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PECULIARITIES OF DECOMMISSIONING WASTE MANAGEMENT

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The paper addresses the issues associated with management of radioactive waste resulting from decommissioning. The paper presents some examples of technical and organizational measures for waste stream optimization. It demonstrates that more effective incentives are required to be implemented to reduce radioactive waste volumes subject to disposal. Lack of acceptance criteria for bulky waste and relevant disposal options is revealed as a problem.

Keywords: decommissioning, radioactive waste, optimization, radioactive waste disposal.

The purpose of this paper is to examine technological and other options enabling the optimization of radioactive waste (RW) generation associated with nuclear facilities decommissioning. Management of decommissioning RW is believed to be a most interesting and topical issue mainly due to the variety of potential difficulties, as well as technological solutions enabling to address them. At the same time, this subject has no "solid foundation" in Russian practice, as the activities on decommissioning of such major facilities as NPP units and radiochemical plants are still to come. Besides, the problem is burdened by common perception that disposal of decommissioning RW shall be funded by the state regardless the effectiveness of decontamination and dismantling technologies applied (similar to the accumulated RW, which are in federal property). This subject, as well as all technological issues have been examined according to selected topics without further description of their interconnection. Although, the latter is evident and may provide a noticeable synergistic effect. Ways to stimulate more efficient RW management practices have been addressed as a separate matter with respect to the performance requirements and organizational procedures, including projects' assessment and optimization. Relevant regulatory issues have not been addressed in detail, as they were substantially considered in [1]. The authors hope that the topic will be further developed in the journal with relevant papers written by direct participants of such activities.

Responsibility for decommissioning RW management

Attempts to address the issue of decommissioning RW were made during the development of the Federal law on RW management. The early versions of the draft law (end of 2008) proposed to classify RW resulting from nuclear facilities decommissioning and spent nuclear fuel management as accumulated radioactive waste in case if no specific legislative provisions to finance this activity from the special reserve fund existed. It seemed to be an effective approach, and this vision was shared by one of the authors. However, opponents have rightly argued that this would mean unlimited liability of

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the state and absence of any motivation for the enterprises to consider RW factor in decommissioning.

Lessons learned during USS RW establishment allow us to conclude that the approach finally implemented is believed to be the most accurate from the legal point of view, and balanced in terms of accounting the interests of different stakeholders. RW generated from past activities is classified as accumulated waste and is considered as federally owned. Whilst the waste generator (i. e. operator) is responsible for any RW that it generated after the adoption of the law, including the decommissioning waste.

Requirements in the field of decommissioning

In light of modern requirements stipulated in international instruments and national law, dismantling decommissioning strategy has become the predominant one supposing that the facility shall be safely dismantled to greenfield or brownfield end-state. By such an approach the nuclear power is positioned as an environmentally acceptable energy source: "the site is selected — the facility is constructed — the site is left free being suitable for future use." At the same time, such an approach is either technically not feasible or too expensive for some, if not the majority of the facilities to be decommissioned in the coming decades, as due consideration to the decommissioning issues was not given during their design, development and operation.

In our view, international standards allow to address the outcomes of past activities from the standpoint of "existing exposure situation" [2, 3]. We would like to remind that in this case a wide dose range (1—20 mSv/year) could be suggested to determine reference levels, compared to "planned exposure situation"[2, 3]. Such an approach allows to manage specific facilities in a flexible manner. The general idea is that the protection strategy for an existing exposure situation is commensurate to the radiation risk, and the results of the efforts overweight the associated detriments [3]. Let us consider this topic in the context of decommissioning, noting that some authors disagree with the above and apply regulations under planned exposure situation not only to occupational exposure during decommissioning, but also to the end state of the sites after decommissioning and even to remediation [4].

The principle of optimization is stated in ICRP and IAEA documents for all three exposure situations. The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (hereafter — Joint Convention) [5] applies the principle of optimization to both operation and decommissioning: the measures undertaken shall ensure that the radiation exposure of the workers and the public is kept as low as reasonably achievable, economic and social factors being taken into account (articles 24, 26). May we, based on the above standards, state that the existing facilities can be regulated by special decommissioning arrangements and less strict radiation safety requirements?

The answer is yes, special arrangements may be applicable if they are needed. For example, according to IAEA documents entombment as a decommissioning strategy may be considered as a solution for so-called historical facilities. This decommissioning option is stipulated in the industry's Decommissioning Concept [6], federal norms and rules NP-057-17 and NP-007-17 and has already been applied to PUGR EI-2 at SCC.

