3D simulation as a tool for improving the safety culture during remediation work at Andreeva Bay

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Abstract

Andreeva Bay in northwest Russia hosts one of the former coastal technical bases of the Northern Fleet. Currently, this base is designated as the Andreeva Bay branch of Northwest Center for Radioactive Waste Management (SevRAO) and is a site of temporary storage (STS) for spent nuclear fuel (SNF) and other radiological waste generated during the operation and decommissioning of nuclear submarines and ships. According to an integrated expert evaluation, this site is the most dangerous nuclear facility in northwest Russia. Environmental rehabilitation of the site is currently in progress and is supported by strong international collaboration. This paper describes how the optimization principle (ALARA) has been adopted during the planning of remediation work at the Andreeva Bay STS and how Russian–Norwegian collaboration greatly contributed to ensuring the development and maintenance
of a high level safety culture during this process. More specifically, this paper describes how integration of a system, specifically designed for improving the radiological safety of workers during the remediation work at Andreeva Bay, was developed in Russia. It also outlines the 3D radiological simulation and virtual reality based systems developed in Norway that have greatly facilitated effective implementation of the ALARA principle, through supporting radiological characterisation, work planning and optimization, decision making, communication between teams and with the authorities and training of field operators.

Keywords: nuclear legacy sites, nuclear decommissioning, environmental remediation, 3D simulation, ALARA, radiological protection.

(Some figures may appear in colour only in the online journal)

1. Introduction

Andreeva Bay in northwest Russia hosts one of the former coastal technical bases of the Northern Fleet and was originally commissioned between 1961 and 1963 as technical base number 569. On the premises of this base, a basin-type storage facility (Building 5) was built in two steps, the first staring in 1962 and the second in 1973, for storing spent nuclear fuel (SNF). In February 1982, personnel observed a falling water level in one basin. As a consequence, urgent removal of the SNF from the basins to dry storage began in 1984 and all subsequent SNF from scheduled re-charges of ships and submarines was transported to dry storage. The stabilization of the situation in Building 5 lasted from 1982 to 1989, during which period about 700 000 tons of highly contaminated water escaped into the Barents Sea. In 1989, the base stopped operations as a technical maintenance base for nuclear submarines and ships with nuclear powered installations and received no further SNF or other radioactive waste (RW).

Due to a national directive, responsibilities for the site were transferred to Minatom in 2000, today called the State Atomic Energy Corporation, or Rosatom. At the time, the condition of the facility’s infrastructure did not fully meet the requirements for nuclear, radiation and environmental safety. The buildings and structures at the site were damaged or collapsed, which made SNF and RW management impossible. As a response to this, an enterprise dedicated to dealing with the situation was created and the site was re-designated as the Andreeva Bay branch of Northwest Center for Radioactive Waste Management (SevRAO), which is a branch of the Federal State Unitary Enterprise - Enterprise for Radioactive Waste Management (RosRAO).

Today the facility is a site of temporary storage (STS) for SNF and other RW and hosts 17 000 m$^3$ of solid radioactive waste, about 1000 m$^3$ of liquid RW, about 100 cores from nuclear submarines and 5000 tons of solid radioactive waste collected from the contaminated areas of the site. In compliance with current regulations, the radio-ecological situation has been significantly improved, creating safe conditions for personnel working within the site. However, according to an integrated expert evaluation of relevant assessment criteria, the SevRAO industrial site is still the most dangerous nuclear facility in northwest Russia [1]. Hence, environmental rehabilitation of the site is in progress and is supported by strong international collaboration [2], mainly with Great Britain, Norway, Italy and Sweden. According to the schedule, final removal of SNF will begin in 2016 and remediation of the site will begin in 2025.

