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WS2 Specialist workshop II: Radiation protection issues in nuclear industry – Oral presentations

The IAEA OSART programme and radiation safety related findings during recent OSART missions

Lipar, Miroslav
IAEA, AUSTRIA

Abstract

The IAEA operational safety review team OSART for nuclear power plants in Member States have been reformed responding to the changes of the environment of both the industry and Member States needs. The IAEA safety standards for Operations are being applied when conducting the Agency's safety services. Our goal is to ensure that the issues and trends resulting from industry operating experience and the Agency safety services can be effectively communicated to Member States and be used to further reform our safety standards and services. Radiation Protection is an important area of OSART review. The relevant Safety Guide serving as a basis for this area is "Radiation Protection and Radioactive Waste Management in the Operation of Nuclear Power Plants", IAEA Safety Standards Series No. NS-G-2.7. The objective of this presentation is, by referring to the above Safety Guide, to discuss the various findings, recommendations, suggestions and good practices from recent OSART missions in different countries that should to be considered in order to improve Radiation Protection in the Operation of NPPs. The following RP areas are assessed during OSART mission: Organization and function, Radiation work control, Control of occupational exposure, Radiation protection instrumentation, protective clothing and facilities, Radioactive waste management and discharges and Radiation protection support during emergencies.

Radiation safety in new build

Alm-Lytz, Kirsi; Vilkamo, Olli
STUK – Radiation and Nuclear Safety Authority, FINLAND

Abstract
STUK reviewed the utility Teollisuuden Voima Oyj's (TVO) application for the Construction Licence of the Olkiluoto 3 nuclear power plant unit in 2004-2005. Based on this review STUK prepared its statement on safety together with a safety assessment report of the new plant to the Government. STUK has continued reviewing the detailed design during the construction of the new plant unit. By virtue of the Nuclear Energy Act (990/87) and the Government Decree on the Safety of Nuclear Power Plants (733/2008), Radiation and Nuclear Safety Authority (STUK) issues detailed regulations, YVL Guides, concerning the safety of nuclear power plants. Several YVL Guides deal with radiation safety (site, abatement of releases, worker radiation protection, emergency arrangements, etc). The paper will discuss some radiation safety related requirements in the design of a new Finnish NPP and their implementation in the licensing documentation.

Introduction
The licensing process of a new nuclear power plant in Finland is shown in Figure 1. The project of the fifth Finnish nuclear power reactor was formally started in May 1998 with Environmental Impact Assessment (EIA) process. Then the utility TVO submitted the application for a Decision in Principle in November 2000. The Finnish Government made the decision in January 2002, which Parliament ratified in May 2002.

Late 2003, TVO proposed the plant site to be Olkiluoto and made a contract with a consortium of AREVA (former Framatome ANP) and Siemens AG to build an EPR (European Pressurised Water Reactor). TVO submitted the application for Construction Licence in the beginning of 2004 and the licence was granted by the Government in February 2005. The commercial operation of the new plant unit is expected to take place in 2012 instead of spring 2009 as originally planned. Longer construction schedule is due to the delays in detailed civil work and system design and problems met in the construction and manufacturing of main components. The Operating Licence evaluation process takes approximately one year.

There are also several new nuclear power plant projects ongoing in Finland. Finnish Government and the Parliament are making decisions during 2010 on three applications for a Decision in Principle.

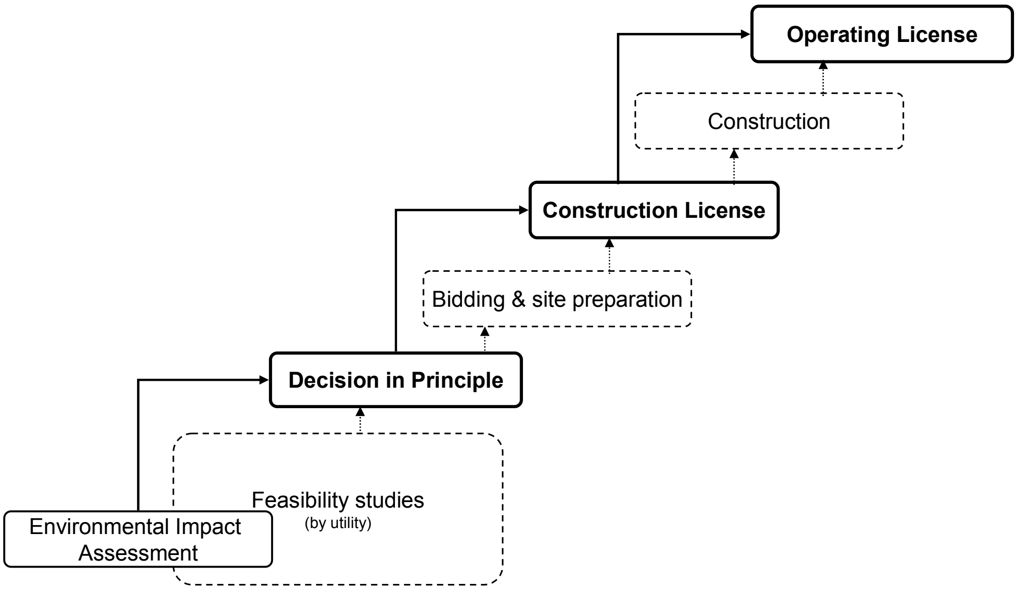

Figure 1. The licensing process of a new nuclear power plant in Finland.

Construction Licence application review at STUK

At the same time as the application for Construction Licence was sent to the Ministry Employment and the Economy (former of Ministry of Trade and Industry), TVO submitted the required licensing documentation to the Radiation and Nuclear Safety Authority (STUK). According to the Finnish Nuclear Energy Decree Section 35, these documents include:

- Preliminary safety analysis report (PSAR)
- Probabilistic risk assessment of the design stage
- Proposal for a Classification Document
- Description of quality management during construction
- Preliminary plans for physical protection, emergency preparedness, and safeguards
- Arrangements for the regulatory control
- Other reports that STUK considers necessary.

Based on the review of these documents, STUK prepared its statement on safety and a safety assessment report, which were submitted to the Ministry in January 2005. STUK's positive statement on safety was a prerequisite for the Government to grant the Construction Licence. In the statement, STUK indicated specific observations on and some further demands for the plant safety.

Radiation safety in YVL Guides

The Guide YVL 7.18, "Radiation safety aspects in the design of NPPs", was updated in 2003 and is now again under revision. This Guide includes radiation safety requirements to be taken into account in the nuclear power plant layout and system design. The Guide covers plant's normal operation, accident situations including severe accidents and aspects of decommissioning. Other relevant radiation guides during the construction licence review were:

- YVL 1.10, "Safety criteria for siting a NPP"
- YVL 7.1, "Limitation of public exposure in the environment of and limitation of radioactive releases from NPPs"
- YVL 7.2, "Assessment of radiation doses to the population in the environment of a NPP"
- YVL 7.3, "Calculation of the dispersion of radioactive releases from a NPP"
- YVL 7.5, "Meteorological measurements at NPPs"
- YVL 7.6, "Monitoring of discharges of radioactive substances from NPPs"
- YVL 7.11, "Radiation monitoring systems and equipment in NPPs".

Further relevant guides for the operating licence review are:

- YVL 7.4, "NPP emergency preparedness"
- YVL 7.7, "Radiation monitoring in the environment of NPPs"
- YVL 7.8, "Environmental radiation safety reporting of NPPs"
- YVL 7.9, "Radiation protection of NPP workers"
- YVL 7.10, "Monitoring of occupational exposure at NPPs".

All of these guides are currently under revision as the whole structure of the STUK's YVL guides will be changed. However, most of these guides were just recently updated, so not major modifications are expected in the revision. The target date for the updated guides is the end of year 2011.

Radiation safety of NPP workers (ALARA)

In the regulatory guide YVL 7.18, a design upper limit for an annual personnel collective dose of 0.5 manSv per 1 GW of net electric power averaged over the plant life is set forth for new reactors. In the European Utility Requirements (EUR) document, the target for annual collective effective dose averaged over the plant life is set as 0.5 manSv per reactor unit.

There are two operating nuclear power plants in Finland; two boiling water reactor (BWR) units at Olkiluoto site and two pressurised water reactor (PWR) units at Loviisa site. They were commissioned between 1977 and 1981. Average personnel collective radiation doses per reactor for existing Finnish NPPs and average values for BWRs and PWRs for the years 1998-2008 are shown in Figure 2. The collective dose at the Olkiluoto NPP has been clearly under the international reference values of the BWR reactors. On the other hand, the comparison of the collective dose at the Loviisa NPP to the PWR reactors does not give such an excellent result. Average collective doses per reactor of the German Konvoi generation NPPs (Emsland 1, Isar 2 and Neckarwestheim 2) and French N4 generation NPPs (Chooz B1 and B2, statistics only from the year 2001) are also shown in Figure 2. The statistics would indicate that the collective dose in the EPR could be low.

The PSAR review of STUK experts on plant radiation sources, shielding, lay-out and radiation protection arrangements, as well as STUK's topical inspection made to the vendor (designer) pointed out some aspects where the applicant and the vendor shall enhance efficient communication between different expert and designer groups. STUK's review on the plant radiation monitoring systems description indicated that the system design covered well the main requirements of YVL 7.11. The detailed design of the systems is now reviewed during the construction phase.

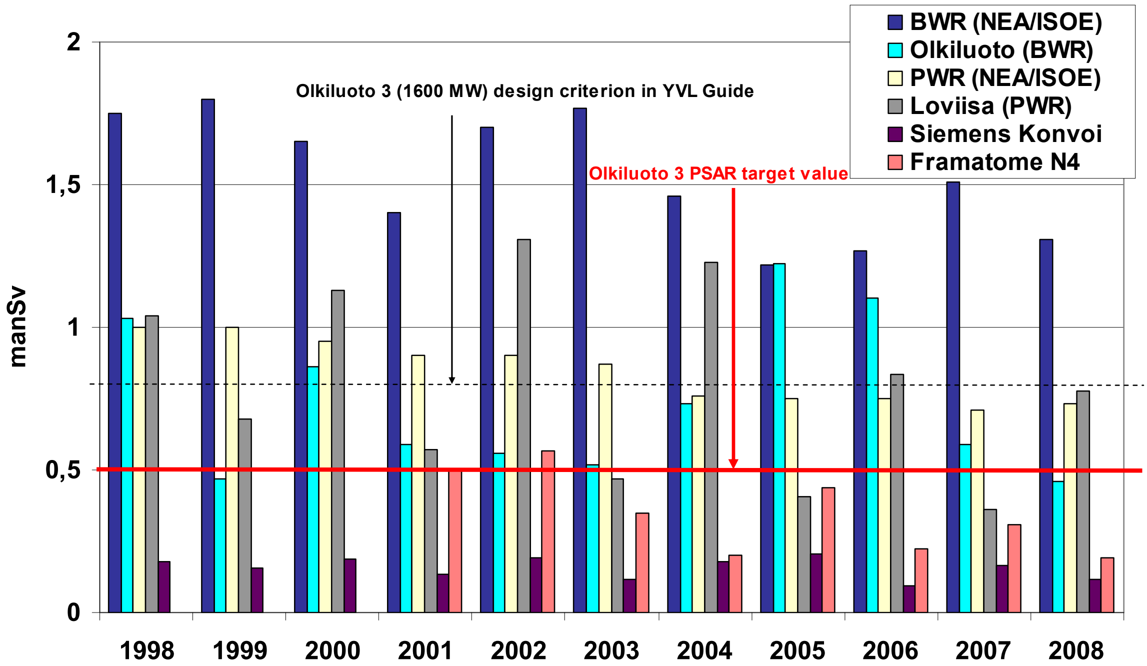

Figure 2. Average personnel collective radiation doses per reactor.

Minimising discharges of radioactive materials during normal operation

The reactor, systems and components containing radioactive substances shall be designed in such a way that releases of radioactive substances and the radiation exposure of the population living in the vicinity of the plant can be kept low. Systems which are capable of cleaning fluids and gases containing radioactive substances shall effectively limit radioactive releases and shall be designed according the principle of Best Available Techniques (BAT). Radioactive releases from a nuclear power plant during normal operation are, to a great extent, determined by leakage from the nuclear reactor fuel rods, reactor coolant and its fission and corrosion products, maintenance operations and waste management (including purification and retention of exhaust gases and liquids).