By less strict requirements we mean the application of the optimization principle to protection and not lowering the level of safety with respect to selected facilities. How can this be expressed? First, in all cases of actions with regard to facilities, the ultimate goal is to increase the level of safety. For example, RW categorization as special waste envisages subsequent transition of relevant storage and conservation facilities into disposal facilities. The status of the facility changes as the higher level of safety is achieved in strict compliance with the Joint Convention provisions for the existing RW management facilities providing that, "if necessary, all reasonably practical improvements are made to upgrade the safety of such a facility" [5]. Second, no international or national document requires complete dismantlement of structures or total removal of radioactivity. It is rather indicated that sites may be released from regulatory control with some restrictions imposed on their use [7,8]. Third, many legacy sites require technically complex and costly solutions which presume finding a reasonable balance between investments and results in terms of radiation protection. Under these circumstances, optimization is not only desirable, but necessary.

Organizational conditions in decommissioning

The amount of generated RW greatly depends on relevant organizational conditions. Let's confine ourselves to a concise example — discussion on enhancing economic effectiveness of decommissioning, facilities maintenance and RW management held at a roundtable of ATOMEXPO forum in May, 2018.

The opening report of A. A. Abramov discussed the options being currently investigated to upgrade the system of legacy management in Russia [9]. Subsequent reports have demonstrated that this is a common trend, starting from arranging the activities of OECD NEA working groups ending with global analytical reports produced by major international business management companies. The first takeaway of the discussion may be summarized as follows: the search for technical solutions may prove to be successful only if the organization is geared towards decommissioning. At the same time, only limited experience in implementing complex decommissioning projects is available (and this experience reveals higher costs (by a mean of 50 %) and longer project duration (by a mean of 70 %) compared to initial estimates), whilst final RW disposal challenge is still to be addressed by most of the countries [10].

The second takeaway is associated with splitting financial responsibilities between the owners and the state which is believed to be a long process. It has involved increasingly thorough calculations, which may result in court decisions committing the Government to compensate for interventions if the operational lifetime of a NPP is reduced [11].

The third takeaway states the importance of comprehensive RW management during decommissioning. As W.Kutscher said, decommissioning and final disposal are two sides of a coin, and it's believed to be impossible to solve one challenge without addressing the another [11]. According to NEA OECD, waste storage and availability of final disposal facilities are seen as a most powerful decommissioning cost driver [12]. For example, RW management costs may amount to up to 30 % of total NPP decommissioning cost [13].

Key aspects of managing decommissioning RW

Let's indicate the key aspects being specific for RW stream resulting from decommissioning:

- RW is generated in a relatively short time-period;
- The amount of decommissioning RW exceeds the one generated during operation by a multiple;
- Large portion of contaminated metal and debris, including large-size items and contaminated soil;
- Wide range of waste types with regard to waste composition and aggregate state, being distinctly different from those generated during nuclear facility operation.

Optimization may proceed with selection of decommissioning and technologies, as well as alternatives to manage the generated waste.

Optimizing the generation of decommissioning RW

A number of practices designed to reduce the RW amount is considered below. All of these are described in a conceptual manner.

1 Reduction of RW generation after the final shutdown of facility

We believe that it's possible to achieve a significant reduction in RW generation at this stage by reducing the scope of maintenance activities originally associated with active operational mode. It can be shown by the example of pumping out the contaminated water from the lower levels of buildings and structures. Should we consider this operation as a must if the flooded building (and the flooded elements of equipment and engineering systems) will never be used as intended? It is not evident either if we should completely give up on these activities (consideration should to be given to actual leaks and groundwater contamination) or if we should continue the pumping out with LRW being generated as before. It is feasible to consider available alternatives if concerns arise regarding the degradation of safety-important elements or systems under the final shutdown mode. For example, trivial engineering solutions ensuring the protection of buildings (installation of a drainage system, etc.) may help to address the issue either with no additional RW generated or resulting in their minimal amount.

2 Selection of dismantling strategy

Oftentimes the long-term strategy suggests that slightly contaminated elements are removed in the first place as the activity of most contaminated units and structure elements decreases with time. Certainly this process will take place, but even after some 20—30 years it proves to be insufficient to decrease the activities to the level allowing the use of essentially simpler dismantling techniques. A case in point demonstrating the above said is the decommissioning of NvNPP units 1 and 2. On the contrary, after long-term storage low-level materials and structures may be no longer categorized as RW. As it comes to contaminated buildings and structures, the development of decontamination technologies has already ensured competitiveness of the immediate dismantling option, including the option when a combination of various methods is being applied to the same facility [14].

