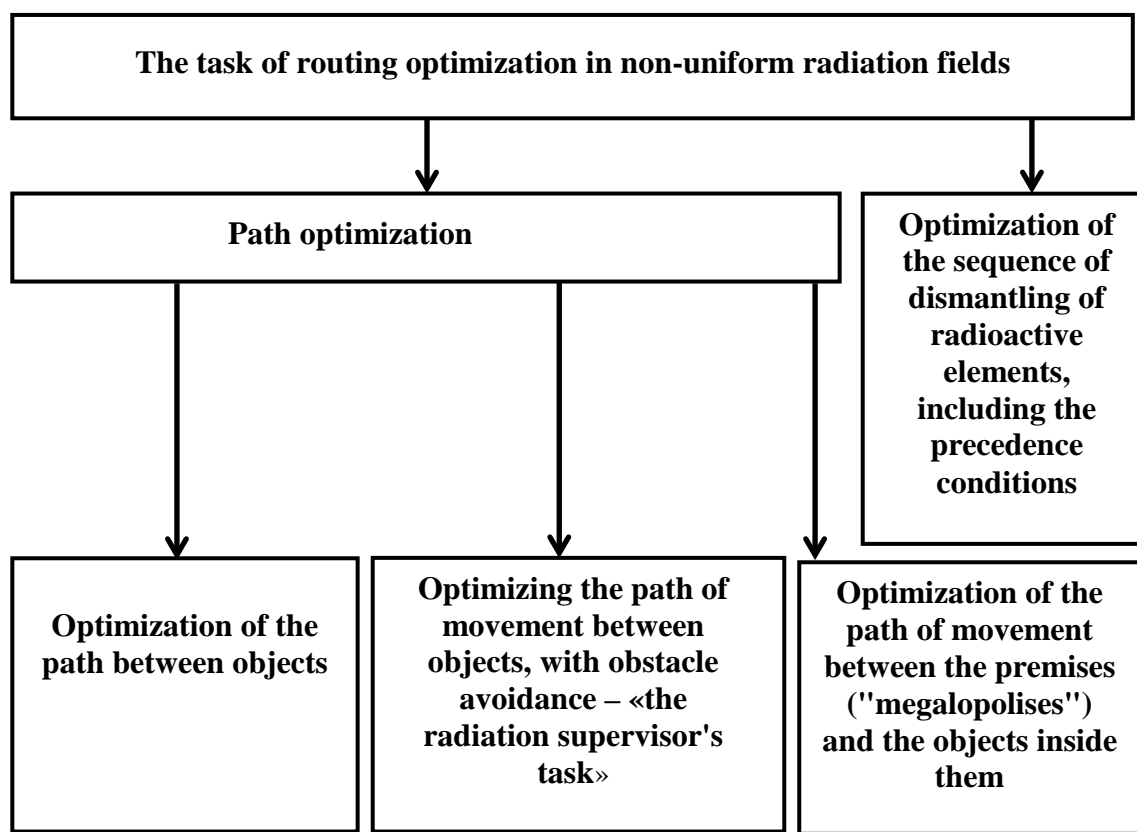
$$\sum_{i=1}^n \dot{H}_i \times t_i \rightarrow \min$$

where  $H_i$  is the dose rate in the  $i$ -th isodose region;  $t_i$  is the time when a person is in the  $i$ -th isodose region of the radiation-dangerous zone.

The work on the construction of methods and algorithms for solving problems of route optimization, focused on applications in applied problems of nuclear energy, has been conducted since the beginning of the 2000s by specialists from the departments “Nuclear Power Plants and Renewable Energy” and “Applied Mathematics” of the Ural Federal University and the Institute of Mathematics and Mechanics of the Ural Region RAS. During this time, a theoretical substantiation of various variants of route optimization has been carried out, computational algorithms for them have been developed, computational experiments have been carried out, including their implementation on the Uran supercomputer of the IMM Ural Branch of the Russian Academy of Sciences [10], [11], [12]. Possible options for route optimization were discussed (Fig. 2).

