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An Approach to Framework of Dealing with Improving the Complexity and Uncertainty for Decommissioning Safety Assessment of a Nuclear Facility

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Abstract : An effective assessment for decommissioning safety of nuclear facilities requires basic knowledge about possible risks, characteristics of potential hazards, and comprehensive understanding of the associated cause-effect relationships within a decommissioning for nuclear facility. This paper proposes an approach to develop the hierarchical structure and hazards of dealing with improving the complexity and uncertainty for decommissioning safety assessment of nuclear facilities and the resolutions are proposed to improve the complexity and uncertainty for decommissioning safety assessment of nuclear facilities. These resolutions can provide a comprehensive view of the risks in the decommissioning activities of a nuclear facility.

Key words: complexity, decommissioning, safety assessment, nuclear facility, uncertainty

1. Introduction

The decommissioning of nuclear facilities is the final phase in the life-cycle after siting, design, construction, commissioning and operation. It is a complex process involving operations such as detailed surveys, decontamination and dismantling of plant equipment and facilities, demolition of buildings and structures, and management of resulting waste and other materials, whilst taking into account aspects of health and safety of the operating personnel and the general public, and protection of the environment [1].

Normally, an effective risk analysis requires basic knowledge about possible risks, characteristics of potential hazards, and comprehensive understanding of the associated cause-effect relationships within a decommissioning for nuclear facility. However such an effective risk assessment method to consistently analyze risks, hazards, and their relationships is unavailable so far because of the complexity and uncertainty existing in real-world decommissioning activities and risk assessment. Therefore, there is a need for research to develop a comprehensive framework according to the requirements of effective risk assessment.

Workers need to be protected by eliminating or reducing the radiological and non-radiological hazards that may arise during routine decommissioning activities and as well as during accidents. The non-radiological or conventional industrial hazards to which workers are subjected during the decommissioning and dismantling process may be greater than those experienced during the operational lifetime of the facility. The hazards associated with decontamination and dismantling of structures and buildings, or with construction of temporary facilities, are important not only because they may be a direct cause of harm to workers, but also because their occurrence may, indirectly, result in increased radiological hazard.

This paper is to develop the hierarchical structure and hazards of dealing with improving the complexity and uncertainty for decommissioning safety assessment of nuclear facilities and the resolutions are proposed to improve the complexity and uncertainty for decommissioning safety assessment of nuclear facilities.

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2. Survey of Hazards for A Decommissioning Safety Assessment

2.1 Hazards during decommissioning

It is widely accepted that the radiological hazards associated with a nuclear facility undergoing decommissioning are substantially less than when in normal operation. This is because removal of fuel elements and radioactive materials in systems, and conditioning and removal of operational waste, all has a major, beneficial effect on reducing the amount, composition and distribution of residual radionuclides at the plant. Even though these hazards may be reduced, however, other more conventional hazards may be introduced or increased. Also, it is necessary to recognize that the inherent need to remove safety systems from service progressively and to destroy confinement barriers, in order to achieve the long-term reduction in hazard, can temporarily increase the short-term hazards [2].

2.2 Radiological hazards

As a general requirement, the established dose limits must be fulfilled and applicable dose constraints should restrict the projected individual doses. The magnitude of individual doses, the number of people exposed, and the likelihood of incurring exposures should be kept as low as reasonably achievable, economics and social factors being taken into account.

2.2.1 Criticality

The occurrence of accidental criticality is not envisaged in shutdown nuclear reactors from which the fuel elements have been completely removed, including from associated stores. The possibility of accidental criticality may be present, however, in the process equipment or waste storage tanks of facilities where fissile materials have been processed, such as fuel-manufacturing plants or spent fuel-reprocessing plants. Criticality must be assumed to be possible until all processed materials and fluids have been removed from all of the facility's systems and storage tanks.

2.2.2 Loss of containment

The possibility of inadvertent loss of containment of the radioactive materials present at a facility must be taken into account in all decommissioning project tasks. This is particularly important in the retrieval of radioactive materials from the various processing units in a facility, in the dismantling of its systems and in the later cleanup of areas where they were located. The containment and ventilation systems used during the operational life of a facility are generally not sufficient for dismantling operations, and special systems often have to be set up to contain and ventilate work areas. The safety features of such special containment systems must match the hazards and radionuclides present in each area and, in this regard, the presence of alpha-emitters is the most significant constraint.