Based on STUK's review on PSAR and detailed design of the systems, due consideration has been given to the minimisation of discharges of Olkiluoto unit 3. Over the past years fuel leaks at the German and French reference plants have been minor. The same is expected to apply to Olkiluoto 3's reactor fuel. The materials for the reactor cooling circuit have been selected and the water chemistry designed with a view to minimising the creation of radioactive corrosion products. The reactor coolant purification system, the processing system for gaseous wastes, the storage and processing system for liquid wastes and the processing system for radioactive concentrates are based on technology used at the German reference plants, with improvements based on operating experience. The purpose of these systems is to limit the releases of radioactive materials into the environment. These systems are designed with due regard to the Best Available Techniques. Adequate exhaust air filters have been designed for installation in the ventilation systems.

Accident analyses, severe accident management and on-site radiation safety

Analyses of radiological consequences of postulated accidents, design basis accidents, design extension conditions and severe accidents were presented in PSAR and reviewed by STUK. The results from the analyses were well below the dose limits defined in the Government Decree 733/2008 the Safety of Nuclear Power Plants.

At Olkiluoto unit 3, severe accident management is based on reliable depressurisation of the primary circuit and proper containment functions with a unique core catcher. These measures will prevent any major release of radioactive materials (Cs-137 release in excess of 100 TBq shall have a probability less than $5{\cdot}10^{-7}$/a). With regard to protection against external threats, Olkiluoto unit 3 is constructed according to the design features which provide safety and prevent significant releases even in the case of a crash of a big passenger aircraft.

In a nuclear power plant, on-site habitability during accident situations has also to be taken into account in the design. The regulatory guide YVL 7.18 requires analyses of the magnitude and location of the possible radiation sources and evaluation of doses in different accident management and emergency preparedness measures. It shall be shown during the design process, that these doses do not exceed the normal dose limits of a radiation worker, i.e. 50 mSv. STUK's assessment on Olkiluoto 3's PSAR showed that adequate shielding and lay-out arrangement existed in the design. A more detailed review was done during the construction phase based on the detailed design of the systems and structures. It showed that the analysed doses of workers were well below the radiation worker's dose limit.

Regulatory oversight during construction

Regulatory oversight during Olkiluoto 3 construction ascertains that the plant is built according to the design and quality criteria approved in the construction licence phase, and that the prerequisites for high quality end result exist and the licensee is getting prepared for the commissioning and operation of the plant. STUK is currently finalising the review of the detailed design of the systems, structures and components and that includes also verifying that radiation safety requirements are fulfilled.

STUK has also established a construction inspection program to inspect TVO's project progress and implementation. One of the inspections focuses on the consideration of radiation safety issues, i.e., fulfilment of radiation safety criteria in the design and plans for radiation protection programme during plant commissioning and operation. In addition, STUK has performed inspections on the plant vendor and two of them concerned also radiation safety aspects.

Conclusions

Several STUK's YVL Guides deal with radiation safety. STUK has reviewed the application for the Construction Licence of the Olkiluoto 3 nuclear power plant unit in 2004-2005 and is currently finalising the review of the detailed design of the systems, structures and components. This review work includes also verifying that radiation safety requirements are fulfilled. The experience gained in the Olkiluoto 3 regulatory oversight project is taken into account in the revision of the STUK's YVL Guides and in the planning of the next possible oversight projects.

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The new IAEA Basic Safety Standards (BSS) and their implementation for the operation of nuclear installations

Lorenz, Bernd[1]; Schwarz, Wolfgang[2]; Holl, Matthias[3]
[1] GNS Gesellschaft für Nuklear-Service mbH, GERMANY
[2] E.ON Kernkraft GmbH, Kernkraftwerk Isar, GERMANY
[3] RWE Power AG , GERMANY

Abstract

After the issue of ICRP 103 /1/ the process of revising the IAEA Basic Safety Standards (BSS) /2/ started. It follows the policy to adopt all the new ICRP considerations as far as possible. This should not be a problem as the ICRP itself stated "stability and continuity" as the headline for its new recommendations.

Indeed, there are few changes in ICRP: the risk factors are nearly the same and became even smaller, the dose quantities remain and, what is essential, the three basic principles justification, optimization and limitation endure. But there are changes. The process based approach is no longer used, there is new terminology and dose constraints were seen as central part of radiation protection not corresponding to the long lasting practice.

The revision of the BSS triggered a lively discussion in which the operators of nuclear installations participated. The large number of comments on the drafts shows that some remains to be done. Clarifications were already possible during the joint meeting of RASSC and WASSC in November 2008. It was e.g. made clear that not an optimized state has to be assured but the process of optimization. Unfortunately this decision was later cancelled, a situation which is not acceptable. It was also revealed that sometimes it was not yet clear who is responsible and what is a requirement and what a guideline. This could be approved in the following drafts, but the reformatted drafts failed to concentrate on "real" requirements.

For operators of nuclear facilities it is essential that changes in the BSS lead to higher safety and not to higher bureaucracy only. The demand for dose constraints for all sources that could be drawn from the text formally would be an example for that.

The drafting of the new BSS is in the hands of the IAEA and its co-sponsors. The operators need to focus on the discussions in the Safety Standards Committees and on comments. This is an important part of the process and we noticed that experience from practice is welcomed.

Material and methods

The basis for the analysis of the possible changes in radiation protection and their implications to the daily practise has been and still is the drafts of the revised BSS. The last is now Draft 3.0, posted for comments by the IAEA Member States until the end of May 2010. The plan is to finish the work at the end of the year, so the discussion here and during the Meetings of the 4 Safety Standards Committees of the IAEA are the last opportunity to correct things which might be misleading, not adequate or imprecise.

Results

The European nuclear industry has taken the opportunity to participate in the discussions about the revised BSS by a rather new organisation, the European Nuclear Installations Safety Standards Initiative (ENISS). ENISS was given an observer status in 3 Safety Standards Committees (NUSSC, RASSC, WASSC). From the very beginning ENISS commented the drafts of the revised BSS. The ENISS comments focused on 2 major issues: the provisions in the BSS about optimization and the prominent role of the Dose Constraints (DC). All other remarks have been of less importance, sometimes editorial or were accepted by the drafters.

Discussion

In addition to justification and the setting of dose limit, optimisation has been one of the basic principles in radiation protection for a long time now. This has not changed, even with the publication of ICRP 103. The main message of ICRP 103 is “continuity and stability”. Persons active in radiation protection will be happy about this message, since it confirms the practical experience in radiation protection so far and calls for its continuation. However, it is in the nature of optimisation not to lead to a standstill. Optimisation means asking yourself constantly if you did everything to keep the risk of radiation exposure as low as reasonably achievable “taking into account all prevailing circumstances”.

The implementation of these radiation protection principles has led to a constant decrease of actual exposures for workers. This is clearly indicated by statistics published by the Federal Office for Radiation Protection, BfS, /3/. They are on such a low level that occasionally the issue is raised if any further decrease could still be possible while maintaining the optimisation principle or if minimisation starts or has already started to dominate as a new principle.

> ”*From 2003 to 2007, the mean annual dose of all persons exposed decreased by an average of 3% per year. Simultaneously, the number of persons exposed increased by an average of 4% per year. The collective dose remained almost constant. Measured in the increase of persons exposed, this presents a relative decrease in the dose. However, this is considerably less than from 1999 to 2003, when as a result of the new Radiation Protection Ordinance entering into force an absolute decrease in the dose could be observed in spite of a considerable increase in the number of the persons exposed.* ***This may indicate that for the majority of the employees the average annual exposure is becoming as low as reasonably achievable by optimisation measures.”***

Fig. 1. Quotation from the BfS Report /3/, bold letters by the authors.

Nevertheless, we state: Radiation protection is on an excellent level implementing the principle of a continuous improvement in the form of optimisation, and a necessity to change the radiation protection concept is therefore not recognisable.

Dealing more intensely with the new basic recommendation of the ICRP of 2007 (ICRP 103), you will find that the ICRP has changed the system in spite of the expectations mentioned above. With the new and specific emphasis on "dose constraints" already introduced in the ICRP 60, these are now seen as one of the most important means of radiation protection optimisation, if not the most important one. This, however, may create a difference between the radiation protection optimisation and the ALARA principle. The reasons for this are difficult to understand.

If you ask around in practical operation, and try to find out where dose constraints are being used, you will learn that they can hardly be found. However, often operational dose restrictions are found that serve to control compliance with dose limits, such as maximum daily doses, maximum monthly doses, permitted dose fractions for external and internal exposure. Furthermore, there are action levels for individual doses that trigger measures when reached, for instance, monitoring. Finally, also collective dose restrictions are defined as standard, in part even as goals for the operation related radiation protection or as decision gates for the planning of radiation protection measures. So one can find a host of dose-oriented criteria of which none complies fully with the "dose constraints" introduced by the ICRP.

It is of interest that Article 7 of the Council Directive 96/29/EURATOM /4/ points moderately to dose constraints: "Dose constraints should be used, where appropriate, within the context of optimisation of radiological protection". The implementation of this Council Directive 96/29/EURATOM into the German Radiation Protection Ordinance does not even include dose constraints. Now, the question is, what does the ICRP aim at by emphasising the dose constraints and will this lead to an improvement of the radiation protection in practical operation?

According to the ICRP, dose constraints are to be determined relative to sources. By definition, they are lower than dose limits. Contrary to the non-compliance with limits a non-compliance with dose constraints should not be a legal offence but needs to be excluded by adequate planning. If the dose constraint is a solely prospective planning measure or is to be used as well for retrospective evaluation of practical operation is controversial and not clearly indicated by ICRP statements.

The definition of "dose constraints relative to a source" creates a problem: Which source is meant? According to the ICRP, a radiation source is everything leading to radiation exposure. This may be an enclosed radiation source, with several kBq or TBq, a nuclear power plant in its entirety or even individual activities within the plant, such as the replacement of a valve, or an X-ray machine in a dental practice. Also the invasive X-ray diagnostics and even the radon exposure in a residential building qualify a "source" according to the ICRP. Already a first glance at the variety of possible radiation exposures shows you there are just as many options to define radiation sources. Does this mean several thousand dose constraints should be determined? For this, the ICRP does not provide selection criteria. So far, for the Council Directive 96/29/EURATOM the magic word "where appropriate" - even connected with the word "should" - was helpful. Such a restriction seems to be indispensable in the future as well; otherwise, a questionable bureaucracy is to be feared with regard to dose constraints. Indeed the BSS contains a lot of phrases such as "as appropriate", "where appropriate", "if appropriate", otherwise DC's could not be accepted at all.

For the application, it is imperative to take the dose levels into account. The significance of constraints for very small doses, for example in the range µSv, must be considered low from the outset.

Ionisation smoke detectors are a typical example, for which a dose constraint would not make sense. Here, other radiation protection measures apply based on the optimisation principle, e.g. only use as much activity as necessary, make the design robust and subject of design approval. As the example shows, it is worthwhile to develop criteria, when and where dose constraints are even "appropriate". In the discussion of new BSS, these considerations have not been included yet. Probably, the definition of dose constraints is only reasonable when there are actual design options regarding radiation protection, for example with complex projects or within the design phase of a source.

Which reasons are given by the ICRP for this particularly emphasised position of the dose constraints?

Dose constraints should limit inequity thus avoiding unacceptable high individual exposures as a result of the radiation protection optimisation.

So far, this objective was attributed to the dose limits, i.e. any exposure below these limits was basically acceptable. It is practise that exposures close to the limit values will be avoided. This is also a preventive action to avoid l exceeding the limits. It is customary as well to assign a higher priority to the reduction of exposures close to dose limits, and also a higher alpha value for quantitative considerations. These two procedures have proven to be efficient in reducing exposures at the upper level. To differentiate the acceptance even below the dose limits, maybe even quantitatively supported by DC's, is very questionable.