Results of previous work [3–6] have shown that the technical tasks involving manipulation of SNF and high-level RW at the SevRAO industrial site involve considerable radiological hazards to personnel. The dangers originate from the following initial conditions at the site.
• Poor information on the radiological and physical condition of SNF and other high-level radioactive waste in one of the buildings at the industrial site, resulting in elevated risk associated with operations involving the removal of radioactive waste and the subsequent decommissioning of the building.
• Urgent movement of SNF from the above mentioned building to a dry storage facility that was not designed for this purpose.
• Lack of information about the presence of defective SNF assemblies.
• The presence of additional industrial buildings and structures used as temporary storage for radioactive waste that contribute to the increased levels of man-made radionuclides and external gamma radiation at the industrial site.
• The necessity of application of some unique technologies and equipment, which were specifically designed for the management of spent fuel and radioactive waste at the industrial site and have no analogues in the nuclear industry.
• The need for conducting several operations related to decommissioning and renovating old structures as well as constructing new facilities, e.g. for treating SNF and other radioactive waste, in parallel within the SevRAO industrial site.
• Unsafe physical conditions of a number of buildings and structures at the industrial site.
• The need for use of specialized personal protection equipment to protect personnel during radiation-hazardous work in open areas and under adverse weather conditions.
• The need for utilisation of special protection for personnel handling SNF and other high-level radioactive waste.
• The lack of sufficient numbers of qualified workers.

As a consequence of these conditions, safety management has become the overarching organizational goal at the SevRAO industrial site.

In the literature, the levels of safety culture are generally categorized as low, medium or high [7]. To achieve a high safety culture, the basic general principles of radiation protection must be fully adopted from all aspects and throughout the entire process. Based on international recommendations, e.g. the IAEA Basic Safety Standards [8], recommendations of the International Commission of Radiation Protection [9] and national legislation Radiation Safety Standards NRB-99 [10], any activity that potentially results in radiation exposure of participants (workers) or the public must be conducted according to three basic principles: the principle of justification, the principle of optimization and the principle of limitation. The principle of optimization dictates that resulting radiation dose (both individual and collective) should be kept as low as reasonably achievable. According to the combination of the principles of limitation and optimization, the dose must be lower than limits imposed by national regulations and internal policy and should be further reduced as much as reasonable, taking into account economic and social factors as well as health (long term risk) issues. While the principle of limitation requires a simple comparison of estimated exposure limits to those applicable to the given situation, the other two principles requires careful balancing of health, economic, technical, social and psychological consequences with finding an optimal solution. In addition to the principle of limitation, the principle of optimization should also be an integral part of the general safety culture of any enterprise. Good safety culture requires high preparedness, situational awareness (including self-awareness of responsibility) and a quality control (including self-control) system that takes into account all factors affecting overall quality of work. The principle of optimization must be applied at all stages of the life-cycle of a nuclear facility, starting with the design stage and continuing during the operation and dismantling phase up until final release of the site.

1The principle of optimization is also known as the ALARA principle (As Low as Reasonably Achievable).
The optimization process is meant to find the best balance between all relevant factors, the most important of which is the health consequences of exposure to radiation. The potential health consequences related to a certain activity that are considered during optimization include:

- Radiation exposure of personnel (workers) performing work during planned situations.
- Exposure of the public due to radioactive pollution released into the environment, including planned releases and disposal of solid radioactive waste resulting from work activities performed.
- Radiation dose to the public resulting from accidental emissions.

The safety control system of any enterprise must have procedures for planning work tasks with efficient methods of assessing the associated radiological risks. The system must also have procedures for preparing personnel to perform scheduled work tasks and emergency preparedness. Training programs for preparation of personnel require efficient techniques for communication of work plans, associated radiation risks and protection measures to ensure good situational awareness, i.e. understanding the plans, risks, and safety measures, of the workers involved.

Finally, the safety control system must incorporate efficient procedures for continuously monitoring radiation exposure of workers and the public during work execution, e.g. continuous as well as periodic and unscheduled monitoring of work by team leaders and radiation protection monitors.

While the principle of optimisation plays an important role during training and monitoring of work, it has a more greatly emphasised role during work planning when alternative solutions are compared and analyzed from various aspects. In contrast with other western countries, in the Russian Federation, the principles of limitation and optimization have been neglected. There are various reasons for this, one being the lack of strict regulations for implementing the principle of optimization in NRB-99 [10]. Due to established international cooperation, SevRAO, especially branch Number 1 located at Andreeva Bay, has a unique opportunity to develop practical approaches and apply the principle of optimization. Norway and several other countries are strongly involved in financing and supporting the activities at Andreeva Bay. In particular, Norway has been providing financial and scientific support to improve the optimization process during planning of work at Andreeva Bay. This includes support for the process of optimizing work procedures based on the ALARA principle as well as optimizing the procedures for preparing (training) personnel and communication within the team and to the authorities (i.e. regulatory supervision) both in Norway and in Russia. For a detailed description of the radiological conditions and reasons for initiating remediation work at the nuclear sites at Andreeva Bay, the reader is referred to additional publications [3, 5].