As a base, the classic traveling salesman (HQ) problem is used, in which a trader, starting from a certain base, must visit each of the  $N$  other cities only once. This one of the most well-known problems of discrete optimization combines simplicity of formulation and computational difficulties, since there is  $N!$  possible routes, one of which, or several, gives minimal costs (in the tasks under consideration, this is a collective radiation dose). This task was adapted to determine the optimal trajectory of the worker in radiation fields in order to minimize the “transit” radiation dose.

Further studies switched to the so-called courier task (LC with precedence conditions), as well as to the generalized courier task. In these studies, the dynamic programming (MDP) method was predominant with the preliminary reduction of constraints, which was the original element. Then, variants of the iteration method were constructed, using tunable SQ models and courier tasks and implementing a system of improved bilateral estimates of global extremum. Finally, in connection with the application of the MDP, a method was constructed that does not use the computation of the entire array of values of the Bellman function and, which is very important, is not losing in quality. Further, in connection with the formulation of tasks related to the dismantling of radiation-contaminated equipment of NPP power units decommissioned, theoretical results were obtained concerning accurate and approximate methods for solving route problems with a complicated criterion, including internal work and explicit dependencies on the list of unfulfilled projects. moment of assignments.



**Figure 2.** Options for route optimization in non-stationary radiation fields

Recently, an important step was taken: a set of constraints in the form of precedence conditions (traditionally considered difficult for optimization methods) was used “in a positive direction”: to overcome computational difficulties, since on this basis the actual reduction of dimension was achieved without loss of quality.

To solve the route problem with precedence conditions and cost functions, taking into account the circumvention of the existing obstacles, the implementation of an independent computation scheme was considered. The studied formulation has as its prototype the well-known intractable task of a traveling salesman, but contains the essential features of the above-mentioned nature. Such a dependence may arise when considering some of the applied problems that are relevant for nuclear energy in the field of minimizing the radiation dose of workers when working in non-stationary radiation fields (for example, eliminating the consequences of radiation accidents, planned work of a radiation supervisor). Also, an important point is the construction of model examples of emergency situations elimination in the accident of the NPP power unit (the initial parameters are taken from the data of radiation reconnaissance and the experience of eliminating the accident at the Chernobyl nuclear power plant). The developed algorithm for solving the problem will allow to automate the construction of the optimal route of movement between given points for emergency rescue specialists (ASF).

Conducting a radiation survey in order to obtain reliable information about the radiation situation both inside the facility and in adjacent territories is the main task at the initial stage of work to eliminate the consequences of an accident at a radiation-hazardous facility or territory. There are various ways to obtain information about radiation fields, the presence of hot spots, etc. Based on these data, it is possible to obtain a cartogram of the radiation situation in the form of isodose lines with the selected resolution.

A promising way to quickly obtain information about the radiation situation is the use of measuring systems for obtaining images of objects emitting photon radiation using mobile measuring systems (gammovisors) [13].

### 3. Optimization of the “off” sequence (dismantling, shielding) of radiation-contaminated equipment (object, source) in order to minimize personnel exposure.

Radioactive objects are located in separate rooms or on an emergency (contaminated) site, creating different radiation dose rates. At the same time, the labour costs for dismantling each of these objects are different. The total dose of radiation received by workers during dismantling work indoors or on site will depend on the time they are in the radiation fields created by radiation-hazardous objects.

When dismantling works are performed, the radiation fields are formed by separate radioactive elements, therefore when removing (dismantling) any object (element), the parameters of the radiation field change. This feature, which consists in the dependence of the background radiation level in the room when performing the next work on the presence of undismantled (unremoved) objects, makes it much more difficult to solve the problem, unlike the previous one.

To solve the problem of minimizing exposure during the dismantling (removal) of radioactive objects located at the emergency (contaminated) site, it was necessary to develop an original Bellman function construct and program implementation of the MTD procedure [14], [15]. The formulation of this task is the determination of the optimal sequence of dismantling (removal) of radioactive objects in order to minimize personnel exposure.