Knowledge gained during the successful operations in high energy fields is being accumulated. A case in point — dismantlement of MR reactor equipment in the Kurchatov institute [15], where a range of remotely operated tools was used. Other arguments based on safety considerations also support the feasibility of the option suggesting that most contaminated elements and structures are dismantled in the first place. These arguments

Fig. 1. Disposal of very low-level waste in France at Centre de Morvilliers site [16]

include the possibility of using to the maximum the remaining lifetime of buildings, structures and equipment, as well as of the infrastructure facilities capable of resuming their operation during the decommissioning.

Hence, there are two options. The first one suggests that active elements are being dismantled, relevant infrastructure remains partially intact, the majority of contaminated items with low activity levels are not categorized as RW owning to their long-term storage. The second one involves dismantling of these low-level elements with subsequent management of the highly contaminated items given that relevant infrastructure is completely dismantled. Apparently, no universal solution exists, however, both options should be considered in detail already at the project development stage.

3 Large units and assemblies

RW management and dismantling costs can be substantially reduced if large-size equipment elements are immediately dismantled and disposed of without being cut. Application of this approach together with the location of the disposal facility at the site resulted in a small portion of waste management costs (8%) in the overall cost of the Loviisa NPP decommissioning: the reactor vessel was used to pack other RW, steam generators and other equipment are being disposed of with no cutting and packaging applied [13]. Another example is very low-level waste disposal facility of the French company ANDRA. The site was originally used to dispose of waste in so called flexible packages (Fig. 1a). Recently, the facility started to accept for disposal large-size unpacked waste, including two steam generators disposed of in 2013 (Fig. 1b). To enable effective cost reduction by using this approach, acceptance criteria for bulky waste are needed, as well as relevant disposal facilities [10].

4 Cutting large elements

It is not that important what particular algorithm is selected with regard to decontamination and cut of large-size and heterogeneously contaminated elements - to cut either the most contaminated part or the least contaminated part from the remaining structure. It is important to continuously calculate and analyze the processes. Some Russian companies have successfully applied these methods [17], including those based on foreign technologies. For example, the photo (Fig. 2) shows the initial cutting of a metal structure with a cutting depth of 100 mm given the overall thickness of 120 mm. This ensured normal operating conditions in terms of radiation exposure and 6-fold reduction in the volume of secondary RW generation.

Fig. 2. Removal of contaminated layer from the metallic assembly [17]

5 Preliminary cleanup of load-bearing elements of buildings and structures

Even in case of extremely high initial levels of contamination, the radioactivity may be removed from most part of load-bearing structures. This was successfully demonstrated during the decommissioning of building B of JSC "VNIINM" (Moscow). Decontamination of locally contaminated premises (for example, the level of β-contamination was reduced from 15 000 to 20 part/cm^2·min in the premise 603) allowed to ensure radiation safety of the building and enabled its further demolition [18]. A similar procedure will be used to decommission other buildings of the institute.

6 Contaminated metal

A wide range of activities may be implemented depending on the level and nature of contamination and the methods used. Technological solutions for metal waste decontamination and their further use either in nuclear industry or in unrestricted manner are available also in Russia and are being further developed. A promising option is to use this metal to manufacture reinforcement bars for reinforced concrete structures and RW containers. In mid-term perspective, the demand for non-reusable disposal containers for RW of 3 and 4 classes is estimated to be some 100,000 units, whereas the one for metal would account for over 100,000 tons [19]. For reference, JSC "Ekomet-S" has so far processed over 30,000 tons of contaminated metal [20], EnergySolutions — over 60,000 tons, Studsvik Nuclear — 32,000 tons of carbon steel and other metals [21].

7 RW segregation by waste types

It is fairly evident that the tasks associated with characterization involving the identification of appropriate measurement methods and applicable clearance criteria, as well as RW segregation based on contamination levels, composition and future management methods should be set for the large amounts of materials generated as the result of decommissioning. Currently RW segregation is generally indicated in the contractual provisions for the decommissioning activities (JSC "VNIINM", JSC "SSC RF-IPPE", FSUE "RFNC-VNIIFT", FSUE "NIIP"). As for JSC "AECC" these provisions were in as much detail as possible specified for each type of dismantled equipment and structures.