In 2008, the State Research Center Burnasyan Federal Medical Biophysical Center (FMBC) of the Federal Medical Biological Agency (FMBA) of Russia issued guidelines [6, pp15–18] to facilitate implementation of the ALARA principle within the work performed by Branch Number 1. These guidelines are intended for use by the Regional Federal Executive Authority of FMBA, also called Regional Management Number 120. Regional Management Number 120 instructed the radiation safety service of the enterprise to carry out sanitary and epidemiological control, during the planning of remediation work at Branch Number 1. According to guidelines developed by the FMBC [6, pp15–18], the optimization procedure should be a continuous process, initiated at the beginning of the preparation (planning, training, etc) stage and continuing throughout implementation of the work plan to the results analysis and evaluation stage (figure 14). In addition [6, pp 15–18], recommends continuous involvement of the entire staff in the optimization process.
In the planning stage, when different options are considered, priority should be given to those resulting in the lowest detrimental impact to workers, the public and the environment. Different options should be balanced, taking into account dose restrictions and projected health consequences to the workers involved. Resulting dose and associated health implications should be assessed and analyzed both for the team as a whole (collective dose) and at the individual level (personal dose). Medical examination on the entire team should be performed to establish control levels prior to workers engaging in planned activities.

Possible alternatives should also be balanced based on possible accidental emissions and planned discharges of radioactivity impacting the public and the environment. Finally, options should be compared in terms of associated economic and psychological implications.

When assessing and comparing various alternatives, the following issues and data, among others, should be considered:

- Lessons learned, e.g. from projected and actual exposure levels in previous or parallel activities in which radiological or other circumstances were similar and extrapolation of results is possible.
- The required optimal team composition (including the number of workers, desired expertise, and envisaged role of the team members) for each of the envisaged work steps.
- Availability of human resources required over the different work periods, available staff, possibility of employees leaving during the process, options for employees who are temporarily or not required and the possibility of acquiring participants possessing their missing expertise, among others.
- Necessity of suitable communication tools among team members, including communication with radiation monitors, in-the-field team leaders, and supervisors in the control room.
- Possibility of efficient (safe and cost/time effective) training of supervisors and field operators.
- Availability of the required tools and equipment (including grippers, manipulators, automation equipment, etc) in-house or in the market.
- Availability of suitable data for preliminary radiological characterisation of the targeted site and possibility (safety and cost implications) of acquiring additional data for a thorough radiological characterisation of the site.
- Physical constraints, e.g. space required by large equipment and components and weight limitations, among others.
- Availability and costs of protection systems, e.g. physical radiation shielding, ventilation and air purification system, coating films and protective clothing, among others.
- Systems for monitoring workers and task execution during the process to ensure efficient protection without significantly deteriorating working conditions and increasing costs.
- Possibilities for ensuring good working conditions for workers during the process, especially in the case of tasks that require working in dark, confined places and in extreme temperatures and high noise and vibration levels.
- The most suitable organisation of the team (roles and responsibilities, chain of command) for achieving low risk and high efficiency.
- Methods to calculate and handle uncertainties in available risk projections.
- The types of permits and authorization required and how they can be obtained.

Regulatory supervision by Regional Management Number 120, based on the guidelines elaborated by the FMBC, will ensure full implementation of the ALARA principle within the remedial actions planned to be performed by SevRAO. This paper describes how the
optimisation principle has been adopted during the planning of remediation work at Branch Number 1 and how a Russian-Norwegian regulatory collaboration has greatly contributed to implementing the ALARA principle in an effective way.

2. Methods

To implement the optimization principle during remediation work at SevRAO in Andreeva Bay, based on the guidelines developed by the FMBC [6, pp 15–18], a Russian-Norwegian bilateral project called DOSEMAP was established. The aim of the DOSEMAP project is to create an information and analytical system (IAS-RSW) to ensure the radiation safety of SevRAO workers and support the optimization process through informed decision making when developing the work plan. The first stage of the DOSEMAP project was carried out in 2008–2010 and resulted in the creation of a software tool based on RADRUE [11], which has successfully been applied in a number of international epidemiological projects for dose reconstruction of the Chernobyl liquidators. The second stage of the project was devoted to development of the IAS-RSW system and was performed in the 2010–2012 timeframe. Field tests during the second stage revealed that while the IAS-RWS system provided a great deal of useful information for the Radiation Safety department of SevRAO, the test users required a long time to gain proficiency in routine application of the system. This conclusion initiated the third stage of the DOSEMAP project, which will be implemented from 2012–2014. During this third stage, the main focus is on simplification of the user interface of the system to reduce the time required for training foreseen users and improv the performance of users in application of the system during work at SevRAO.