Occupationally exposed persons know about possible hazards caused by exposure. They also know how to influence the level of exposure by one's own behaviour. Apart from that, the development of the exposures has been showing a decreasing tendency for many years, as already specified above, and is now on a level clearly below the limits /5/. Higher exposures have also decreased continuously. In radiation applications in the medical field approx. 1%, in the industrial field approx. 2% of the exposed persons are exposed "to a higher degree", i.e. they receive doses of more than 1 mSv. For the few exposure groups with higher exposures, in the first place this affects flight attendants and pilots (approx. 9% of the persons monitored are in the dose range between 1 and 6 mSv), it may be reasonable to consider specific measures to reduce these exposures. However, this reasoning should not justify a change of the entire protection philosophy, as would be provided by a global introduction of dose constraints.

Dose constraints should prevent exceeding dose limits in case of exposures to multiple sources.

This goal has always existed. Its achievement is simple. The personal dosimetry applies to professionally exposed persons. For severely changing exposure situations, the official personal dosimetry performed at longer intervals is supplemented by an operation related dosimetry, which can be evaluated immediately. Thus, intervention to prevent exceeding limits even under consideration of several sources is always possible.

Public exposures are caused by discharges of radioactive material and direct radiation. In Germany, these exposures are controlled by considering the already existing radiological burden within the licensing procedure specified by the Radiation Protection Ordinance. Other countries may have similar regulations. In extreme cases, this regulates new discharges or new direct radiation fractures stricter than the ones already approved for a site. This must be accepted by someone arriving later. There is absolutely no problem for public exposure in the vicinity of such plants. So, even control of multiple exposures does not require the introduction of dose constraints

Apart from that, and this is even stipulated by the ICRP in publication 103, there is usually only an exposure to one source (meaning here one plant, one application technology) both for occupational and public exposure.

Dose constraints are to exclude solutions, which are not considered optimal.

In connection with the principle of optimisation, this presents a problem: How should one know, which is the optimised solution prior to the implementation of the optimisation itself? A way out could be considered the so-called "best practices" for certain applications of ionising radiation, from which preferred solutions could be derived. Strictly speaking, however, general specifications contradict the ALARA principle according to which the circumstances of the individual case must be taken into account. Missing criteria and methodical references for a derivation of dose constraints are another relevant problem. Unfortunately, ICRP 103 is of no help here.

Dose constraints could be understood as being results derived from the optimisation process. Here it is also easy to envision that for comparable technologies or activities dose constraints defined by reference numbers could be useful. This, however, contradicts the ICRP statement that optimisation is required below the dose constraints. Thus, certain arbitrariness exists in the definition of dose constraints, and this is definitely misfortunate.

Another problem is that the ICRP does not provide clear information as to who is to be responsible for finding and setting the dose constraints. ICRP considers the plant operator responsible for optimisation, but recognises a certain necessity to co-ordinate dose constraints with the authorities. Here, there is a lot of room for discussion with regard to the future integration into European and national regulations, and in particular with regard to the subsequent practical operation, which is not of much help to radiation protection.

Ensure that protection and safety are optimized.

The second item of importance for the discussion of the revised BSS is the inadequate formulation of the optimization principle in the BSS, stating that “operators/licensees have to ensure that protection and safety are optimized”. We still believe that this is a crucial item for the implementation of radiation protection in practice. The principle of optimization based on ICRP 103 is correctly described in the introductory chapter 1 of the BSS as a process. In the main text of the BSS optimization has several times been reduced to the misleading phrase "to ensure that protection is optimized". This could create difficulties in practice as there are no clear criteria for the "optimized solution". As we believe, there is no principal difference among the radiation protection experts about the optimization principle, we suggested to change the corresponding formulations. In the RASSC/WASSC Meeting in November 2008 this change was accepted unanimously. However, during the next meetings of the drafting group a backchange was decided. Unfortunately in the following meetings of the Safety Standards Committees a deep going discussion of this issue did not take place.

To explain the concerns with the too short wording of the BSS regarding optimization some questions may enlighten the situation:

- What is optimization in legal terms?
- What are the criteria of being optimized?
- When and how often do operators have to demonstrate that protection and safety is optimized?

Optimization in legal terms

As described in chapter 1 of the BSS according to ICRP optimization is one of the principles of radiation protection and it is definitely a process.

> *"The optimization of protection and safety, when applied to the exposure of workers, members of the public and comforters and carers of patients undergoing radiological procedures, is a process for ensuring that the magnitudes and likelihood of exposures and the numbers of individuals exposed are as low as reasonably achievable, taking social and economic factors into account. This means that the level of protection should be the best under the prevailing circumstances, maximizing the margin of benefit over harm, and will thus not necessarily be the option with the lowest risk or dose. Optimization is a forward-looking iterative process requiring both qualitative and quantitative judgements, and may be used, if appropriate, in conjunction with individual source-related values of dose or risk that serve as boundaries in defining the range of options in optimization."*(BSS Draft 3.0 para 1.14)

ICRP has issued so-called foundation documents in connection with ICRP 103 and the one dealing with optimization is the ICRP Publication 101 /6/. It is clearly stated there that optimization is a process and not dedicated to a specific result. The outcome of the optimization process will always be specific under the prevailing circumstances. From the legal point of view a legal requirement can therefore only be directed towards the process or the principle. The nuclear industry has made time and again a proposal for changing the text into "have to ensure that protection and safety are subject to an optimization process". As said this was already accepted in November 2008.

A counterargument was since then that having a process only is too soft and does not guarantee that results of the process will be implemented. Although this argument is not very convincing one could in addition demand in the BSS that results of the optimization process have to be implemented. From the standpoint of radiation protection practice this is logical anyway.

The current situation in many radiation protection legislations is that only the principle of optimization is fixed legally. A prominent example is the Council Directive 96/29/EURATOM, where Article 6 says, that ”each Member State shall ensure that in the context of optimization all exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account.” The German Radiation Protection Ordinance e.g. indeed contains only this principle. Note that the provision is directed to the Member States only. The BSS addresses not only the regulator and competent authorities but also operators.

Criteria for being optimized

Optimization in the textversion of the ALARA Principle may be interpreted differently: one may stress the word ”low”, asking for exposures in the µSv-range or even Zero-dose, one may stress the ”reasonably” as operators are often said to do so, or one may stress the ”achievable”, as engineers might willing to do. Social factors may be seen differently from a workers point of view and a stakeholders point of view. These examples easily show the great variety of interpretation of being optimized. There are no clear criteria. Getting a licence may be an indicator for being optimized, otherwise an authority would probably not have issued the licence. Getting a type approval is also an indicator. The question than remains what to do during operation. The BSS do not answer this questions and give no indication for the fulfillment of its strict requirement to ensure being optimized. But such a situation is dangerous for any development of protection. Operators might be forced not to change their operational mode as the fear not to get a renewed licence.

When and how demonstrate ”being optimized”?

The optimized solution today may be obsolete tomorrow. The circumstances change permanently. For any radiation protection expert in the field it is clear that one cannot change the rules everyday. Operation needs stability. The BSS do not contain details of how to ensure the optimized solution. In the planning of the framework of IAEA standards a guide about optimization is not to see. Without guidance on optimization it will be difficult to implement the requirement. The experience so far goes along the line of having a process of optimization. With the new formulation of the optimization requirement in the BSS the proven system will be questioned and the outcome is unclear. A situation which is not suited to foster protection and safety.

Conclusions

In summary, it becomes clear that dose constraints according to the ICRP version are needed neither in Germany nor in the EU or elsewhere to achieve excellent radiation protection. Care should rather be taken to avoid new bureaucracy from developing that would do more harm than good.

Dose constraints, defined and applied flexibly and with a sense of proportion make sense when used by the operators of nuclear plants as management tools for a proven practical operation and as a result of optimisation considerations. It may be reasonable to determine a few operation related values. Optimisation, however, is by far more than the determination of such dose constraints.

The shortening of the optimization principle to the requirement “to ensure that protection and safety are optimized” is inadequate, not in line with the ICRP philosophy and the guidance given in ICRP 102. The drafters of the BSS need to come back to the decision from 2008 and reinstall the formulation “ ensure that protection and safety are subject to an optimization process”.

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/3/ BfS-SG-12/09; The Occupational Radiation Exposure in Germany in 2007, Report of the Radiation Protection Register, page 23:

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Radiation protection culture in the nuclear industry

Le Guen, Bernard
Électricité de France, FRANCE

Occupational radiation exposure – an overview on the exposure of the workers in facilities of the nuclear fuel cycle

Kaulard, Joerg; Schmidt, Claudia; Strub, Erik
Gesellschaft fuer Anlagen- und Reaktorsicherheit (GRS), mbH, GERMANY

Abstract
Workers are subject to radiation exposure in several industries. This contribution will provide an overview of the exposure of workers in facilities of the nuclear fuel cycle. Following a first overview, details on the exposure in nuclear power plants in operation as well as under decommissioning are addressed. Based on recent data, trends in the exposure of workers will be discussed and some examples will be given on how experiences contribute to improvements concerning the exposure of workers.

The data available show, that with time in general the exposure of the individual worker decreases. This is a result of a manifold effort by all parties involved in the radiation protection in nuclear facilities, which is mainly based on a consequent experience feedback from past operation to improve design and operation and regulations relevant for the nuclear sector.

Introduction
In its 2008 report to the United Nations General Assembly, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) estimates, that today more than 22.8 million workers are exposed to ionizing radiation (UNSCEAR 2008). About 13 million workers are subject to ionizing radiation from natural sources. The remaining 9.8 million workers belong to all sectors of artificial sources, 75 % of them related to the medical sector. Among the 25 % of the 9.8 million workers are those working in facilities of the nuclear fuel cycle (nuclear sector).

This contribution to the Third European IRPA Congress addresses worldwide trends in the occupational exposure in facilities of the nuclear sector. For that, a first overview on the situation worldwide is given, followed by a focus on the situation in nuclear power plants as – in general – one of the main sources for exposure. The factors which influence the occupational exposure and its decrease at nuclear power plants are manifold. As an example for more details and influencing factors, some German trends in occupational exposure in nuclear power plants are explained.

Trends in the occupational exposure in the nuclear sector worldwide

In its 2000 report UNSCEAR has published data on the occupational exposure related to work in different types of facilities related to the nuclear sector (UNSCEAR 2000). The data published cover the years 1975 until 1994 (Note: Currently, an update of this report is under preparation which will be published early 2010 but was not available at the time of preparation of this contribution). The nuclear sector comprises facilities for uranium mining and milling, for uranium enrichment and conversion, for fuel fabrication, for operation of nuclear power plants (NPP), for reprocessing and for research within the nuclear fuel cycle. Although waste management is another branch in the nuclear sector within the UNSCEAR survey only little data become available separately as they are mainly covered in the other branches mentioned.