2.2.3 External exposure

In situations where remote handling systems cannot be used and after all practicable steps have been taken to decontaminate an area or equipment, the exposure of staff undertaking dismantling activities from external sources should be optimized.

2.2.4 Ingestion and inhalation of radionuclides

If radionuclides are present in the work area in the form of removable surface contamination, staff may be subjected to internal radiation exposure by ingestion or inhalation. The potential for inhalation is of particular concern in the case of activities carried out in areas or premises contaminated with alpha-emitting radionuclides and appropriate measures must be taken to prevent or minimize the potential for inhalation. The ALARA principle should be observed.

2.3 Non-radiological hazards

2.3.1 Fire

Fire is the conventional hazard that most frequently occurs in facility dismantling projects. The methods used for certain equipment dismantling operations (e.g. thermal cutting techniques) or for decontamination of surfaces (e.g. aggressive decontaminating solutions, etc.) are often the cause of localized fires. Moreover, while dismantling activities are in progress, the temporary accumulation of combustible materials and waste (plastic, cotton, etc.) is common, thus increasing the potential for fires in the area. Fortunately, such fires can be promptly detected and extinguished by appropriate fire protection measures, and are generally of little importance.

Fire hazards during decommissioning activities must therefore be examined thoroughly, specifically the techniques and reagents to be used, the conditions under which the activities will be carried out, and the arrangements for storage of materials that will be generated in the operation. Fire protection measures should then be determined on the basis of this analysis.

2.3.2 Explosion

In addition to normal fires, explosions may occur during decontamination and dismantling as result of the chemical reagents and equipment used, (e.g. decontaminating solutions, thermal cutting devices such as blowpipes fuelled by highly inflammable materials, etc.) Such explosions may even be caused by reaction of such reagents with radioactive materials remaining in tanks or associated with equipment due for decontamination, thus creating both radiological and non-radiological hazards.

Some materials generated in the process of dismantling a facility, such as inflammable dusts, may in certain circumstances acquire explosive characteristics.

Also, at facilities where a considerable time has elapsed since shutdown and chemical reagents or liquid waste have been awaiting conditioning for lengthy periods of time, there is a possibility of auto-concentration phenomena that may cause explosive conditions, and special care must be exercised in such circumstances.

2.3.3 Toxic and hazardous materials

The dismantling of nuclear facilities sometimes reveals that they were built using materials that are now banned and whose removal requires special measures because of their toxic or hazardous properties of the building materials. It is common, for example, to find asbestos used in thermal insulation or in fire barriers, lead in paint, counterweights and shielding, and polychlorobiphenyls (PCBs) in oils and electrical insulation. Furthermore, some of the materials used in the decommissioning process, such as decontaminating solutions may, in and of themselves, be toxic and hazardous. All require appropriate protective measures to be taken. Particular care should be taken when these non-radioactive hazardous/toxic materials are either chemically combined or contaminated with radioactive material. In these instances operators may need to devise safety and disposal strategies that address both the radiological and non-radiological hazard. In some instances, implementing normal safety procedures for one hazard may increase the potential for the other. Thus, careful analysis of the safety (and disposal) requirements for this mixed material should be performed by specialists familiar with the inherent hazards. Safety and disposal practices should be implemented only after this analysis has been performed and practices developed that address the hazards from both materials.

2.3.4 Electrical hazards

The dismantling of electrical installations in an environment where live wiring may be present, and inadvertently cut, is a hazard that must be recognized and addressed effectively for decommissioning activities. For this reason, it may be prudent to use new, completely separate electrical systems and to disconnect the original ones.

2.3.5 Physical hazards

The physical hazards typically associated with demolition activities, or with the construction and use of temporary facilities, are also important, (e.g. collapse of structures, falling of heavy objects, working at heights, etc.) and need to be addressed.