In 2010, the Norwegian Radiation Protection Authority (NRPA) drew the attention of the Burnasyan FMBC to the research and development activities performed at the Institute for Energy Technology (IFE) in Halden, Norway. An expert meeting between the IFE and the FMBC revealed that real-time 3D simulation and visualization technology, developed for supporting the nuclear industry, in conjunction with the tools developed by the FMBC, could greatly increase efficiency (increase safety and decrease costs) of the activities planned at SevRAO by supporting a highly efficient and informed optimization of the work plan. The combination of the two systems could open a series of new possibilities that would not be possible by application of the individual systems separately. As a consequence, in 2011, in parallel with the DOSEMAP project, the bilateral DRIVE project was initiated between IFE with FMBC, which was concluded in 2013. The aim of the DRIVE project was the development of an integrated system for work planning and optimization by connecting the systems developed separately by the two institutions.

The expert meeting between the IFE and the FMBC clearly showed that the system being developed within the DOSEMAP project by the FMBC and the 3D simulation and virtual reality technology had a series of complementary functionalities and aided in development of the radiological toolkit by IFE. For example, the radiometric and dosimetric computations implemented in the radiological system of IFE, at the time, mainly consisted of deterministic modelling based on user supplied characteristics of the radiation sources present within the modelled scene. In contrast, the FMBC system was mainly focused on generating continuous radiation maps via interpolation based on scattered input radiological measurements. The two functionalities would complement each other and form a more complex system applicable to a wider variety of situations and more independent of the type of available radiological input.

The IAS-RWS system developed within the DOSEMAP project is based on three software tools. The Mazur Interface is a user interface for entering topographical data (generated
with the help of a Geographic Information System (GIS) such as Google Earth, and scattered radiological measurements within the defined geographical area to characterize the radiation situation. The Tesnov Interface is a user interface for inputing data describing the routes of participants through the geographical area defined via the Mazur Interface. The third unit of the IAS-RWS system is an analytical module that receives data from both of the above mentioned interfaces and performs radiometrical and dosimetrical calculations based on the received data. The output data generated by this analytical module (figure 1) consists of dose maps, i.e. a set of maps consisting of radiation dose values on the nodes of a uniform mesh covering the modelled geographical area computed with the application of Ordinary Kriging interpolation [12] of the input scattered data. Further, the analytical module calculates personal (individual and collective) doses of participants based on the worker trajectories (and speeds) supplied by the Tesnov Interface.

The IAS-RWS is a complete and efficient system for many of the tasks foreseen at the industrial site of SevRAO. However, one of the shortcomings of this system is the lack of appropriate radiometric and dosimetric models for simulating radiation transport. This technology is very efficient for estimating radiological conditions in areas where extrapolation of measurements is not possible and in environments where planned work is foreseen to significantly alter initially measured exposure conditions and for estimating personal doses primarily originating from direct exposure when contribution of secondary radiation is low in comparison. In addition, the IAS-RWS can readily estimate dose associated with work protocols, which can easily be described by routes through large geographical areas. However, calculation of dose corresponding to more complex work scenarios and involving more complex trajectories within buildings requires more detailed modelling of the environment (the building or a part of it) and the work procedure planned. Worker routes within the Tesnov Interface are stored as Keyhole Markup Language (KML) files. Generating this type of file manually is

![Figure 1. The five-layers formed by the input (upper three) and output (lower two) data in the analytical module of the IAS-RWS system.](image)
not user friendly but GIS based applications offer a very user friendly way of inputting routes through geographical areas. The expert meeting between the IFE and the FMBC revealed that while the system developed by IFE lacks functionalities integrated into the IAS-RWS system, IFE’s system contains very efficient solutions for the shortcomings previously mentioned.