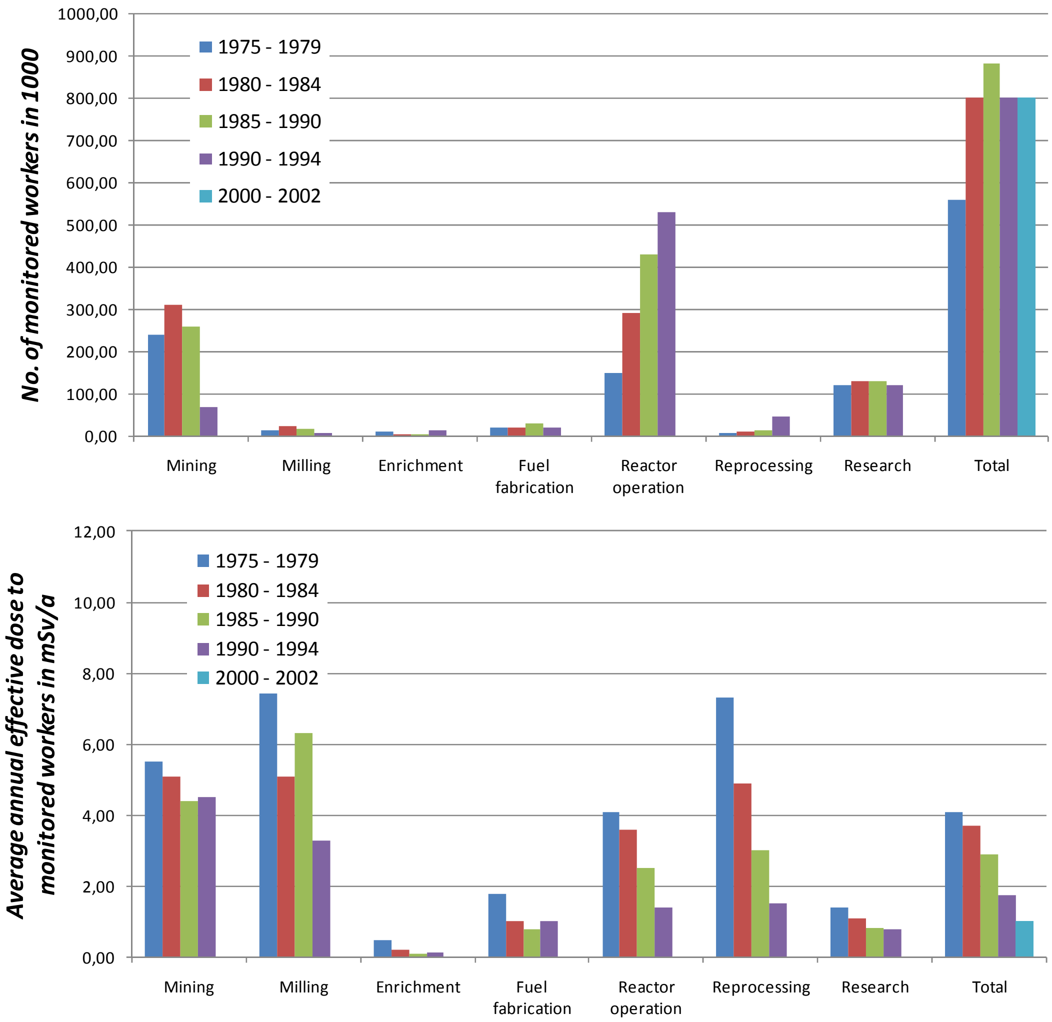

Fig. 1. Number of monitored workers in thousands and average annual collective doses for the different branches in the nuclear sector.

Fig. 1 and Fig. 2 present the trends of estimated numbers of monitored workers, estimated average annual collective doses, the resulting average annual effective doses of monitored workers and the fraction of monitored workers with an annual effective dose of more than 15 mSv for the different branches within the nuclear sector. The data

1975 – 1994 are taken from the 2000 report of UNSCEAR (UNSCEAR 2000), the data 2000 – 2002 are taken from the 2008 report (UNSCEAR 2008), but not for all items 2000 – 2002 numbers were available.

The UNSCEAR data were obtained by surveys of occupational radiation exposure, requesting information from various national authorities and institutions and by collecting supplementary data, e.g. from the Information System on Occupational Exposure (ISOE) of the OECD Nuclear Energy Agency (NEA). As a matter of fact the data reported differ due to national differences e.g. in the statutory dosimetry systems, on reporting of exposed or monitored workers, on the national reporting levels. In addition, not for each period and for all nuclear branches data for all facilities have been supplied. Especially in case of the mining branch, some estimates became necessary to achieve a more complete view on the worldwide situation for the data of the period 1990 – 1994, resulting in some larger uncertainties in the number of monitored workers and the related average annual collective effective dose. Nevertheless, the data prepared allow important insights in the occupational exposure of workers in the nuclear sector.

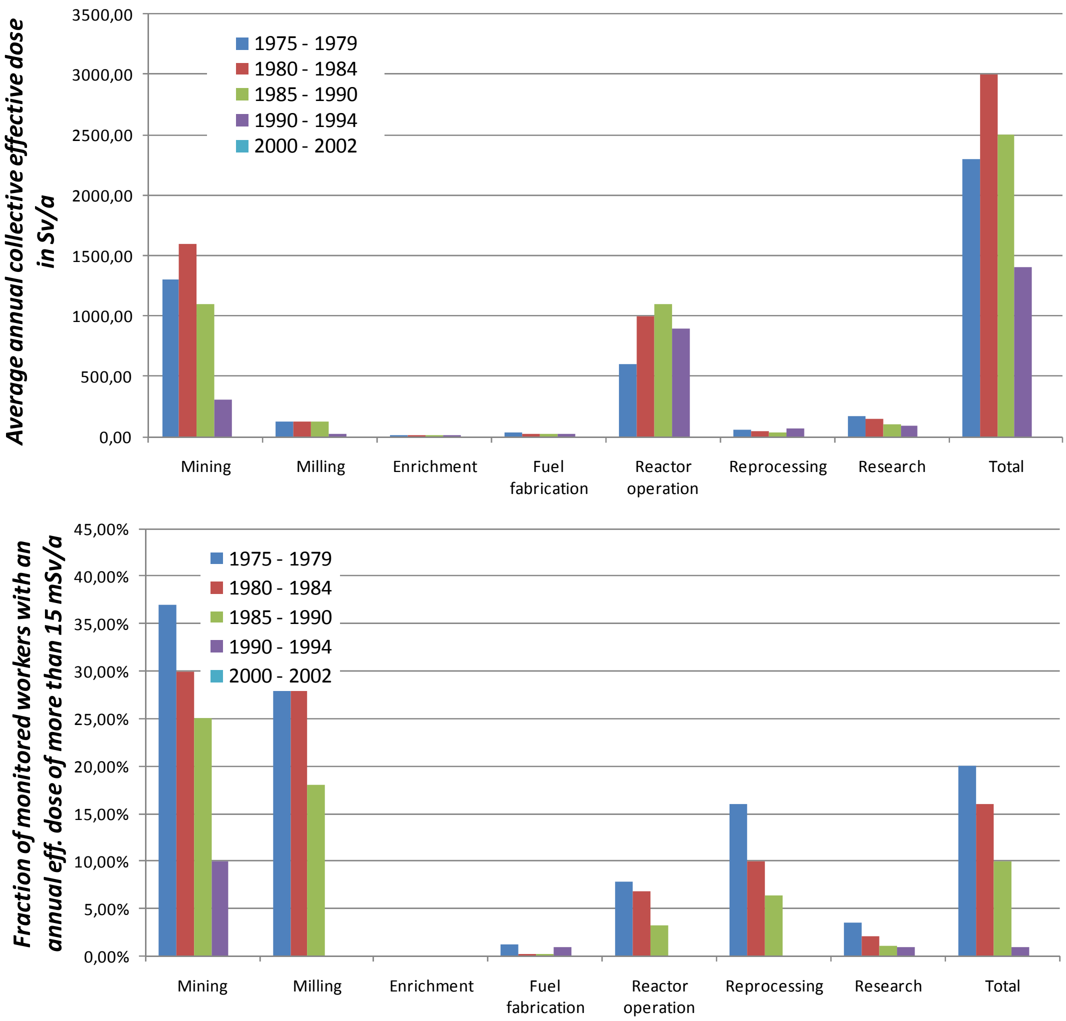

Fig. 2. Average annual effective doses of monitored workers and fraction of monitored workers with an annual effective dose of more than 15 mSv/a for the different branches in the nuclear sector.
(Note: for several branches the fraction for doses of more than 15 mSv is close to 0 in 1990-1994)

Independent from the uncertainties mentioned, the figures and numbers show, that

(a) NPP operation (reactors) is the branch with the highest number of monitored workers in the last period but not with the highest average annual effective dose to monitored workers,

(b) for all branches a decrease in the annual collective effective dose to monitored workers can be observed in the last periods,

(c) the fraction of monitored workers with an annual effective dose of more than 15 mSv decreases over time, but for the mining and milling branches the fraction is still the highest.

As such the data show a general worldwide trend of decreasing occupational exposure by ionizing radiation in the nuclear sector. The average annual effective doses of monitored workers in the nuclear sector decreased from 1975 to 1994 from 4.1 mSv to 1.75 mSv; the recent data of the 2008 report indicate a further decrease to about 1 mSv.

Details on the occupational exposure in nuclear power plants worldwide

While UNSCEAR collects and analyses data on all aspects on the effects of ionizing radiation, the Information System on Occupational Exposure (ISOE) of the OECD Nuclear Energy Agency (NEA) focuses on the occupational exposure of workers in NPPs. Established in 1992 by the OECD-NEA, the overall goal of the ISOE is to facilitate the optimisation of worker radiological protection in NPPs through collection and assessment of relevant data and the exchange of experiences on radiation protection in NPPs. As of January 2010, 63 operators of NPPs in 27 countries are official participants of the ISOE, representing 311 NPPs in operation and 40 NPPs under decommissioning. The central database of ISOE contains data for many more NPPs in operation (401 NPPs) and under decommissioning (about 80). As such the ISOE database represents the largest database on data on the occupational exposure in NPPs under operation.

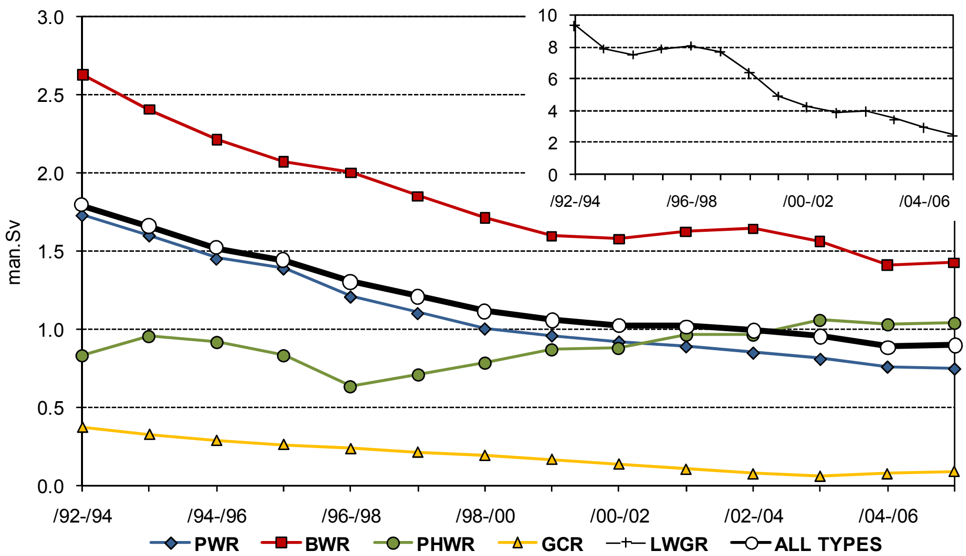

Fig. 3. Three years rolling average annual collective effective dose per nuclear power plant for different reactor types (Ahier 2008, ISOE 2009).

Fig. 3 shows the three years rolling average annual collective effective dose for all NPPs participating in ISOE and for different reactor types. The data show a decreasing trend in the exposure, which supports the conclusions drawn by the UNSCEAR. Nevertheless, it should be taken into account, that the data of the different reactor groups are based on the data of different numbers of NPPs. E.g. for the year 2007 for PWR group (including VVER) about 230 nuclear power plants provided data, while for BWR about 70 nuclear power plants, for PHWR about 30 and for LWGR only 1 NPP provided data (ISOE 2008). Accordingly extraordinary work during outage or refurbishment in an individual NPP has different impact on the averaged dose depending on the reactor group. Such an influence can be recognized in the data of the PHWR, which is representing the CANDU reactor type. Since 1999 (ISOE 2001) an additional NPP provides its data which are significant higher than the average at that time. In combination with major work in other NPPs this resulted in an increase of the average dose overlaying any decreasing trend due to improvements made.

The database data contains also data on the occupational exposure at NPPs under decommissioning. Fig. 4 shows the average annual collective effective dose and the number of the related reporting NPPs under decommissioning (ISOE 2009). The evolution of the average dose with time may be interpreted as a decreasing trend. In fact, such an interpretation is not correct, as – different to the operation of a NPP – the exposure strongly depends on kind and amount of decommissioning work of a year which change during progress of a decommissioning project dramatically. The increase of the reporting NPPs is related to the fact, that ISOE promotes the collection of decommissioning related data within the last years and that new decommissioning projects were started.