3. Proposed Solutions to Improve the Complexity and Uncertainty of Decommissioning Safety Assessment

Decommissioning activities of a nuclear facility, in general, has various configurations, scales, and uncertain operational and environmental conditions, which make them complex and introduce uncertainties in risk assessment. Complexity and uncertainty are two main hurdles that limit the extensive applications of those existing methods.

The complexity of a decommissioning for nuclear facility mainly arises from the composition of a large number of components or subsystems (including water sources, treatment, distribution, etc.) which, in turn, comprise of further sub-subsystems or components. Firstly, the exact definition of components, subcomponents, and sub-subcomponents depends on the level of details of the required analysis and, to somewhat greater extent, on the level of available data. Secondly, these components depend directly upon each other and as a result effect the performance of one another [3]. This introduces difficulties in establishing cause-effect relationships for specific risk in a decommissioning for nuclear facility. Furthermore, as discussed in preceding sections, components in a water supply system are vulnerable to both natural hazards and human-caused threats such as extreme weather, chemical/biological contamination, etc. Therefore both knowledge of components and their relationships are important for a thorough understanding of the operation of the overall system. A risk assessment would be effective and comprehensive if it could be consistently performed at both component and the overall system levels.

The other factor, as important as complexity, is uncertainty of risk assessment. Normally, risk analysts are always finding difficulties in either representing risk information precisely or describing the risk mechanism of complex systems like a water supply system [4]. In a practical water supply system, the sources of uncertainty are various and diverse. Two main uncertainties frequently mentioned by analysts are insufficient data for statistic inferences and vagueness and variations of risk information. Natural hazards usually belong to the former, while human-caused failures are the latter. Data of human error are limited, and the knowledge of analysts about this kind of error is also incomplete or in some degree vague and fuzzy. These uncertainties introduce difficulties in controlling or predicting risks with an acceptable degree of accuracy [5]. Thus the probabilistic theory, which is useful to express the former uncertainty, will be challenged and questioned when applied to deal with the latter uncertainty. Furthermore it is very difficult or even impossible in many cases to precisely determine the parameters of a probability distribution for a given hazard event due to the existing uncertainties in practice.

Additionally, as engineering risk analysis is a general methodology for the quantification of uncertainty and evaluation of its consequences [6], the first step in any risk analysis is to identify the risk, clearly detailing all sources of uncertainty that may contribute to the risk of failure. Then quantification of the risk is second step by analyzing the risk levels of each component and/or subsystem and their contribution to the overall system. For the first step, probability theory alone in traditional risk analysis has limited applicability in representing all types of the uncertain information. For the second step, risk of the overall system is not easily obtained by considering contributions from components and subsystems because of few specific models have been proposed. Therefore, there is a need to propose a new risk assessment framework that is able to overcome these limitations.

3.1 Proposed solutions to the complexity

To deal with the complexity, hierarchical structure analysis is one of the promising methods [7]. Since the composition of a decommissioning for nuclear facility is hierarchical in nature, risk assessment of such systems is also driven by this hierarchical structure reality. Furthermore, the hazards and potential consequences associated with each component can also be simulated in a similar hierarchy. In this kind of hierarchical structure, risk levels of components/systems at a higher level are contributed by risk levels of components/subsystems at relative lower levels. The risk evaluation of the overall water supply system can then be obtained by knowing both the risk information of each basic element at the lowest level and their combination rules.

3.2 Proposed solutions to the uncertainty

Two types of uncertainties are considered in this study. One is uncertainty with random characteristics, and the other is uncertainty with vague, fuzzy, and incomplete properties. For the uncertainty introduced by random variables, probability theory is applicable and practical methods are available. For uncertainty brought by vagueness or incomplete data, applications of probability theory are challenged. An alternative method, fuzzy sets theory, can be adopted to give a fundamental support for risk analysis [8]. In fuzzy sets theory, the vague information is described by fuzzy number, and risk evaluation thus becomes a process of dealing with fuzzy numbers rather than normal probabilistic numbers from the mathematic point of view. Furthermore, fuzzy sets had been used to effectively represent and analyze human reliability or subjective risk analysis in many studies.