The system offered by the IFE is primarily based on two software applications. The Andreeva Planner (figure 2) is a further developed and customized version of the Halden Planner [13–15], which is specifically designed for simulating and optimizing complex work scenarios at the SevRAO industrial site. The tool is based on comprehensive modelling of the environment (including the interior of buildings), detailed simulation of the planned work steps and complex simulation of radiation transport within the modelled environment. The second part of the IFE system consists of a GIS based application for radiological mapping over large geographical areas called the Andreeva Terrain Viewer (figure 3). The Andreeva Terrain Viewer (ATV) was also developed within the DRIVE project to complete the IAS-RWS system by providing user friendly ways of visualizing the entire SevRAO industrial site. In addition to visualizing the terrain and buildings, the tool can also visualize the radiological situation and its evolution over time, as well as visualize and define worker routes through an advanced visual interface.

Hence, as the meeting between IFE and FMBC revealed, fusion of the two systems would enable user-friendly 3D visualization of the radiation maps generated by the IAS-RWS system, as well as estimation of personal doses both within the 2D IAS-RWS system, based on simple user-defined worker routes and within the 3D DRIVE system, based on complex user-defined work scenarios.

Figure 4 demonstrates how the systems developed within the DRIVE and the DOSEMAP projects interact with each other. The analytical part of the IAS-RWS system generates dose grids based on scattered measurements supplied via the Mazur Interface. The dose grids can be visualized both in the Andreeva Planner, inside and around buildings and structures and the ATV, across the whole industrial site. The dose grid is also utilized by the Andreeva Planner for computing worker doses based on work scenarios, defined through the Andreeva Planner’s 3D user interface, within the supplied dose grid. Works steps, which can be
described as simple worker routes throughout the entire industrial site, are defined within the ATV via a user friendly 3D GIS type user interface. Worker routes defined within the ATV are transferred to the Tesnov Interface where they are grouped by worker (one KML file work for each worker).

Figure 5 shows worker routes for five different workers throughout the SevRAO industrial site. The worker route information is then transferred to the analytical part of the IAS-RWS system to calculate individual and collective doses.

3. Results

This section describes how the system based on the software tools developed in the DOSEMAP and DRIVE projects has been successfully applied to support the optimization of project plans. The following explains how the system developed through Russian-Norwegian bilateral cooperation has significantly improved and contributed to optimizing the different steps of the project execution.

Naturally, and in line with the guidance in [6, pp 15–18], the first stage of the project implementation focused on assessing the initial radiological situation within the targeted site. This stage involved the assessment of the available data (data from the environmental monitoring system in place) and performing some additional sampling and measurements within the site. For decision making (choosing the optimal strategy), the radiological data available had to be analyzed in an efficient and user friendly manner. The system, based on combining the DOSEMAP and the DRIVE project results, offers very efficient ways of presenting data to decision makers in an easy to understand manner. Hence, all the data available has been
transferred into the system. The Mazur Interface (figure 6) of the IAS RSW system has proven to be an efficient tool for assembling and organizing all available radiological data characterizing the site.

Guidance in [6, pp 15–18] recommends that, based on data resulting from a thorough radiological survey, detailed radiological characterization of the targeted area should be performed. Based on the results, characterization zones with different restrictions (safe zones and hot zones with different levels of risks) should be established. The established zones should be clearly visualized to the decision makers for informed work planning allowing for worker routes resulting in optimal exposure. For example, when presence in controlled zones is not required, work should be in free (low risk) areas. Integration of the analytical part of the IAS RSW system with the Andreeva Planner and the Andreeva Terrain Viewer has proven to result in a highly effective tool for visualizing radiological conditions and establishing zones (figure 7).

In the following step of project execution, i.e. work planning, [6, pp 15–18] recommends that all possible options should be considered and balanced against each other to find an optimal strategy. The most important parameters that should be considered and balanced during this process are safety (including safety of workers, the public and the environment), the costs entailed and the time required for the operations.
As previously mentioned, the IAS RSW system combined with the user interface of the Andreeva Terrain Viewer allows estimation of radiation risk to workers performing work tasks that can easily be described by routes throughout the SevRAO industrial site. The combined system has proven to be highly useful in optimizing work plans for tasks in which dose was primarily dependent on worker routes defined on large scale maps and details of the work protocol significantly influences the estimated radiological risk. The optimization of such work tasks can be broken down into three basic problems:

1. Finding the route from point A to point B resulting in the lowest dose.
2. Finding the route leading through a set of intermediate destinations (control points) with the lowest total dose.
3. Finding a route that traces all roads within the site, i.e. how to traverse all roads on the industrial site of SevRAO with the lowest dose.