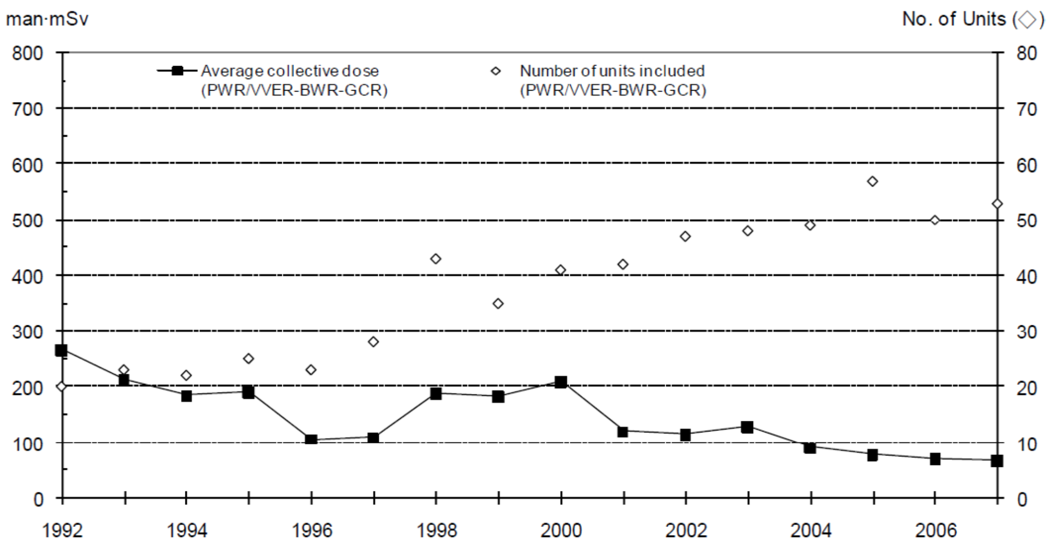

Fig. 3. Three years rolling average annual collective effective dose per nuclear power plant for different reactor types (ISOE 2009).

However, the data available for NPPs under decommissioning show that the average annual collective effective dose is much lower than in case of NPPs in operation. The ratio varies strongly from year to year at least due to the changing decommissioning work.

A spotlight to a national situation – examples from Germany

As already discussed in the context of the UNSCEAR data, main branches for occupational exposure in the nuclear sector are mining and milling and nuclear power plants. Today, in Germany no mining and milling facilities of the nuclear fuel cycle are in operation anymore. 17 nuclear power plants at 12 sites are in operation and 17 nuclear power plants (at 13 sites) are under decommissioning while 2 nuclear power plants were completely dismantled meanwhile.

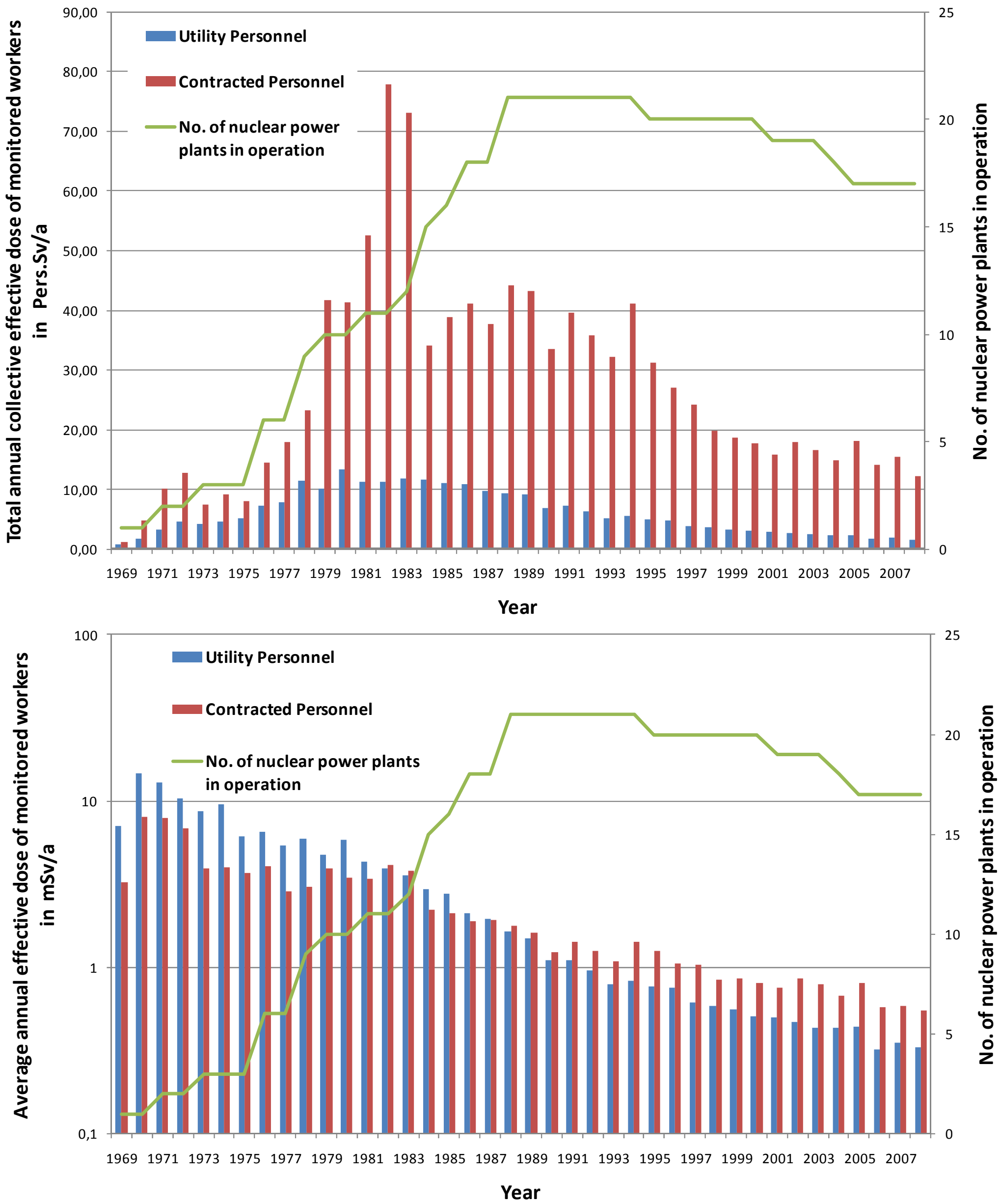

Fig. 5. Total annual collective dose and average annual effective dose of monitored workers for German nuclear power plants in operation.

Fig. 5 and Fig. 6 show the total annual collective dose and the average annual effective dose to monitored workers for all German NPPs in operation and under decommissioning. Both figures are based on data from the occupational dosimetry systems operated by the operators of the NPPs. Thus contracted workers are attributed to each single NPP even, if they entered two or more NPPs during the year. Accordingly, the number of contracted workers in the figures is higher than the number of real persons or the related number of workers registered in the German statutory dosimetry. As a consequence, the average annual effective dose for monitored workers is lower than in case of using the official data of the statutory dosimetry.

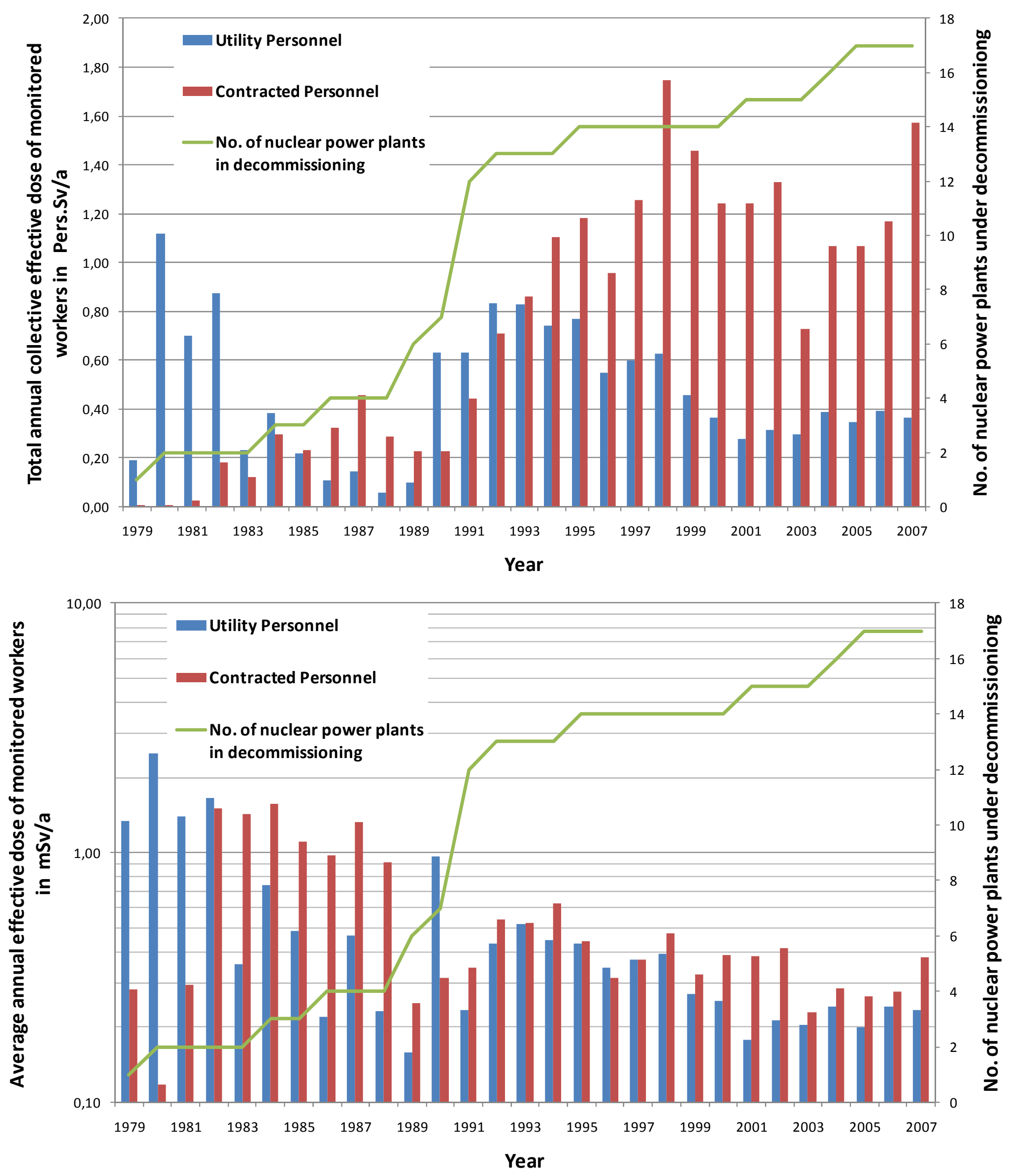

Fig. 6. Total annual collective dose and average annual effective dose of monitored workers for German nuclear power plants under decommissioning.

Fig. 5 shows a clear long term trend of lower total annual collective doses and average annual effective dose of monitored workers. In general terms, this trend is due to a consequent experience feed back and radiation protection work planning process (so called IWRS radiation protection planning) during operation and due to improvements in the design of newer NPPs. For some NPPs, back fitting activities were performed during operation improving also the radiological work conditions. Especially the long term trend for the average annual effective dose of monitored workers indicates that in general the working conditions for workers changed and improved. A further analysis of the distribution of the individual annual effective dose of the monitored workers in German NPPs confirms that the fraction of workers with a higher dose decreases (e.g. Fig. 7 on the distribution of the fraction of monitored utility workers). Since 2001 exposures above the German dose limit above 20 mSv/a, did not occur.