3.3 Integration of radiological, chemical, and industrial hazards

The risk of exposure of workers and public to radiation (radiological hazards) on a nuclear decommissioning site can be categorized as external and internal. Potential routes for exposure include inhalation and ingestion resulting from loss of containment and release of particulate or liquids, as well as exposure to direct radiation sources. Radioactive contamination of wounds caused during cutting operations can be a significant mechanism for worker exposure. A criticality excursion can present a risk to both nearby members of workers. Fires causing the discharge of airborne activity are another potential initiating event for off-site exposure. This could arise from fires within facilities or fires involving the on-site transport of radioactive material.

Safety assessment is directed primarily at those pathways and event sequences with potential for off-site doses or significant doses to staff on site. The safety assessment of these event sequences and the engineering and procedural controls that may be put into place as a result of the safety assessment are then documented in the safety assessment as part of the overall set of safety arguments.

The management of contaminated land is a consideration on many legacy sites, and the potential for significant exposure pathways needs to be assessed. Leakage into the water table is of interest to the nuclear and environmental regulatory bodies due to the potential drinking and irrigation pathways of exposure to members of a critical group

It is important to consider exposure to toxic and other dangerous chemicals for inclusion in the safety assessment since many legacy sites used chemical process plants, and these can represent a significant source of risk during post-operational cleanup and decommissioning.

The most significant risk to workers on decommissioning sites will normally arise from industrial hazards that are common on any site with building and demolition work taking place. Therefore, assessment of these hazards against the decommissioning project work plans is important. The safety measures at a facility normally have requirements in place for the control of physical work to mitigate the effect of radiological, chemical, and industrial hazards, which would afford significant protection if well managed and enforced.

A key requirement of the safety measures is for the hazards associated with planned tasks to be assessed during the development of procedures and task-specific instructions, both for routine tasks within a decommissioning project and for tasks performed once only, in order to identify any necessary controls. This is best achieved by a description of the scope of the planned tasks that is then subject to a hazard assessment to identify potential hazards and to determine the control measures necessary to reduce risk to an acceptable level.

It is important to recognize that the safety controls measures arising from a facility's safety assessment and those that arise from the assessment of the industrial hazards present during the execution of decommissioning tasks is complementary.

The controls arising from the task level safety assessment are designed to ensure that individual work packages can be conducted safely and will specify controls such as respiratory protection, the sue of safety harnesses, isolation of live systems and personal protective equipment.

Where chemical or other hazardous substances may represent a significant hazard to workers, there may be national legal requirements for their control.

4. Practival Methods of Dealing with Complexity and Uncertainty of Decommissioning Activities

Safety assessment is generally developed as part of a decommissioning plan (preliminary or final) and therefore needs to be based on and also to be consistent with the elements of the plan. The safety assessment is one component of the overall decommissioning plan. Several of the other components of the decommissioning plan also contain information that is directly used in performing and reviewing the safety assessment.

4.1 Methods of dealing with complexity of decommissioning

Hierarchical framework method is considered to be straightforward and effective to deal with complexity by many researchers. In risk assessment, one of the most valuable and critical contributions of hierarchical framework is its ability to facilitate the evaluation of subsystems risks and their corresponding contributions to the risks of the overall. Particularly, its ability to model the intricate relationships among the various subsystems and to account for all relevant and important elements of risk and uncertainty renders the risk assessment process more tractable, representative, and encompassing. In the following sections, literature is reviewed on applications of hierarchical structure to different aspects of risk assessment of decommissioning activities.

4.2 The hierarchical structure model of safety assessment for a nuclear facility

Fig. 2 A example of hierarchical structure model for decommissioning safety assessment

Safety assessment is required for decommissioning of various types of facilities that vary in hazard, scale, design, etc. For simpler projects (e.g. laboratories) the entire decommissioning safety assessment can be documented in a single report supported by key reference documents. It has been found however that for larger projects (e.g. nuclear power plants, fuel reprocessing plants) that may have a number of discrete stages defined in the decommissioning plan that may occupy a