The three tasks listed above are solved by the analytical part of IAS RSW system by the application of discrete mathematics (graph theory) to the fifth layer ‘graph lattice’ (figure 1) of the input database of the IAS RSW system. Figure 8 illustrates results generated by the
analytical module for the above listed ‘extremum’ tasks. The user does not have to accept solution proposed by the system and may propose user-defined trajectories based on their own experience. In this case, the dose corresponding to the user-defined trajectory will also be calculated and compared with the trajectory proposed by the system. In the figure, the route resulting in an exposure of 0.494 \( \mu \text{Sv} \) was proposed by an experienced operator. The route resulting in 0.316 \( \mu \text{Sv} \), the optimal solution, was generated by the system.

In addition to calculating dose associated with single routes of individual workers, the analytical module of the IAS RSW system allows users to calculate dose resulting from any number of routes of any number of employees, i.e. collective dose (figure 9). This functionality has shown special usefulness for optimization of work plans both in terms of individual and collective exposure.

As mentioned before, optimization and comparison of more complex work protocols, where dose is highly sensitive to details of work implementation, require more detailed modelling of the work steps. The system resulting from the bilateral collaboration described in this paper has proven to be very effective in comparing different work strategies. The Andreeva Planner offers an efficient way to model (simulate) work scenarios and estimate associated radiological risks in real-time. In addition, the tool allows the user to easily identify the source of exposure.

Figure 8. Route from point A to point B with the lowest dose (a), leading through a set of intermediate destinations with the lowest total dose (b) and tracing all roads within the site (c). Numbers in the right panel indicate the sequence of visiting intersections and the number of times tracing a path.

Figure 9. Dose rate map (left panel), combined routes of staff coloured by collective time cost (middle panel), and collective dose (right panel) for the SevRAO industrial site.
to participants of the modelled scenario. The user is able to quickly associate elevated dose to radiation sources or radionuclides present in the scene and to work steps within the scenario. This allows the user to quickly find alternative solutions that result in more optimal exposure. The real-time capability of the Andreeva Planner permits the user (decision maker) to see how exposure changes dynamically with only the slightest modification of the work strategy. This allows the user to dynamically modify the strategy and experiment with alternative solutions until an optimal solution is found. The real-time capability also grants the user the ability to see how radiological conditions within the scene dynamically change as a result of changes to the scene resulting from actions of workers, e.g. due to adding or removing biological shielding (figure 10). This capability makes it easy for the user to determine the optimal directions for updating a work scenario in the process of finding better alternatives. However, in some situations, very different multiple work strategies, involving different technology and different number of participants, need to be compared. The Andreeva Planner offers user-friendly functionalities for storing work scenarios and quickly comparing multiple scenarios in terms of multiple parameters, e.g. individual and collective dose and time requirements.

Similar to other types of work that involve risks to the participants, all work tasks at the SevRAO industrial site must have an associated work permit that incorporates the following information:

- Title identifying the work task.
- Schedule associated with the work steps (start date).
- The site affected by the work step.
- Reference levels of radiation exposure (dose rate from external gamma radiation, beta volumetric activity levels, etc)
- Maximum allowed exposure levels (effective dose equivalents).
- Time foreseen to be spent in controlled areas.
• Applied individual and collective protection equipment (IPE).
• List of the safety protocols in place (relevant to the task).

The analytical part of the IAS RSW system provides functionality for filling out and printing work permits. An example of such a work permit is provided in figure 11. This functionality also contributes to efficient optimization of the work at the SevRAO industrial site.

Recommendations in [6, pp 15–18] dictate that a reliable radiation control system must be determined and established prior to work execution. Such a system has to provide sufficient monitoring during both normal (planned) operations and in the case of emergencies. The IAS RSW system has greatly contributed to optimization of the work strategy at the SevRAO industrial site by supporting the establishment of an efficient radiation control system. The IAS RSW system offers two different methods for improving radiation control systems, taking into account a user-defined allowable maximum error in determining the parameters of the radiation situation. Both systems calculate the critical locations where radiation control requires special attention. The first method is based on the peak values of dose rate gradients. The second method is based on peaks of the error in determining the dose rate (the cross-validation method). An example of application of the two methods with the same input data is shown in figure 12.