Is such level of detail in setting the performance requirements really needed? The answer is not evident — if necessary conditions are established, the organization will be capable of selecting the best option on its own.

8 RW processing and conditioning

Another point to note is if processing results in RW volume reduction, it is sometimes worthwhile to stop at some point to escape falling into the waste class with higher disposal costs. In cases suggesting significant increase of waste volume, for example, involving cementation methods applied to some LRW types, consideration should be given to alternative technologies.

9 Effective packaging

Better results can be obtained by maintaining certain flexibility in the formation of RW packages. Two conditions need to be met in this case. Firstly, each container shall be specifically selected according to its purpose, i.e. shall not have too excessive safety margin, as it happens in case of NZK containers for LLW. Secondly, effective filling of the container should be ensured, i.e. the activity level shall be close to the upper boundary specified for the RW class rather than slightly exceeding the lower one, as it happens in some cases.

10 In-situ disposal

In some ideal case this decommissioning option may be implemented so that no waste requiring retrieval and off-site shipment occurs.

11 VLLW management

Evidently incomplete legal framework covering this category of RW can be seen as significant obstacle impeding the build-up of effective disposal activities in this area. Nevertheless, even if these issues are not resolved, it is still possible to consider the option of long-term storage (for decay).

12 RW characterization

Characterization is considered to be a key element ensuring effective material management, including characterization before, during and after dismantlement, as well as before, during and after remediation. At the same time, characterization requirements specifying if waste shall be categorized as radioactive waste, cleared or considered for restricted use should to be developed at an early stage. Otherwise characterization efforts performed prior to these activities may prove to be useless [22]. Let

Fig. 3. Facility for 100% measurement of milled brick and stone with a capacity of 50 t/hour

us note that characterization during decommissioning is viewed as a fundamentally important and large part of efforts being distinctly different from the activities performed during operation. In terms of RW management, the importance of this stage is currently being largely underestimated. For example, specific high capacity installations are required for large amounts of material. Fig. 3 shows such a facility designed to measure gamma-radiation with isotope separation operated by NUKEM. It was used in the decommissioning of fuel fabrication plant "NUKEM-A" in Hanau, Germany. As for the cost, the example of the Czech Republic is quite indicative — due to economic considerations, characterization of all materials (from both NPPs) potentially subject to clearance is carried out at Dukhovany NPP [23].

13 Optimization tools

Modern technologies offer a wide range of optimization tools ranging from those applied during safety case development [24] to IT systems supporting decommissioning activities [15]. Some decontamination and dismantling instruments and equipment have already been briefly described. Let's take a closer look at modern calculation and forecasting tools helping to plan and evaluate the options before the start of activities and during their implementation. They also allow to monitor the implementation process. In many cases, such tools have been designed specifically for decommissioning purposes, for example, Digital Decommissioning software [25] or calculation code TRACT [26]. In combination with modern information technologies it opens the potential for virtual testing and optimization of dismantling technologies [15, 25].

Practice and prospects for setting RW requirements in decommissioning projects

The system for determining the requirements is currently being fine-tuned. Let us summarize some of the requirements applied.

RW volume restrictions

Such restrictions are generally considered feasible. Currently these are set by indicating maximum volumes of RW generation (up to "n" m^3, also specified for different RW classes) with or with no account of disposal containers. In addition to this or separately, the estimates regarding the scope of work associated with particular RW class, RW morphological composition or source term are being provided, for example: VLLW/LLW/ILW, metal/non-metal, bricks/concrete/tiles/plastics/soil, filters/pipes/ exhaust hoods /hot cells, etc. The requirements shall offer certain flexibility to the contractor. This is provided, for example, by indicating that actual amount of RW and other waste may differ from the calculated values. Of critical importance is that the waste generation volumes are not initially overestimated, whilst actual waste generation below the estimates shall not be judged by the customer as non-compliance with the overall scope of activities. Such requirements shall also leave room for optimization with regard to RW volume and classes, for example, in terms of reducing the waste hazard class ("more LLW — less ILW", "less RW — more other waste types", etc.).

Clearance

In accordance with NP-091-14 [27], all materials generated during decommissioning shall be subject to radiation control, based on which RW shall be separated from materials suitable for restricted and unrestricted reuse and non-radioactive waste. Some terms of references specify the amount of material which may be decontaminated and cleared in volumetric (m^3) or specific (%) values. However, management of RW and management of non-contaminated materials are considered as stand-alone type of activities, whilst requirements to materials characterization and methods applied are not indicated. No specific requirements concerning the restricted use materials were found in the terms of references. Requirements on waste segregation were set only for RW.