Fig. 6 shows the numbers for nuclear power plants under decommissioning. A trend similar to that of Fig. 5 can not be recognized as was already mentioned during discussion of data from the ISOE. This is due to the fact that the annual effective dose for each nuclear power plant strongly depends on the decommissioning work and the related radiological conditions and which change form year to year, following the overall work planning and decommissioning strategy for the NPP. Obviously, the type, inventory and operational history of the NPP influence the radiological conditions. As such no trends can be expected. But, improvements e.g. due to experience feedback take place and can be identified on the level of an individual NPP. Comparing the data of German NPPs under decommissioning it turns out as a rule of thumb that the decommissioning related average annual effective dose of monitored workers is about 10% to 20% of that for operating, but this ratio depends on the NPP and – as mentioned – the work to be performed.

The influence of the design of the German NPP on the occupational exposure during operation can be easily recognized in Fig. 8 in which the average annual collective effective dose of the works in German NPPs, belonging to a specific design generation, is presented. While the figure considers all commercial NPPs in operation in former West Germany the six NPPs of the former East Germany are not considered, as they belong to another design generations of Russian design. The NPPs of PWR type are divided into 4 generations; during design of the PWRs of the fourth generation (so called Konvoi reactor) all previously made experiences, esp. from operation of PWRs of the first generation, were considered (e.g. on the use of material with low neutron activation, design of compartments to separate components with high dose rates from those with low dose rates to reduce exposure during later maintenance work, design requirements for low dose rates at frequently accessed locations). As such, the Konvoi reactors offer well improved radiological conditions due to design.

Fig. 8 illustrates also the different contributions from the German NPPs to the total annual collective effective dose of the German NPPs in operation and the related annual effective dose of monitored workers. As an example on the different situation in the individual NPPs, for 2008 the average annual effective dose for monitored utility workers varied between 0.04 mSv/a and 0.78 mSv/a. As already mentioned, the individual contributions may change significantly, typically more for the earlier generations, as they are due to the height of their dose contribution more sensible to changes in workload than the Konvoi reactors.

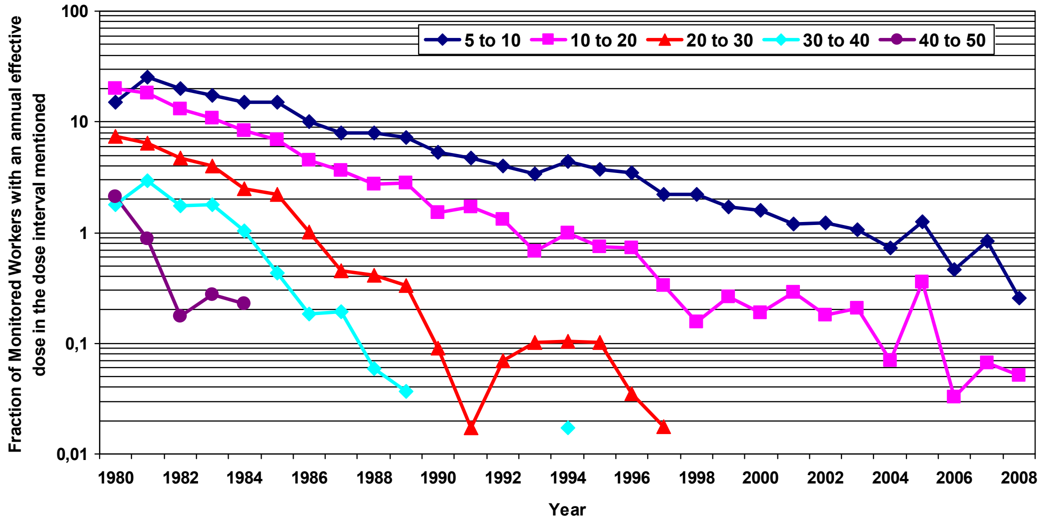

Fig. 7. Distribution of the fraction of monitored utility workers with a specified annual effective dose for German nuclear power plants in operation (in %).

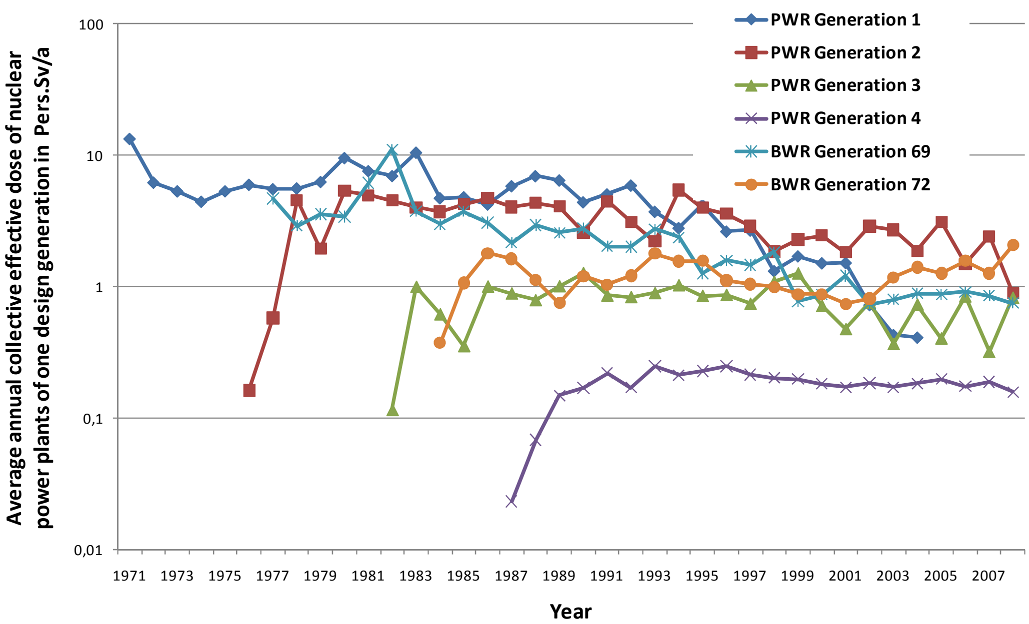

Fig. 8. Average annual collective dose of workers, averaged for German nuclear power plants of similar design generation.

Conclusions

Recent international data of UNSCEAR show, that the occupational exposure for workers in the nuclear sector has decreased during the last three decades. Although these data, especially those related to the mining and milling branch within the nuclear sector, are connected with some uncertainties, but the trend shown can be regarded as realistic.

When focussing on the situation within NPPs, the international data of the ISOE publicly available allow a more specific analysis of the situation including a separation between NPPs in operation and under decommissioning. For the common reactor types

PWR (including VVER) and BWR, a decreasing trend on the average annual collective effective dose for nuclear power plants in operation can be observed; the data for the group of NPPs of reactor type PHWR show an increasing trend, which is due to the increasing number of reporting NPPs in ISOE and the contributions of single NPP with high doses on the average value.

Finally, best insight can be obtained by analysis of national data allowing a high degree of differentiation. As such an example, the data on the occupational exposure in German NPPs show again a decreasing trend for the total annual collective effective dose of German NPPs in operation and for the average annual effective dose of the monitored workers. Depending on the type and generation of the NPP, the improvements during operation are different due to the resulting radiological conditions. Improvements can be observed for all NPPs but the extent of improvement, e.g. expressed in terms of dose savings, depends on the radiological conditions – typically savings are higher in NPPs of the first generations. The national example shows also that an adequate design will ensure best improvements in radiation protection.

Concerning the occupational exposure in NPPs under decommissioning, the available data and their trend are dominated by the specific situation during decommissioning; different to operation, the annual work for a NPP under decommissioning changes dramatically with completely different radiological conditions. As such, the annual collective effective dose of a NPP under decommissioning changes significantly due to the nature of work from year to year. As a consequence, no trends in the annual data can be expected which allow an easy conclusion on radiation protection improvements. But, experiences show, that such improvements take place, resulting e.g. in a much lower real exposure of monitored workers than was expected during planning of the decommissioning.

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Radiation protection issues in fuel-manufacturing

Mellander, Hans
Westinghouse Fuel Sweden, SWEDEN

Floating nuclear power reactors – Fiction or future?

Reistad, Ole[1]; Hansell, Cristina[2]
[1] Norwegian Radiation Protection Authority, NORWAY
[2] James Martin Center for Nonproliferation Studies, UNITED STATES

Abstract

Russia's current floating nuclear power plant (FNPP) plans were initiated nearly 20 years ago, with a competition to develop small-scale power plants for the Russian Arctic. While the locations where the first plants will be sited have been altered several times, the basic design of the prototype plant remains the one that won the competition in 1994: a variant of the Russian icebreaker reactor. This paper describes the development in the Russian plans for building floating nuclear power plants (FNPP), and the status for the ongoing construction project. There have been two major changes since 1994: Russia has promised to fuel the reactors with low enriched uranium (LEU) fuel – whereas icebreakers use 36–90% enriched uranium fuel – and exporting FNPPs has become a key goal for its developers. The project now under realization has also been redesigned to increase safety. Attention to proliferation-resistance has also been highlighted in many Russian presentations on the FNPPs, making a switch back to HEU less likely. Redesigns to increase safety have also been widely touted. While there are many detailed reports about the fuel design, though, there is no data on performance – indeed, it is not clear that performance has indeed been sufficiently demonstrated. There are reports (without data) that testing of the fuel has occurred in other Russian reactor types, however, and Russian designers appear satisfied with the current fuel design. Russian has also approached the IAEA in order to have the Agency involved in assessing the safety of the plant design. Despite these developments, though, there are still several major questions about Russia's FNPP plans that raise concern. Much of the FNPP project remains shrouded in secrecy. Economic calculations, which will surely effect expenditures on safety, security, etc., are unknown – the total cost estimates given vary widely, and do not appear to include security, transport, or back end costs

Assessment of potential consequences of possible radiological accidents in the seas of the Northwest Region of the Russian Federation

Krylov, Alexey; Pavlovski, Oleg
Nuclear Safety Institute of the Russian Academy of Sciences, RUSSIA

Abstract

There are the sites for the storage and decommissioning of the retired nuclear submarines, their nuclear reactors, spent nuclear fuel and radioactive waste, located in Northwest Russia. Many of those sites are not isolated and protected. There are also nuclear shipbuilding facilities, naval objects and nuclear powered vessels (submarines, icebreakers) in the seas. All these sites present potential threat of radiological releases. This was the reason for implementation of the International Project "Enhancement of Radiation Monitoring and Emergency Response System in the Murmansk Region" (Project), managed by the European Bank for Reconstruction and Development. The Nuclear Safety Institute (NSI) of the Russian Academy of Sciences was the main executor of the Project. Possible scenarios and consequences of accidental radioactive contamination of coastal waters of Northwest Russia are discussed in this work. The scenarios assume the location of the potential accidents in the White Sea and in one of the Bays of the Barents Sea. The modelling of possible consequences of radiological accidents was implemented for water objects that strongly differ in size (from 5 to 300 kilometres), tides, currents and characteristic times of water exchange with the Arctic Ocean. The modelling of migration of the radioactive substances was carried out with the use of computer model developed by the NSI specialists. This model is based on the well-known three-dimensional Princeton Ocean Model.

Introduction

There are a lot of seas, gulfs and bays in the world that have been contaminated by radioactivity or are in danger of such contamination. The nuclear Navy facilities and especially nuclear submarines are the main sources of the danger.

The Soviet Union built about 250 nuclear submarines, more than 30 nuclear maintenance service vessels and coastal maintenance bases. The lifetime of most of the submarines and ships is over. The infrastructure proved to be unprepared for the necessary rate of decommissioning. It has resulted in the fast accumulation of the storage facilities for the retired nuclear submarines with spent nuclear fuel on board. The condition of the hulls of the submarines is worsening, presenting a threat of radioactive contamination of the environment. In Russia the sites for the storage and decommissioning of retired nuclear submarines, their nuclear reactors, spent nuclear fuel and radioactive waste are located at the coasts of the Barents Sea, White Sea, Kamchatka peninsula and at the Russian Far East (Takano et al., 2001; Nikitin et al., 1996; Compton et al., 2003; Vysotsky, 2008).

It is necessary to mention that the hazards are not hypothetical. For example, in 1985 the reloading of nuclear fuel at the nuclear submarine in the Chazhma Bay in the Russian Far East resulted in the accident with discharge of the large amount of radioactivity (Sivintsev, 2000).