For the final stage of the preparations for work, [6, pp 15–18] recommends in-depth preparation (training) of field operators (workers) for the tasks to be performed. An efficient training programme must be developed that ensures the workers involved:

• Are familiar with (understand) the tasks to be performed.
• Have some sort of experience in performing the tasks planned.
• Are aware of the risk associated with the tasks.
• Have a good understanding of the safety protocols in place.
• Understand that the developed strategy is optimal and deviation results in higher risk.
• Understand what kind of accidents are considered possible, and are prepared to respond well in such crisis situations.

In [6, pp 15–18] it is also stated that virtual (simulation based) training should be considered due to the advantages offered in terms of safety and cost effectiveness. In addition to supporting optimization of work protocols, the Andreeva Planner is also highly useful for preparing (training) participants for the tasks envisaged. The scenario playback capability of the tool and its realistic 3D visual output makes the Andreeva Planner an efficient tool for classroom training. Trainees are able to see realistic simulations of planned work tasks with easy to understand visualization of associated dangers, i.e. radiation dose (figure 13). In addition to demonstrating the planned (optimal) strategy, the tool can also be applied to present sub-optimal work protocols in order to explain the detrimental consequences of deviating from the plan (figure 13). Finally, but equally importantly, the Andreeva Planner can also be utilized to present possible mishaps and optimal response strategies.

The next phase towards project completion, following the preparatory phase, is the work execution phase. For this phase, [6, pp 15–18] prescribes that radiation exposure of all participants is systematically monitored throughout the entire operation in order to ensure protection in harmony with the ALARA principle. For this purpose, all participants must be accompanied by radiation monitors and equipped with active personal monitoring equipment. The technology described in this paper is now being further developed to support advanced monitoring of the personnel involved in remediation work at the SevRAO industrial

Figure 12. Identification of positions where radiation control requires special attention based on maximums of the dose rate gradient (method 1), and maximums of the interpolation error, i.e. the method of cross-validation (method 2).
Regarding the work execution phase, [6, pp 15–18] also recommends that, in addition to training prior to work execution and monitoring throughout activities, participants should also be motivated and provided with in-situ tools for continuously monitoring calculated and measured radiological conditions, work plans and associated planned personal exposure levels relevant to their pending tasks. The Andreeva Terrain Viewer is compatible with handheld mobile devices and is foreseen to be applied to provide in-situ online maps showing the distribution of radiation exposure risks within the site for participants throughout the planned activities. In addition, due to the user friendly 3D interface of the Andreeva Planner, the IAS-RSW system combined with the Andreeva Planner could also be applied to provide more detailed in-situ risk information for participants. The possibilities for this are being investigated.

For the final step of each work phase, [6, pp 15–18] recommends that actual (measured) personal exposure levels should be compared with those anticipated. In case of deviations, especially exposures higher than planned, the origin of the excess dose should be thoroughly investigated and the results applied for updating plans and safety procedures to avoid similar incidents throughout the rest of the project execution. In the case of such deviations, the combined system developed within the Russian-Norwegian collaboration will be applied for reconstruction of the actual work steps and calculation of dose based on recorded measurements. The results of such an investigation will be extremely valuable both for identifying deviations from the work plan that lead to excess exposure and for identifying and eliminating gaps in the safety protocols supported by the software tools presented in this paper.

Figure 14 summarizes the issues related to implementation of the optimization principle highlighted in [6, pp 15–18] that are addressed by the system developed by the Russian-Norwegian collaboration described in this paper for each consecutive step of the iterative process of work implementation at the SevRAO industrial site.
Figure 14. Issues related to the optimization principle in different stages of work implementation.
4. Conclusions

ALARA is an important principle that has been applied internationally for many years in radiation protection practice. While the meaning of the principle has remained unchanged, the technology supporting its implementation has undergone immense evolution. Advanced computer simulation aided systems are being more and more commonly applied in the nuclear industry to enhance efficiency and safety. The IAS-RSW system developed by FMBC is such an advanced system specifically designed to improve the safety of workers during remediation work at the SevRAO industrial site. The 3D simulation and virtual reality based systems developed in Norway are being technically extended based on general current needs of the nuclear industry and have been successfully applied in several countries for many years. Combined, the two systems enable a whole series of new possibilities for advanced application of the ALARA principle, through supporting radiological characterisation, work planning and optimization, communication among team members and with the authorities and preparation (training) of field operators. In addition the system is foreseen to be applied to enhance dynamic monitoring of workers, providing in-situ risk information to field operators and evaluating the results of accomplished work phases.

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