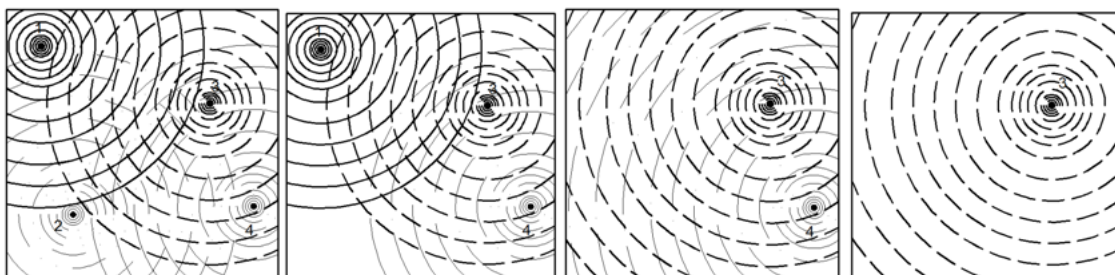
Consider as an example the finding of the optimal sequence of dismantling for the simplest option - four radioactive objects located on the emergency site. For simplicity, we will not take into account the effect on the dose rate of the distance from the radiation source to the worker.

In the general case, when dismantling  $N$  objects in sequence  $\alpha(1), \alpha(2), \dots, \alpha(N)$ , the radiation dose:

$$E = t_{\alpha(1)}(\dot{H}_{\alpha(1)} + \dot{H}_{\alpha(2)} + \dots + \dot{H}_{\alpha(N)}) + t_{\alpha(2)}(\dot{H}_{\alpha(2)} + \dot{H}_{\alpha(3)} + \dots + \dot{H}_{\alpha(N)}) + \dots + t_{\alpha(N)}\dot{H}_{\alpha(N)}$$

where  $\dot{H}_{\alpha(i)}$  is a radiation dose rate generated by the  $m$  element;  $t_{\alpha(i)}$  is the time of the dismantling of the  $i$ -th element (in this task  $t_{\alpha(i)}$  does not depend on the number of the next object to be dismantled, since the time of movement between the objects is neglected). When dismantling object No. 1, its further influence on personnel irradiation in the form of radiation dose rate is excluded, while dismantling object 2, its further influence on radiation in the form of radiation dose rate, etc. is excluded. When dismantling an object, its further influence on irradiation in the form of radiation dose rate is excluded.

As mentioned above, there is  $N!$  solutions to the problem of route optimization, i.e. For the simplest example (four objects in the room), there are 24 solutions [16]. As a result of calculations of the considered example, the optimal sequence of dismantling (2–1–4–3) was found, corresponding to the minimum dose of radiation (Fig. 3).



**Figure 3.** Diagram of the effects of radiation fields created by objects in the room during dismantling

The software implementation of several dozen examples for various radiation-polluted technological systems consisting of 10–20 elements showed the computational efficiency of the developed technique. Optimization of the sequence of dismantling allows reducing personnel radiation doses by 25 ... 40%.

In reality, the removal (shutdown, dismantling) of a radioactive object (source) cannot be carried out in any sequence. There are restrictions associated with the order of dismantling of some objects (for example, located at different elevations, connected structurally). This raises the problem of optimizing the sequence of dismantling with restrictions in the form of precedence conditions. This, to a certain extent, reduces the number of searches in the solution, but required the development of a special approach, which reduces the number of possible “bypass” options.

In the context of eliminating the effects of radiation accidents, in addition to the task of determining the optimal route of movement, it is necessary to solve a combined task that combines both finding the optimal trajectory of movement and determining the optimal “shutdown” (removal or shielding) sequence of the most “significant” sources in terms of generating radiation fields radiation. The main goal of such a combined task in the context of eliminating radiation accidents is to minimize the collective dose of personnel or to observe (not exceed) the established dose budget (limit) for emergency rescue units.

#### 4. Conclusion

- The constantly expanding use of radiation sources in various fields of activity updates the requirement of constant readiness to respond to possible radiological emergencies to ensure the safety of cities, territories and regions, taking into account the human factor.
- The developed routing optimization algorithms using mathematical modeling methods for eliminating possible radiological emergencies are an effective and low-cost way to minimize the radiological impact on the personnel of emergency formations.
- The results of computational experiments to assess the reduction of personnel exposure during work in non-uniform radiation fields using the developed route optimization algorithms show their effectiveness.
- The developed routing optimization algorithms for work in radiation hazardous conditions can be used to minimize radiation loads on personnel during maintenance and repair of radioactive equipment and decommissioning of nuclear facilities.

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