As it comes to clearance, more careful planning and characterization of materials, as well as selection of appropriate methods, devices and installations is considered to be essential.

RW handover

Technical requirements mandatory stipulate the further fate of the generated RW. Most commonly, RW is handed over to a specialized organization for conditioning and temporary storage (up to 5 years) or for reprocessing, conditioning with subsequent transfer to FSUE "NO RAO". In some cases, RW is sent for reprocessing and conditioning performed at the installations available at the site of the organization.

Obviously, in the coming years this requirement will be finalized resulting in any chain of specialized contractors that will eventually transfer the RW for disposal.

RW fragmentation and packaging

Some terms of references also contain requirements on at-site packaging of all RW into containers, as well as fragmentation of bulky RW to smaller pieces for containerisation. In this case RW is subsequently sent for reprocessing to a specialized organization. We consider that such packaging requirements are sometimes excessive, for example for VLLW, whilst the need for fragmentation is not always evident. These requirements should be more focused to specify onsite activities aimed at placing RW into containers for disposal or packing RW for the purpose of its further handing over for processing. A case in point of such refined requirements is the indication on applying returnable containers to hand the waste over to a specialized organization. However, it's not clear if it can be considered feasible for soil and debris categorized as VLLW as compared to single use packages widely utilized in construction. We believe that most correct wording is "primary fragmentation of dismantled structures" and "emplacement of waste into transport technological packages" (according to provision of the terms of references on JSC "AECC" projects), allowing for certain flexibility so that the contractor could chose the size of transported RW and RW packages.

Other possible requirements

Regardless of the place where RW is being brought into compliance with waste acceptance criteria – at the site of its generation or at the site of a specialized organization, it is important to ensure that RW packages are formed in the upper range of values for each class of waste. In terms of cost, the benefit seems to be evident for large RW volumes. For small RW batches (up to several tens of m^3) this may prove to be technically challenging. However, if packaging operations are performed at the site, the organization may optimize the process by virtue of other RW sources. Specialized organizations may face some legal difficulties in trying to combine RW received from different waste organizations. But we believe that they should learn to overcome such difficulties.

Organizational issues

For optimization purposes, given the future scope of decommissioning activities so far being at the deployment stage only, it seems feasible to examine decommissioning projects from a conceptual point of view.

Who should initiate such optimization? Probably a public contracting authority should act as such in case if the activities are carried out under FTP. In case if activities are funded from reserves or other funds of an organization, an independent expert assessment is also considered feasible. The reasoning behind is that the existing management system of operating organizations does not provide the mechanisms enabling flexible assessment of managers' performance in terms of such financial indicators as the cost of maintenance after shutdown or the decommissioning cost. This activity may become part of some organizational or small investment projects of the State Corporation "Rosatom" launched to reduce the maintenance costs when a facility is no longer operated according to the originally intended purposes and to optimize RW generation during decommissioning.

An essential measure would be stimulating FSUE "NO "RW" to expand the scope of RW accepted for disposal, including VLLW and large-size RW. Currently no such incentives are available.

Conclusion

So far activities associated with decommissioning RW management have just been initiated. It will be possible to implement the full scope of such activities, including the stage of RW disposal, in a few years already.

The reasoning behind the tendency suggesting the minimization of RW generation during decommissioning is not limited to the desire of saving money alone. It provides the implementation of the basic principle on minimization of waste generation stipulated by the Joint Convention and Russian regulations [5, 22]. Most of the approaches described can be readily implemented already now.

A set of measures should enable the full implementation of the decommissioning RW minimization principle. These measures should first of all address the development of a regulatory framework and arranging for expert assessment of project design activities. They should provide efficient incentives enabling to apply the whole range of effective technological solutions for decommissioning RW management.

In spite of the number and the variety of different facilities, the overall conclusion remains the same - amounts and types of waste generated during decommissioning critically depend on the technical capabilities and competences of the contractor. This means that with a fixed cost of work, which is targeted for the level of competencies above the average, the organization has still a strong incentive to reduce the amount of RW. It is important to take measures so that these incentives not only remain in place, but are further strengthened by technical requirements to the implementation of relevant activities and appropriate organizational environment arranged for the implementation of decommissioning projects.

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