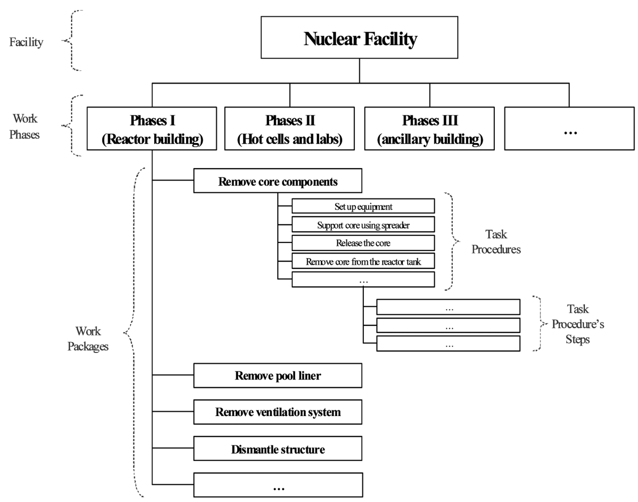

Fig. 2. A example of hierarchical structure model for decommissioning safety assessment

Table 1. Decommissioning tasks of uranium refining and conversion

Planning Phases	Work Packages
Material shipping, receiving and storage areas	• Remove product/yellow-cake inventories • Decontaminate and remove equipment, tools, conveyors, hoists, etc.
Digester process area	• Remove contents and loose contamination from primary and secondary digesters • Dismantle digester vessels • Remove ancillary piping, valves and electrics • Remove other equipment and tools
Solvent extraction process area	• Remove contents of vessels and piping • Decontaminate and dismantle feed tanks • Decontaminate and dismantle column trains • Decontaminate and dismantle settling tanks • Dismantle ancillary piping, valves, electrical and conveyance systems
Reactor areas	• Remove contents of denitrification reactors • Decontaminate and dismantle reactor vessels • Decontaminate and remove reaction gas scrubber system • Remove active drains
Effluent management systems	• Remove content of effluent neutralization vessels • Remediate effluent monitoring and treatment lagoons • Remediate storm water management lagoon • Remove final effluent discharge line • Decontaminate sumps • Decontaminate and remove raffinate evaporators • Decontaminate and remove liquor evaporators
Emission control systems	• Remove baghouse filter system • Remove central vacuum system
Solid waste management areas	• Decontaminate uranium scrap area • Decontaminate and remove refuse incinerator • Decontaminate drum cleaning and processing area • Remove inventory and decontaminate low-level storage area
Maintenance and trades shops	• Remove tools and equipment • Remove other materials and stores • Remove work benches, furniture, etc. • Dismantle mechanical and electrical rooms
Administrative offices and labs	• Remove equipment, furniture and fixtures • Decontaminate laboratories and remove equipment
Chemical tank farm	• Remove inventory • Dismantle and dispose of tanks
Building surfaces and structure	• Decontaminate interior floors, walls and ceiling s as required • Decontaminate exterior surfaces as required • Remove HVAC ductwork • Remove plumbing, electrical and other services • Demolish structures
Site	• Remove waste piles and other potentially contaminated materials • Remove contaminated soil and asphalt • Grade and revegetate immediate area • Final release survey

Table 2. Decommissioning tasks of pool type research reactor

Planning Phases	Work Packages
Reactor building/ room	• Remove control/absorber rods and drive assembly • Remove core components • Remove experimental sites/equipment • Remove primary heat exchangers and piping • Dismantle secondary cooling system • Drain pool water • Remove pool liner • Dismantle pool walls • Dismantle water purification system • Remove fuel and fuel storage equipment • Remove control room equipment • Remove ventilation system • Remove water, electrical, sever and other services • Dismantle cranes and hoists • Dismantle structure
Hot cells and labs	• Remove equipment and supplies • Remove active drains • Remove fume hoods and breathing air ventilation • Dismantle hot cells • Remove water, electrical, sewer and other services • Dismantle structures
Ancillary buildings	• Remove equipment, tools and supplies • Remove water, electrical, air and sever supplies • Dismantle structures
Site	• Grade and revegetate immediate area • Final survey