Four Russian and two American nuclear submarines sank during combat duty. They lay on the ocean bed throughout the world. One Russian decommissioned submarine sank in the Barents Sea during transportation. Moreover several reactor units of the nuclear submarines were dumped with nuclear fuel on board (Reistad, 2006; IASA, 2003).

There are also regions of ocean that are radioactively pure nowadays, but with intense traffic of nuclear submarines. Underwater collisions of submarines represent another potential threat (IASA, 2003).

Thus, the geography of potential radioactive contamination of the World Ocean is broad enough. Integration of a radioactivity transport model into the Princeton Ocean Model (POM) could give the necessary tool to nuclear safety specialists.

At present in Northwest Russia, especially at the coast of the Barents Sea in the Murmansk Region, there are a lot of sites for the storage and decommissioning of the retired nuclear submarines, their nuclear reactors, spent nuclear fuel and radioactive waste. The highest radiation potential (~45% of total in the region) have nuclear submarines, located at the naval bases in the Murmansk region. The radiation potential of the storage sites in this part of Russia is higher than activity of long-lived radionuclides, released during the Chernobyl accident (Sarkisov, 2009). Some of those sites are not isolated and protected. This was the reason of implementing of the international Project “Enhancement of Radiation Monitoring and Emergency Response System in the Murmansk Region” (Project), managed by the European Bank for Reconstruction and Development (Amozova, 2007). Under this Project two crisis centres were established and equipped by the software necessary for nuclear safety specialists. Within the frame of the Project specialists of Nuclear Safety Institute of the Russian Academy of Sciences implemented initial improvements of the POM code.

Description of the regions of modelling

The Sayda Bay is situated in the Murmansk Region of the Russian Federation. The size of the Bay is about 5.6 km from east to west and 5.1 km from south to north (see Figure 1). The Sayda Bay is a restricted territory and is not used economically by local population. The bay is connected by narrow neck with Kola Bay of Barents Sea, There is no major rivers flow into the Sayda Bay. The tides in this bay are considerable. There is hydro-meteorological station at the Yekaterininskaya Harbor in the Kola Bay near the mouth of the Sayda Bay. The recorded tides are up to the 4 meters.

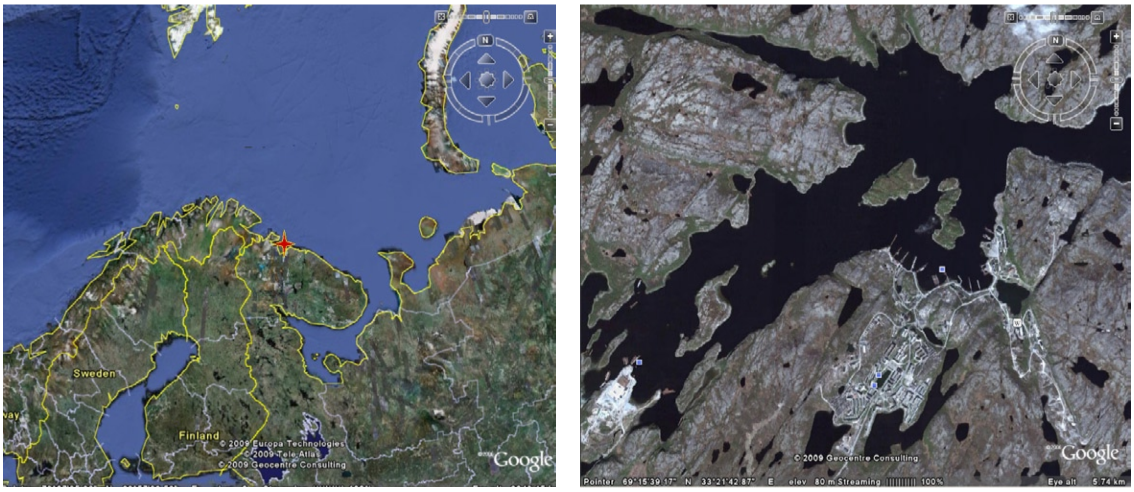

Fig 1. Location (left) and satellite photograph (right) of the Sayda Bay.

White Sea belongs to the internal seas of the Arctic Ocean. In the north it connects to the Barents Sea through the Gorlo and Voronka straits. The area of the sea is $8.7*10^{10}$ m^2, the volume of water - about $6*10^{12}$ m^3, the average water depth - 67m, and the greatest - 350m. (Figure 2, left). Annual runoff averages $2.2*10^{11}$ m^3.

The horizontal circulation of waters of the White Sea is formed under the combined effect of wind, river runoff, tides, compensation flows, so it is diverse and complex in detail. The resulting motion forms counterclockwise movement of waters under the influence of the Coriolis forces, peculiar to the seas of the Northern Hemisphere (Figure 2, right) - (Dobrovolskiy 1982).

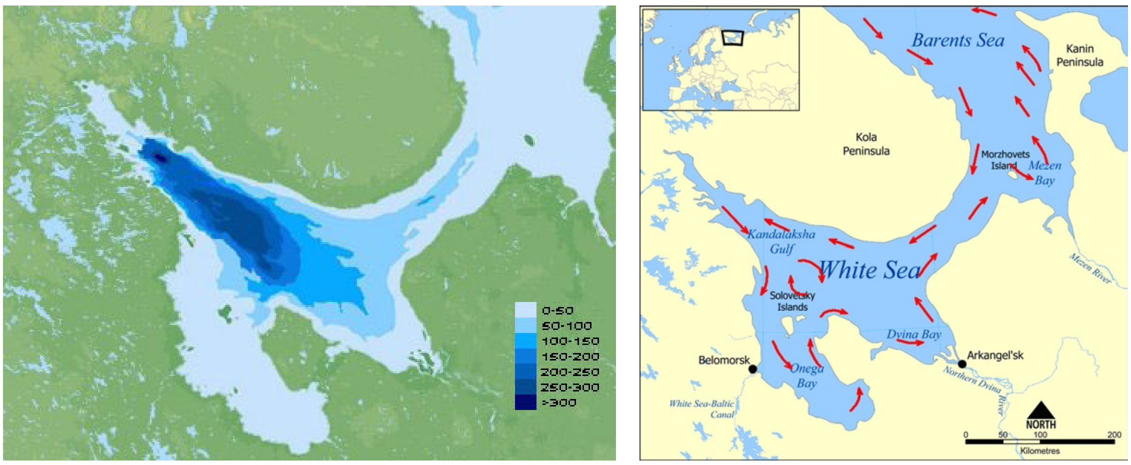

Fig 2. Depths (left) and a constant surface currents (right) in the White Sea.

The velocities of the constant currents are small and usually equal to 0.1 – 0.15 m/s in narrow waters and reach 0.3 – 0.4 m/s around capes. In some areas tidal currents have much higher speeds. In Gorlo strait and Mezenski Bay they reach 2.5 m/s, in Kandalaksha bay - 0.30 – 0.35 m/s, in Onega Bay - 0.8 – 1.0 m/s. In the sea basin velocity of the tidal currents is approximately equal to velocity of the constant currents (Dobrovolskiy 1982).

Improvements of the POM necessary to enable modelling of the radioactivity transport

Radioactive substances in the marine environment are transported in solute and sorbed on particles, first of all, on the finest fractions of the suspended matter. Modelling of radioactivity migration in the solute can be done by analogy with salinity. It is necessary to mention that calculation of salinity as a function of time and space is included into the POM.

In order to model radioactivity sources it is necessary to apply appropriate boundary conditions. The most probable types of radioactive contamination sources of the marine environment are as follows:

- A permanent point source on the seabed. It can include leakage of radioactivity from a sunken submarine, a piece of nuclear fuel or another radioactive fraction of a ship as it was in the Chazhma Bay accident.
- A permanent point source on the coast. It can include leakage from a coastal radioactively dangerous object or the mouth of a contaminated river.
- A short-term or instantaneous point source. It can include accidental radioactivity discharge from a nuclear vessel, submarine or from a coastal facility. It might even be deliberate discharge of liquid radioactive waste into the sea.
- A spatial surface source. Such sources can occur in case of an accident with a radioactivity discharge to the atmosphere and subsequent fallout on the sea surface. The area of fallout can be vast, its duration can be prolonged and the intensity can be extremely variable.

There are no significant difficulties in modelling of permanent sources. Boundary conditions should add the necessary amount of radioactivity each time step to the appropriate cells of the grid. Modelling of instantaneous point sources is also easy. But for this type of sources it is very important to spin up the model before adding the radioactivity. The spatial sources of radioactivity are most difficult for modelling as source characteristics require close interaction of models of contaminant dispersion in the marine environment and atmosphere.

It should be mentioned that POM computer code has no special module for the calculation of radioactive contaminant dispersion. Therefore authors of the paper have decided to use for this purpose seawater salinity forecast approaches used in POM code (Krylov 2009). It should be taken into account that unlike the salinity, the radioactive contaminants can be not always considered conservative. In most cases it is not necessary to take into account radioactive decay for long-lived radioactive substances, like ^{137}Cs or ^{90}Sr, as their half-life time is 30 years. And if the time of simulation is much less the decay can be neglected. But for accidents with a discharge into marine environment radionuclides with the half-life time of several days, like ^{131}I, it is very important to take into account their radioactive decay. For this purpose it is necessary to add the exponential decrease of the amount of radioactivity throughout the calculation grid.

Taking into account daughter radionuclides is much more difficult task. Daughter radionuclide can be much more dangerous than the maternal one. For example ^{241}Pu decays to ^{241}Am which is much more dangerous to the humans and the environment. In most cases daughter radionuclides are taken into account implicitly - dose coefficients of maternal radionuclide include effects of daughter ones. But if migratory characteristics of mother and daughter radionuclides differ significantly it may be necessary to model daughter radionuclides explicitly.

There is the mode splitting mechanism in the POM to use appropriate time steps for fast external gravity waves and slow internal gravity waves (internal and external modes). As the variability of radionuclides concentration fields can differ significantly from variability of fields of currents, salinity, temperature it is reasonable to develop further the mode splitting and to develop the «radioactivity mode» (the analogue of the «internal mode») enabling calculation of transport of radioactivity with a different time step.

To take into account the transport of sorbed radioactive substances it is necessary to take into consideration the processes of particle sedimentation, resuspension and transport of suspended particles and of course processes of sorption and desorption of radioactivity on suspended matter. The coupling of sediment transport model with the POM model was done by Dr. Wang (Wang, 2002; Wang et al., 2005).

Let us assume that transport of radioactivity sorbed on different fractions of suspended matter can be described with the use of one effective fraction of suspended matter with the effective sorption and physical characteristics. The models taking into account several fractions of suspended matter are similar. They are more detailed but more vulnerable to inaccuracies due to uncertainty in the values of characteristics of all of the fractions.

Explicit dynamic modelling of sorption and desorption is the difficult problem because even in case of first-order approximation of the processes there are three parameters (the rates of reversible sorption, irreversible sorption and the rate of desorption) that are unknown functions of the chemical composition of the water and suspended particles. Accurate assessment of the sorption and desorption rates is a complex problem.

Fortunately, in many cases explicit modelling of the sorption and desorption processes can be avoided. Equilibrium between radionuclides sorbed on suspended particles and in solution is reached relatively quickly (from hours to tens of hours) (Ferronski 1977; Venicianov, 1983). The assumption of the equilibrium enables one to model migration of sorbed radioactive substances with the use of distribution factors. Values of the factors can be measured or if it is impossible they can be estimated on the base of recommendations of the International Atomic Energy Agency (IAEA, 2001).

In this case following expressions can be used:

$$C_{sorbed} = K_d C_{dissolved} \quad (1)$$

$$C = S_{eff} C_{sorbed} + C_{dissolved} \quad (2)$$

$$Q = K_d S_{eff} Q_{suspended\_matter} + Q_{dissolved} \quad (3)$$

Where: C – total specific activity of a radionuclide in the water, Bq/m^3; $C_{dissolved}$ – specific activity of the dissolved phase, Bq/m^3; C_{sorbed} – specific activity of the sorbed phase, Bq/kg; Q – total flux of a radionuclide, Bq/s; $Q_{dissolved}$ – flux of a radionuclide in the dissolved state, Bq/s; $Q_{suspended\_matter}$ – effective flux of suspended matter, kg/s; K_d – distribution coefficient, m^3/kg; S_{eff} – effective concentration of the suspended matter, kg/m^3.