Table 3. Decommissioning tasks of CANDU Nuclear Power Plant

Planning Phases	Work Packages
Calandria vault	• Dismantle calandria internals and sheels • Decontaminate vault • Segment and remove calandria vault
Reactor building	• Remove steam generators • Remove primary heat transport pumps and piping • Remove moderator dump tanks • Dismantle and remove emergency core cooling system • Remove fuelling machine and ducts • Dismantle and remove internal concrete structures and shielding • Remove steel walkways, ladders and stairs • Dismantle containment structures and floor slab
Vacuum building and ducts	• Dismantle structures (decontaminate as necessary)
Reactor auxiliary bay	• Remove inventory of irradiate fuel • Drain and decontaminate bays • Segment and remove bays • Remove control center equipment • Remove standby generators • Demolish structure
Turbine hall	• Remove turbine generators • Remove other electrical and ancillary equipment • Demolish structure
Turbine auxiliary bay	• Remove condenser • Remove condenser water circulating and service pumps/piping • Remove de-aerator • Remove feedwater heaters, piping and other equipment • Raise structure
Service building	• Remove inventory of liquid and solid wastes • Decontaminate, dismantle and remove waste management equipment • Remove equipment from and decontaminate maintenance shops • Remove equipment from and decontaminate laboratories • Remove other equipment and materials from stores • Demolish structure
Heavy water treatment and storage facility	• Remove inventory of heavy water • Remove other equipment and materials • Decontaminate and dismantle structures
Water treatment system	• Remove pumphouse • Remove water treatment equipment • Dismantle structures
Administration building	• Remove contents • Dismantle structures
Site	• Remove services, roads, etc. • Final radiological and contaminants survey • Grade and landscape

number of years, a staged approach to the development of safety assessment can have considerable program, cost and quality advantages.

The structure is a hierarchical one by breaking down into work phases, work packages, tasks, and task's steps (See Fig. 2).

Decommissioning tasks for different types of facilities are illustrated as below (See Table 1~Table 3) [9].

5. Conclusion and Future Works

The decommissioning of nuclear facilities must be accomplished according to its structural conditions and radiological characteristics. An effective risk analysis requires basic knowledge about possible risks, characteristics of potential threats/hazards, and comprehensive understanding of the associated cause-effect relationships within a decommissioning for nuclear facility.

This paper proposes an approach to develop the hierarchical structure and hazards of dealing with improving the complexity and uncertainty for decommissioning safety assessment of nuclear facilities and the resolutions are proposed to improve the complexity and uncertainty for decommissioning safety assessment of nuclear facilities. These solutions can provide a comprehensive view of the risks in the decommissioning activities of a nuclear facility.

Afterwards, based on these solutions of safety assessments for decommissioning of nuclear facilities, the technique and a program of quantitative and probabilistic safety assessments for a decommissioning of nuclear facilities will be developed and the hazards and risks of the associated decommissioning tasks are expected to be quantitatively identified and assessed.

References

[1] IAEA, "Organization and Management for Decommissioning of Large Nuclear Facilities", Technical Reports Series No. 399, 2000.

[2] OECD/NEA, "Achieving the Goals of the Decommissioning Safety Case", WPDD, 2000.

[3] K.S. Jeong and H.K. Lim, "Systematic approach to the safety assessment for a decommissioning of nuclear facilities", APSS, 2007.

[4] Mays, L.W., "Water Supply Systems Security", McGraw-Hill Professional Engineering, 2004.

[5] Ang, H.S. and H. Tang, Probability Concepts in Engineering Planning and Design, 1984.

[6] El-Baroudy, I. and S.P. Simonovic, "Fuzzy Criteria for the Evaluation of Water Resources Systems Performance", Water Resources Research, Vol.40, W10503, 2004.

[7] Ganoulis, J.G., "Engineering Risk Analysis of Water Pollution: Probabilities", VCH, Weinheim, Netherlands, 1994.

[8] Haimes, Y.Y., "Risk Modeling, Assessment, and Management", John Wiley & Sons Inc., 2004.

[9] Zadeh, L.A., "Fuzzy Sets, Information and Control", Vol.8, No.3, pp.129-142, 1965.

[10] Canadian Nuclear Safety Commission, "Decommissioning Planning for Licensed Activities", Regulatory Guide G-219, CNSC, 2000.