Interaction between the radioactivity in the boundary layer and in the seabed can be taken into consideration by the boundary conditions. The principal processes on this border are particle sedimentation and resuspension. Diffusive mass-transfer between seabed and water is usually less significant.

And at last but not least, it is necessary to take into account that many-hour simulation can be unacceptable in case of real accident when decisions are to be made very promptly. Prompt modelling of radioactivity transport in some cases can be achieved by separating calculation of radioactivity transport from calculation of currents and transport of particles. I.e. it is reasonable to develop capability of calculation of radioactivity transport with the use of calculated beforehand varying in time current fields.

The improved computational code was used to model consequences of the hypothetical radioactivity discharge into the Sayda Bay and White Sea. To model tides we have developed the subroutine taking into account 21 fundamental harmonics (Rotter, 2000). It can be used for other sites if parameters for the harmonics are known. The tide model was successfully validated against the data of water levels at the Yekateriniskaya Harbor (69.2000° N, 33.4667° E) and Port Kem (64.9833° N, 34.7833° E), using data provided at http://www.mobilegeographics.com/.

Calculations for the Sayda Bay

Wind and tidal forcing was taken into account. As it was mentioned above, the main objective of modelling the Sayda Bay was to find out possibility of quick transport by sea of significant quantity of radioactivity out from the Sayda Bay in case of an accident at the temporary storage facility of reactor units. Thus the modelling period of several days is most important because this time is necessary to establish full-scale radiation control in the Sayda Bay and taking appropriate population and environmental protecting measures.

The uniform computational grid with 89 steps (63m each) from East to West and 77 steps (66 m each) from South to North was used. In vertical direction non-uniform sigma coordinate computational grid with 7 steps from water surface to bottom was used. Outline of the modelling area is shown at the Figure 3. Southwest part of the area was chosen for more detailed analysis.

The velocity fields and spatial distribution of radioactivity were calculated for a 120 hours period after the accident. The source of radioactivity was considered instantaneous, located near the sea surface and comparable in order of magnitude with the radioactive inventory of a reactor unit of a nuclear submarine.

The sorption and radioactive decay were not taken into account. Neglecting sorption approach will be accurate for radionuclides tending to migrate in solute (strontium, technetium, uranium, iodine, tritium, etc). For radionuclides tending to be sorbed on particles (plutonium, cesium, cobalt, etc) it can lead to somewhat over-dispersion of the radioactivity.

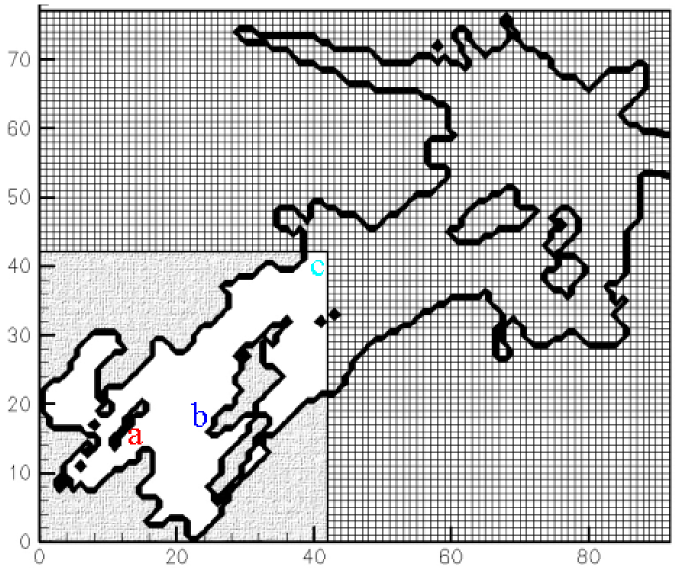

Fig 3. Outline of the modelling area. The red ("a") point indicates the place of the hypothetical accident. The blue ("b") and the pale blue ("c") indicate reference points at the distance of 570 and 2300 meters from the point of accident accordingly.

As it was mentioned above, for instantaneous sources it is important to spin up the model before adding the radioactivity. Concentration of the radioactive substance was calculated for the Southwest part of the Sayda Bay in one and in five days after the hypothetical accident. The calculation results have shown that two and five days of the preliminary spin up gave almost identical results. Therefore two days of spin up are enough for the scale of the Sayda Bay and all subsequent modelling was conducted with two days of preliminary spin-up.

The modelling was conducted for different weather conditions and tide phases in the period of the hypothetical accident. Figure 4 shows that the accident, taking place in the time of low-tide results in much wider dispersion of radioactivity than the one, taking place in the time of high-tide. The influence of wind direction and speed on the processes of radioactivity dispersion in the bay has been estimated. Calculations showed that these factors have significantly less influence than tidal effects.

In addition, we calculated the area of radioactive contamination of the bay with the values of the concentration of radioactive substances exceeding certain prescribed standard. As one of the options of such calculations it was assumed that the total activity of ^{137}Cs in water revenues in the accident was 37 TBq (1 kCi). Further, based on the allowable concentration of this nuclide in foods intended for international trade (1 kBq / kg) (IAEA, 2003) and the factor of accumulation of ^{137}Cs in marine fish in comparison with its content in sea water (100 times) (IAEA, 2001), it was found that within 5 days after the accident, the area of the bay with a water contaminated above allowable level will not exceed 2-5% of its total land area (depending on the time of the accident with regard to tidal currents and surface wind velocity). In addition, this area of contamination would be far from the bay mouth and radioactivity will not be discharged into the open part of the Barents Sea.

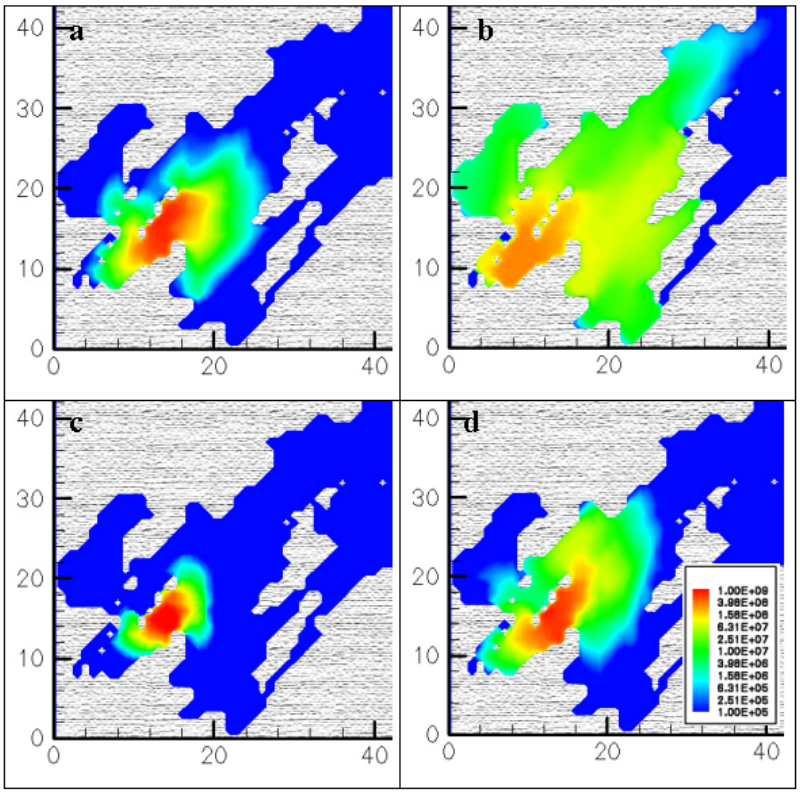

Fig 4. Predicted radioactive pollution of the surface layer depending on the phase of tide at the moment of accident, rel. units. No wind. "a" and "b" – low-tide (0,67 m). "c" and "d" - high-tide (3,56 m). "a" and "c" – 24 hours after the accident. "b" and "d" – 120 hours after the accident.

Calculations for the White Sea

Testing of the calculation module was implemented also for the White Sea. Calculations were performed on two versions of a computational grid with the number of cells 91*93 and 182*186, with the size of cells varied from 3.5 – 5.0 to 1.7 – 2.5 km. With the increase in cell size and the large area of the calculated zone, it was decided to increase also the duration of the pre-calculations, which amounted to 10 days. One of the variants of the calculations is shown in Figure 5. The calculations assumed that the intake of radioactive material occurs in August during the peak of the tidal wave and wind speed above the sea surface amounting to10 m. The wind direction - from the Gorlo strait into the sea. As it is clear from the Figure for this variant of calculation the contamination spot moves along the south-eastern part of Kola Peninsula due to the continuous surface current in this sea area and wind-induced recession. Calculations on the size of contamination zone, with the values of ^{137}Cs concentration in sea water above allowable levels, similar to those described above for the Sayda Bay, showed that within a few days the size of such zone is practically reduced to zero, which is connected with a significantly large scale of actual mixing zone of sea water.

Analysis of simulation of contaminants dispersion in the marine environment by the example of the small sized Sayda Bay showed that tides appear to be the main factor affecting the speed of dispersion processes, especially in the first few days after the accident.

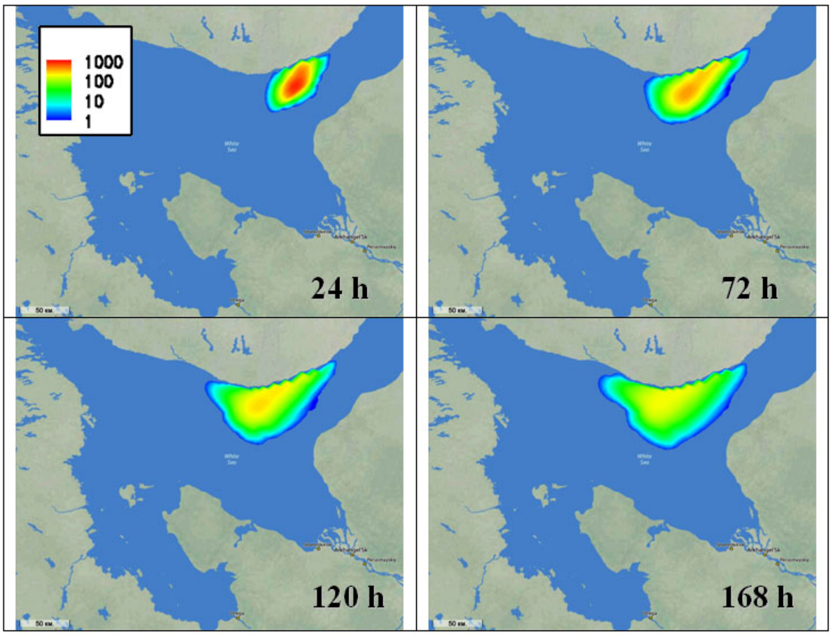

Fig 5. Calculated values of radionuclide concentrations in the surface layer of the White Sea, depending on the time after the emergency discharge, rel. units.

As far as modelling of the hydrological processes in the White Sea are concerned, besides the tide currents the significant factors are the gradients of the temperature and salinity as well as stable currents.

Conclusions

Modelling of the contaminant dispersion processes in the Sayda Bay and water area of the White Sea has shown that the improved computational code gives reasonable results on radioactivity transport in the marine environment. In the present state the model is applicable for periods up to several days for radioactive substances that tend to be sorbed by particles and for longer periods for substances that tend to migrate in the solute.

From the author's point of view the most important tasks for the future are:

- to study the influence of air and water temperatures at various sea depths on the change of rates of contaminant dispersion;
- to implement validation of the hydrodynamic model based on measurements of the sea surface elevation, fields of the currents velocities and salinity in different parts of the White Sea;
- to make possible modelling of radioactive decay and separate migration of maternal and daughter radionuclides if their sorption characteristics differ significantly;
- to enable modelling of radioactivity transport on suspended particles and to enable the use of fields of currents calculated beforehand.

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